EVALUATION OF MAIZE AND SUNFLOWER PRODUCTION IN A SEMI-ARID AREA USING IN-FIELD RAINWATER HARVESTING

by

John Jacobus Botha

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Promoter: Prof. L.D. van Rensburg
Co-promoter: Dr. M. Hensley

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DECLARATION

I declare that the thesis hereby submitted by me for the Philosophiae Doctor in Soil Science degree at the University of the Free State is my own independent work and has not previously submitted by me to another University/Faculty. I further cede copyright of the thesis in favour of the University of the Free State.

John Jacobus Botha

Signature________________

Date: November, 2006

Place: Bloemfontein, South Africa

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ABSTRACT

Subsistence farmers occupy a large area east of Bloemfontein around Thaba Nchu in the Free State Province of South Africa. They do not enjoy food security because the area is marginal for crop production. There are three reasons for this: (a) low and erratic rainfall that amounts to a mean of 543 mm per annum; (b) a corresponding high evaporative demand of 2198 mm per annum; (c) dominantly duplex and clay soils on which rainwater productivity (RWP) is low due to high runoff (R) and evaporation (Es) losses. It was hypothesised that the in-field rainwater harvesting (*IRWH*) technique could improve crop yields compared to conventional tillage (*CON*), and thereby serve to improve food security. Field experiments were conducted on the Glen/Bonheim; Glen/Swartland (dark brown A horizon); Khumo/Swartland and Vlakspruit/Arcadia ecotopes to study the benefits of the *IRWH* technique on maize and sunflower yields.

This thesis distinguishes between ex-field (R_{Ex}) and in-field runoff (R_{In}). R_{In} is transportation of water over the 2 m runoff strip in the *IRWH* technique. R_{Ex} occurs on *CON* and represents a loss of water and soil. Runoff and sedimentation results indicate that *IRWH* stops R_{Ex} completely and has the ability to harvest extra rainwater in the basins through R_{In} and minimize sedimentation. The results also indicate that mulch on the runoff area decreases R_{In} and sedimentation.

The Es process with different surface coverings was studied on two ecotopes *viz.* Glen/Bonheim and Glen/Swartland (red-brown A horizon). The soil coverings were as follows: bare soil; stone and organic mulch covering 50% of the surface; and organic mulch covering 100% of the surface. The studies were conducted during summer (69 days) and winter (52 days). Results indicated that the % cover affected Es more than mulch type, and that the influence of mulch on Es was more efficient when the drying-out period did not exceed 16 days. New terminology for the various Es stages was introduced. The role of E_o, water content and hydraulic conductivity during the Es process were clarified. Es measurements shallower than 300 mm were shown to be unreliable.

Field experiments were conducted on four ecotopes over two to seven growing seasons during the period 1996/1997 to 2002/2003 with maize and sunflower. The treatments were *CON*; *IRWH* with a bare basin and bare runoff area (*BbBr*); *IRWH* with organic mulch in the basins and a bare runoff area (*ObBr*); *IRWH* technique with organic mulch in the basins, stones on the runoff area (*ObSr*); *IRWH* technique with organic mulch in the basins, organic mulch on the runoff area (*ObOr*); *IRWH* technique with stones in the basins, organic mulch on the runoff area (*SbOr*).

Results showed that *IRWH* significantly increased maize and sunflower yields compared to *CON*. This was shown to be due to the ability of *IRWH* to stop R_{Ex} completely; enhance R_{In} and its resulting beneficial redistribution of water in the soil profile; minimize Es/ET, and contribute towards higher transpiration. Both yield and RWP results showed that *IRWH* stabilises crop production on these ecotopes, compared to *CON*. Comparing the *IRWH* techniques revealed that there was a consistent trend in yield and RWP *viz.* *ObSr* > *ObOr* ≈ *SbOr* > *ObBr* > *BbBr*. All the *IRWH* treatments with mulch on the runoff area produced higher RWP values and yield increased between 7 and 16% compared to *ObBr*. Although Es/ET results indicated that the *IRWH* treatments with mulch on the runoff area lost smaller portions of ET to Es than *ObBr*, mulch type on the runoff area and basins did not significantly affect Es in any of the years.

The most reliable way to describe the effectiveness with which rainwater was converted into grain by various techniques was by using the parameter RWP_n. It was computed by using long-term experimental and simulated yield data, which included rainfall during the fallow and growing seasons.

An empirical crop water stress model "Crop Yield Prediction for Semi-Arid Areas" (CYP-SA) was developed. Model composition and validation results with maize and sunflower are described. CYP-SA was used to make long-term maize and sunflower yield predictions with long-term climate data (81-year period). Cumulative probability functions of simulated long-term maize and sunflower yields have shown that *IRWH* is significantly superior to *CON*. The *ObSr* treatment was shown to be the best. It was also shown that it is advisable to plant maize or sunflower early in January, especially when the soil water profile is between ¾ full and full.

The *IRWH* technique was introduced to rural communities in the target area to improve household food production. The thesis reports on the rapid spread of the application of *IRWH* amongst homesteads, and on its ability to eradicate poverty at household level. Selected case studies were reported. Very promising results were obtained showing that households can reduce poverty by selling the produce.

The five pillars of sustainability, as defined by Smyth & Dumanski (1993) *viz.* agronomic productivity; crop production risk; conservation of natural resources; economic viability and social acceptability, were investigated in relation to *IRWH.* Results indicate that in the agro-ecological and socio-economic environment present in the rural communities around Thaba Nchu *CON* was non-sustainable and that *IRWH* was sustainable.

Keywords: semi-arid; evaporation; ex-field and in-field runoff; in-field rainwater harvesting; conventional tillage; mulching; maize; sunflower; rainwater productivity; sustainability; agronomic productivity; crop production risk; conservation of natural resources; economic viability; social acceptability; ecotope; water stress model.

OPSOMMING

Bestaansboere bewoon 'n groot area oos van Bloemfontein in die Vrystaat Provinsie van Suid Afrika. Hulle geniet nie voedsel sekuriteit nie omrede die area marginaal is is vir gewas verbouing. Daar is drie redes hiervoor: (a) lae en wisselvalige reënval met 'n gemiddelde jaarlikse reënval van 543 mm; (b) ooreenstemmende hoë verdampingsaanvraag (E_o) van 2198 mm per jaar; (c) hoofsaaklik dupleks en kleigronde waarop die reënwater produktiwiteit (RWP) laag is agv hoë afloop (R) en verdampings verliese (Es). Die hipotese was dat landeryreënwateropvang (*IRWH*) tegniek gewas opbrengste kan verbeter in vergelyking met konvensionele bewerking (*CON*), en sodoende voedsel sekuriteit verbeter. Veld eksperimente is uitgevoer om die voordele van *IRWH* op mielie en sonneblom obrengste te bestudeer op die Glen/Bonheim; Glen/Swartland (donkerbruin A horison); Khumo/Swartland en Vlakspruit/Arcadia ekotope.

Die verhandeling onderskei tussen buite landse (R_{Ex}) en binne landse afloop (R_{In}). R_{In} is die vervoer van water oor die 2 m afloop area in die *IRWH* tegniek. R_{Ex} kom op die *CON* voor en word geasosieer met water en grond verliese. R en sedimentasie resultate dui aan dat *IRWH* R_{Ex} geheel en al stop en die potensiaal het om ekstra reënwater in die bakkie area op te vang deur R_{In} en sedimentasie van bakkies vertraag. Die resultate dui aan dat R_{In} en sedimentasie van die bakkies beinvloed word deur deklae op die afloop area.

Es vanaf kaal grond, klip en organiese deklae wat 50% van oppervlak bedek, en organiese deklaag wat 100% van oppervlak bedek was bestudeer gedurende somer (69 dae) en winter (52 dae) periodes. Die resultate bewys dat % bedekking 'n groter invloed op Es het as deklaag tipe en dat deklae baie meer effektief is as die uitdroog siklus korter is as 16 dae. Nuwe terminologie vir die verdampings proses is bekend gestel en die rol van E_o, water inhoud an hidroliese gelydingsvermoë gedurende Es word word verduidelik. Es meetings vlakker as 300 mm is onakkuraat.

Veld experimente op vier ekotope oor periodes wat strek vanaf twee tot sewe jaar (1996/97 – 2002/03) was uitgevoer met mielies en sonneblom. Die behandelings was

CON, *IRWH* met kaal bakkie en afloop areas (*BbBr*); *IRWH* met organiese deklaag in bakkie area en kaal afloop area (*ObBr*); *IRWH* met organiese deklaag in bakkie area en klip deklaag op afloop area (*ObSr*); *IRWH* met organiese deklaag in en op bakkie en afloop areas (*ObOr*); *IRWH* met klip deklaag in bakkie area en organiese deklaag op afloop area (*SbOr*).

Resultate dui aan dat *IRWH* mielie en sonneblom opbrengste betekenisvol verhoog teenoor *CON*. Die redes hiervoor word toegeskryf aan die vermoë van *IRWH* om R_{Ex} te stop; R_{In} te bevorder en die daaropvolgende herverspreiding van water in die profiel bevorder; die verlaging van Es/ET wat aanleiding gee tot hoër transpirasie. Opbrengs sowel as RWP resultate dui aan dat die *IRWH* tegniek gewas produksie stabiliseer op die ekotope in vergelyking met *CON*. Vergelyking van die *IRWH* tegnieke ten opsigte van opbrengs en RWP dui 'n konstante tendens aan van *ObSr* > *ObOr* ≈ *SbOr* > *ObBr* > *BbBr*. Al die *IRWH* behandelings met deklae op die afloop area het hoër RWP waardes sowel as opbrengs verhogings van tussen 7 en 16% geinduseer in vergelyking met *ObBr*. Alhoewel Es/ET resultate aandui dat dat die *IRWH* behandelings met deklae op die afloop area kleiner hoeveelhede van ET aan Es verloor het, het deklaag tipe op die afloop sowel as bakkie areas Es nie betekenisvol beinvloed gedurende enige van die jare nie.

Die mees betroubare, gewenste en aanvaarbare manier om die effektiwiteit waarmee verskillende tegnieke reënwater omgeskakel in graan opbrengs is deur gebruik te maak van die parameter RWP_n, met langtermyn eksperimentele data oor 'n hoeveelheid agtereenvolgende seisoene wat die braak en groeiseisoen insluit.

'n Empiriese gewas water stremmings model "Crop Yield Prediction for Semi-Arid Areas" (CYP-SA) is ontwikkel. Model samestelling en validasie word beskryf vir mielies en sonneblom. CYP-SA met langtermyn klimaat data (81 jaar) is gebruik om langtermyn mielie en sonneblom opbrengs voorspellings te maak. Kummalitiewe waarskynlikheids funksies van langtermyn mielie en sonneblom opbrengste dui aan dat *IRWH* superieur is bo *CON*, *ObSr* is die beste behandeling, en dat mielies en sonneblom vroeg in January geplant moet word verkieslik wanneer die grond water profile tussen ¾ vol en vol is.

Die *IRWH* was bekendgestel in landelike gemeenskappe in die teiken area om huishoudelike voedsel sekuriteit te bevorder. Die verhandeling bespreek die onverwagte verspreiding van die toepassing van die tegniek onder huishoudings en die potensiaal om armoede op 'n huishoudelike vlak te verlig deur gebruik te maak van gevallestudies. Baie belowende resultate is verkry wat aandui dat huishoudings armoede verlig deur hul produkte te verkoop.

Die vyf pilare van volhoubaarheid soos aangedui deur Smyth & Dumanski (1993), nl. agronomiese produktiwiteit; gewas produksie risiko; bewaring van natuurlike hupbronne; ekonomiese vohoubaarheid en sosiaal aanvaarbaarheid was bestudeer. Volhoubaarheids resultate van *CON* en *IRWH* binne die spesifieke agro-ekologiese and sosio-ekonomiese omgewing teenwoording in die landelike gemeenskappe rondom Thaba Nchu dui aan dat *CON* nie volhoubaar is nie en *IRWH* wel.

Sleutelwoorde: semi-arid; verdamping; afloop; landeryreënwateropvang; konvensionele bewerking; reste/deklaag; mielies; sonneblom; reënwater produktiwiteit; volhoubaarheid; agronomiese produktiwiteit; gewas produksie risiko; bewaring van die natuurlike hulpbronne; ekonomiese vohoubaarheid; sosiaal aanvaarbaarheid; ekotoop; water stremmings model.

LIST OF ABBREVBIATIONS

α = parameter characterizing the Es process (mm $d^{-0.5}$) / slope of the relationship of ΣEs vs $t^{0.5}$ for intermediate stage of evaporation
ADEQI = adult equivalent income (R/month)
AI = aridity index (rainfall/evaporation)
APSIM = Agricultural Production Systems sIMulator
ARC-ISCW = Agricultural Research Council - Institute for Soil, Climate and Water

β = an evaporation characteristic soil parameter ($mm^{0.5}$)
Bare = flat crusted surface on the runoff plot with minimum surface storage/no mulch on the soil surface
BbBr = *IRWH* with a bare basin and a bare runoff area
Br = bare runoff area of the *IRWH* technique
BD = bulk density (Mg m^{-3})
Bo = Glen/Bonhein-Onrus ecotope
Br = brown

C = carbon
Ca = calcium
CEC = cation exchange capacity ($cmol^{+}$ kg^{-1} soil)
CF = crop factor
Cl = clay
ClLm = clay loam
CMUL = crop modified upper limit of available water (mm)
CON = conventional tillage
CPF = cumulative probability function
CYP-SA = Crop Yield Predictor for Semi-Arid areas

D = deep drainage (mm)
DAP = days after planting

DAS = days after saturation
DBSA = Development bank of Southern Africa
D-index = index of agreement
DkBr = dark brown
DkRBr = dark red brown
DOY = day of the year
DSSAT = Decision Support System of Agrotechnology Transfer
DUL = drained upper limit of available water (mm)

Ed = atmospheric evaporative demand
E_o = atmospheric evaporative demand (mm)
EoCF = crop water requirement
E_{pot} = potential evaporation (mm)
Es = evaporation from the soil surface (mm)
Es_{bare} = evaporation from the bare soil for a specific period (mm)
Es_1 = first phase evaporation
Es_2 = second phase evaporation
ESW_b = extractable soil water at the beginning of a day
ESW_e = extractable soil water at the end of a day
ET = evapotranspiration (mm)
Ev = evaporation from the crop (transpiration) (mm)

FAO = Food and Agriculture Organization
FDR = frequency domain reflectometry
F_p = fallow period
fSat = field saturation
FSM = Free State Mission
FSP = Free State Province
FTESW = fraction of total extractable soil water
$FTESW_{aa}$ = adapted fraction of total extractable soil water

GI = galvanized iron
G_p = growing season

HI = harvest index

I = infiltration
IR = in-field runoff
IR_b = water harvested from bare runoff surfaces (mm)
IR_s = water harvested from stone runoff surfaces (mm)
IR_o = water harvested from organic runoff surfaces (mm)
IRWH = in-field rainwater harvesting
ISF = integrated stress factor

K = hydraulic conductivity
K = potassium
k = transpiration efficiency coefficient (g m^{-2} mm^{-2})
KS = Kolmogorov-Smirnov test

LL = lower limit of plant available water (mm)
LT = long-term

M = organic mulch
MAR = mean annual rainfall (mm)
Mg = magnesium
ml = melanic diagnostic soil horizon
Mottl = mottled

N = nitrogen
Na = sodium
NEPAD = New Partnership for African Development
NWM = neutron water meter

Ob = organic mulch in the basins of the *IRWH* technique
ObBr = *IRWH* with organic mulch in basin and a bare runoff area
ObOr = *IRWH* with organic mulch in basin and organic mulch on the runoff area

ObSr = *IRWH* with organic mulch in basin and stone mulch on the runoff area
Or = organic mulch on the runoff area of the *IRWH* technique
Organic = organic reed mulch on the flat (crusted before mulch applied) surface on the runoff area
θ = soil water content (mm)
$\theta_{h(n-1)}$ = rootzone water content at harvesting of previous crop (mm)
$\theta_{h(n)}$ = rootzone water content at harvesting of the current crop (mm)
θm = soil water content (mm) determined gravimetrically
θ_p = rootzone water content at planting
$\theta_{p(n)}$ = rootzone water content at planting of current crop (mm)
$\theta_{p(n-1)}$ = rootzone water content at planting of the previous crop (mm)
θr = soil water content (mm) of the rootzone determined by NWM
θr_a = water content of rootzone, not adapted to cater for values above CMUL
θr_b = adapted water content of rootzone, to cater for values not to exceed CMUL
θv = volumetric soil water content
OSWU = Optimizing Soil Water Use Consortium
ot = orthic diagnostic soil horizon

P = phosphate
P = precipitation (mm)
PAW = plant available water (mm)
PAW_p = plant available water at planting (mm)
$PAW_{T/F}$ = plant available water at tasseling/flowering (mm)
P_f = rainfall during the fallow period (mm)
P_g = rainfall during the growing period (mm)
P_p = production period
PRA = Participatory Rural Appraisal
PTA = Pretoria
PUE = precipitation use efficiency (kg ha^{-1} mm^{-1})

PUE_g = precipitation use efficiency during the growing season (kg ha^{-1} mm^{-1})
PUE_{fg} = precipitation use efficiency over the preceding fallow period and the current growing season (kg ha^{-1} mm^{-1})
ΣP_n = total precipitation over n consecutive years (mm)

R = runoff (mm)
r^2 = correlation coefficient
R_{Ex} = ex-field runoff (mm) from the *CON* treatment
R_{In} = in-field runoff (mm)
RMSE = root mean square error
$RMSE_s$ = systematic root mean square error
$RMSE_u$ = unsystematic root mean square error
R_p = reproductive period
RSE = rainfall storage efficiency (%)
RWP_n = rainwater productivity over a period of n consecutive years (kg ha^{-1} mm^{-1})

S = stone mulch
ΔS = water stored in the rootzone (mm)
ΔS_f = change in soil water content of the rootzone during the fallow period (mm)
SaCl = sandy clay
SaClLm = sandy clay loam
SADC = Southern African Development Community
SbOr = *IRWH* with stone mulch in basin and organic mulch on the runoff area
SbSr = *IRWH* with stone mulch in basin and stone mulch on the runoff area
Se_b = amount of sediment collected in basins from bare runoff area (g m^{-2})
Se_o = amount of sediment collected in basins from organic mulch runoff area (g m^{-2})

Se_s = amount of sediment collected in basins from stone runoff area (g m^{-2})
SF = crop water stress factor
So = saprolite diagnostic soil horizon
SPAC = soil-plant-atmosphere continuum
Sr = stones on the runoff area of the *IRWH* technique
SS = soil water content at first severe stress (mm)
SSA = sub-Saharan Africa
Stone = inorganic stone mulch on the flat crusted surface of the runoff area/stones on the soil surface covering 50% of the area
suffix f = fallow
suffix gf = growing season plus fallow period
Sw = Glen/Swartland - Rouxville ecotope (dark brown A horizon)
Swr = Glen/Swartland - Rouxville ecotope (red brown A horizon)
SWAMP = Soil Water Management Programme
SWE = soil water extraction

t = time after preceding rainfall (d)
t = time (h) after drainage commenced at the 0 - 300 mm soil layer or rootzone
T = temperature (^{o}C)
TESW = total extractable soil water (mm)
TSF = integrated stress index/factor

U = upper limit of stage 1 drying (mm)

Va = Vlakspruit/Arcadia-Lonehill ecotope
Ve = vertic
V_p = vegetative period
Vp = pedocutanic diagnostic soil horizon
Vp = porosity value

WCT = water conservation tillage
WP_{Ev} = water productivity (kg ha^{-1} mm^{-1})

WRB = World Reference Base for soil resources
WRC = Water Research Commission
WUE = water use efficiency (kg ha^{-1} mm^{-1})
WUE_{Ev} = water use efficiency in terms of water used for transpiration (kg ha^{-1} mm^{-1})

Y = water content of the soil layer$_n$ or rootzone at time t (mm)
Yg = grain yield (kg ha^{-1})
ΣYg_n = total grain yield over n consecutive years (kg ha^{-1})

λ = stress weighting factor

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Rainfed agriculture is predominant in the world. Almost 80% of the cultivated land is in use by rainfed production systems, providing 60% of the world food production; whereas in sub-Saharan Africa (SSA), dryland agriculture makes up more than 95% of farm output (Kauffman, Mantel, Ringersma, Dijkshoorn, van Lynden & Dent, 2003; Stroosnijder, 2003). In semi-arid regions, rainfed agriculture is confronted with unreliable rainfall, poor soils and recurrent droughts with subsequent production failures (Fofana, Wopereis, Zougmoré, Breman & Mando, 2003; Stroosnijder, 2003). Food production in SSA has not kept pace with population growth. Since an increasing population requires an increased food production, more efficient use of rain in rainfed agriculture therefore deserves increased scientific attention.

One of the main factors limiting food production over large areas in SSA is a shortage of water. It is also true that a large proportion of the rain that does fall is not used productively to produce food. Every drop of rain that is wasted contributes to the problem of food insecurity. The problem is more serious for those people who depend on small areas of land for their food requirements. If food insecurity needs to be reduced the focus should be first on the needs of these people. Stroosnijder (2003) claims that when a natural landscape is transformed into a cultural landscape, the field water balance is affected and runoff and evaporation increase, while infiltration and transpiration decrease. This has direct and indirect effects on the precipitation use efficiency (PUE). Water conservation practices reduce erosion, improve soil qualities and increase PUE. Stroosnijder (2003) further claims that in semi-arid Africa water conservation can easily double PUE and contribute to food security.

According to Weibe (pers. comm., 2000, United States Department Of Agriculture: Economic Research Service, Washington D.C., USA.) a food security programme can be defined as a strategy to provide access for all persons in a community to an affordable, nutritionally adequate and culturally acceptable diet (food) needed for a healthy life. For people in developing countries who are dependent on what they grow themselves, it involves the production of an adequate quantity and variety of food in keeping with their need for protein, calorie and vitamin intake. For urban dwellers or others not directly involved in the production of food, it is essential that they have sufficient income to buy food. Food security programmes confront hunger and poverty. The purpose and scope of these programmes should be to:

- meet the food needs of low income people;
- increase the food self-reliance of communities;
- promote comprehensive responses to local food, farm and nutrition issues.

In the semi-arid areas of Southern Africa, scarce water supplies and low soil fertility are two of the main factors limiting food production. Developing communities are the most seriously affected by the resultant unsatisfactory level of food security and sustainability, which prevails in these areas. In South Africa, as is the case in other developing countries, levels and incidence of poverty tend to be disproportionately high amongst the rural population. The poorest of the rural households mostly live in semi-arid and arid areas and rely heavily on rainfed crop production for their livelihoods, often farming on marginal and fragile soils. In dry areas, lack of adequate water poses a major constraint to increasing agricultural production, and attempts to develop other economic activities. However, many agricultural scientists agree that with the use of appropriate production techniques, especially those that encourage conservation of water and soil resources, it is possible to increase and sustain agricultural output in semi-arid areas (Hatibu, 2002). In relation to smallholder agricultural needs in the semi-arid regions of the Southern African Development Community (SADC), Kronen (1994) accentuates the need to develop water harvesting and water conservation techniques. She estimates that 10 million people live in these areas. In the Free State Province of South Africa there are a large number of households living on smallholdings under similar conditions (Department of Agriculture - Free State, 1996). In particular, various water conservation techniques, among them rainwater harvesting, are seen as having the potential for increasing available water for successful crop production in semi-arid areas. While in many cases the biophysical properties of such techniques are well understood and their ability to increase yield proven, the lack of their widespread use remains a problem.

According to Directorate: Agricultural Statistics (2002), the area of South Africa is 122.3 million hectares (ha) of which 100.7 million ha (82.3%) consists of farmland including potential arable land and grazing land. The potential arable land is only 16.7 million ha or 13,7% of the total area of the country of which only 1.4 million ha is irrigable. The relative small portion of arable land is an indication that the natural resources of South Africa are limited. According to Ortman & Machethe (2003), almost 32% of the country receives an average annual rainfall of less than 300 mm and almost 60% of the area receives less than 500 mm per annum (Figure 1.1). This increases the risk of crop failures. In other words, the natural resources are limited while on the other hand population growth is taking place at rate of 1,56% per annum. This increases the pressure on the natural resources in terms of the increased food production. There is a great need therefore to quantify risk and improve crop yields by employing sustainable production techniques.

In South Africa's semi-arid areas rainfall is unevenly distributed, highly variable and decreases from east to west. Long droughts are typical. South Africa's problems are exacerbated by an increase in potential evaporation from east to west, in most parts much higher than the rainfall (Figure 1.1.). According to Bennie & Hensley (2001), 80% of South Africa has a semi-arid or arid climate. They also state that most of the dryland crop production occurs in the semi-arid zones where the aridity index varies between 0.2 and 0.5. These zones can be divided into winter and summer rainfall areas. The largest area of the country (± 85%) receives summer rainfall with droughts as common phenomena. Rainfall distribution is erratic and in the summer rainfall areas where most of the cereals are grown, it can represent a considerable constraint to crop production (Morse, 1996).

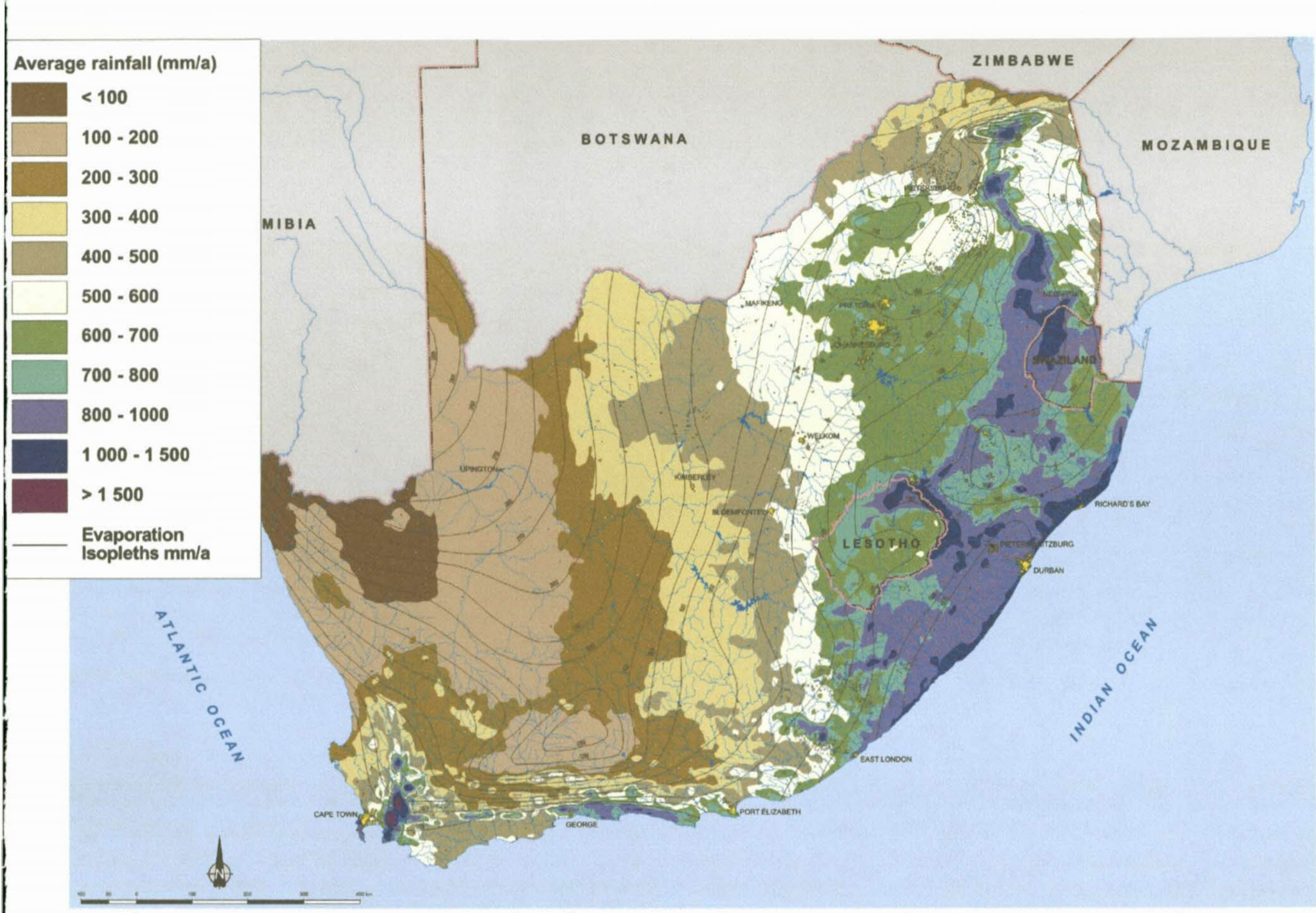

Figure 1.1 Mean annual rainfall (mm) and mean annual evaporation isopleths (mm) for South Africa (Anonym, 2006).

Irrigation agriculture is currently the biggest consumer of South Africa's scarce water resources. Savings on irrigation water through efficient farming practices will free precious water supplies for human and industrial consumption. Assisting small-scale farmers to optimally utilize the water resources at their disposal is therefore of critical importance. The mission of the Department of Agriculture in the Free State is to create a better life for the people in the Free State through self-reliance and utilization of agriculture and other resources within a sustainable living environment. An important objective of subsistence farmers is to produce food to sustain approximately four to five family members.

Insufficient water is a major constraint for the achievement of the South African Governments' vision of sustainable agriculture and rural development to foster macro-economic objectives necessary to counteract poverty and its multitude of consequences. Ideally, sustainable dryland farming systems should promote soil and water conservation, counteract and reverse land degradation, and reduce the need for external inputs to improve and sustain soil fertility and soil productivity. The stark realities facing South Africa are, however, that 33% of the total population living in communal areas, as well as more than 40% of the population living in densely populated, informal tenancy and mission settlements, are progressively experiencing food insecurity (De Villiers, Barnard, Botha, Monde, Anderson, & Beukes, 2005). The natural resources are also being exploited at an alarming rate. These are the driving forces behind the Free State's projects in the form of interventions aimed at tipping the balance towards household food security, affordable food and natural resource conservation.

Poverty, food insecurity and unemployment are three of the most critical challenges faced by the Free State. Close to 56% of the population of the Free State are living in poverty while the unemployment rate is estimated at 31% (Department of Agriculture - Free State, 2006). The Free State has identified the following as primary development objectives, which are part of the Free State Provincial Growth and Development strategy (2005 – 2014):

- Stimulate economic development
- Develop and enhance infrastructure for economic growth and social development
- Reduce poverty through human and social development
- Ensure a safe and secure environment for all people of the province
- Promote effective and efficient governance and administration.

To give effect to these developmental objectives, the Province has identified 11 areas that need to be addressed by 2014. Some of these areas are:

- To reduce unemployment from 39% to 20%.
- To reduce the number of households living in poverty by 5% per year.

In the Free State there are also a large number of households living on smallholdings (Department of Agriculture - Free State, 1996). A large area east of Bloemfontein, sometimes termed the "resettlement area", has been earmarked for developing farmers. There is a large population in the scattered villages and the two towns of Thaba Nchu and Botshabelo (Figure 1.2). The area is marginal for crop production because of, (a) relatively low and erratic rainfall (520 mm to 600 mm per annum), and

(b) predominantly duplex and clay soils on which high water losses occur due to runoff (R) and evaporation from the soil surface (Es). These losses cause a low PUE, resulting in low yields.

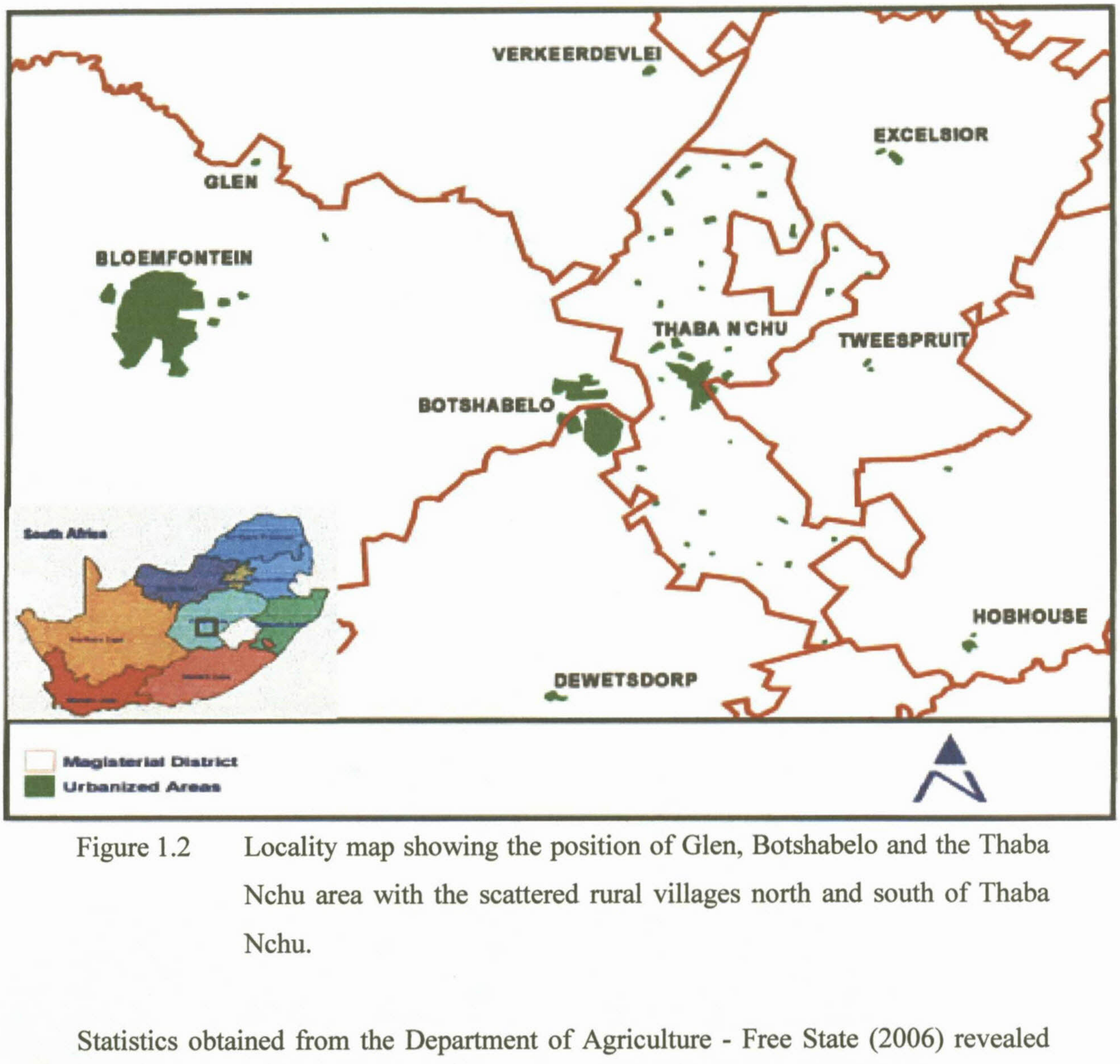

Figure 1.2 Locality map showing the position of Glen, Botshabelo and the Thaba Nchu area with the scattered rural villages north and south of Thaba Nchu.

Statistics obtained from the Department of Agriculture - Free State (2006) revealed that Free State agriculture contributes on average 4.6% of the gross geographical product of the Province. It also contributes 9.2% to agricultural production in South Africa. This makes it the third biggest contributor to the economy of the Province after mining and tourism. Crop production in the Free State generally contributes approximately 34%, 53%, 37% and 45% to South Africa's maize, sorghum, wheat and sunflower production, respectively. This makes the Free State the largest producer of grain crops in South Africa, and this is the reason behind its reputation as, "The Bread Basket of South Africa".

A simplified water balance equation for dryland crop production in soils without a water table and without significant internal lateral water movement for a specific period can be written as follows:

Water for yield = water gains - water losses

$$Ev = (P \pm \Delta S) - (ES + R + D) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.1)$$

where:

Ev = evaporation from the crop (transpiration) (mm)
P = precipitation (mm)
ΔS = change in water stored in the rootzone (mm)
Es = evaporation from the soil (mm)
R = runoff (mm)
D = deep drainage (mm).

In the semi-arid crop production areas in the central part of South Africa, the problem of low and erratic rainfall is exacerbated by two major unproductive soil water losses, *viz.* R and Es. These losses hamper the efficient use of available water for crop production. These losses must be minimized in order to optimize PUE. An improved soil water regime can be achieved by increasing the amount of water stored in the root zone by reducing losses through Es, R, and D. Deep drainage is generally negligible on duplex and clay soils and all coarser textured soils underlain by an impermeable layer within the root zone. The two main losses are therefore Es and R. Various South African researchers have found the loss of R to be between 6 and 30% of the annual rainfall on various soils under conventional tillage (*CON*) conditions (Haylett, 1960; Du Plessis & Mostert, 1965; Bennie, Strydom & Vrey, 1998). Runoff from croplands is usually associated with water induced soil erosion. Bennie & Hensley (2001) claim that between 50 and 75% of the annual precipitation is lost through Es. Water loss by Es is severe, especially during long fallow periods (Unger & Stewart, 1983; Hensley, 1986). This is the main cause for low rainfall storage efficiency (RSE). Most rainfall events in the Central and Western Free State are less than 20 mm. On a dry soil this is only sufficient to wet the evaporation zone. If no further rain falls within about a week, all this water will have been lost by evaporation (Hensley, 1986).

The questions that need to be answered can be stated as follows:

- Could an appropriate production technique be developed which can:
  - reduce R and Es and
  - increase crop water use, growth and yields?
- Would such a production technique contribute to an improvement in agronomic productivity?
- Would such a production technique be sustainable in terms of the five pillars of sustainability namely, increase agronomic productivity, reduce crop production risk, conservation of natural resources, economic viability and social acceptability?
- Would this technique be utilized by the people to help them to overcome food insecurity, reduce poverty and create jobs?

The in-field rainwater harvesting technique (*IRWH*), developed by the Agricultural Research Council - Institute for Soil, Climate and Water (ARC-ISCW) at Glen combines the advantages of water harvesting, no-till, basin tillage and mulching on high drought risk clay soils (Hensley, Botha, Anderson, Van Staden & Du Toit, 2000) (Figure 1.3). This innovative water conservation technique has the potential to eliminate runoff and reduce Es considerably, resulting in potentially increased yields due to increased plant available water. The technique consists of promoting runoff on a 2 m wide strip between alternate crop rows, and storing the runoff water in the basins. The water collected in this way can infiltrate deep into the soil below the surface layer from which evaporation takes place. After the basins have been constructed no-till can be applied to the land as a whole. Due to the absence of cultivation a crust soon develops on the runoff strip, enhancing runoff towards the basin. The *IRWH* technique is specifically suited to many ecotopes in the area around Thaba Nchu shown in Figure 1.2. The term ecotope can be defined as an area of land on which the natural resources (climate, topography and soil) that influence yield, are reasonably homogeneous (MacVicar, Scotney, Skinner, Niehaus & Loubser, 1974).

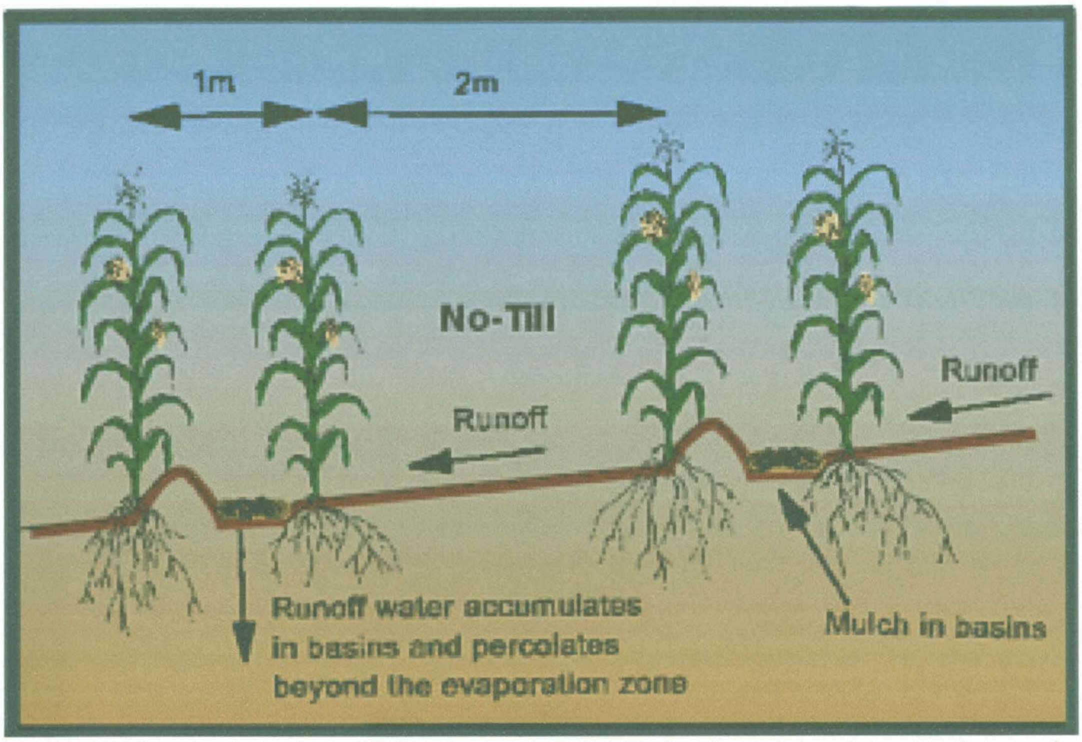

Figure 1.3 A diagrammatic representation of the in-field rainwater harvesting technique.

In the name of an ecotope the following occurs: location/soil form - soil family e.g. Glen/Bonheim – Onrus. The locality is an approximate description of the geographical location and provides for most readers a general description of the prevailing climate. The soil forms give an indication of the unique vertical sequence of diagnostic horizons and/or materials (Van der Watt & Van Rooyen, 1995). Most soil forms are divided into a number of soil families, which have in common the properties of the soil form, but are differentiated within the form on the basis of other defined properties (Van der Watt & Van Rooyen, 1995). According to these authors the range of variation at the family level is thus narrower than at the soil form level.

It was hypothesized that *IRWH* is a sustainable crop production technique that could increase crop yields by minimizing the unproductive losses (Es and R) and maximizing PUE in the semi-arid areas east of Bloemfontein (Figure 1.2). The requirements for sustainable crop production according to Smyth & Dumanski (1993) are improvement in agronomic productivity, reduction in production risk, conservation of the natural resource base, economic viability and social acceptability.

1.2 OBJECTIVES

The objectives of the various chapters were as follows.

- The objective of Chapter 2 was to quantify, on two ecotopes at Glen, the effect of different mulches placed on the runoff strip on runoff and sedimentation.
- The objective of Chapter 3 was to quantify and model the influence of different mulch strategies on Es from a clay and a duplex soil located in a semi-arid area at Glen.
- The objective of Chapter 4 was to compare maize production over a period of four seasons (1999/2000 – 2002/2003) on the Glen/Bonheim ecotope using *CON* and the *IRWH* technique with various combinations of mulch types in the basins and on the runoff areas. This Chapter also discusses effects of various combinations of mulch types in the basins and on the runoff area of the *IRWH* system in terms of crop yield and PUE.
- The general objective of Chapter 5 was to evaluate the agronomic productivity of the *IRWH* technique in terms of its ability to convert rainwater into sunflower seed yield in a sustainable manner by minimizing the unproductive losses (Es and R) and maximizing PUE. Normal *CON* tillage was compared with various *IRWH* treatments, with on-station (Glen/Bonheim and Glen/Swartland) and on-farm Khumo/Swartland and Vlakspruit/Arcadia) field experiments and sunflower as reference crop. This Chapter discusses effects of various combinations of mulch types in the basins and on the runoff area of the *IRWH* system in terms of crop yield and PUE.
- The general objective of Chapter 6 was to develop a simple empirical stress model that is able to deal with the very complicated *IRWH* system, and thereby provide useful information for the comparison between *CON* and *IRWH* with different mulch treatments.
- The objective of Chapter seven was to use the empirical stress model and long-term climate data to conduct long-term maize and sunflower yield simulations to quantify risk of crop failure with various tillage treatments and

management practices on the Glen/Bonheim, Khumo/Swartland and Vlakspruit/Arcadia ecotopes.

- The objective of Chapter eight was to demonstrate and implement the application of *IRWH* in rural villages in the quest for farmers to fight food insecurity and poverty. This study was aimed at evaluating the contribution that home gardens and croplands made towards alleviating food insecurity and poverty.
- Chapter nine discusses the sustainability of the *IRWH* technique in terms of the five pillars of sustainability namely, agronomic productivity, crop production risk, conservation of natural resources, economic viability and social acceptability.

This thesis is a typical example where research was conducted, research results disseminated and a researched and proven technique applied by the people who really need it.

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CHAPTER 2: WATER HARVESTING THROUGH IN-FIELD RUNOFF

ABSTRACT

This chapter distinguishes between ex-field and in-field runoff. In-field runoff refers to the transportation of water over the 2 m runoff strip in the in-field rainwater harvesting (IRWH) technique. Ex-field runoff is that which occurs on cultivated lands on which conventional tillage (CON) is practised, and which represents a loss of water. To quantify the amount of in-field runoff harvested by IRWH, runoff was measured with automatic tipping bucket runoff meters on separate runoff plots, each 2 m long and 3 m wide, on the Glen/Bonheim and Glen/Swartland ecotopes at Glen in the Free State Province of South Africa. These ecotopes are representative of a large semi-arid area in South Africa with clay or duplex soils that is marginal for crop production using CON techniques. The runoff plot treatments were: (a) flat crusted surface with minimum surface storage (bare); (b) organic reed mulch on the flat (crusted before mulch applied) surface (organic mulch); and (c) inorganic stone mulch on the flat crusted surface (stone mulch). Water and sediment from the 2 m runoff strip were also measured to predict soil movement from the runoff area towards the basin area. Runoff measurements over three rain seasons showed that the responses on the two ecotopes were very similar. This made it acceptable to pool the results. Based on the pooled results linear regression equations that described the precipitation/in-field runoff relationships on the different runoff strips were computed. These equations were used together with local long-term rainfall data to determine the in-field runoff harvesting potential of the three treatments on the two ecotopes in the long-term. The long-term predictions indicate that organic mulch, stone and bare treatments on these ecotopes have an 80% probability of harvesting 22 mm, 90 mm and 156 mm of in-field runoff every season, respectively. For predicting long-term ex-field runoff with CON, results from an earlier long-term runoff experiment at Glen on a comparable ecotope were used. Predictions showed that with CON on these ecotopes there was a very high probability (80%) of losing 40 mm of rainwater every year through ex-field runoff. Sediment yields from the bare, stone covered and organic mulch covered runoff areas amounted to 3724, 1958 and 551 grams per m^2 *of* *runoff area, respectively. Estimates indicated that, depending on the treatment applied on the runoff strip and in the basins, it would take between 12 and 82 years for the basins to become filled with sediment.*

Keywords: in-field runoff, ex-field runoff, in-field rainwater harvesting, mulches and sediment

2.1 INTRODUCTION

Runoff is negatively perceived by crop farmers, and rightfully so, because valuable water and soil are lost in the process. Various short-and long-term runoff studies have been conducted in the past 50 years in South Africa, not only to determine the extent of these losses, but also to investigate measures to counter the negative impacts on water and soil conservation. Some of the most important studies reported in South Africa are Haylett (1960), Du Plessis & Mostert (1965), and Bennie, Strydom & Vrey (1998). The Haylett experiment stretched over a period of 27 years at Pretoria on a red sandy loam soil (Hutton form) and mean annual rainfall (MAR) of 730 mm. Runoff (R) was measured on two slopes, 3.8% and 7%. There were many treatments including the following: monocrop maize with conventional tillage, plots conventionally tilled annually and left bare, and permanently bare untilled plots. Runoff, expressed as a percentage of the rainfall measured during each of the 27 seasons of the experiment, averaged to 24%, 25% and 48% respectively for these three treatments when the datasets for the two slopes were combined. These results clearly demonstrate how much water becomes unavailable for crop growth due to runoff losses on this semi-arid ecotope. The results indicate that R amounts to an average of around 175 mm per year for maize production using conventional tillage. This is in spite of the fact that this soil is rapidly permeable. The exacerbating influence of bare crusted soil on R is clearly demonstrated, causing it to be nearly twice that on the bare tilled plot, and amounting to nearly half of the MAR. According to Haylett (1960) the soil losses through runoff on mono-crop maize with conventional tillage amounted to 7 500 kg ha^{-1} year^{-1} or a loss of 0.5 mm of topsoil per year (assuming that bulk density is 1.50 Mg m^{-3}). Results for the conventionally tilled bare treatment were even worse. Soil losses amounted to 9 800 kg ha^{-1}, or 0.7 mm loss of topsoil per year. These results demonstrate how susceptible this soil was to erosion by water. Soil erosion is a problem of worldwide concern because of its consequences in terms of the loss of productivity and increased potential for sediment pollution in streams, lakes and water reservoirs (Agassi, 1990).

Du Plessis & Mostert's experiment at the Glen Agricultural Institute near Bloemfontein lasted for 18 years (1937/38 - 1954/55). The MAR is 543 mm. The runoff plots were located on a soil of Tukulu form (Zere, 2003) situated on a 5% slope. The texture of the topsoil is loamy fine sand to fine sandy loam with between 11% and 15% clay and 19% silt and clay (Du Plessis & Mostert, 1965; Zere, 2003). Du Plessis & Mostert (1965) reported average runoff losses of 8.5%, 10.3% and 31.9% of annual rainfall respectively for plots with the following treatments: monocrop annual maize with conventional tillage; conventionally tilled annually as for maize production but the plots left bare; and plots left bare permanently and never tilled. As in the case of the Pretoria experiment the exacerbating effect of soil crusting on runoff was again clearly demonstrated. Soil erosion on the mono-crop maize conventional treatments amounted to 8 600 kg ha^{-1} or 0.6 mm loss of topsoil per year. The conventionally tilled bare treatment was even worse, with a loss of 13 200 kg ha^{-1} of soil, or 0.9 mm topsoil per year.

Bennie *et al.* (1998) measured runoff over a number of years on soils with varying textures at four localities in the central part of South Africa. They selected only rain events of more than 2 mm of known rainfall intensity. Runoff estimates amounted to 25% of the rainfall from plots that were conventionally tilled annually but left bare.

These results have certainly helped to establish an awareness about runoff and therefore the obvious negative impact it will have on crop production. On the other hand municipalities and the Department of Water Affairs, depend heavily on runoff to fill dams and hence to lower their risks. These users perceive runoff in a positive light. Irrigation farmers have another view on catchment runoff; they depend on it as a production resource and like to see full dams. They will however take measures to counter surface runoff from irrigated lands.

Baumhardt, Wendt & Moore (1988) claim that maximizing infiltration is the most effective way to decrease losses of rainwater by runoff and evaporation. Morin & Benyamini (1990) propagated basin tillage systems with large surface storage capacities to prevent runoff and maximize infiltration. Lang & Mallett (1984) reported a reduction in runoff and soil loss with residue cover exceeding 30% at Cedara in KwaZulu-Natal on a highly weathered and weakly structured clay loam soil. Hensley, Botha, Anderson, Van Staden & Du Toit (2000) reported runoff losses from 3 m x 20 m bare untilled runoff plots over a period of three years on the Glen/Bonheim and Glen/Swartland ecotopes. Runoff ranged from 13% to 31% of measured rainfall. McPhee (1988) stated that for optimal resource conservation and development, farmers and agricultural advisors must have knowledge of the important characteristics of soils, such as depth, fertility, texture and soil erodibility. He also stated that they must know that special measures, like conservation tillage practices or no-till, need to be considered when erodible soils are used for annual cropping. High runoff and erosion rates are associated with the formation of soil crusts. The high runoff rates caused by crusting promote the transport of soil. It is known that raindrop impact can cause surface compaction and therefore contributes to the formation of soil crusts. Hoogmoed & Stroosnijder (1984) found that rainfall characteristics play a key role in crust formation. Stroosnijder & Hoogmoed (1984) indicated that crusts strongly reduce the infiltration capacity of a soil. According to Hoogmoed & Stroosnijder (1984) the presence of a crust on untilled soils is a permanent feature. Both these authors claim that basin tillage and tied ridges could prevent ex-field runoff by as much as 50% due to the creation of surface storage.

It is obviously not possible for logistical and economic reasons to do detailed research work on every ecotope used for crop production in a country. To maximize research efficiency it is therefore advantageous to focus attention on carefully selected benchmark ecotopes that represent a wide range of ecotope characteristics (Hensley, Anderson, Botha, Van Staden, Singels, Prinsloo & Du Toit, 1997; Hensley *et al.*, 2000). To ensure efficient extrapolation of the results obtained on these ecotopes to other similar ones (i.e. pedotransfer actions), it is desirable that the main ecotope characteristics that affect productivity be characterized in detail (Hensley *et al.*, 2000). Using the data presented by Eloff (1984) it is possible to make an estimate of the area in the Free State Province, considered as marginal for conventional crop production, on which significantly increased yields could be expected using the in-field rainwater harvesting (*IRWH*) technique. The estimated area is 800 000 ha (Tekle, 2005). The two benchmark ecotopes used in this study are representatives of parts of this area. A portion occurs between the towns of Dewetsdorp and Excelsior. It includes the region surrounding Thaba Nchu and Botshabelo (Figure 1.2) where there are a large number of rural households.

Hensley *et al.* (2000) developed an *IRWH* technique (Figure 1.3) for high drought risk clay and duplex soils on semi-arid ecotopes. The technique combines the advantages of basin tillage, no-till and mulching. They showed that in-field runoff can be harnessed positively and used to enhance crop production, soil and water conservation, and sustainability. Ex-field runoff, which occurs on conventionally tilled land (*CON),* was eliminated completely with this technique.

The *IRWH* system is regarded as a special form of water harvesting, categorised as mini-catchment runoff farming by Oweis, Hachum & Kijne (1999). It is particularly relevant for clay and duplex soils in semi-arid areas. The ability of the system to convert water into grain yield was well demonstrated by Hensley *et al.* (2000), and Botha, Van Rensburg, Anderson, Hensley, Macheli, Van Staden, Kundhlande, Groenewald & Baiphethi, (2003), where the technique was compared to conventional tillage (*CON*). Seed yield advantages above *CON* varied between 20 and 50% depending on the year and crop type.

Hensley *et al.* (2000) measured runoff from 2-metre bare untilled runoff strips within the *IRWH* cropping area on the Glen/Bonheim and Glen/Swartland ecotopes for a short period and found it to be 39% and 35% of the measured rainfall respectively, with an average of 37%. These measurements were different from those on the 3 m x 20 m runoff plots. It is not clearly understood why the runoff values already mentioned for the 20 m plots were much lower than those from the short 2 m plots. It is possible, however, that the latter measurements were made during a relatively wet period, and furthermore that the complications involved with overland flow on the long plots caused runoff to be reduced. The runoff measurements per event from the 20 m and 2 m strips were combined by Hensley *et al.* (2000) and correlated against the amount of rainfall (P) for each event. Small rainfall events of < 8 mm were excluded. The runoff result of this exercise was given by Equation 2.1.

$$R = (0.473 \times P) - 2.168 \qquad (2.1)$$

It refers to runoff from bare, crusted untilled soil. The runoff values represented the amount of rainfall that could be harvested from the runoff strips, and employed to increase precipitation use efficiency (PUE). The *IRWH* technique was developed further and tested in greater detail by Botha *et al.* (2003). The influence of different kinds of mulches placed on the runoff strip was studied in particular.

It had been shown that the *IRWH* system with a bare runoff strip was able to stop ex-field runoff and soil erosion. The aim of this chapter is to quantify, on two ecotopes at Glen, the effect of different mulches placed on the runoff strip on runoff and sedimentation. The latter process is important as it influences the maintenance of the system and its sustainability.

2.2 PROCEDURE

The runoff experiments were conducted at the Glen Agricultural Institute (28°57` S; 26°20` E), 25 km north east of Bloemfontein in the Free State Province of South Africa on the Glen/Bonheim and Glen/Swartland ecotopes.

2.2.1 DESCRIPTION OF ECOTOPES

2.2.1.1 Soil

Important soil characteristics of the two ecotopes studied i.e. the Glen/Bonheim ecotope, and the Glen/Swartland ecotope, are summarised in Table 2.1. Soil profile descriptions and analytic data for the soils of the two ecotopes are presented by Hensley *et al.* (2000). These ecotopes form part of land type Ea39c (Land Type

Survey Staff, 2002). The soil of the Glen/Bonheim ecotope is classified as belonging to the Onrus Family of the Bonheim (Bo) Form (Soil Classification Working Group, 1991), and a vertic phaeozem in the classification system of the World Reference Base for Soil Resources (1998). It is a dark brown clay soil overlying $CaCO_3$ enriched sandstone saprolite at a depth of 800 mm. The parent material of the solum is a mixture of dolerite and sandstone colluvium, with dolerite dominating. The underlying saprolite is sufficiently weathered to a depth of at least 1200 mm and offers no significant impedance to root development to that depth. The effective root zone is considered to be 1200 mm. The soil has a high clay content in the A and B horizons (40 - 45%), with a high proportion of smectite clay minerals resulting in strongly developed structure and a high CEC (24 - 25 $cmol_c$ kg^{-1} soil). Dry spells cause large cracks that penetrate deep into the soil. Additionally, the surface soil has a high plasticity index of between 21 and 33, and self-mulching properties, which promote erosion when high intensity rain falls on the dry soil. In the surface soil the exchangeable Na content is low (0.7 $cmol_c$ kg^{-1} soil) and it cannot therefore be the course for exacerbating the swell-shrink properties. However, the relatively high exchangeable Mg content (11 - 12 $cmol_c$ kg^{-1} soil) may promote cracking (Hensley *et al.,* 2000).

The soil of the Glen/Swartland ecotope is classified as belonging to the Rouxville Family of the Swartland (Sw) Form (Soil Classification Working Group, 1991). It is a vertic chromic cambisol in the classification system of the World Reference Base for Soil Resources (1998). The morphology of the profile can be described according to Hensley *et al.* (2000) as a dark brown, poorly structured, fine sandy clay orthic A horizon with a clear transition at about 250 mm to a strongly structured, dark brown, sandy clay, pedocutanic B horizon. The structure of the B horizon becomes moderately strong below 400 mm, and merges into calcareous, sandstone saprolite at 1000 mm. The saprolite is well weathered, offering no significant impedance to root development to at least 1200 mm. The soil has a high CEC (23 - 27 c mol_c kg^{-1} soil) throughout, low exchangeable Na content, and considerably more exchangeable Mg (7 - 11 mol_c kg^{-1} soil) than Ca (5 - 7 mol_c kg^{-1} soil) up to a depth of 800 mm. Wide cracks appear in the B horizon when the soil is dry. When extremely dry these cracks are transmitted to the A horizon as well. The plasticity index of the surface soil is relatively low (22) compared to the Bonheim soil (Hensley *et al.*, 2000).

The Glen/Bonheim ecotope is situated 300 m from the Glen/Swartland ecotope on the same footslope terrain unit with a western aspect and 1% slope. The climate and topography of both ecotopes are therefore very similar.

Table 2.1 Important soil characteristics of the ecotopes studied (Hensley *et al.*, 2000)

Profile detail						
Soil form	Horizon	Depth to lower boundary (mm)	Colour	Clay (%)	BD [*1] (Mg m^{-3})	Diagnostic horizon
Bo	A	400	Dark brown	45	1.30	Melanic
	B1	550	Dark brown	43	1.45	Peductanic
	B2	800	Dark brown	40	1.45	Peductanic
	C	1300	Many coloured geogenic mottles and lime	38	1.45	Saprolite: well weathered sandstone
Sw	A	250	Dark brown	38	1.50	Orthic
	B1	600	Dark brown	40	1.66	Pedocutanic
	B2	900	Dark brown	44	1.51	Pedocutanic
	C	1200	Many coloured geogenic mottles and lime	35	1.46	Saprolite: well weathered sandstone

[*1] Bulk density.

2.2.1.2 Climate

Rainfall and temperature data for Glen have been recorded for 81 years (1922 - 2003) and class A-pan evaporation data for 42 years (1958 - 2000). Monthly mean values are presented in Table 2.2. The high mean annual evaporative demand of 2198 mm and relatively low mean annual rainfall (MAR) of 543 mm make this a semi-arid climate. The worst conditions of the crop-growing season generally occur during December and January, with aridity index (AI) values (rainfall/evaporation) of 0.23 and 0.30 respectively. Rainfall during these months is generally very erratic with much of it in the form of high intensity rainfall events. The fact that the rainfall during March is relatively high and reliable, while the evaporative demand is relatively low (AI = 0.45), can be used advantageously by planting crops with a short growing season early in January. Low temperatures are experienced during the winter, coupled with very little rain. There is generally no shortage of radiation and hence the high evaporation from the soil surface (Es). This fact accentuates the need for water conservation techniques to include efficient procedures to minimize Es.

Table 2.2 Long-term monthly and annual climate data from the Glen meteorological station (ARC-ISCW data); rain & temperature 1922 - 2003; evaporation 1958 – 2000

Item	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Long-term mean
Rain (mm)	8.1	11.6	19.3	49.0	68.2	66.6	83.4	77.6	80.7	49.3	19.9	9.0	542.7
Evap*[1] (mm)	93.5	140.6	197.5	239.1	256.0	291.6	276.5	207.7	177.1	126.1	110.6	81.9	2198.2
MaxT*[2]	17.8	20.6	24.4	25.4	28.3	30.2	30.8	29.5	27.4	23.9	20.5	17.9	24.8
Min T	-1.6	0.9	5.2	9.2	12.0	14.0	15.3	14.8	12.6	7.8	2.8	-1.1	7.5
Ave. T	8.1	10.7	14.8	17.5	20.1	22.0	23.0	22.1	19.9	15.8	11.6	8.2	16.2
AI*[3]	0.087	0.083	0.098	0.205	0.266	0.228	0.302	0.374	0.456	0.391	0.180	0.110	0.232

*[1] Class A pan.

*[2] T = temperature in °C; mean values for the month.

*[3] Aridity index = rain/evaporation.

2.2.2 RUNOFF MEASUREMENT

Runoff was measured with automatic tipping bucket runoff meters from plots 2 m long and 3 m wide on the Glen/Bonheim and Glen/Swartland ecotopes. The runoff areas of all three runoff plots were prepared in the same way as in the different treatments of the field experiments described by Botha *et al.* (2003). The three runoff treatments (Figure 2.1) were as follows: (i) runoff measured on a flat crusted surface with minimum surface storage (bare); (ii) runoff measured with organic reed mulch covering 60% of the flat crusted runoff surface (mulch); (iii) runoff measured with stone mulch covering 60% of the flat crusted runoff surface (stones).

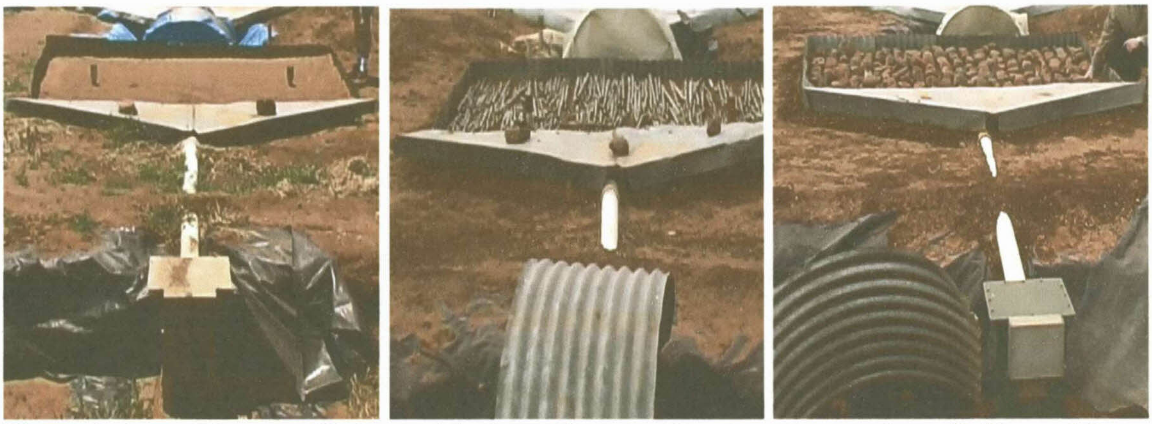

Figure 2.1 The runoff plots with the various surface treatments: bare (left), mulch (middle) and stones (right).

2.2.3 SEDIMENT MEASUREMENT

In order to quantify soil erosion from the runoff areas, separate 3 x 2 m plots were prepared with the same treatments as described above. Water and sediment were collected in a 120-litre drum using a galvanized gutter to direct the flow of the suspension. The sediment load in the suspension was determined by the following procedure after each rainfall event. The bulk of the surface portion of the collected suspension was carefully transferred to a calibrated 25-liter container without disturbing the sediment in the 120-liter drum, and leaving a depth of about 100 mm of the suspension in the drum. For every 25-liter of bulk suspension, two samples were taken to determine its sediment load. The remaining 100 mm of the suspension in the receiving drum was then stirred thoroughly, and while stirring five samples were taken. The rest of the suspension was then carefully transferred to a calibrated 25-liter container to determine its volume. All the samples were weighed, and then the water was evaporated in an oven. After drying (104°C) the samples were weighed again and the amount of sediment calculated. The method was verified as follows: one kilogram of oven dry soil was mixed with 10 liter of water. After a settling time of 2 hours the sample procedure described above was followed. It was concluded that the procedure was valid because the recovery was 97%, indicating a systematic error of 3%.

2.3 RESULTS AND DISCUSSION

2.3.1 RAINFALL CHARACTERISTICS

Although the MAR (Table 2.2) may appear to be adequate for the production of cash crops, the intensities and distribution are of such a pattern that the water available during the crop growth cycle is generally inadequate to support a good crop. The long-term rainfall pattern (1922 - 2003) is characterized in Table 2.3.

Table 2.3 Characterization of the rainfall pattern at Glen from January 1922 to June 2003

Parameter	Classes of rainfall amount per event				Total
	0 – 10 mm	11 – 20 mm	21 – 30 mm	>30 mm	
Amount of rainfall (mm)	13564	12954	6833	10607	43958
% of total	31	29	16	24	100
Number of rainfall events	4335	944	281	246	5806
% of total	75	16	5	4	100
Mean no. of rain events per annum	54	12	4	3	73

Of all the rainfall events, 75% were between 0 and 10 mm, contributing 31% of the total rainfall. Water losses by evaporation after these events are expected to be very high. Nine percent of the rainfall events occurred in the form of heavy thundershowers of more than 20 mm, representing 40% of the total rainfall. Adequate water storage during these storms is therefore essential for reasonable crop yields. This reveals two important facts in relation to water conservation techniques for promoting sustainable crop production with a Glen type of rainfall, i.e. the need to minimize water losses by both runoff and evaporation. That is exactly what the *IRWH* technique attempts to achieve.

2.3.2 EFFECT OF MULCHES ON RUNOFF

Runoff results for different mulch treatments for both the Glen/Bonheim and Glen/Swartland ecotopes, are summarised in Table 2.4.

Table 2.4 Rainfall and runoff on the Glen/Bonheim and Glen/Swartland ecotopes for the 1999/2000, 2000/2001 and 2001/2002 seasons with three different surface treatments

Ecotope	Glen/Bonheim							Glen/Swartland						
Season	Rain	Runoff						Rain	Runoff					
		Bare		Stone		Organic			Bare		Stone		Organic	
	mm	mm	%^{*1}	mm	%^{*1}	mm	%^{*1}	mm	mm	%^{*1}	mm	%^{*1}	mm	%^{*1}
99/00	479	110	30^{*2}	59	12	16	3	489	167	38^{*3}	80	16	11	2
00/01	544	255	47	175	32	26	5	544	214	39	124	23	16	3
01/02	591	280	47	168	28	54	9	567	228	40	115	20	32	6
Average	538	215	43	134	25	32	6	533	203	39	106	20	20	4

^{*1} = runoff as % of rainfall.

^{*2} = % based on a total rainfall of 363 mm.

^{*3} = % based on a total rainfall of 444 mm.

^{*2} & ^{*3} Necessary because of the tipping bucket runoff meter being out of action for part of the time.

A few runoff events were not recorded during the 1999/2000 season on both ecotopes, due to repairs being made to the tipping bucket runoff meter. However, it can be stated that the number of recorded events was representative of the season. The total annual rainfall for the ecotopes shows that the 99/00 season was slightly below average, the 00/01 season normal, and the 01/02 season was a relatively wet season. The rainfall also differed significantly between ecotopes during the 01/02 season. The results of the first season indicated that runoff was lower in all the treatments, compared to the following two years. This can probably be attributed to the experiment being newly established (i.e. soil crust not yet fully formed), and/or the low rainfall intensities during the rain events during the 99/00 season.

The results show that the treatment of the runoff area has a major influence on runoff and therefore water harvesting. Similar results were obtained on the two ecotopes. The bare treatments had the highest runoff of 43% and 39% of the rainfall running off on the Bonheim and Swartland soils, respectively. Runoff was enhanced by the formation of a surface crust, a natural characteristic of these soils. On the other hand, organic mulch clearly suppressed runoff and enhanced infiltration. The average runoff from the organic mulch treatment was almost seven times less than from the bare plot on the Bonheim soil and nearly ten times less on the Swartland soil. The stone mulch treatment exhibited characteristics intermediate between the organic mulch and bare treatments. In this case the average runoff was around 20 to 25% of the rainfall. It is noticeable that there was quite a large increase in runoff from the organic mulch on both ecotopes, relative to the other two treatments, during the 01/02 season compared to 00/01. This was indicative of decomposition of the organic mulch on the runoff area, but could also partly be attributed to a difference in the rainfall distribution pattern during these two seasons. The general trend that applied to both ecotopes over the three seasons was that stones greatly reduced runoff on the runoff area when compared to bare soil, and that the organic mulch produced the greatest reduction in runoff of all the treatments.

The implication of the results is that with the *IRWH* technique it is possible with all these treatments to stop ex-field runoff completely. With a bare runoff strip it is possible to concentrate about 40% of the seasons rainfall in the basin area (Figure 1.3). This water would be stored in the soil volume below the basins, much of it conserved below the evaporation zone, and therefore available for transpiration. With stones on the runoff area a considerable amount of rainwater will run off (R), but the amount that infiltrates (I) into the runoff area will be considerably more than on the bare runoff area. The organic mulch on the runoff area has the smallest amount of runoff, in other words the smallest contribution of the three treatments to extra water storage in the basin. Of the three treatments, organic mulch will therefore generally contribute the most to water infiltration in the runoff area. For the runoff area on all the treatments, the ratio R/I for a particular season is expected to be strongly influenced by the rainfall pattern for that season, the different treatments probably responding in different ways. An extra benefit of mulch treatments on the runoff area might be the suppression of evaporation from the soil surface (Es). The effect of mulches on Es on the Glen/Bonheim ecotope has been studied in greater deatail (Botha, Anderson, Van Staden, Van Rensburg, Beukes & Hensley, 2001; Van Rensburg, Nhlabathi, Anderson, Botha, Van Staden & Kuschke, 2003). Results indicate that stone and organic mulch treatments reduce Es from the runoff area, compared to the bare treatment. The question is: which combination of effects will generally be the most beneficial in terms of precipitation use efficiency in the long-term?

All the runoff events measured on the Glen/Bonheim and Glen/Swartland ecotopes over the three years (2000 - 2002) were plotted in Figure 2.2 against the corresponding rainfall. It was considered acceptable to do this, because of the similarity of the results on the two ecotopes. A linear function for each treatment was fitted through the data to obtain in-field runoff (IR) equations to estimate water harvesting from the 2-m runoff area on both ecotopes (Equations 2.2, 2.3 and 2.4). As expected the coefficients of determination were not high as runoff depends not only on the amount of a rain event but also on its intensity. It was nevertheless considered that the correlations would be useful for estimating runoff on these and similar ecotopes.

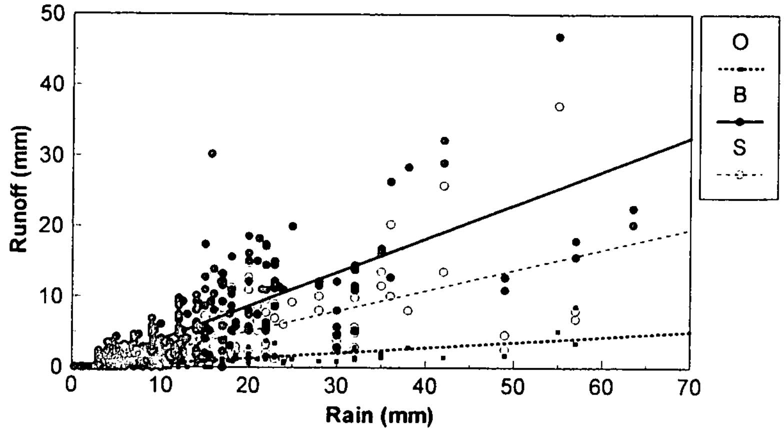

Figure 2.2 Runoff data from the different treatments plotted against the corresponding daily rainfall on the Glen/Bonheim and Glen/Swartland ecotopes (O = organic; B = bare; S = stones).

$$IR_b = -0.87915 + 0.47417 \times P \text{ ....} (r^2 = 0.64) \text{ ....} (2.2)$$

$$IR_s = -0.66351 + 0.29001 \times P \text{ ....} (r^2 = 0.51) \text{ ....} (2.3)$$

$$IR_o = -0.2124 + 0.07684 \times P \text{ ....} (r^2 = 0.55) \text{ ....} (2.4)$$

Where:

IR_b = water harvested from 2-m bare runoff surfaces (mm)
IR_s = water harvested from 2-m stone runoff surfaces (mm)
IR_o = water harvested from 2-m organic runoff surfaces (mm)
P = precipitation (mm).

2.3.3 LONG-TERM RUNOFF PREDICTIONS FOR *IRWH* SYSTEMS

Equations 2.2, 2.3 and 2.4 were applied in the crop model, CYP-SA (Botha *et al.*, 2003), to estimate the water harvested through in-field runoff (IR) for each rainfall event during the 81 years for which rainfall data is available.

Runoff from the *CON* treatment was estimated using an adapted version of the prediction equation developed during previous studies on the ecotope (Hensley *et al.*, 2000). Rainfall events smaller then 8 mm were excluded. Hensley *et al.* (2000) tested the reliability of their runoff equation against results of runoff experiments made by Du Plessis & Mostert (1965) over 18 seasons at Glen. The Glen/Tukulu ecotope on which their measurements were made (Zere, 2003) is considered to have comparable characteristics, in relation to runoff, to the two ecotopes described in this study. For example Zere (2003) used the Morin and Cluff (1980) runoff model to simulate runoff on the site of the Du Plessis & Mostert (1965) plots. He succeeded in predicting the runoff results over 18 years obtained by Du Plessis & Mostert in a satisfactory way. The "best fit" value for the final infiltration rate (I_f) was found to be 5 mm h^{-1} for the bare crusted plots. The equivalent value for both the Glen/Swartland and Glen/Bonheim ecotopes is reported by Hensley *et al.* (2000) to be 6 mm h^{-1}. Du Plessis & Mostert (1965) reported an average annual runoff as a percentage of annual rainfall of 8.5% from conventionally tilled maize plots during the period of their experiment. Hensley *et al.* (2000) applied their equation to each rainfall event greater then 8 mm during the period 1937/38 – 1954/55 and estimated runoff for each season. They found that their equation was sufficiently reliable to use for predicting runoff from bare crusted untilled plots. The equation of Hensley *et al.* (2000) was therefore appropriately adapted (see Eqaution 4.5) and used for predicting ex-field runoff from the *CON* treatments.

Cumulative probability functions (CPFs) of simulated long-term runoff over a period of 81 years (1922 – 2003) from the *CON* and *IRWH* production techniques on the two ecotopes are presented in Figure 2.3. The closer the graph is to the right-hand bottom corner of the figure, the higher is the in-field runoff harvesting potential of the production strategy. The organic mulch, stone and bare surface treatments have an 80% probability of harvesting in-field runoff water into the basins of 22 mm, 90 mm and 156 mm per year, respectively. It is necessary to compare the water advantage that the *IRWH* treatments have in the basin area over the equivalent area on *CON*. The CPF graph also indicates that *CON* tillage has an 80% probability of losing 40 mm of rainwater per year to ex-field runoff. These predictions indicate that the organic mulch, stone and bare treatments will have an advantage of 62 mm, 130 mm and 196 mm rainwater in the basins, respectively, over the *CON* treatment. At a 50% probability the predicted amounts of in-field runoff harvested by the organic mulch, stone and bare treatments are 30 mm, 116 mm and 199 mm per year, respectively. At the same probability level *CON* has a 50% probability of losing 55 mm of rainwater annually to ex-field runoff. In practice this means that a farmer using *IRWH* with the organic mulch, stone and bare treatments would have a rainwater advantage in the basins of 85 mm, 171 mm and 254 mm per year over *CON* respectively. These benefits should contribute greatly towards increasing crop yields. It is necessary, however, to appreciate that crop yield responses are not directly correlated with these "rainwater advantage" values for a number of reasons. Water retention on the runoff strip under organic and stone mulches has been shown to be advantageous for the crop, compared to a bare runoff area which has the highest runoff into the basins (see Chapters 4 and 5). The water stored under the runoff strip probably provides a reserve that only becomes available when the root ramification has reached maximum development. As this occurs approximately at tasseling/flowering, this reserve water is probably more beneficial than a similar amount stored in the quickly available, densely rooted region below the basins.

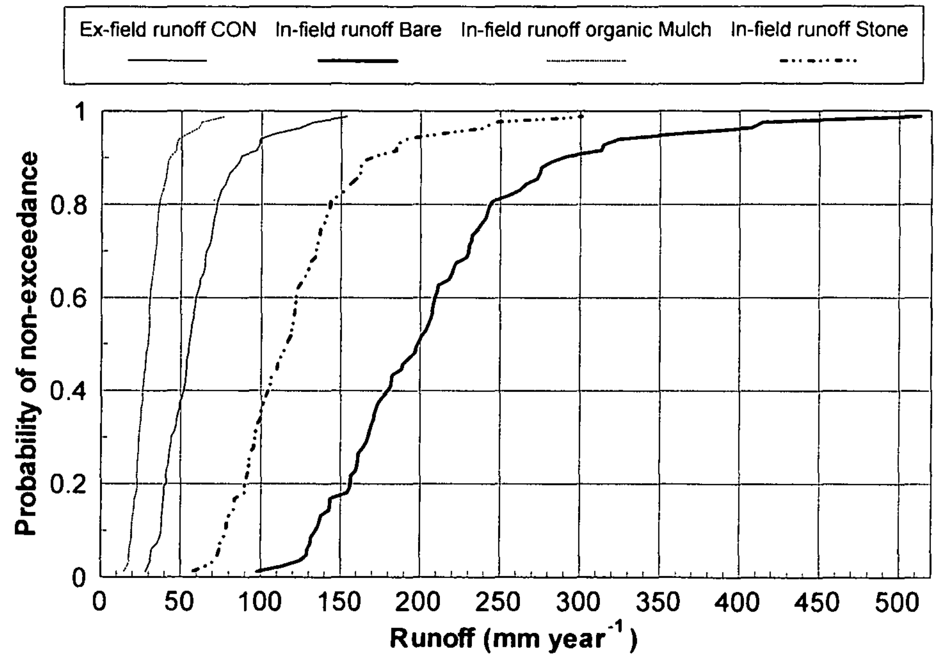

Figure 2.3 CPF graphs of predicted long-term runoff from the 2 metre runoff strips on the Glen/Bonheim - and Glen/Swartland ecotopes with different surface treatments. The rainfall data used are for the 81-year period, 1922 - 2003.

2.3.4 MULCHING EFFECTS ON SEDIMENTATION IN BASINS

The advantage of the *IRWH* system is that ex-field runoff can be stopped completely if the system is correctly designed and maintained. No erosion from the field as a whole will therefore occur. However, runoff will induce the movement of sediment towards the basin. The sedimentation rates will affect the storage capacity of the basins and hence the long-term sustainability of the *IRWH* system.

The estimated amounts of sediment collected in the basins of the respective treatments on the Glen/Bonheim ecotope are presented in Table 2.5. The results show that the most soil transportation occurred on the bare surface treatment, followed by the stone and mulch treatments. It is therefore concluded that mulch on the runoff area will be the best treatment in terms of sustainability regarding the surface storage capacity of the basin. The capacity of the basins with a bare runoff area will be reduced relatively quickly, and progressively lose their designed water storage capacity. The land will then eventually have the same surface characteristics as with *CON*. It must be emphasized that the *IRWH* technique, if not properly designed, (i.e. the capacity of the basin must be able to hold the maximum expected amount of runoff), and implemented in terms of the contour layout, has the potential to be more detrimental than *CON* in terms of erosion.

Table 2.5 The amount of runoff induced sediment (g m^{-2} $season^{-1}$) collected form the runoff strips of the respective treatments on the Glen/Bonheim ecotope (O = organic; B = bare; S = stones)

Season	Sediment load (g m^{-2} $season^{-1}$)		
	B	S	O
00/01	4204	1673	539
01/02	3244	2242	562
Average	3724	1958	551

The following assumptions were made in an attempt to calculate the number of seasons that would cause the basins to completely silt up:

a. The bulk density of the deposited material is 1.5 g cm^{-3}.

b. Stones in the basins occupy 50% of its volume.

c. Mulches in the basins occupy 40% of its volume.

d. Average basin size initially is 3 m long, 1 m wide and 0.1 m deep, serving a runoff area of 6 m^2 (2 m x 3 m).

Results are presented in Table 2.6. The actual realization of the theoretical results in Table 2.6 will be influenced by:

(1) The decomposition rate of the organic mulch.

(2) Deterioration of the ridge. After the basin is made, the rainfall intensity of the first two or three rain events is critical in this regard.

(3) Although no-till is practised, chemical weed and pesticide control must be done. To prevent trampling, which causes deterioration of the mulch on the runoff area, it should preferably not be walked on. Stones on the runoff area impair walking there. Consequently the ridge of the basin becomes the most preferred place to walk, causing it to be flattened.

(4) The rainfall pattern per season in terms of intensity and amount.

(5) The size of the basin.

(6) The frequency and extent of basin maintenance options.

Table 2.6 Estimates of the time required for the silting-up process in the basins with different treatments

Procedure	Treatment					
	BbBr[*1]	*ObBr*[*2]	*SbSr*[*3]	*SbOr*[*4]	*ObSr*[*5]	*ObOr*[*6]
1. Volume of basin (cm^3)	300 000	180 000	150 000	150 000	180 000	180 000
2. Amount of sediment needed to fill basin (g)	450 000	270 000	225 000	225 000	270 000	270 000
3. Average sediment load per season (g)[*7]	22 344	22 344	11 748	3 306	11 748	3 306
4. Number of seasons for basins to become filled with sediment	20	12	19	68	23	82

[*1] = *IRWH* with bare basin, bare runoff area.

[*2] = *IRWH* with organic mulch in basin, bare runoff area.

[*3] = *IRWH* with stone mulch in basin, stone mulch on runoff area.

[*4] = *IRWH* with stone mulch in basin, organic mulch on runoff area.

[*5] = *IRWH* with organic mulch in basin, stone mulch on runoff area.

[*6] = *IRWH* with organic mulch in basin, organic mulch on runoff area.

[*7] = Since the area of the runoff strip is 6 m^2 the value in Table 2.5 must be multiplied by six.

Sedimentation results indicate that the *ObOr* treatment is the longest lasting in terms of maintaining the surface storage capacity of the basin over time. It is followed by the *SbOr*, *ObSr*, *BbBr*, *SbSr*, and *ObBr* treatments. These results also indicate that the *BbBr*, *ObBr*, *ObSr* and *SbSr* treatments are relatively less sustainable in terms of maintaining the surface storage capacity of the basins over time. For these treatments maintenance will be needed. It is also necessary to realize that long before the basins are full of sediment, their storage capacity will be below the threshold value needed to prevent them overflowing during high intensity storms of long duration. The need for a certain amount of maintenance to the basins is therefore inevitable.

The choice of treatment should not be based on these results only. It is necessary to also consider the measured crop yields, the socio-economic aspects associated with each treatment, and maintenance costs involved in keeping the water storage capacity of the basins at an adequate level.

All the measured sediment data (dependent variable) on the Glen/Bonheim ecotope over two years (2001 - 2002) is plotted in Figure 2.4 against the corresponding measured rainfall (independent variable). A linear function for each treatment was fitted through the data to obtain equations to predict sedimentation in the basins from the 2 m no-till runoff area (Equations 2.5, 2.6 and 2.7).

$Se_b = -221.355 + 55.2770 \times P$ ....($r^2 = 0.64$)..................................(2.5)

$Se_s = -115.128 + 28.9705 \times P$ ....($r^2 = 0.57$)..................................(2.6)

$Se_o = -65.6549 + 10.4807 \times P$ ....($r^2 = 0.44$)..................................(2.7)

Where:

Se_b = amount of sediment collected in basins (g m^{-2}) from a bare runoff area

Se_s = amount of sediment collected in basins (g m^{-2}) from a stone covered runoff area

Se_o = amount of sediment collected in basins (g m^{-2}) from an organic mulch covered runoff area.

Note: the runoff distance on these plots was 2 m and plot width was 3 m - see Figure 2.1.

Although these correlations are useful as first approximations, the low r^2 values are revealing. They indicate the importance of rainfall intensity on runoff sediment load. Of particular importance is the amount of rain above the intensity equal to the final infiltration rate of the crusted soil. Supporting evidence is provided by the results reported by Walker & Tsubo, 2003. A fruitful avenue for future research is revealed here - especially for model building purposes. An appropriate model could make this valuable information extrapolateable to a wide range of ecotopes in Sub-Saharan Africa.

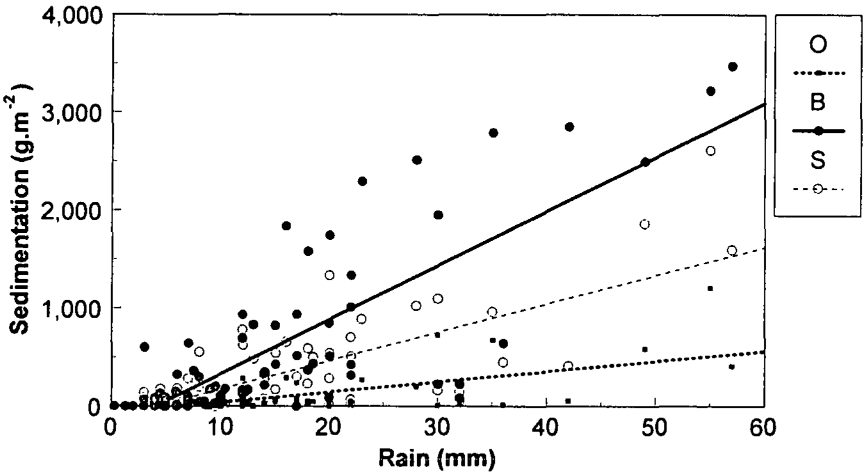

Figure 2.4 Sedimentation data from the different treatments plotted against the corresponding measured daily rainfall measured on the Glen/Bonheim ecotope (O = organic; B = bare; S = stones).

2.4 CONCLUSIONS

The main focus of this chapter was on the characterization of rainfall/in-field runoff relationships as influenced by mulches on the runoff strip in the *IRWH* crop production technique. Negative perceptions of runoff amongst crop farmers, extension officers and researchers need to be changed. Runoff is defined by Van der Watt & Van Rooyen (1995) as water "lost" by surface flow. This gives runoff a negative connotation. The driving force behind water harvesting is precisely to turn the "loss" into a "gain" by collecting the water in appropriate structures, depending on the magnitude of the catchment area. Runoff can be divided into ex-field and in-field runoff. In-field runoff refers to the transportation of water over a short distance of 2 m, while ex-field runoff refers to water lost from the whole area of a cultivated land. Results from ex-field runoff studies, especially where treatments included bare surfaces, are generally applicable to the *IRWH* system.

It has been possible to establish linear relationships that quantify the precipitation/in-field runoff relationship on runoff strips with the treatments bare, organic mulch and stone mulch. These relationships were used together with long-term rainfall to predict the in-field runoff harvesting potential on ecotopes similar to Glen/Bonheim and Glen/Swartland on a long-term basis. The results indicate that organic mulch, stone and bare treatments have an 80% probability of harvesting 22 mm, 90 mm and 156 mm every year into the basins, respectively, compared to the *CON* tillage, which has a 80% probability of losing 40 mm of rainwater every year by ex-field runoff. This implies that the organic mulch, stone and bare treatments have resulted in estimated mean annual amounts of 62 mm, 130 mm and 196 mm, respectively, more rainwater being received in the 1 m basin area between crop rows than *CON*. This has been made possible by the total elimination of ex-field runoff, and the in-field harvesting of rainwater. It may be concluded from these results that the bare treatment could be expected to produce the highest grain yield. This is, however, an erroneous conclusion as other important factors that influence crop growth are involved.

As indicated, ex-field runoff was completely stopped by the *IRWH* system and hence also ex-field soil erosion. An area of concern that influences the sustainability of the

IRWH system is the siltation of the basins through the in-field runoff process. Sediment measurements and estimates have shown that the basins will take between 12 and 82 years to become filled if no sediment is removed from them. The period depends on the type of mulch on the runoff area and also in the basins. Mulch on the runoff area restricts sediment movement. The extent of this depends on mulch type. Mulch type in the basin influences the capacity of the basin to absorb sediment. However, it is also necessary to realize that all the *IRWH* techniques will need some degree of maintenance to prevent overflowing during heavy rainstorms. It is essential that the volume of the basins be maintained above a critical threshold value to prevent this from happening.

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CHAPTER 3: QUANTIFYING EVAPORATION UNDER VARIOUS MULCHING STRATEGIES ON TWO ECOTOPES

ABSTRACT

In the semi-arid crop production areas of South Africa, the problem of low and erratic rainfall is exacerbated by two major unproductive water losses, viz. runoff (R), and evaporation from the soil surface (Es). Runoff can be controlled by the basins in in-field rainwater harvesting, leaving Es that needs to be minimized, both during the fallow and crop growing periods.

The hypothesis was that appropriate mulching techniques would reduce Es. For this purpose field experiments were laid out on two ecotopes. On the one the texture of the surface soil was sandy loam, and on the other it was clay. Measurements were made for both a summer and winter period. Four treatments with three replications were applied on 2 m x 2 m plots. The treatments were: (a) bare soil; (b) stone mulch covering 50% of the soil surface; (c) organic mulch covering 50% of the soil surface; (d) organic mulch covering 100% of the soil surface. Changes in soil water content were measured with a neutron water meter and gravimetrically. The experimental procedure consisting of first obtaining the drainage curves on two soils according to the standard procedure. Thereafter all plots were again saturated with water, to a depth of at least 600 mm. The mulches were applied immediately after excess water had disappeared. Soil water losses were calculated from consecutive measurements and the drainage component deducted to obtain Es. The latter was accumulated for the period of measurement, being 69 days for the summer and 52 days for the winter.

During the summer the 100% organic mulch reduced Es on the clay and sandy loam ecotopes to 127 mm and 103 mm, respectively, compared to a mean Es of 150 mm from the bare soil. Smaller reductions in Es were recorded for the 50% organic and stone mulches. Summer Es values were higher than winter values because of higher inputs of water (through summer rain) and solar energy. Although the 100% organic mulch gave the best result, the surprising result was that the 50% stone mulch *performed as well as the 50% organic mulch. The parameter characterizing the Es process (α) used in the Black and Ritchie evaporation equations was calculated for the different treatments on both ecotopes. The determined α value (mm day$^{-0.5}$) for a bare soil on the clay and sandy loam ecotopes of 3.5 and 3.0, respectively, compares well with the mean α value used by Ritchie (1972) for a range of soils of 3.5. Alfa values for winter and summer periods should be determined which would be valuable information for crop models. Differences in α values for winter and summer periods could be avoided by relating Es to ΣE_o to give an ecotope specific β value as suggested by Boesten and Stroosnijder (1986). The local Soil Water Management Model (SWAMP) was tested against the experimental Es data. Bare soil Es was estimated fairly well especially during winter. Initially the model could not cater for the influence of the mulches, but after inputs from this study it was able to do this.*

If enough crop residues are available, a 100% residue cover is recommended to increase soil water storage and decrease Es. A 50% stone mulch will probably be the best practice to recommend in the rural areas because of the scarcity of crop residues, as well as the urgent need for animal feed during winter. In order to gather reliable Es data measurements should at least include the 0 - 300 mm soil layer. Measurements shallower than 300 mm should be regarded as unreliable.

Keywords: evaporation, mulch, drainage, soil temperature

3.1 INTRODUCTION

Evaporation from the soil surface (Es) is the process by which water in the soil is changed to a vapour or gas (Van der Watt & Van Rooyen, 1995), and lost to the atmosphere. According to Unger (1990), Es is responsible for soil water losses between 40% and 75% of the total rainfall in the Great Plains of the United States. Bennie, Hoffman, Coetzee & Vrey (1994) claimed that their results in semi-arid areas of South Africa indicated that between 60% and 85% of the rainfall evaporates before it could make any contribution to crop production. According to Jalota & Prihar

(1990), three conditions are necessary for evaporation to take place, i.e. (a) supply of energy needed for latent heat of vaporisation of water; (b) existence of a vapour pressure gradient between the soil and the atmosphere; (c) supply of water to the evaporating surface. The first two conditions are influenced by meteorological factors *viz.* radiation, air temperature, wind velocity and relative humidity. The soil water content of the surface layer and the soil layer immediate below, as well as the hydraulic conductivity, influence the third condition. Hatfield (1990) therefore considered that full understanding of the meteorological and soil water conditions are needed to utilize or understand Es information. Es is a very complex process as it involves intensive dynamic interaction between a number of factors. These include the following: (a) atmospheric evaporative demand (E_o); (b) the condition of the soil surface, i.e. roughness, the degree of crusting, its colour and resulting albedo, any covering material, e.g. mulch which may be present; (c) the water content (θ) of the surface layer and underlying layers; (d) the relationship between θ and hydraulic conductivity (K) of the surface layers and underlying layers.

Although there are many research reports about Es measurements all the relevant factors are generally not described. This makes it difficult to reach logical conclusions about the complete dynamics of the process. In order to develop efficient production techniques to suppress Es on different ecotopes, this complete understanding will be needed.

Es occurs in three stages, with the greatest potential for reducing Es occurring during the first two stages (Lemon, 1956). During the first stage (constant rate stage) evaporation is rapid and steady and depends on the net effects of water transmission to the surface and aboveground climatic conditions. According to Ritchie (1972) the soil is sufficiently wet during stage 1 for water to be transported to the surface at a rate at least equal to the evaporative demand of the atmosphere. Es decreases rapidly as the soil water supply decreases during the second stage (falling rate stage). During this stage soil factors control the rate of water movement to the soil surface and above ground climatic conditions have little influence on Es (Unger, 1990). According to Lemon (1956), capillary flow, vapor transfer, and the combination of the two in the capillary condensation evaporation process dominate the picture during the second stage. According to Lemon (1956) and Unger (1990), during the third stage Es is controlled by adsorptive forces at the solid-liquid interface in the soil, and is therefore extremely slow.

Philip (1957) claimed that the transition from the constant rate stage to the falling rate stage is quite sharp. He suspected that the transition point is not fixed and it depends on the evaporation rate. The higher the evaporative demand (E_0) the higher the Es rate becomes and the faster the transition point would be reached. Jackson, Idso & Reginato (1976) confirmed these results and claim that the transition from stage 1 to stage 2 may extend from one to five days or even more, depending on the location, time of year, and the weather conditions. Their experience with field experiments has shown that the soil surface will change from wet to dry within a period of one to two days except during the winter months, when it may take considerably longer. Various authors have argued that soil water might be conserved under a high E_0 compared with a low E_0 through the formation of a dry soil surface layer, which would impede water movement to the atmosphere. Gardner & Hillel (1962) studied evaporation from laboratory soil columns as a function of potential evaporative conditions. Their results indicated that a lower drying rate during stage 1 evaporation is maintained for a longer time, and the opposite for a higher E_0. Although the lower drying rate is maintained for a longer time, the higher drying rate still results in a greater cumulative loss at any given time (Gardner & Hillel, 1962). They also claimed that soon after the end of the first stage of drying the rate of Es will become independent of the initial drying rate and will depend only upon the water content of the soil.

Various procedures have been used in an attempt to suppress Es. One of these involves decreasing turbulent transfer of water vapor to the atmosphere by procedures such as adding mulching material, or increasing soil surface roughness (Lemon, 1956). He also indicated, using net radiation and temperature data obtained with mulched and bare field soils, that the increased heat storage under a plant residue mulch may account for the surprising lack of Es suppression where large amounts of chopped plant residue mulching (25 ton ha^{-1}) had been practiced. Lemon (1956) also speculated that the lower the evaporative demand the more nearly alike the initial Es rates become with different mulching strategies.

Crop residue mulches decrease evaporation. Mulches affect many soil properties and soil conditions, either directly or indirectly. Among these are improved soil water content through runoff control, increased infiltration, decreased evaporation, weed control, ameliorated soil temperature through radiation shielding, improved soil fertility and soil structure, improved biological regime and root distribution through organic matter additions, and in some cases decreased soil salinity through leaching and evaporation control (Unger, 1995). Probably of greatest importance, however, for agriculture in semi-arid and arid regions is the influence of mulches on soil water, temperature, soil structure, and salinity.

In South Africa crop yield increases and improved water use efficiencies have been reported as a result of mulching and reduced tillage. Van Averbeke and Mkile (1996) conducted a field experiment in a lysimeter with maize in the Eastern Cape Province of South Africa. They investigated the potential of stones as a mulch to suppress evaporation. They found that stone mulching reduced evapotranspiration by 18% and increased water use efficiency of maize by 39% compared to the control. Beukes, Bennie & Hensley (1998) reported the effect of stubble and conventional tillage practices on cumulative infiltration and yield of grain sorghum on a vertisol in the Highveld Region near Potchefstroom. They reported that the retention of stubble (combined with tine tillage or no tillage) increased the mean cumulative infiltration by 82% and mean yield by 166% compared to tine tillage or no tillage with stubble removed.

Evaporation studies in South Africa have shown that the length of the drying cycle is also an important factor determining the ability of mulches to reduce evaporation. Hoffman (1997) estimated that mulching loses its water conservation advantage when the drying cycles exceed 15 - 20 days during the fallow period under semi-arid conditions. Berry & Mallett (1988) found that maize residue, covering greater than 70% of the surface, reduced evaporation considerably under sub-humid conditions provided the drying period was shorter than 14 days.

Methods of estimating Es fall within three general categories, direct and indirect methods, and simulation models of the soil water balance. Micro-lysimeters are a popular direct measuring method (Ritchie & Johnson, 1990), neutron probes are acceptable techniques as well as time domain reflectometry and many others (Hatfield, 1990). Hensley (1980) indicated that laboratory and field measured soil-water parameters differ and recommended that field measured data should be obtained for accurate results. Boesten & Stroosnijder (1986) show that ∑Es measurements for stage 1 carried out on sieved soils in laboratories differ from field measured ∑Es values. Field measurements gave considerable lower values of ∑Es. Ritchie (1972) reported stage 1 ∑Es, heralding the end of the stage, values of 6, 9, 12 and 6 mm for Plainfield sand, Yolo loam, Adelanto clay loam and Houston black clay, respectively. Boesten & Stroosnijder (1986) reported stage 1 ∑Es values of 4 - 8 mm for sand, loamy sand and clay respectively. Boesten & Stroosnijder (1986) reported stage 1 ∑Es values determined in laboratories from a number of authors in the range of 20 to 60 mm. As the values for field experiments were an order of magnitude lower than those reported for sieved soils in the laboratory, Boesten & Stroosnijder (1986) concluded that data from laboratory experiments with sieved soils could not be used to describe evaporation behaviour in soils under field conditions.

Under semi-arid conditions, stage 2 of Es dominates most of the time. This implies that this stage of Es is largely controlled by the hydraulic characteristics of the soil (Hillel, 1972). Hoffman (1997) states that ∑Es increases with increased silt plus clay content. Black, Gardner & Thurtell (1969) measured Es from a bare cultivated Plainfield sand soil with a lysimeter under natural rainfall conditions. They found that cumulative evaporation at any stage was proportional to the square root of time following each heavy rainfall. Black *et al.* (1969) formulated an equation to estimate Es during stage 2 drying of an initially wet, deep soil (Equation 3.1).

$$\sum Es = \alpha t^{0.5} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

where: α = parameter characterizing the Es process (mm $d^{-0.5}$)
t = time after preceding rainfall (d).

According to Ritchie (1972) α is dependent mainly on the hydraulic properties of a soil. Values for α can be determined experimentally from cumulative evaporation data for a single drying cycle. Es data for stage 2 are plotted on a graph as a function of $t^{0.5}$.

Time 0 corresponds to the time when the cumulative evaporation for stage 1 ends and stage 2 starts.

Ritchie (1972) modified Equation 3.1 to include both stages (1 and 2). This proposal is presented in Equation 3.2. The Ritchie (1972) equation which predicts Es from a bare soil surface is employed in many of the crop models used locally, for example: DSSAT (Tsuji, Uehara & Balas, 1994); ACRU (Schulze, 1995); SWAMP (Bennie, Strydom & Vrey, 1998).

$$\sum Es_1 = \sum E_{pot} \qquad \text{for } t \leq t_1$$

$$\sum Es_2 = \sum Es_1 + \alpha(t - t_1)^{0.5} \qquad \text{for } t > t_1 \ldots\ldots (3.2)$$

where: E_{pot} = potential evaporation (mm).

Black *et al.* (1969) obtained an α value of 5 mm $d^{-0.5}$ for a bare cultivated Plainfield sand in a lysimeter experiment over a period of 12 days. Ritchie (1972) reported α values from various authors (Van Bavel & Reginato, 1965; Black *et al*, 1969; LaRue, Nielsen & Hagan, 1968 and his own work) between 3 and 5 mm $d^{-0.5}$, for four field experiments with lysimeters where the soil water content was at least at field capacity at the beginning of the drying cycle. These values are as follows for Plainfield sand, Yolo loam, Adelanto clay loam and Houston black clay, 3.34, 4.04, 5.08 and 3.50 mm $d^{-0.5}$ respectively. Stroosnijder & Hoogmoed (1984) and Stroosnijder (2003) reported an α value, that apparently worked well for a wide spectrum of soils that ranged from sand to clay in West Africa of 3.50 mm $d^{-0.5}$. Hall & Dancette (1978) reported an α value of 3.34 mm $d^{-0.5}$ for a slightly leached tropical ferruginous coarse sandy soil at Bambey in Senegal. A sensitivity analysis was conducted by Hall & Dancette (1978) to determine the extent to which variations in α may influence predicted ΣEs. Analyses indicated that errors in determination of α of 29% could cause a deviation in the predicted ΣEs of 10%. Stroosnijder (2003) indicates that soil hydraulic properties are not of primary importance in comparison to other factors such as potential evapotranspiration, leaf area index and length of drying cycle when one is dealing with Es from a cropped land.

Jackson *et al.* (1976) found with field experiments on a loam soil that the α value varies with not only soil type but also with season. The season's effect is a result of a temperature dependence. They found that the α value was 2 mm $d^{-0.5}$ in the winter and 4 mm $d^{-0.5}$ in the summer (Figure 3.1). Gill & Prihar (1983) measured evaporation from tilled soil columns in a laboratory under various constant levels of E_{pot} over a period of 50 days. They found that the α value increased from 7 to 13 mm $d^{-0.5}$ with an increase in E_{pot} from 4 to 16 mm d^{-1}. Results from Jackson *et al.* (1976) and Gill & Prihar (1983) indicate that E_{pot} has a considerable effect on especially stage 2 Es and stage 3 Es and therefore on the α value. Boesten & Stroosnijder (1986) concluded that E_{pot} would be better than the time used in the equations suggested by Black *et al.* (1969) and Ritchie (1972) and used E_{pot} (a conversion of E_o) against which to relate ΣEs.

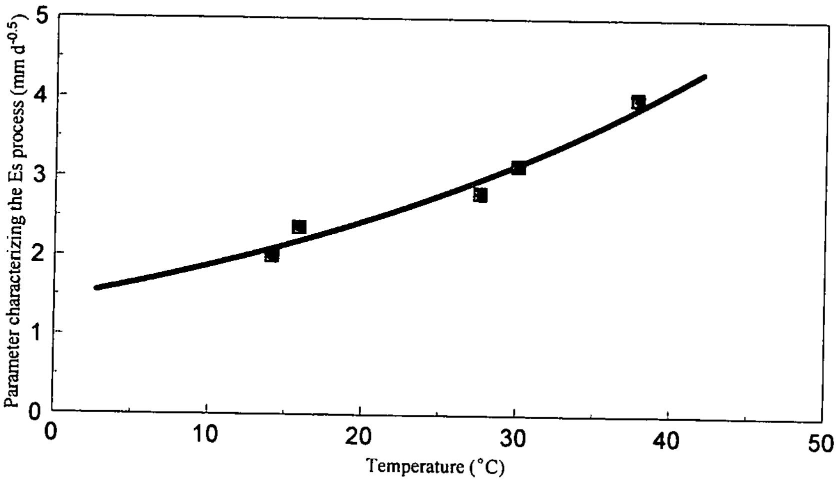

Figure 3.1 The temperature dependence of the α value in a soil (Jackson *et al.*, 1976).

Boesten & Stroosnijder (1986) developed a simple parametric model to estimate daily Es from fallow tilled soil under spring conditions in a temperate climate where E_{pot} rates commonly fluctuate (Equation 3.3). In spring in the Netherlands, the daily average of E_{pot} may vary considerable from 1 to 6 mm d^{-1}. The criteria for the new model were: (a) it should contain only one or two easily measured field soil parameters; (b) these parameters should not depend on E_{pot} because of the variation in the Netherlands; (c) it should make use of the fact that for constant E_{pot} a $t^{0.5}$ type relationship fits most experimental data; (d) it should use meteorological data.

According to them, evidence from a literature study indicates that this model is an improvement on models in which ΣEs is related to the square root of time.

$$\sum Es_1 = \sum E_{pot} \qquad \text{for } \Sigma E_{pot} < \beta^2 \text{ or } \Sigma E_{pot} = \Sigma Es_I = \beta^2$$

$$\sum Es_2 = \beta\left(\sum E_{pot}\right)^{0.5} \qquad \text{for } \Sigma E_{pot} > \beta^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.3)$$

where: β = an evaporation characteristic soil parameter ($mm^{0.5}$).

The slope of the linear regression of ΣEs versus $\Sigma E_{pot}^{0.5}$ gives the β value (Boesten & Stroosnijder, 1986). This equation only contains one soil parameter (β) and ΣEs depends on E_{pot} and not on time. This implies that to each day a weight is attached which is directly proportional to the rate of E_{pot} for the day. Boesten & Stroosnijder (1986) also reported that the advantage of using β above α is that β is less dependant on E_{pot} than α. Boesten & Stroosnijder (1986) reanalysed the data of Gill & Prihar (1983) and obtained β values of 3.4, 3.1 and 3.2 $mm^{0.5}$ for E_{pot} values of 4, 8 and 16 mm d^{-1}. Stroosnijder (1987) claimed that in the case of temperate climates where E_{pot} is not constant and fluctuates a lot, or under some subtropical circumstances, ΣEs relates better to the square root of ΣE_{pot} than the square root of time. Boesten & Stroosnijder (1986) reported a β value of 1.7 $mm^{0.5}$ obtained with micro-lysimeters to a depth of 120 mm from a field experiment carried out on a loamy sandy soil at the Noordoost Polder in the Netherlands. According to them the value for β of 1.7 $mm^{0.5}$, which implies that ΣEs_I (β^2) was only 3 mm, is in the low range of values for field soils. The reason might be that their measuring depth was too shallow. Stroosnijder (1987) reported that results from field experiments carried out on a loamy sand soil near Niono in the Republic of Mali in the West-African Sahel with gravimetric soil samples of the top 30 cm layer, yielded a value for β of 1.65 $mm^{0.5}$. Stroosnijder (1987) found similar results for a clay loam soil and therefore use a mean β value of 1.65 $mm^{0.5}$ to calculate ΣEs. Hattingh (1993) reported a β value of 1.6 $mm^{0.5}$ obtained from a fine sandy loam soil (Hutton soil form) at Glen in South Africa. He measured with micro-lysimeters to a depth of 150 mm. This results correlates well with those of Stroosnijder (1987). Hattingh (1993) also found the model of Boesten & Stroosnijder (1986) to be very reliable but claims that the Ricthie (1972) model performed better.

Most of the results obtained from fieldwork reported so far in this Chapter by various authors were presumably measured on homogenous soil profiles. Philip (1957) for example excluded the complications of hysteresis, colloid swelling and the effects of electrolytes on the permeability of clays. Therefore it seems that good correlations occur between different authors for the α value of 3.5 mm $d^{-0.5}$, and the β value of 1.65 $mm^{0.5}$ respectively on various soils, the latter measured to shallow depths only. It is expected that for duplex soils these values might be somewhat different because of the different soil physical conditions caused by the layered nature of the top 600 mm soil. A duplex soil is one with a clear transition from the A to the B horizon, the latter generally having a considerable higher clay content, a stronger structure and lower permeability. Ritchie & Johnson (1990) mention that the cumulative evaporation amount for stage 1 drying or the upper limit of stage 1 drying (*U*) varies from about 5 mm in sands and heavy shrinking clays to about 14 mm in clay loams. They also claim that these limits apply only to soils where a shallow water table is not present, where drainage is not greatly impeded, and where evaporation and redistribution commence immediately following wetting. In duplex soils internal drainage is greatly impeded by the more slowly permeable B horizon.

The objectives of this research are closely related to in-field rainwater harvesting experiments conducted at Glen (on-station) and Thaba Nchu (on-farm) in the Free State Province, South Africa. Hensley, Botha, Anderson, Van Staden & Du Toit (2000) showed that considerable yield increases with maize and sunflower generally occur when this technique is used, but failed to clarify the contribution of mulch in the basins to these benefits. It was considered that a separate critical experiment, free of the complexing influence of plant growth, was necessary to clarify the contribution of mulching - especially mulching as a technique to increase soil water storage. For a fallow period this benefit can be quantified by the parameter, rainfall storage efficiency (RSE), which is defined as $\Delta S_f/P_f$ (Mathews & Army, 1960). ΔS_f is the change in soil water content of the rootzone during the fallow period. P_f is the precipitation during the fallow period. For crop production purposes RSE is therefore a critical parameter for evaluating different mulches.

The question that needs to be answered is: whether an appropriate production mulching technique be developed which can reduce Es, especially on duplex and clay soils? It was hypothesised that appropriate mulching techniques will do this. The aim of the study was to quantify and model the influence of different mulch strategies on Es from a clay and a duplex soil located in a semi-arid area.

3.2 MATERIALS AND METHODS

Field experiments were conducted on two ecotopes (about 300 m apart in well-fenced camps) at the Glen Agricultural Institute (28°57` S; 26°20` E), situated in a semi-arid area 25 km north east of Bloemfontein. The one was a clay soil of the Onrus family of Bonheim form, and the other a duplex soil of the Rouxville family of the Swartland form, with a red brown A horizon. These selected ecotopes on the Glen Agricultural Institute are representative of large areas of land in the Free State Province on which a large number of rural households exists. The Onrus soil is described in detail by Hensley *et al.* (2000), and important characteristics are presented in Chapter 2. The characteristics of the red brown A horizon Rouxville soil are presented in Table 3.3. Note that this soil is not the same as the Rouxville soil with the dark brown A horizon (38% clay) described in Chapter 2. Important differences are the lower clay content (17%) and the red brown colour of the A horizon in the soil studied in this experiment.

3.2.1 EXPERIMENTAL PLAN

To test the hypothesis four treatments with three replications were employed. The four treatments were as follows:

(a) No mulch on the soil surface (bare).

(b) Stones on the soil surface covering 50% of the area (stone).

(c) Organic mulch (reeds) on the soil surface covering 50% of the area (50%).

(d) Organic mulch (reeds) on the soil surface covering 100% of the area (100%).

On each ecotope three levelled experimental plots (4 m x 4 m) were prepared. Each plot was divided into four 2 m x 2 m plots. The treatments were applied randomly to the plots as indicated in Figure 3.2.

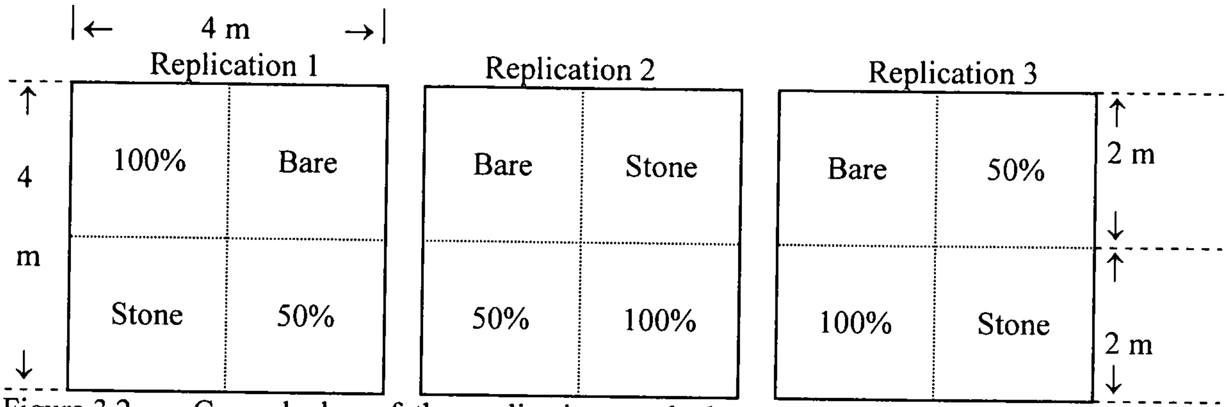

Figure 3.2 Ground plan of the replications and plots at each site; 12 plots per ecotope each 2 m x 2 m.

Reeds with a diameter ranging from 11 to 29 mm, with an average of 19 mm, were used as the organic mulch. This type of reed is readily available in the study area. Dolerite stones with an average diameter of 113 mm and ranging from 90 to 160 mm were used as the stone mulch. These stones are abundant in the study area.

3.2.2 MEASUREMENTS

Drainage and evaporation determinations were made on the plots. Three neutron water meter (NWM) access tubes were inserted in each of the 2 m x 2 m plots. Measurements were taken regularly at 300 mm intervals to a depth of 1800 mm during the drying cycles to be able to calculate Es. The Campbell Pacific 503 DR NWM was calibrated for each soil layer by using gravimetrically determined soil water content (θm) measurements and bulk density (BD) values (Robinson & Hubbard, 1990). For calibration purposes a range of NWM readings were taken for each soil layer, under wet and dry conditions, and at the same time gravimetric samples were taken for θm determinations. The linear relation between NWM counts and the θv (volumetric soil water content) values provided the calibration equation. A detail description of the procedure used for NWM calibration is described by Hensley *et al.* (2000) and Botha, Anderson, Van Staden, Van Rensburg, Beukes & Hensley (2001).

A drainage determination was made on each of the three experimental 4 m x 4 m level plots on each ecotope. A trench, 700 mm deep, was dug around the levelled plots and galvanized iron (GI) inserted in the trench to isolate the monolith from the surrounding soil. The trench was filled in again with soil around the GI sheet so that it was pressed as firmly as possible against the sides of the monolith. A smectite rich clay slurry was poured into the gap between the GI sheet and the sides of the monolith, to prevent leakage of water downwards through this gap. The purpose of the GI sheet was to prevent lateral water movement, which is especially prone to occur at the transition between the A and the less permeable B horizon. A low earth wall was made around the area to prevent runoff water from entering. The water content of the whole profile was measured before any additions of water. A water cart was used to fill the plots with water, and keep them full until continuous NWM readings showed that the wetting front had reached about 1200 mm, the bottom of the root zone. Additions of water were then discontinued. The plots were then carefully covered with a plastic sheet and allowed to drain over a period of approximately a month. The soil water contents were measured regularly during the draining period.

Es determinations were commenced on the same experimental plots after the drainage curve measurements were completed. The plastic sheet was removed and the profile filled again with water to a depth of 600 mm. As soon as the last surface water had disappeared into the soil, the various mulching treatments were applied on each of the plots. NWM readings were then immediately taken of the different soil layers (0 - 1200 mm). For the first two days readings were taken early in the morning and late in the afternoon. After that readings were taken at the same time every morning for about a week, followed by less frequent readings until the change in the water content was minimal. The drying cycles lasted at least 66 days during the summer (February, March and April) and 49 days during the winter (July, August and September) period. Two soil samples were also taken at the following depth increments for the determination of θm: 0 - 50 mm; 50 - 100 mm; 100 - 150 mm; 150 - 200 mm; 200 - 300 mm. The averages of two θm samples were used for each depth. A Veihmeyer sampling tube was used to take the samples. In the stone mulch treatment one sample was taken underneath a stone and the other one from the bare soil between the stones. θm measurements were used to monitor water loss by Es and to calibrate the NWM. θm measurements were carried out regularly during the evaporation determinations.

During the course of the Es measurements, due to the procedure being used here, water losses from the soil surface between saturation and the drained upper limit (DUL) will occur in two directions, i.e. upwards by Es and downwards by drainage (D). The decreases in water content during this period, i.e. Es + D, was subdivided by subtracting values for D obtained from the determined drainage.

Weather data, namely wet and dry bulb temperature, radiation, wind speed and direction, and rainfall, were measured with an automatic weather station.

Soil temperature on a depth of 25 and 75 mm parallel to the soil surface was measured in each treatment (one replicate) with two temperature sensors, coupled to a Hobo XT logger, on both ecotopes.

3.3 RESULTS

3.3.1 CLIMATE

Long-term climate data for these ecotopes is presented in Section 2.3.1. The semi-arid climate with no shortage of radiation, and hence high Es, accentuates the need for water conservation techniques.

3.3.2 TOPOGRAPHY

The experimental plots were located on an upper foot slope terrain unit with a 1% slope in westerly direction.

3.3.3 GLEN/BONHEIM-ONRUS ECOTOPE (Bo)

3.3.3.1 Soil

The soil classification and important features are described in Section 2.3.1.

3.3.3.2 Drainage characteristics

A drainage curve for the 0 - 300 mm layer, using the mean water contents obtained from all the plots during the drainage period, is presented in Figure 3.3. Equation 3.4 provides a mathematical description of the drainage process and enables the drainage rate at any time after field saturation (fSat) to be calculated.

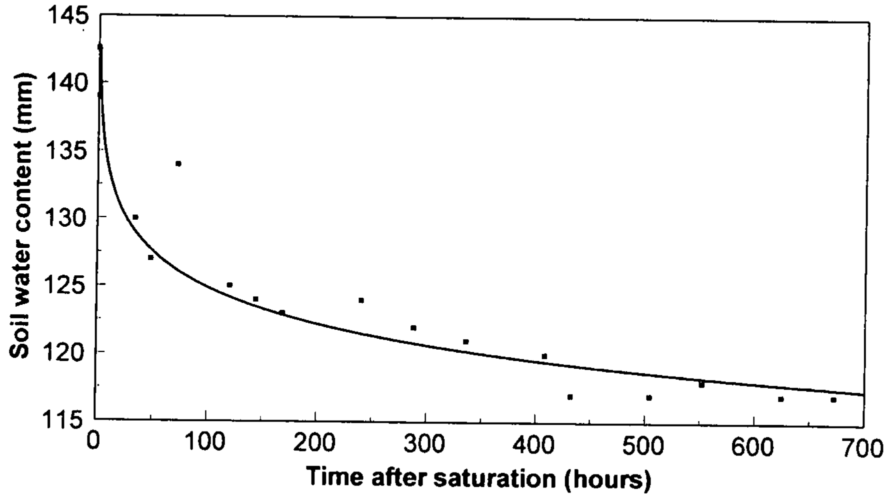

Figure 3.3 Drainage curve for the 0 - 300 mm layer of the Bo soil determined with NWM.

$$Y = 142.56 - 3.84(\ln t) \ldots\ldots\ldots\ldots r^2 = 0.83 \ldots\ldots\ldots\ldots (3.4)$$

where:

Y = water content of the 0 - 300 mm soil layer (mm)

t = time (h) after drainage commenced at the 0 - 300 mm soil layer.

The curve confirms the slow drainage characteristics of the soil. A total of 26 mm drained over the entire period from which 12 mm drained during the first 24 hours after saturation (0.50 mm h^{-1}). For the following 22 days the profile drained at a mean rate of 0.023 mm h^{-1}. Equation 3.4 makes it possible to calculate D from the soil layer when rain had refilled the water content above the specified DUL. This is necessary to quantify ΣEs and the water balance (Equation 1.1).

DUL is 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 layer or profile is about 0.1 to 0.2% per day (Ratliff, Ritchie, & Cassel, 1983). DUL (0 - 1200 mm) was taken as the rootzone water content (θr), when the change in θr became negligible. The water content of each soil layer at that stage gave the DUL value for the individual layers. Since the DUL plot was free of vegetation, and covered by a plastic sheet to prevent evaporation, DUL depends solely on the properties of the soil profile. Crop and climate influence are excluded.

3.3.3.3 Evaporation characteristics with various mulching treatments

Es curves for different treatments for the 0 - 300 mm soil layer on the Bo soil were determined during the summer and winter by means of gravimetric measurements (θm). Results are presented in Figure 3.4. Results from the summer cycle showed that both the percentage coverage and type of mulch restricted Es. The organic mulch covering 100% was the most effective in reducing Es. The cumulating Es over the 71 days (3 February 2000 - 14 April 2000) was 23 mm lower (i.e. 127 mm) than on the bare treatment (ΣEs = 150 mm). It was followed by the 50% organic mulch (ΣEs = 134 mm) and stone mulch (ΣEs = 135 mm). The surface mulch conserved soil water, which would contribute to less crop water stress in a semi-arid environment. A surface mulch would give crop roots time to extract a greater portion from the soil surface after each rainfall event compared to a bare surface. This should lead to higher transpiration and therefore higher crop yields.

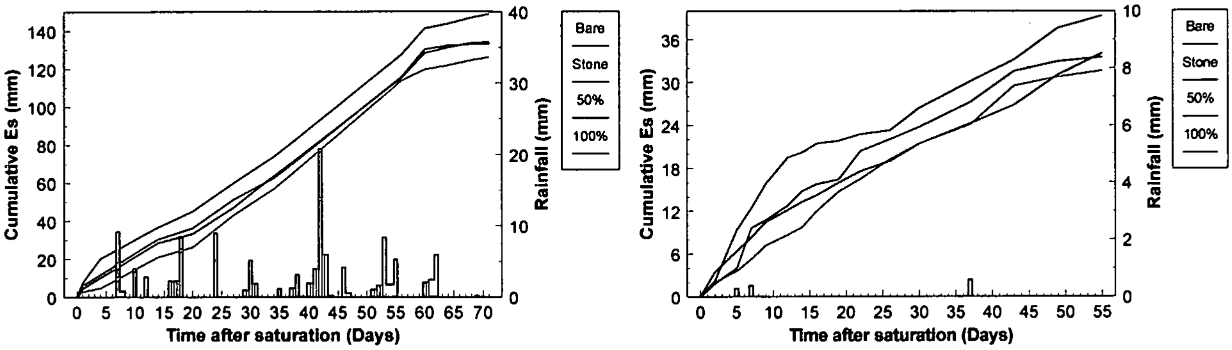

Figure 3.4 Summer (left) and winter (right) evaporation curves for various surface treatments on the Bo soil measured gravimetrically for the 0 - 300 mm layer.

Winter evaporation curves (measurement period = 55 days: 19 July - 6 September 2000) for the different treatments indicate that the bare treatment lost the most water, followed by the 50% organic mulch, 50% stone and then the 100% organic mulch. The trends are similar to the summer curves, but differ in magnitude. The higher Es values for the summer treatments are, *inter alia* due to more and larger rainfall events than in the winter, as well as the higher energy supply during the summer. The latter promotes an increase in Es. During the summer season Es oscillates between the first stage of evaporation (dominated by E_0 where climate plays an important part in determining Es, generally ceased after about 3 days), and the second stage (dominated by the hydraulic properties of the soil and E_0), due to the frequent rainstorms (Figure 3.4). These conditions explain the deviation in the shape of the summer Es curves compared to the conventional shape present in the winter curves. Although almost no rain occurred during the winter, Es seems to continue at a certain rate. Ritchie & Burnett (1971) found similar results and attributed them to the presence of large soil shrinkage cracks that continually open channels to moist soil deeper in the profile when the topsoil is dry.

Results from the winter evaporation curve in Figure 3.4 indicate that the differences between different treatments were the largest around 12 - 14 days after saturation and then started to decrease. $\sum$Es results for the different treatments on day 12 after saturation are presented in Table 3.1. Results indicate that the stone, 50% organic and 100% organic treatments were able to reduce Es with 37, 34 and 50% in comparison to bare, respectively. The $\sum$Es results after 55 days indicate that the difference between treatments was substantially less. After 55 days stone, 50% organic and 100% organic were 13, 15 and 20% lower than the bare treatment, respectively. The results indicate that surface mulch applications can decrease Es significantly over the first 12 days after wetting and thereby contribute towards better rainwater conservation and higher yields. Similar results were found by Berry & Mallett (1988) and Hoffman (1997), which indicated that mulching, loses its suppressing effect on Es when the drying cycles exceed 14 - 20 days.

Table 3.1 Cumulative evaporation from the soil surface (mm) for the different treatments on days after saturation (DAS)

DAS	Parameter	Bare	Stone	50% organic	100% organic
12	ΣEs (mm)	19.5	12.2	12.8	7.7
	Reduction in Es (%)	-	37	34	60
55	ΣEs (mm)	39.3	34.1	33.5	31.6
	Reduction in Es (%)	-	13	15	20

During the first three to five days of the winter Es curve it seems that stage 1 was absent, and started only between days four and five with a sharp rise in ΣEs. One of the driving forces of Es, especially during stage 1 when Es is dominated by the supply of energy to the surface, is temperature. Low temperatures would therefore affect Es (Walker, pers. comm., 2006, Dept. Soil, Crop and Climate Sciences, University of the Free State, Bloemfontein). Ritchie (1972) also claimed that during stage 1 drying, the supply of energy reaching the soil surface limits Es. During the first three days after the start of the winter curve the minimum air temperature varied between -0.67 and -8.55°C (Table 3.2). According to Walker (pers. comm., 2006, Dept. Soil, Crop and Climate Sciences, University of the Free State, Bloemfontein), when the water in the top layers of the soil is frozen (solid phase) much energy is needed to change the water to a liquid and then into vapour. Such conditions would suppress Es during stage 1, and could prolong it. This might be what happened during the first four days of the winter curve and hence the slow start of the ΣEs vs. time curve.

Table 3.2 Climatic variables for the start of the winter evaporation curve

Day of year	Days after saturation	Radiation mJ/m^2	Ave. Temp. °C	Wind speed m s^{-1}	Max. Temp. °C	Min. Temp. °C	Max. Rel. Humidity %	Min. Rel. Humidity %	E$_o$ mm day^{-1}
197		7.44	0.50	3.30	9.00	-8.00	100.00	66.58	0.88
198		14.54	0.30	1.97	8.60	-8.00	98.00	33.73	0.88
199		14.12	3.23	1.52	14.69	-6.73	80.50	18.94	2.28
200		13.49	10.26	3.25	20.90	-1.67	61.36	13.82	4.20
201	0	13.85	7.46	2.62	12.36	-0.67	68.12	25.85	2.82
202	1	13.36	0.63	1.75	8.48	-4.69	86.20	29.04	1.70
203	2	14.82	0.74	0.99	12.80	-8.55	80.40	15.31	1.98
204	3	14.37	3.11	1.53	15.82	-8.22	67.45	10.92	2.39
205	4	9.48	10.15	5.24	16.40	1.04	71.60	26.40	3.05
206	5	9.47	11.35	3.19	16.56	6.59	80.50	32.84	2.44

Data regarding the modification of soil temperatures during the summer and winter by mulching is presented in Figure 3.5. The highest hourly summer air temperature (33.2°C) was recorded during day 37 after the start (DAS) of the Es determinations. The lowest hourly winter minimum air temperature (-8.6°C) occurred during the second day after starting the Es determinations. The hourly-recorded temperatures are plotted for DAS 37 and DAS 2 in Figure 3.5.

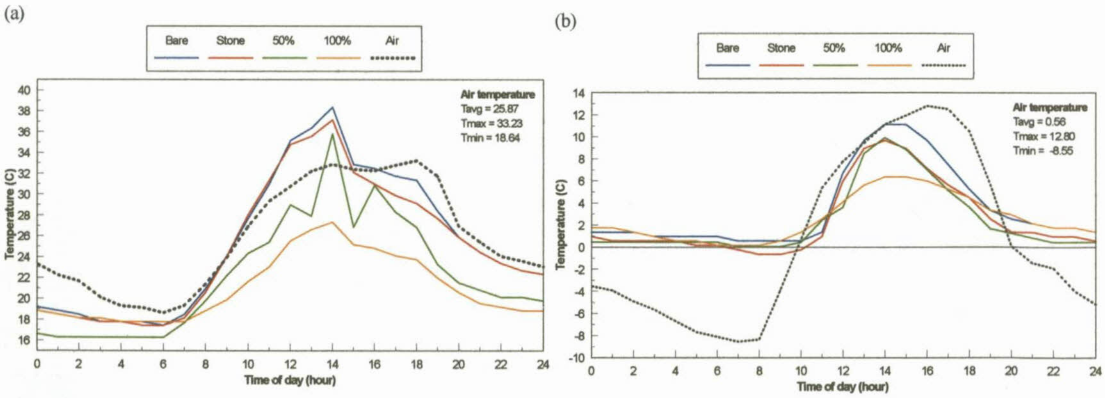

Figure 3.5 Changes in soil temperatures at a depth of 25 mm as influenced by mulches during a 24-hour cycle on DAS 37 during summer (a), and DAS 2 during winter (b).

These data showed that both the extreme maximum and minimum air temperatures differed from those of the soil temperatures in the different surface treatments. In the case of DAS 37 soil temperatures at a depth of 25 mm on the bare, stone and 50% organic treatment were 5.5°C, 4.3°C and 2.9°C warmer, respectively, than the air at peak time. In contrast the 100% mulch was 5.6°C and 11.0°C cooler, respectively, than the air and bare soil temperatures. It is also interesting to note that from approximately 16h00 the air temperature rises above the soil temperatures and remains above until around mid-morning of the next day.

For the winter period on DAS 2 the lowest air temperature (-8.55°C) was measured at 07h00. At that stage the soil temperature varied between -0.3°C and 0.3°C, depending on the mulch treatment. It was only the stone treatment that cooled down to freezing point. In this case the heat that had been stored in the stones during the day was continuously emitted during the night until approximately 08h00 when it had reached the lowest value of approximately -1°C. According to Philip (1957) the influence of climate on Es is less at "screen height" than close to the soil surface. Therefore the temperature at the soil surface would be lower than at "screen height" during the night and early in the mornings, while it would be the opposite during the day. There is also a steep gradient from a depth of 25 mm in the soil to the surface where it is much colder. This is an indication that the early morning temperature at the soil surface of all the treatments was probably well below zero °C, and therefore much lower than displayed in Figure 3.5 (b).

Using the procedure proposed by Ritchie (1972), the winter Es data presented in Figure 3.4 were used to determine the α values. Results were 3.51, 3.11, 3.14 and 2.70 mm $d^{-0.5}$ for the bare, stone, 50% organic mulch and 100% organic mulch respectively. The value for the bare clay soil compares well with the mean α value of 3.5 mm $d^{-0.5}$ reported by Ritchie (1972) and Stroosnijder & Hoogmoed (1984) for a range of soils. Values for α are not given for the summer curves since Es oscillates between the first and second stages of evaporation. There was a considerable difference between the evaporative conditions of the late summer and winter. The daily average air temperature was 20 °C for the summer and 11 °C for the winter period. Thirty-two rainfall events occurred during the 71-day summer Es measuring period. This provided measuring periods too short for determining an α value. Only three rainfall events were recorded during the winter. Winter rainfall was less than 1 mm per rain event and can be regarded as an insignificant factor in the evaporation process. However, it would be valuable to determine an α value for this soil during summer to compare winter and summer determined α values. Since we are dealing here with second stage Es, which is influenced in the bare soil by the hydraulic properties of the soil and E_0, there is strong indication that α values during winter and summer should differ (Jackson *et al.*, 1976; Boesten & Stroosnijder (1986); Walker, pers. comm., 2006, Dept. Soil, Crop and Climate Sciences, University of the Free State, Bloemfontein).

3.3.4 GLEN/SWARTLAND - ROUXVILLE ECOTOPE (Swr)

3.3.4.1 Soil

The soil is classified as belonging to the Rouxville Family of Swartland Form (Soil Classification Working Group, 1991). A summary of the most relevant characteristics of the profile is presented in Table 3.3.

Table 3.3 Characteristics of the Rouxville soil with a red brown A horizon (Swr)

Profile detail					
Horizon	Diagnostic horizon	Colour	Clay (%)	BD[*1] (Mg m^{-3})	Depth to lower boundary (mm)
A	Orthic	Red brown	17	1.62	200
B1	Pedocutanic	Dark brown	31	1.66	400
B2	Pedocutanic	Dark brown	37	1.51	900
C	Saprolite	Many coloured geogenic mottles and lime	35	1.46	1200

[*1] Bulk density.

The surface soil consists of a red brown poorly structured, fine sandy loam, orthic A horizon with a clear transition at about 200 mm to the B horizon. The latter has a moderately strong structure, and is a dark brown sandy clay, pedocutanic B horizon. It merges into calcareous, sandstone saprolite at 900 mm. The saprolite is well weathered, offering no significant impedance to root development. The effective rootzone is considered to be 900 mm. The B horizon has a CEC of 12 - 14 $\text{cmol}_c\ \text{kg}^{-1}$ soil, which is considerably lower than the Bonheim - Onrus soil. The exchangeable Na content of the B horizon is low and the Ca:Mg ratio is 1:1.

3.3.4.2 Drainage characteristics

A drainage curve determined with the NWM for the 0 - 300 mm soil layer is presented in Figure 3.6. Equation 3.5 describes the curve, and facilitates the calculation of the drainage rate at any stage, and therefore quantification of the water balance. For the meaning of the symbols see Equation 3.4.

The curve confirms that the drainage rate of the soil is a little slower than the Bo. The amount that drained during the first 24 hours after saturation was 11 mm (0.46 mm h^{-1}) compared to the 12 mm of the Bo. During the following 22-day period the profile drained at a mean rate of 0.021 mm h^{-1} compared to the similar rate of the Bo of 0.023 mm h^{-1}. Equation 3.5 makes it possible to calculate D from the soil layer when rain had refilled the water content above the specified DUL. This is necessary to quantify the ΣEs (Equation 3.2).

$$Y = 96.722 - 3.481(\ln t) \ldots\ldots\ldots\ldots r^2 = 0.94 \ldots\ldots\ldots\ldots (3.5)$$

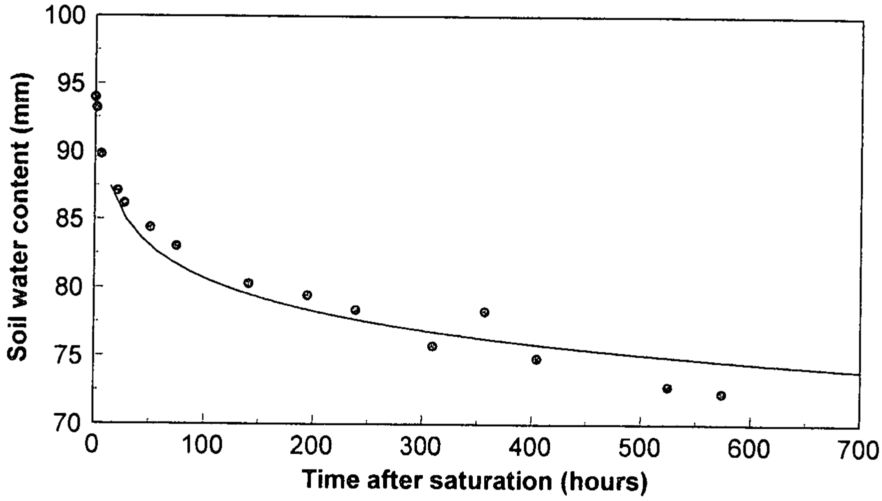

Figure 3.6 Drainage curve for the Swr soil: 0 - 300 mm layer determined with NWM.

3.3.4.3 Evaporation characteristics with various mulching treatments

Evaporation curves constructed using θm measurements during the summer and winter are presented in Figure 3.7. Evaporation curves (8 February 2000 - 14 April 2000: measuring period = 66 days) for the different treatments measured during the summer for the 0 - 300 mm soil layer reveals that the bare treatment lost the most water (ΣEs = 149 mm), followed by the 50% organic and stone mulches which were almost identical (ΣEs = 142 mm and 143 mm, respectively). The best treatment was the 100% organic mulch (ΣEs = 103 mm). Results indicate that 100% organic mulch was 45, 39 and 38% more effective than bare, stone and 50% organic mulch respectively, at suppressing Es.

Cumulative evaporation curves (25 July 2000 - 12 September 2000: measured period = 49 days) for different treatments during the winter for the 0 - 300 mm soil layer reveals that trends are similar to those of the summer curves. The bare treatment lost the most water (ΣEs = 37 mm). The 100% organic mulch was once again the most effective treatment in conserving soil water (ΣEs = 31 mm) followed by the stone mulch and 50% organic mulch (for both ΣEs = 34 mm).

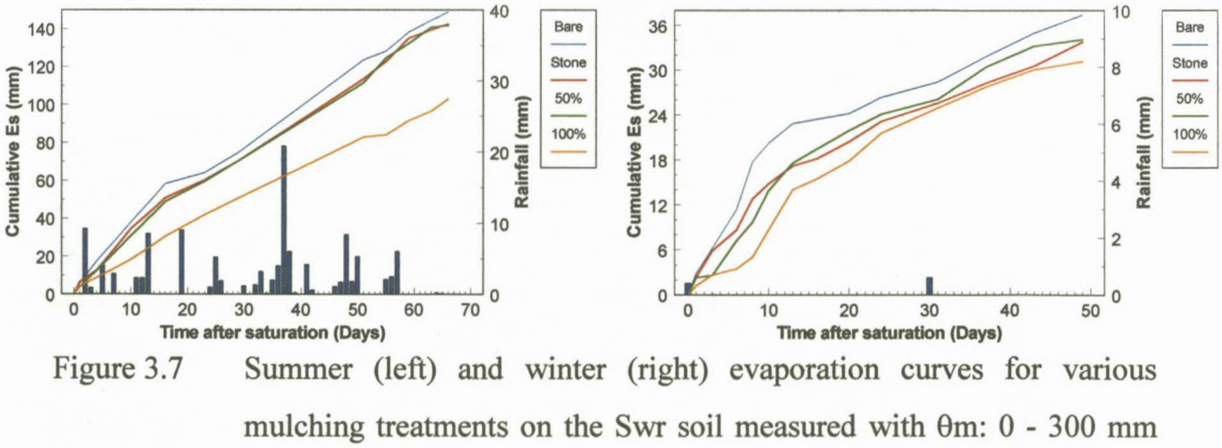

Figure 3.7 Summer (left) and winter (right) evaporation curves for various mulching treatments on the Swr soil measured with θm: 0 - 300 mm layer.

Results from the winter evaporation curve in Figure 3.7 indicate that the biggest differences between different treatments occur between 8 - 14 days after start (DAS) and then started to decrease. ∑Es (mm) results for the different treatments on DAS 8 and 49 are presented in Table 3.4. Results indicate that the mulch treatments; stone, 50% organic and 100% organic were suppressing Es with 28, 45 and 72% more effective than bare, respectively during DAS 8. ∑Es (mm) results for DAS 50 indicate that the differences between different treatments were substantial less. The stone, 50% organic and 100% organic were then only 10, 9 and 17% better than bare in suppressing Es. These results support results by Berry & Mallett (1988) and Hoffman (1997) that mulches lose their water conservation advantage when the drying cycles exceed about 14 days during the fallow period under semi-arid conditions.

Table 3.4 Cumulative evaporation from the soil surface (mm) for the different treatments on days after saturation (DAS)

DAS	Parameter	Bare	Stone	50% organic	100% organic
8	∑Es (mm)	17.8	12.8	9.7	5.0
	Reduction in Es (%)	-	28	46	72
49	∑Es (mm)	37.4	33.8	34.1	31.2
	Reduction in Es (%)	-	10	9	17

Following the Ritchie (1972) procedure the following α values were obtained: 3.00, 2.85, 2.86 and 2.56 mm $d^{-0.5}$ for bare, stone, 50% organic mulch and 100% organic mulch, respectively. The value for the bare soil compares favourably with the mean α values of 3.50 mm $d^{-0.5}$ reported by Ritchie (1972) and Stroosnijder & Hoogmoed (1984) for a range of soils. The results highlight the importance of field-determined data. To determine the α value for the summer curve was difficult because of the frequent rain events (32 events). However it would be valuable to obtain α values for winter and summer periods, since various authors have indicated that these would differ.

3.4 GENERAL DISCUSSION

3.4.1 MODELLING

The soil water management model (SWAMP – Bennie *et al.,* 1998) was used to estimate Es for the 0 - 300 mm soil layer of both ecotopes during the summer and winter periods. Predictions of ΣEs from the bare treatments for the summer were 173 mm compared to the measured value of 149 mm on the Bo soil, and 133 mm compared to the measured 149 mm on the Swr soil. During the winter the predicted ΣEs was 44 mm compared to the measured 39 mm measured on the Bo and 30 mm compared to the measured 37 mm on the Swr soil. Despite the slightly over prediction on the Bo soil and under predictions on the Swr soil the model proved to be realistic.

Unfortunately, it was not previously possible to simulate Es as influenced by surface treatments due to the absence of such a subroutine in the SWAMP model. This can mainly be the attributed to the fact that such data were not available to the SWAMP modellers. An algorithm to overcome this shortcoming was developed and is presented in Equation 3.6. The evaporation ratio ($\Sigma Es_{(\%\ \text{ground cover})}/\Sigma Es_{\text{bare}}$) was grouped into 0% (bare), 50% (stone and organic) and 100% (organic) ground cover irrespective of soil and season. The percentage ground cover was plotted against the evaporation ratio ($\Sigma Es_{(\%\ \text{ground cover})}/\Sigma Es_{\text{bare}}$). The non-linear equation (Holliday from the statistical programme NCSS 6.0.21) (Hintze, 1996) was fitted through the data points ($r^2 = 0.99$). The benefit of this equation is that the suppressing effect of mulch on evaporation could be quantified irrespective of soil and season for any period. This equation allows the modeller to predict evaporation for a specific % ground cover when evaporation from the bare soil for a certain period is known as well as the % ground cover.

$$Es_{(\%cover)} = \left(1/\left((0.099)+\left(0.0018\times(\%cover)+7.57\times10^{-6}\right)\times(\%cover)\times(\%cover)\right)\right)\times Es_{bare} \quad ....(3.6)$$

where:

Es_{barc} = evaporation from the bare soil for a specific period (mm)

% cover = percentage ground cover by mulch (%).

3.4.2 MEASURING DEPTH

ΣEs was determined at various depths, mainly with θm (0 - 50 mm; 0 - 100 mm; 0 - 150 mm; 0 - 200 mm; 0 - 300 mm), NWM (0 - 300 mm; 0 - 1200 mm) and frequency domain reflectometry (FDR) (0 - 50 mm; 0 - 100 mm). Results are presented in Figure 3.8. ΣEs results determined at various depths indicate the inaccuracy of shallow measurements compared to the 0 - 300 and 0 - 1200 mm measurements. ΣEs results from both ecotopes after about 55 days indicate that only about 40, 57, 70 and 76% of the ΣEs that occurred from 0 - 1200 mm layer could be attributed to the 0 - 50 mm; 0 - 100 mm; 0 - 150 mm and 0 - 200 mm layers, respectively. ΣEs results indicate that the 0 - 300 layer accounted for 94% of the ΣEs that occurred from the 0 - 1200 mm layer. Results from both ecotopes therefore indicate that in order to get reliable Es data, measurements should at least cover the 0 - 300 mm soil layer. Measurements shallower than 300 mm should be regarded as unreliable.

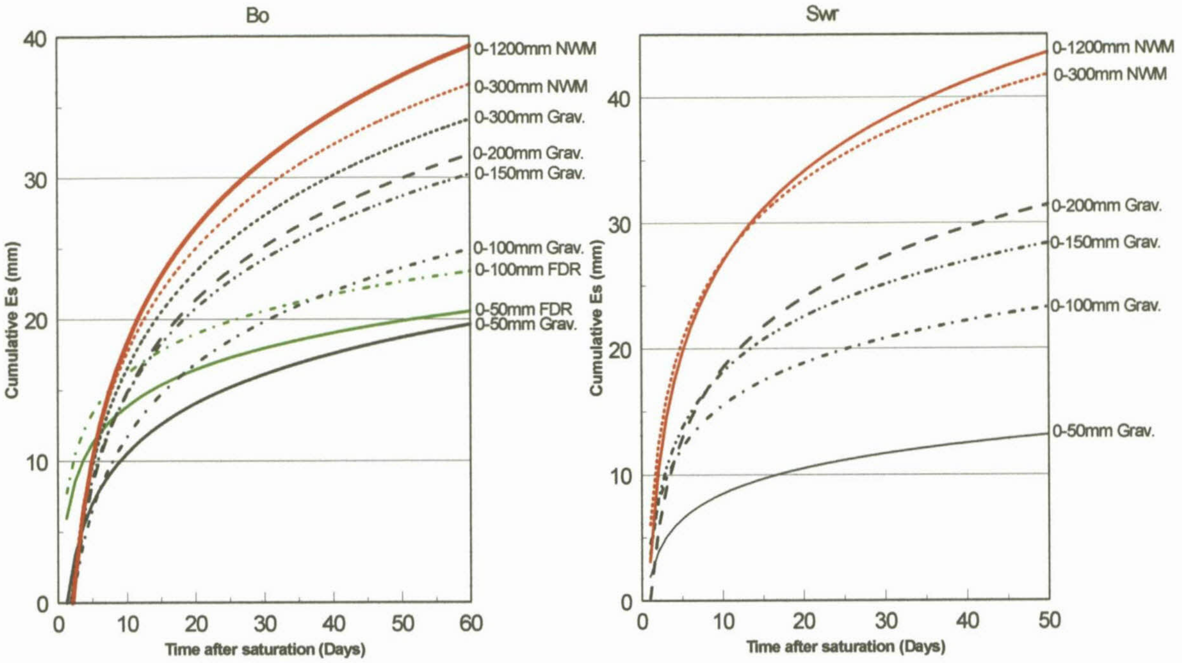

Figure 3.8 ΣEs measured at various depths on the Bo and Swr soils during the winter.

ΣEs curves for the Bo and Swr soils (values for the 0 – 300 mm layer) are given in Figure 3.9 and compared with other curves given by Ritchie (1972), Meyer, Walker & Green (1979) and Hattingh (1993). The Shorrocks soil curve from Pretoria (PTA) from Meyer *et al.* (1979) can be compared to the Glen/Shorrocks from Hattingh (1993) in terms of climate and soil characteristics. When the ΣEs curves of the two soils are compared it is clear that they are far apart and not at all comparable. Meyer *et al.* (1979) measured Es in weighing lysimeters up to a depth of 1000 mm. Hattingh (1993) used portable micro-lysimeters measuring the top 150 mm of the soil. This is clearly the reason for differences between the two similar soils. It can therefore be concluded that Es studies should not take measurements shallower than at least 300 mm, but preferably to a depth of around 1000 mm. This is probably particularly important in duplex soils because of the high water holding capacity of the B horizon in these soils. The Bo and Swr curves appear to compare well with the results of the other soils determined in lysimeters probably at least 1000 mm deep. It needs to be remembered, however, that the results for Bo and Swr are only for the 0 – 300 mm layer. The results in Figure 3.8 show that Es is still continuing quite strongly after 50 days when measurements were taken to 1200 mm. This is probably due to efficient capillary rise feeding from the high clay B horizon.

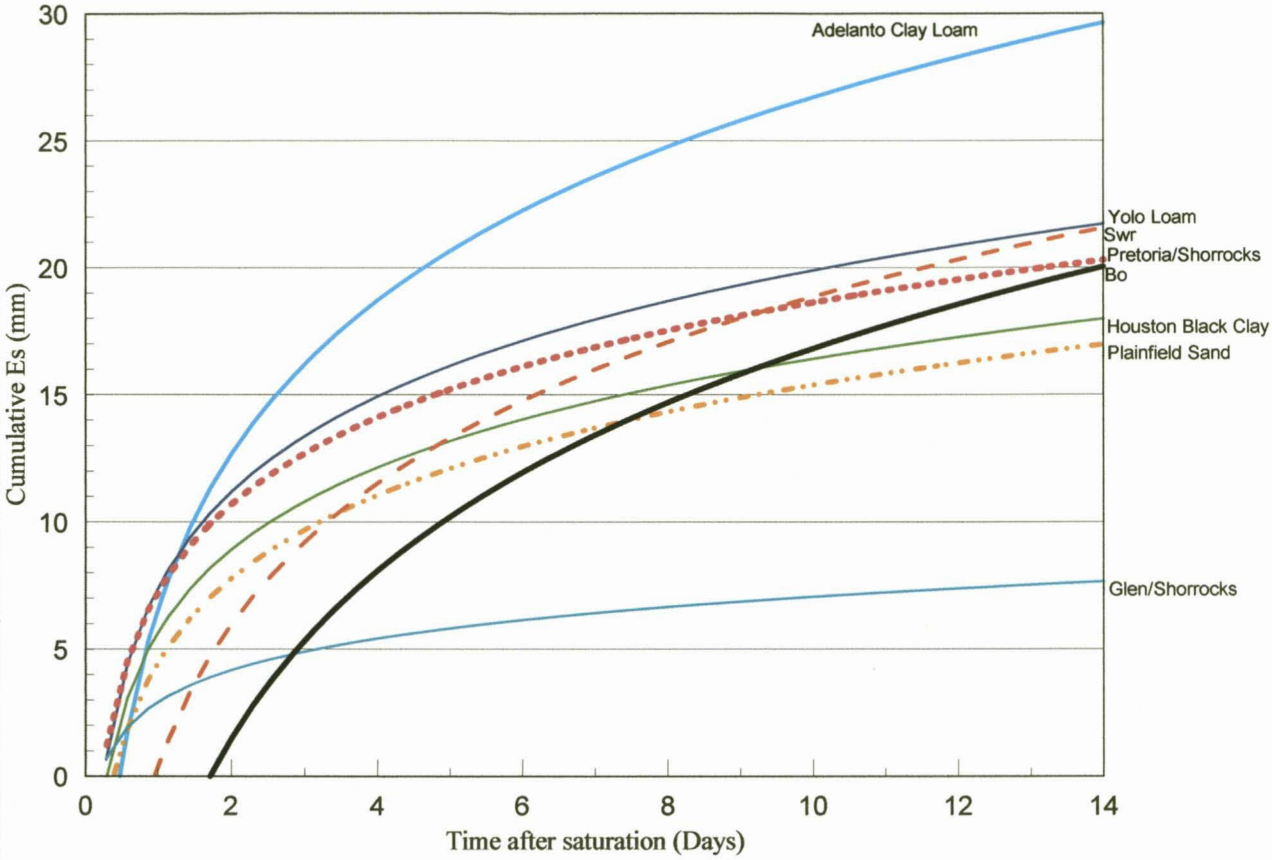

Figure 3.9 ΣEs of bare soil surfaces. Values for Adelanto clay loams; Yolo loams, Houston black clay, and Plainfield sand from Ritchie (1972); Pretoria/Shorrocks from Meyer *et al.*, 1979; Glen/Shorrocks from Hattingh, 1993; Bo and Swr from this study.

3.4.3 CLIMATE INFLUCENCE

It is necessary from the outset to clearly appreciate the conditions under which measurements were made. The focus was placed on the 0 - 300 mm layer from which it was expected that most of the Es occurs during the time intervals used here. This layer and those immediately below, were at field saturation when Es measurements started. The results indicate that first stage of Es (Es_1) generally ceased after about 3 days. Thereafter, in the absence of rain, stage two (Es_2) would have occurred followed by the third stage. During the summer rain season, however, Es oscillates mainly between Es_1 and Es_2 depending on the frequency and amounts of rainfall events. In addition, since Es_1 is strongly controlled by E_o, climate plays an important part in determining Es during the rain season, i.e. when crops are growing. This also explains the need to use the word "ecotope" when dealing with Es. The shape of the Es curves here for the summer measuring period have therefore largely been determined by the rainfall pattern, which was the same for both ecotopes with a total of 120 mm. There were 32 rainfall events, most of them (23) less than 5 mm, and eight were between 5 and 10 mm, and there was one fairly large event of 21 mm. There were seldom more than four days between the events. A good RSE value with such a rainfall pattern cannot be expected. The results for the summer period presented in Figure 3.4 and Figure 3.7 confirm this by showing that in all cases on both ecotopes, except for the 100% organic mulch treatments, ΣEs exceeds 120 mm, i.e. giving a negative RSE.

Es from a soil without any vegetation is already a very complex process as it involves intensive dynamic interactions between the atmosphere and the soil (condition of the surface soil, water content or wetness of the surface and underlying layers, and the hydraulic conductivity). To complicate the Es process even further different authors used different terminology for various Es processes. A number of authors have found that Es occurs in three stages, stage one or the constant rate stage, stage two or the falling rate stage and stage three or reduced evaporation rate stage. These authors also claimed that Es_1 depends on the net effects of water transmission to the surface and aboveground climatic conditions, during the second stage soil factors control the rate of water movement to the soil surface and above ground climatic conditions have little influence on Es and the third stage Es is controlled by adsorptive forces at the solid-liquid interface in the soil.

In order to avoid any confusion with the various terminologies it is recommended to use early, intermediate and late stage of Es (Figure 3.10) to replace the various terminologies used for first, second and third stage of Es, respectively. Results from the literature review and the field experiment from this study indicate the following: (a) during early stage Es, E_o dominates but the relationship between the water content and hydraulic conductivity of the surface layer and the under laying layers is also very important; (b) during intermediate Es, E_o domination gradually reduces while the importance of the water content and hydraulic conductivity relationship gradually increases; (c) during late Es the relationship between water content and hydraulic conductivity of the surface layer and the under laying layers dominates and E_o still plays an important but minor role.

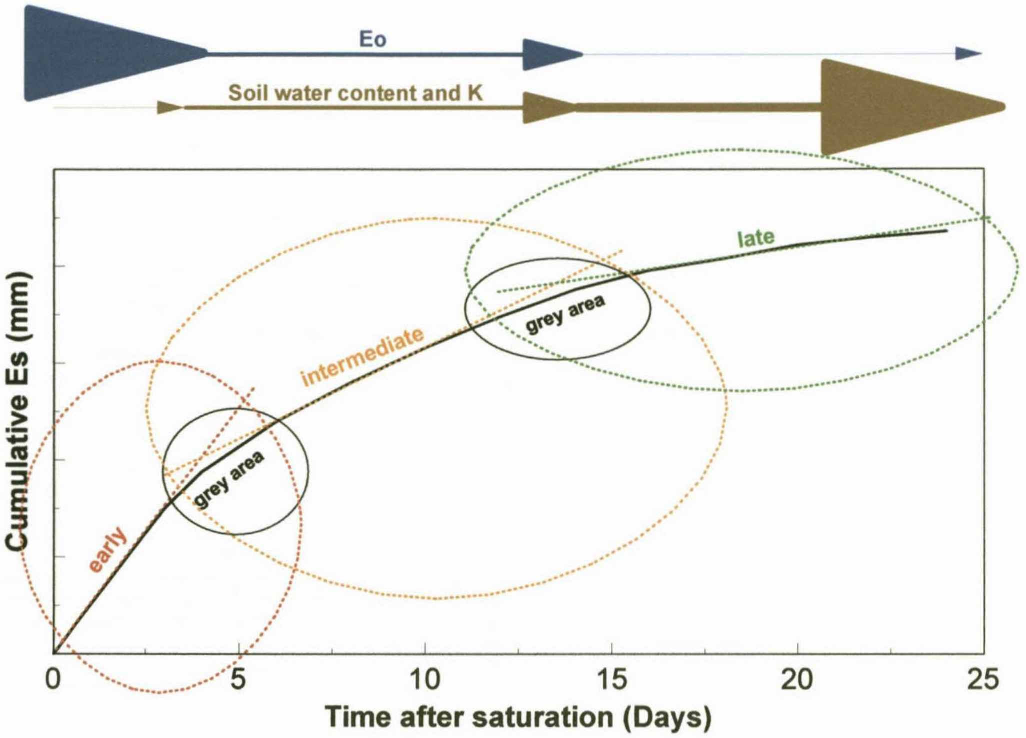

Figure 3.10 A hypothetical diagrammatic representation of the Es process with early, intermediate and late Es.

3.5 SUMMARY AND CONCLUSIONS

The reduction in Es, and therefore the beneficial effect on plant water availability of the 100% organic mulch treatment is clearly shown on both ecotopes during both the summer and winter measuring periods. The influence of the 50% organic mulch and stone treatments on Es reduction was generally very similar on both ecotopes and always far less effective than the 100% organic mulch. The considerably greater beneficial effect of all the mulches on Bo compared to Swr is surprising considering that ΣEs for both summer and winter measuring periods on the two ecotopes was almost exactly the same. No reasonable scientific explanation is available. It was also found that the biggest difference between treatments occurred between DAS 8 - 16, thereafter the effect of mulches seemed to decrease drastically. The mulch treatments with the higher water contents than the bare treatments indicate a benefit for plant growth resulting in higher crop yields.

Es measurements should be taken for the 0 - 300 mm soil layer but preferably be taken to around 1 m for reliable results especially on duplex soils. Compare Figures 3.8 Bo versus Swr. Shallower measurements are shown to be unreliable. The α value used by Ritchie (1972) and Stroosnijder & Hoogmoed (1984) for a range of soils of 3.5 mm $d^{-0.5}$ compares well with α values obtained for the Bo and Swr soils of 3.5 and 3.0 mm $d^{-0.5}$ respectively. α Values for winter and summer periods should be determined which would be valuable information for crop models. These differences can possible be avoided by relating Es to ΣE_o to give an ecotope specific β value as suggested by Boesten and Stroosnijder (1996).

SWAMP over predicted ΣEs during summer on the Bo (bare treatment), and under predicted ΣEs on the Swr (bare treatment). SWAMP predicted ΣEs reasonably well on both the soils during the winter. Previously it was not possible to make any simulations concerning the influence of mulching on Es with the SWAMP model. An algorithm to overcome this shortcoming was developed and with a r^2 value 0.99. The benefit of this equation is that the suppressing effect of mulch on evaporation could be quantified irrespective of soil and season for any period. This equation allows the modeller to predict evaporation for a specific percentage ground cover when evaporation from the bare soil for a certain period is known as well as the percentage ground cover.

In order to avoid any confusion with the various terminologies it is recommended to use early, intermediate and late stage of Es to replace the various terminologies used for first, second and third stage of Es, respectively. Results from the literature review and the field experiment from this study indicate from the beginning of early stage of Es through to the intermediate and the late stage E_o dominates during the early stage and the domination gradually reduces until E_o plays a minor but important role during the late stage. The relationship between the water content and hydraulic conductivity of the surface layer and the under laying layers plays an important but minor role at the beginning of the early stage but during intermediate stage its importance gradually increases until it dominates.

Borlaug (1997) has described sub-Saharan Africa as the most famine prone area in the world. A major environmental factor limiting food security in this area, as well as in West Asia and North Africa, is water. As there are three processes by which rainwater becomes unavailable for crop production viz., runoff (R), D and Es, optimum precipitation use efficiency requires that these losses be minimised. On clay soils where D is negligible in dry areas, and R can be prevented (and employed beneficially) by in-field rainwater harvesting (Hensley *et al.*, 2000), the remaining challenge is to minimize Es. This study has shown that Es can be reduced by 8 - 20% using different mulches over long periods. The effect, however, over the short-term (8 - 16 DAS) is much greater and varied between 28 and 72%. This will give crop roots time to extract a greater portion of the rainwater and therefore use it more productively through transpiration. This would lead to less water being lost by evaporation.

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CHAPTER 4: IMPROVING MAIZE YIELDS ON A SEMI-ARID ECOTOPE USING IN-FIELD RAINWATER HARVESTING

ABSTRACT

Subsistence farmers occupy a large area east of Bloemfontein in the Free State Province of South Africa. They do not enjoy food security; one of reasons is that the area is marginal for crop production. There are three reasons for this: (a) low and erratic rainfall that amounts to a mean of 543 mm per annum; (b) a corresponding high evaporative demand of 2198 mm per annum; (c) dominantly duplex and clay soils on which precipitation use efficiency (PUE) is low due to high runoff (R) and evaporation (Es) losses. It was hypothesised that the in-field rainwater harvesting (IRWH) technique could improve crop yields compared to the conventional tillage (CON) normally employed, and thereby serve to improve food security.

To test the hypothesis a field experiment was laid out on the nearby Glen Agricultural Institute on an ecotope similar to those in the target area. Maize was chosen as one of the crops because of its suitability for the prevailing socio-economic and climatic conditions. Four variations of the IRWH technique were compared with CON over the four growing seasons 1999/2000 to 2002/2003. The mean grain yields over the four seasons for CON and the mean of the four IRWH treatments were 1641 and 3182 kg ha^{-1}*, respectively, i.e. an overall mean improvement of 94%. For each season the yield from each IRWH treatment was statistically better (*$P \leq 0.05$*) than CON. Water balance measurements showed that the reason for the yield improvement by IRWH was due to more water being available for transpiration (Ev) by R being reduced to zero and Es decreased. Mean values of Ev (mm), and Es expressed as a percentage of Ev/ET for CON and IRWH (means of four treatments,) over the four seasons were 75 mm and 129 mm, respectively, and 29% and 42%, respectively. It was concluded that the most reliable, appropriate and acceptable way to describe the effectiveness with which rainwater is converted into grain by various treatments is by using the parameter rainwater productivity (*RWP_{n}*). RWP is based on long-term experimental data over a number of consecutive seasons and includes the fallow and growing* *seasons. Its values are 3.22 and 6.26 kg ha^{-1} mm^{-1} for CON and IRWH (mean of four treatments) over the four seasons (99/00 – 02/03), respectively. The experiment also showed that there were significant differences between the four IRWH techniques, the best one having mulch in the basins and stones on the runoff strip (ObSr).*

Based on the scientific evidence it can be concluded that the subsistence farmers could improve food security significantly by adopting IRWH.

Keywords: conventional tillage, in-field rainwater harvesting, maize, precipitation use efficiency, rainwater productivity

4.1 INTRODUCTION

The area of South Africa is 122.34 million ha, with less than 14% suitable for dryland and rainfed cropping, of which only about a quarter is land of high productive potential (Beukes, Bennie & Hensley, 2004). More than 60% of the country receives less than 500 mm per annum. Rainfall is extremely variable, with wide deviations from the mean annual values, especially in low rainfall areas. It is therefore clear that the natural resources are limited, while on the other hand population growth occurs at 1.56% per annum. This increases the pressure on the natural resources in terms of the need for increased food production. There is therefore a great need to quantify risk and improve crop yields by employing efficient and sustainable production techniques.

Subsistence farmers occupy a large area east of Bloemfontein in the Free State Province of South Africa. They do not enjoy food security because the area is marginal for crop production. There are three reasons for this: (a) low and erratic rainfall that amounts to a mean of 543 mm per annum; (b) a corresponding high evaporative demand of 2198 mm per annum; (c) dominantly duplex and clay soils on which the precipitation use efficiency (PUE) is low due to high runoff (R) and evaporation (Es) losses. To improve PUE it is therefore necessary to adopt water conservation production techniques. To optimise efficiency these techniques need to include water conservation during the growing and fallow seasons. Equation 4.1 is a suitable simplified formula for calculating PUE for this purpose (Hensley, Snyman & Potgieter, 1990) as it facilitates comparisons between the water conservation efficiencies of different production techniques:

$$PUE_{fg} = \frac{Yg}{P_f + P_g + (\theta_{h(n-1)} - \theta_{h(n)})} \text{........(kg ha}^{-1}\text{ mm}^{-1}\text{).........................(4.1)}$$

where: Yg = grain yield (kg ha^{-1})
$\theta_{h(n-1)}$ = rootzone water content at harvesting of the previous crop (mm)
$\theta_{h(n)}$ = rootzone water content at harvesting of the current crop (mm)
P_f = rainfall during the fallow period (mm)
P_g = rainfall during the growing period (mm).

PUE_{fg} refers to the period from harvesting of the previous crop to harvesting of the current crop. The denominator therefore defines all the water that has been available to the crop.

Because of the droughtiness in many parts of Sub-Saharan Africa (SSA) water conservation technologies have been studied by a considerable number of researchers. The following are examples: Reij, Mulder & Begemann (1988) – paying special attention to water harvesting in SSA; Kronen (1994) – focussing on smallholder crop production systems in semi-arid areas of the Southern African Development Community (SADC); Hatibu, Mahoo, Senkondo, Simalenga, Kayombo & Ussiri (1995) – relating to the semi-arid areas of Tanzania; Finkel & Segerros (1995) – paying special attention to water harvesting in the SADC region. Hensley, Botha, Anderson, Van Staden & Du Toit (2000) showed that using an in-field rainwater harvesting (*IRWH*) crop production technique maize yields could be increased by around 50% compared to conventional tillage (*CON*) during an average rain season. It was, however, realized that the full agronomic potential of this technique had not yet been reached. It was hypothesized that the factors that restrict the potential of *IRWH* to convert rainwater into food could be attributed to: (i) unnecessary water losses due to Es; and (ii) inefficient surface redistribution of water. The proposed solution was to introduce mulches in the system, applied into various combinations on the runoff area and in the basin area.

The effect of mulches on Es was studied on the Glen/Bonheim ecotope by Botha, Anderson, Van Staden, Van Rensburg, Beukes, & Hensley (2001); and Van Rensburg, Nhlabathi, Anderson, Botha, Van Staden & Kuschke (2002). Their results showed that different types of mulch gave similar results, and that the percentage ground cover has an important influence on Es. Classical evaporation studies clearly indicate that atmospheric evaporative demand is also an important factor. Es studies in South Africa have shown that the length of the drying cycle is also an important factor determining the ability of mulches to reduce Es. Hoffman (1997) estimated that mulching loses its water conservation advantage when the drying cycles exceed 15 - 20 days during the fallow period under semi-arid conditions. Berry & Mallett (1988) found that maize residue, covering greater than 70% of the surface, reduced evaporation considerably under sub-humid conditions provided the drying period was shorter than 14 days.

Under semi-arid conditions intermediate phase of the Es process (old stage two) dominates most of the time. This implies that Es is largely dominated during this phase by the hydraulic characteristics of the soil matrix (Hillel, 1972) and to a lesser extent the evaporative demand (Chapter 3). Hoffman (1997) states that cumulative Es (ΣEs) increases with increased silt plus clay content. On the other hand, a simple model proposed by Stroosnijder & Koné (1982), cited by Stroosnijder (2003), indicates that soil hydraulic properties are not of primary importance with regard to ΣEs during a crop growing season compared to other factors such as the frequency and size of rainfall events, potential evapotranspiration, leaf area index of the crop, and length of the drying cycle. They used a constant that apparently worked well for a wide spectrum of soils that ranged from sand to clay in their model.

4.2 PROCEDURES

To test the hypothesis an *IRWH* field experiment was laid out at the Glen Agricultural Institute on the Glen/Bonheim ecotope. The ecotope (climate, slope, soil) selected is similar in essential aspects to a large fraction of the area used by the subsistence farmers. A detailed description of this margalitic clay soil is presented in Hensley *et al.* (2000). Important soil, climatic and topographic characteristics of the Glen/Bonheim ecotope are summarised in Chapter 2.

A diagrammatic representation of the *IRWH* layout is given in Figure 1.3.

The experiment consisted of a randomised block design with 5 treatments and 3 replicates. Maize was planted annually. The treatments were as follows:

- *CON.*
- *IRWH* technique with organic mulch in the basins and bare runoff area (*ObBr*).
- *IRWH* technique with organic mulch in the basins and stones on the runoff area (*ObSr*).
- *IRWH* technique with organic mulch in the basins and organic mulch on the runoff area (*ObOr*).
- *IRWH* technique with stones in the basins and organic mulch on the runoff area (*SbOr*).

A short growing season (± 120 days to physiological maturity) maize cultivar (PHB3394) with a plant population of 22 000 plants ha^{-1} was used. Planting was done by hand between middle December and early in January. Planting and harvesting dates for the different seasons were: 07/01/00 - 06/06/00; 04/01/01 - 24/05/01; 19/12/01 - 23/04/02; 10/01/03 - 03/06/03. The fallow period was therefore about eight months. All fertilizer was applied at planting according to soil analyses for a target yield of 2 750 kg ha^{-1}. Ammonium nitrate was used as the nitrogen (N) source and applied at a rate of 43 kg N ha^{-1}. Super phosphate as the phosphate (P) source and applied at a rate of 13 kg P ha^{-1}. The soil potassium (K) status was very high and hence K application was ignored.

Crop growth, climate and soil water content were monitored throughout the growing seasons. Climatic variables were measured with an automatic weather station installed at the experimental site. The aridity index (AI) was calculated with Equation 4.2.

$$AI = \frac{P}{E_o} \qquad (4.2)$$

where: P = precipitation (mm)

E_o = evaporative demand (mm).

To monitor the soil water content of the rootzone (θr) neutron water meter (NWM) access tubes were inserted to a depth of 1.3 m, i.e. to a greater depth than that of the rootzone. NWM access tubes were located one in the middle of the 1m-basin area and one in the middle of the 2 m runoff strip. θr was measured with a Campbell Pacific 503 DR NWM. Measurements of θr were carried out before planting, at planting, and frequently during the growing season. Measurements were made at 300 mm depth intervals starting at 150 mm. A summary of the calibration process is presented in Chapter 3 while a detail description of the procedure used for NWM calibration is described by Hensley *et al.* (2000) and Botha *et al.* (2001). To define the upper limit of available water a field drainage curve determination was made to quantify the drained upper limit (DUL) of the rootzone (Ratliff, Ritchie & Cassel, 1983). The process used for field drainage curve determination is described in Chapter 3. The lower limit of plant available water (LL) was determined during the course of the growing seasons. LL was taken as the lowest θr for each soil layer measured over the four growing seasons. LL is the lowest field-measured water content of a soil after plants have stopped extracting water and is at or near premature death, or has become dormant as a result of water stress (Ratliff *et al.*, 1983). Since LL depends on soil, crop and climate characteristics, it is not meaningful to speak of the LL value of a soil on its own. LL needs to be related to a specific crop-ecotope. Crop modified upper limit of available water (CMUL) describes the maximum amount of water available from the rootzone for a particular crop at a particular growth stage and at a particular evaporative demand (Hattingh, 1993; Hensley, Hattingh & Bennie, 1993). CMUL is always more than DUL because plants can take up water while percolation is occurring within the rootzone. The critical factor is the drainage rate of the rootzone and how it changes with time, i.e. the shape of the drainage curve. CMUL is based on a field measured drainage curve and was determined as described by Hattingh (1993).

Grain yield was determined by harvesting 6 plant rows each 4 m in length. The grain was weighed, oven-dry and adapted to 13% moisture content and expressed as kg ha^{-1}. Biomass was measured at harvest from 6 rows each 1 m long. Biomass was expressed as oven dry material in kg ha^{-1}. Harvest index was calculated as the ratio of grain yield to the total aboveground biomass yield (Bennie, Strydom & Vrey, 1998).

$$HI = \frac{Yg}{Yb} \quad \text{..} (4.3)$$

where: HI = harvest index
Yb = total above-ground biomass (kg ha^{-1})
Yg = grain yield (kg ha^{-1}).

Biomass was used to determine transpiration (Ev) using the procedure proposed by Tanner & Sinclair (1983), including their transpiration efficiency coefficient (k) for maize of 9.5 g m^{-2} mm^{-1}, and the factor they proposed to make allowance for root mass, i.e. total biomass = 1.2 x above ground biomass. To implement the procedure the mean saturation deficit during daylight hours for each growing season was determined from data obtained from the automatic weather station. It was possible to estimate evapotranspiration (ET = Ev + Es) by employing a simplified water balance equation suitable for semi-arid conditions (Equation 4.4).

Equation 4.4 is a rearrangement of Equation 1.1. For the meaning of the symbols see Equation 1.1:

$$Ev+Es=(P\pm\Delta S)-(R+D)\ \text{...(mm)..} (4.4)$$

Previous θr measurements on this ecotope had shown that deep drainage (D) was negligible in this soil with its high content of swelling clay (Hensley *et al.*, 2000). Separate runoff plots, of the same length and with the same surface treatments (mulches) as those used on the *IRWH* field plots, were constructed to obtain measurements of R from each of the treatments (Chapter 2). Measurements were made throughout the course of the experiment. Ex-field (R_{Ex}) runoff from the *CON* treatment was estimated with Equation 4.5, a slightly adapted version of an equation developed during the previous studies on this ecotope (Hensley *et al.*, 2000). It was assumed that R_{Ex} would be zero if precipitation were less than 8 mm. Since all the items on the right hand side of Equation 4.4 are either measured or equal to zero, Ev + Es can be determined. Es is then obtained by subtracting the value of Ev, obtained via the biomass procedure already described, from Ev + Es.

$$R_{Ex} = \left[(0.473 \times P) - 2.17\right] \times 0.4 \text{ ....(mm)..................................(4.5)}$$

Rainfall storage efficiency (RSE) was calculated using the equation of Mathews & Army (1960). RSE describes the ability of the soil to store water in the soil profile during the fallow season:

$$RSE = \frac{\theta_{p(n)} - \theta_{h(n-1)}}{P_f} \times 100 \text{ ...(\%)...(4.6)}$$

where: $\theta_{p(n)}$ = rootzone water content at planting of the current crop (mm)

Water use efficiency (WUE) was determined with a slightly adopted version of an equation used by Hillel (1972), Passioura (1983) and Tanner & Sinclair (1983):

$$WUE_{Ev} = \frac{Yg}{Ev} \text{ ....(kg ha}^{-1}\text{ mm}^{-1}\text{)..(4.7)}$$

WUE therefore measures the efficiency with which a particular crop can convert the water available to it, during a particular growing season, into grain yield. PUE_{fg} was calculated with Equation 4.1. PUE_{fg} in Equation 4.1 is inversely proportional to the magnitude of the water losses through R_{Ex} + Es + D during the growing season and fallow period. Increases in these losses would cause PUE_{fg} to decrease, whereas a decrease in these losses would cause PUE_{fg} to increase. Precipitation use efficiency based on the growing season (PUE_g) is probably the simplest way of expressing the efficiency of converting rainwater into food:

$$PUE_g=\frac{Yg}{P_g+(\theta_{p(n)}-\theta_{h(n)})}\ldots\ldots(\text{kg ha}^{-1}\ \text{mm}^{-1})\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.8)$$

It is based on the simple principle that the system that produces the highest yield per unit area represents the best practice. The assumption is made that water conserved by restricting losses, although not directly measured, will be reflected in the higher yield obtained.

Analysis of variance was done on the results of the different treatments using the statistical software NCSS 6.0.21, 1996 for Windows (Hintze, 1996). Means were compared using the Tukey Kramer test ($P \leq 0.05$).

4.3 RESULTS AND DISCUSSION

4.3.1 DRAINAGE AND SOIL WATER EXTRACTION

A drainage curve for the whole rootzone, which provides the information for determining DUL, is presented in Figure 4.1. The high water holding capacity of the rootzone is expressed by the DUL value of 456 mm. That this is a high value is shown by comparing it for example with the DUL value of 224 mm reported by Hensley, Anderson, Botha, Van Staden, Singels, Prinsloo & Du Toit (1997) for the Setlagole Clovelly loamy fine sand with a rooting depth of 2100 mm.

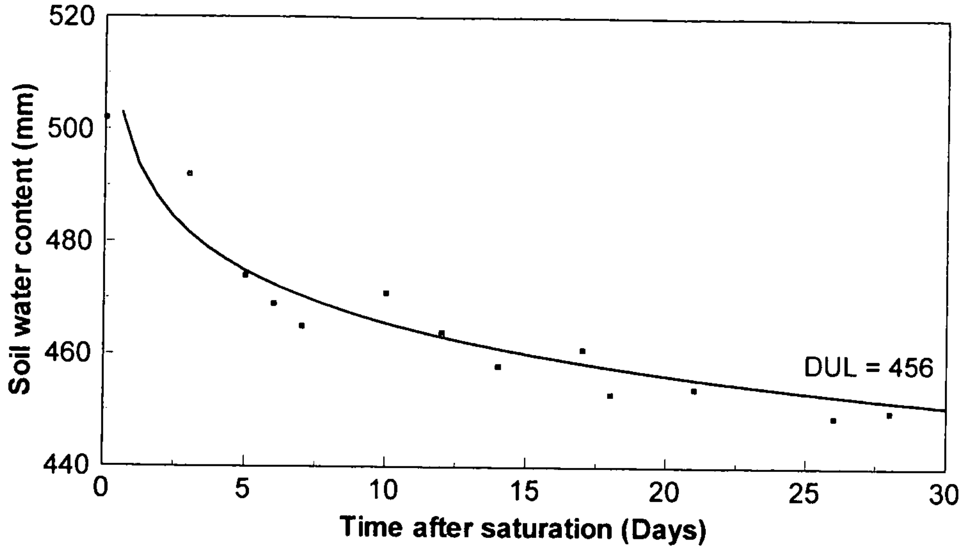

Figure 4.1 Drainage curve for the Glen/Bonheim ecotope: rootzone 1200 mm.

Equation 4.9 provides a mathematical description of the curve and enables the drainage rate at any time after field saturation (fSat) to be calculated:

$$Y = 511.55 - 8.92\,(ln\,t) \ldots\ldots r^2 = 0.80 \ldots\ldots (4.9)$$

where:

Y = water content of the rootzone (mm)

t = time after the drainage starts at a rootzone water content of fSat (hrs).

Equation 4.9 makes it possible to make estimates of D after periods of heavy rain. This is necessary to quantify the water balance (Equations 1.1 and 4.4). For these estimates to be reliable, another factor needs to be taken into account, viz. when θr exceeds DUL, D does not proceed at the predicted rate. While the water percolating slowly through the rootzone, it is also extracted by plant roots. The CMUL concept of Hattingh (1993) caters for this phenomenon. Using that procedure the CMUL value for maize is 485 mm (Table 4.1), i.e. 29 mm above DUL. The CMUL concept as originally formulated is, however, inadequate as it assumes equal distribution of extraction in terms of Es + Ev (evapotranspiration) from each of the soil layers. Since the intensity of root ramification is greater in the surface soil, and decreases with depth, the rate of soil water extraction is expected to follow the same pattern (Hensley *et al.*, 2000).

Table 4.1 The soil water extraction properties of the Glen/Bonheim ecotope. The effective rootzone for maize recorded is considered to be 0 - 1200 mm

Profile detail					Soil water extraction properties: Maize		
Horizon	Clay (%)	BD [*1] (Mg m^{-3})	Depth (mm)	DUL (mm)	LL (mm)	TESW[*2] (mm)	CMUL (mm)
A	45	1.30	300	122	39	83	
B1	43	1.45	600	123	74	49	
B2	40	1.45	900	106	74	32	
C	38	1.45	1200	105	76	29	
Total				456	263	193	485

[*1] Bulk density

[*2] Total extractable soil water (DUL - LL).

4.3.2 CLIMATE

To characterize the climatic conditions during the four seasons they were each sub-divided into three periods, *viz.* (i) fallow period (F_p), stretching from harvesting of the previous crop until planting of the next crop; (ii) vegetative growth (V_p) stretching from planting to flowering; (iii) reproductive period (R_p) stretching from flowering until harvest (Table 4.2). The growing period (G_p), therefore consists of V_p + R_p; and the overall production period (P_p), is: $F_p + V_g + R_p$.

Table 4.2 Precipitation (P), evaporative demand (E_o) and aridity index (AI) values for subdivisions of the four seasons in relation to long-term (LT) means for maize on the Glen/Bonheim ecotope. F_p = fallow period; V_p = vegetative period; R_p = reproductive period; G_p = crop growing period; P_p = production period

Parameter	Season	Period				
		F_p	V_p	R_p	G_p	P_p
P (mm)	99/00	157	95	133	228	385
	00/01	233	82	199	281	514
	01/02	360	161	86	247	607
	02/03	315	97	118	215	530
	Mean	**266**	**109**	**134**	**243**	**509**
	LT mean	**228**	**161**	**145**	**306**	**534**
E_o (mm)	99/00	315	347	229	646	891
	00/01	1143	465	290	755	1898
	01/02	863	352	301	653	1516
	02/03	1229	410	297	708	1936
	Mean	**888**	**394**	**279**	**691**	**1561**
	LT mean	**1361**	**533**	**395**	**928**	**2289**
AI	99/00	0.50*	0.27	0.58	0.35	0.43
	00/01	0.20	0.18	0.69	0.37	0.27
	01/02	0.42	0.46	0.29	0.38	0.40
	02/03	0.26	0.24	0.40	0.30	0.27
	Mean	**0.28**	**0.29**	**0.48**	**0.35**	**0.33**
	LT mean	**0.17**	**0.30**	**0.37**	**0.33**	**0.23**

* ND = excluded from mean.

Results indicate that the average rainfall over the four seasons was 63 mm lower than the long-term (LT) mean for the G_p period. Water shortage occurred mostly in the vegetative period. From the means for the experimental period, it is clear that maize received approximately 67% and 92% of the long-term mean for the V_p and R_p periods' rainfall. The rainfall during the R_p period for the 01/02 season was approximately 41% less than the long-term mean. Comparing the mean AI values of

G_p vs. LT show that the climatic conditions were slightly better than average during the experimental periods. What is of significance is the fact that the climatic conditions for R_p, which has a major influence on the crop yield, were generally, excepting for the 01/02 season, considerably more favorable than average. The average climatic conditions for V_p were typical for the ecotope, with one very dry season (00/01) and one very wet season (01/02). The AI values for the fallow period (F_p) were generally considerably above the average. The generally good cropping conditions indicated by the higher AI values can be attributed to lower potential evaporation rather than good rains. The AI values for the fallow period of the 99/00 season were excluded in the estimation of the experimental average. Due to the late start of the experiment the necessary measurements had not been made.

4.3.3 WATER BALANCE COMPONENTS

4.3.3.1 Soil water content

Conservation of water during the fallow period is essential in semi-arid environments to give a higher pre-plant water advantage. The plant available water at planting (PAW_p) and tasseling (PAW_T), and rainfall storage efficiency (RSE) values for each treatment are summarized in Table 4.3.

Mulch treatments affected RSE but with no particular pattern relative to the different treatments. It seems as if the *IRWH* treatments with the bare runoff area (*ObBr*) and the runoff area covered with stones (*ObSr*) induced higher RSE values compared to the treatments with organic mulch on the runoff area (*SbOr* and *ObOr*). In Chapter 2 in-field runoff results indicated that more rainwater water could be harvested from the bare runoff area, followed by the runoff area covered with stones. It is expected that less rainwater could be harvested from the runoff area covered with organic mulch. This possibly explains why *ObBr* and *ObSr* induced slightly higher RSE values. Higher RSE values were generally obtained on all the *IRWH* treatments compared to the *CON* treatment, except for the 01/02 season. During this season *CON* performed slightly better than all *IRWH* treatments. The reason for this unexpected higher RSE value of *CON* is that all the *IRWH* treatments ended the 00/01 growing season with relative high soil water contents because of above mean rainfall (> 54 mm) during the

00/01 reproductive period (Table 4.2). During this period 144 mm of the 199 mm came from rainfall events larger than 10 mm, while 96 mm came from three rainfall events larger than 20 mm. All the *IRWH* treatments harvested lots of rainwater in the basin area during these high potential runoff rainfall events compare to *CON* where 24 mm of rainwater was lost due to ex-field runoff (Table 4.4). The *IRWH* treatments therefore ended with soil water contents close to DUL while *CON* was 144 mm below DUL. This means that the *CON* treatment had a large storage capacity to fill (144 mm) during the fallow period if enough rain was available. The *ObBr*, *ObSr*, *SbOr* and *ObOr* treatments had significantly lower available storage capacities of 82, 50, 44 and 43 mm, respectively. This, and the 360 mm of rain received during the fallow period (132 mm more than the long-term mean) enabled *CON* to perform slightly better than the *IRWH* treatments.

Statistical analyses of the PAW_p values indicate that mulch type did not significantly affect PAW_p but all *IRWH* treatments had PAW_p values that were significantly higher than *CON* during all the seasons ($P \leq 0.05$). The *IRWH* treatments started the growing seasons with a mean of 78 mm pre-plant water advantage above *CON*. In semi-arid areas pre-plant water advantage is a critical factor in crop growth, especially during dry seasons. The PAW_T values of all the *IRWH* treatments were significantly higher than those of *CON* during all four seasons. There were no significant differences among the PAW_T values of the different *IRWH* treatments. These results clearly demonstrate the build up of available water in the rootzone on the *IRWH* plots compared to *CON*. This advantage at the critical tasseling stage is of particular significance for promoting better yields.

Table 4.3 Plant available water (mm) at planting (PAW_p), at tasseling (PAW_T) and rainfall storage efficiency (RSE) for the rootzone (0 – 1200 mm) on the different treatments during four growing seasons

Water content (mm)	Year	Treatment					
		CON	*ObBr*	*ObOr*	*ObSr*	*SbOr*	Mean *IRWH*
PAW_p (mm)	99/00	71^{a}	137^{b}	118^{b}	128^{b}	143^{b}	132
	00/01	47^{a}	101^{b}	96^{b}	114^{b}	112^{b}	106
	01/02	99^{a}	147^{b}	152^{b}	155^{b}	155^{b}	152
	02/03	37^{a}	152^{b}	176^{bc}	198^{c}	179^{bc}	176
	Mean	**64**	**134**	**136**	**149**	**147**	**142**
PAW_T (mm)	99/00	30^{a}	53^{b}	45^{b}	53^{b}	62^{b}	53
	00/01	23^{a}	42^{b}	57^{b}	53^{b}	57^{b}	52
	01/02	28^{a}	64^{b}	78^{b}	73^{b}	101^{b}	79
	02/03	29^{a}	65^{b}	75^{b}	77^{b}	81^{b}	75
	Mean	**28**	**56**	**64**	**64**	**75**	**65**
RSE (%)	99/00	37^{a}	57^{a}	42^{a}	46^{a}	51^{a}	49
	00/01	11^{a}	22^{b}	18^{b}	23^{b}	20^{b}	21
	01/02	14^{a}	10^{a}	1^{b}	3^{b}	2^{b}	4
	02/03	8^{a}	32^{b}	39^{bc}	43^{c}	37^{bc}	38
	Mean	**18**	**30**	**25**	**29**	**28**	**28**

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

4.3.3.2 Ex-field runoff

To quantify R_{Ex} from the *CON* treatment during the four seasons, they were sub-divided into the same five periods as presented in Section 4.3.2, *viz.* (i) F_p; (ii) V_p; (iii) R_p; (iv) G_p; (v) P_p. No R_{Ex} occurred from any of the *IRWH* treatments therefore only runoff from the *CON* treatment is reported.

Table 4.4 Ex-field runoff from the *CON* treatment estimated with Equation 4.5 for subdivisions of the four seasons for maize on the Glen/Bonheim ecotope

Parameter	Season	Period				
		F_p	V_p	R_p	G_p	P_p
R_{Ex} (mm)	99/00	15	8	8	16	31
	00/01	24	8	24	32	56
	01/02	39	15	10	25	64
	02/03	28	7	17	24	52
	Mean	**27**	**10**	**15**	**24**	**51**
R_{Ex} as % of P	99/00	10	8	6	7	8
	00/01	10	10	12	11	11
	01/02	11	9	12	10	11
	02/03	9	7	14	11	10
	Mean	**10**	**9**	**11**	**10**	**10**

During the 99/00, 00/01, 01/02 and 02/03 growing periods *CON* lost 16, 32, 25 and 24 mm of rainwater to R_{Ex}, respectively, which is a mean loss of 10% of the total rainfall over the four growing periods. The mean R_{Ex} during the four seasons for F_p, V_p, R_p, G_p, and P_p periods were 27, 10, 15, 24 and 51 mm, respectively. Severe water losses of 24 mm and 17 mm, due to R_{Ex}, occurred during the critical R_p period of the 00/01 and 02/03 seasons, respectively. These unproductive losses could seriously hamper maize yields. R_{Ex} (mm and % of P) differs between the various seasons and depends most of all on the rainfall characteristics. During the R_p period of the 99/00 season, where 92% of the long-term mean P occurred (133 mm, Table 4.2), only 8 mm or 6% of the 133 mm was lost to R_{Ex}. Comparing the R_p periods of two drier seasons (01/02 and 02/03), that received only 59% (86 mm) and 81% (118 mm) of the long-term mean P respectively, reveals that much more R_{Ex} occurred during this two drier seasons compared to the 00/01 season. During the R_p period of the 01/02 and 02/03 seasons 10 mm (12% of 86 mm) and 17 mm (14% of 118 mm) were lost to R_{Ex}, respectively. The 01/02 season received 86 mm of rain during the R_p period from 15 rainfall events. Only three events were more than 10 mm but resulted in 64 mm (14, 20 and 30 mm), which amounted to 74% of the rain that occurred during this period.

The R_p period of the 02/03 season received 118 mm of rain during the R_p period from 18 rainfall events. Only four of the 18 events were more than 10 mm (17, 51, 28 and 12 mm). These account for 92% of the P received during this critical period. During both seasons three or four large rainfall events resulted in more than 74% of the rainfall from which between 12 and 14% were lost to R_{Ex}. During the R_p period of the 99/00 season 34 rainfall events resulted in 133 mm of P. Only 3 events were more than 10 mm (21, 15 and 12 mm). These amounts to 36% of P received during this period. Only 8 mm of 133 mm or 6% were lost to R_{Ex}.

4.3.3.3 Soil water extraction

Figure 4.2 illustrates the measured changes in the soil water content of the rootzone during all growing seasons, which helps to explain yield and water balance data. Lines represent the mean of three replicates. The water management boundaries of plant available water (PAW), CMUL, DUL and LL are also included in the graphs.

Vegetative period (V_p):

During the vegetative period the yield potential is being determined. A favourable vegetative period will result in large strong plants (factories) with a high yield potential. During unfavourable conditions small weak plants would develop with a limited yield potential. Comparing the vegetative periods of the four seasons revealed that the 01/02 and 02/03 seasons, in all cases excepting for *CON* in 02/03, had a considerably higher PAW_p compared to the other two seasons. This was the effect of very favorable fallow periods. The AI of the 01/02 season is also the highest, 0.46 in comparison to the 0.27, 0.18 and 0.24 for the 99/00, 00/01 and 02/03 seasons, respectively (Table 4.2). The worst climatic conditions were associated with the V_p of the 00/01 season, with only 82 mm of rain and a cumulative E_o of 465 mm. This rainfall was far below the long-term mean of 109 mm. It was also poorly distributed. During the first 45 days after planting only 28 mm of rain occurred from 11 rainfall events with only one event of 12 mm that was more than 5 mm. In a semi-arid environment it is expected that most of the rain received from these small rainfall events will evaporate without significant contribution towards yield. This resulted in the development of small plants and therefore a low potential yield. However, according to the soil water content trends (Figure 4.2b), the plants on the *IRWH* treatments still had between 42 and 57 mm of plant available water at the beginning of tasseling compared to the *CON* treatment with only 23 mm, and therefore close to LL. The *CON* treatment started all four seasons with a considerably lower PAW_p compared to all the *IRWH* treatments, especially during the 02/03 season with a PAW_p of only 29 mm compared to the mean for the *IRWH* treatments of 75 mm. The soil water content of *CON* never came close to that of the *IRWH* treatments, which is an indication that *CON* never recovered from the low water contents at the beginning of every season. This is clearly reflected in the soil water patterns of the 00/01, 01/02 and 02/03 seasons. During the 01/02 season for example, (Figure 4.2c) 29 mm of rain occurred on day of year (DOY) 27. All the *IRWH* treatments responded with a sharp rise in soil water content compared to the almost unchanged soil water content of the *CON* treatment. *CON* evidently lost a large amount of rainfall to R compared to the *IRWH* treatments on which R was zero. There are clear trends in the soil water content patterns of the different treatments during the vegetative periods of the last three seasons, *ObSr* > *SbOr* > *ObOr* > *ObBr* > *CON*. According to the DUL and CMUL limits, no significant drainage could have occurred during any of the seasons during the vegetative period.

Reproductive period (R_p):

The potential yield that is determined during V_p, is either realized or minimized during the critical R_p, depending on the climatic conditions and the soil water content. Comparing the water content trends of the 99/00 season, the *ObBr* treatment fluctuates between the *SbOr* and *ObOr* treatments. The water content was relatively constant until DOY 118, when a series of four rain events slightly increased the soil water content. A characteristic of this period was the high frequency of small rain events, i.e. 34 events compared to the 15 of the 01/02 season.

As is often the case in a semi-arid environment, climatic conditions can change dramatically in a short time. For example, during the 00/01 season there was a change from unfavourable during the V_p/R_p transition period (days of year 60 to 80 – Figure 4.2b) to very favourable in the R_p after day of year (DOY) 80. The crop received 199 mm of rain during R_p (Table 4.2), while the corresponding E_o amounted to only 290 mm. This caused the rootzone water content of all the treatments except for *CON* to rise sharply in response (Figure 4.2b).

During 01/02 climatic conditions became unfavourable towards the end of the season. Only 59% (86 mm) of the long-term mean rainfall occurred during this R_p, of which 55 mm occurred between DOY 99 and 101 and was almost too late to significantly influence maize yield. The water content declined to close to the LL, before rain recharged the profile at the end of the period (Figure 4.2c). The *ObBr* treatment showed the lowest water content of all the *IRWH* treatments during this period, but the difference between treatments was not significant at tasseling. If it had not been for the relative high PAW_p and good rains that occurred during the V_p, the unfavourable climatic conditions towards the end of the 01/02 season would have seriously depressed maize yields.

Although plant available water was still at a reasonable level above LL at the start of tasseling during the 02/03 season, yields would have been seriously hampered if good rains had not fallen during tasseling. The crop received 118 mm of rain during R_p, of which 96 mm occurred in the first 10 days after the start of tasseling, consisting of events of 17, 51 and 28 mm on days 8, 9 and 10 after the start of tasseling, respectively. This caused the rootzone water content of all the treatments to rise sharply; with the *IRWH* treatments responding to a far greater extend than *CON* (Figure 4.2d). This once again confirms the advantage of *IRWH* above *CON* in terms of the reduction of total R to zero. If it had not been for the good rains during this period maize yields would have been very low as there was very little rain (22 mm) during the remainder of the season (Figure 4.2d). However, in the case of *CON* very small maize plants with a low yield potential had developed during V_p because of the very low PAW_p of only 37 mm (Table 4.3). Table 4.4 indicate that 14% of the rainfall that occurred during R_p was lost to R. The low yield potential and high R therefore contributed towards a very low maize yield of only 459 kg ha^{-1} on the *CON* treatment (Table 4.6).

In general the soil water content of the *ObBr* treatment remained significantly lower than the other *IRWH* treatments during the last three seasons, while the water content of *CON* remained significantly lower than all the *IRWH* treatments during all four seasons. As can be seen from the DUL and CMUL limits of 456 mm and 485 mm, respectively, the water content was never close to the limit at which drainage would occur during any of the seasons.

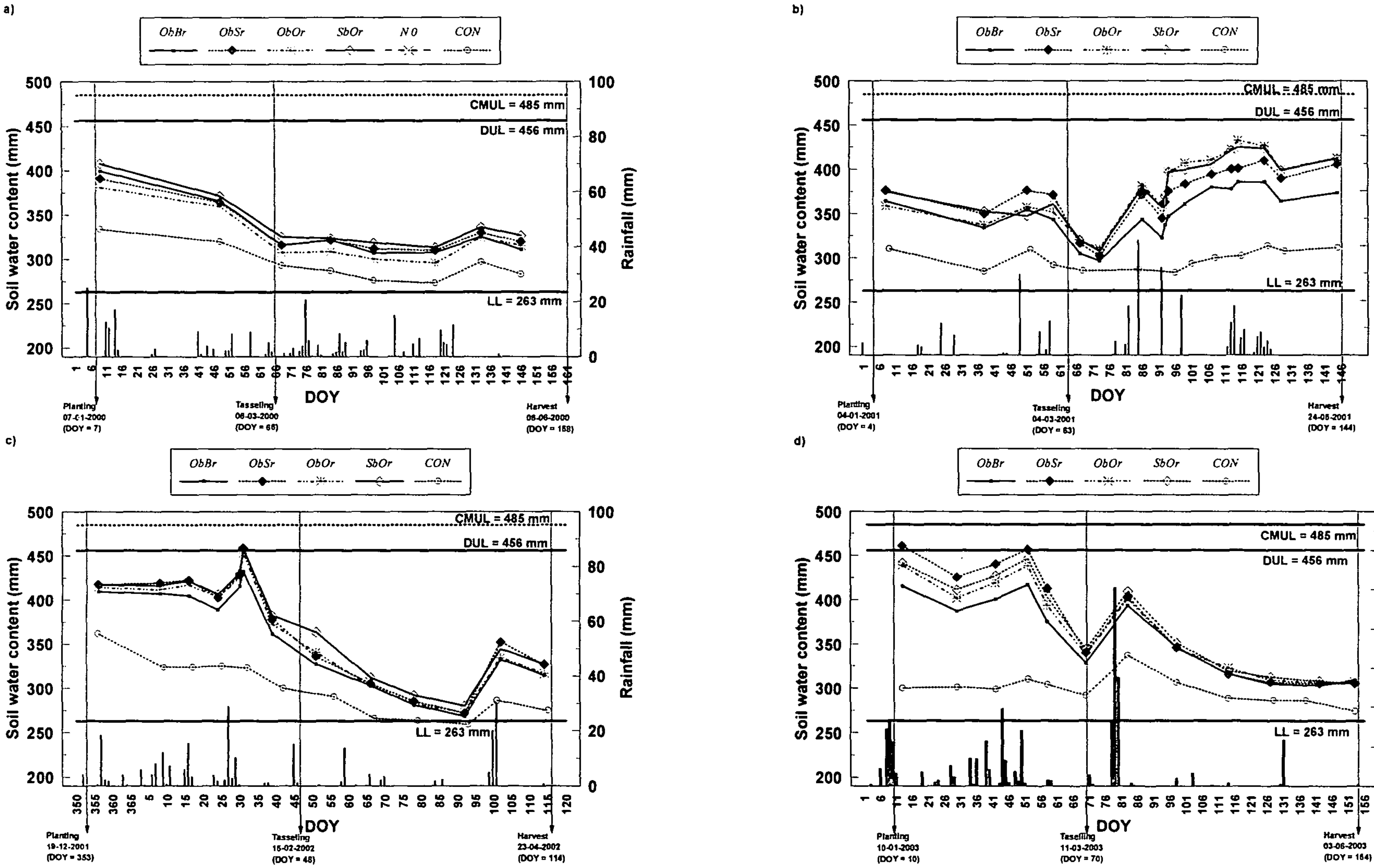

Figure 4.2 Changes in the mean soil water content of the maize rootzone (0 - 1200 mm) during the: (a) 99/00; (b) 00/01; (c) 01/02; (02/03) seasons on the Glen/Bonheim ecotope.

4.3.3.4 Evapotranspiration

Results on the separation of Ev and Es are presented in Table 4.5.

Table 4.5 Evapotranspiration (ET=Ev+Es), evaporation from the soil surface (Es) and transpiration (Ev) during the growing period for the four seasons for the different treatments

Parameter	Growing season	Treatment					
		CON	*ObBr*	*ObOr*	*ObSr*	*SbOr*	Mean *IRWH*
Ev (mm)	99/00	104^{a}	131^{b}	128^{b}	137^{b}	124^{b}	130
	00/01	64^{a}	99^{b}	115^{c}	123^{c}	113^{c}	113
	01/02	65^{a}	113^{b}	123^{b}	121^{b}	116^{b}	118
	02/03	62^{a}	131^{b}	151^{cd}	163^{c}	147^{bd}	148
	Mean	**74**	**119**	**129**	**136**	**125**	**127**
Es (mm)	99/00	160^{a}	186^{a}	166^{a}	163^{a}	184^{a}	175
	00/01	187^{a}	171^{b}	111^{c}	127^{bc}	130^{bc}	135
	01/02	254^{a}	230^{a}	208^{b}	217^{ab}	222^{ab}	219
	02/03	140^{a}	197^{b}	198^{b}	209^{b}	203^{b}	202
	Mean	**186**	**196**	**171**	**179**	**185**	**183**
ET (mm)	99/00	264^{a}	317^{b}	294^{b}	300^{b}	308^{b}	305
	00/01	251^{a}	270^{a}	226^{a}	250^{a}	243^{a}	247
	01/02	319^{a}	343^{b}	331^{c}	338^{bc}	338^{bc}	338
	02/03	202^{a}	328^{b}	348^{c}	372^{c}	349^{c}	349
	Mean	**259**	**315**	**300**	**315**	**310**	**310**
Es/ET (%)	99/00	61	59	56	54	60	57
	00/01	75	63	49	51	53	55
	01/02	80	67	63	64	66	65
	02/03	69	60	57	56	58	58
	Mean	**72**	**63**	**57**	**57**	**60**	**59**

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

These results provide the opportunity to analyze the general effect of *CON* and *IRWH* on ET, Ev and Es, as well as the specific effect of mulch type placement on the *IRWH* system. Comparing *CON* with the mean *IRWH* clearly shows that ET was three out of four seasons higher at the *IRWH* treatments than the *CON*. The mean increase is about 20%. Differentiation of ET into its components suggests that the mean increase in ET at *IRWH* can mainly be attributed towards higher Ev, as Es was found to be approximately similar during the growing seasons. This leads to the conclusion that the: (1) higher PAW_p, (2) total stoppage of R_{Ex} and (3) in-field runoff process (surface redistribution of water) that contributed towards better plant available water, induced higher Ev's at the *IRWH* treatments.

On the other hand, as shown in Chapter 3, Es can be reduced through mulching if the drying period is not longer than approximately 16 days. Hence, comparing the three *IRWH* treatments with organic mulch in the basins (*Ob*) with different mulch type on the runoff area (*Br*, *Or* and *Sr*) reveals that in two of the four years mulch on the runoff area suppressed Es significantly in comparison to the bare. Mulch type on the runoff area did not affect Es in any of the years. This is also true for the basin area when *ObOr* and *SbOr* are compared.

Ev/ET is an indication of the portion of ET that was used productively to produce food, while Es/ET is the portion of ET that was lost to Es. The mean Ev/ET results for maize on *CON*, *ObBr*, *ObOr*, *ObSr* and *SbOr* are 28, 37, 43, 43 and 40% respectively, while the Es/ET results of the same treatments are 72, 63, 57, 57 and 60% respectively. This shows that all the *IRWH* treatments lost smaller portions of ET to Es, in other words all the *IRWH* treatments were much more successful in minimizing the unproductive loss of water through Es. On average the *IRWH* treatments were 13% more successful than *CON* in minimizing the portion of ET lost to Es. Of all the *IRWH* treatments, *ObOr* and *ObSr* were the best treatments in this respect. All the *IRWH* treatments with mulches on the runoff area performed 5% better than the treatment with the bare runoff area in terms of minimizing Es.

Expressing mean Es as a percentage of the mean rainfall during the growing season shows clearly that the greatest loss remains soil evaporation. The mean of the four seasons varied from 70 to 81% of the rainfall (G_p). The four-year mean of the *IRWH* treatments with mulch on the runoff area, is 7% lower than the bare runoff area treatment. This experiment demonstrates clearly the importance to study Es, especially during the crop growing period. This is however a complicated system where ET should be separated into Es and Ev. Correct procedures on separating Es and Ev should be questioned and improved before the actual contribution of Es can be truly quantified.

4.3.4 YIELD RESPONSE

Grain and biomass yields, and the harvest index for the different treatments are summarized in Table 4.6.

Over the four years grain yields of individual treatments varied between 459 and 3962 kg ha^{-1} with a very strong yield trend of *ObSr* >*ObOr* ≈ *SbOr* > *ObBr* > *CON* (Table 4.6). The grain yields of all the *IRWH* treatments were significantly higher than *CON* over all seasons ($P \leq 0.05$). This was expected, as the soil water content of *CON* was always lower than in any of the *IRWH* treatments throughout the seasons (Figure 4.2). Reduced soil water levels result in lower daily ET's, especially during the grain filling stage, and hence reducing the rate of photosynthate supply to the seeds which is critical for optimum seed filling (Rhoads & Bennett, 1990.) On average the *IRWH* treatments produced 94% more grain that *CON*. Comparing the *IRWH* treatments, show that *SbOr*, *ObOr* and *ObSr* produced 7, 10 and 19% more grain, respectively, than *ObBr*. The *ObSr* grain yields were significantly better than *ObBr* in the three out of the four years.

Biomass yields of individual treatments over the four years varied between 2968 and 8143 kg ha^{-1}, with a pattern similar to the grain yields, *viz. ObSr* >*ObOr* ≈ *SbOr* > *ObBr* > *CON*. The statistical results revealed that the treatments with mulches on the runoff area increased the biomass significantly more than the treatment with a bare runoff area during the 00/01 and 02/03 seasons ($P \leq 0.05$). The reasons might be that: (a) according to Table 4.5, of all *IRWH* treatments *ObBr* lost the highest amount of water to Es during the 00/01 season; (b) only one rainfall event larger than 25 mm occurred during the V_p of the 00/01 season, which indicates that there were no good runoff opportunities for *ObBr* to harvest more rainwater in the basins compared to the other *IRWH* treatments; (c) according to Table 4.3 and Figure 4.2d, the PAW_p of *ObBr* was considerably lower than in the other *IRWH* treatments for the 02/03 season.

All the *IRWH* treatments produced significantly more biomass during all four seasons compared to *CON* ($P \leq 0.05$).

Table 4.6 Maize grain and biomass yields, and harvest index for the different treatments during four seasons

Parameter	Year	Treatment					
		CON	*ObBr*	*ObOr*	*ObSr*	*SbOr*	Mean *IRWH*
Grain (kg ha^{-1})	99/00	3093^{a}	3455^{b}	3519^{b}	3962^{c}	3500^{b}	3609
	00/01	1489^{a}	2543^{b}	2908^{c}	3098^{c}	2731^{b}	2820
	01/02	1521^{a}	3281^{b}	3325^{b}	3607^{b}	3288^{b}	3375
	02/03	459^{a}	2401^{b}	3066^{d}	3272^{c}	2952^{d}	2923
	Mean	**1641**	**2920**	**3205**	**3485**	**3118**	**3182**
Biomass (kg ha^{-1})	99/00	6003^{a}	7565^{b}	7408^{b}	7911^{b}	7186^{b}	7518
	00/01	4218^{a}	6505^{b}	7606^{c}	8143^{d}	7427^{c}	7420
	01/02	4203^{a}	7273^{b}	7916^{b}	7797^{b}	7460^{b}	7612
	02/03	2968^{a}	6334^{b}	7276^{cd}	7878^{c}	7084^{bd}	7143
	Mean	**4348**	**6919**	**7552**	**7932**	**7289**	**7423**
Harvest index	99/00	0.51^{a}	0.46^{a}	0.48^{a}	0.50^{a}	0.49^{a}	0.48
	00/01	0.35^{a}	0.39^{a}	0.38^{a}	0.38^{a}	0.37^{a}	0.38
	01/02	0.36^{a}	0.45^{b}	0.42^{b}	0.46^{b}	0.44^{b}	0.44
	02/03	0.15^{a}	0.39^{b}	0.42^{c}	0.42^{bc}	0.42^{bc}	0.41
	Mean	**0.34**	**0.40**	**0.43**	**0.43**	**0.43**	**0.42**

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

The harvest index of individual treatments over the four years varied between 0.15 and 0.51 during the four seasons. Values for the 00/01 and 02/03 seasons were lower than the other years. These values, except for *CON* during the 02/03 season, indicate that water supply in the vegetative period was sufficient to meet the crop water demand to a reasonable extent; i.e. very severe water stress did not occur. Grain and biomass yields and harvest index values indicate that all the treatments with mulch on the runoff area were superior to the treatment with a bare runoff area and that all the

IRWH treatments were superior to *CON*. Comparing the grain and biomass yields of *ObSr*, *ObOr*, and *ObBr* reveals that of the *IRWH* techniques stone mulch is the best mulch on the runoff area. Comparing grain and biomass yields of *ObOr* and *SbOr* shows that organic mulch performed better than stone mulch in the basins of the *IRWH* techniques.

4.3.5 WATER USE EFFICIENCY (WUE) AND PRECIPITATION USE EFFICIENCY (PUE)

Water use efficiency based on transpiration (*WUE_{Ev}*): The results in Table 4.7 show that over the four years WUE_{Ev} of individual treatments varied between 7.4 and 29.8 kg grain ha^{-1} mm^{-1}. All the *IRWH* treatments performed significantly better than *CON* during the 00/01, 01/02 and 02/03 seasons. The mean efficiency trend observed was *ObSr* > *SbOr* ≈ *ObOr* > *ObBr* > *CON*. The mean values also indicate that all the *IRWH* treatments are on average 21% more efficient in converting rainwater into grain yield than *CON*, and that the *ObSr*, *ObOr* and *SbOr* treatments are slightly more efficient in converting rainwater into grain yield than the *ObBr* treatment. The similar mean values of the *IRWH* treatments highlight that WUE_{Ev} is a crop related parameter and therefore more suitable to compare different crops with each other.

Precipitation use efficiency based on annual rainfall (PUE_g): The efficiency of individual treatments over the four years varied between 2.0 and 13.2 kg seed ha^{-1} mm^{-1} rain during the four seasons with the values for the *IRWH* treatments always significantly better ($P \leq 0.05$) than the *CON* during the 00/01, 01/02 and 02/03 seasons (Table 4.7). A common trend of *ObSr* > *ObOr* ≈ *SbOr* > *ObBr* > *CON* was observed during the experimental period. *ObSr* was for all the seasons significantly better than the *ObBr* ($P \leq 0.05$). On average the *IRWH* treatments were 82% more efficient in converting rainwater into grain yield than *CON*.

Table 4.7 WUE and PUE data for maize on the different treatments during the four seasons

Relevant parameters	Year	Treatment					
		CON	*ObBr*	*ObOr*	*ObSr*	*SbOr*	Mean *IRWH*
WUE_{Ev} (kg ha^{-1} mm^{-1})	99/00	28.1^{a}	24.9^{b}	25.9^{ab}	27.3^{a}	26.5^{ab}	26.2
	00/01	23.3^{a}	25.7^{b}	25.3^{c}	25.2^{c}	24.2^{c}	25.1
	01/02	23.4^{a}	29.0^{b}	27.0^{c}	29.8^{b}	28.3^{bc}	28.5
	02/03	7.4^{a}	18.3^{b}	20.3^{c}	20.1^{c}	20.1^{c}	19.7
	Mean	**20.6**	**24.5**	**24.6**	**25.6**	**24.8**	**24.9**
PUE_{g} (kg ha^{-1} mm^{-1})	99/00	11.0^{a}	10.9^{a}	12.0^{ab}	13.2^{b}	11.4^{a}	11.9
	00/01	5.3^{a}	9.4^{b}	12.9^{cd}	12.4^{c}	11.2^{cd}	11.5
	01/02	4.4^{a}	9.6^{b}	10.0^{cd}	10.7^{c}	9.7^{cd}	10.0
	02/03	2.0^{a}	7.3^{b}	8.8^{c}	8.8^{c}	8.5^{c}	8.4
	Mean	**5.7**	**9.3**	**10.9**	**11.3**	**10.2**	**10.4**
PUE_{fg} (kg ha^{-1} mm^{-1})	99/00	7.2^{a}	8.7^{b}	9.7^{b}	10.8^{b}	9.5^{b}	9.7
	00/01	3.1^{a}	5.9^{b}	7.5^{cd}	7.9^{d}	6.9^{c}	7.1
	01/02	2.0^{a}	4.9^{b}	4.9^{b}	5.3^{b}	4.9^{b}	5.0
	02/03	0.9^{a}	4.4^{b}	5.6^{cd}	5.9^{c}	5.4^{d}	5.3
	Mean	**3.3**	**6.0**	**6.9**	**7.5**	**6.7**	**6.8**
$RWP_{1999/00-2002/03}$ (kg ha^{-1} mm^{-1})		**3.22^{a}**	**5.74^{b}**	**6.30^{b}**	**6.85^{b}**	**6.13^{b}**	**6.26**

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

Precipitation use efficiency based on the complete water balance (PUE_{fg}): This is the most comprehensive and important efficiency term, and essential for comparing different water conservation techniques for dryland purposes. All the *IRWH* treatments had significantly higher PUE_{fg} values ($P \leq 0.05$) than *CON* during all four seasons (Table 4.7). Efficiencies of individual treatments over the four years varied between 0.9 and 10.8 kg grain ha^{-1} mm^{-1}. A common trend of *ObSr* > *ObOr* ≈ *SbOr* > *ObBr* > *CON* was observed. Mean PUE_{fg} results indicate that the *IRWH* treatments were on average 106% more efficient than *CON* in converting rainwater into maize grain. The superiority of the *IRWH* treatments was due to the ability of the technique to stop R completely, inducing in-field runoff, the beneficial influence of a higher PAW_p and the reduction in the portion of ET lost to Es. Of all the *IRWH* treatments *ObSr* was by far better than the rest (15% more efficient). On average all the *IRWH* treatments with mulch on the runoff area were 17% more efficient than *ObBr* in converting rainwater into food. All the *IRWH* treatments with mulch on the runoff area were significantly better than *ObBr* during the 00/01 and 02/03 seasons.

Equation 4.1 has a disadvantage when considered for a single season because of the influence of the term $(\theta_{h(n-1)} - \theta_{h(n)})$ on PUE_{fg}. The disadvantage is exposed by considering the following two scenarios.

Scenario A: Rainfall high towards the close of season (n-1), and low towards the end of the season (n). The value of the term $(\theta_{h(n-1)} - \theta_{h(n)})$ will be positive for season (n), and most probably higher for a water conservation tillage (*WCT*) treatment than for a conventional tillage (*CON*) treatment. This would promote PUE_{fg} (*WCT*) < PUE_{fg} (*CON*) for season (n). This tendency would however be balanced to some extent by the plant available water at planting (PAW_p) of the *WCT* treatment being higher than PAW_p (*CON*), and therefore promote a higher Yg value. The beneficial influence of the *WCT* treatment on decreasing R and Es during growing season would also promote an increased Yg value and therefore increased PUE_{fg} (*WCT*) compared to PUE_{fg} (*CON*).

Scenario B: Rainfall low towards the close of the season (n-1), and high towards the end of season (n). The value of $(\theta_{h(n-1)} - \theta_{h(n)})$ will be negative, and most probably more negative for *WCT* than for *CON*. This would promote PUE_{fg} (*WCT*) > PUE_{fg} (*CON*) for season (n).

In the long-term, however, these negative and positive influences of the term $(\theta_{h(n-1)} - \theta_{h(n)})$ can be expected to balance each other – especially in semi-arid areas with extremely variable rainfall patterns. Because of the beneficial influence of the *WCT* treatment in reducing R and Es during the fallow and growing seasons its PUE_{fg} value will inevitably be higher than tillage treatments not designed to reduce these water losses. Hence the validity of Equation 4.1 in the long-term.

During the 99/00 season the highest Yg values were obtained because of well-distributed rainfall (Figure 4.2a) although the rainfall during P_p was the lowest of all the seasons. The result was the highest PUE_{fg} compared to all the seasons. During the 00/01 season "Scenario B" as explained above occurred, i.e. where a high $\theta_{h(n)}$ and a low $\theta_{h(n-1)}$ resulted in a negative value of $(\theta_{h(n-1)} - \theta_{h(n)})$, therefore a moderate Yg and moderate rainfall during P_p resulted in the second highest PUE_{fg}. During the 01/02 season "Scenario A" as explained above occurred, i.e. where a high $\theta_{h(n-1)}$ and a low $\theta_{h(n)}$ resulted in a positive $(\theta_{h(n-1)} - \theta_{h(n)})$ and therefore promoting a lower PUE_{fg}. In spite of Yg (01/02) > Yg (00/01) PUE_{fg} obtained during the 01/02 season was lower than that of the 00/01 season for the reasons given and PUE_{fg} during the 01/02 season was also the lowest of all the seasons. During the 02/03 season $\theta_{h(n-1)}$ and $\theta_{h(n)}$ were very similar and therefore $(\theta_{h(n-1)} - \theta_{h(n)})$ was almost zero. In spite of high rainfall during the P_p of the 02/03 season relative to the other three seasons, the rainfall was poorly distributed and therefore low Yg was obtained that resulted in a low PUE_{fg}. These results reveal the value of long-term values of RWP_n, which gives a true reflection of the ability of a specific treatment to convert rainwater into grain and where the influence of the variable $(\theta_{h(n-1)} - \theta_{h(n)})$ is eliminated.

Another problem with Equation 4.1, semantic in nature, is the objection by Gregory (1989) and De Jager (pers. comm., 1997, Dept. Soil, Crop and Climate Sciences, University of the Free State) to the use of the term "efficiency". Strictly speaking this term should have the same units for the numerator (output) and denominator (input) so that the result is unitless with a maximum value of 1.0. This objection can be avoided by using the word "productivity" instead of "efficiency", as used in a similar sense by Passioura (2006).

Because of these considerations it was concluded that the most reliable, appropriate and acceptable way to describe the effectiveness with which rainwater is converted into grain was by using Equation 4.9 with experimental data over a number of consecutive seasons.

$$RWP_n = \frac{\sum Yg_n}{\sum P_n} \text{......................(kg ha}^{-1}\text{ mm}^{-1}\text{)................................(4.9)}$$

where:

RWP_n = rainwater productivity over a period of n consecutive years (kg ha^{-1} mm^{-1})

ΣYg_n = total grain yield over n consecutive years (kg ha^{-1})

ΣP_n = total precipitation over n consecutive years (mm)

Rainwater productivity over a period of four consecutive years ($RWP_{1999/00-2002/03}$)*:* $RWP_{1999/00-2002/03}$ varied between 3.22 and 6.85 kg seed ha^{-1} mm^{-1} rain over the four consecutive seasons with a mean $RWP_{1999/00-2002/03}$ value of 6.26 kg ha^{-1} mm^{-1} for the *IRWH* treatments compared to the 3.22 kg ha^{-1} mm^{-1} for *CON*. This is an indication that for every 1 mm of rain that occurred during the four consecutive seasons the *IRWH* treatments produced 6.26 kg of maize grain yield per hectare compared to the 3.22 kg from *CON*. These results indicate that all the *IRWH* treatments are on average 94% more effective than *CON* in converting rainwater into grain yield. This is a remarkable difference especially in a semi-arid environment where every drop of rainwater is needed to produce food. The superiority of the *IRWH* treatments is the result of their ability to stop R_{Ex} completely and induces in-field runoff (R_{In}) within the system and therefore utilize every drop of rainwater far better than *CON*. Comparing the different *IRWH* treatments $RWP_{1999/00-2002/03}$ results reveal a trend of *ObSr* > *ObOr* ≈ *SbOr* > *ObBr*. $RWP_{1999/00-2002/03}$ results indicate that *ObSr*, *ObOr* and *SbOr* are respectively 19, 10 and 7% more effective than *ObBr* in converting rainwater into grain yield.

4.4 CONCLUSIONS

The objective was to compare maize production on the semi-arid Glen/Bonheim ecotope using *CON* with various *IRWH* techniques, having different combinations of mulch types in the basins and on the runoff areas. The indicators used were grain yield, dry matter production, transpiration, precipitation use efficiency (PUE) and water use efficiency (WUE). Results showed that all the *IRWH* treatments were significantly better in all these respects than *CON* over all four seasons. Reasons for this phenomenon were initially hypothesised due to the ability of *IRWH* to stop R_{Ex} completely and to minimize Es. Currently the Es results, calculated with the Tanner and Sinclair (1983) transpiration efficiency based concept using Equation 4.4, showed that evaporation was not modified differently among the *IRWH* treatments. Thus, suggesting that the R_{In} process and its resulting redistribution of water in the soil profile plays a much more important role than anticipated. The parameter considered being the most important for evaluating the effectiveness of a water conservation production technique is RWP_n, since it assesses the effectiveness with which rainwater is converted into grain by using long-term experimental data over a number of consecutive seasons and includes the fallow and growing seasons. The mean values of $RWP_{1999/00-2002/03}$ over the four growing seasons for *CON* and *IRWH* (means of four treatments) were 3.22 and 6.26 kg ha^{-1} mm^{-1}, respectively. This result clearly demonstrates the superiority of *IRWH* for growing maize on this and similar ecotopes. The best *IRWH* treatment was *ObSr*, followed by *ObOr* ≈ *SbOr*, and *ObBr*.

It was concluded that in particular subsistence farmers in the semi-arid area east of Bloemfontein, South Africa, could improve maize yields considerably by replacing the *CON* practices with *IRWH*. This would improve their level of food security.

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CHAPTER 5: EVALUATING SUNFLOWER PRODUCTION ON SEMI-ARID ECOTOPES USING CONVENTIONAL TILLAGE AND IN-FIELD RAINWATER HARVESTING

ABSTRACT

In semi-arid regions, rainfed agriculture is coping with unreliable rainfall, poor soils and recurrent droughts with subsequent production failures. In addition to that rainwater producrivity (RWP) in semi-arid areas is low because of high losses due to ex-field runoff (R_{Ex}) and evaporation from the soil surface (Es). To improve the productivity with which rainwater is converted into food, it is therefore necessary to minimize these losses. Since an increasing population requires an increased food production, more efficient use of rain in rainfed agriculture therefore deserves an increased scientific attention. The general objective of this chapter was to evaluate the agronomic sustainability of the in-field rainwater harvesting (IRWH) technique in terms of its ability to convert rainwater into sunflower seed yield by minimizing the unproductive losses (Es and R_{Ex}) and maximizing RWP. Normal conventional (CON) tillage was compared with various IRWH treatments during two separate experiments, with on-station and on-farm field experiments on four ecotopes. The first experiment was carried out during 1996/97 to1998/99 seasons with on-station (Glen/Bonheim and Glen/Swartland) and during 1997/98 and 1998/99 seasons with on-farm (Khumo/Swartland and Vlakspruit/Arcadia) experiments. The treatments were CON tillage; IRWH with a bare basin and bare runoff area (BbBr); IRWH with organic mulch in the basins and a bare runoff area (ObBr). Results of the fist experiment showed that IRWH was remarkable better than CON due to the reduction in R_{Ex}, promotion of in-field runoff (surface redistribution of water) and the portion of ET lost to Es and therefore increased in seed yield and RWP. Mulch in the basins was beneficial and future research should focus on reducing Es. Therefore mulches have been introduced on the runoff area of the IRWH. The second experiment was conducted over four seasons (1999/2000 to 2002/03) on the Glen/Bonheim ecotope and over a three seasons (1999/2000 to 2001/02) on the Khumo/Swartland and Vlakspruit/Arcadia ecotopes. The treatments for the on-station experiments were

CON tillage; ObBr; IRWH technique with organic mulch in the basins, stones on the runoff area (ObSr); IRWH technique with organic mulch in the basins, organic mulch on the runoff area (ObOr); IRWH technique with stones in the basins, organic mulch on the runoff area (SbOr). The treatments for the on-farm experiments were CON tillage; ObBr; ObSr; SbOr. The indicators of crop response to different treatments used were seed yield, water balance components and RWP.

The natural resource components (climate, topography and the soil) that affect the productivity of these ecotopes were described. The experimental plots are located on upper foot slope terrain units with a 1 to 3% slope. The effective rootzones are considered to be 0 - 1200 mm. The soils have a high clay content and has the capacity to swell and shrink markedly in response to moisture changes. The ecotopes are situated in a semi-arid region with low and erratic rainfall where conditions are marginal for crop production. There is no shortage of radiation and hence the high evaporation from the soil surface (Es). This fact accentuates the need for water conservation techniques to include efficient procedures to minimize Es.

Results from the first experiment showed that IRWH significantly increased crop yields compared to CON through its ability to stop R_{Ex} *completely and minimize Es/ET. Results indicated that the IRWH techniques are significantly more productive than CON at converting rainwater into seed yield (RWP). During two of the growing seasons both IRWH treatments contributed towards significantly higher sunflower yields, compared to CON. Both seed yield and RWP results showed that the IRWH stabilise crop production on this ecotope. It is also recommended that where field experiments were conducted RWP must be calculated. Future research needs to focus on suppressing Es by any possible means.*

The results of the second experiment confirmed that IRWH techniques are superior to CON and are far more productive than CON at converting rainwater into food. Results have also indicated that mulches on the runoff area of the IRWH technique increase RWP (7 – 15%); and that the IRWH technique produces sustainable higher sunflower yields during various climatic conditions. The ObSr treatment was overall the best treatment, followed by ObOr, SbOr, ObBr, BbBr and CON.

Keywords: ecotope, soil characteristics, in-field rainwater harvesting, sunflower, runoff, evaporation, semi-arid, rainwater productivity, mulching.

5.1 INTRODUCTION

Mr. Erwin Northoff, Information Officer, FAO said on 12 March 2002 that productivity of both irrigated and rainfed production needs to be improved. Investments in smarter water-saving agricultural techniques and better water management practices are urgently required. The agricultural potential of relevant areas need to be unlocked to resolve the world's water problems and to use scarce water resources much more productively. The technical solutions must focus on "more crop per drop".

The questions are: What can be done to overcome this problem? How can rainwater in agriculture be used more productively to produce more food with the same amount of rainfall? We know that it is almost impossible to increase the rainfall but we can definitely try to reduce the amount of water wasted.

In Sub-Saharan Africa (SSA) food production depends almost entirely on rainfed agriculture. The scope for further irrigation development is limited as water resources are becoming increasingly scarce and the most suitable sites have already been developed (Kauffman, Mantel, Ringersma, Dijkshoorn, Lynden & Dent, 2003). The increase in population all over the world requires more and higher food production from a fixed natural resource base. The challenge is to use rainwater more efficient to produce more food, especially in dryland agriculture, and is effectively expressed in the very popular slogan of "more crop per drop". According to Kauffman *et al.* (2003), there are from a biophysical point of view, three main soil-related constraints that contribute to low yields: low rainwater use efficiency; low fertilizer usage; and inadequate soil and water conservation.

In dryland crop production the major limitation in South Africa is a deficiency of water caused by short seasonal or long annual droughts that lead to uncertain yields and frequent crop failures. According to Christiansen (1979), water availability is one of the major factors that determine the productivity of dryland crop production in semi-arid areas. Arnon (1975) also claims that for dryland crop production in semi-arid areas water availability is a critical yield-limiting factor. Rainfall in semi-arid regions is low with uneven distribution. In many cases where the total rainfall may appear to be adequate for the production of particular crops, its intensity and distribution are of such a pattern that the water available during the crop growth cycle is inadequate to support a good harvest (Stewart & Steiner, 1990; Unger, 1990; Morin, 1993; Joudeh, 1994; Lövenstein, 1994; Ofori, 1994; Shatanawi, 1994; Sow, Hossner, Unger & Stewart, 1996). In semi-arid regions, rainfed agriculture also generally has to cope with low potential soils (Fofana, Wopereis, Zougmoré, Breman & Mando, 2003 and Stroosnijder 2003). The problem of inadequate soil water is not only caused by low and unfavourable distribution of rainfall, but is even exacerbated by high unproductive water losses through evaporation from the soil surface (Es), runoff (R) and deep drainage (D) (Boers, Zondervan & Ben-Asher, 1986; Arnon, 1975 and Arnon & Gupta, 1995). The two main water losses are Es and R. Rockström (2003) estimated that in SSA, the green water fraction (productive use of rainwater through the process of transpiration) is only between 15 to 30% of the total rainwater. This low proportion is a result of high unproductive losses through R and Es, which are encouraged by low infiltration into the soil especially during high-intensity rains. These losses therefore remain as the dominating cause of water loss that needs to be minimized, both during the fallow and crop growing seasons, in order improve the rainwater productivity (RWP).

Excessive R often poses the greatest water management problem on rainfed croplands. Not only does it cause the loss of water, but it may cause damaging soil erosion (Aina, 1993). Surface runoff is likely to occur when rainfall intensities are high and the infiltrability of the soils is low. Surface runoff also depends on the slope and roughness of the soil. As much as 70% of a single rainstorm can be lost due to R. This may cause soil erosion and the associated loss of nutrients (Reij, Mulder & Begemann, 1988; Aina, 1993; Tripathi & Singh, 1993; Joudeh, 1994; Lövenstein, 1994). Results obtained by Du Plessis & Mostert (1965) on a long-term (18 year) runoff experiment at Glen confirm the high runoff losses expected locally. They found that on continuous bare fallow with a minimum amount of soil disturbance the average annual R comprised 32% of the rainfall. The comparable figure for a plot on which maize was grown annually was 8.5%. Bennie, Strydom & Vrey (1994) found that between 60% and 85% of the rainfall evaporates before it could make any contribution to production in semi-arid and arid areas.

Stroosnijder (2003) stated that when a natural landscape is transformed into a cultural landscape, the field water balance is affected and R and Es increase, while infiltration and transpiration (Ev) decrease. This has direct and indirect effects on the RWP. Water conservation practices reduce erosion, improve soil qualities and increase RWP. He further claimed that in semi-arid Africa water conservation could easily double precipitation use efficiency (PUE) and guarantee food security, by minimizing R and Es and maximizing Ev. This also implies that RWP could be doubled. The theoretical aspects of water conservation technologies for dryland cropping were summarized by Hensley & Bennie (2003). The basic principle of efficient utilization of precipitation for dryland plant production lies in maximizing the gains and minimizing the losses of water from the soil. On clayey soils in areas with marginal and erratic rainfall, especially where a large proportion falls as thunderstorms, the major forms of water loss are runoff and evaporation.

Many agricultural scientists agree that with the use of appropriate production techniques, especially those that encourage conservation of water and soil resources, it is possible to increase and sustain agricultural output in semi-arid areas (Hensley, Botha, Anderson, Van Staden & Du Toit, 2000; Hatibu, 2002; Botha, Van Rensburg, Anderson, Hensley, Macheli, Van Staden, Kundhlande, Groenewald & Baiphethi, 2003). These include water harvesting (Boers & Ben-Asher; 1982, Boers *et al.*, 1986; Reij *et al.*, 1988; Kronen, 1994; Ojasvi, Goyal & Gupta, 1999; Oweis, Prinz & Hachum, 2001), no-till (Lamarca, 1996) and mulching (Allmaras & Nelson, 1971; Davis, 1975; Unger 1995; Ojasvi *et al.*, 1999).

Authors of books and articles on water harvesting employ a wide variety of terms and definitions to describe the various methods aimed at using runoff water to increase the availability of water for plant production in arid and semi-arid regions. Many authors use terms specific for their own purposes, rather than attempting to adhere to strict definitions (Reij *et. al.,* 1988). Water harvesting is usually employed as an umbrella term describing a whole range of methods of collecting and concentrating various forms of runoff (rooftop runoff, overland flow, stream flow, etc. from various sources such as precipitation, dew, etc.), and using if for various purposes (eg. agricultural, livestock, domestic and other purposes). Oweis *et al.* (2001) defined rainwater harvesting as the process of concentrating or collecting precipitation through runoff and storage for beneficial use. Van Rensburg, Botha, Anderson & Joseph (2005) proposed a classification system whereby water harvesting methods are categorized simply as ex-field (outside the field boundary), in-field (within the field) or non-field (e.g. rooftops), according to the location of the catchment area. Water harvesting is an ancient method of water supply that has received renewed interest at various times in the past 30 years. Irrespective of the technique used to collect and store the water, or the ultimate use of the water, all water harvesting systems have two major components: (1) a catchment area for collecting and concentrating the precipitation, and (2), the water storage facility for holding the collected water until it is needed (Frasier, 1993). Boers & Ben-Asher (1982) concluded that all different rainwater harvesting methods have three characteristics in common: (a) They are applied in arid and semi-arid regions where runoff is intermittent in nature; (b) they depend upon local water such as surface runoff, springs or soaks and therefore do not include storing river water in large dams or the extraction of groundwater; (c) they are consequently relatively small-scale operations in terms of catchment area, volume of storage and capital investment. Water harvesting is considered to be more efficient than fallowing, in which water is conserved from one season to the other and the entire area is cropped in one year out of two (Arnon & Gupta, 1995; Hensley *et al.*, 2000). Most soil conservation methods, such as strip cropping, contour ploughing and terracing aim at reducing runoff, and are therefore also effective in increasing the amount of water that is stored in the soil (Arnon & Gupta, 1995). Birch, van der Sandt & Strauss (1986) as cited by Hensley & Bennie (2003), found that basin tillage was the most effective way to retain rainfall, thereby improving soil water storage and consequently, sunflower yields on heavy clay soils.

Arnon (1975) claims that methods to suppress Es are most likely to be effective during the first or constant rate stage that is recently renamed to initial stage (Chapter 3) and second or falling rate stage that is renamed to intermediate stage of evaporation. Taking in consideration what Berry & Mallet (1988) and Hoffman

(1997) found it is therefore expected that the application of mulches will have a bigger advantage during the growing season of summer growing crops in large parts of South Africa compared to the fallow period. Mulches are used for various reasons, but water conservation and erosion control are undoubtedly the most important objectives of this practice in dryland cropping in semi-arid and arid regions. While the effectiveness of mulches for water conservation is variable, mulches when properly managed are definitely effective for wind and water erosion control (Unger, 1995). Many soil properties and conditions are affected by mulches, either directly or indirectly. Among these is improved soil water content through runoff control, increased infiltration, decreased evaporation, weed control, ameliorated soil temperature through radiation shielding, improved soil fertility and soil structure, biological regime and root distribution through organic matter additions, and in some cases decreased soil salinity through leaching and evaporation control (Unger, 1995).

There are various soil and water conservation techniques, which may increase the amount of green water. One of them is the in-field rainwater harvesting (*IRWH*) technique developed by a group of researchers from the Agricultural Research Council - Institute for Soil, Climate and Water (ARC-ISCW) (Hensley *et al.,* 2000). The *IRWH* technique combines the advantages of a number of water conservation techniques like water harvesting, no-till, basin tillage and mulching in order to reduced R and Es. The technique consists of promoting runoff on a 2 m wide strip between alternate crop rows, and storing the runoff water in the basins. Mulches can be applied in the basin to suppress evaporation (Figures 1.3 and 5.2.1).

South Africa was considered to be the leading sunflower producing country in Africa during the 1970's (Putt, 1978). According to the FAO (1999), statistics revealed that in terms of area coverage sunflower production in South Africa has increased by 66% between 1989 and 1991, and that 70% of all the land devoted to sunflower production in Africa is occurs in South Africa. Sunflower is a crop that can add diversity to marginal rainfall areas especially because of its ability to extract soil water to lower potential levels than most small grain cereals (Halverson, Black, Krupinsky, Merrill & Tanaka, 1999). According to Robinson (1978) the higher water extraction capacity of the root system is a mechanism of drought tolerance and makes sunflower perform well under dry conditions. According to Knowles (1978), sunflower has a strong taproot and prolific laterals and therefore the crop responds well to water conservation practices.

Hensley & Bennie (2003) concluded that water conservation techniques are ecotope specific. For water harvesting systems to be successful in a sustainable way, the relevant processes in the particular soil-plant-atmosphere continuum (SPAC) being utilized need to be well understood and quantified. The natural resources that influence these processes, and therefore productivity therefore also need to be well understood and quantified (MacVicar, Scotney, Skinner, Niehaus, & Loubser, 1974; Hensley, 1995; Hensley & Bennie, 2003). The characteristics, productivity, and stability of SPAC depend on the three natural resource factors (climate, topography and soil). Figure 5.1.1 can be considered to represent the modal SPAC of a specific three-dimensional system (as it occurs in the landscape) in which the atmosphere (climate), topography, and soil are reasonably homogenous. The boundaries of such a system are determined by points in the landscape at which the characteristics of one or more of the factors climate, topography or soil change significantly (Hensley, 1995). The specific three-dimensional unit of the landscape outlined by these boundaries describes an ecotope as defined by MacVicar *et al.* (1974). According to Hensley, Anderson, Botha, Van Staden, Singels, Prinsloo & Du Toit (1997), SPAC is the solar driven engine of nature's factory for the production of all the land grown food, natural fiber, wood, and paper used by mankind. Optimal management of SPAC to the benefit of mankind requires that its functioning be well understood (Hensley *et al.*, 1997).

It is obviously not possible to do detailed research work on every ecotope used for crop production in a country. Hensley *et al.* (2000) recommended that attention be focused on carefully selected benchmark ecotopes in order to maximize research efficiency. It is desirable that the main ecotope characteristics that affect productivity be characterized in detail to ensure efficient extrapolation of the results obtained on these ecotopes to all the others (i.e. pedotransfer actions), (Hensley *et al.*, 2000).

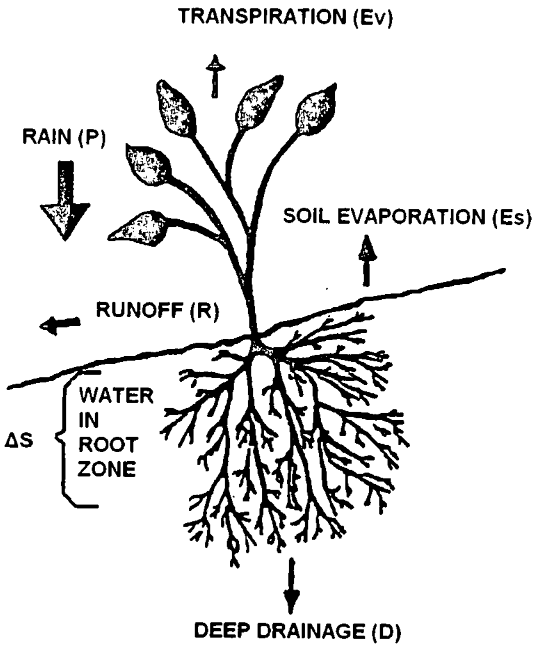

Figure 5.1.1. A diagrammatic representation of the soil-plant-atmosphere continuum (SPAC), showing the important water balance processes.

The questions that need to be answered can be stated as follows: (a) Is the application of the *IRWH* technique going to decrease R and Es and therefore increase sunflower yields and RWP? (b) is the application of mulches in the basins and runoff area of the *IRWH* technique going to further increase RWP and sunflower yields by minimizing Es? It was hypothesized that: (a) the *IRWH* technique will stop R and therefore increase sunflower yields and RWP compared to conventional (*CON*) tillage; (b) mulch applications in the basins and runoff area of the *IRWH* technique will minimize Es and therefore increase sunflower yields and RWP. The general objective of this chapter is to evaluate the agronomic sustainability of the *IRWH* technique in terms of its ability to convert rainwater into seed yield in a sustainable manner by minimizing the unproductive losses (Es and R) and maximizing RWP. Normal *CON* tillage was compared with various *IRWH* treatments, with on-station and on-farm field experiments, and using sunflower as the reference crop. This chapter discusses effects of various combinations of mulch types in the basins and on the runoff area of the *IRWH* system in terms of crop yield and RWP. The indicators of crop response to different treatments used were seed yield, dry matter production, harvest index, water balance components and RWP. The chapter also describes the natural resource factors, i.e. climate, topography and soil, which have a major influence on the productivity of a system as a whole.

5.2 PROCEDURE

To test the hypotheses, and in a quest for improving the "crop per drop", on-station and on-farm field experiments were conducted with different production techniques using sunflower as the test crop. On-station field experiments were conducted on two soils (Bonheim and Swartland) at the Glen Agricultural Institute, 25 km north east of Bloemfontein. On-farm field experiments were conducted on two farmers' fields in the resettlement area between Thaba Nchu and Excelsior (Swartland and Arcadia soils). The first experiments continued for a period of 3 seasons. The results of these experiments were used to formulate an improved hypothesis, which was tested in the second set of experiments.

The six water balance components identified in Equation 1.1 play an important role in the functioning, productivity and sustainability of SPAC (Figure 5.1.1). For good understanding of the system, which is crucial to the development of technological options for sustainable management of soil and water resources, it is necessary that these processes be monitored. Good understanding will promote optimization of these processes and so enhance sustainable crop production. To monitor these processes, soil, plant and climate measurements were taken regularly during the growing season.

5.2.1 SOIL PARAMETERS

To monitor the soil water content of the rootzone (θr), neutron water meter (NWM) access tubes were installed to a depth of 1.3 m, i.e. to a greater depth than that of the rootzone. NWM access tubes (A and C) were located as shown in Figure 5.2.1. Measurements of θr were carried out before planting, at planting, and during the growing season at 300 mm depth intervals starting at 150 mm. A Campbell Pacific 503 DR NWM was used. This procedure ensures that the different pedological layers in the soil have been adequately represented. The NWM was calibrated for every soil layer as presented in Chapter 3. A detailed description of the procedure used for NWM calibration is described by Hensley *et al.* (2000) and Botha *et al.* (2003).

Drained upper limit (DUL) is 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 profile is about 0.1 to 0.2% per day (Ratliff, Ritchie & Cassel, 1983). DUL determination is described in Chapter 3. Crop modified upper limit of available water (CMUL) describes the maximum amount of water available from the rootzone for a particular crop at a particular growth stage and at a particular evaporative demand. Hattingh (1993) and Hensley, Hattingh & Bennie (1993) introduced the CMUL concept to accommodate water uptake slightly above DUL. Although crop models make allowance for the available water above DUL, estimated values are generally used for the drainage rate. CMUL is based on a field measured drainage curve and was determined as described by Hattingh (1993). Lower limit of plant available water (LL) is the lowest field-measured water content of a soil after plants have stopped extracting water and are at or near premature death, or have become dormant as a result of water stress (Ratliff *et al.,* 1983). Since LL depends on soil, crop and climate characteristics, it is not meaningful to speak of the LL value of a soil on its own. LL needs to be related to a specific crop-ecotope. The LL for sunflower on each soil was determined during the course of the growing seasons of the two experiments. It was taken as the lowest NWM reading for each soil layer.

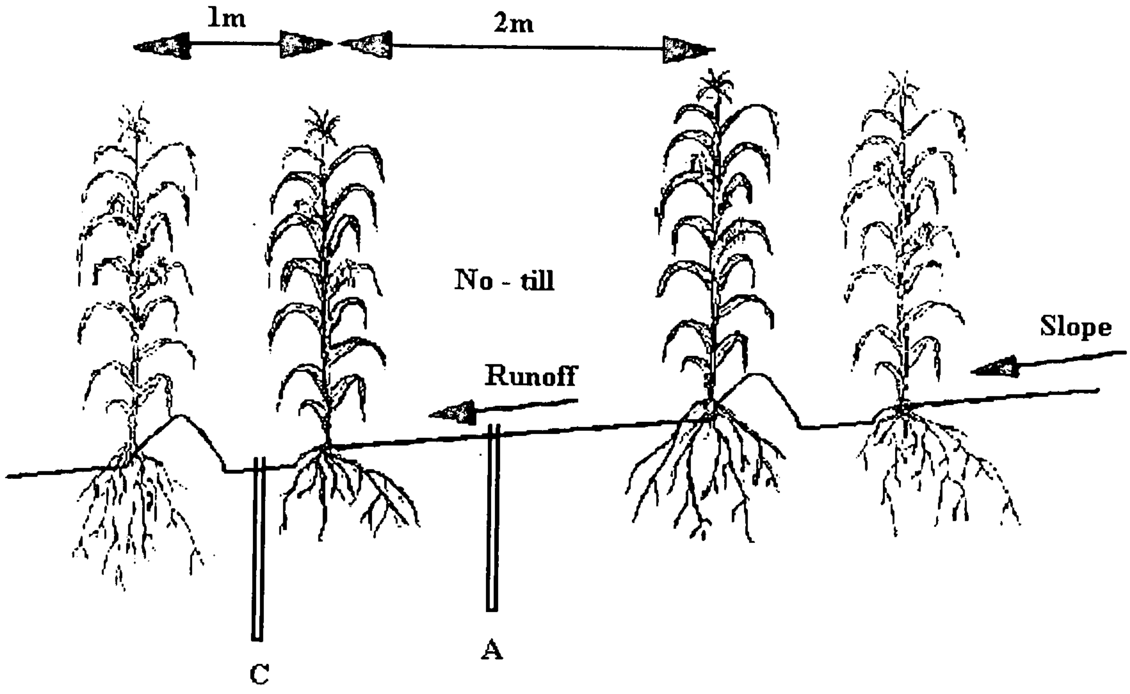

Figure 5.2.1 The distribution of access tubes (A and C) in the plots. The same plant distribution was used in the conventional treatment.

Bulk density (BD) of each soil layer in the rootzone was measured using a core sampler. BD can also give an indication of any soil compaction in the rootzone and is needed for the crop model input dataset. Core samples were taken at a fixed water content (DUL) to stabilize the procedure as the soils contain high portions of smectite clay minerals. Detailed measurements for the 0 - 1200 mm soil layers were carried out at 300 mm depth intervals. The slope of each ecotope was determined by using a dumpy level.

Runoff (R) was measured with automatic tipping bucket runoff meters from runoff plots, separate from the field experiment, on the Glen/Bonheim and Glen/Swartland ecotopes. The aim of the runoff plots was to measure the runoff from the different tillage treatments used in the on-station and on-farm experiments. The runoff surface of all the runoff plots was prepared in the same way as the different treatments of the field experiments. During the first experiment R was measured from 3 m wide and 20 m long runoff plots. The treatments were *CON* and *IRWH* (B*b*B*r* – bare). They are described in detail by Hensley *et al.* (2000). During the second experiment R was measured from runoff plots each 2 m long and 3 m wide, and are described in detail in Chapter 2 and also by Botha *et al.* (2003). The treatments were: (a) runoff measured on a flat crusted surface with minimum surface storage (bare); (b) runoff measured with organic reed mulch covering 60% of the area of the flat surface with minimum surface storage (mulch); (c) runoff measured with stone mulch covering 60% of the area of the flat surface with minimum surface storage (stones). Runoff from the *CON* treatment (R_{ex}), especially on the Vlakspruit/Arcadia and Khumo/Swartland ecotopes, was estimated using a prediction equation (Equation 4.5) adapted from the one developed during the previous studies on this ecotope (Hensley *et al.*, 2000).

Deep drainage (D) is defined as the loss of water from the deepest soil layer of the rootzone, and therefore out of reach of crop roots. D only occurs when the soil water content of the deepest soil layer exceeds DUL. It can be estimated by interpreting soil water extraction graphs during the growing season in relation to the drainage curve.

Rainfall storage efficiency was calculated using the equation of Mathews & Army (1960) and is presented in Equation 4.6. Transpiration (Ev) was determined with the procedure proposed by Tanner & Sinclair (1983) as described in Chapter 4. The transpiration efficiency coefficient (k) value of 4.5 g m^{-2} mm^{-1} suggested by Chapman, Hammer & Meinke (1993) was used for sunflower.

5.2.2 PLANT PARAMETERS

The critical growth stages of sunflower were recorded throughout the growing season and visual symptoms were of plant water stress were noted (Turner, 1986; Laker, Ceulemans & Vanassche, 1991).

Biomass for sunflower was measured by harvesting 6 rows, each 1 m long to determine the final above-ground biomass from each replication. Biomass was expressed as oven dry material in kg ha^{-1}. Results were also used to determine Ev. Grain yield (Yg) was determined by harvesting 6 rows, each 4 m in length from each replication. The grain was weighed oven-dry and adjusted to 13% moisture content and expressed as kg ha^{-1}. Harvest index (HI) was calculated as the ratio of grain yield to the total above-ground biomass yield (Bennie, Strydom & Vrey, 1998) and presented in Equation 4.3.

Water use efficiency (WUE) was determined with the equation used by Hillel (1972), Passioura (1983) and Tanner & Sinclair (1983) and presented in Equation 4.7. Where Ev was available, WUE_{Ev} was expressed as Yg/Ev. WUE therefore measures the efficiency with which a particular crop can convert the water transpired, during a particular growing season, into seed yield. While maintaining the same descriptive equation, the term "water use efficiency" (WUE_{Ev}) will be replaced here by "water productivity" (WP_{Ev}) to avoid the valid criticism of Gregory (1989) that WUE as generally defined is strictly not an efficiency as the units of the numerator and the denominator are different. Rainwater productivity (RWP_n) was calculated with Equation 4.9 from experimental data over a number of consecutive seasons ($_n$). RWP is the most reliable, appropriate and acceptable way to describe the effectiveness with which rainwater is converted into sunflower seed.

5.2.3 CLIMATIC PARAMETERS

Weather parameters, namely wet and dry bulb air temperature, solar radiation, wind speed and direction, and rainfall, were measured with an automatic weather station, installed near the trails at Glen Agricultural Institute.

5.2.4 STATISTICAL ANALYSES

Analysis of variance was done on the results of the different treatments using the statistical software NCSS 6.0.21, 1996 for Windows (Hintze, 1996). Means were compared using the Tukey Kramer test ($P \leq 0.05$).

5.3 GLEN/BONHEIM - ONRUS ECOTOPE

5.3.1 DESCRIPTION OF THE ECOTOPE

The on-station field experiment was conducted on the Glen Agricultural Institute (28°57` S, 26°20` E), 25 km north east of Bloemfontein. The soil is classified, according to the Soil Classification Working Group (1991), as belonging to the Onrus

Family of the Bonheim Form. In the World Reference Base for Soil Resources systems the soil is classified as a Vertic phaeozem (WRB, 1998). A detailed description of the soil and its chemical properties is presented by Hensley *et al.* (2000). Important soil, climatic and topographic characteristics of the Glen/Bonheim ecotope are summarized in Chapter 2.

Important soil water properties are presented in Table 5.3.1. The soil has a high water holding capacity in the rootzone with a DUL value of 456 mm. A drainage curve for the whole rootzone, which provides the information for determining DUL, is presented in Figure 4.1. The soil water extraction properties are slightly different to those presented by Hensley *et al.* (2000). The values presented in Table 5.3.1 were determined later at a new site and are considered to be more representative.

Table 5.3.1 Important characteristics of the soil component of the Glen/Bonheim ecotope. The effective rootzone is considered to be 0 - 1200 mm

Profile detail					Soil water extraction properties for Sunflower			
Diag.[*1] Horizon	Colour	Clay (%)	BD[*2] (Mg m^{-3})	Depth (mm)	DUL (mm)	LL (mm)	TESW[*3] (mm)	CMUL (mm)
ml	DkBr	45	1.30	300	122	45	77	
vp	DkBr	43	1.45	600	123	67	56	
vp	DkBr	40	1.45	900	106	67	39	
so	Mottled due to $CaCO_3$ concretions	38	1.45	1200	105	61	44	
Total					456	240	216	485

[*1] Abbreviations from Soil Classification Working Group (1991): ml = melanic; vp = pedocutanic; so = saprolite

[*2] Bulk density

[*3] Total extractable soil water (DUL - LL).

A clearer picture of water extraction by sunflower from this soil is presented in Figure 5.3.1. The area of each rectangle, representing a soil depth of 300 mm, is proportional to total extractable soil water (TESW) for that layer. In spite of the high clay content and strong structure of the B horizon, root water extraction to LL is shown to be very similar from each 300 mm layer of the subsoil to the bottom of the rootzone. A considerable fraction of TESW probably occurs between first serious stress (SS) and LL, and therefore presumably does not contribute a great deal to seed yield. This water is nevertheless able to keep the plant alive to enable growth to be resumed if further rainfall occurs before LL is reached. It seems that the amount of water held between SS and LL is around 20 mm (Figure 5.3.4) or about 9% of TESW. This water can therefore be described as "slowly available".

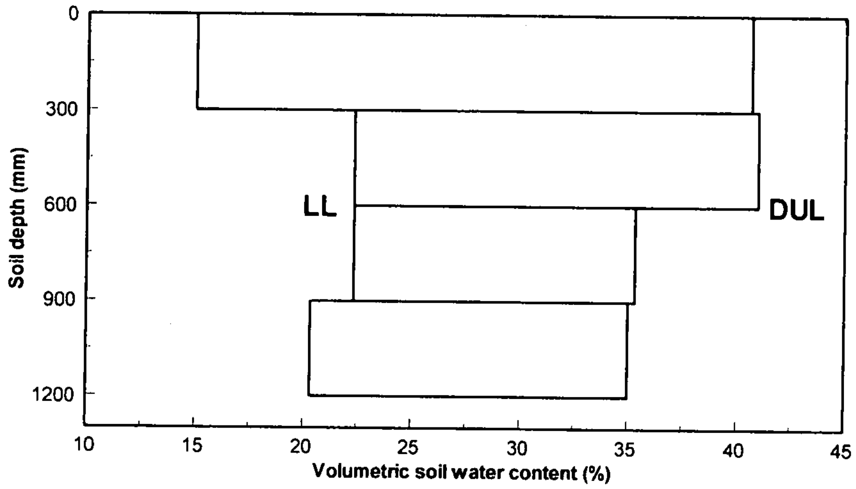

Figure 5.3.1 Soil water extraction for sunflower on the Glen/Bonheim ecotope: rootzone 1200 mm.

The ecotope is situated in a semi-arid area with a high evaporative demand and relatively low rainfall. Detailed climate data is presented in Table 2.2 and the climate is described in detail in Section 2.2.1.2.

The experimental plots were located on a upper foot slope terrain unit with a 1% slope and a westerly aspect.

5.3.2 PROCEDURE

Two separate experiments were carried out. The first was over the three seasons 1996/97, 1997/98 and 1998/99. The second experiment was conducted over the four seasons following the first experiment, viz. 1999/2000, 2000/01, 2001/02 and 2002/03. The results of the first experiment were used to formulate an improved hypothesis, which was tested in the second experiment.

5.3.2.1 Experimental layout

First experiment:

For the first experiment a randomized block design with three treatments and three replicates was employed. The crop used was sunflower, cultivar SNK 37. Sunflower was planted annually by hand with a plant population of 33 333 plants ha^{-1}. Planting and harvesting dates for the three seasons were: 17/12/96 – 22/04/97, 13/01/98 - 12/05/98 and 05/01/99 - 08/05/99. Soil samples were taken for fertility tests prior to each growing season. Since water was the main limiting factor on this ecotope, fertilizer (50 kg ha^{-1} of 3:1:0 (28%) + Zn) aimed at a moderate yield was applied. The treatments were normal *CON* tillage, and two *IRWH* treatments. The latter consisted of firstly, a bare basin and runoff area in which no mulch was placed (*BbBr*) – see Figure 1.3; and secondly a basin area in which organic mulch had been placed and a bare runoff area (*ObBr*). The latter treatment was only introduced during the second season.

Second experiment:

For the second experiment a randomised block design with 5 treatment combinations and 3 replicates was employed. Sunflower, cultivar SNK 74, was planted annually with a plant population of 33 333 plants ha^{-1}. The treatments were as follows:

- *CON* tillage,
- *IRWH* technique with organic mulch in the basins and bare runoff area (*ObBr*),
- *IRWH* technique with organic mulch in the basins, stones on the runoff area (*ObSr*),
- *IRWH* technique with organic mulch in the basins, organic mulch on the runoff area (*ObOr*) and
- *IRWH* technique with stones in the basins, organic mulch on the runoff area (*SbOr*).

Planting and harvesting dates for the different seasons were: 28/01/00 - 14/06/00; 05/01/01 - 16/05/01; 18/12/01 - 26/04/02; 10/01/03 - 04/06/03. The fallow period was therefore a short one of around eight months. All fertilizer was applied at planting according to soil analyses for a target yield of 1 750 kg ha^{-1}. Limestone ammonium nitrate was used as the nitrogen (N) source and applied at a rate of 50 kg N ha^{-1}. Super phosphate as the phosphate (P) source and applied at a rate of 10 kg P ha^{-1}. The soil potassium (K) status was very high and hence K application was ignored.

5.3.3 RESULTS AND DISCUSSION

5.3.3.1 First experiment (1996 – 1999)

Seed yield, biomass, harvest index and precipitation for the three growing seasons (P_g) are presented in Table 5.3.1.1. From the precipitation values it can be seen that sunflower was produced under conditions ranging from extremely dry (98/99) to average conditions (96/97 and 97/98). The rainfall for the 98/99 growing season was 157 mm lower than the January-April long-term average of 296 mm. It was clearly a very abnormal season. The extremely droughty conditions during the 98/99 season are clearly shown in Figure 5.3.1.2. The crop suffered severe stress from about 40 days after planting (DAP) up to the end of the growing season. Growing conditions were clearly far more favourable during the 97/98 season (Figure 5.3.1.1).

The fact that this soil is regarded as marginal for crop production using *CON* can be seen from the variation in crop yields over the two seasons. Sunflower yields varied over all the treatments between 594 and 2806 kg ha^{-1}. The *CON* treatment average yield (1435 kg ha^{-1}) is below the average yield (1782 kg ha^{-1}) obtained with *BbBr* and *ObBr*. The average yield advantage for *BbBr* (three seasons) and *ObBr* (two seasons) above the *CON* was: 23 and 34% respectively. Both *IRWH* treatments produced significantly higher seed and biomass yields compared to *CON* during the average 97/98 season. During the 98/99 season only the *ObBr* treatment produced significantly higher seed and biomass yields than *CON*. This result reflects the advantage of having mulch in the basins. The average biomass yield advantages for *BbBr* (three seasons) and *ObBr* (two seasons) above the *CON* treatments were 20 and 28%, respectively. The beneficial influence of mulching on both seed and biomass, when comparing *BbBr* with *ObBr*, are not statistically significant during both years. Harvest index (HI) values indicate that *ObBr* performed slightly better than *CON* and *BbBr* with no significant difference during any year.

Table 5.3.1.1 Seed yield, biomass, harvest index and P_g (growing season rainfall) values for the *CON* and *IRWH* treatments on the Glen/Bonheim ecotope over three seasons

Parameter	Year	P_g (mm)	*CON*	*BbBr*	*ObBr*
Seed (kg ha^{-1})	96/97	296	1612^a	1853^a	-
	97/98	294	2098^a	2773^b	2806^b
	98/99	139	594^a	651^{ab}	804^b
	Mean	**243**	**1435**	**1759**	**1805**
Biomass (kg ha^{-1})	96/97	296	4133^a	4751^a	-
	97/98	294	4695^a	5888^b	5948^b
	98/99	139	1453^a	1730^{ab}	1906^b
	Mean	**243**	**3427**	**4125**	**3927**
Harvest index	96/97	296	0.39^a	0.39^a	-
	97/98	294	0.45^a	0.47^a	0.47^a
	98/99	139	0.41^a	0.38^a	0.42^a
	Mean	**243**	**0.42**	**0.42**	**0.45**

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

Water productivity data are presented in Table 5.3.1.2. Passioura (2006) reviewed WP_{Ev} results for oilseed and grain legumes. He states that maximum values for these crops seem to range from about 8 to 15 kg ha^{-1} mm^{-1}. The results in Table 5.3.1.2 for the overall period are therefore favourable compared to the international results reported by Passioura. The values are low compared to WP_{Ev} results for maize averaging around 26 kg ha^{-1} mm^{-1} obtained by Hensley *et al.* (2000) for the 97/98 season. The difference is due to the fact that sunflower seed is much richer in energy, due to the high oil content, than maize grain. The same amount of primary assimilate (1 g) converts to about 0.83 g carbohydrates and only 0.33 g of lipid (Gregory, 1989).

This means that to compare WP_{Ev} values for the two crops the value for maize must be multiplied by about 0.39. On this basis an equivalent value for maize would be about 10 kg ha^{-1} mm^{-1}. The considerable higher values for sunflower reflect the advantage of sunflower as a crop for this ecotope compared to maize, since both of them were growing under exactly the same conditions. The advantages of sunflower compared to maize are even more strongly exposed by comparing the WP_{Ev} results for the overall period. For the *ObBr* treatment the WP_{Ev} value for maize was 5.3 kg ha^{-1} mm^{-1} (Hensley *et al.*, 2000) compared to the equivalent value of 14.7 kg ha^{-1} mm^{-1} for sunflower.

RWP is an important indicator of agronomic sustainability. It is also the parameter, which exposes the differences between different water conservation production techniques (see Section 4.3.5 and Equation 4.9). WP_{Ev} does not do this. RWP results are presented in Table 5.3.1.2. The results revealed that the *BbBr* and *ObBr* techniques produced a significantly RWP advantage above *CON* of 22 and 49% respectively, and *ObBr* was significantly better than *BbBr*.

Table 5.3.1.2 Water productivity and rainwater productivity values for sunflower for *CON* and *IRWH* treatments on the Glen/Bonheim ecotope over experimental period

Water productivity indicators (kg ha^{-1} mm^{-1})	Year	*CON*	*BbBr*	*ObBr*
WP_{Ev}	overall	14.0^a	14.3^a	14.7^a
$RWP_{1996/97-1998/99}$	overall	3.7^a	4.5^b	5.5^c

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

Water balance components are presented in Table 5.3.1.3. The absence of deep drainage (D) losses on all the treatments is noticeable. The result has been promoted by two factors. Firstly, very efficient water extraction by the sunflower roots (Figure 5.3.1.1) resulting in the soil becoming rapidly dried out to relatively low values before the next rain. The steep slope of the line in Figure 5.3.1.1 after the large rainfall event on DAP 35, clearly reflects this rapid extraction of water by the roots. Secondly, due to the high water holding capacity of the soil (Table 5.3.1). The relatively high R loss on the *CON* treatments during the 97/98 season of 30 mm (10% of P) is clearly the reason for the significantly lower seed yields compared to the *IRWH* treatments where R was zero.

Table 5.3.1.3 Water balance components for the *CON* and *IRWH* treatments on the Glen/Bonheim ecotope over three seasons

Water balance components (mm)	Year	*CON*	*BbBr*	*ObBr*
P	96/97	296		
	97/98	294		
	98/99	139		
ΔS	96/97	64^a	78^a	-
	97/98	35^a	29^a	31^a
	98/99	43^a	127^b	146^b
D	96/97	0^a	0^a	-
	97/98	0^a	0^a	0^a
	98/99	0^a	0^a	0^a
R	96/97	13^a	0^a	-
	97/98	30^a	0^b	0^b
	98/99	0^a	0^a	0^a
Es	96/97	231^a	241^a	-
	97/98	164^a	154^a	154^a
	98/99	125^a	198^b	210^b
Ev	96/97	116^a	133^a	-
	97/98	135^a	169^b	171^b
	98/99	57^a	68^a	75^a
ET	96/97	347^a	374^a	-
	97/98	299^a	323^b	325^b
	98/99	182^a	266^b	285^b
Es/ET (%)	96/97	67^a	64^a	-
	97/98	55^a	48^a	47^a
	98/99	69^a	74^a	74^a

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

A full set of figures showing changes in the soil water content of the rootzone during the 97/98 and 98/99 growing seasons are presented in Figures 5.3.1.1 and 5.3.1.2. The figures help to elucidate resultant yield and water balance data. Figure 5.3.1.1 for example shows firstly, the advantage that the *IRWH* treatments had by starting the growing season with a much higher soil water content compared to the *CON*. It amounted to about 40 mm. This phenomenon was due to the total stoppage of R by the basins and minimizing effect on Es by mulches. This is one of the reasons why the *IRWH* treatments yielded higher than the *CON*. Secondly, although the rootzone water content at planting was considerably below DUL at planting (± 100 mm and 140 mm below for *IRWH* and *CON* respectively, Figure 5.3.1.1), the rainfall event of 83 mm on DAP 34 (Figure 5.3.1.1) was extremely advantageous. The timing of this event in relation to flowering was particularly beneficial for the crop. This large event consisted mainly of low intensity rain with 5.6 and 2.9 mm of runoff being recorded on the flat, crusted surface plot and total soil tillage runoff plots respectively (Hensley *et al.*, 2000). Comparing this result to another event of 85 mm with 55 mm of measured runoff on DOY 322 during 1996 accentuates the influence of rainfall intensity on *IRWH*. The similar rootzone water content increase on *CON* of about 50 mm, compared to about 45 mm on the *IRWH* treatments (Figure 5.3.1.1) can be explained by the low intensity of the rainfall and also by the fact that the soil water content measurements were made about four days after the event. The larger *IRWH* plants would have extracted far more water during these four days than the smaller *CON* plants. After DAP 34 there followed fairly good and well-distributed rainfall events, which resulted in relative good yields for this ecotope. The low available water content of the rootzone (about 16% of TESW) during the critical flowering period was a serious disadvantage. The relatively good yields achieved, in spite of this disadvantage, provides strong evidence for the drought resistant qualities of sunflower.

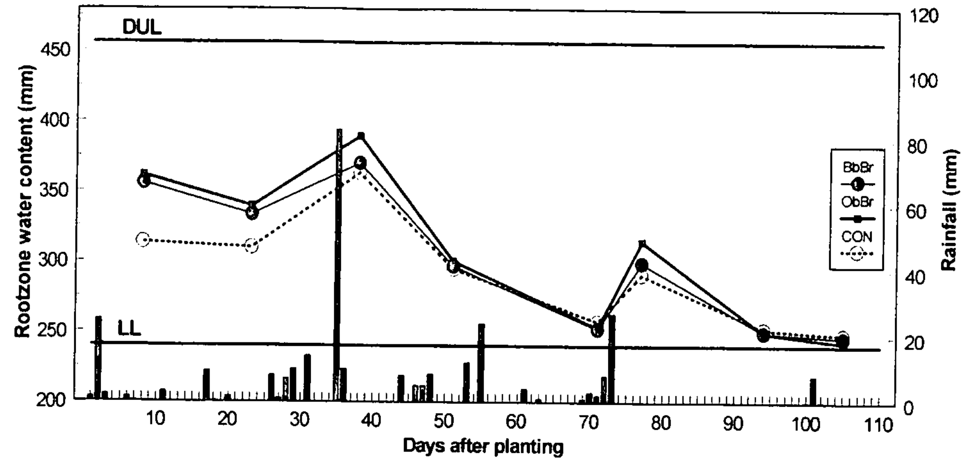

Figure 5.3.1.1 Measured changes in the rootzone water content of sunflower on the three treatments during the 97/98 season on the Glen/Bonheim ecotope.

The following are important features of the 98/99 season shown in Figure 5.3.1.2. It seems that the most critical factors are the amount and distribution of rainfall during the growing season, and the soil water content at planting. The latter was satisfactory for the two *IRWH* treatments, at about 370 mm, better in fact than for the 97/98 season. The equivalent value for *CON* was very low at about 285 mm. High soil water content at planting provides a buffer against low rainfall later in the season. From DAP 48 to DAP 110 there was only 45 mm of rain with no event greater than 10 mm. This phenomenon clearly depressed the sunflower yields severely, causing the resultant low yields. The fact that on all the *IRWH* treatments seed yields exceeded ½ ton ha^{-1} under these extreme and abnormal conditions reflects the strong drought resistant properties of sunflower. In contrast maize grain yields during the same season were 0, 35 and 132 kg ha^{-1} for the *CON*, *BbBr* and *ObBr* treatments respectively (Hensley *et al.*, 2000).

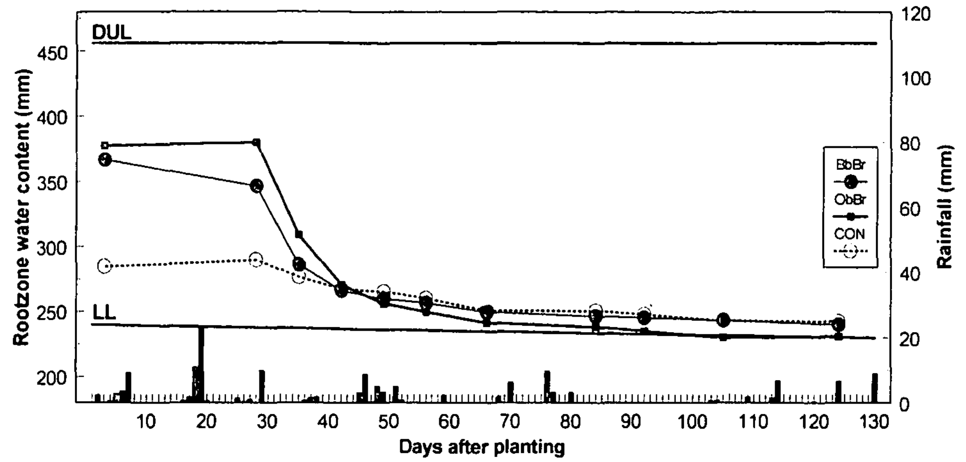

Figure 5.3.1.2 Measured changes in the rootzone water content of sunflower on the three tillage treatments during the 98/99 season on the Glen/Bonheim ecotope.

It seems that when the rootzone water content falls below about 260 mm serious stress (SS in Figure 5.3.1.3) sets in and yield becomes impaired, especially if this occurs during the drought sensitive growth stage, approximately between DAP 45 and 85 (Figure 5.3.1.3). The critical water regime period is demarcated in the figure. It shows that the soil water regime of the *BbBr* during the critical period was far lower during the 98/99 season than during the 97/98 season. For the former season the graph indicates that the crop was severely stressed throughout the sensitive period. Grain yields were proportionally depressed i.e. 651 and 2773 kg ha^{-1} respectively. It needs to be kept in mind that an outstanding dryland yield of sunflower is around 3000 kg ha^{-1}. It seems that this would have been achieved had there been a good rain around DAP 65 during the 97/98 season.

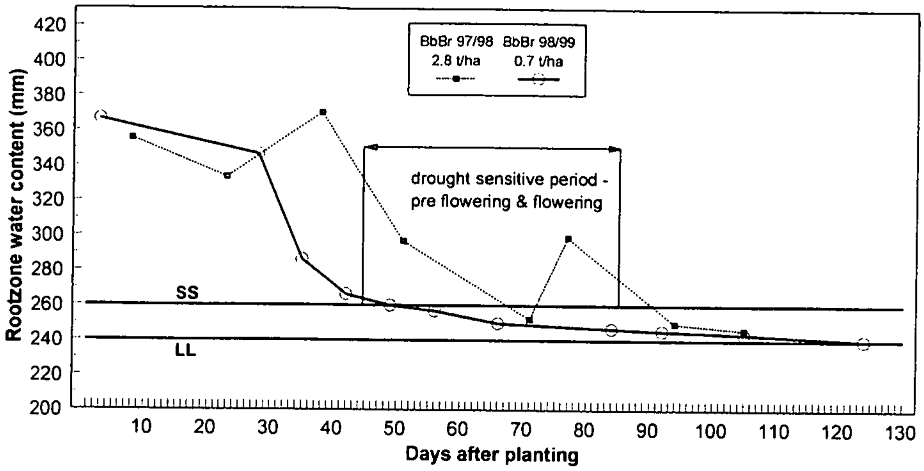

Figure 5.3.1.3 The rootzone water regime of sunflower for the *BbBr* treatment during 97/98 and 98/99 growing seasons on the Glen/Bonheim ecotope.

5.3.3.1.1 Conclusions

The results showed that *IRWH* significantly increased sunflower yields compared to *CON* through its ability to stop R completely and minimize Es. This resulted in considerably higher rainwater productivity values for *IRWH.* It was also showed that mulch in the basins was beneficial, and that future research needed to focus on reducing Es as much as possible. Sunflower was shown to have better drought resistant properties than maize.

5.3.3.2 Second experiment (2000 – 2003)

5.3.3.2.1 Climate

For the analysis of the water balance components of the experiment the production season was divided into three periods, *viz.* (i) the fallow period (F_p), from harvesting of the previous crop until planting of the next crop; (ii) the vegetative period (V_p), from planting to flowering; and (iii) the reproductive period (R_p), from flowering until harvest. This provides an opportunity to analyze the three periods separately and also the combined effect on the growing season (G_p), i.e. $V_p + R_p$, and the overall production period (P_p), i.e. $F_p + V_g + R_p$.

Table 5.3.2.1 Precipitation (P), evaporative demand (E_o) and aridity index (AI) values for subdivisions of the four sunflower production seasons in relation to the long-term (LT) means on the Glen/Bonheim ecotope. F_p = fallow period, V_p = vegetative period, R_p = reproductive period, G_p = crop growing period and P_p = production period

Parameter	Year	Period				
		F_p	V_p	R_p	G_p	P_p
P (mm)	99/00	205	109	70	179	384
	00/01	232	82	198	280	512
	01/02	360	161	87	248	608
	02/03	315	101	115	216	531
	Mean	**278**	**113**	**118**	**231**	**509**
	LT mean	**221**	**175**	**108**	**283**	**504**
E_o (mm)	99/00	427	340	123	463	890
	00/01	1086	508	217	725	1811
	01/02	841	373	292	665	1506
	02/03	1241	445	265	710	1951
	Mean	**899**	**417**	**224**	**641**	**1540**
	LT mean	**1311**	**534**	**284**	**818**	**2129**
AI	99/00	ND*	0.32	0.57	0.39	0.43
	00/01	0.21	0.16	0.91	0.39	0.28
	01/02	0.43	0.43	0.30	0.37	0.40
	02/03	0.25	0.23	0.43	0.30	0.27
	Mean	**0.30**	**0.29**	**0.55**	**0.36**	**0.35**
	LT mean	**0.17**	**0.33**	**0.38**	**0.35**	**0.24**

ND* = Not determined, excluded from mean.

Precipitation (P), evaporative demand (E_o) and the aridity index (AI) value, summarized in Table 5.3.2.1, were used to characterize the climatic conditions experienced during the experimental period from the start of the 1999/00 season to the end of the 2002/03 season. Comparing the mean climatic conditions of the experimental cycle (4 years) with the long-term mean reveals that climatic conditions are typical for the ecotope. The mean rainfall of P_p is similar to the long-term, while the AI is slightly better than the long-term due to slightly lower evaporative conditions during the experimental cycle. The AI values of the P_p indicate that the climate of the experimental cycle compares well with the long-term mean. A deeper assessment reveals that the climate of the R_p were three of the years better than the long-term, while the opposite is true for the V_p. It is very rare that climatic conditions will be perfect during all the growing periods. In fact one of the certainties of a semi-arid ecotope, is the unpredictable climatic condition during and over seasons. For example, the rainfall varied between 205 and 360 mm over the experimental cycle during the F_p; between 82 and 161 mm in the V_p; between 70 and 198 mm during the R_p. The impact of variation on grain yield will be discussed in terms of the full water balance in the sections that will fallow.

5.3.3.2.2 Water balance components

5.3.3.2.2.1 Soil water content and drainage

Fallow period:

The sunflower cultivar (SNK 74) that was used during the experimental period was a short growing season cultivars, i.e. ± 120 days from planting to maturity. This implies a F_p of 7 to 8 months. Conservation of water during this period is essential in semi-arid environments to give the valuable higher pre-plant water advantage. The plant available water at planting (PAW_p) and flowering (PAW_F) and rainfall storage efficiency (RSE) for each treatment is summarized in Table 5.3.2.2.

Two aspects are important, *viz.* (i) RSE during the F_p; and (ii) PAW_p. RSE values indicate that all the *IRWH* treatments produced significantly higher RSE values, almost three times higher, during the fallow periods of all four seasons compared to the *CON* treatment. The *IRWH* treatments stopped ex-field R completely, whereas *CON* lost on average 28 mm of water due to ex-field R, or 10% of the P that occurred during the F_p (Table 5.3.2.5). The *CON* treatment also lost on average 32 mm more water to Es during the F_p compared to the *IRWH* treatments. These results indicate that *CON* lost on average 60 mm more water to Es and R compared to the *IRWH* treatments during F_p. Hence the significantly higher RSE values on the *IRWH* treatments. Mulch treatments affected RSE but with no particular pattern. Es results during the F_p from Table 5.3.2.3 indicated that *ObBr* and *ObOr* lost the same amount of water to Es. *SbOr* performed slightly better and *ObSr* was the best treatment in terms of Es suppression during the F_p. *ObSr* produced significantly higher RSE values than *ObBr* during the 99/00 and 00/01 seasons, and also significantly better than *ObOr* during the 00/01 season. The trend in RSE values for the *IRWH* treatments correlates well with the corresponding Es data obtained during the F_p.

Table 5.3.2.2 Plant available water (mm) at planting (PAW_p), flowering (PAW_F) and rainfall storage efficiency (RSE) for the rootzone (0 – 1200 mm) on the different treatments during the four growing seasons

Water content (mm)	Year	Treatment					
		CON	*ObBr*	*ObOr*	*ObSr*	*SbOr*	Mean *IRWH*
PAW_p (mm)	99/00	104^{a}	137^{b}	144^{b}	151^{b}	154^{b}	147
	00/01	63^{a}	145^{b}	142^{b}	154^{b}	155^{b}	149
	01/02	114^{a}	210^{b}	224^{b}	231^{b}	223^{b}	222
	02/03	71^{a}	168^{b}	181^{c}	188^{c}	186^{c}	181
	Mean	**88**	**165**	**173**	**181**	**180**	**175**
PAW_F (mm)	99/00	54^{a}	66^{a}	70^{a}	70^{a}	77^{a}	71
	00/01	44^{a}	32^{a}	29^{a}	31^{a}	37^{a}	32
	01/02	52^{a}	65^{a}	70^{a}	63^{a}	67^{a}	66
	02/03	50^{a}	55^{a}	58^{a}	59^{a}	63^{a}	59
	Mean	**50**	**55**	**57**	**56**	**61**	**57**
RSE (%)	99/00	35^{a}	43^{b}	47^{bc}	51^{c}	50^{bc}	48
	00/01	5^{a}	42^{b}	41^{b}	47^{c}	44^{bc}	44
	01/02	8^{a}	21^{b}	18^{b}	20^{b}	19^{b}	20
	02/03	4^{a}	29^{b}	30^{b}	31^{b}	30^{b}	30
	Mean	**13**	**34**	**34**	**37**	**36**	**35**

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

The statistical analyses of PAW_p indicate that mulch type did not significantly affect PAW_p, but tillage treatments did. The PAW_p of all the *IRWH* treatments were similar.

PAW_p of all the *IRWH* treatments were significantly higher than the *CON* during all four seasons. The significantly higher PAW_p of all the *IRWH* treatments compared to the *CON* treatment is a direct result of the higher RSE values. Sunflower planted during the 01/02 season started with higher PAW_p values than the 00/01 season, mainly due to the higher rainfall during the fallow period of the 01/02 season. This made a considerable difference in the water supply to the crop during 01/02 season (Figures 5.3.2.1 b and c) and hence the yield in comparison to 00/01 (Table 5.3.2.6). The *IRWH* treatments and *CON* of 01/02 yielded 32 and 192% more seed than in the 00/01 season, respectively. This was achieved despite a rising water content during the reproductive period of the 00/01 season (Figure 5.3.2.1 b). The relatively dry vegetative period probably restricted plant growth to an extent that it could not reach its full potential at flowering. A short dry spell before and after flowering (DOY 58 – 75) had aggravated the problem of water supply to the crops of all the treatments.

No significant trend or differences between different treatments occurred at PAW_F. However, PAW_F results clearly indicate that the 00/01 season was a relative droughty season. During this season the lowest PAW_F values were obtained on all the treatments, with the values for all the *IRWH* treatments considerably lower than *CON*. The reason for this is most probably due to the far larger *IRWH* plants (average final biomass of 4951 kg ha^{-1}) extracting much more water from the rootzone than *CON* (final biomass of 1610 kg ha^{-1}) during the rainless period from DOY 58 to DOY 74. These results correlate well with P and AI values during the V_p of the 00/01 season (Table 5.3.2.1) and are reflected in the lowest yields obtained by the different treatments during this season compared to the other seasons (Table 5.3.2.6). These results also confirm the importance of this critical period, as there is a highly significantly ($r^2 = 0.89$), but positive, relationship between PAW_F (x) and seed yield (y) ($y = -5942 + 1593.6\ln(x)$).

5.3.3.2.2.2 *Evaporation and evapotranspiration*

Fallow period:

Es results in Table 5.3.2.3 indicate that only during the fallow periods of the 00/01 and 02/03 seasons did all the *IRWH* treatments lose significantly less water to Es compared to *CON*. The fallow periods of these two seasons were also characterized by the lowest AI and the highest E_o values (Table 5.3.2.1). Es losses from *CON* during all four seasons were 17% higher than from the mean of the *IRWH* treatments. Mean Es results obtained during the F_p indicated that *CON*, *ObBr*, *ObOr*, *ObSr* and *SbOr*, respectively, lost on average 79, 69, 69, 65 and 67% of the mean P that occurred during the F_p of the four seasons to Es. The *IRWH* treatments managed to suppress the portion of P lost to Es by an average of 12% compared to *CON*. Mulch treatments did not influence Es with any particular pattern.

Growing period:

Es, ET and Ev results are presented in Table 5.3.2.3. The mean Es value of *CON* and the mean of all the *IRWH* treatments during the G_p showed that the *IRWH* treatments reduced Es by 15% compared to *CON*. Water conserved this way led to a 117% increases in Ev compared to *CON*. All the *IRWH* treatments produced significantly lower Es (during G_p) values during the 99/00, 00/01 and 02/03 seasons and significantly higher Ev and ET values, during all four seasons, compared to *CON*. This is an indication that the *IRWH* technique not only suppresses Es significantly better than *CON* during the F_p but also during the G_p, i.e. during the whole P_p. What must also be kept in mind is the fact that the *IRWH* treatments were constantly wetter than *CON* and therefore it was to be expected that Es from the *IRWH* treatments might be higher than from *CON*. Es from the *IRWH* treatments were only significantly higher than *CON* during the 01/02 season. The reason might be that all the *IRWH* treatments started the 01/02 growing season with a very high soil water content, on average about 6 mm above DUL, and significantly higher than *CON* (Figure 5.3.2.1 c). During the first 28 days of the growing season (DOY 352 – 15), when sunflower plants were still small, 17 rainfall events occurred and amounted to 92 mm. This kept the soil water content of all the *IRWH* treatments close to DUL and far wetter than that of the *CON* treatment at about 93 mm below DUL during this period. As more water evaporates from a wet soil surface compared to a drier surface, the higher Es from the *IRWH* treatments compared to *CON* is understandable.

Comparing the mean Es values for *ObOr*, *ObSr* and *SbOr* with *ObBr* shows that the relative reductions in Es amounted to 15, 8 and 18%, respectively during the G_p; apparently resulting in corresponding relative increases in Ev of 12, 10 and 17% respectively. The results showed that *ObBr* produced the highest mean Es and lowest mean Ev of all the *IRWH* treatments during all four seasons during G_p. This is an indication that mulch on the runoff area of the *IRWH* technique suppressed Es effectively during the G_p.

Table 5.3.2.3 Cumulative evaporation from the soil surface (Es) during the fallow period, cumulative evapotranspiration (ET), Es and transpiration (Ev) during the growing period of the four seasons for the different treatments on the Glen/Bonheim ecotope

Period	Parameter	Season	Treatment					
			CON	*ObBr*	*ObOr*	*ObSr*	*SbOr*	Mean *IRWH*
F_p	Es (mm)	99/00	113^{a}	117^{a}	109^{a}	100^{a}	102^{a}	107
		00/01	197^{a}	135^{b}	138^{b}	124^{b}	129^{b}	132
		01/02	292^{a}	286^{a}	295^{a}	288^{a}	291^{a}	290
		02/03	273^{a}	224^{b}	221^{b}	217^{b}	219^{b}	220
		Mean	**219**	**191**	**191**	**182**	**185**	**187**
G_p	Ev (mm)	99/00	107^{a}	167^{b}	197^{b}	196^{b}	215^{b}	194
		00/01	52^{a}	153^{b}	158^{b}	166^{b}	173^{b}	163
		01/02	126^{a}	174^{b}	182^{b}	188^{b}	182^{b}	182
		02/03	90^{a}	248^{b}	293^{c}	268^{bc}	297^{c}	277
		Mean	**94**	**186**	**208**	**205**	**217**	**204**
	Es (mm)	99/00	114^{a}	101^{b}	78^{c}	88^{c}	66^{c}	83
		00/01	174^{a}	136^{b}	105^{c}	110^{c}	108^{c}	115
		01/02	153^{a}	207^{b}	203^{b}	201^{b}	199^{b}	203
		02/03	120^{a}	100^{b}	73^{c}	100^{b}	69^{c}	86
		Mean	**140**	**136**	**115**	**125**	**111**	**122**
	ET (mm)	99/00	221^{a}	268^{b}	275^{bc}	284^{c}	281^{bc}	277
		00/01	226^{a}	289^{b}	263^{c}	276^{bc}	281^{bc}	277
		01/02	279^{a}	381^{b}	385^{b}	389^{b}	381^{b}	384
		02/03	210^{a}	348^{b}	366^{c}	368^{c}	366^{c}	362
		Mean	**234**	**322**	**322**	**329**	**327**	**325**
	Es/ET (%)	99/00	52^{a}	38^{b}	28^{c}	31^{c}	23^{c}	30
		00/01	77^{a}	47^{b}	40^{bc}	40^{bc}	38^{c}	41
		01/02	55^{a}	54^{b}	53^{b}	52^{b}	52^{b}	53
		02/03	57^{a}	29^{b}	20^{c}	27^{b}	19^{c}	24
		Mean	**60**	**42**	**35**	**37**	**33**	**37**

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

The mean percentage Ev/ET results for *CON*, *ObBr*, *ObOr*, *ObSr* and *SbOr* were 40, 58, 65, 63 and 67%, respectively, while the Es/ET results of the same treatments were 60, 42, 35, 37 and 33%, respectively (Table 5.3.2.3). This is an indication that all the *IRWH* treatments lost smaller portions of ET to Es, in other words all the *IRWH* treatments were much more successful in minimizing the unproductive loss of water through Es. On average the *IRWH* treatments were 24% more successful than *CON* in minimizing the portion of ET lost to Es. Comparing the mean percentage Es/ET results for *ObOr*, *SbOr* and *ObSr* indicate that mulch type on the runoff area did not affect the portion of ET lost to Es.

Production period:

Cumulative Es (as mm and % P) during the P_p are summarized in Table 5.3.2.4.

Table 5.3.2.4 The relationship between Es and P during P_p for the different treatments during four seasons on the Glen/Bonheim ecotope

Parameter	Season	Treatment					
		CON	*ObBr*	*ObOr*	*ObSr*	*SbOr*	Mean *IRWH*
Es (mm)	99/00	227	218	187	188	168	190
	00/01	371	271	243	234	237	246
	01/02	445	493	498	489	490	493
	02/03	393	324	294	317	288	306
	Mean	**359**	**327**	**306**	**307**	**296**	**309**
Es/P (%)	99/00	59	57	49	49	44	50
	00/01	72	53	47	46	46	48
	01/02	73	81	82	80	81	81
	02/03	74	61	55	60	54	58
	Mean	**70**	**63**	**58**	**59**	**56**	**59**

The amount of rainwater lost to Es amounts to 70% for *CON* compared to the between 56 and 63% for the *IRWH* treatments. The *IRWH* treatments therefore reduced the portion of P lost to Es on average by 11% compared to *CON*. The R losses on *CON* amounted to only 10% of P (Table 5.3.2.5), showing that Es dominates the water loss processes. The average water loss through Es from all the different treatments is shown to amount to 61% of P over the four production periods. Comparing Es from the *ObSr*, *ObOr* and *ObBr* treatments shows that stones and organic mulch on the runoff strip reduced Es by 5% compared to the *ObBr* treatment with a bare runoff area. Assuming that the methodology of separating Es and Ev is correct, this result clearly indicates that evaporation remains the most important process to be studied in the quest for maximizing rainwater productivity. An interesting possibility is the introduction of plastic on the runoff area, or a 100% stone or gravel mulch. If Es could be reduced by a further 25%, yields could be doubled. Attention should be given to the socio-economic and agronomic aspects of artificial mulch options.

5.3.3.2.2.3 Ex-field runoff

No ex-field runoff (R_{Ex}) occurred from any of the *IRWH* treatments during the experimental period therefore only runoff from the *CON* treatment is reported in Table 5.3.2.5. To quantify R_{Ex} from the *CON* treatment during the four seasons, they were sub-divided into the same five periods as presented in Section 5.3.3.2.1, *viz.* (i) F_p; (ii) V_p; (iii) R_p; (iv) G_p; (v) P_p.

The results show considerable variation in the percentage of rainfall lost to R_{Ex} during the different seasons, eq. for the R_p the variation is from 6% to 15%. The variations is probably mainly due to variations in the rainfall pattern and especially rainfall intensity and therefore accentuates the importance of these processes in water conservation studies. An example is provided by comparing R_{Ex} during the V_p of the 99/00 and 00/01 seasons. Rainfall during the V_p of the 99/00 and 00/01 seasons amounted to 109 mm (62% of LT mean) and 82 mm (47 % of LT mean) respectively (Table 5.3.2.1). The rainfall pattern was very different during the two periods, with 19% and 66% of the rainfall consisting of events smaller than 10 mm, respectively, and equivalent R_{Ex} values of 6 and 8 mm. The larger events during the 00/01 season clearly contributed greatly to the difference in R_{Ex}.

Table 5.3.2.5 Ex-field runoff (R_{Ex}) from the *CON* treatment for subdivisions of the four seasons for sunflower on the Glen/Bonheim ecotope

Parameter	Season	Period				
		F_p	V_p	R_p	G_p	P_p
R (mm)	99/00	20	6	4	10	30
	00/01	24	8	24	32	56
	01/02	39	15	10	25	64
	02/03	29	6	17	23	52
	Mean	**28**	**9**	**14**	**23**	**51**
R/P (%)	99/00	10	6	6	6	8
	00/01	10	10	12	11	11
	01/02	11	9	11	10	11
	02/03	9	6	15	11	10
	Mean	**10**	**8**	**12**	**10**	**10**

In this semi-arid environment where every drop of rainwater counts and conservation and optimal use of the rainfall vital, these losses are significant and have hampered sunflower yields considerably compared to the yields obtained from the *IRWH* treatments where no R_{Ex} occurred (Table 5.3.2.6). Whereas cumulative Es results during the P_p of the 01/02 season (Table 5.3.2.4) indicated that *CON* lost less water to Es than the *IRWH* treatments, R_{Ex} results for the same period (Table 5.3.2.5) show that *CON* lost 64 mm of P to R_{Ex} as compared to the zero from the *IRWH* treatments. In spite of this the *IRWH* treatments still produced on average 50% more seed yield during this season (Table 5.3.2.6). Although R_{Ex} stopped by the *IRWH* treatments was not solely responsible for the 50% yield increase, these results confirm the advantage of *IRWH* above *CON* in terms of R reduction. Due to considerable R_{Ex} losses (24 mm) during the very favorable R_p of the 00/01 season *CON* was unable to respond adequately – as clearly shown in Figure 5.3.2.1 b relative to the *IRWH* treatments.

5.3.3.2.3 Soil water extraction

Graphs with measured changes in the soil water content of the rootzone during growing seasons help to explain yield and water balance data. A full set of graphs showing changes in the soil water content of the rootzone during the 99/00, 00/01, 01/02 and 02/03 growing season are presented in Figures 5.3.2.1 a to d. The water management borders, *viz*. CMUL, DUL and LL of PAW are also included in the graphs.

Vegetative period:

Comparing the climatic conditions (Table 5.3.2.1) of the V_p, using the corresponding AI values, reveal that the most favorable crop production conditions occurred during the 01/02 season (AI = 0.43), followed by the 99/00 (AI = 0.32), 02/03 (AI = 0.23) and the 00/01 season (AI = 0.16). The very high PAW_p values, high rainfall and relative low E_o conditions during the V_p of the 01/02 season caused relatively favorable cropping conditions, compared to the other seasons resulting in the best yield. During the 99/00 season very good distribution of the low rainfall (only 76% of the LT mean) and relative low E_o values, were responsible for a reasonable yield on *CON* of 1024 kg ha^{-1}, compared to the 582 kg ha^{-1} for the 00/01 season with more rain. The water contents at flowering were considerably lower than at planting for all treatments and seasons (Table 5.3.2.2). This indicated that rainfall was not sufficient to maintain the crop water demand, and the crop had to rely on the soil to supply the water deficit. Fortunately, the water supply by rain and soil water together was generally enough in all the seasons to protect sunflower from severe water stress. The exception was the *CON* treatment during the 00/01 season with the rootzone water content remaining at 28% of TESW, and the crop therefore probably seriously stressed, for most of the season. It is not surprising that the yield was only 582 kg ha^{-1}. This is clearly shown by water content patterns (Figure 5.3.2.1), which were always above LL. *CON* had the lowest water content values during all the seasons. Except for the *ObBr* treatment, which had the lowest water content values during all four seasons of the *IRWH* treatments, there was no consistent trend in the soil water patterns of the other *IRWH* treatments. At the beginning of the 01/02 season the water content of some of the *IRWH* treatments was slightly higher than DUL but not higher than CMUL. Hence, it was estimated that drainage was insignificantly low during this period. The *CON* treatments started the 00/01 season with a very low PAW_p and never seemed to recover from that during a very harsh V_p. If it had not been for the relative high PAW_p of the *IRWH* treatments during the 00/01 season, due to significantly higher RSE values (Table 5.3.2.2) compared to *CON*, their yields would probably have been affected in a similar way than that of *CON* by the very critical dry period between DOY 58 and DOY 80 (Figure 5.3.2.1 b).

Reproductive period:

Due to unfavourable rainfall conditions during the R_p of the 99/00 and 01/02 seasons, the crop depended heavily on stored water in the profile to maintain the crop water demand. In both cases almost 80% of the total available water had been extracted towards the end of the growing season (Figures 5.3.2.1 a and c). There was no clear differentiation in the water content trends between the different treatments in any of the seasons. The *CON* ended the 00/01 and 01/02 seasons with the lowest soil water content of all the treatments while the *ObBr* treatment ended up with the lowest water content of the *IRWH* treatments during these two specific seasons. The *CON* treatment ended the 02/03 season with the highest water content because of small sunflower plants that were unable to extract the available soil water (Figure 5.3.2.1 c) at a rate similar to that of the *IRWH* plants. Their final biomass was only 1610 kg ha^{-1} compared to the mean value for the *IRWH* treatments of 4951 kg ha^{-1}. Sunflower planted in the 00/01 season experienced an exceptionally good R_p, with 19 rainfall events providing 198 mm compared to a very low corresponding E_o of 217 mm. Of particular importance were the good rains (95 mm) that occurred in the first five days after flowering. Without this rain very low sunflower yields would have been realized. This caused the water content of the rootzones of all the *IRWH* treatments to rise sharply, with *CON* responding only slightly.

That no significant amount of deep drainage occurred during the R_p in any season is clearly shown by the rootzone water content (θr) results presented in Figure 5.3.2.1. Deep drainage can only be expected when θr exceeds CMUL. At no time during the R_p of any of the four seasons did θr even approach this level.

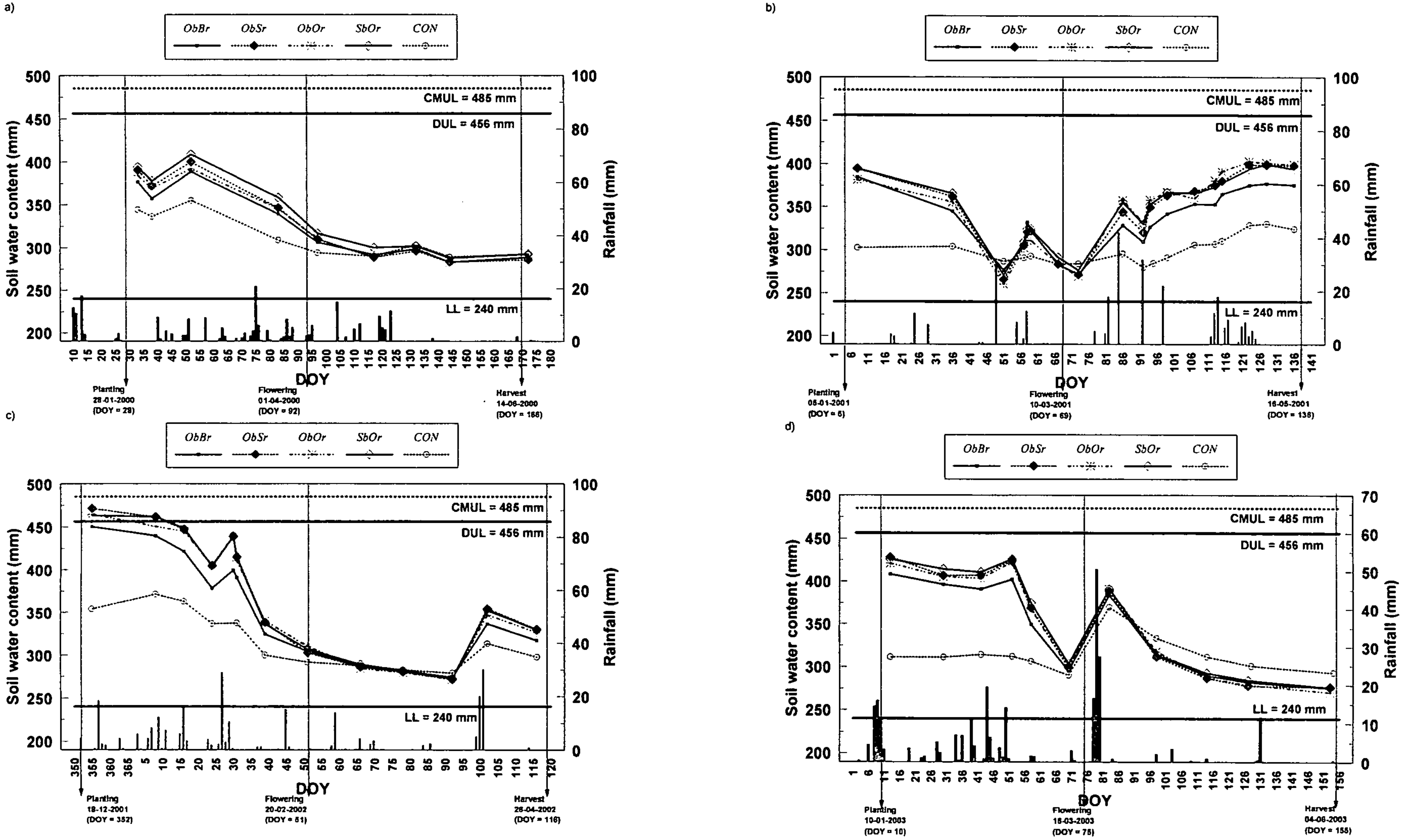

Figure 5.3.2.1 Changes in the soil water content of the sunflower rootzone (0 - 1200 mm) during the: (a) 99/00; (b) 00/01; (c) 01/02; (d) (02/03) seasons on the Glen/Bonheim ecotope.

5.3.3.2.4 Yield response

Grain and biomass yields and harvest index (HI) are presented in Table 5.3.2.6.

Table 5.3.2.6 Sunflower seed and biomass yields, and harvest index for the different treatments during four seasons on the Glen/Bonheim ecotope

Parameter	Year	Treatment					
		CON	*ObBr*	*ObOr*	*ObSr*	*SbOr*	Mean *IRWH*
Seed (kg ha^{-1})	99/00	1024^a	1879^b	2190^b	2346^c	2251^b	2167
	00/01	582^a	1716^b	1971^c	2138^d	1882^c	1927
	01/02	1699^a	2340^b	2519^c	2704^d	2622^c	2546
	02/03	1025^a	2208^b	2490^c	2596^c	2548^c	2461
	Mean	**1083**	**2036**	**2293**	**2446**	**2326**	**2275**
Biomass (kg ha^{-1})	99/00	2919^a	4582^b	5396^b	5368^b	5885^b	5308
	00/01	1610^a	4672^b	4804^b	5045^b	5283^b	4951
	01/02	3827^a	5184^b	5560^b	5736^b	5543^b	5506
	02/03	2280^a	5711^b	6741^c	6170^c	6831^c	6363
	Mean	**2659**	**5037**	**5625**	**5580**	**5886**	**5532**
Harvest index	99/00	0.35^a	0.41^a	0.41^a	0.44^a	0.38^a	0.41
	00/01	0.36^a	0.37^a	0.41^a	0.42^a	0.36^a	0.39
	01/02	0.44^a	0.45^a	0.45^a	0.47^a	0.47^a	0.46
	02/03	0.45^a	0.39^a	0.37^a	0.42^a	0.37^a	0.39
	Mean	**0.40**	**0.40**	**0.41**	**0.44**	**0.40**	**0.41**

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

The following are the main results reflected in Table 5.3.2.6:

- There was a wide range in seed yields, from 582 and 2704 kg ha^{-1} over the four seasons. Yields from all the *IRWH* treatments were in all four years significantly higher than *CON*, the overall average benefit amounting to 110%.
- Based on mean values seed yields decreased in the order *ObSr*, *SbOr*, *ObOr*, *ObBr*, *CON*; with *ObSr* significantly higher than all the other *IRWH*

treatments in three of the four years (99/00, 00/01 and 01/02), and significantly higher than *ObBr* in 02/03.

- Seed yields of *ObOr* and *SbOr* were significantly higher than *ObBr* during three of the four seasons (00/01, 01/02 and 02/03); The overall benefit of these two treatments and *ObSr* over *ObBr* amounting to 13, 14 and 20% respectively.
- Relative to each other these yields are similar to those from maize over the same period on this ecotope.
- It is concluded that the reasons for the higher yields from all the *IRWH* treatments is their ability to stop R_{Ex} completely and suppress Es to a significant extent. Annual averages over the four seasons were as fallows: Es from *CON* and mean *IRWH* amounted to 359 and 309 mm, respectively; R_{Ex} from *CON* and mean *IRWH* amounted to 51 and 0 mm respectively; total unproductive average P_p losses of rainfall therefore amounted to 410 mm (81%) and 309 mm (61%), respectively.

The pattern of biomass yields was the same manner as the seed yields, excepting that *ObBr* produced the lowest yields of all the *IRWH* treatments during all the years; with the difference being significant for the 02/03 season. All the *IRWH* treatments performed significantly better than the *CON* during all four years. Biomass yields varied from 1610 to 6831 kg ha^{-1}, with the lowest during the 00/01 season presumably due to the very dry V_p with the very low AI of 0.16 (Table 5.3.2.1). The second lowest biomass yield on *CON* was produced during the 02/03 season, which also had a very low AI value of 0.23 during the V_p. The *IRWH* treatments responded in a different way to *CON* during the 02/03 season. Due to better conservation of P during the F_p (mean RSE of 30% compared to 4% for *CON*) all the *IRWH* treatments started with a significantly higher PAW_p (Table 5.3.2.2 and Figure 5.3.2.1 c). The *IRWH* treatments were therefore able to produce bigger plants during the V_p for which were able to utilize the good rains during the R_p far more efficiently than on *CON*. The result was the large difference of 4083 kg ha^{-1} between the biomass yields on *CON* and mean *IRWH*.

The harvest index varied between 0.35 and 0.47 over the four seasons The highest harvest index occurred during the 01/02 season and correlates well with climatic results (Table 5.3.2.1) and water extraction graphs (Figure 5.3.2.1 c), which indicated that, the G_p and P_p of the 01/02 season was the most favorable of all the seasons.

5.3.3.2.5 Water productivity (WP_{Ev}) and rainwater productivity (RWP)

The relevant data are presented in Table 5.3.2.7.

Water productivity on Ev (WP_{Ev}): The results indicate that the WP_{Ev} varied between 10.7 and 11.9 kg ha^{-1} mm^{-1}. WP_{Ev} results fit well in to the maximum values of Passioura (2006) that range from 8 to 15 kg ha^{-1} mm^{-1}. Comparing mean WP_{Ev} of sunflower and maize (Chapter 4) over the same period on this ecotope on the basis of an equivalent value for maize as suggested by (Gregory, 1989) would be 9.4 kg ha^{-1} mm^{-1}. The considerable higher values for sunflower reflect the advantage of sunflower as a crop for this ecotope compared to maize, since both of them were growing under exactly the same conditions during these seasons.

Table 5.3.2.7 WP_{Ev} and RWP data for sunflower of the different treatments over a four seasons period on the Glen/Bonheim ecotope

Water productivity indicators (kg ha^{-1} mm^{-1})	Treatment					
	CON	*ObBr*	*ObOr*	*ObSr*	*SbOr*	Mean *IRWH*
WP_{Ev}	11.5^{a}	10.9^{a}	11.0^{a}	11.9^{a}	10.7^{a}	11.1
$RWP_{1999/00-2002/03}$	2.1^{a}	4.0^{b}	4.5^{bc}	4.8^{c}	4.6^{bc}	4.5

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

Rainwater productivity (RWP): RWP is probably the simplest and most comprehensive way of expressing the productivity of converting rainwater into seed yield. $RWP_{1999/00-2002/03}$ varied between 2.1 and 4.8 kg seed ha^{-1} mm^{-1} rain during the four seasons. A common trend of *ObSr* > *SbOr* ≥ *ObOr* > *ObBr* > *CON* was observed during the experimental period. All the *IRWH* treatments produced significantly higher $RWP_{1999/00-2002/03}$ values compared to *CON*. *ObBr*, *ObOr*, *ObSr* and *SbOr* produced 129, 119, 114 and 90% higher $RWP_{1999/00-2002/03}$ compared to *CON*. The superiority of the *IRWH* treatments is the result of their ability to stop R_{Ex} completely and induce in-field runoff (R_{In}) and also to minimize to Es and therefore utilize every drop of rainwater far better than *CON*.

All the *IRWH* treatments with mulch on the runoff area induced higher $RWP_{1999/00-2002/03}$ values than *ObBr*, with only *ObSr* significantly better. Comparing the $RWP_{1999/00-2002/03}$ values of the *IRWH* treatments with organic and stone mulch on the runoff area (*ObOr* and *ObSr*) with the bare runoff area (*ObBr*) indicate that *ObOr* and *ObSr* produced 13 and 20% higher $RWP_{1999/00-2002/03}$ values than *ObBr*. The reason for the higher $RWP_{1999/00-2002/03}$ values from the treatments with mulch on the runoff area might be because of the higher Ev's compared to *ObBr* (Table 5.3.2.4 and Section 5.3.3.2.2.2) due to the dual effect of in-field runoff and Es suppression. Both these processes improved the water availability to the crop and therefore better utilization of P to produce higher seed yields (Table 5.3.2.6).

5.3.3.2.6 Conclusions

It was hypothesized that mulch applications in the basins and runoff area of the *IRWH* technique would minimize Es and therefore increase PUE and sunflower yields. To test the hypothesis a field experiment was conducted on the Glen/Bonheim ecotope at the Glen Agricultural Institute. Four variations of the *IRWH* technique with different mulch combinations in and on the runoff area were compared with *CON* over the four growing seasons 1999/2000 to 2002/2003. The indicators of crop response to different treatments used were seed yield, dry matter production, harvest index, water productivity and rainwater productivity.

The results showed that *IRWH* significantly increased sunflower yields on average over the four seasons by 110% compared to *CON*. The advantage of the *IRWH* was its ability to stop R_{Ex} completely and minimize Es, both during the fallow and growing periods. Annual averages over the four seasons were as fallows: Es from *CON* and mean *IRWH* amounted to 359 and 309 mm, respectively; R_{Ex} from *CON* and mean

IRWH amounted to 51 and 0 mm respectively; total unproductive average P_p losses of rainfall therefore amounted to 410 mm (81%) and 309 mm (61%), respectively.

The *IRWH* treatments with stone or organic mulch on the runoff area gave the best yields. The most productive *IRWH* treatment was *ObSr*, followed by *SbOr*, *ObOr* and *ObBr*. Stone and organic mulch on the runoff area, compared to bare, reduced evaporation by 8 and 15% respectively during the growing season and on average 5% during the fallow and growing season The parameter considered being the most important for evaluating different water conservation technique is RWP due to its ability to assesses the effectiveness with which rainwater is converted into seed by using experimental data over a number of consecutive seasons. $RWP_{1999/00\text{-}2002/03}$ values over the four growing seasons for *CON* and *IRWH* (means of four treatments) were 2.1 and 4.5 kg ha^{-1} mm^{-1}, respectively. This result clearly demonstrates the superiority of *IRWH* for growing sunflower on this and similar ecotopes. Considerable higher WP_{Ev} values for sunflower as compared to maize reflect the advantage and suitability of sunflower as a crop on this and similar ecotopes.

5.4 GLEN/SWARTLAND - ROUVILLE ECOTOPE

5.4.1 DESCRIPTION OF THE ECOTOPE

The on-station field experiment was conducted on the Glen Agricultural Institute (28°57' S, 26°20' E), 25 km north east of Bloemfontein. The soil is classified, according to the Soil Classification Working Group (1991) as belonging to the Rouxville Family of the Swartland Form, and a Vertic chromic cambisol according to the WRB system. A detailed description of the soil and its chemical properties are presented by Hensley *et al.* (2000). Important soil, climatic and topographic characteristics are described in Chapter 2, while some of the morphological and physical properties related to the soil water management levels are summarized in Table 5.4.1.

Table 5.4.1 Important characteristics of the soil component of the Glen/Swartland ecotope. The effective rootzone is considered to be 0- 1200 mm

Profile detail					Soil water extraction properties for Sunflower			
Diag.[*1] Horizon	Colour	Clay (%)	BD[*2] (Mg m^{-3})	Depth (mm)	DUL (mm)	LL (mm)	TESW[*3] (mm)	CMUL (mm)
ot	DkBr	38	1.50	300	82	23	59	
vp	DkBr	40	1.66	600	96	62	34	
vp	DkBr	44	1.51	900	96	62	34	
so	Mottled due to $CaCO_3$ concretions	35	1.46	1200	84	60	24	
Total					358	207	151	393

[*1] Abbreviations from Soil Classification Working Group (1991): ot = orthic; vp = pedocutanic; so = saprolite

[*2] Bulk density

[*3] Total extractable soil water (DUL - LL).

The restrictive influence of the strongly structured B1 horizon (approx. 300-600 mm) on root water extraction, and therefore presumably on root ramification, is disclosed by the similar and slightly higher LL values for sunflower in the 300-600 mm layer compared to the 600-900 and 900-1200 mm layers, respectively.

Soil water extraction is effective to the bottom of the rootzone. A clearer picture of water extraction by sunflower is presented in Figure 5.4.1. The area of each rectangle representing a soil depth of 300 mm is proportional to TESW for that layer.

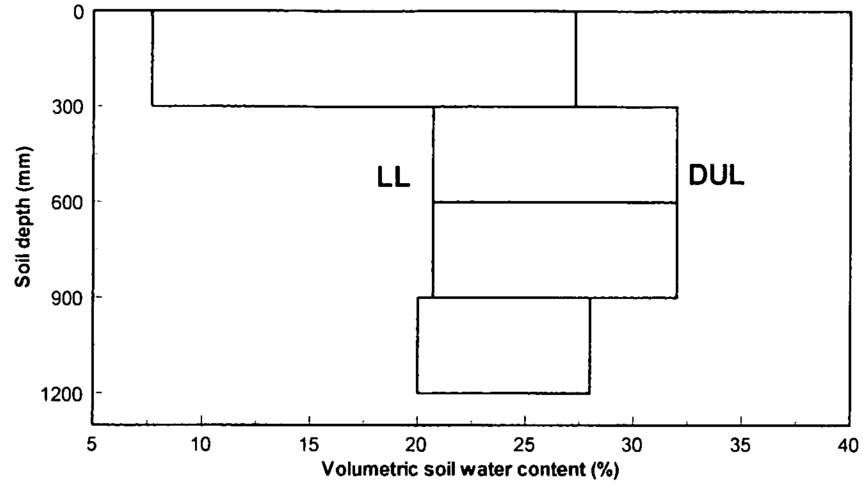

Figure 5.4.1 Soil water extraction graph for sunflower on the Glen/Swartland ecotope: rootzone 1200 mm.

5.4.2 PROCEDURE

The experiment was conducted over a period of three seasons *viz.* 1996/97, 1997/98 and 1998/99. This experiment was part of a larger project, sponsored by the Water Research Commission, which was carried out over a period of three seasons (1996/97; 1997/98; 1998/99).

5.4.2.1 Experimental layout

A randomised block design with three treatments and three replicates were employed. The crop used was sunflower, cultivar SNK 37. Sunflower was planted annually by hand at a plant population of 33 333 plants ha^{-1}. Planting and harvest dates were as follows: 1996/97: 17/12/96 – 22/04/97; 1997/98: 14/01/97 – 06/05/97; 1998/99: 06/01/98 – 06/05/98. Since water is the main limiting factor on this ecotope, fertilizer applications aimed at a moderate yield were applied [50 kg ha^{-1} of 3:1:0 (28%) + Zn].

The treatments were:

- normal conventional (*CON*) tillage,
- *IRWH* technique with a bare basin and runoff area (*BbBr*) and
- *IRWH* technique with organic mulch in the basins and a bare runoff area (*ObBr*). This treatment was only started during the second season.

5.4.3 RESULTS AND DISCUSSION

Seed and biomass yields, harvest index and precipitation during the growing season (P_g) data for the three growing seasons are presented in Table 5.4.2. From the precipitation values it can be detected that sunflower was produced under conditions stretching from extremely dry (98/99) to average (96/97 and 97/98). The average rainfall of 243 mm for the sunflower growing season is 40 mm lower than the January-April long-term average of 283 mm. The seed yields of both *IRWH* (*BbBr* and *ObBr*) treatments were significantly better than *CON* over the last two growing seasons. For the 96/97 season the *BbBr* treatment was disadvantaged by the fact that the basins and the runoff strip had not been in position during the preceding fallow period. Because of this plant available water at planting (PAW_p) of *CON* and *BbBr* were similar for this season whereas for the 97/98 and 98/99 seasons the PAW_p values for *BbBr* were around 30 mm more than the PAW_p for *CON* during both seasons. This is probably an important factor for the absence of a significant difference in yield for the 96/97 season. During the 98/99 season the seed yield of *ObBr* was also significantly higher than *BbBr*. Seed yields varied between 506 and 2558 kg ha^{-1} over the three years. A strong yield trend was established in each of the last two seasons, *viz. ObBr* > *BbBr* > *CON*. The average seed yields show that *BbBr* (over three seasons) and *ObBr* (over two seasons) produced 20 and 33% more seed, respectively, than *CON*. Biomass yields varied between 1392 and 5522 kg ha^{-1}, with the same pattern that was observed with the seed yields. The statistical results revealed that both *IRWH* treatments increased biomass significantly more than *CON* during the 97/98 season while only the *ObBr* treatment increased biomass yield significantly more than *CON* during the very dry 98/99 season. The *IRWH* treatments produced on average 20% more biomass compared to *CON*. The harvest index varied between 0.36 and 0.47. Values for the 98/99 season were lower than the 97/98 season due to an extremely dry season especially from day after plant (DAP) 40 until the end of the season (Figure 5.4.3). Seed and biomass yields and harvest index values indicate that both *IRWH* treatments were superior to *CON* and *ObBr* performed slightly better than *BbBr*. It seems that the efficient deep taproot system of sunflower counteracts its dependence on surface layer protection in the form of mulch from having a significant influence on yield. Although this proves to be correct for the wet 97/98 season, under the droughty 98/99 conditions mulch is shown to have had a significantly beneficial influence on the yields.

Table 5.4.2 Seed yield, biomass, harvest index and rainfall during the growing season (P_g) for the *CON* and *IRWH* treatments on the Glen/Swartland ecotope over three seasons

Parameter	Year	P (mm)	*CON*	*BbBr*	*ObBr*
Seed (kg ha^{-1})	96/97	296	1540^a	1751^a	-
	97/98	294	2028^a	2462^b	2558^b
	98/99	139	506^a	661^b	815^c
	Mean	**243**	**1358**	**1625**	**1687**
Biomass (kg ha^{-1})	96/97	296	3949^a	4498^a	-
	97/98	294	4552^a	5270^b	5522^b
	98/99	139	1392^a	1627^{ab}	1832^b
	Mean	**243**	**3298**	**3798**	**3677**
Harvest index	96/97	296	0.39^a	0.39^a	-
	97/98	294	0.45^a	0.47^a	0.46^a
	98/99	139	0.36^a	0.41^b	0.44^b
	Mean	**243**	**0.40**	**0.42**	**0.45**

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

Water productivity based on Ev (WP$_{Ev}$) and rainwater productivity (RWP) data are presented in Table 5.4.3. The WP$_{Ev}$ varied between 13.6 and 14.4 kg ha^{-1} mm^{-1} over the three seasons for the three treatments. The RWP$_{1996/97-1998/99}$ results produced the same trend as observed with the yields, *viz. ObBr* > *BbBr* > *CON*, and RWP$_{1996/97-1998/99}$ results for sunflower on the Glen/Bonheim ecotope for the same period. RWP$_{1996/97-1998/99}$ values obtained on the Glen/Swartland ecotope are lower higher than that of the Glen/Bonheim ecotope. RWP$_{1996/97-1998/99}$ varied between 3.5 and 5.1 kg ha^{-1} mm^{-1}. RWP$_{1996/97-1998/99}$ results indicated that *BbBr.* and *ObBr* produced respectively 20 and 46% significantly higher sunflower seed yields as compared to *CON* over the experimental period with the same amount of rainfall received. This is an indication that the *IRWH* treatments have the ability to utilize rainwater much more efficiently, effectively and productively as compared to *CON*. *ObBr* was significantly better than *BbBr*.

Table 5.4.3 Water and rainwater productivity for sunflower from the *CON* and *IRWH* treatments on the Glen/Swartland ecotope over experimental period

Water productivity indicators (kg ha^{-1} mm^{-1})	*CON*	*BbBr*	*ObBr*
WP_{Ev}	13.6^a	14.1^a	14.4^a
$RWP_{1996/97-1998/99}$	3.5^a	4.2^b	5.1^c

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

Water balance data for the two growing seasons are presented in Table 5.4.4. The complete suppression of ex-field runoff (R_{Ex}) by both *IRWH* treatments against the considerable amount of R_{Ex} on *CON* is reflected in the seed and biomass yields (Table 5.4.2). During the wetter 96/97 and 97/98 seasons *CON* lost 28 and 40 mm of precipitation (P) to R_{Ex} respectively, i.e. 9 and 14%, respectively. No deep drainage (D) occurred over the two growing seasons, not even during the 96/97 and 97/98 seasons. This could be attributed to the very efficient soil water extraction by the sunflower roots.

Average Es results for the treatments show that on average over all the seasons 66, 77 and 87% of P was lost to Es during the growing season from the *CON*, *BbBr* and *ObBr* treatments, respectively. The consistently higher Es losses from the *IRWH* treatments are surprising. A possible explanation is that there was a larger loss of water by interception from the larger plants, and by evaporation from the wetter mulch and soil surface in the basins. ET values from both *IRWH* treatments were higher than that of *CON* during all the seasons. The differentiation of ET into its components suggests that the mean increase in ET at *IRWH* can mainly be attributed towards higher Ev, as Es from the *IRWH* treatments were consistently higher than *CON*. This could be due to: (1) higher PAW_p, (2) total stoppage of R_{Ex} and (3) in-field runoff process (surface redistribution of water) that contributed towards better plant available water, which induced higher Ev's at the *IRWH* treatments. The 98/99 growing season was characterized by 39 small rainfall events, 26 events totaling 102 mm during the vegetative period (only two events more than 10 mm), and 13 events totaling 37 mm during the reproductive period (all < 10 mm). The very high evaporative demand (E_o) during the vegetative and reproductive periods of the 98/99 season of 639 and 350 mm respectively, together with the very low rainfall resulted in very low aridity index values of 0.16 and 0.11 respectively for these periods. In an environment with such low aridity index values, Es is expected to be very high especially during the vegetative period when the crop canopy was not yet fully developed. The large amounts of small rainfall events also contributed towards high Es values.

The similarity of Es values on *BbBr* and *ObBr* during the 97/98 growing season is surprising. This may be due to losses from *ObBr* by intercepted water from small rainfall events evaporating from the mulch before it reaches the soil. During the 97/98 and 98/99 growing seasons ET values on both *IRWH* treatments were significantly higher than for *CON*. The average ET advantage for *BbBr* and *ObBr* above the *CON* is: 16% and 21%, respectively. On average over the relevant seasons Ev values on the *BbBr* and *ObBr* treatments were 15 and 24% higher than *CON*, respectively.

Table 5.4.4 Water balance components for *CON* and *IRWH* treatments on the Glen/Swartland ecotope over three seasons

Water balance components (mm)	Year	*CON*	*BbBr*	*ObBr*
P	96/97	296		
	97/98	294		
	98/99	139		
ΔS	96/97	8^a	30^b	-
	97/98	47^a	54^a	64^a
	98/99	65^a	94^b	116^b
D	96/97	0^a	0^a	-
	97/98	0^a	0^a	0^a
	98/99	0^a	0^a	0^a
R_{Ex}	96/97	28^a	0^b	-
	97/98	40^a	0^b	0^b
	98/99	0^a	0^a	0^a
Es	96/97	165^a	200^b	-
	97/98	168^a	193^a	196^a
	98/99	148^a	168^b	182^b
Ev	96/97	111^a	126^a	-
	97/98	133^a	155^b	162^b
	98/99	56^a	65^{ab}	73^b
ET	96/97	276^a	326^a	-
	97/98	301^a	348^b	358^b
	98/99	204^a	233^b	255^b
Es/ET (%)	96/97	60^a	61^a	-
	97/98	56^a	55^a	55^a
	98/99	73^a	72^a	71^a

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

Soil water extraction graphs describing the soil water regime during the 97/98 and 98/99 growing seasons are presented in Figures 5.4.2 and 5.4.3. The 97/98 season was characterized by high and well-distributed rainfall. The result was relative good yields on all the treatments (Table 5.4.2). Both *IRWH* treatments started the growing season with a much higher soil water content compared to the *CON* (*BbBr* = 32 mm and *ObBr* 49 mm higher). This was due mainly to the total prevention of R_{Ex} by the basins and the in-field runoff (R_{In}) process (surface redistribution of water) that contributed towards better plant available water. This advantage contributed to higher yields from the *IRWH* treatments.

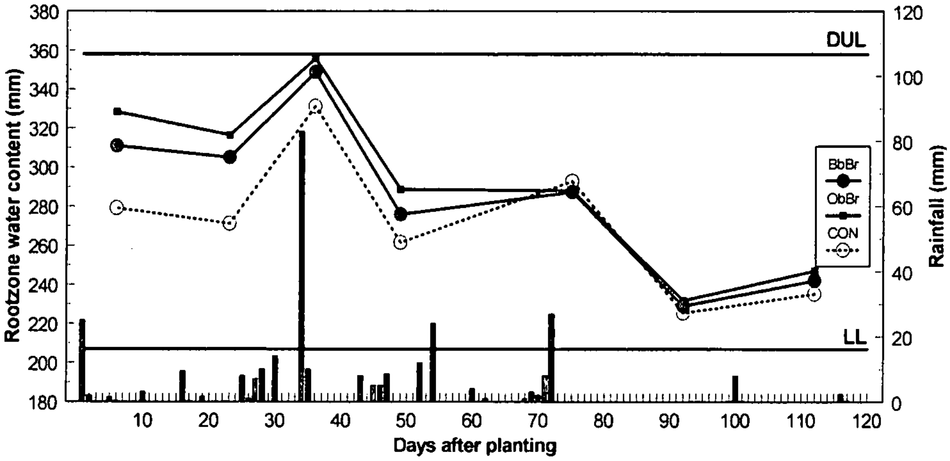

Figure 5.4.2 Measured changes in the soil water content of the rootzone during the 1997/98 season on the Glen/Swartland ecotope: Sunflower.

The 98/99 season was extremely dry. Figure 5.4.3 shows that complete crop failure was avoided by the relative high soil water contents at planting. In terms of rainfall the most critical factors are, (a) amount and (b), distribution during the growing season. The soil water content at planting also influences yield a great deal by buffering the crop against low rainfall later during the season. From DAP 48 to DAP 110 there was only 36 mm of rain with no event greater than 10 mm. If it were not for the water accumulated in the soil during the fallow period, no yields would have been realized. Higher ΔS values (Table 5.4.4) during the 98/99 season as compared to the 97/98 season is an indication that sunflower plants depended almost solely on the stored water in the rootzone during the 98/99 season.

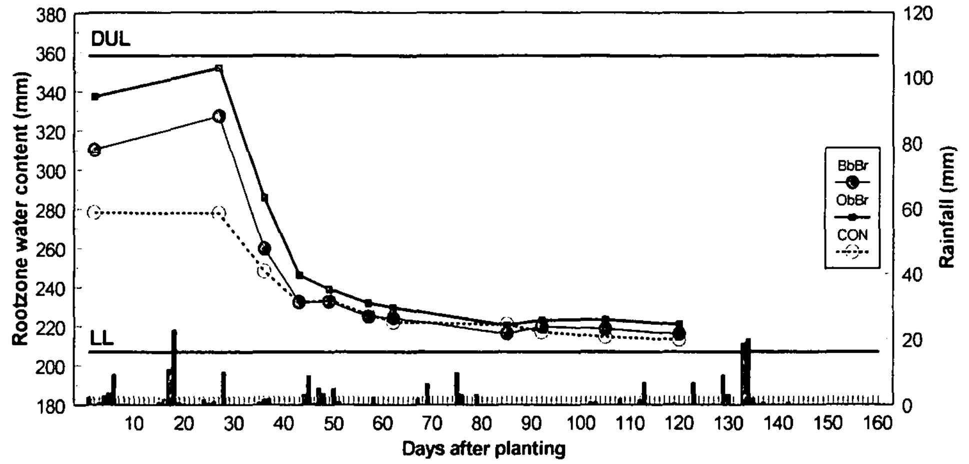

Figure 5.4.3 Measured changes in the soil water content of the rootzone during the 1998/99 season on the Glen/Swartland ecotope: Sunflower.

The importance of the threshold water content below which serious stress (SS) sets in is demonstrated in Figure 5.4.4. Yields are generally seen to increase approximately in proportion to the extent to which the soil water content value stays above this line. During the very dry 98/99 season the soil water content of *BbBr* was below SS (240 mm) during the entire drought sensitive period, compared to the 97/98 season during which the soil water content of *BbBr* was never below SS. There was a good correlation between these conditions and seed yields, i.e. 700 kg ha^{-1} and 2400 kg ha^{-1}, respectively for two seasons.

Comparing the SS values of the Glen/Bonheim and the Glen/Swartland ecotopes indicate that SS on the Glen/Bonheim ecotope only sets in when about 91% of plant available water is extracted, compared to 78% on the Glen/Swartland ecotope. $RWP_{1996/97-1998/99}$ on the Glen/Bonheim ecotope was higher by 7% than on the Glen/Swartland ecotope. It also seems that sunflower plants on the Glen/Bonheim ecotope reacted slightly better to the *IRWH* treatments as compared to sunflower plants on the Glen/Swartland ecotope. This might be due to the higher water holding capacity in the rootzone of the former, as well as an albedo effect caused by lighter coloured soil, which might have resulted in higher Es values from the Glen/Swartland ecotope.

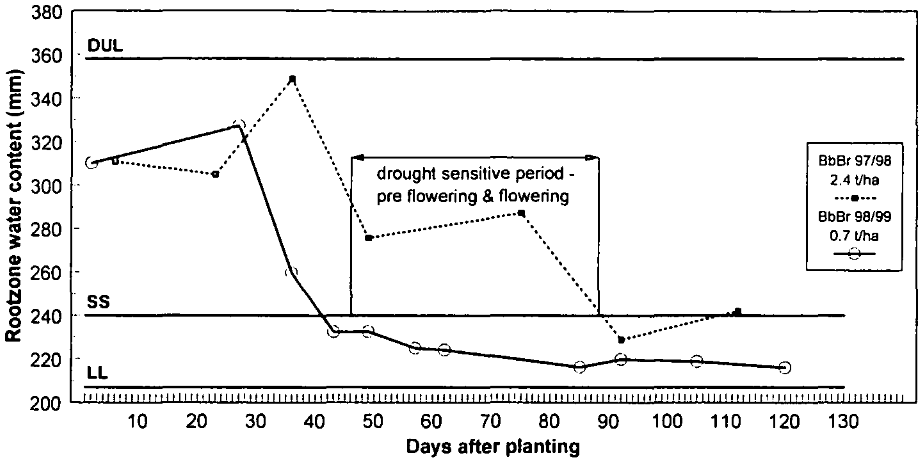

Figure 5.4.4 The growing season rootzone water regime of sunflower for the *BbBr* treatment during two growing seasons on the Glen/Swartland ecotope.

5.4.4 CONCLUSIONS

Precipitation values indicate that sunflower was produced under climatic conditions varying from extremely dry (98/99) to average (96/97 and 97/98). Seed yields of both *IRWH* (*BbBr* and *ObBr*) treatments were significantly better than *CON* over two of the growing seasons. During 98/99 the seed yield of *ObBr* was significantly better than *BbBr*. The average seed yields show that *BbBr* and *ObBr* produced 20 and 33% more seed, respectively, than *CON*. Both *IRWH* treatments produced significantly more biomass yield than *CON* during the 97/98 season and only *ObBr* increased the biomass yield significantly more than *CON* during the 98/99 season. The *IRWH* treatments produced on average 20% more biomass compared to *CON*.

$RWP_{1996/97-1998/99}$ values show that *BbBr* and *ObBr* converted rainwater into seed 20 and 47% more efficiently than *CON*, respectively. During the 96/97 and 97/98 seasons *CON* lost 9 and 14%respectively of P during the growing season to R_{Ex} compared to zero on the *IRWH* techniques. No deep drainage (D) occurred over the growing seasons on any of the treatments (Table 5.4.4.).

The success of the *IRWH* technique depends on stopping water losses by R_{Ex} and Es. Results show that Es is still a serious avenue for water loss. Future research therefore needs to focus on suppressing this process by any possible means.

5.5 KHUMO/SWARTLAND - AMANDEL ECOTOPE

5.5.1 DESCRIPTION OF THE ECOTOPE

The Khumo/Swartland ecotope is situated in the resettlement area between Thaba Nchu and Excelsior on the farm Khumo (29°04`00`` S, 26°56`39`` E) of Mr. Thekisho. This ecotope is representative of a large area of land in the South Eastern Free State on which a large number of rural households live.

5.5.1.1 Procedure for ecotope characterization

5.5.1.1.1 Climate

Long-term rainfall was obtained from 71-year records made at a nearby farm "North Bend" (29°04`30`` S, 26°56`00`` E). Daily rainfall is available for the period 1913 to 1984. The farm is situated about 4 km west of Khumo. Temperature data of the Land Type Climate Zone No. 46S and class A pan evaporation data for Glen for 42 years (1958 - 2000) were used.

5.5.1.1.2 Topography

The slope was determined using a dumpy level. The terrain unit was also described.

5.5.1.1.3 Soil

Description of the soil profile:
The soil profile was described in detail at a soil pit dug at the site. The objective was to record the main morphological characteristics relevant to crop production and also to classify the soil. The soil colour was read by using a Munsell Color Chart (Munsell Color Company, 1975). Soil samples were taken of each horizon. Soil analyses were done at the Agricultural Research Council – Institute for Soil, Climate and Water laboratory in Pretoria.

Drained upper limit of available water (DUL):

To define the upper limit of available water a field drainage curve determination was made on a 4 m x 4 m area to quantify the drained upper limit (DUL) of the rootzone (Ratliff *et al.*, 1983). The procedure used for the site preparation and DUL determination is described in detail in Chapter 3 under Section 3.2.2. Three neutron water meter (NWM) access tubes (1.5 m long), spaced at about 0.75 m from each other, were installed in the centre of the area. The water content of the whole profile was measured before any addition of water. Measurements were made at 300 mm intervals at the following depths (mm): 150, 450, 750, 1050 and 1350. A water cart was used to fill the plot with water, and keep it full until continuous NWM readings showed that the wetting front had reached about 1200 mm, the bottom of the rootzone. Addition of water was then discontinued. The time was recorded when the last surface water had disappeared into the soil, and the water content of the whole profile was then measured. The plot was then carefully covered with a plastic sheet. Care was taken to ensure that there was a good seal around the protruding access tubes to prevent wetting by rain. The water content of the rootzone plotted against time after saturation describes the drainage curve. DUL for the root zone (0 - 1200 mm) was taken as the water content when the change in soil water content became negligible. The water content of each soil layer at that stage gave the DUL value for the individual layers. Since the DUL plot was free of vegetation, and covered by a plastic sheet to prevent evaporation, DUL depends solely on the properties of the soil profile. Crop and climate influences are excluded.

Crop modified upper limit of available water (CMUL); lower limit of plant available water (LL); and bulk density (BD):

See Section 5.2.1.

Evaporation curve:

Evaporation is the process by which water in the soil is changed to a vapour or gas and lost to the atmosphere (Van der Watt & Van Rooyen, 1995). An evaporation curve was determined on the same 4 m x 4 m area used to determine DUL, after the drainage curve measurements had been completed. Es determination is described in detail in Section 3.2.2. It was conducted during the summer as a summer crop (sunflower) was identified for the field trail. Es plays an important role during the growing season. During the course of the Es measurements, due to the procedure being used here, water losses from the soil surface between saturation and DUL occurred in two directions, i.e. upwards by Es and downwards by drainage (D). The water content decrease during this period, i.e. Es + D, was subdivided by subtracting values for D obtained from the drainage curve made at the same site.

5.5.1.2 Results of ecotope characterization

5.5.1.2.1 Climate

Long-term monthly and annual climate data is presented in Table 5.5.1.1.

Table 5.5.1.1 Long-term monthly and annual climate data for the Khumo/Swartland ecotope

Parameter	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Long-term mean
Rain (mm)	11	13	23	48	77	69	91	81	88	57	20	10	588
evap.*^{1}	96	143	219	248	264	301	313	216	186	129	118	84	2317
max T*^{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	24.2
min T	-0.9	1.1	5.5	9.4	12.1	14.0	14.8	14.6	12.3	7.7	3.1	-0.9	7.7
ave. T	8.3	10.5	14.8	17.8	20.0	21.8	22.5	21.8	19.5	15.5	11.5	8.0	16.0
AI*^{3}	0.11	0.09	0.11	0.19	0.29	0.23	0.29	0.38	0.47	0.44	0.17	0.12	0.25

*^{1} Class A pan evaporation

*^{2} T = temperature in $^{\circ}$C; mean values for the month

*^{3} Aridity index = rain/evaporation.

The Khumo/Swartland ecotope is situated in a semi-arid region with low and erratic rainfall where conditions are marginal for crop production. The average total long-term rainfall may appear to be adequate for the production of a cash crop but the intensities and distribution are of such a pattern that the water available during the crop growth cycle is inadequate to support a good harvest. The high evaporative demand and relatively low rainfall, makes this a semi-arid climate, with worst conditions for crop production generally occurring during December and January.

Rainfall during these months is generally very erratic with much of it in the form of high intensity rainfall events. March rainfall is the second highest and also the most reliable, with the additional advantage that this month also has the lowest evaporative demand of the summer growing season. Low temperatures are experienced during the winter, coupled with very little rain. In this sort of climate there is generally no shortage of radiation as can be seen from the mean monthly temperatures.

5.5.1.2.2 Topography

The experimental plots are located on an upper foot slope terrain unit with a straight, 2% slope in a northwesterly direction.

5.5.1.2.3 Soil

Pedological characteristics

A detailed profile description is presented in Table 5.5.1.2. Land Type climate data and the relevant analytical data in Table 5.5.1.3. This ecotope occurs in land type Db37. The soil is classified as belonging to the Amandel Family of the Swartland Form (Soil Classification Working Group, 1991). Its dominant morphological features consist of a dark brown, poorly structured, fine sandy loam, orthic A horizon with 17% clay, overlying an unusual reddish brown horizon interposed between the A and the characteristic pedocutanic B horizon. Below this at 700 mm is sandstone saprolite, with sesquioxide and $CaCO_3$ concretions to a depth of 1200 mm. The underlying saprolite is sufficiently weathered to a depth of at least 1200 mm and offers no significant impedance to root development to that depth. The effective root zone is considered to be 0 - 1200 mm. The soil has a strong structure in the B horizon and a high content of smectite clay minerals that cause large cracks that penetrate deep into the soil when it is very dry. The A horizon has a low organic carbon content (0.37%), relatively low CEC (8.01 $cmol_c\,kg^{-1}$ soil) in the A horizon and a low exchangeable Na content throughout. The exchangeable cation suite is dominated by Ca and Mg. The dark reddish brown horizon at 300 – 400 mm is a unique feature quite common in the soil of this region. It is expected that this feature has an ameliorating influence on internal drainage, in contrast to the abrupt transition to the B horizons of Estcourt and Sterkspruit forms.

Table 5.5.1.2 Soil profile description: Khumo

NATIONAL SOIL PROFILE NO: 6224	**Soil Form:** Swartland
Map / photo: 2926BB Thaba Nchu	**Soil Family:** Amandel
Latitude & Longitude: 29°04´00´´ / 26°56´39´´	**Surface rockiness:** None
Land type No: Db37	**Surface stoniness:** < 2% exposed surface, angular, stones
Climate zone: 46S	**Occurrence of flooding:** None
Altitude: 1520 m	**Wind erosion:** None
Terrain unit: Upper Foot slope	**Water erosion:** Sheet slight, stabilized
Slope: 2%	**Vegetation / Land use:** Agronomic cash crops
Slope shape: Straight	**Water table:** 0 mm
Aspect: North-West	**Described by:** M. Hensley, P.A.L. le Roux, J.J. Botha & L.D. van Rensburg
Micro relief: None	**Date described:** 1999 - 05
Parent material solum: Origin binary, local colluvium, solid rock	**Weathering of underlying material:** Moderate physical, moderate chemical
Underlying material: Sandstone (feldspatic)	**Alteration of underlying material:** Ferruginised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizons**
A	0 - 300	Moist; dry, brown 7.5YR5/4, moist, reddish brown 5YR4/3; disturbed; fine sandy loam; apedal massive; few normal fine pores; few coarse pores; water absorption: 1 second; common roots; gradual smooth transition.	Orthic
AB	300 - 400	Moist; moist dark reddish brown 5YR3/4; undisturbed; clay; strong fine angular blocky; slightly firm; common normal fine pores; few coarse pores; common clay cutans; very few fine sesquioxide concretions: water absorption: 3 second(s); common roots; clear smooth transition.	Pedocutanic
B1	400 - 550	Moist; moist, brown to dark brown 7.5YR4/4; undisturbed; clay; many coarse distinct grey and yellow illuvial humus mottles; few fine distinct black oxidized iron oxide mottles; strong coarse angular blocky; firm; few normal fine pores; many clay cutans; very few fine sesquioxides concretions; water absorption: 3 second(s); few roots; gradual smooth transition.	Pedocutanic
B2	550 - 700	Moist; moist brown to dark brown 10YR4/3; undisturbed; clay; many coarse distinct grey and yellow illuvial humus mottles; few fine distinct black oxidized iron oxide mottles; strong coarse angular blocky; firm; few normal fine pores; many slickensides; many clay cutans; very fine sesquioxide concretions; water absorption: 5 second(s); few roots; gradual smooth transition.	Pedocutanic
C1	700 - 1200	Moist; moist dark yellowish brown 10YR4/4; undisturbed; clay; fine distinct black oxidized iron oxide mottles; common medium faint grey, yellow and olive illuvial humus mottles; strong coarse angular blocky; very firm; few normal fine pores; many slickensides; very few fine sesquioxide concretions; very few fine lime concretions; water absorption: 5 second(s); few roots; gradual transition.	Saprolite

Survey name: BEP - SW1122 NATIONAL SOIL PROFILE NO: 6224

Table 5.5.1.3 Soil analytical data: Khumo/Swartland-Amandel

Horizon	A1	AB	B1	B2	C1
Depth (mm)	0-300	300-400	400-550	550-700	700-1200
Lab No	M3552	M3553	M3554	M3555	M3556
Particle size distribution (%)					
>2 mm					
c sand 2-0.5 mm	2.1	0.7	0.6	0.5	0.5
m sand 0.5-0.25 mm	3.0	1.5	0.9	0.7	0.7
f sand 0.25-0.106 mm	27.1	15.1	10.4	11.3	10.9
vf sand 0.106-0.05 mm	29.4	18.1	14.5	17.4	19.8
c silt 0.05-0.02 mm	11.9	8.3	8.1	10.8	12.4
f silt 0.02-0.002 mm	6.8	4.9	4.8	6.8	10.1
clay > 0.002 mm	17.5	48.7	58.5	50.1	42.8
Texture	fiSaLm	Cl	Cl	Cl	Cl
Chemical analysis					
C (%)	0.37				
Resistance (ohm)	2800	1800	1600	1400	1400
pH H_20	6.0	6.1	6.9	7.8	8.8
pH KCl	4.5	4.6	5.2	6.1	7.3
Exchangeable / extractable cations (c mol_c/kg soil)					
Na	0.07	0.50	0.72	0.90	1.50
K	0.56	0.73	0.98	0.87	0.96
Ca	2.30	5.32	7.24	6.84	10.63
Mg	1.21	4.34	6.94	7.29	9.35
S value	4.14	10.89	15.88	15.9	22.44
T value (CEC)	8.01	14.66	16.92	16.48	19.00

Soil water extraction and drainage characteristics

Important soil water extraction features are summarized in Table 5.5.1.4.

Table 5.5.1.4 The soil component and water extraction properties of the Khumo/Swartland ecotope. The effective rootzone for sunflower recorded is considered to be 0 - 1200 mm

Profile detail					Soil water extraction properties (Sunflower)			
Diag. Horizon[*1]	Colour	Clay (%)	BD [*2] (Mg m^{-3})	Depth (mm)	DUL (mm)	LL (mm)	TESW[*3] (mm)	CMUL (mm)
ot	Br	17.5	1.50	300	69	35	34	
vp	DkRBr to DkBr	52.2	1.43	600	103	72	31	
vp	DkBr	45.2	1.42	900	110	61	49	
so	Mottl.	42.17	1.54	1200	103	60	43	
Total					385	228	157	423

[*1] Abbreviations from Soil Classification Working Group (1991): ot = orthic; vp = pedocutanic; so = saprolite

[*2] Bulk density

[*3] Total extractable soil water (DUL - LL).

The high water holding capacity of the 0 – 1200 mm rootzone is expressed by the high DUL value of 385 mm. The low value of the 0 - 300 mm layer (69 mm) compared to the 122 mm of the Glen/Bonheim soil (Chapter 2 and Section 5.3.1) is because of a coarser texture. The DUL value of 69 mm is high for an orthic A horizon with a clay content of 17%. The retarding influence on internal drainage caused by the relatively slowly permeable B horizon is probably a contributing factor. This accentuates the importance of a field determined DUL value.

The soil water extraction graph for sunflower is presented in Figure 5.5.1.1. The area of each rectangle, representing a soil depth of 300 mm, is proportional to the total extractable soil water (TESW = DUL - LL) for that layer.

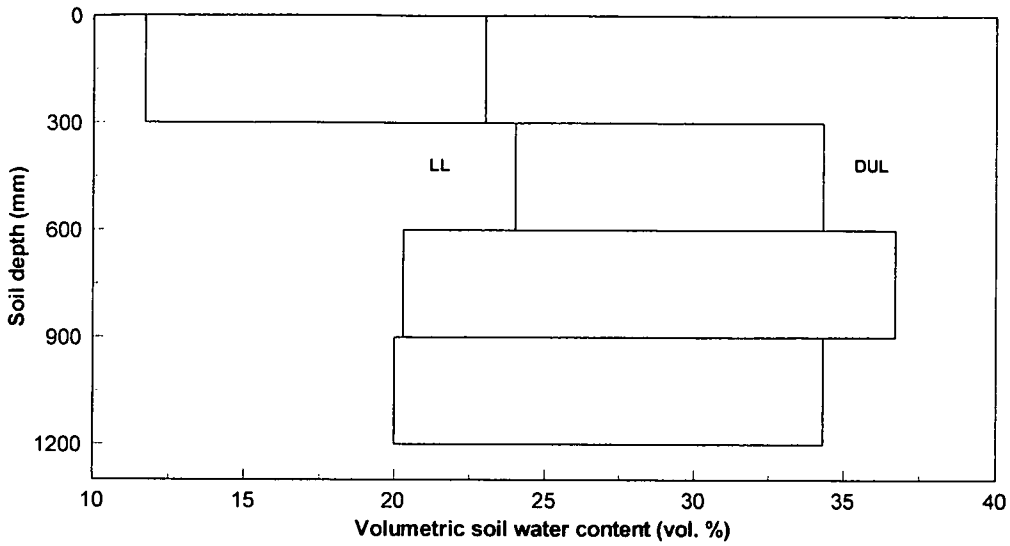

Figure 5.5.1.1 Soil water extraction graph for sunflower on the Khumo/Swartland ecotope.

A drainage curve for the whole rootzone, which provides the information for determining DUL and CMUL, is presented in Figure 5.5.1.2. Equation 5.5.1 provides a mathematical description of the curve and enables the drainage rate and water content at any time after field saturation (fSat) to be calculated.

$$Y = 446.64 - 6.84 (\ln t) \quad r^2 = 0.95 \qquad (5.5.1)$$

where:

Y = water content of the rootzone (mm)

t = time (hrs) after drainage started, i.e. rootzone water content at fSat.

Equation 5.5.1 can be used to calculate drainage out of the rootzone after a heavy rainstorm has occurred and the soil water content exceeds DUL. The authenticity of the water content determinations can be checked by comparing the fSat value in Figure 5.5.1.2 and Equation 5.5.1 (447 mm) with an estimated fSat value based on the mean porosity value (Vp) for the rootzone. The latter works out at 44.5%. Assuming fSat ~ 0.85Vp then the mean fSat water content would be 37.8%, and expressed as mm for the rootzone equals 454 mm which compares satisfactorily with the measured value.

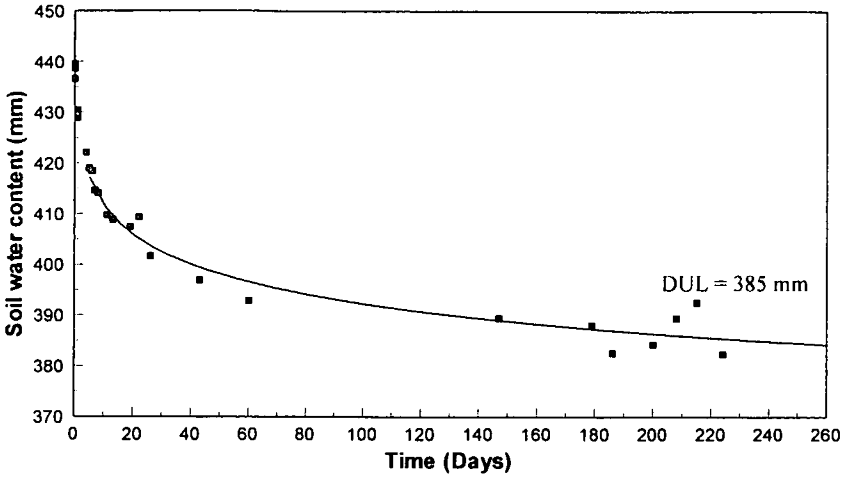

Figure 5.5.1.2. Drainage curve for the Khumo/Swartland ecotope: rootzone of 1200 mm.

Equation 5.5.2 describes the drainage curve for the 0 - 300 mm layer. Symbols are the same as for Equation 5.5.1.

$$Y = 102.06 - 3.70 (\ln t) \quad r^2 = 0.93 \ldots\ldots (5.5.2)$$

Evaporation characteristics

The evaporation curve from a bare soil surface for the Khumo/Swartland ecotope measured with the NWM for the 0 - 300 mm layer during summer is presented in Figure 5.5.1.3. Es oscillates continually between early and intermediate stages (Chapter 3), during the summer measuring period, due to the summer rain. The 0 - 300 mm soil layer lost 170 mm during a 70-day period. It is estimated that this consisted of 114 mm of added rainwater and the rest being provided by drying out of the soil, mainly the 0 – 300 mm layer.

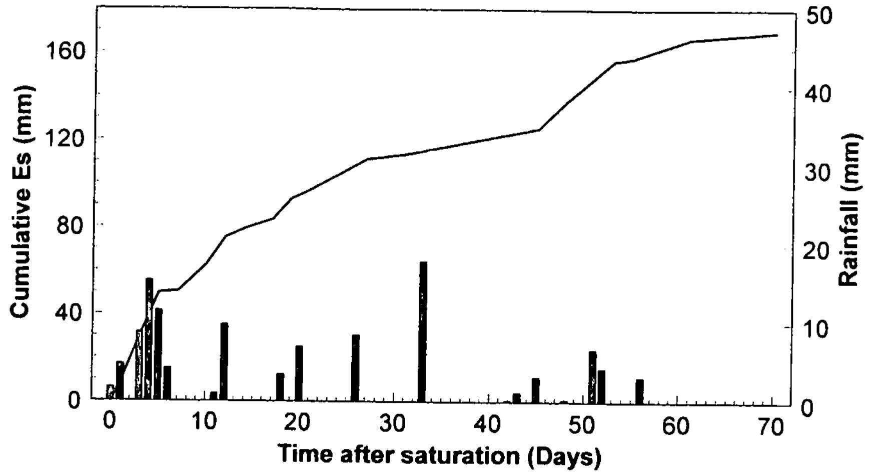

Figure 5.5.1.3 Evaporation curve for 0 – 300 mm layer of the Khumo/Swartland ecotope with a bare surface measured during the summer.

Using the procedure proposed by Ritchie (1972), the Es data presented in Figure 5.5.1.3 between days 53 – 74 (seven measuring points) was plotted against √t, where t is the time after the start of intermediate phase of Es. The slope of the resultant line gave the α value (Ritchie, 1972), which can be used in crop models. The Ritchie (1972) equation which predicts Es from a bare soil surface is used in many of the crop models used locally, for example: DSSAT (Tsuji, Uehara & Balas, 1994); ACRU (Schulze, 1995); SWAMP (Bennie *et al.*, 1998). The α value obtained by Ritchie (1972) for a range of soils is 3.50 mm day^{-1}. The measured α value for the Khumo/Swartland ecotope was 3.44 mm day^{-1} (r^2 = 0.96). This compares well with Ritchie's (1972) mean value as well as an α value of 3.5 mm day^{-1} reported by Stroosnijder & Hoogmoed (1984) and Stroosnijder (2003), that apparently worked well for a wide range of soils. However an α value of 3.44 mm day^{-1} is considered to be high for a soil with 17% clay in the A horizon. This could be due to the specific hydraulic properties of this duplex soil. The result also compares well with the α value (3.00 mm day^{-1}) of the Glen/Swartland soil. The slightly higher value for Khumo series could be due to one or more of the following, (a) the sharp increase in the clay content of the second layer (49%) compared to that of the Glen/Swartland (31%), (b) the unique dark reddish brown B horizon at 300 – 400 mm which could be an efficient avenue of water supply to the A horizon. This once again highlights the importance of field-measured data. To determine the α value for the summer curve is difficult since the slope is highly dependent on the rainfall pattern during a specific season and Es oscillates continually between the early and intermediate phases of evaporation.

5.5.2 PROCEDURE – FIELD EXPERIMENTS

Two separate field experiments were carried out. The first experiment was carried out over two seasons (1997/98 and 1998/99). The second experiment was conducted over three seasons (1999/2000, 2000/01 and 2001/02) following the first experiment. The results of the first experiment were used to formulate an improved hypothesis, which was tested in the second experiment.

5.5.2.1 Experimental layout

First experiment:

For the first experiment a semi-statistical design was employed with sunflower as the reference crop. Three tillage treatments and three replications were used. The treatments were:

- Normal conventional tillage (*CON*)
- *IRWH* technique with a bare basin area and a bare runoff area (*BbBr*)
- *IRWH* technique with organic mulch in the basin area and a bare runoff area (*ObBr*).

The layout of the replications and treatments used is presented in Figure 5.5.2.1.

CON	*ObBb*	*ObBr*
CON	*ObBb*	*ObBr*
CON	*ObBb*	*ObBr*

N
→

Figure 5.5.2.1 Experimental plan of the replications and treatments on the Khumo/Swartland ecotope (97/98 and 98/99).

The sunflower cultivar SNK 37 with a plant population of 33 333 plants ha^{-1} was used. Planting was done by hand early in January. Sunflower was planted on 7 January 98 and 8 January 99, respectively, and harvested on 21 May 98 and 16 May 99, respectively. Since water was the main limiting factor on this ecotope, fertilizer (50 kg ha^{-1} of 3:1:0 (28%) + Zn) aimed at a moderate yield was applied. All the fertilizer was applied at planting. Rainfall (amount and intensity) was measured with an automatic hobo rain gauge about 300 m from the experimental site.

Second experiment:

For the second experiment a semi-statistical design was employed with four tillage treatments and three replications. Sunflower, cultivar SNK 74 was planted annually. The treatments were:

- *CON*
- *IRWH* technique with organic mulch in the basin area and a bare runoff area (*ObBr*),
- *IRWH* technique with organic mulch in the basins, stones on the runoff area (*ObSr*),
- *IRWH* technique with stones in the basins, organic mulch on the runoff area (*SbOr*).

The layout of the replications and treatments is presented in Figure 5.5.2.2.

CON	*ObBr*	*ObSr*	*SbOr*
CON	*ObBr*	*ObSr*	*SbOr*
CON	*ObBr*	*ObSr*	*SbOr*

N
→

Figure 5.5.2.2 Experimental plan of the replications and treatments on the Khumo/Swartland ecotope (99/00 – 01/02).

Crop and fertilization details for the three growing seasons (99/00 - 01/02) are presented in Table 5.5.2.1. Planting was done by hand in all cases. The amount of fertilizer applied was based on the analyses of soil samples taken prior to each growing season. All the fertilizer was applied at planting. Ammonium nitrate was used as the N-source and super phosphate as the P-source. The soil potassium (K) status was relative low and hence K was applied.

Table 5.5.2.1 Cropping and fertilization details over the three growing seasons (99/00 - 01/02)

Fertilizer detail			Crop detail			
Fertilizer (kg ha^{-1})			Target yield (kg ha^{-1})	Plant population (plants ha^{-1})	Planting date	Harvest date
Nitrogen	Phosphate	Potassium				
50	15	10	1 750	33 333	31/01/00	04/07/00
					19/01/01	25/05/01
					06/12/01	18/04/02

5.5.3 RESULTS AND DISCUSSION – FIELD EXPERIMENTS

5.5.3.1 First experiment (1997 – 1999)

Seed and biomass yield, harvest index and precipitation during the growing season (P_g) data for the two seasons are presented in Table 5.5.2.2. The 97/98 season was characterized by slightly less than normal rainfall during the growing period (long-term mean = 320 mm). The 98/99 season's rainfall was very low and uneven comparing to that for 97/98. Seed yields varied between 1096 kg ha^{-1} and 1876 kg ha^{-1} over the two seasons. During both growing seasons both *IRWH* treatments produced significantly higher seed yields than *CON*, with *ObBr* significantly better than *BbBr* during the 98/99 season. On average *BbBr* and *ObBr* produced a seed yield advantage above *CON* of 29% and 52%, respectively. On average *ObBr* performed 17% better than *BbBr*. Biomass yields varied between 2826 and 4525 kg ha^{-1}. *BbBr* and *ObBr* produced significantly higher biomass yields than *CON* during both seasons. The average biomass yield advantage above *CON* for *BbBr* and *ObBr* were 26 and 43%, respectively. Harvest index values varied between 0.38 and 0.41 with no significant difference between treatments. The variations between the 97/98 and 98/99 seasons, are due to the extreme drought conditions during 98/99 season.

Table 5.5.2.2 Seed and biomass yield, harvest index and rainfall during the growing season (Pg) values for *CON* and *IRWH* treatments on the Khumo/Swartland ecotope over two seasons

Parameter	Year	P_g (mm)	*CON*	*BbBr*	*ObBr*
Seed (kg ha^{-1})	97/98	290	1216^a	1734^b	1876^b
	98/99	229	1096^a	1260^b	1628^c
	Mean	**260**	**1156**	**1497**	**1752^a**
Biomass (kg ha^{-1})	97/98	290	3188^a	4245^b	4525^b
	98/99	229	2826^a	3327^b	4081^b
	Mean	**260**	**3007**	**3786**	**4303**
Harvest index	97/98	290	0.38^a	0.41^a	0.41^a
	98/99	229	0.39^a	0.38^a	0.40^a
	Mean	**260**	**0.39**	**0.40**	**0.41**

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

Figures 5.5.2.3 is a soil water extraction graph for the 97/98 growing season. After a favourable start and well distributed rainfall the crop never suffered from serious water stress. During the critical drought sensitive period between DAP 45 - 80, soil water content for all the treatments were close to DUL or above DUL. During this period soil water content for the *IRWH* treatments were above DUL. This explains the higher yields compared to the *CON* treatment. The result was good yields on all the treatments, with both *IRWH* treatments significantly better than *CON*, and O*b*B*r* not significantly better than B*b*B*r*.

At the end of the 97/98 season the farmer inadvertently ploughed the whole area on which the experimental plots were located. Although tillage treatments were repeated on the original plot locations valuable soil water regime information was lost. A soil water graph for the 98/99 season is therefore not presented. Differences between the treatments are reflected in the sunflower yields.

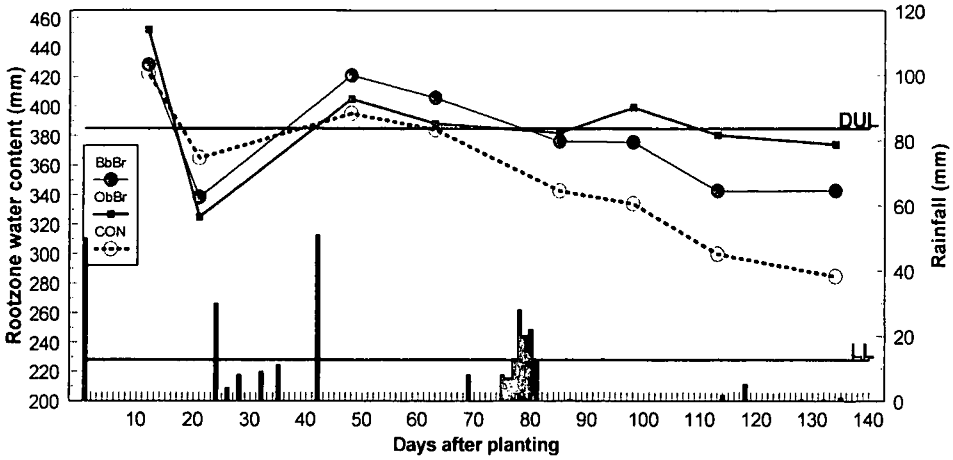

Figure 5.5.2.3 Measured changes in the soil water content of the rootzone during the 97/98 season on the Khumo/Swartland ecotope: Sunflower.

After a favourable start at the beginning of the 98/99 season the crop suffered severe visual water stress from DAP 50 up till the end of the growing season. Well-distributed small rainfall events and high temperatures characterized this period. Twenty-six of the rainfall events were less than 10 mm, all of which would almost immediately have been lost to Es. There were six rainfall events between 10 and 20 mm, and only two between 20 and 30 mm both of which were in the first 15 DAP. If these rainfall events are compared with those in 97/98 a totally different pattern emerges. During 97/98 there were 12 rainfall events less than 10 mm, four events between 10 - 20 mm, three events between 20 - 30 mm and two well-distributed events between 40 - 52 mm. This explains why there were better yields in 97/98.

Water balance data for the two growing seasons are presented in Table 5.5.2.3. Relatively high water losses due to R_{Ex} and Es on *CON* compared to the *IRWH* treatments are definitely the reason for their lower yields. These losses amounted to an average of 300 mm over the two seasons compared to 209 and 191 mm on the *BbBr* and *ObBr* treatments, respectively (Table 5.5.2.3). No drainage occurred during both seasons on any of the treatments.

Table 5.5.2.3 Water balance components for *CON* and *IRWH* treatments on the Khumo/Swartland ecotope over two seasons

Water balance components	Year	*CON*	*BbBr*	*ObBr*
P (mm)	97/98	290		
	98/99	229		
	Mean	**260**		
ΔS (mm)	97/98	138^a	72^a	73^a
	98/99	144^a	80^b	82^b
	Mean	**141**	**76**	**78**
D (mm)	97/98	0^a	0^a	0^a
	98/99	0^a	0^a	0^a
	Mean	**0**	**0**	**0**
R_{Ex} (mm)	97/98	31^a	0^b	0^b
	98/99	14^a	0^b	0^b
	Mean	**23**	**0**	**0**
Es (mm)	97/98	306^a	240^b	233^b
	98/99	247^a	177^b	149^b
	Mean	**277**	**209**	**191**
Ev (mm)	97/98	91^a	122^b	130^b
	98/99	112^a	132^b	162^c
	Mean	**102**	**127**	**146**
ET (mm)	97/98	397^a	362^b	363^b
	98/99	359^a	309^b	311^b
	Mean	**328**	**336**	**337**
Es/ET (%)	97/98	77^a	66^a	64^a
	98/99	69^a	57^b	48^c
	Mean	**73**	**62**	**56**

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

The *CON* treatment lost on average 45% more rainwater to Es compared to the *ObBr* treatment during both seasons, while the *BbBr* treatment lost 9% more rainwater to Es compared to *ObBr*. The two *IRWH* treatments lost on average 39% less water to Es during the two growing seasons as compared to *CON*. The ability of the *IRWH* treatments to suppress R_{Ex} and Es made it possible for the *BbBr* and *ObBr* treatments to use rainwater 25% and 43% more productive than *CON* through Ev.

Overall water productivity based on Ev (WP_{Ev}) and rainwater productivity (RWP) for the experimental period are presented in Table 5.5.2.4. Relatively low WP_{Ev} values (the highest being 12 kg ha^{-1} mm^{-1}) as compared to WP_{Ev} for sunflower on the Glen/Bonheim and Glen/Swartland ecotopes (96/97 – 98/99) that varied between 13.6 and 14.7 kg ha^{-1} mm^{-1}. Although the WP_{Ev} values for sunflower on this ecotope is relative low it is still higher than the equivalent value for maize on the Glen/Swartland of 10.7 kg ha^{-1} mm^{-1} reported by Hensley *et al.* (2000). This result indicated that sunflower use water much more effectively than maize; one of the reasons might be the advantage of the taproot system of sunflower.

Table 5.5.2.4 Water use efficiency and precipitation use efficiency data for Sunflower for *CON* and *IRWH* treatments on the Khumo/Swartland ecotope over two seasons

Efficiencies (kg ha^{-1} mm^{-1})	*CON*	*BbBr*	*ObBr*
WP_{Ev}	11.4^{a}	11.8^{a}	12.0^{a}
$RWP_{1997/98-1998/99}$	2.8^{a}	3.6^{b}	4.2^{b}

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

$RWP_{1997/98-1998/99}$values indicate that the ability of *BbBr* and *ObBr* treatments to effectively convert rainwater into seed yield is 29% and 50% significantly better than the *CON* treatment. This once again highlights the importance of conserving rainwater better through the ability of the *IRWH* techniques to stop R_{Ex} and to minimize Es (Tabel 5.5.2.3) especially with the application of mulches in the basins.

5.5.3.1.1 *Conclusions*

The important parameters used to compare the different treatments were: seed and biomass yields, and rainwater productivity. During both growing season both *IRWH* treatments produced significantly higher seed and biomass yields than *CON*, with *ObBr* having significantly higher seed yields than *BbBr* during the 1998/99 season. On average *BbBr* and *ObBr* produced a seed yield advantage above *CON* of 29% and 52%, respectively. *ObBr* performed 17% better than *BbBr*. $RWP_{1997/98-1998/99}$ values indicate that the ability of *BbBr* and *ObBr* treatments to efficiently convert rainwater into food and is 29% and 50% better than the *CON* treatment. The reason for this far better productivity of rainwater is due to the ability of the *IRWH* treatments to stop R_{Ex} complete, inducing of R_{In} and minimizing Es. During the two growing seasons *CON* lost on average 300 mm of rainwater to R_{Ex} and Es compared to 209 and 191 mm on the *BbBr* and *ObBr* treatments, respectively.

5.5.3.2 Second experiment (2000 – 2003)

Crop response indicators, *viz.* seed yield, biomass yield and harvest index, are summarized in Table 5.5.3.1 for the various treatments.

All the *IRWH* techniques (*ObBr*, *SbOr* and *ObSr*) produced significantly higher seed yields than the *CON* treatment during all seasons. The mean seed yield for *CON* over the experimental period was 1285 kg ha^{-1} compared to an average means seed yield for the three *IRWH* treatments of 1817 kg ha^{-1}. Comparing the three *IRWH* techniques revealed that there is a consistent trend during the experimental period, *viz. ObSr* > *SbOr* > *ObBr*. The mean seed yields for the observed trend were 1893, 1822 and 1737 kg ha^{-1}, respectively. There were no statistical differences between *IRWH* treatments, except for the 99/00 season where *ObSr* was significantly higher than *ObBr*. The mean biomass yields reflected the same trend, with differences between the *IRWH* treatments not significant during the course of the three seasons. Biomass for *CON* (mean = 4249 kg ha^{-1}) was significantly lower than *ObSr* and *SbOr* in two out of the three seasons (99/00 and 01/02) and significantly lower *ObBr* during the 01/02 season. All the *IRWH* treatments produced during all three seasons higher harvest index (HI) values than *CON* with significantly differences only during the 00/01 season where all the *IRWH* treatments produced significantly higher HI values than *CON.*

Table 5.5.3.1 Seed and biomass yield and harvest index results obtained from different techniques on the Khumo/Swartland ecotope over three seasons

Parameter	Year	Treatments				Mean
		CON	*ObBr*	*ObSr*	*SbOr*	*IRWH*
Seed (kg ha^{-1})	99/00	1049^{a}	1315^{b}	1578^{c}	1504^{bc}	1466
	00/01	978^{a}	1362^{b}	1441^{b}	1345^{b}	1383
	01/02	1829^{a}	2535^{b}	2661^{b}	2618^{b}	2605
	Mean	**1285**	**1737**	**1893**	**1822**	**1817**
Biomass (kg ha^{-1})	99/00	3505^{a}	3957^{ab}	4790^{b}	4619^{b}	4455
	00/01	3598^{a}	3783^{a}	4195^{a}	3771^{a}	3916
	01/02	3915^{a}	4650^{b}	4931^{b}	4854^{b}	4812
	Mean	**4249**	**4831**	**5483**	**5221**	**5178**
Harvest index	99/00	0.30^{a}	0.33^{a}	0.33^{a}	0.33^{a}	0.33
	00/01	0.27^{a}	0.36^{b}	0.34^{b}	0.36^{b}	0.35
	01/02	0.47^{a}	0.55^{a}	0.54^{a}	0.54^{a}	0.54
	Mean	**0.31**	**0.37**	**0.37**	**0.37**	**0.37**

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

Water balance data for the different treatments are presented in Table 5.5.3.2. *IRWH* treatments affected RSE but with no particular pattern between them, but their response were significantly different from *CON.* During the 99/00 season the RSE values for the *IRWH* treatments were considerably higher than *CON* but not significantly. During the 00/01 season they were all significantly higher and during 01/02 season all significantly lower than *CON.* These variations need to be interpreted. RSE (Equation 4.6) is influenced by the water content at harvesting of the previous season and rainfall (amount and distribution) during the fallow period. The higher and closer water content at harvesting of the previous season is, the lower the potential for a high RSE, even if good rains occur during the fallow period. RSE results of the *IRWH* treatments during the 00/01 and 01/02 seasons are good examples. At the end of the 99/00 growing season the water content of all the *IRWH* treatments were below 290 mm. During the fallow period of the 00/01 season 302 mm of rain occurred and the *IRWH* treatments produced a mean RSE of 26%. All the *IRWH* treatments ended the 00/01 season with high soil water content of more than 330 mm (Figure 5.5.3.1 b). Although 59 mm more rain occurred during the fallow period of the 01/02 season compared to the 00/01 season, the *IRWH* treatments produced a much lower mean RSE (16 %) compared to the 00/01 season. The high soil water content at harvesting during the 00/01 season lowered the potential for a high RSE during the fallow period before the 01/02 season. In contrast *CON* ended the 00/01 season with a low rootzone water content of only 262 mm (Figure 5.5.3.1 b). This dry soil was able to store 31% of the rain during the fallow period, compared to the 16% of *IRWH* treatments.

The changes in soil water content during the growing seasons are presented in Figures 5.5.3.1a, b and c. Plant available water at planting (PAW_p) showed a consistent trend of *ObSr* > *SbOr* > *ObBr* > *CON* during the experimental period with vakues for the *IRWH* treatments in all cases significantly higher than *CON* (Table 5.5.3.2). The *IRWH* treatments did not differ significantly from each except during the first season when *ObSr* was significantly higher than *ObBr*. The disadvantage of a low PAW_p experienced by the *CON* treatment generally increased as the growing season progressed, as indicated by the soil water content patterns during the vegetative period. Ex-field runoff was zero for the *IRWH* treatments during all three seasons and 25, 48 and 24 mm for the *CON* treatment for the 99/00, 00/01 and 01/02 growing seasons, respectively. This means that the *CON* treatment lost on average 10% (32 mm) of the rainfall during the growing seasons to ex-field runoff. Drainage was zero for all treatments, irrespective of season.

As observed for particular seasons on the Glen/Bonheim ecotope, and particularly on the Glen/Swartland ecotope Es values from the *IRWH* treatments are frequently higher than from *CON*. This probably caused by a specific kind of rainfall and evaporative demand pattern that occurred during those seasons. A contributing factor is that in the case of the *IRWH* techniques, because R_{Ex} is stopped completely water harvested from the 2 m-runoff area collects in the basins, providing a water surface and more water available to evaporate than the *CON*. Es is therefore not a useful parameter on which to focus attention. Its variable influence on ET also makes this an unreliable parameter in relation to yield benefit. Ev is the one that matters because of its direct relationship with biomass. Ev results indicated that all the *IRWH* treatments used rainwater more productively than *CON* during all three growing seasons. Mean Ev and ET values also reflected the general trend *viz. ObSr* > *SbOr* > *ObBr* > *CON*.

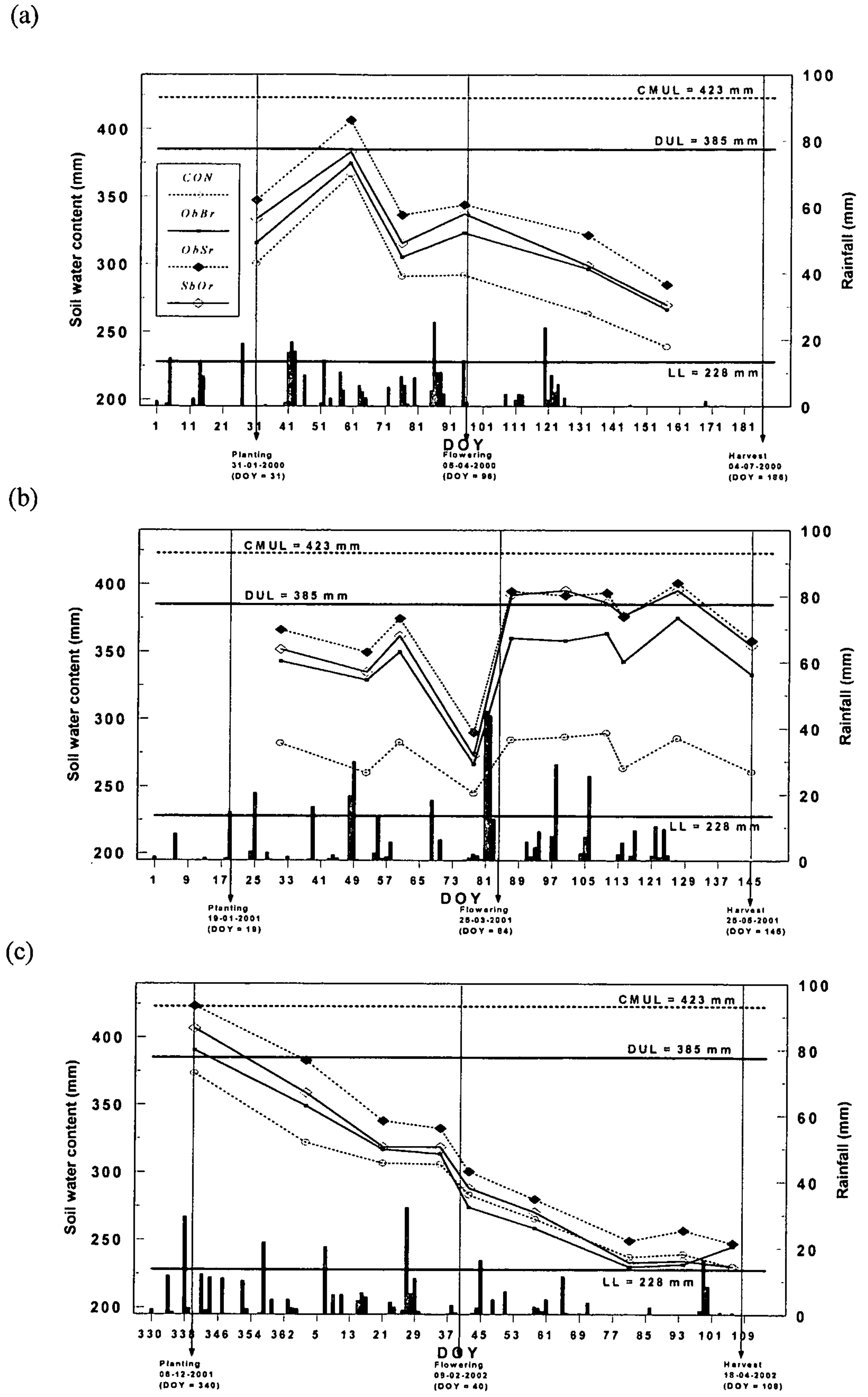

Figure 5.5.3.1 Measured changes in the soil water content of the rootzone (0 – 1200 mm) during the (a) 99/00, (b) 00/01 and (c) 01/02 growing seasons on the Khumo/Swartland ecotope.

Table 5.5.3.2 Water balance data for the different treatments demonstrated on the Khumo/Swartland ecotope over three seasons

Parameter	Year	Treatments				Mean *IRWH*
		CON	*ObBr*	*ObSr*	*SbOr*	
Pf (mm)	99/00	288				
	00/01	302				
	01/02	361				
	Mean	**317**				
Pg (mm)	99/00	275				
	00/01	384				
	01/02	276				
	Mean	**312**				
PAW_p (mm)	99/00	96^a	111^b	142^c	128^{bc}	127
	00/01	77^a	138^b	161^b	147^b	149
	01/02	168^a	186^b	218^b	202^b	202
	Mean	**114**	**145**	**174**	**159**	**159**
R_{Ex} (mm)	99/00	25^a	0^b	0^b	0^b	0
	00/01	48^a	0^b	0^b	0^b	0
	01/02	24^a	0^b	0^b	0^b	0
	Mean	**32**	**0**	**0**	**0**	**0**
Es (mm)	99/00	186^a	182^a	166^a	170^a	173
	00/01	287^a	320^a	310^a	308^a	313
	01/02	239^a	345^b	369^b	347^b	354
	Mean	**237**	**283**	**282**	**275**	**280**
Ev (mm)	99/00	126^a	143^a	172^a	169^a	161
	00/01	70^a	75^a	82^a	73^a	76
	01/02	94^a	112^b	118^b	117^b	116
	Mean	**97**	**110**	**124**	**120**	**118**
ET (mm)	99/00	312^a	325^a	338^a	339^a	334
	00/01	357^a	394^a	392^a	381^a	389
	01/02	333^a	457^b	487^b	463^b	469
	Mean	**334**	**392**	**406**	**395**	**397**
Es/ET (%)	99/00	60^a	56^a	49^b	50^{ab}	52
	00/01	80^a	81^a	79^a	81^a	80
	01/02	72^a	75^a	76^a	75^a	76
	Mean	**71**	**71**	**68**	**69**	**69**
RSE (%)	99/00	21^a	29^a	37^a	32^a	33
	00/01	14^a	25^b	27^b	27^b	26
	01/02	31^a	16^b	18^b	15^b	16
	Mean	**22**	**23**	**27**	**25**	**25**

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

The efficiency of the *IRWH* system in comparison to *CON* is clearly visible in the soil water content response to the large rainfall events totaling 102 mm just before flowering during the 00/01 season (Figure 5.5.3.1b). The increase in the rootzone water content of the *IRWH* treatments averaged 106 mm, whereas in the *CON* treatment the equivalent increase was only 40 mm. This boosted the water supply of the *IRWH* systems throughout the reproductive period, giving yields that varied between 1345 and 1441 kg seed ha^{-1}, whereas the yield from *CON* was only 978 kg ha^{-1} (Table 5.5.3.1). The highest yields were obtained during the 01/02 season of the experiment. Inspection of the soil water content patterns of the 01/02 season clearly demonstrates the value of the profile as a water storage medium, even for *CON*. The soil water content was near or above the DUL at planting for all treatments. As the season progressed, the water content gradually declined, in spite of the relatively good rainfall, amounting to 190 mm, between planting and flowering. The total water use during this 65 day period amounted to an average of about 290 mm over all the treatments, i.e. about 4.5 mm day^{-1}, compared to an average of 2.1 mm day^{-1} for the season as a whole. It is clear that the high PAW_p values on all the treatments had produced large plants, which consumed relatively large amounts of water. The stored water played an essential role towards meeting the crop water demand during the reproductive period. The overall benefit is reflected in seed yields averaging around 81% higher during this season than during the other two seasons (Table 5.5.3.1). The large crop almost extracted all the available water from the profile as it approached the end of the season, evidence of good root development.

Water supplied this way led to higher water productivity based on Ev (WP_{Ev}) and rainwater productivity (RWP) presented in Table 5.5.3.3. All the *IRWH* treatments produced significantly higher WP_{Ev} and $RWP_{1999/00-2001/02}$ than *CON*, with no significant difference amongst the *IRWH* treatments. WP_{Ev} results for the overall period compare very favourable with maximum international results reported by Passioura (2006). A common $RWP_{1999/00-2001/02}$ response was observed, *viz. ObSr* > *SbOr* > *ObBr* > *CON*. The *IRWH* treatments produced a mean $RWP_{1999/00-2001/02}$ advantage above *CON* of 45%. The *IRWH* treatments with mulch on the runoff area (*ObSr* and *SbOr*) produced an average 5% higher $RWP_{1999/00-2001/02}$ than *ObBr*.

Table 5.5.3.3 WP_{Ev} and RWP data for sunflower for different treatments on the Khumo/Swartland ecotope over a three seasons period

Parameter (kg seed $ha^{-1}mm^{-1}$)	Treatments				Mean *IRWH*
	CON	*ObBr*	*ObSr*	*SbOr*	
WP_{Ev}	13.2^a	15.8^b	15.3^b	15.2^b	15.4
$RWP_{1999/00-2001/02}$	2.0^a	2.8^b	3.0^b	2.9^b	2.9

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

5.5.3.2.1 Conclusions

The results showed the advantage of the *IRWH* system in conserving water during the fallow period as well as during the growing season. Plant available water at planting was significantly higher in all the *IRWH* treatments in comparison with the *CON* treatment. Good water conservation during the fallow period led to better plant establishment and larger plants, while water conserved during the growing period led to higher sunflower yields, ET, Ev and $RWP_{1999/00-2001/02}$. All the *IRWH* techniques (*ObBr*, *SbOr* and *ObSr*) produced significantly higher seed yields than the *CON* treatment, irrespective of the season. The mean seed yield for *CON* over the experimental period was 1285 kg ha^{-1} compared to an average mean increase in seed yield for the three *IRWH* treatments of 41%. Comparing the three *IRWH* treatments revealed that there is a consistent trend during the experimental period, *viz. ObSr* > *SbOr* > *ObBr*. The mean seed yields for these treatments were 1893, 1822 and 1737 kg ha^{-1}, respectively. There were no statistical differences between the *IRWH* treatments, excepting for the 99/00 season when *ObSr* was significantly higher than *ObBr*.

Ex-field runoff was zero for the *IRWH* treatments during all three seasons while the *CON* treatment lost on average 10% (32 mm) of the rainfall during the growing seasons to ex-field runoff. Mulching also restricted evaporation, although differences were not significant. The most important parameter for comparing the different tillage treatments is $RWP_{1999/00-2001/02}$. The mean value for *IRWH* treatments of 2.9 kg seed $ha^{-1}mm^{-1}$ is significantly higher than the *CON* value of 2.0 kg seed $ha^{-1}mm^{-1}$. Results show little difference between *ObSr* and *SbOr*, with both slightly better than *ObBr* (Table 5.5.3.3).

5.6 VLAKSPRUIT/ARCADIA -LONEHILL ECOTOPE

5.6.1 DESCRIPTION OF THE ECOTOPE

The ecotope is situated on the farm Vlakspruit (29°05`37`` S, 26°54`33`` E) of Mr. Ramagaga in the resettlement area between Thaba Nchu and Excelsior, in the Free State Province. This ecotope is representative of many thousands of hectares of land in the region around the towns of Thaba Nchu and Botshabelo in which a large number of rural households live.

5.6.1.1 Procedure for ecotope characterization

The procedure followed to characterize the ecotope was the same as that used for the Khumo/Swartland – Amandel ecotope.

5.6.1.2 Results of ecotope characterization

5.6.1.2.1 Climate

Since the ecotope is situated about five kilometers from Khumo/Swartland, the climate is as described under 5.5.1.2.1.

5.6.1.2.2 Topography

The plot is located on an upper foot slope terrain unit with a straight, 3% slope in a north westerly direction.

5.6.1.2.3 Soil

Pedological characteristics

A detailed profile description together with analytical data is presented in Tables 5.6.1.1 and 5.6.1.2. The Vlakspruit/Arcadia ecotope occurs in land type Db37 and the soil is classified, according to the Soil Classification Working Group (1991), as belonging to the Lonehill Family of the Arcadia Form. It is a dark coloured clay loam Vertic soil with 42% clay in the A horizon. The effective rootzone is considered to be 0 - 1200 mm. The soil has a high clay content and strong structure with a high portion of smectite clay minerals resulting in a high CEC (22 - 35 $\mathrm{cmol_c\,kg^{-1}}$ soil). A horizons like this, with high clay content and where the clay mineral is predominantly smectitic clay, have the capacity to swell and shrink markedly in response to moisture changes. Dry spells cause large cracks that penetrate deep into the soil. Additionally, the surface soil is plastic when moist and sticky when wet. The unspecified material underlying the A horizon has the characteristics of a pedocutanic layer. It has a high clay content and a high proportion of smectite clay minerals resulting in a strongly developed structure and many slickensides.

Table 5.6.1.1 Soil profile description: Vlakspruit/Arcadia

NATIONAL SOIL PROFILE NO: 6225	**Soil Form:** Arcadia
Map / photo: 2926BB Thaba Nchu	**Soil Family:** Lonehill
Latitude & Longitude: 29°05′37′′ / 26°54′33′′	**Surface rockiness:** None
Land type No: Db37	**Surface stoniness:** None
Climate zone: 46S	**Occurrence of flooding:** None
Altitude: 1500 m	**Wind erosion:** None
Terrain unit: Upper Foot slope	**Water erosion:** None
Slope: 3%	**Vegetation / Land use:** Agronomic cash crops
Slope shape: Straight	**Water table:** 0 mm
Aspect: North-West	**Described by**: M. Hensley, P.A.L. le Roux, J.J. Botha & L.D. van Rensburg
Micro relief: None	**Date described:** 1999 - 05
Parent material solum: Origin single	**Weathering of underlying material:** Moderate physical, moderate chemical
Underlying material: Basic extrusive rocks	**Alteration of underlying material:** Calcified

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizons**
AP	0 - 150	Wet; disturbed; dark grey brown clay loam; strong fine blocky; slightly sticky, plastic; few normal fine pores; few clay cutans; few roots; gradual smooth transition.	Vertic
A	150 - 540	Wet; undisturbed; dark grey brown clay; strong fine angular blocky; sticky, very plastic; few normal pores; many clay cutans; very few mixed-shape gravel; very few fine sesquioxide concretions; few roots.	Vertic
B1	540 - 1000	Wet; undisturbed; dark grey clay; common medium faint white mottles; strong coarse angular blocky; sticky, very plastic; few normal pores; non-hardened free lime, moderate effervescence; many slickensides; many clay cutans; few fine sesquioxide concretions; few roots.	Unspecified

Survey name: BEP - VLAKSPRUIT / ARCADIA
NATIONAL SOIL PROFILE NO: 6225

Table 5.6.1.2 Soil analytical data: Vlakspruit/Arcadia

Horizon	Ap	A1	B1
Depth (mm)	0-150	150-540	540-1000
Lab No	D1421	D1422	D1423
Particle size distribution (%)			
>2 mm			
c sand 2-0.5 mm	1.1	0.6	0.3
m sand 0.5-0.25 mm	1.5	0.9	0.7
f sand 0.25-0.106 mm	20.4	14.7	12.1
vf sand 0.106-0.05 mm	21.1	14.6	14.4
c silt 0.05-0.02 mm	9.6	8.0	8.3
f silt 0.02-0.002 mm	7.3	7.1	7.9
clay > 0.002 mm	37.0	52.4	54.1
Texture	ClLm	Cl	Cl
Chemical analysis			
C (%)	0.82	0.69	
Resistance (ohm)	1600	1400	460
pH H_20	8.07	8.83	9.03
pH KCl	6.41	6.71	7.36
Exchangeable / extractable cations (c mol+/kg soil)			
Na	0.31	1.02	1.70
K	0.50	0.63	0.43
Ca	9.38	10.13	17.71
Mg	7.11	10.00	14.82
S value	17.30	21.78	34.66
T value (CEC)	21.77	27.50	34.77

Soil water extraction and drainage characteristics

Important features are summarized in Table 5.6.1.3. The water holding capacity of the 0 - 1200 mm rootzone is very high giving a DUL value of 456 mm. The high value for the 0 - 300 mm layer (113 mm) compared to the Khumo/Swartland ecotope of 69 mm

(Section 5.5.1.2.3) is an important characteristic of this soil. It results in a high total extractable soil water $(TESW)_{0\text{-}300\ mm}$ value of 76 mm for sunflower, similar to the Glen/Bonheim ecotope.

Table 5.6.1.3 The soil profile and water extraction properties of the Vlakspruit/Arcadia ecotope. The effective rootzone is considered to be 0 - 1200 mm

Profile detail					Soil water extraction properties (Sunflower)			
Diag. horizon[*1]	Colour	Clay (%)	BD[*2] (Mg m^{-3})	Depth (mm)	DUL (mm)	LL (mm)	TESW[*3] (mm)	CMUL (mm)
ve	DkBr	42.1	1.38	300	113	37	76	
ve	DkBr	53.5	1.43	600	109	75	34	
vp	DkBr	53.5	1.44	900	119	75	44	
vp	DkBr	53.5	1.49	1200	115	71	44	
Total					456	261	195	479

[*1] Abbreviations from Soil Classification Working Group (1991): ve = vertic; vp = pedocutanic

[*2] Bulk density

[*3] Total extractable soil water (DUL - LL).

The soil water extraction graph for sunflower on Vlakspruit/Arcadia is presented in Figure 5.6.1.1. As in the case of the Khumo/Swartland ecotope (Section 5.5.1.2.3) water extraction is effective to the bottom of the rootzone although most of the water for plant growth is extracted from the topsoil layer.

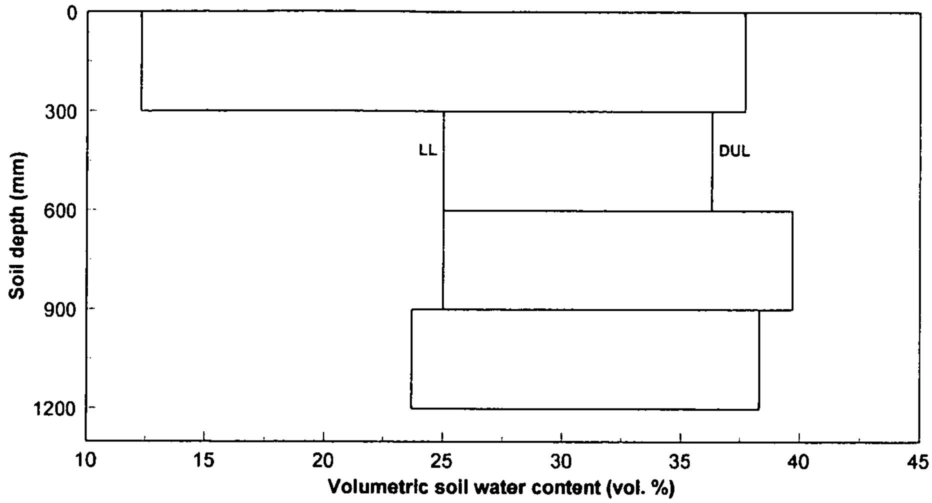

Figure 5.6.1.1 Soil water extraction graph for sunflower on the Vlakspruit/Arcadia ecotope.

A drainage curve for the whole rootzone, which provides the information for determining DUL and CMUL, is presented in Figure 5.6.1.2. Equation 5.6.1 provides a mathematical description of the curve and enables the drainage rate at any time after field saturation (fSat) to be calculated.

$$Y = 490.77 - 4.53 (\ln t) \ldots\ldots\ldots\ldots r^2 = 0.91 \ldots\ldots\ldots\ldots (5.6.1)$$

where:

Y = water content of the rootzone (mm)

t = time (hrs) after drainage started, i.e. rootzone water content at fSat.

Equation 5.6.1 can be used to calculate drainage out of the rootzone after a rainstorm. This is necessary to quantify the water balance. The water balance equation for dry land crop production in soils without a water table and without significant internal lateral water movement is presented in Chapter 1 (Equation 1.1):

Equation 5.6.2 describes the drainage curve for the 0 - 300 mm layer. Symbols are the same as for Equation 5.6.1.

$$Y = 136.08 - 3.04 (\ln t) \ldots\ldots\ldots\ldots r^2 = 0.96 \ldots\ldots\ldots\ldots (5.6.2)$$

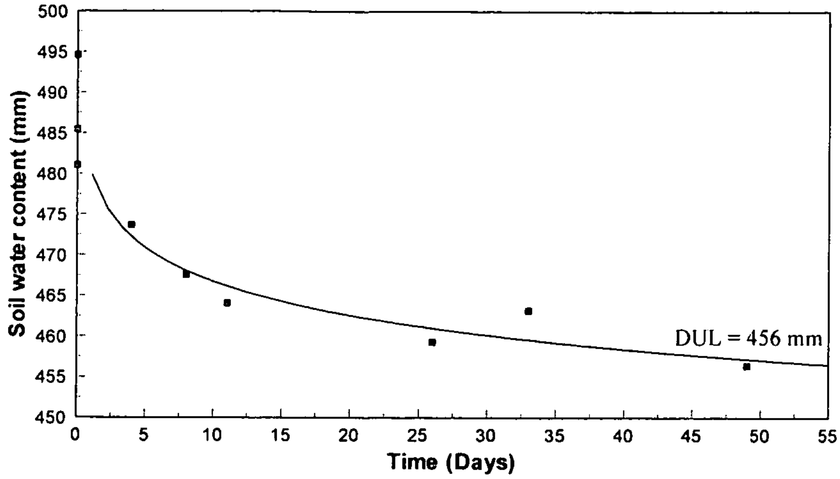

Figure 5.6.1.2 Drainage curve for the Vlakspruit/Arcadia ecotope: rootzone 1200 mm.

Evaporation characteristics

The evaporation curve from a bare soil surface for the Vlakspruit/Arcadia ecotope measured with the NWM for the 0 - 300 mm layer during summer is presented in Figure 5.6.1.3.

Es oscillates continually between the early and intermediate stages of evaporation during the summer measuring period due to the frequent rainfall events. The water content of the 0 - 300 mm soil layer started with a water content close to DUL and lost 170 mm during a 70 day period. It is estimated that this consisted of 110 mm of added rainwater and the rest being provided by drying out of the soil, mainly the 0 – 300 mm layer. This accentuates the importance of minimizing soil water loss to Es in any water conservation production technique.

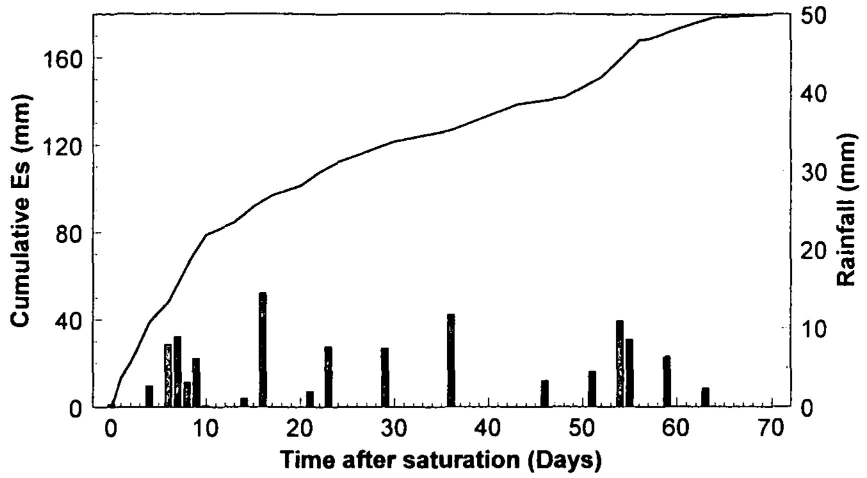

Figure 5.6.1.3 Evaporation curve for a bare surface during the summer on the Vlakspruit/Arcadia ecotope measured with NWM: 0 - 300 mm layer.

Using the procedure proposed by Ritchie (1972) and summarized in Chapter 3, the Es data presented in Figure 5.6.1.3 between days 36 – 52 (four measuring points) was plotted against √t, where t is the time after the start of the intermediate phase of Es. The slope of the resultant line gave the α value (Ritchie, 1972), which can be used in crop models. The Ritchie (1972) equation, which predicts Es from a bare soil surface, is used in many of the crop models used locally, for example: DSSAT (Tsuji *et al.*, 1994); ACRU (Schulze, 1995); SWAMP (Bennie *et al.*, 1998). The α values obtained by Ritchie (1972), Stroosnijder & Hoogmoed (1984) and Stroosnijder (2003) for a wide range of soils are around 3.5 mm day^{-1}. The α value for the Vlakspruit/Arcadia ecotope was determined as 3.41 mm day^{-1} ($r^2 = 0.93$), which compares well with the results quoted above, and also well with the values of 3.44 and 3.51 mm day^{-1} obtained for the Khumo/Swartland and Glen/Bonheim ecotopes, respectively.

5.6.2 PROCEDURE - FIELD EXPERIMENTS

Two separate field experiments were carried out. The first experiment was carried out over a two seasons period (1997/98 and 1998/99). The second experiment was conducted over a three-season period (1999/2000, 2000/01 and 2001/02) fallowing the first experiment. The results of the first experiment were used to formulate an improved hypothesis, which was tested in the second experiment.

5.6.2.1 Experimental layout

First experiment:

For the first experiment a semi-statistical design was employed with sunflower as the reference crop. Three tillage treatments and three replications were used. The treatments were:

- Normal conventional tillage (*CON*)
- *IRWH* technique with a bare basin area and a bare runoff area (*BbBr*)
- *IRWH* technique with organic mulch in the basins area and a bare runoff area (*ObBr*).

The experimental plan of the treatment-replications used on the demonstration plots on the Vlakspruit/Arcadia ecotope is presented in Figure 5.6.1.4.

N ↘

CON	*ObBb*	*ObBr*
CON	*ObBb*	*ObBr*
CON	*ObBb*	*ObBr*

Figure 5.6.1.4 Experimental plan of the replications and treatments on the Vlakspruit/Arcadia ecotope for 97/98 to 98/99 growing seasons.

The sunflower cultivar SNK 37 with a plant population of 33 333 plants ha^{-1} was used. Planting was done by hand early in January. Planting and harvesting dates for the two seasons were: 08/01/98 – 21/05/98 and 06/01/99 - 12/05/99. Soil samples were taken for fertility tests prior to each growing season. Since water was the main limiting factor on this ecotope, fertilizer (50 kg ha^{-1} of 3:1:0 (28%) + Zn) aimed at a moderate yield was applied. All the fertilizer was applied at planting. Rainfall (amount and intensity) was measured with an automatic hobo rain gauge at the experimental site.

Second experiment:

For the second on-farm field experiment a semi-statistical design was employed with four tillage treatments and three replications. Sunflower, cultivar SNK 74 was planted annually. The treatments were:

- *CON*
- *IRWH* technique with organic mulch in the basins area and a bare runoff area (*ObBr*),
- *IRWH* technique with organic mulch in the basins, stones on the runoff area (*ObSr*),
- *IRWH* technique with stones in the basins, organic mulch on the runoff area (*SbOr*).

The experimental plan of the replications and treatments used is presented in Figure 5.6.1.5.

N↘

CON	*SbOr*	*ObSr*	*ObBr*
CON	*SbOr*	*ObSr*	*ObBr*
CON	*SbOr*	*ObSr*	*ObBr*

Figure 5.6.1.5 Experimental plan of the replications and treatments on the Valkspruit/Arcadia ecotope (99/00 – 01/02).

Crop and fertilization details for the three growing seasons (99/00 - 01/02) are presented in Table 5.6.1.4. Planting was done by hand in all cases. The amount of fertilizer applied was based on the analyses of soil samples taken prior to each growing season. All the fertilizer was applied at planting. Ammonium nitrate was used as the N-source and super phosphate as the P-source.

Table 5.6.1.4 Sunflower and fertilization details over three growing seasons (1999/2000 - 2001/2002) on the Vlakspruit/Arcadia ecotope

Fertilizer (kg ha^{-1})			Target yield (kg ha^{-1})	Plant population (plants ha^{-1})	Planting date	Harvest date
Nitrogen	Phosphate	Potassium				
50	10	0	1 750	33 333	31/01/00	05/07/00
					17/01/01	21/05/01
					12/12/01	19/04/02

5.6.3 RESULTS AND DISCUSSION - FIELD EXPERIMENTS

5.6.3.1 First experiment (1997 – 1999)

Seed and biomass yield, harvest index and precipitation during the growing season (P_g) data for two seasons (97/98 and 98/99) are presented in Table 5.6.2.1. Although the 97/98 season's rainfall during the growing period (268 mm) was less than normal it was characterized by high and well distributed rainfall events (Figure 5.6.2.1). The 98/99 season's rainfall was also less than normal and although it was 27 mm more than the 97/98 season it was a very dry season due to a large number of very small and low intensity rainfall events (Figure 5.6.2.2).

Seed yields varied between 2937 kg ha^{-1} and 1045 kg ha^{-1}. Both *IRWH* treatments produced significantly higher seed yields compared to *CON* during both growing seasons. *ObBr* produced significantly higher seed yields than *BbBr* during the 98/99 season. The mean seed yield advantage of *BbBr* and *ObBr* above *CON was* 39% and 55%, respectively. On average the *IRWH* treatments produced 47% higher seed yields compared to *CON*, because of the ability of the *IRWH* technique to stop R completely and minimize the fraction of ET lost to Es (Table 5.6.2.2). *ObBr* produced 11.5% on seed yield average higher than *BbBr* presumably because of the ability of the mulches in the basins to suppress Es. This effect was particularly accentuated during the very dry 98/99 season resulting in significantly higher seed yields and significantly lower % Es/ET values for *ObBr* than *BbBr*.

Table 5.6.2.1 Seed and biomass yield, harvest index and P_g values for *CON* and *IRWH* treatments on the Vlakspruit/Arcadia ecotope over two seasons

Parameter	Year	P_g (mm)	*CON*	*BbBr*	*ObBr*
Seed (kg ha^{-1})	97/98	268	2134^a	2835^b	2937^b
	98/99	295	1045^a	1588^b	1997^c
	Mean	**282**	**1590**	**2212**	**2467**
Biomass (kg ha^{-1})	97/98	268	5031^a	6360^b	6549^b
	98/99	295	2812^a	4564^b	5991^b
	Mean	**282**	**3922**	**5462**	**6270**
Harvest index	97/98	268	0.42^a	0.46^a	0.42^a
	98/99	295	0.37^a	0.35^a	0.33^a
	Mean	**282**	**0.40**	**0.41**	**0.38**

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

Biomass yields varied between 6549 and 2812 kg ha^{-1}. *BbBr* and *ObBr* produced significantly higher biomass yields than *CON* during both seasons, on average amounting to 39 and 60%, respectively. The mean biomass yield advantage of *ObBr* above *BbBr* was not significant but amounted to 15%. Harvest index (HI) values varied between 0.33 and 0.46 with no significant difference between treatments. The HI values of the two growing seasons differ quite substantially, on average amounting to 43% and 35% for the 97/98 and 98/99 seasons, respectively. The reason for the difference is the fact that all the treatments depleted their total extractable soil water just before the very critical reproduction period during the 98/99 season, which resulted in severe stress on all the treatments (Figure 5.6.2.2) and relatively low seed yields. The *IRWH* treatments experienced much more water stress that the *CON* treatment during the reproductive period because the bigger plants on the *IRWH* plots extracted the available soil water much more vigorously compared to *CON* (Figure 5.6.2.2).

The soil water extraction in Figure 5.6.2.1 and Figure 5.6.2.2 describe the water regime during each growing season and help to explain the difference in yield and water balance data. The most critical factors are the amount and distribution of rainfall during the growing season and the soil water content at planting. A high soil water content at planting provides a buffer against a bad rainfall season especially later in the season.

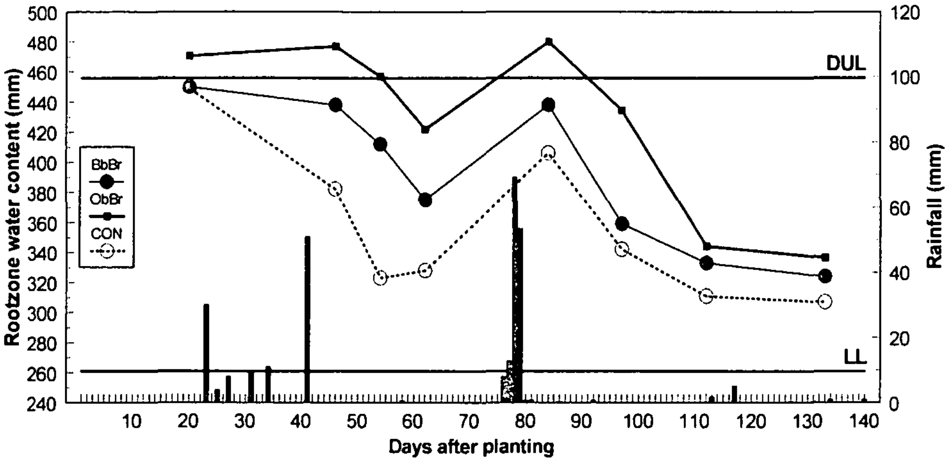

Figure 5.6.2.1 Measured changes in the soil water content of the rootzone during the 97/98 season on the Valkspruit/Arcadia ecotope: Sunflower.

Figure 5.6.2.1 shows changes in the soil water content of the rootzone during the 97/98 growing season. After a favourable start the crop did not experience any stress throughout the growing season. The rainfall during the season of 268 mm is less than the normal rainfall but the season was characterized by high intensity rainfall events (4 rainfall events more than 30 mm), which were well distributed. The result was good yields on all the treatments with the *BbBr* and *ObBr* significantly better than *CON*. During the critical drought sensitive period (DAP 45 - 80), soil water content of *BbBr* and *ObBr* were constantly close to DUL while *CON* was far less than DUL but without any severe stress. The 97/98 growing season is a very good example of how the *IRWH* treatments conserved rainwater better in the rootzone compared to *CON*. Between days after planting 20 and 46, 113 mm of rain fell. The soil water content of both *IRWH* treatments increased sharply compared to the soil water content of the *CON*, which decreased due to ex-field runoff (R_{Ex}) on the latter. Another contributing reason towards the lower soil water content on the *CON* treatment might be that Es from the *CON* treatment was slightly higher as compared to the *IRWH* treatments during the 97/98 season (Table 5.6.2.2).

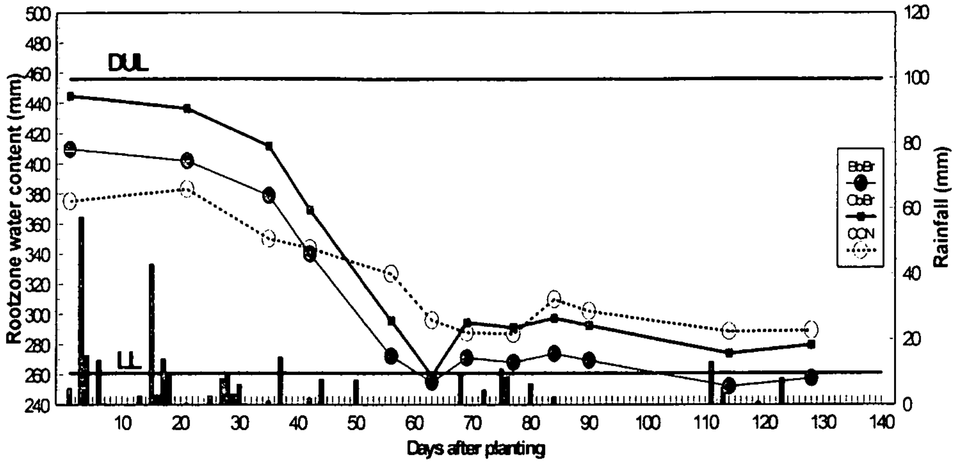

Figure 5.6.2.2 Measured changes in the soil water content of the rootzone during the 98/99 season on the Vlakspruit/Arcadia ecotope: Sunflower.

Figure 5.6.2.2 shows that the 98/99 season was extremely dry from DAP 50. Although the distribution of the rainfall events was satisfactory the disadvantage was that they were all small. During the growing season there were 22 events less than 10 mm, which would have been lost almost immediately to Es; six rainfall events between 10 and 20 mm; one between 20-30 mm; and only two rainfall events between 40 and 60 mm both in the first 60 DAP. The result was low yields especially on the *CON* treatment.

The importance of the other critical factor of pre-plant water advantage is clearly demonstrated by comparing treatments *CON*; *BbBr* and *ObBr* for the 98/99 season. Although all the treatments suffered severe stress from DAP 50 the pre-plant water advantage of the *BbBr* and *ObBr* treatments over *CON*, which amounted to around 32 and 67 mm, respectively, (Figure 5.6.2.2) clearly made a valuable contribution to the significantly higher yields from the two *IRWH* treatments (Table 5.6.2.1). The reasonable yield obtained during the stressful 98/99 season expresses the drought resistant property of sunflower.

Water balance data for the two growing seasons are presented in Table 5.6.2.2.

Table 5.6.2.2 Water balance components for *CON* and *IRWH* treatments on the Vlakspruit/Arcadia ecotope over two seasons

Water balance components	Year	*CON*	*BbBr*	*ObBr*
P_g (mm)	97/98	268		
	98/99	295		
	Mean	**282**		
ΔS (mm)	97/98	142^a	126^a	134^a
	98/99	86^a	153^b	165^b
	Mean	**114**	**140**	**150**
D (mm)	97/98	0^a	0^a	0^a
	98/99	0^a	0^a	0^a
	Mean	**0**	**0**	**0**
R (mm)	97/98	38^a	0^b	0^b
	98/99	48^a	0^b	0^b
	Mean	**43**	**0**	**0**
Es (mm)	97/98	228^a	212^a	214^a
	98/99	222^a	267^a	223^a
	Mean	**225**	**240**	**219**
Ev (mm)	97/98	144^a	182^b	188^b
	98/99	111^a	181^b	237^c
	Mean	**128**	**182**	**213**
ET (mm)	97/98	372^a	394^a	402^a
	98/99	333^a	448^b	460^b
	Mean	**353**	**421**	**431**
Es/ET (%)	97/98	61^a	54^a	53^a
	98/99	67^a	60^b	48^c
	Mean	**64**	**57**	**51**

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

The following are considered to be important features of the results of Table 5.6.2.2:

(a) *CON* vs *IRWH*

No D occurred on any of the treatments. The complete suppression of R_{Ex} at all the *IRWH* treatments and high water losses at the *CON* treatment due to R_{Ex} is clearly one of the reasons for the lower yield of this treatment. The *CON* treatment lost on average over both season 43 mm to R_{Ex}, i.e. 15% of P_g. Although Es data produced no specific trend in terms of differences between different treatments, very important differences are observed by comparing the Es/ET data. In a good water conservation tillage technique this ratio should be as small as possible. Es/ET data reveal a very strong trend during both seasons of *CON* > *BbBr* > *ObBr* with relevant means for the treatments of 64%, 57% and 51%, respectively. The differences are, however, only significant for the 98/99 season. The Ev results show that by reducing R_{Ex} to zero and promoting the in-field runoff process (surface redistribution of water), and suppressing Es, the Ev advantage of the *BbBr* and *ObBr* treatments amounted to 42% and 66% respectively. This advantage contributed towards seed yield increases compared to *CON* of 39 and 55%, respectively.

(b) *BbBr* vs *ObBr*

Both *IRWH* treatments stopped R_{Ex} completely. The difference between the two treatments was enhanced Es suppression due to mulch in the basins of the *ObBr* treatment. The extend of this benefit was negligible and not significant for the relative wet 97/98 season, but considerable (44 mm) significant for the very dry 98/99 season. This result is also reflected in the Es/ET ratios and seed yields (Table 5.6.2.1).

Water productivity based on Ev (WP_{Ev}) and rainwater productivity (RWP) data for the two-year period are presented in Table 5.6.2.3. WP_{Ev} varied between 11.6 and 12.5 kg ha^{-1} mm^{-1}. $RWP_{1997/98-1998/99}$ values varied between 3.6 and 5.7 kg ha^{-1} mm^{-1}and compare well with comparable RWP values for the Glen/Bonheim and Glen/Swartland ecotopes but are considerably higher than equivalent values obtained on the Khumo/Swartland ecotope. Both *IRWH* treatments produced significantly higher $RWP_{1997/98-1998/99}$ values compared to *CON*, with no significant difference amongst them. *BbBr* and *ObBr* produced 42 and 58% higher $RWP_{1997/98-1998/99}$ values than *CON*, respectively. *ObBr* was 12% more productive compared to *BbBr*.

Table 5.6.2.3 WP_{Ev} and RWP data for Sunflower for *CON* and *IRWH* treatments on the Vlakspruit/Arcadia ecotope over a two seasons period

Water productivity over two seasons (kg ha^{-1} mm^{-1})	*CON*	*BbBr*	*ObBr*
WP_{Ev}	12.5^a	12.2^a	11.6^a
$RWP_{1997/98-1998/99}$	3.6^a	5.1^b	5.7^b

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

5.6.3.1.1 Conclusions

The parameters to evaluate the different treatments were seed and biomass yield, R_{Ex}, Es/ET and $RWP_{1997/98-1998/99}$. Seed yields varied between 2937 kg ha^{-1} and 1045 kg ha^{-1}. Both *IRWH* treatments produced significantly higher seed yields compared to *CON* during both growing seasons. *ObBr* produced significantly higher seed yields than *BbBr* during the dry 98/99 season. The mean seed yield advantage of *BbBr* and *ObBr* above *CON was* 39% and 55%, respectively. Biomass yields varied between 6549 and 2812 kg ha^{-1}. *BbBr* and *ObBr* produced significantly higher biomass yields than *CON* during both seasons. The mean yield advantage above *CON* for *BbBr* and *ObBr* were 39 and 60%, respectively over two growing seasons. $RWP_{1997/98-1998/99}$ values varied between 3.6 and 5.7 kg ha^{-1} mm^{-1} over the two-year period. Both *IRWH* treatments produced significantly higher $RWP_{1997/98-1998/99}$ values compared to *CON*, amounting to and average advantage 50% and *ObBr* 12% better than *BbBr*. The Ev results show that by reducing R_{Ex} to zero; promoting the in-field runoff process (surface redistribution of water); and suppressing the portion of ET lost to Es, the average Ev advantage of the two *IRWH* treatments amounted to 54%. This advantage contributed towards seed yield and RWP increases.

5.6.3.2 Second experiment (2000 – 2003)

Rainfall during the fallow period (P_f) and rainfall storage efficiency (RSE) data are presented in Table 5.6.3.1. The records show that the three rainfall seasons were normal and above normal with ample opportunities to harvest water in the basins. The total rainfall for the 99/00, 00/01 and 01/02 seasons, which include rainfall during the fallow (Table 5.6.3.1) and growing season (Table 5.6.3.3), was 532, 807 and 623 mm, respectively. Of the total rainfall 53, 47 and 58% fell during the fallow period. Mean RSE values were 17, 17, 14 and 5% for *ObSr*, *SbOr*, *ObBr* and *CON*, respectively. The % RSE values for the *IRWH* treatments were significantly better than *CON* for the 99/00 and 01/02 seasons. Comparing *ObSr* and *SbOr* with the *ObBr* treatments indicated that mulch on the runoff area did not affect the RSE significantly in any of the years, but contributed towards an increase in RSE of 3% on average.

Table 5.6.3.1 Rainfall during the fallow period (P_f) and rainfall storage efficiency (RSE) data obtained from different techniques on the Vlakspruit/Arcadia ecotope over three seasons

Parameter	Year	Treatment				Mean
		CON	*ObBr*	*ObSr*	*SbOr*	*IRWH*
Pf (mm)	99/00	280				
	00/01	378				
	01/02	364				
	Mean	**341**				
RSE (%)	99/00	10^a	20^b	24^b	20^b	21
	00/01	0^a	12^a	12^a	17^a	14
	01/02	4^a	10^b	16^b	13^b	13
	Mean	**5**	**14**	**17**	**17**	**16**

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

Important crop growth parameters, *viz.* seed yield, biomass yield and harvest indices are summarized in Table 5.6.3.2. The results of the soil water contents during the three growing seasons are presented in Figure 5.6.3.1.

Table 5.6.3.2 Seed yield, biomass yield and harvest index for sunflower from different techniques on the Vlakspruit/Arcadia ecotope over three seasons

Parameter	Year	Treatment				Mean
		CON	*ObBr*	*ObSr*	*SbOr*	*IRWH*
Seed (kg ha^{-1})	99/00	1062^{a}	1706^{b}	1944^{b}	1814^{b}	1821
	00/01	1116^{a}	1506^{b}	1623^{b}	1498^{b}	1542
	01/02	1389^{a}	2878^{b}	3117^{b}	3079^{b}	3025
	Mean	**1189**	**2030**	**2228**	**2130**	**2129**
Biomass (kg ha^{-1})	99/00	3324^{a}	4262^{b}	6271^{c}	5022^{bc}	5185
	00/01	2685^{a}	4296^{b}	4742^{b}	4976^{b}	4671
	01/02	3686^{a}	5480^{b}	5988^{b}	5818^{b}	5762
	Mean	**3232**	**4679**	**5667**	**5272**	**5206**
Harvest index	99/00	0.32^{a}	0.40^{b}	0.31^{a}	0.36^{ab}	0.36
	00/01	0.42^{a}	0.35^{ab}	0.34^{ab}	0.30^{b}	0.33
	01/02	0.38^{a}	0.53^{b}	0.52^{b}	0.53^{b}	0.53
	Mean	**0.37**	**0.43**	**0.39**	**0.40**	**0.41**

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

The soil water pattern lines in Figure 5.6.3.1 highlights the fact, clearly demonstrated on all the ecotopes in all seasons, how difficult it is in the case of *CON* for the profile to become recharged during the crop-growing season, especially with low PAW_p levels. There was a considerable difference in the available water content during the vegetative period of the three *IRWH* treatments versus the *CON* during all the seasons. The soil water patterns of all the seasons clearly indicate that from prior to flowering onwards the *CON* treatment depends heavily on the inadequate rainfall to meet crop water demand. This resultant crop water stress in all the seasons caused an average reduction in seed yield compared to *IRWH* which amounted to 71, 38 and 118% for the 99/00, 00/01 and 01/02 seasons, respectively. The seed and biomass yields of the *IRWH* treatments were significantly higher than the *CON* in all the seasons.

Water balance data and PAW_p data are presented in Table 5.6.3.3. The statistical analysis of PAW_p reflected similar results as the RSE results (Table 5.6.3.1): (i) mulches did not affect the available water in any of the seasons, and (ii) the *IRWH* systems provided significantly more available water at planting. The mean PAW_p for the *IRWH* systems was 80, 113 and 109 mm higher during the 99/00, 00/01 and 01/02 seasons, respectively, than the corresponding *CON* values. *CON* lost on average 10% of the total rainfall during all three growing seasons to ex-field runoff (R_{Ex}). Drainage was zero for all treatments irrespective of season.

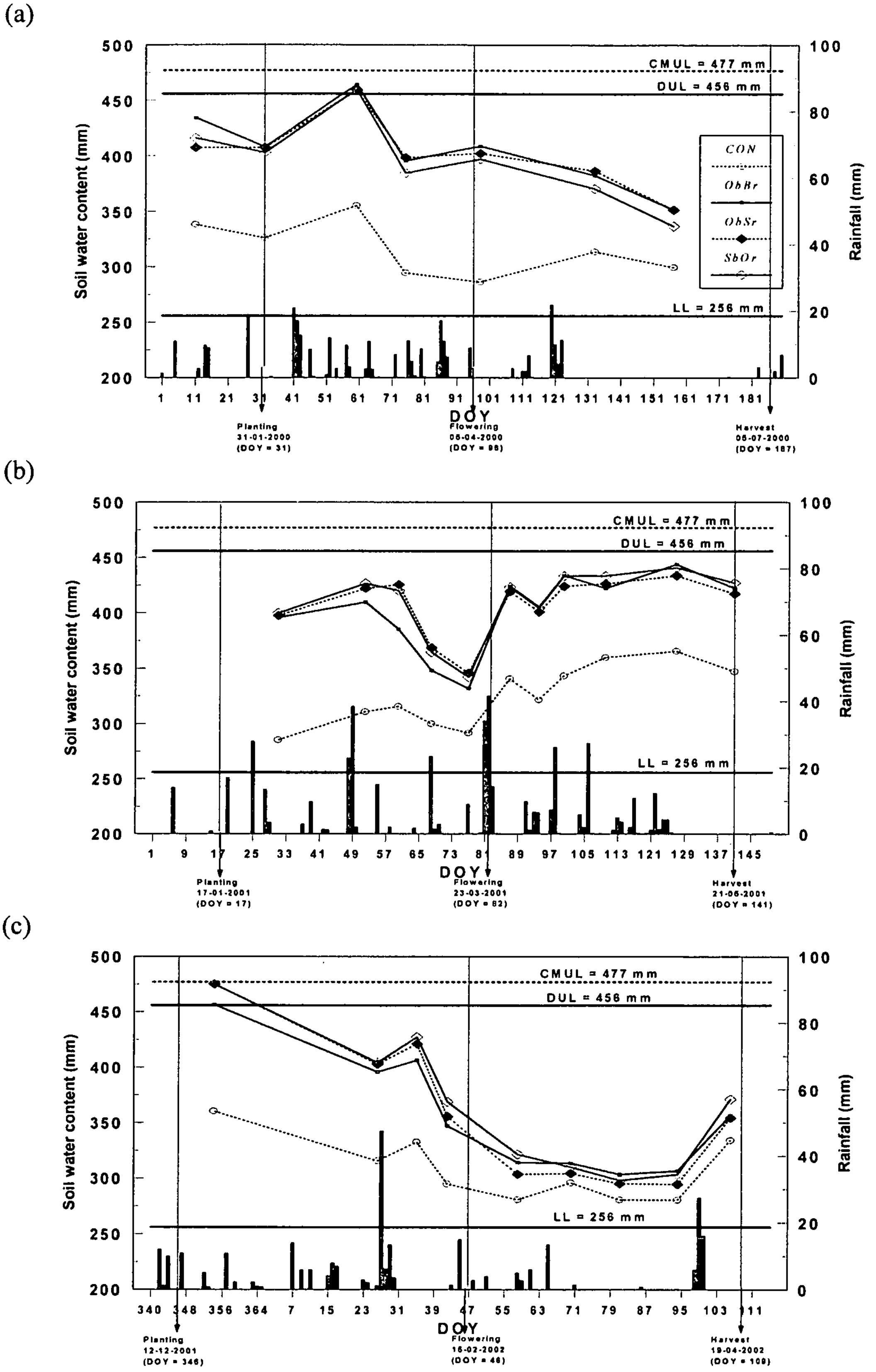

Figure 5.6.3.1 Measured changes in the soil water content of the rootzone (0 – 1200 mm) during the (a) 99/00, (b) 00/01 and (c) 01/02 growing seasons on the Vlakspruit/Arcadia ecotope: sunflower.

Table 5.6.3.3 Water balance data from different treatments on the Vlakspruit/Arcadia ecotope over three seasons

Parameter	Year	Treatment				Mean
		CON	*ObBr*	*ObSr*	*SbOr*	*IRWH*
P_g (mm)	99/00	252				
	00/01	429				
	01/02	259				
	Mean	**313**				
ΔS (mm)	99/00	26^a	56^b	56^b	66^b	59
	00/01	-62^a	-26^b	-19^b	-27^b	-24
	01/02	26^a	101^b	121^b	104^b	109
	Mean	**-3**	**44**	**53**	**48**	**48**
PAW_p	99/00	70^a	152^b	152^b	147^b	150
	00/01	29^a	140^b	142^b	144^b	142
	01/02	104^a	201^b	219^b	219^b	213
	Mean	**68**	**164**	**171**	**170**	**168**
R_{Ex} (mm)	99/00	25^a	0^b	0^b	0^b	0
	00/01	48^a	0^b	0^b	0^b	0
	01/02	21^a	0^b	0^b	0^b	0
	Mean	**31**	**0**	**0**	**0**	**0**
ET (mm)	99/00	253^a	308^b	308^b	318^b	311
	00/01	319^a	403^b	410^b	402^b	405
	01/02	264^a	360^b	380^b	363^b	368
	Mean	**270**	**357**	**366**	**361**	**361**
Ev (mm)	99/00	120^a	153^b	226^c	181^b	187
	00/01	53^a	85^b	94^c	98^c	92
	01/02	90^a	133^b	145^b	141^b	140
	Mean	**88**	**124**	**155**	**140**	**140**
Es (mm)	99/00	133^a	155^a	92^b	127^a	125
	00/01	266^a	317^a	315^a	303^a	312
	01/02	174^a	227^a	235^a	222^a	228
	Mean	**205**	**244**	**217**	**223**	**228**
Es/ET (%)	99/00	53^a	50^a	29^b	41^b	40
	00/01	83^a	79^a	77^a	76^a	77
	01/02	66^a	63^{ab}	62^b	61^b	62
	Mean	**69**	**65**	**56**	**60**	60

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

The differences in ET between the *IRWH* treatments were non-significant, although a mean trend of *ObSr* > *SbOr* > *ObBr* was observed (Table 5.6.3.3). All the *IRWH* treatments produced a significantly higher ET than the *CON*, during all seasons. ET on *CON* amounted to 23, 27 and 39% as less on average than the mean ET of the *IRWH* treatments over the three seasons. Es/ET results indicate that all the *IRWH* treatments were more successful than *CON* to suppress Es in relation to ET during all three growing seasons. All the *IRWH* treatments with mulches on the runoff area (*ObSr* and *SbOr)* were more successful in suppressing Es in relation to ET compared to the treatment with the bare runoff area (*ObBr*). Ev is the productive part of ET, which results in plant growth, and is classified as "green water". All the *IRWH* treatments produced significantly higher Ev values during all three seasons as compared to *CON*. The mean Ev of the three *IRWH* treatments was 56, 74 and 56% higher than *CON* during the 99/00, 00/01 and 01/02 seasons. *ObSr* produced significantly higher Ev values than *ObBr* during two of the three seasons (99/00 and 00/01). *SbOr* only produced a significantly higher Ev than *ObBr* during the 00/01 season.

Water productivity based on Ev (WP_{Ev}) and rainwater productivity results (RWP) over a three year period are presented in Table 5.6.3.4.

Table 5.6.3.4 WP_{Ev} and RWP for sunflower from different treatments on the Vlakspruit/Arcadia ecotope over three tear period

Water productivity (kg seed ha^{-1} mm^{-1})	Treatment				Mean
	CON	*ObBr*	*ObSr*	*SbOr*	*IRWH*
WP_{Ev}	13.5^a	16.4^a	14.4^a	15.2^a	15.3
$RWP_{1999/00-2001/02}$	2.1^a	3.6^b	4.0^b	3.8^b	3.8

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

The high WP_{Ev} results show the advantage of sunflower as a crop for this ecotope. $RWP_{1999/00-2001/02}$ results show a common trend for the treatments, *viz. ObSr* > *SbOr* > *ObBr* > *CON*. All the *IRWH* treatments produced significantly better $RWP_{1999/00-2001/02}$ values than *CON*. $RWP_{1999/00-2001/02}$ results indicate that the *IRWH* treatments were on average 81% more efficient than *CON* in converting rainwater into seed yield. For every 1 mm of rain ha^{-1}on this ecotope *CON* would produce 2.1 kg sunflower seed compared to a mean of 3.8 kg sunflower seed for the *IRWH* treatments. The significant higher productivity of the *IRWH* treatments is the effect of total stoppage of R_{Ex} and the minimization of the portion of ET lost to Es. Differences between *IRWH* treatments were not significant with the treatments with mulch on the runoff are (*ObSr* and *SbOr*) performing on average 8% better than *ObBr*.

5.6.3.2.1 Conclusions

Rainfall records revealed that the three rainfall seasons were normal and above normal with ample opportunities to harvest water in the basins. Rainfall storage efficiency (RSE) and plant available water at planting indicated that all the *IRWH* treatments conserved more rainwater during the fallow period than the *CON* treatment during all three seasons. This gave an average pre-plant water advantage over the three seasons of 93 mm to the *IRWH* treatments compared to *CON*. Results indicated that mulch on the runoff area did not affect the RSE significantly in any of the years.

Soil water patterns of all the seasons indicated, from prior to flowering onwards, that because of low PAW_p *CON* had to depend heavily on inadequate rainfall to meet crop water demand. This resulted in considerable crop water stress in all the seasons compared to the *IRWH* treatments which produced on average 79% higher seed yields over the three seasons. The seed yields of the *IRWH* treatments were significantly higher than *CON* in all the seasons. Comparing the three *IRWH* techniques revealed that there is a consistent trend during the experimental period, *viz. ObSr* > *SbOr* > *ObBr*, but without any statistical differences between these treatments. R_{Ex} was zero for the *IRWH* treatments while the *CON* treatment lost on average 10% of the total rainfall during all three growing seasons to R_{Ex}. Drainage was zero for all treatments irrespective of season.

Es/ET results indicate that all the *IRWH* treatments were more successful than *CON* to suppress Es in relation to ET. All the *IRWH* treatments produced a significantly higher $RWP_{1999/00\text{-}2001/02}$ than *CON*. The *IRWH* systems were between 71 and 90% more effective in converting rainwater into seed yield compared to *CON*. $RWP_{1999/00\text{-}}$

$_{2001/02}$ results indicate that for every 1 mm of rainwater ha^{-1} *CON* would produce 2.1 kg of sunflower seed yield compared to 3.8 kg from the *IRWH* treatments. This indicated that the *IRWH* treatments were on average 81% more efficient than *CON* during the experimental period. *ObSr* and *SbOr* produced on average 8% better $RWP_{1999/00-2001/02}$ values than *ObBr* without any significant differences between these treatments.

5.7 SUMMARY AND CONCLUSIONS

The general objective of this chapter was to evaluate the agronomic sustainability of the in-field rainwater harvesting (*IRWH*) technique in terms of its ability to convert rainwater into sunflower seed yield by minimizing the unproductive losses, evaporation from the soil surface (Es) and ex-field runoff (R_{Ex}), and maximizing the very important parameter *viz.* rainwater productivity (RWP). Normal conventional tillage (*CON*) was compared with various *IRWH* treatments during two separate field experiments on four ecotopes *viz.* Glen/Bonheim; Glen/Swartland; Khumo/Swartland; Vlakspruit/Arcadia. The treatments were *CON* tillage; *IRWH* with a bare basin and bare runoff area (*BbBr*); *IRWH* with organic mulch in the basins and a bare runoff area (*ObBr*); *IRWH* technique with organic mulch in the basins, stones on the runoff area (*ObSr*); *IRWH* technique with organic mulch in the basins, organic mulch on the runoff area (*ObOr*); *IRWH* technique with stones in the basins, organic mulch on the runoff area (*SbOr*). The indicators of crop response to different treatments used were seed yield, dry matter production, water balance components, transpiration and various RWP.

The natural resource components (climate, topography and the soil) that affect the productivity of these ecotopes were described. The experimental plots are located on upper foot slope terrain units with a 1 to 3% slope. The effective rootzones of these ecotopes are considered to be 0 - 1200 mm. The soils have high clay contents and high water holding capacities. The ecotopes are situated in a semi-arid region with low and erratic rainfall where conditions are marginal for crop production. The average long-term annual rainfall varies between 540 and 590 mm.

Rainfall records revealed that the rainfall seasons were normal, below and above normal with ample opportunities to harvest water in the basins. Rainfall storage efficiency (RSE) and plant available water at planting (PAW_p) indicated that all the *IRWH* treatments conserved more rainwater during the fallow period than *CON*. This gave a significantly higher PAW_p or pre-plant water advantage to all the *IRWH* treatments compared to *CON*. R_{Ex} was zero for the *IRWH* treatments during all seasons while the *CON* treatment lost on average 10% of the P to R_{Ex}. Es results indicate that all the *IRWH* treatments were more successful than *CON* to suppress Es in relation to evapotranspiration (ET) during all growing seasons. The results showed that *IRWH* significantly increased sunflower yields compared to *CON* through its ability to stop R_{Ex} completely and minimize Es/ET. All *IRWH* treatments produced significantly higher seed yields than *CON* during all seasons.

Comparing the *IRWH* techniques revealed that there is a consistent trend in seed yield during the experimental period, *viz. ObSr* > *SbOr* > *ObOr* > *ObBr*. All the *IRWH* treatments with mulch on the runoff area produce higher ET and transpiration (Ev) values, and hence seed yield increases between 7 and 16% compared to *ObBr*. Es results indicated that the *IRWH* treatments with mulch on the runoff area lost smaller portions of Es/ET than *ObBr*, which mean that they used bigger portions of ET more productively through Ev.

Results have indicated clearly that the *IRWH* techniques are far more efficient than *CON* at converting rainwater into seed yield. A common trend in RWP was *ObSr* > *SbOr* > *ObOr* > *ObBr* > *CON*. In all these cases the *IRWH* treatments were significantly higher than *CON* irrespective of the locality. The *IRWH* treatments produced between 45 and 114% higher RWP values than *CON*. When comparing RWP values of *IRWH* the treatments with mulches on the runoff area produced between 7 and 15% more seed yield with the same amount of rainwater than to *ObBr*.

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CHAPTER 6: DEVELOPMENT AND VALIDATION OF AN EMPERICAL CROP WATER STRESS MODEL FOR IN-FIELD RAINWATER HARVESTING

ABSTRACT

Models utilize long-term climate data to provide long-term yield simulations, which can serve to quantify production risk especially in semi-arid areas where rainfall is marginal and erratic with regard to amount, distribution and intensity. To be able to make reliable recommendations concerning the best production techniques for a crop on a particular ecotope it is desirable to have long-term yields. The use of crop models and long-term climate data to achieve this objective has been widely used in agriculture for more than a decade. However, the application of this approach for the production techniques used in this study requires more than standard crop modelling procedures. The latter will be satisfactory for the conventional (CON) treatment. However, for in-field rainwater harvesting (IRWH), to correctly simulate the soil water regime in the region of the basins requires that one is able to correctly predict runoff (R) from the runoff strip (bare, or covered with stone or organic mulch) for each rainfall event recorded in the long-term weather data set. Where mulch is applied in the basins or on the runoff area, the suppression of evaporation from the soil surface (Es) by the mulch needs also to be taken into account. In addition, the effect of the different mulches on the interaction between runoff, infiltration and evaporation from the soil surface in the basins and on the runoff area needs to be quantified.

Because of these considerations an empirical crop water stress model termed "Crop Yield Predictor for Semi-Arid Areas" (CYP-SA) was developed to enable long-term yield predictions to be made for the IRWH technique. The composition of the model for maize and sunflower is described in detail, together with validation results. Validation results for the short-term yield predictions were reasonable good. It was therefore concluded that CYP-SA was suitable for making long-term yield predictions for maize and sunflower with long-term climate data.

Keywords: in-field rainwater harvesting, semi-arid areas, water stress model, maize, sunflower

6.1 INTRODUCTION

A crop model can be defined as a quantitative scheme for predicting the growth, development and yield of a crop, given a set of genetic coefficients and relevant environmental variables (Monteith, 1996). Crop models have many current and potential uses for answering questions in research, crop management, and policy (Boote, Jones & Pickering, 1996). Researchers can use these models as research tools to conduct research faster and more cost-effectively, while the extension officers and producers can use them to determine the risk involved in certain production practices, especially in dry areas with erratic rainfall (Hensley & Snyman, 1991). The farmer can use a model to assist in pre-season and in-season management decisions on cultivation practices, fertilization, irrigation and pesticide use (Bennie, Coetzee, van Antwerpen, van Rensburg & Burger, 1988; Bennie, Strydom & Vrey, 1998; De Jager & Singels, 1990). Crop models can assist policy makers by predicting soil erosion, leaching of agrochemicals, effects of climatic change, and by making large-area yield forecasts (Schulze, 1995). Simulation models are used to estimate potential yield in new areas, to forecast yields before harvest, to estimate sensitivity of crop production to climate change, and to compare management options, technology level, and performance of varieties (Muchow, Hammer & Carberry, 1990).

While crop models cannot produce all the answers to crop production problems, when reasonably constructed they can be important heuristic tools in teaching, research, and management. They can be used to test hypotheses and the validity of standard practices, thereby allowing the user to reason more consistently about factors or conditions that deserve thought, additional experimental study by researchers, or more attention from growers. Crop models cannot replace observation, experimentation, and experience, but they can be well supported by them. Because of the large number of situations where the heuristic function of crop models can be a crucial if not an indispensable tool, crop modelling can be expected to have a productive future (Sinclair & Seligman, 1996).

To be able to make reliable recommendations concerning the best production techniques for a crop on a particular ecotope it is desirable to have long-term yields. The need for this is accentuated for ecotopes in semi-arid areas where rainfall is marginal and also erratic with regard to amount, distribution and intensity. The use of crop models with long-term climate data to achieve this objective has been widely used in agriculture for more than a decade. However, the application of this strategy for the production techniques used in this study requires more than standard crop modelling procedures. The latter will be satisfactory for the conventional (*CON*) treatment. However, for in-field rainwater harvesting (*IRWH*), to correctly simulate the soil water regime in the region of the basins requires the ability to correctly predict R from the runoff strip (bare, or covered with stone or organic mulch) for each rainfall event recorded in the long-term weather data set. Where mulch (stone or organic) is applied in the basins or on the runoff area, the suppression of Es by the mulch needs also to be taken into account. In addition, the effect of the different mulches on the interaction between runoff, infiltration and evaporation from the soil surface in the basins and on the runoff area needs to be quantified.

The aim of this chapter is to describe the development of a simple empirical crop water stress model that is able to deal with a very complex water regime within the *IRWH* system, and thereby provide useful information for the comparison between *CON* and *IRWH* (with different mulch treatments) on the Glen/Bonheim ecotope.

6.2 DETAILED DESCRIPTION OF THE MODEL

6.2.1 GENERAL FEATURES

The model has been named CYP-SA, standing for Crop Yield Predictor for Semi-Arid areas. The inputs required by the model are crop modified upper limit of available water (CMUL); drained upper limit of available water (DUL); lower limit of available water (LL); rainfall (P); evaporative demand (E_o) and soil water content at planting (θ_p). Details concerning the various processes and parameters are presented below.

The model is based on a similar principle to that used by Rasmussen & Hanks (1978). The difference is that in this case the degree of water stress is described as the "dryness" of the root zone rather than an estimated ET/E_o value as used by Rasmussen & Hanks (1978).

A reliable field measured value of total extractable soil water (TESW = DUL - LL) is of fundamental importance. The level of water stress being experienced by the crop is defined as the fraction of TESW (FTESW) present at any particular time. Although FTESW is a satisfactory parameter to describe stress while the soil is drying, it is not satisfactory after a rainfall event, which may, for example, just wet the top 0 - 300 mm soil layer. In that situation the crop will suffer relatively little stress while it depletes the water in the surface soil, even if the rest of the root zone is relatively dry. An adaptation to cater for this situation has been introduced. It is based on field measurements of ET/E_o on relatively dry soils after rainfall events. The adapted FTESW value is designated as $FTESW_{aa}$. Allowance is also made for deep drainage (D) to occur when the water content of the rootzone (θr) exceeds CMUL.

An $FTESW_{aa}$ value is calculated for each day and an average taken for periods of 15 days for sunflower and maize to give a water stress factor (SF) for that period. The growing season is subdivided into eight 15-day periods for sunflower and maize, and a stress-weighting factor (λ) allocated to each period in accordance with its importance in relation to yield determination. An integrated stress index, or factor, termed TSF is obtained as a multiplicative summation of the SF values for the individual periods each raised to the power of λ.

The model was created to cater specifically for the following treatments with maize and sunflower as crops:

- *CON*;
- *IRWH* technique with a bare basin and runoff area (*BbBr*);

- *IRWH* technique with organic mulch in the basins and bare runoff area (*ObBr*);
- *IRWH* technique with organic mulch in the basins and stones on the runoff area (*ObSr*);
- *IRWH* technique with organic mulch in the basins and organic mulch on the runoff area (*ObOr*);
- *IRWH* technique with stones in the basins and organic mulch on the runoff area (*SbOr*);
- *IRWH* technique with stones in the basins and stones on the runoff area (*SbSr*).

6.2.2 DETAILS CONCERNING VARIOUS PROCESSES AND PARAMETERS

Catering for ex-field runoff (R_{Ex}) with *CON* and in-field runoff (R_{In}) with *IRWH* by adjusting rainfall (P) for different treatments.

***CON* (P - R_{Ex}):**

$$\begin{aligned}&IF\ (P < 8)\ P = (P - 0)\\&IF\ (P > 8)\ P = (P - ((0.473 \times P) - 2.168) \times 0.4)\end{aligned} \quad \ldots\ldots(r^2 = 0.60)\ldots\ldots(6.1)$$

(after Hensley, Botha, Anderson, Van Staden. & Du Toit, 2000)

***IRWH* (P + R_{In}) - bare, organic mulch and stone mulch:** (see Chapter 2 for details).

Bare:

$$\begin{aligned}&IF\ (-0.8791 + 0.4742 \times P) < 0:\ P_{BARE} = (P \times 0)\\&IF\ (-0.8791 + 0.4742 \times P) > 0:\ P_{BARE} = (-0.8791 + 0.4742 \times P)\end{aligned} \quad \ldots(r^2 = 0.64)\ldots\ldots(6.2)$$

Stone:

$$\begin{aligned}&IF\ (-0.6635 + 0.2900 \times P) < 0:\ P_{STONE} = (P \times 0)\\&IF(-0.6635 + 0.2900 \times P) > 0:\ P_{STONE} = (-0.6635 + 0.2900 \times P)\end{aligned} \quad \ldots(r^2 = 0.51)\ldots\ldots(6.3)$$

Organic:

$$\begin{aligned}&IF\ (-0.2124 + 0.0768 \times P) < 0:\ P_{ORGANIC} = (P \times 0)\\&IF(-0.2124 + 0.0768 \times P) > 0:\ P_{ORGANIC} = (-0.2124 + 0.0768 \times P)\end{aligned} \quad \ldots(r^2 = 0.55)\ldots\ldots(6.4)$$

Crop factor (CF):

Maize and sunflower:

$$CF = 0.0119 \times DAP^{1.5582} \times EXP \times (-0.0327 \times DAP) \ldots\ldots(r^2 = 0.98)\ldots\ldots(6.5)$$

This is an adaptation of the equation of Bennie, Strydom & Vrey (1998) to give one which only has one input i.e. days after planting (DAP). The maize and sunflower cultivars used both have a growth period of approximately 120 days and therefore the same equation.

Crop water requirement (E_0CF):

In order to get the crop water requirement per day, E_0 must be multiplied by CF.

$$E_oCF = E_o \times CF \qquad (6.6)$$

Extractable soil water at the beginning of a day (ESW_b):

$$ESW_b = \theta r - LL \qquad (6.7)$$

Fraction of total extractable soil water (FTESW):

$$FTESW = \frac{ESW_b}{TESW} \qquad (6.8)$$

Adapted Fraction of total extractable soil water ($FTESW_{aa}$):

$$\begin{aligned} &IF\ (\frac{P}{E_o} < 0.2):\ FTESW_{aa} = (FTESW) \\ &IF(\frac{P}{E_o} > 0.2):\ FTESW_{aa} = (FTESW + (\frac{P}{E_o}) \times 0.4052 - 0.0729) \end{aligned} \qquad (6.9)$$

only up to a maximum of 1

During a period where ESW_b is low and it rains during that day, the model did not take the rain in consideration, and penalized the extraction too much. That is why there is an adapted: $FTESW_{aa}$, which takes the rain during a day into consideration.

SWE: Soil water Extraction

Empirical constants, based on observations, have been included in the equations for the different kinds of cover on the runoff area to compensate for their differing influence on SWE, especially on Es.

***CON*:**

$$SWE_{CON} = (-E_oCF \times FTESW_{aa}) + P_{CON} \qquad (6.10)$$

***BbBr*:**

$$SWE_{BbBr} = (-E_oCF \times FTESW_{aa}) + P_{BARE} \tag{6.11}$$

***ObBr*:**

$$\begin{aligned} &IF\ (-(E_oCF \times FTESW_{aa}) + P_{BARE}) < 0:\ SWE_{ObBr} = ((-(E_oCF \times FTESW_{aa}) + P_{BARE}) \times 0.982) \\ &IF(-(E_oCF \times FTESW_{aa}) + P_{BARE}) > 0:\ SWE_{ObBr} = ((-(E_oCF \times FTESW_{aa}) + P_{BARE}) \times 1.018) \end{aligned} \tag{6.12}$$

***ObOr*:**

$$\begin{aligned} &IF(-(E_oCF \times FTESW_{aa}) + P_{ORGANIC}) < 0:\ SWE_{ObOr} = ((-(E_oCF \times FTESW_{aa}) + P_{ORGANIC}) \times 0.802) \\ &IF(-(E_oCF \times FTESW_{aa}) + P_{ORGANIC}) > 0:\ SWE_{ObOr} = ((-(E_oCF \times FTESW_{aa}) + P_{ORGANIC}) \times 1.198) \end{aligned} \tag{6.13}$$

***ObSr*:**

$$\begin{aligned} &IF(-(E_oCF \times FTESW_{aa}) + P_{STONE}) < 0:\ SWE_{ObSr} = (-(E_oCF \times FTESW_{aa}) + P_{STONE}) \times 0.839) \\ &IF(-(E_oCF \times FTESW_{aa}) + P_{STONE}) > 0:\ SWE_{ObSr} = ((-(E_oCF \times FTESW_{aa}) + P_{STONE}) \times 1.161) \end{aligned} \tag{6.14}$$

***SbOr*:**

$$\begin{aligned} &IF(-(E_oCF \times FTESW_{aa}) + P_{ORGANIC}) < 0:\ SWE_{SbOr} = ((-(E_oCF \times FTESW_{aa}) + P_{ORGANIC}) \times 0.807) \\ &IF(-(E_oCF \times FTESW_{aa}) + P_{ORGANIC}) > 0:\ SWE_{SbOr} = ((-(E_oCF \times FTESW_{aa}) + P_{ORGANIC}) \times 1.193) \end{aligned} \tag{6.15}$$

***SbSr*:**

$$\begin{aligned} &IF(-(E_oCF \times FTESW_{aa}) + P_{STONE}) < 0:\ SWE_{SbSr} = ((-(E_oCF \times FTESW_{aa}) + P_{STONE}) \times 0.844) \\ &IF(-(E_oCF \times FTESW_{aa}) + P_{STONE}) > 0:\ SWE_{SbSr} = ((-(E_oCF \times FTESW_{aa}) + P_{STONE}) \times 1.156) \end{aligned} \tag{6.16}$$

Water content of rootzone, not adapted to cater for values above CMUL (θr_a):

Maize and sunflower:

CON, *BbBr* and *ObBr*:

$$\theta r_a = \left[(ESW_b \times 0.997) + Extraction + LL\right] \tag{6.17}$$

ObOr, *ObSr*, *SbOr* and *SbSr*:

$$\theta r_a = (ESW_b + Extraction + LL) \tag{6.18}$$

Adapted water content of rootzone, to cater for values not to exceed CMUL (θr_b):

$$\begin{aligned} &IF(\theta r_a < CMUL):\ \theta r_b = (\theta r_a) \\ &IF(\theta r_a > CMUL):\ \theta r_b = (CMUL) \end{aligned} \tag{6.19}$$

This equation is to make sure that θr_b does not exceed CMUL, because when $\theta r >$ CMUL, D occurs, and therefore everything above CMUL is wasted as D.

Extactable soil water at the end of a day (ESW_e):

$$ESW_e = \theta r_b - LL \tag{6.20}$$

ESW_e is used to start the following day (ESW_b)

Crop water stress factor (SF):

Maize and sunflower:

$SF_{0\text{-}15}$ = sum of $FTESW_{aa}$ for a period of 15 days. Each period is calculated separately. SF is the average $FTESW_{aa}$ for a set of 15 day periods up to a maximum of 8 periods.

Period 1 (SF_1): $SF_{0\text{-}15\ \mathrm{DAP}}$
Period 2 (SF_2): $SF_{16\text{-}30\ \mathrm{DAP}}$
Period 3 (SF_3): $SF_{31\text{-}45\ \mathrm{DAP}}$
Period 4 (SF_4): $SF_{46\text{-}60\ \mathrm{DAP}}$
Period 5 (SF_5): $SF_{61\text{-}75\ \mathrm{DAP}}$
Period 6 (SF_6): $SF_{76\text{-}90\ \mathrm{DAP}}$
Period 7 (SF_7): $SF_{91\text{-}105\ \mathrm{DAP}}$
Period 8 (SF_8): $SF_{106\text{-}120\ \mathrm{DAP}}$

Integrated stress factor (ISF) and the stress weighting factor (λ):

For every SF period a stress weigh factor (λ) is allocated according to the critical importance of the period with regard to yield determination. The λ values range between 0 and 1 and their sum equals 1. The ISF value is obtained by a multiplicative summation of the individual SF values. For sunflower the period DAP 46 - 60 is the critical period just before flowering. DAP 61 - 75 is the critical flowering period. Any water deficiency during these two periods has an important influence on sunflower yield. That is why these two periods in the case of sunflower have high λ values. The periods 0 - 15 DAP; 91 - 105 DAP and 106 - 120 DAP were considered to be of very low importance regarding sunflower yield, especially the last two periods. For maize the most critical period is from the start of flowering at about 60 DAP for a period of about 30 days up to 90 DAP. The λ values allocated to each SF period for maize and sunflower are presented below:

Maize:

$$ISF = \left(SF_1^{0.06} \times SF_2^{0.05} \times SF_3^{0.04} \times SF_4^{0.15} \times SF_5^{0.30} \times SF_6^{0.20} \times SF_7^{0.15} \times SF_8^{0.05}\right) \ldots\ldots\ldots\ldots (6.21)$$

Sunflower:

$$ISF = \left(SF_1^{0.03} \times SF_2^{0.07} \times SF_3^{0.15} \times SF_4^{0.27} \times SF_5^{0.30} \times SF_6^{0.10} \times SF_7^{0.03} \times SF_8^{0.01}\right) \qquad (6.22)$$

A flow diagram of the CYP-SA model is presented in Figure 6.1.

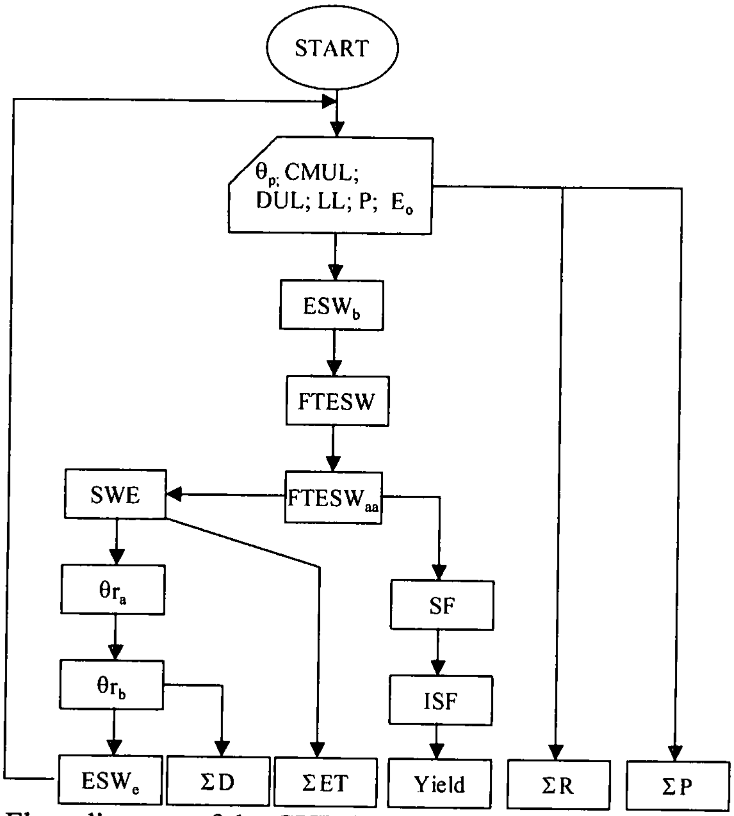

Figure 6.1 Flow diagram of the CYP-SA model.

6.3 FORMULATION AND CALIBRATION OF THE MODEL

6.3.1 MAIZE

An empirical approach was used. For each of the crops the regression of yield on the integrated stress factor (ISF) as determined for a number of growing seasons. The resultant equation describes the model. The r^2 value of the regression equation is considered to provide a calibration index.

Maize yields on the Glen/Swartland ecotope from the *CON*, *BbBr* and *ObBr* treatments for the 96/97, 97/98 and 98/99 seasons were used to formulate the model. ISF values were calculated for each data set and a regression analysis performed of measured yields (Yg) against the ISF values. The result was:

$$Yield = 10772.60 \times (1 + ((-0.3478) - 1) \times EXP(-(0.5460) \times ((ISF) - (-0.3091))))^{\left(\frac{1}{1-(-0.3478)}\right)} .(r^2 = 0.97)..(6.23)$$

6.3.2 SUNFLOWER

Sunflower yields on the Glen/Bonheim and Glen/Swartland ecotopes from the treatments, *CON*, *BbBr* and *ObBr*, for the 97/98 and 98/99 seasons from Hensley *et al.* (2000) were used to calibrate the model. ISF values were calculated for each data set and a regression analysis performed of measured yields (Yg) against the ISF values. The result was:

$$Yield = (6188.56 \times ISF) - 1607.37 \ldots\ldots (r^2 = 0.81) \ldots\ldots (6.24)$$

6.4 VALIDATION OF THE MODEL

6.4.1 INTRODUCTION

The next step was the validation of the CYP-SA model. Model reliability tests were done by using the procedure of Willmott (1981). Willmott (1982) points out that in a accurate model the systematic root mean square error ($RMSE_s$) should approach zero, while the index of agreement (D-index) should approach one. The difference between the unsystematic root mean square error ($RMSE_u$) and $RMSE_s$ is a measure of the potential accuracy of the model. The $RMSE_s$ should be as small as possible; a large $RMSE_s$ indicates bias. The $RMSE_u$ should be as close as possible to the root mean square error (RMSE), indicating that the deviations of simulated from measured values are random. Whether accuracy or potential accuracy is evaluated, no single measure can describe model performance, and therefore an array of complementary measures should be used as suggested by Willmott (1982). According to Willmott (1982) the use of scatter plots (1:1 graphs), in conjunction with an array of complementary measures, is useful in evaluating model performance.

Statistical evaluation of model performance was carried out with the MODEVAL program (Houston & Berry, 1996). The following values for the different statistical parameters were used to provide approximate guidelines for the assessment: $RMSE_s <$ 65 % of RMSE; D-index > 0.8; $r^2 > 0.8$. Values, which met these requirements, were considered to indicate good agreement, whereas deviations indicated less satisfactory agreement. It must be mentioned that the aim of CYP-SA was not to create a new model to compete with existing models, it was only developed because we are dealing here with a very complicated system. Ritchie (pers. comm., 1997, Michigan State University, USA) stated during an inspection of the *IRWH* experimental site that it is a very complicated system and that the runoff area and basins should be modelled separately. To complicate the whole system even more, mulch (organic and stone) were added later to the runoff area and in the basins. At this stage none of the existing models can simulate such a complicated system. So a simple custom-made stress model was developed. However, when used correctly it can provide useful information for decision-making regarding agricultural water management. This is the use of CYP-SA in this study, for decision-making regarding these particular production techniques.

6.4.2 MAIZE

Validation was accomplished using measured yield data from all the treatments on the Glen/Bonheim ecotope (99/00 - 01/02). Results of model reliability tests using the procedure of Willmott (1981) are presented in Figure 6.2.

The performance of the model was very good. The systematic error ($RMSE_S$) is 49 % of RSME, lower than the threshold value of 65 % used by modellers. The D-index and r^2 values were good at 0.95 and 0.83 respectively, both higher than 0.80 which indicates good agreement.

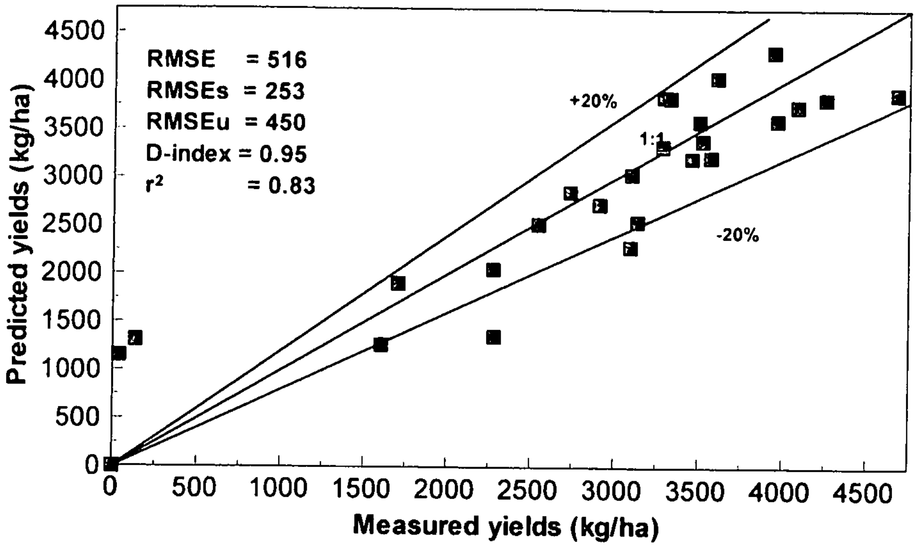

Figure 6.2 Measured versus simulated maize yields (kg ha^{-1}) by CYP-SA for all the treatments on the Glen/Bonheim ecotope during the 99/00 - 01/02 seasons.

6.4.3 SUNFLOWER

The next step was validation of the CYP-SA sunflower model on the Glen/Bonheim (99/00 - 01/02), Khumo/Swartland (97/98 - 01/02) and Vlakspruit/Arcadia (97/98 - 01/02) ecotopes with measured yield data from the *CON, BbBr, ObBr, ObSr*, and *SbOr* treatments. Results of model reliability tests using the procedure of Willmott (1981) are presented in Figure 6.3.

The model performed reasonably well. The D-index and r^2 values are good, 0.84 and 0.76 respectively, while the systematic error ($RMSE_S$) was 64 % of RMSE, which is lower than the threshold value of 65 %. The model simulates the yields reasonably accurately, although it seems that the model under-predicts some of the lower yields and tends to over-predict the higher yields.

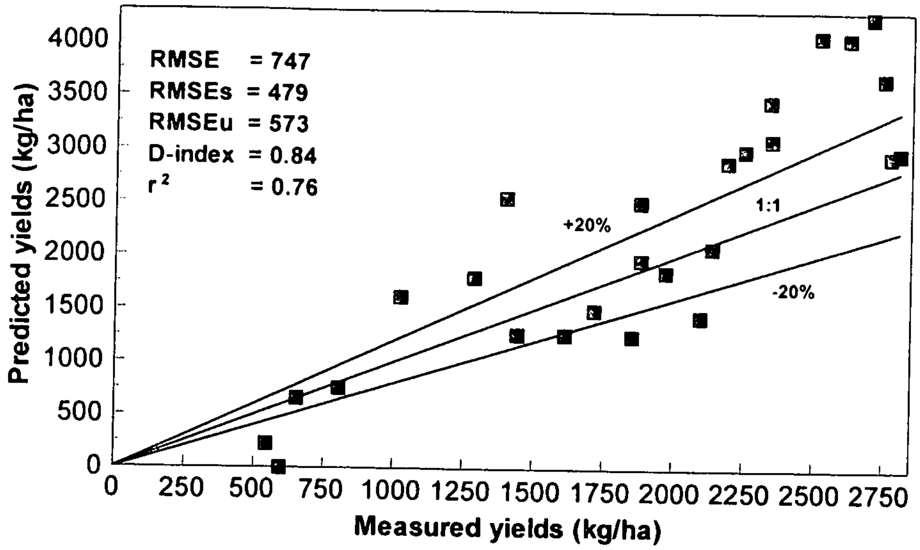

Figure 6.3 Measured versus simulated sunflower yields (kg ha^{-1}) by CYP-SA for different treatments on the Glen/Bonheim (99/00 - 01/02), Khumo/Swartland (97/98 - 01/02) and Vlakspruit/Arcadia (97/98 - 01/02) ecotopes.

6.5 SUMMARY

Various crop models were used for the prediction of crop yields as affected by mulch combinations within the in-field rainwater harvesting and micro-basin tillage (*IRWH*) systems. Unfortunately, none of the models that have been used or tested were able to make satisfactory yield predictions (Hensley *et al.*, 2000; Botha, Van Rensburg, Anderson, Hensley, Macheli, Van Staden, Kundhlande, Groenewald & Baiphethi, 2003). As a last resort an empirical Crop Yield Predictor for Semi-Arid areas (CYP-SA) model for sunflower and maize was developed to predict seed yield from the *IRWH* technique and as affected by various mulch combinations. The model was created to cater specifically for the following production techniques: *CON*; *IRWH* technique with a bare basin and runoff area (*BbBr*); *IRWH* technique with organic mulch in the basins and bare runoff area (*ObBr*); *IRWH* technique with organic mulch in the basins and stones on the runoff area (*ObSr*); *IRWH* technique with organic mulch in the basins and organic mulch on the runoff area (*ObOr*); *IRWH* technique with stones in the basins and organic mulch on the runoff area (*SbOr*); *IRWH* technique with stones in the basins and stones on the runoff area (*SbSr*). CYP-SA was not created to compete with existing models; it was only developed to serve as a tool for decision-making regarding crops water management, especially in the field of *IRWH*. The inputs required by the model are crop modified upper limit of available water (CMUL), drained upper limit of available water (DUL), lower limit of available water (LL), rainfall (P), evaporative demand (E_o) and soil water content at planting (θ_p). The CYP-SA model was validated against measured data. Results for the short-term yield predictions were reasonable good. It was therefore concluded that CYP-SA was suitable for making long-term yield predictions with long-term climate data.

Improvements in the CYP-SA model for maize and sunflower, and other crops are necessary. An efficient *IRWH* adapted crop model would make a valuable contribution towards the "NEPAD" expressed aim of improving rainfed crop production in Africa by means of water harvesting. The model would make it possible to extrapolate results to a wide range of ecotopes in Africa.

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CHAPTER 7 LONG-TERM AGRINOMICAL RISK ASSESSMENT OF MAIZE AND SUNFLOWER PRODUCTION UNDER IN-FIELD RAINWATER HARVESTING

ABSTRACT

A valuable property of models is their ability to utilize long-term climate data to provide long-term yield simulations, which can serve to quantify risk especially in semi-arid areas where rainfall is marginal and erratic with regard to amount, distribution and intensity. To be able to make reliable recommendations concerning the best production techniques for a crop on a particular ecotope it is desirable to have long-term yields. The use of crop models with long-term climate data to achieve this objective has been widely used in agriculture for more than a decade.

An empirical stress model "Crop Yield Predictor for Semi-Arid Areas" (CYP-SA) was developed to enable long-term yield predictions to be made. Validation results indicated that the model predicts maize and sunflower yields reasonable well on the Glen/Bonheim ecotope. One of the advantages of crop models is that they facilitate the pedo-transfer process. They enable predictions to be made for properly characterized ecotopes where experiments with a particular production technique have not been carried out. CYP-SA was used to make long-term maize and sunflower yield predictions with long-term climate data (81-year period) on the Glen/Bonheim, Khumo/Swartland and Vlakspruit/arcadia ecotopes. Cumulative probability functions (CPFs) of simulated long-term yields for maize and sunflower on these ecotopes using different production techniques were computed. The overall conclusions from this study are that the ObSr treatment is the best, and it is advisable to plant maize or sunflower early in January, especially when the soil water profile is between ¾ full and full. This strategy could help a farmer on this ecotope to reduce the risks of crop and financial failure, and in so doing promote food security.

Keywords: in-field rainwater harvesting, semi-arid areas, crop water stress model, maize and sunflower; long-term yield, risk

7.1 INTRODUCTION

According to Ritchie (1991), crop growth simulations models have achieved a certain level of popularity especially amongst agronomists and environmental researchers due to their importance for both the achievement of optimal sustainable crop production, and to give answers regarding ongoing negative effects of crop production on the environment. A crop model can be defined as a quantitative scheme for predicting the growth, development and yield of a crop, given a set of genetic coefficients and relevant environmental variables (Monteith, 1996). According to Passioura (1996), crop simulation models can be divided into two groups: those that aspire to improve the understanding of those physiology and environmental interactions and science of crops, and those that aspire to provide sound management advice on practical issues i.e. to solve current problems (engineering). Passioura (1996) further states that with a few exceptions those that aspire to improve the understanding of those physiology and environmental interactions and science of crops, have failed to meet their aspirations and are typically flawed by being based on untested guesses about the processes that control growth, but might provide useful self-education for their developers. The best "engineering" type models are based on robust empirical relations between plant behaviour and the main environmental variables, but due to their empirical nature they should not be applied outside the range of environmental variables used to calibrate them while on the other hand some of them have proved to be useful in providing sound management advice if they are used within their calibrated ranges (Passioura, 1996).

A valuable feature of models is their ability to utilize long-term climate data to provide long-term yield simulations, which can serve to quantify risk. Before crop models were available, land use decisions had to be based on the results of field experiments at a limited number of sites and generally over relatively few seasons. This procedure has serious limitations, which can be largely overcome by the judicious use of crop models, providing they are reliable. One of the advantages of crop models is that they facilitate the pedo-transfer process. They enable predictions to be made for properly characterized ecotopes where experiments with a particular production technique or crop have not been carried out. Other valuable applications of crop models are their use to extrapolate results to ecotopes on which field experiments have not been conducted, and their use together with long-term climate data to identify the most profitable production techniques under current economic and technology conditions, e.g. which crop, best planting date, best population, best variety, best rotation etc. Anderson, Botha & van Rensburg (2003) indicate that suitability of crop production technologies can be assessed through the use of crop models. Models can also assist in synthesis of research understanding about the interactions of genetics, physiology, the environment and integration across disciplines. Crop models can assist policy makers by predicting soil erosion, leaching of agro-chemicals, effects of climatic change and by making large-area yield forecasts (Schulze, 1995). Simulation models are used to estimate potential yield in new areas, to forecast yields before harvest, to estimate sensitivity of crop production to climate change, to compare management options and technology level and performance of varieties (Muchow, Hammer & Carberry, 1990).

Various crop models like DSSAT-V3 (Tsuji, Uehara & Balas, 1994); PUTU-Maize (Singels & De Jager, 1995); SWAMP (Bennie, Strydom & Vrey, 1998); and APSIM version 1.55 (APSRU Software Engineering Group, 1999) were tested for the prediction of crop yields as affected by mulch combinations within the in-field rainwater harvesting and micro-basin tillage (*IRWH*) systems. Unfortunately, none of the models that have been used or tested were able to make satisfactory yield predictions. As a last resort an empirical Crop Yield Predictor for Semi-Arid areas (CYP-SA) model for sunflower and maize was developed to predict seed yield from the *IRWH* technique and as affected by mulches (Chapter 6).

The aim of this chapter is to quantify risk and to plan production strategies for marginal maize and sunflower production on the Glen/Bonheim, Khumo/Swartland and Vlakspruit/Arcadia ecotopes using the CYP-SA crop water stress model.

7.2 PROCEDURE

Risk assessment was carried out for sunflower and maize on the Glen/Bonheim, Khumo/Swartland and Vlakspruit/Arcadia ecotopes. The latter two ecotopes are representative of a large area of land in the Free State Province, especially in the Tribal area of Thaba Nchu district on which a large number of rural households exits. The ecotopes were characterized with the procedure presented in Chapter 5 section 5.5.1. The different tillage treatments with maize and sunflower were:

- *CON*;
- *IRWH* technique with a bare basin and runoff area (*BbBr*);
- *IRWH* technique with organic mulch in the basins and bare runoff area (*ObBr*);
- *IRWH* technique with organic mulch in the basins and stones on the runoff area (*ObSr*);
- *IRWH* technique with organic mulch in the basins and organic mulch on the runoff area (*ObOr*);
- *IRWH* technique with stones in the basins and organic mulch on the runoff area (*SbOr*);
- *IRWH* technique with stones in the basins and stones on the runoff area (*SbSr*).

Rainfall data for Glen have been recorded for 81 years (1922 - 2003) and class A-pan evaporation data for 42 years (1958 - 2000). Daily rainfall for a nearby farm "North Bend" in Thaba Nchu at latitude 29°04`30`` S and longitude 26°56`00`` E is available from 1913 to 1984. The rainfall of North Bend for the period 1922 to 1984 was used for the long-term simulations on the Khumo and Vlakspruit ecotopes. Since the rainfall pattern of Glen is similar to that experienced in the Thaba Nchu area it was decided to use the Glen rainfall data for the period 1985 to 1996. For the period 1997 to 2002 the rainfall measured at Khumo and Vlakspruit was used. Since no evaporative demand (E_o) values were available for the Thaba Nchu district it was decided to use the recorded E_0 values of the Glen meteorological station. This newly constructed weather data set was used as one of the inputs for the CYP-SA model for long-term yield predictions. The other ecotope-related inputs used in the model are summarized in Table 7.1. The inputs required by the model are crop modified upper limit of available water (CMUL); drained upper limit of available water (DUL); lower limit of available water (LL); rainfall (P); E_o and soil water content at planting (θ_p). The CYP-SA model was validated against measured data. Results for the short-term yield predictions were reasonable good (Chapter 6). The model was therefore employed to assess risk on the selected ecotopes.

Table 7.1 Various soil and plant variables used in long-term yield simulations with the CYP-SA model

Water management borders	Crop	Soil water extraction properties (mm)		
		Glen/Bonheim	Khumo/Swartland	Vlakspruit/Arcadia
CMUL	Maize	485	423	479
DUL		456	385	456
LL		263	250	286
CMUL	Sunflower	485	423	479
DUL		456	385	456
LL		240	228	261

Long-term evaluation of production techniques was achieved by comparing long-term cumulative distribution functions of yield using the CYP-SA model and long-term climate data. This model was used for each ecotope, together with long-term daily climate data, to construct cumulative probability functions (CPFs) of crop yields to quantify the risk in the long-term associated with each production technique. According to Hensley (1995) CPFs provide a quantitative assessment of risk. From CPFs the best crop-ecotope combination and a suitable management option can be selected based on statistical analyses (Anderson, Dillon & Hardaker, 1977; Boehlje & Eidman, 1984; Steel, Torrie & Dickey, 1997; Zere, Hensley & van Huyssteen, 2006).

A problem that arises when making long-term simulations is that the water content at planting (θ_p) in each of the growing seasons is unknown. Another problem is that the models generally simulate the water balance poorly during fallow seasons, especially in a complex system as the *IRWH* (Anderson *et al.*, 2003). The result is that if one makes an uninterrupted long-term simulation including fallow seasons, and starting with an estimated initial water content in the first year, the water content at planting in any particular year could be incorrect by a significant amount. An alternative strategy has been employed here. The same θ_p value (½ full) was used for all treatments each year. A weakness of this procedure is that it will generally under-estimate θ_p for *IRWH*. Spring rains before planting will generally cause this treatment to have a higher θ_p than *CON*. The planting date was taken as 17 December every year. In spite of the weaknesses in this strategy it will expose marginal and unsatisfactory treatments. It could also be used to identify suitable ecotopes and production techniques. After the different tillage treatments were compared the best treatment was used with three planting dates, *viz.*, early (5th October), intermediate (17th December) and late (5th January), at the same θ_p value (½ full), in order to try to identify the best planting date. After the best planting date was identified the best treatment with the best planting date were used in a simulation study with CYP-SA to show the influence of increasing θ_p values, *viz.* empty, ¼, ½, ¾ and full, on maize and sunflower yields.

All statistical tests on cumulative probability functions were done with the Kolmogorov-Smirnov procedure as suggested by (Steel, Torrie & Dickey, 1997; Langyintuo, Yiridoe, Dogbe & Lowenberg-Deboer, 2002).

7.3 RESULTS AND DISCUSSION

7.3.1 GLEN/BONHEIM-ONRUS ECOTOPE

7.3.1.1 Ecotope characteristics

These are described in Chapters 2, 4 and 5.

7.3.1.2 Long-term risk assessment: Maize

Tillage methods:

The cumulative probability functions of maize yields simulated with CYP-SA on the Glen/Bonheim - Onrus ecotope using the proposed production techniques are depicted in Figure 7.1 a, b and c. Figure 7.1 a shows clearly that the *IRWH* treatments will all performed significantly better ($P \leq 0.01$) at any risk level than the *CON* treatment. Both *IRWH* treatments with stones on the runoff area (*ObSr* and *SbSr*) are significantly better than *BbBr* ($P \leq 0.01$) and *ObBr* ($P \leq 0.05$). The graphs predict that at a very low level of risk i.e., for an 80% chance of exceedance, when starting with a half-full profile the *CON*, *BbBr*, *ObBr*, *SbOr*, *ObOr*, *SbSr* and *ObSr* treatments will produce 770, 1600, 1650, 1850, 1875, 2000 and 2020 kg grain ha^{-1}, respectively. At this level of risk the *BbBr* treatment, which will be the departure point for any farmer, yielded 830 kg ha^{-1} higher than the *CON* treatment. Also all the treatments with mulch (organic or stone) on the runoff area produced on average 286 kg ha^{-1} higher yields than the *ObBr* treatment.

Steyn (pers. comm., 2003, Agricultural Research Council – Institute for Soil, Climate and Water, Pretoria) has found in the Eastern Cape Province of South Africa that a household of between 6 and 10 members need, as staple food, between 1000 kg and 1500 kg maize per annum. De Lange (pers. comm., 2003, International Water Management Institute, Pretoria) and Groenewald (pers. comm., 2003, Department of Sociology, University of the Free State, Bloemfontein) estimate that a household consisting of 5 members would need about 960 kg of maize per year. The households in the area east of Bloemfontein consist on average of 5 members (Kundhlande, Groenewald, Baiphethi, Viljoen, Botha, Van Rensburg & Anderson, 2004). Using the results on a typical ecotope in the Thaba Nchu area similar to the Glen/Bonheim in Figure 7.1 a, CYP-SA predicts that the risk involved for a farmer to harvest 960 kg ha^{-1} maize with *CON* tillage would be 28%. Assuming that a household has 1 ha of arable land tilled conventionally it can be derived that one out of four years the family would experience severe staple food shortages. This is normally the onset of the poverty spiral as the family have to make use of their resources to buy maize meal. For the small scale-farmer who cannot afford to fail, where it could mean life or death, this probability of failure is too high. With the *BbBr*, *ObBr*, *SbOr*, *ObOr*, *SbSr* and *ObSr* treatments the risk of failing (not harvesting 960 kg ha^{-1}) is only 12%, 10.5%, 8%, 7.8%, 6% and 5.7% respectively. With these techniques a household would have between an 88% and 96% probability of realizing a yield of 960 kg ha^{-1}. This is a very low and acceptable risk. The risk of failing with the *BbBr* treatment compared to the *CON* treatment is more than halved. It is clear that the *IRWH* techniques decrease the risk of crop failure tremendously. Assuming an 80% probability of success of reaping 960 kg of maize to be acceptable, it is predicted that the areas that would be needed using different tillage techniques would be 1.25 ha, 0.6 ha and 0.48 ha using the *CON*, *BbBr* and *ObSr* treatments, respectively. Using the better techniques would, relative to *CON*, therefore allow the farmer to plant other crops on the "spare" land to improve the balance of his family's diet or to sell the produce to the local markets.

Planting dates:

Figure 7.1 b shows that the early January planting is probably the best. The predicted mean long-term yields (80% probability) for early, intermediate and late planting are 1100 kg ha^{-1}, 2000 kg ha^{-1} and 2150 kg ha^{-1}, respectively. CYP-SA further predicts that a farmer will have an 83% probability of obtaining a yield of 2000 kg ha^{-1} with a late planting date, 80% with intermediate, and only a 56% probability with an early planting date. The results indicate that late and intermediate plantings are significantly better ($P \leq 0.01$) than early planting, and that there is no significant difference between intermediate and late planting on this ecotope.

Soil water content at planting:

The effect of pre-plant soil water levels is clearly illustrated in Figure 7.1 c. The higher the pre-plant soil water content the lower the production risk. Water stored between DUL and LL before planting is regarded as productive water as it contributed mainly transpiration and to a lesser extent Es. Calculations based on the water transpired support this, *viz*. for every mm crop yields will increase significantly. The second contribution of soil water to reduce risk is that it can maintain a longer photosynthate rate through the additional water supply to take the crop to the next rain event. This was clearly demonstrated in the soil water extraction curves in Figure 4.2 of Chapter 4. The value of planting with a rootzone that is at least ¾ full is clearly demonstrated, the predicted long-term yield (80% probability) being almost three times that with θ_p at empty (Table 7.2).

Table 7.2 Summary of long-term maize yield and statistical results with *ObSr* technique planting on 5 January with 5 different θ_p values on the Glen/Bonheim ecotope

θ_p	Predicted yield obtained with 80% probability (kg ha^{-1})	Statistics of CPFs	
		Comparison	P- level
Full	2775	> ½, ¼, Empty	0.01
¾	2500	> ¼, Empty	0.01
½	2150	> ¼	0.05
		> Empty	0.01
¼	1700	Empty	0.01
Empty	850		

All the above mentioned results indicate that for farmers to reduce the risk of crop failure it is more advantageous to use the *IRWH* technique instead of the *CON* treatment. By simply changing from *CON* to *BbBr* a farmer's probability of failing to harvest 960 kg ha^{-1} will be decreased by 43%. This will help the farmer to have an 88% probability to realize a maize yield of 960 kg ha^{-1}. This benefit can be attributed to the fact that *IRWH* has the ability to conserve more rainwater in the soil profile due to the total prevention of R. CYP-SA also indicates that a farmer, when using the *ObSr* treatment and planting early in January on a full profile, has a 98% probability (i.e. almost 100% certainty) of realizing a maize yield of 960 kg ha^{-1}. This is probably due to the fact that the mulch reduces Es.

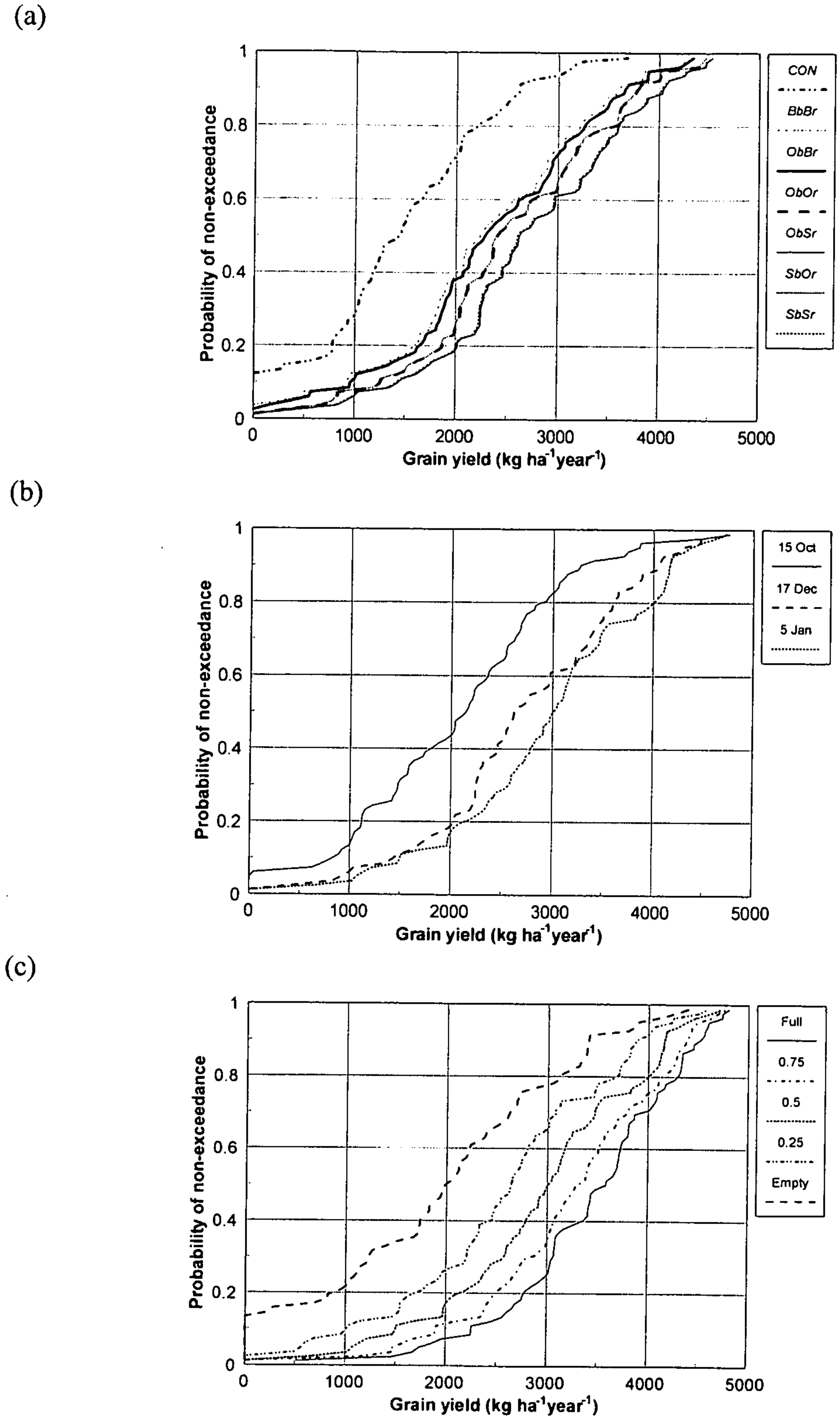

Figure 7.1 CPF graphs of long-term maize yields simulated with CYP-SA on the Glen/Bonheim - Onrus ecotope: (a) different tillage techniques, $\theta_p = \frac{1}{2}$ full, planted on 17 December; (b) *ObSr*, $\theta_p = \frac{1}{2}$ full, using three planting dates; (c) *ObSr*, planting on 5 January with 5 different θ_p values. Climate data used are for the 81-year period 1922-2003.

7.3.1.3 Long-term risk assessment: Sunflower

Tillage methods:

CPFs of long-term sunflower yields simulated with CYP-SA using different production techniques are presented in Figure 7.2 a, b and c. The symbols used for the various production techniques are indicated on the figures. The functions in Figure 7.2 a were used to calculate production risk at 80, 50 and 20% risk levels and the results are summarized in Table 7.3.

Table 7.3 Summary of long-term sunflower yield results with different tillage techniques, θ_p ½ full and planted on 17 December on the Glen/Bonheim ecotope

Production technique	Predicted mean long-term yield (kg ha^{-1})			Statistics of CPFs	
	Chance of success			Comparison	P - level
	80%	50%	20%		
ObSr	1120	1840	3075	> *CON, BbBr*	0.01
				>*ObBr*	0.05
SbSr	1100	1810	3060	> *CON, BbBr*	0.01
				>*ObBr*	0.05
ObOr	1015	1700	2830	>*CON*	0.01
SbOr	990	1670	2720	>*CON*	0.01
ObBr	785	1475	2550	>*CON*	0.01
BbBr	742	1425	2500	>*CON*	0.01
CON	315	800	1500		

The superiority of all the *IRWH* treatments over the *CON* treatment for all risk levels is clearly shown, with the best *IRWH* treatments yielding 3.5 times as much as *CON* at a low risk level. Even at the low level of risk, i.e. 80% chance of success, the *BbBr* yielded more than twice that of the *CON* treatment. *ObBr* produced a slightly higher yield than *BbBr,* presumably due to the suppressing effect of the organic mulch in the basins on Es, especially during the vegetative stage. All the treatments with a mulch (organic or stones) on the runoff area yielded (80% chance) on average 271 kg ha^{-1} more than the *ObBr* treatment. This result draws the attention to the importance of water conservation on the runoff area, in addition to that which takes place in the basins.

Planting dates:

Figure 7.2 b predicts that the best planting date for sunflower on the Glen/Bonheim ecotope is around 5 January, and that the intermediate planting date around 17 December is slightly better than the early planting date around 15 October. Late planting is significantly better ($P \leq 0.01$) than early and intermediate planting. The reason for this might be that sunflower will experience a more favourable climate (especially temperature and rain) during the flowering period, which would be during March, when planted in January. The graphs also indicate that farmers would have an 80% probability of harvesting 675 kg ha^{-1}, 1000 kg ha^{-1} and 1580 kg ha^{-1} with early, intermediate and late plantings respectively. In principle this means that a farmer would generally harvest 905 kg ha^{-1} more if he planted sunflower late instead of early on this specific ecotope. From the graphs it can be derived that for harvesting 2000 kg ha^{-1} the chance of succeeding by planting late, intermediate and early are 33%, 38% and 61%, respectively. These guidelines could easily make the difference between economic success and failure.

Soil water content at planting:

The CPFs for different pre-plant soil water levels are presented in Figure 7.2 c. The functions were used to calculate the yield risk at 80 and 20% probability and the results are summarised in Table 7.4. The benefits of having a rootzone filled up with water at planting are clearly demonstrated. It needs to be kept in mind that these results were obtained using the best tillage technique (Figure 7.2 a) and the best planting date (Figure 7.2 b). The poor results with θ_p values of half-full and less are also clearly exposed. For example, it would be possible to harvest 1850 kg ha^{-1} and 2500 kg ha^{-1} more sunflower by planting with a profile at ¾ full and a full plant available water (PAW), respectively, than starting with an empty profile. Based on this information, farmers on this ecotope can be guided that it may be economically advantageous to plant when θ_p is at least ¾ full. A possible management strategy indicated is therefore to delay planting until the rootzone is close to full - even if it means sometimes not planting during a particular season. This strategy could lead to economic gains in the long-term. A detailed economic study would however be needed to test the validity of such a strategy.

Table 7.4 Summary of long-term sunflower yields with the *ObSr* technique planting on 5 January with 5 different θ_p values on the Glen/Bonheim ecotope

θ_p	Predicted mean long-term yield (kg ha^{-1})		Statistics of CPFs	
	Chance of success			
	80%	20%	Comparison	P - level
Full	2650	3850	> ¾	0.05
			> ½, ¼, Empty	0.01
¾	2000	3690	> ½	0.05
			> ¼, Empty	0.01
½	1580	3270	> ¼, Empty	0.01
¼	1075	2895	Empty	0.01
Empty	150	2220		

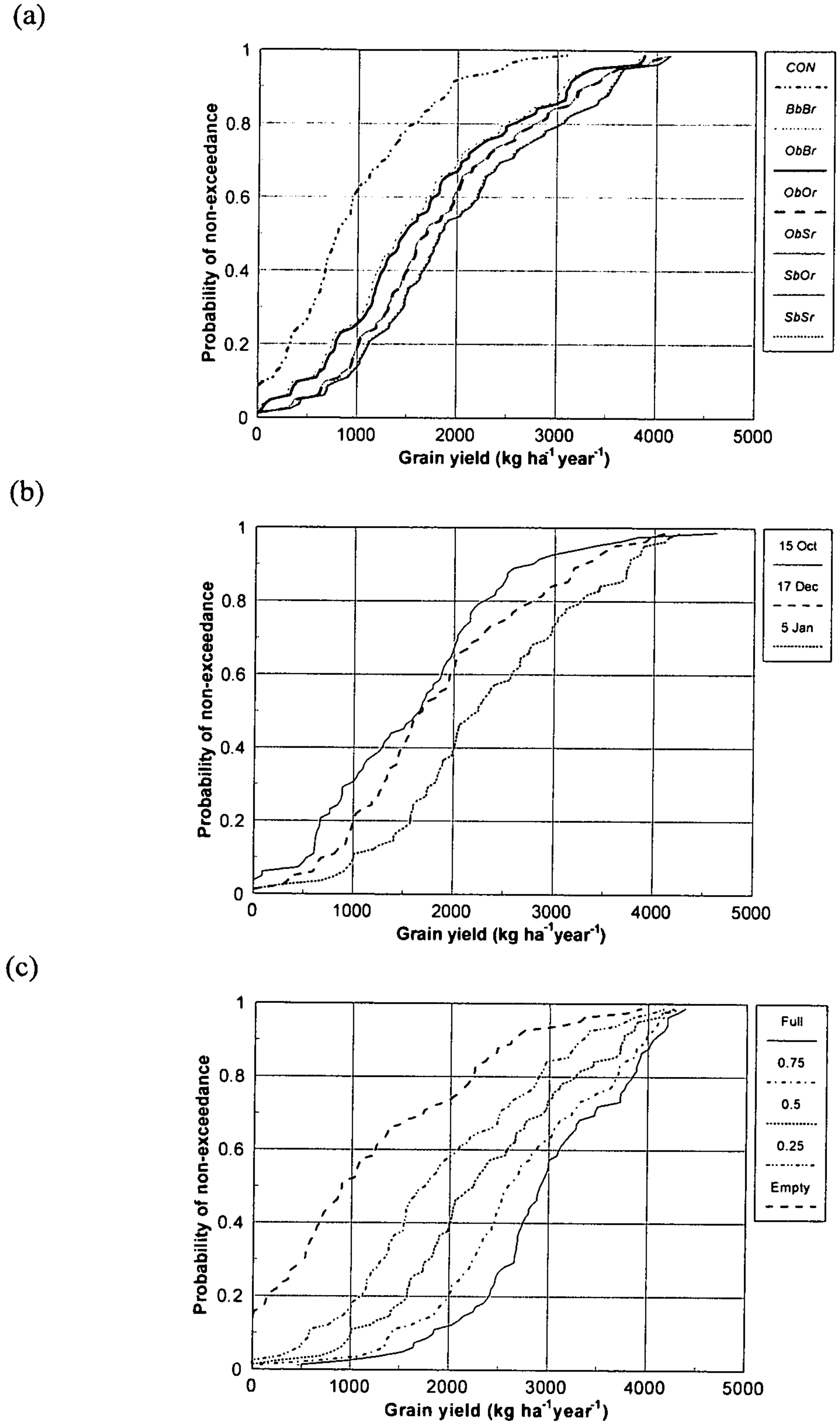

Figure 7.2 CPF graphs of long-term sunflower yields simulated with CYP-SA on the Glen/Bonheim – Onrus ecotope: (a) different tillage techniques, θ_p = ½ full, planted on 17 December; (b) *ObSr*, θ_p = ½ full, using three planting dates; (c) *ObSr*, planting 5 January and with 5 different θ_p values. Climate data used are for the 81-year period 1922 – 2003.

7.3.2 KHUMO/SWARTLAND-AMANDEL ECOTOPE

7.3.2.1 Ecotope characteristics

These are described in Chapter 5.5.

7.3.2.2 Long-term risk assessment: Maize

It was argued that CYP-SA for sunflower and maize do not differ that much and therefore CYP-SA for maize, although not validated against measured maize yield data obtained from the Khumo/Swartland ecotope, was used to simulate long-term maize yields on the Khumo/Swartland ecotope. CPFs of long-term maize yields simulated with CYP-SA (maize) on the Khumo/Swartland ecotope using different production techniques are presented in Figure 7.3 a, b and c. The production techniques tested in each case are depicted on the figures.

The results in Figure 7.3 a show that all the *IRWH* treatments are significantly better ($P \leq 0.01$) than the *CON* treatment. *ObSr* and *SbSr* are significantly better ($P \leq 0.01$) than *BbBr*. *ObBr* is significantly ($P \leq 0.05$) lower than *SbSr* and *ObSr*. The graphs indicate that at a 80% chance of exceedance yields of 1500, 1570, 1650, 1680, 1800 and 1850 kg ha^{-1} can be obtained using *CON*, *BbBr*, *ObBr*, *SbOr*, *ObOr*, *SbSr* and *ObSr* treatments, respectively, when starting with a half-full profile. Producing maize with *CON* at a risk of 80% chance of exceedance indicated that a household would need at least 2.4 ha to realize the needed 960 kg of maize for own consumption. Using the *BbBr* or *ObSr* treatments, for which the comparable predicted yields are 1500 and 1850 kg ha^{-1} respectively, a household would need only 0.64 and 0.52 ha respectively to produce the maize needed for home consumption. These more efficient strategies would allow the household to use more land to plant other crops to improve the balance of their diet, or to plant more maize to sell. The results indicate that it would be beneficial for a farmer, in terms of reducing risk and realizing higher sustainable yields, to use *IRWH* instead of *CON*, plant late rather than early, and preferably only plant when the soil water profile is more than half-full.

7.3.2.3 Long-term risk assessment: Sunflower

CPFs of long-term sunflower yields simulated with CYP-SA on the Khumo/Swartland ecotope using different production techniques are presented in Figure 7.4 a, b and c. The production techniques tested in each case are depicted on the figures.

From the graphs it can be derived that the mean long-term yield at 80% chance of exceedance when starting with a half-full profile for the *CON*, *BbBr*, *ObBr*, *SbOr*, *ObOr*, *SbSr* and *ObSr* treatments are 60, 620, 660, 780, 790, 815 and 930 kg ha^{-1} respectively. The superiority of all the *IRWH* treatments over the *CON* treatment for all risk levels is clearly shown, with the best *IRWH* treatments yielding 15 times as much as *CON* at a low risk level. Even at the low level of risk, i.e. 80% chance of success, the *BbBr* yielded more than 10 times that of the *CON* treatment. This again confirms the superiority of the *IRWH* techniques above *CON*. The results also show the superiority of late planting over early and intermediate planting. Figure 7.4 b predicts that a farmer would have an 80% probability of harvesting 575 kg ha^{-1}, 930 kg ha^{-1} and 1416 kg ha^{-1} with early, intermediate and late plantings respectively. In principle this means that a farmer would generally harvest 841 kg ha^{-1} more if he planted sunflower late instead of early on this specific ecotope. The benefits of having a root zone as full as possible at planting are clearly demonstrated in Figure 7.4 c. The CPF graphs indicate that a pre-plant water advantage plays an important role in decreasing the level of risk, but that at a high-risk level the role of pre-plant water advantage decreases. This clearly indicates the superiority of planting when θ_p is above half-full to reduce the risk of crop failure.

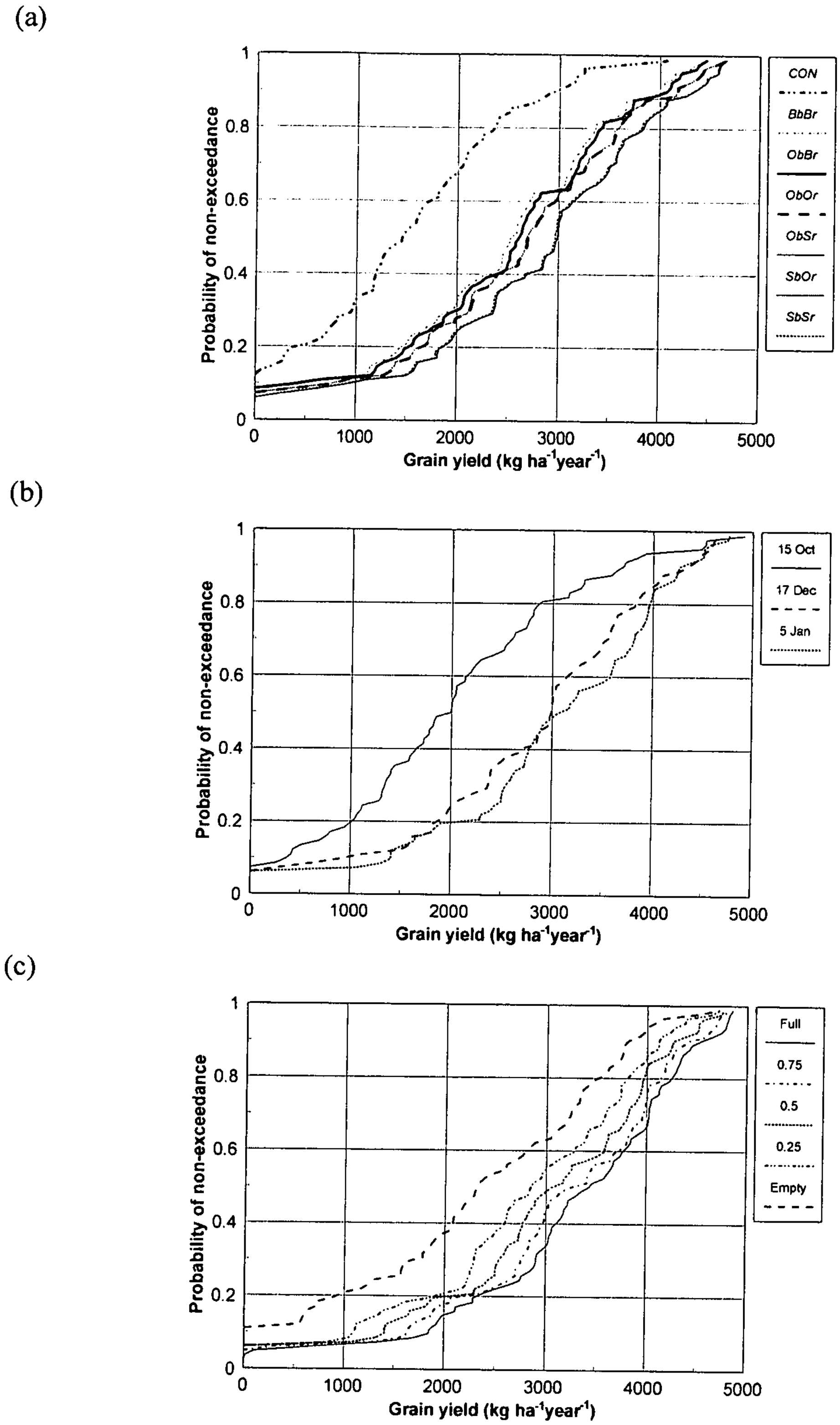

Figure 7.3 CPF graphs of long-term maize yields simulated with CYP-SA on the Khumo/Swartland - Amandel ecotope: (a) different tillage treatments, θ_p = ½ full, planted on 17 December; (b) *ObSr*, θ_p = ½ full, using 3 planting dates; (c) *ObSr*, planting on 5 January, and with 5 different θ_p values. Climate data used are for the 81-year period, 1922 – 2003.

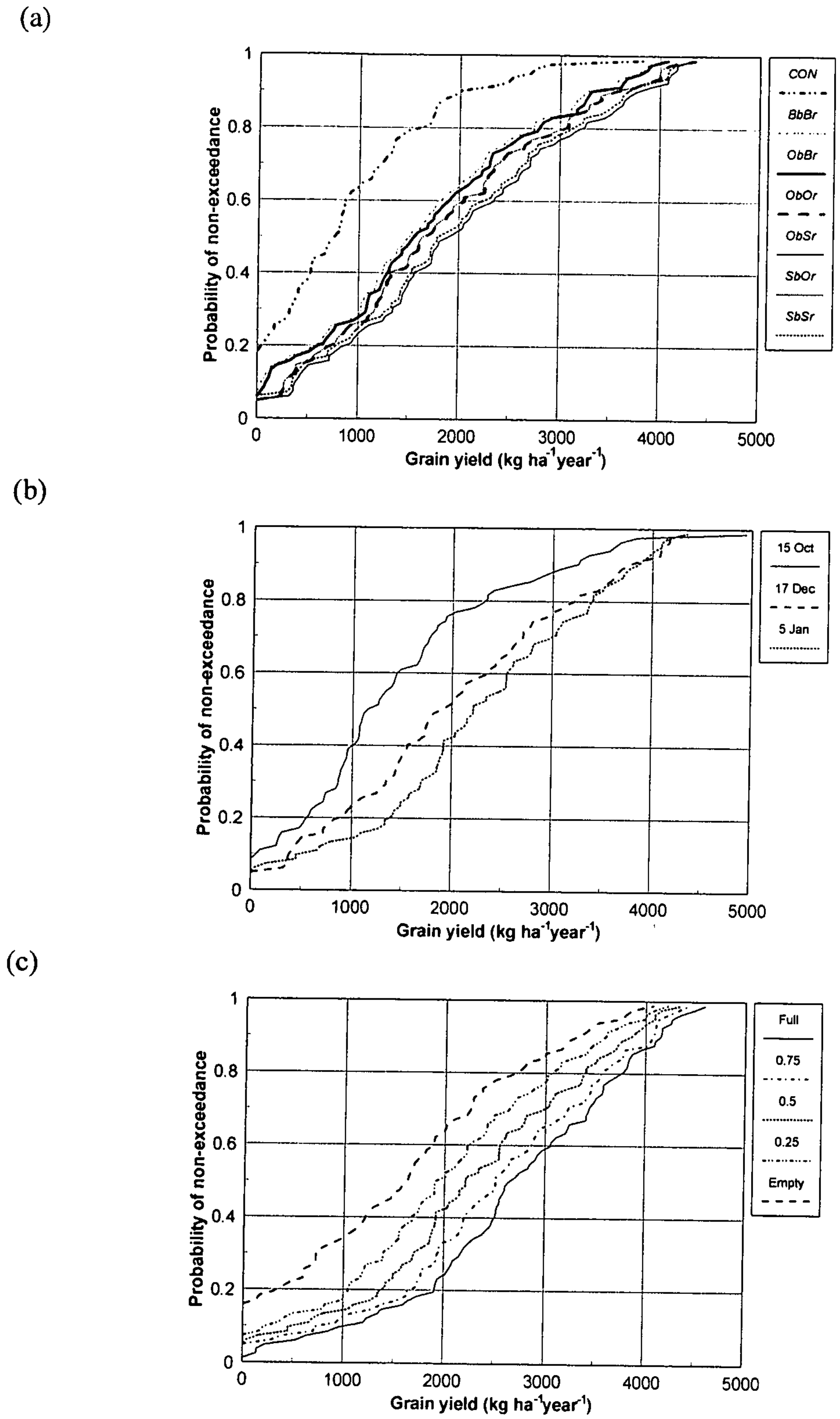

Figure 7.4 CPF graphs of long-term sunflower yields simulated with CYP-SA on the Khumo/Swartland - Amandel ecotope: (a) different tillage treatments, θ_p = ½ full, planted on 17 December; (b) *ObSr*, θ_p = ½ full, using 3 planting dates; (c) *ObSr*, planting on 5 January and with 5 different θ_p values. Climate data used are for the 81-year period, 1922 – 2003.

7.3.3 VLAKSPRUIT/ARCADIA-LONEHILL ECOTOPE

7.3.3.1 Ecotope characteristics

These are described in Chapter 5.6.

7.3.3.2 Long-term risk assessment: Maize

The same argument about the use of CYP-SA for maize on the Khumo/Swartland ecotope applies here; therefore CYP-SA for maize, although not validated against measured maize yield data obtained from the Vlakspruit/Arcadia ecotope, was used to simulate long-term maize yields. CPFs of long-term maize yields were simulated for different production techniques presented in Figure 7.5 a, b and c. The production techniques tested in each case are depicted on the figures.

Exactly the same trends can be seen here as on the Khumo/Swartland ecotope for maize. The only difference is that the maize yields are slightly higher on the Vlakspruit/Arcadia ecotope. The *CON*, *BbBr*, *ObBr*, *SbOr*, *ObOr*, *SbSr* and *ObSr* treatments have an 80% chance that yields of 614, 1550, 1600, 1780, 1800, 1960 and 1980 kg ha^{-1}, respectively, will not be exceeded. The closer the graph is to the right hand bottom corner of the figure, the higher is the potential of the production strategy. The simulations in Figure 7.5 b indicated that a farmer would have an 80% probability of harvesting 1200 kg ha^{-1}, 1980 kg ha^{-1} and 2475 kg ha^{-1} with early, intermediate and late plantings respectively. In principle it means that a farmer would harvest on average around 780 kg ha^{-1} and 1275 kg ha^{-1} more with intermediate and late plantings instead of early on this specific ecotope. In Figure 7.5 c the results of a simulation study with CYP-SA to show the influence of increasing θ_p values are presented. The planting date was 5 January and five θ_p values were used, *viz*. empty, ¼, ½, ¾ and full. In practice the results indicate that a farmer would generally harvest 166% more maize per hectare by planting on a full profile compared to an empty one. The benefits on this ecotope of soil water content of at least half-full at planting are also clearly demonstrated. In general the long-term CPF graphs of simulated maize yields indicate that it would be beneficial for a farmer, in terms of risk reduction and realizing higher sustainable yields on this ecotope, to use the *IRWH* production technique instead of *CON*, to plant rather late than early, and preferably only plant when θ_p is more than half-full.

7.3.3.3 Long-term risk assessment: Sunflower

CPFs of long-term sunflower yields simulated with CYP-SA on the Vlakspruit/Arcadia ecotope using different production techniques are presented in Figure 7.6 a, b and c. The production techniques tested in each case are depicted on the figures.

Exactly the same trends can be seen here as on the Khumo/Swartland ecotope for sunflower. The only difference is that the yields are slightly higher here. In general the long-term CPF graphs indicate that it would be beneficial for a farmer on this ecotope to use the *IRWH* production technique, to plant late, and to only plant when the soil water profile is more than half-full.

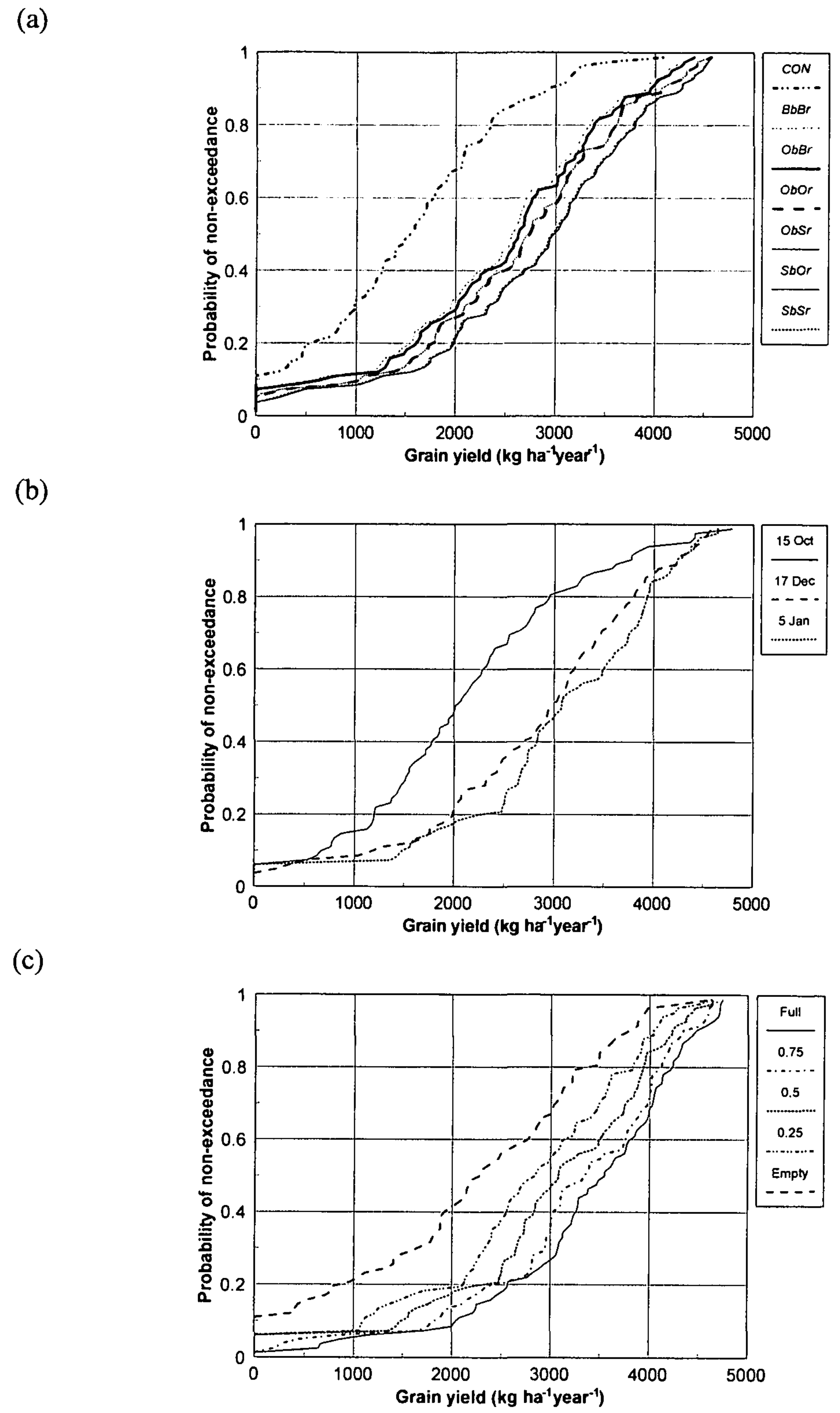

Figure 7.5 CPF graphs of long-term maize yields simulated with the CYP-SA on the Vlakspruit/Arcadia - Lonehill ecotope: (a) different tillage treatments, $\theta_p = ½$ full, planted on 17 December; (b) *ObSr*, $\theta_p = ½$ full, using 3 planting dates; (c) *ObSr*, planting on 5 January, with 5 different θ_p values. Climate data used are for the 81-year period, 1922 – 2003.

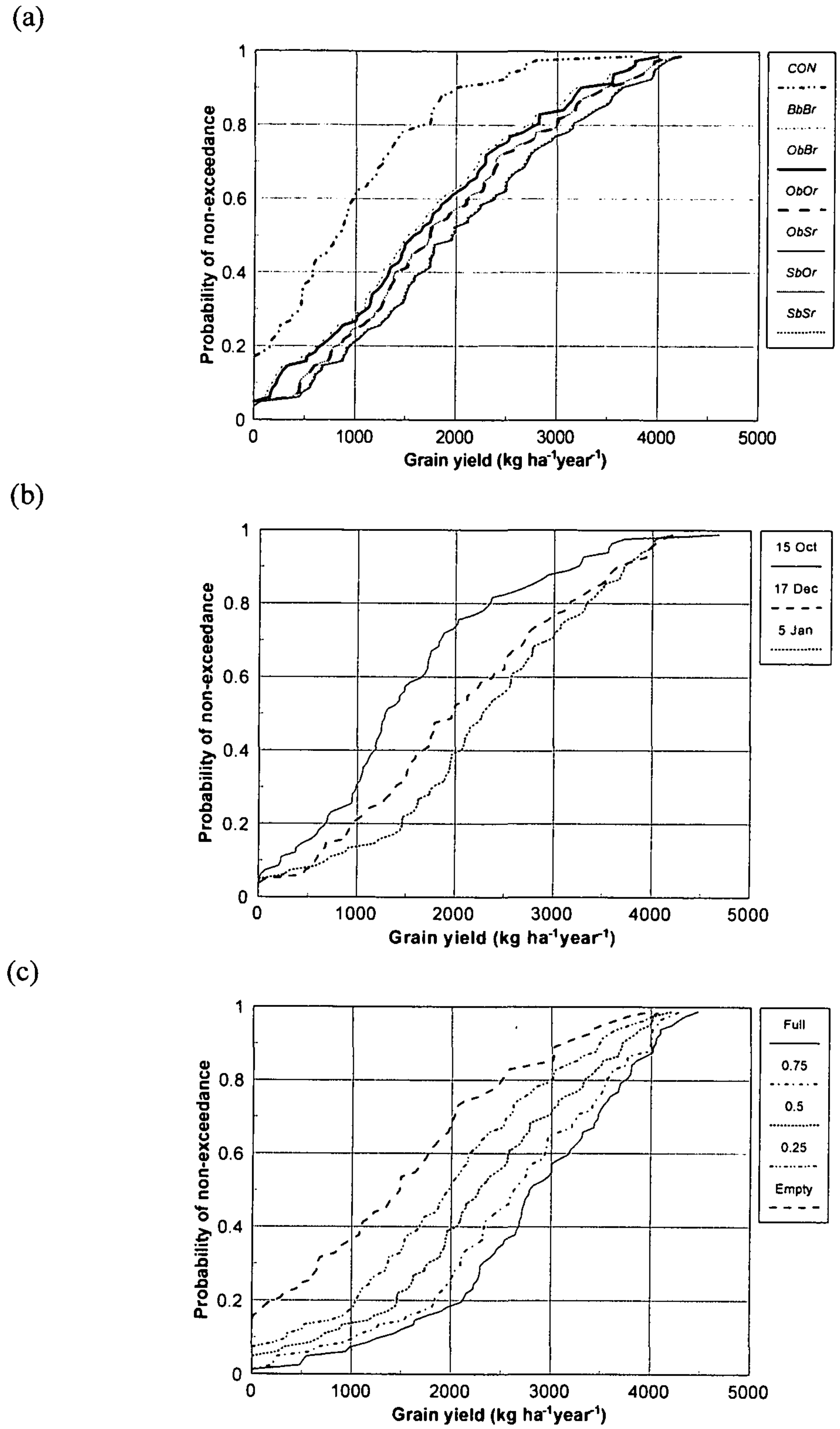

Figure 7.6 CPF graphs of long-term sunflower yields on the Vlakspruit/Arcadia - Lonehill ecotope: (a) different tillage treatments, θ_p = ½ full, planted on 17 December; (b) *ObSr*, θ_p = ½ full, using 3 planting dates; (c) *ObSr*, planting on 5 January, with 5 different θ_p values. Climate data used are for the 81-year period, 1922 – 2003.

7.4 SUMMARY AND CONCLUSIONS

Long-term yields were simulated with CYP-SA using in-situ determined soil and crop variables to quantify risk. Cumulative probability functions (CPFs) of simulated long-term yields for maize and sunflower on the Glen/Bonheim, Khumo/Swartland and Vlakspruit/Arcadia ecotopes using different production techniques were developed. The main aim with long-term weather data and the model CYP-SA was to differentiate between different tillage treatments on different ecotopes. Out of these results a few management recommendations could be made. The Kolmogorov-Smirnov test indicated that both maize and sunflower produced with the *IRWH* techniques statistically ($P \leq 0.01$) out-performed the *CON* tillage. Furthermore that the *ObSr* and *SbSr* treatments performed statistically better than the *BbBr* treatment for both maize and sunflower ($P \leq 0.01$). It has also indicated that with maize and sunflower crops the *ObSr* and *SbSr* treatments performed statistically better ($P \leq 0.05$) than the *ObBr* treatment.

CYP-SA indicates that maize yields will increase by 71% through changing from *CON* to *BbBr*, by another 3% when changing from *BbBr* to *ObBr* and by a further 17% when changing from *ObBr* to *ObSr*. CYP-SA simulates that sunflower yield will increase by 93% when changing from *CON* to *BbBr*, by another 7% when changing from *BbBr* to *ObBr* and by a further 47% when changing from *ObBr* to *ObSr*.

Certain management practices are more important for certain crops. CYP-SA simulated that it would be more advantageous for a farmer to plant maize on similar ecotopes between mid-December and early January with pre-plant soil water levels higher than ¾ full. The same strategy can be followed for sunflower, except that it would be much more of an advantage to plant late. These guidelines could help farmers on these ecotopes to reduce the risks of crop and financial failures, and in so doing promote food security.

When comparing the different ecotopes in terms of risk at 80% probability of succeeding, the best ecotope to plant maize on would be the Glen/Bonheim and Vlakspruit/Arcadia ecotopes, and in the case of sunflower the Glen/Bonheim ecotope, although higher yields are possible on the other ecotopes. When comparing the ecotopes in terms of crop yields at all risk levels, the Vlakspruit/Arcadia ecotope is the best for ecotope and higher maize and sunflower yields are possible on this ecotope.

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CHAPTER 8: ALLEVIATING HOUSEHOLD FOOD INSECURITY THROUGH IN-FIELD RAINWATER HARVESTING

ABSTRACT

Poverty and food insecurity are generic to the rural communities of poor countries in the sub-Saharan African region. South Africa, with its huge rural population is not excluded from the adversity of poverty. Recent surveys on monthly consumption expenditure for households living in Thaba Nchu and Botshabelo districts, located east of Bloemfontein, showed that the mean is R278 per household. Household members consist of three (3) adults and two (2) children. For such households to be classified as poor the threshold is regarded as R907 using 2004/2005 monetary values. This is clear that the communities under investigation are poor and in a great need as they only have one meal per day most of the time. It was hypothesized that the in-field rainwater harvesting (IRWH) techniques can improve household food security by applying it in the garden area of their homesteads. This paper reports on the unexpected spread of the application of the IRWH techniques amongst homesteads also on the potential towards eradicate poverty at household level using selected case studies. Household members obtained the necessary skills to apply the technique in an innovative manner at their homesteads. They were able to expand the technique by using vegetables, which were planted on own initiative. Results indicated that excess produce could be sold on local markets, which can ensure a sustainable living. Several recommendations were made to the farmers, administrators and policy makers to create awareness about the potential application of the IRWH techniques elsewhere in South Africa and beyond.

Keywords: in-field rainwater harvesting, household food security, poverty, homesteads and semi-arid.

8.1 INTRODUCTION

Poverty and food insecurity are generic to the rural communities of poor countries in the sub-Saharan African region. People in these areas usually depend on rainfed agriculture and the exploitation of natural resources for household consumption and income generation. Usually these areas lack industries and are often marginal crop production areas due to a number of biophysical constrains. On 17th December 2002, an official from the UN Food and Agriculture Organization (FAO) reported in Rome, Italy, that some 40 million people in sub-Saharan Africa are threatened by severe food shortages and a major humanitarian crisis is deepening in Southern Africa. South Africa, with its large rural population is not excluded from this problem. DBSA (1993), estimate that more than 50% of the population of South Africa live below the poverty line, with the largest numbers being rural black people domiciled in the former homelands. In a more recent report Charlton & Rose (2002), National Treasury (2003) and the Human Sciences Research Council (2004) stated that more than 14 million people, or about 35% of the population in South Africa are severely vulnerable to food insecurity and that 43% of the households suffer from food poverty. The majority (about two thirds) of the poor and food insecure people live in rural areas where they rely mostly on rainfed agriculture (National Department of Agriculture, 1998 and 2001; Ngwane, Yadavalli & Steffens, 2001; Ortmann and Machethe, 2003; Human Sciences Research Council, 2004). In the Free State Province where the study was conducted, 54% of the population is regarded as food insecure, 56% suffer from poverty and 31% are unemployed (Free State Provincial Department, 2005; Department of Agriculture - Free State, 2006).

The main reason for certain former homeland areas being marginal for crop production in South Africa is low rainfall. Generally, only a small proportion of the land is under some form of irrigation (Vink & Kirsten, 2003). This implies that rainfed agriculture will, for the foreseeable future, be a dominating source of food for the people in these areas (FAO, 1990; Parr, Stewart, Hornick & Singh, 1990; Vink & Kirsten, 2003). Thus, improved and sustained growth in agricultural productivity is seen as critical for improving food security for rural populations (Weibe, 2001; Ortmann and Machethe, 2003). In line with the above, the Free State Mission (FSM) on rural investment recognized that poverty and food insecurity are the major problems facing the Free State rural people (FSP/World Bank, 1997). The FSM aims to encourage the creation of sustainable livelihoods in the rural areas and in the peri-urban economy of the Free State (FSP/World Bank, 1997).

In the Free State small-scale resource poor farmers occupy a large area east of Bloemfontein. The area has a large population living in 42 communities scattered around the two towns of Thaba Nchu and Botshabelo. These were formerly parts of the Bophuthatswana homeland. This semi-arid study area is marginal for crop production because of relatively low and erratic rainfall and predominantly duplex and clay soils. These conditions result in low and often no yield because of high water losses due to runoff and evaporation from the soil surface.

A recent socio-economic survey in the Thaba Nchu district showed that the average consumption expenditure for a household is R278 per month (Kundhlande, Groenewald, Baiphethi, Viljoen, Botha, Van Rensburg & Anderson, 2004). The equivalent poverty line for a household in the Free State that comprises of 5 members (including 3 adults) is R953 per month. This clearly indicates that most of the households are living below the South African poverty line for rural households, which according to Carter & May (1999) and Fraser, Monde & Averbeke (2003) was R476.30 in 1999 per adult equivelant. Most households in the study area may be classified as ultra poor (below half of the poverty line) based on the adult equivalent income per household. Government support in the form of old age pensions and child support grants evidently comprise the largest part of cash income. This information indicates that there is a need for measures that will increase the household food and/or income. If successful such measures could contribute significantly towards eradicating poverty and food insecurity. It was hypothesized that by the application of in-field rainwater harvesting (*IRWH*) techniques could empower farmers in the study area to produce their own crops using the land in their homesteads, hence eliminates food insecurity.

8.2 MATERIALS AND METHODS

8.2.1 DESCRIPTION OF THE STUDY AREA

Despite of the fact that most households in the area have access to about 2 to 4 ha of arable land, they do not currently use the available land to produce crops (Botha, Van Rensburg, Anderson, Hensley, Macheli, Van Staden, Kundhlande, Groenewald & Baiphethi, 2003b). Each community has a fixed amount of land that is divided into the following categories: residential; arable land and grazing (Table 8.1). A Participatory Rural Appraisal (PRA) survey conducted in the study area revealed that most households have given up crop farming using conventional tillage (*CON*), due to continuous crop failures caused by unfavourable climate, poor soils and lack of management skills. Traditional crop farming skills are almost non-existent in the study area. The reason for this is that the small-scale farmers became dependent prior to 1994 on government to supply equipment, inputs and expertise for land preparation, planting and maintenance of the crops. These services were terminated after 1994, leaving the farmers to survive on their own. The result was that most families stopped crop production, leaving them to depend on the communal pastures for their livestock, as the only agricultural means of earning an income.

According to Baiphethi, Kundhlande, Viljoen, Botha & Van Rensburg (2003) some of the families tried their best to produce crops on their communal lands, using their own recourses, but the reason for failure is the lack of appropriate production technologies, low returns from production and other constraints. Some of the arable land has not been cultivated for the last three to five years or even more. In addition, to cropland households have on average 0.2 ha of homestead land, part of which they can use to produce crops in homestead gardens. Currently the homestead gardens are used far more productively than the croplands, with production largely aimed at household consumption. Most community members have indicated that their present circumstances are not satisfactory and that improving agricultural production would provide a potential means for more secure livelihoods. This has led to suggesting to farmers that they try *IRWH* as a new production technique. According to Botha, Van Rensburg, Anderson, Kundhlande, Groenewald & Macheli (2003a), converting croplands into sustainable enterprises presents a considerable challenge to all involved in such a project.

Table 8.1 Community sizes; arable and grazing land capacity at Thaba Nchu (ha)

Village name	Residential	Arable (ha)	Grazing (ha)
Balaclava	20	354	846
Bofulo	34	215	2 017
Kommisiedrift	40	260	1 989
Feloané	30	80	1 208
Gladstone	60	378	2 972
Grootdam	20	200	840
Houtnek	50	290	1 649
Kgalala 1	70	300	1 974
Kgalala 2	80	300	2 028
Klipfontein	20	320	878
Longridge	10	110	260
Maraisdal	10	160	730
Merino	40	170	1 995
Middeldeel	25	190	1 852
Motlatla	50	148	2 041
Moroto	25	134	1 240
Mothusi	30	327	1 727
Morago	70	300	1 650
Nogaspost	40	137	1 992
Paradys	40	274	1 795
Potsane	30	110	830
Post	10	195	300
Rhakhoi	20	200	1 175
Rooibult	60	216	2 017
Rooifontein	50	260	3 704
Rietfontein	66	231	1 723
Ratau	90	250	1 650
Sediba Trust	50	250	1 049
Sediba Scheme	15	80	225
Seroalo	24	180	1 434
Spitskop	42	190	1 964
Springfontein	18	160	716
Talla	52	514	2 486
Tiger River	40	230	1 790
Thubisi	26	300	1 528
Tweefontein	40	280	1 210
Victoria Nek	15	150	1 104
Woodbridge Scheme	15	110	320
Woodbridge Trust	15	130	870
Yoxford	36	266	2 179
Total	**1 478**	**8 929**	**59 957**

Source: Free State Department of Agriculture, Thaba Nchu office, 1998.

8.2.2 DESCRIPTION OF THE PRODUCTION TECHNIQUE

The *IRWH* technique developed by Agricultural Research Council - Institute for Soil, Climate and Water (ARC-ISCW) researchers at Glen (Hensley, Botha, Anderson, van Staden & du Toit, 2000), combines the advantages of water harvesting, no-till, basin tillage and mulching on high drought risk ecotopes (Figures 1.3 and 8.1). This innovative water conservation technique has the ability to reduce total runoff to zero, and also reduce evaporation (Es) to a considerable extent, resulting in increased plant available water and therefore increased yields (Chapters 4 and 5).

Figure 8.1 A picture of the in-field rainwater harvesting technique shortly after a rain event.

The *IRWH* technique is described in detail in Chapter 1. Intensive field experiments conducted over a period of six years on duplex and clay soils at Glen (on-station) and in Thaba Nchu (on-farm) have indicated that conserving water this way led to crop yield increases that varied between 30 and 110% above *CON* ploughing practises (Chapters 4 and 5).

8.2.3 TECHNOLOGY EXCHANGE

During the 01/02 growing season four communities that needed immediate attention in terms of poverty alleviation and those that would represent the diversity of the economic activities and geographic position of the Thaba-Nchu - Botshabelo area have been selected with the help of an extension officer. The communities selected were Talla from the Northern region, Feloanè and Paradys from the Central region and Yoxford from the Southern region. With the first contact with the members of the different communities, it was clear that technology exchange would be a mammoth task and social acceptability of the *IRWH* an intense process that will last for years. The main reason for this is the fact that most of the existing farmers adopted *CON* as a method of crop production. However, the members from the different communities accepted the offer to demonstrate both the *CON* and *IRWH* techniques in their communities with on-farm demonstration/training plots. These demonstration/training plots were applied at the croplands and/or at homesteads. During the field visits it was observed that: (i) some of the residents produced dryland maize in their homesteads mainly for household consumption; (ii) yields were very low (Figure 8.2). Knowing that most of the residents or households have access to 1 – 5 ha of cropland it was therefore decided to use the homesteads as a stepping-stone to empower the people argonomically. In other words homesteads were used as a "class room" to educate families on the new technique. Consequently, demonstration/training plots were laid out in homesteads, with the difference that the family should manage the *CON* treatment according to their own practices. It was agreed that the technical assistants from the ARC-ISCW would manage the *IRWH* treatments. The project provided agronomic inputs for both treatments. Farmers from the surrounding rural communities visited these demonstration/training plots during farmers' days. From the 02/03 growing season onwards the farmers and residents showing interest in applying the *IRWH* technique were visited at regular intervals during the year. They were assisted to master the technical aspects of the production technique, i.e., land preparation, planting, weeding, etc.

Apart from the day-to-day activities, various formal technology exchange activities took place. These included activities such as formal and informal educational training courses, pre- and post-harvest focus group discussions, information days, farmer-to-farmer training, and water harvesting festivals over periods of four to five days. At the focus group discussion certain aspects were discussed and a lot of planning and goal setting took place during these sessions. Formal and informal educational sessions were first conducted with extension officers and thereafter extension and the researchers conducted the same training with the farmers. Educational training session did not only focus on *IRWH*, but much broader topics were addressed. Training focussed on different soil types, crop nutrition, weed control, insect control, management practices, record keeping and budgeting, markets and marketing, the role and function of committees, conflict resolution, communication skills, etc. The technology exchange actions and strategy are explained in more detail by Van Rensburg, Groenewald, Botha, Anderson, Van Staden & Kundhlande, 2003 and Botha, Groenewald, Anderson, Mdibe, Nlhabatsi, Zere & Baipethi, 2006.

Figure 8.2 Mr Danïel Mataung, a farmer from the community Feloanè demonstrating the difference in crop height between mature maize plants on the *CON* (left) and *IRWH* (right) plots.

8.2.4 CASE STUDIES

The extension section of the research group (technical assistants) recorded the number of farmers who implemented the *IRWH* technique monthly by gathering the relevant data at the focus group discussions.

Case studies of a number of residents from different communities were analysed to assess the potential of *IRWH* to relieve household food insecurity and poverty. This study was aimed at evaluating the contribution that homestead gardens and croplands could make towards alleviating food insecurity and poverty. Homestead gardens and croplands of individuals with two seasons experience of the *IRWH* technique, and others with only one seasons experience were used in these studies.

In order to gather information regarding crop yield and income data 38 households from various communities was interviewed at the end of the 03/04 growing season. Households with one and two seasons experience of the *IRWH* technique were interviewed. The areas planted with different crops were measured and farmers kept accurate records of yields. Technical assistants were used to monitor the farmers on a weekly basis and verify results obtained from the farmers. Prices obtained from formal and informal markets from Thaba Nchu were used to calculate the gross income that the farmers could have made if they had sold the crops that they produced, or if they had been forced to buy what had been produced. The input costs for seeds, fertilizers and weed control were subtracted to get the net profit.

8.2.5 ANALYSIS OF HOUSEHOLD CONSUMPTION

In order to gather information regarding household expenditure/consumption and to determine the contribution of *IRWH* to household's income a structured questionnaire was developed. Prof Dirk Groenewald from the Department of Sociology, University of the Free State - Bloemfontein, approved the questionnaire. Prof. Groenewald trained the interviewers beforehand. Household consumption/expenditure data from different communities in the study area were collected during 2001, before the *IRWH* technique had been introduced, and then again later during 2004, after three growing seasons. The data included household composition, income sources and the expenditure on food by the household. The data were used to determine the adult equivalent income (ADEQI) in R/month, and the percentage of ADEQI used to purchase food. This information was plotted in a scatter plot and a trend line fitted to the plot. The statistical package of Microsoft Excel was used for regressing the data. During 2001, 124 interviews were conducted with either the head or a representative of households from the four selected communities (Feloanè, Paradys, Talla, and Yoxford). At the end of the 03/04 growing season 97 interviews were conducted with randomly selected households from eight communities (Balaclava; Feloane; Klipfontein; Modutung; Potsane; Rooibult; Woodbridge 2; Yoxford).

8.3 RESULTS AND DISCUSSION

8.3.1 OVERVIEW OF EXPANSION: *IRWH* APPLICATION TRENDS

Results of the expansion in the application of the *IRWH* technique are presented in Figure 8.3 in terms of amount of households applying the technique in the garden area of their homestead and the number of communities involved. During the first growing season (01/02) the *IRWH* technique was demonstrated in homesteads of six households from four communities. By 02/03 the numbers increased to 108 families and six communities. In 03/04 the numbers increased further and amounted to a total of 400 households from 37 communities. The number of households in the communities that applied the *IRWH* technique during the 03/04 season varied between one and 55 families per community. Before planting time for the 04/05 season the number had further increased to more than 1033 households in 42 communities and one trust farm. The number of households in the communities that applied the *IRWH* technique before the 04/05 season, varied between three and 100 families per community. From the graph it is clear that the application of *IRWH* spread quickly amongst the households and communities. Since the introduction of the six households during the 01/02 growing season, an exponential increase in application of the *IRWH* technique was observed. It seems that this result was due to the combined impact of an efficient extension programme from the research team and an effective new crop production technique, which was self-demonstrating. The expansion of the *IRWH* technique is discussed in more detail in Botha *et al.* (2003b) and Botha *et al.* (2006).

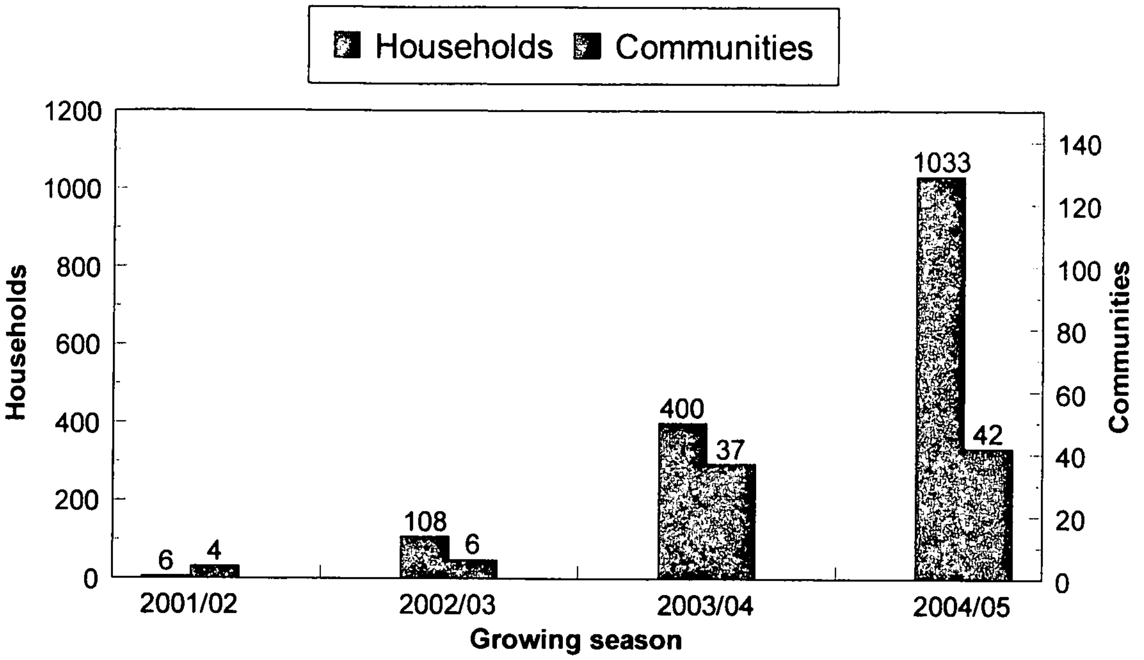

Figure 8.3 A graphical representation of the expansion in application of *IRWH* by households in their homesteads from different rural communities during the 2001/02, 2002/03, 2003/04 and 2004/05 growing seasons.

8.3.2 CASE STUDIES:

Homestead gardens:

The residents of the different communities generally planted a variety of crops as part of their *IRWH* strategy to combat food insecurity. During the 03/04 growing season 15 different crops were planted. The minimum area in a homestead garden used to produce food with the *IRWH* system was 180 m^2, while the maximum was 1422 m^2 and the average *IRWH* plot size in homestead gardens about 679 m^2. Maize, considered as a staple food, was the crop planted on the largest area (mean of ± 402 m^2) in most of the homestead gardens. Beans, pumpkins, squashes and watermelons were also very popular. Net profits obtained from homestead garden production with the *IRWH* technique varied between R36 and R8146 per household, with an average from 38 households of R1929. The net profit in R m^{-2} varied between 0.12 and 11.07, while the average was 3.04. Using this figure together with the average area per household indicates that on average, a profit of R2064 can be realized from homestead garden production. This shows that homestead garden food production using *IRWH* can make a significant impact on food security through: (i) the ability of the people to buy food with the money obtained through selling of their produce; and (ii) the cultivation of a variety of crops for own consumption. This has resulted in change in the attitudes, confidence and hope of the people. They have started to believe in themselves and have hope for a better future.

Examples of profits that could have been obtained by different households are presented in Table 8.2. Mr. Dibeco from the community Ratabane was the first person to make use of the *IRWH* technique in his community during the last growing season (03/04). This was also the first time he used the technique. With the profits he obtained from his homestead garden production it was possible to keep his daughter in a good school in Bloemfontein. Without this income this would not have been possible. Motivated by the success of Mr. Dibeco 18 people prepared their land to implement the *IRWH* technique in the community during the 04/05 season.

Table 8.2 Results of case studies to assess the potential of *IRWH* to relieve household food insecurity and poverty: Profits obtained at some of the homestead gardens from different communities during the 03/04 growing season

Person	Years of *IRWH* experience	Crop	Area (m^2)	Net Profit (R)	Profit ($R\ m^{-2}$)
Mr. Lonake	2nd year	Maize	414	740	1.79
		Tomatoes	81	1381	17.05
		Beans	138	38	0.28
		Beetroot	54	155	2.87
		Spinach	54	3	0.05
		Pumpkin	54	133	2.46
		Total	**795**	**2450**	**3.08**
Mrs. Salman	2nd year	Maize	252	1654	6.56
		Dry beans	36	424	11.79
		Tomatoes	9	540	59.95
		Total	**297**	**2618**	**8.81**
Mrs. Mokgothu	1st year	Maize	360	1981	5.50
		Beans	18	212	11.76
		Carrots	18	198	11.00
		Pumpkin	72	1122	15.58
		Watermelon	72	253	3.51
		Beetroot	18	230	12.76
		Spinach	18	217	12.07
		Total	**576**	**4213**	**7.31**
Mr. Dibeco	1st year	Maize	360	3985	11.07
		Total	**360**	**3985**	**11.07**
Mrs. Choane	1st year	Maize	108	519	4.81
		Beans	90	305	3.38
		Pumpkin	81	1010	12.46
		Beetroot	18	331	18.37
		Spinach	9	168	18.62
		Total	**306**	**2333**	**7.62**

Homestead gardens and croplands:

Results of a case study involving Mr. Chwane of the community Woodbridge 2 are presented in Table 8.3. The contributions of homestead garden and cropland food production on food security and poverty alleviation are shown. Mr. Chwane total net profit is shown to be R7037, consisting of R414 and R6623 from the homestead garden and cropland respectively. This income exceeds the amount of ± R5000 that is required to eradicate poverty per household per year.

Results from Mr. Chwane and from 38 households that produced food in their homestead gardens indicate that homestead garden food production with the *IRWH* technique can contribute significantly to household food security, while production on the cropland can contribute to both food security and alleviation of poverty. It is therefore critical for people in rural areas, not only to make use of the *IRWH* technique in homestead gardens to fight food insecurity, but also to use the *IRWH* technique on the croplands in order to turn the croplands into a sustainable enterprise to fight food insecurity and poverty.

Table 8.3 Net profit obtained by Mr. Chwane of Woodbridge 2, from his homestead garden and cropland during the 03/04 growing season

Homestead garden			
Crop	Area (m^2)	Net Profit (R)	Profit ($R\ m^{-2}$)
Dry Beans	756	414	0.55
Total	**756**	**414**	**0.55**
Cropland			
Sweet melon	180	368	2.04
Watermelon	1080	3476	3.22
Pumpkin	6720	2611	0.39
Onions	600	169	0.28
Total	**8580**	**6623**	**0.77**

8.3.3 ANALYSIS OF HOUSEHOLD CONSUMPTION

Results are presented in Figures 8.4 and 8.5. According to Figure 8.4, most of the households in 2001 in Thaba Nchu spent on average about 40% of their adult equivalent income (ADEQI) on food. While in 2004, the proportion of income used to purchase food is above 40%. This may seem to imply that the households were worse off in 2004 than they were in 2001. But looking at the graphs from another angle tends to imply the opposite of that. The graph for 2004, while on average households spent more on food, it also has shifted to the right and it means that generally the households had more available income than in 2001. What must also be kept in mind is the fact that households produced more food in their homesteads during 03/04 growing season than previously.

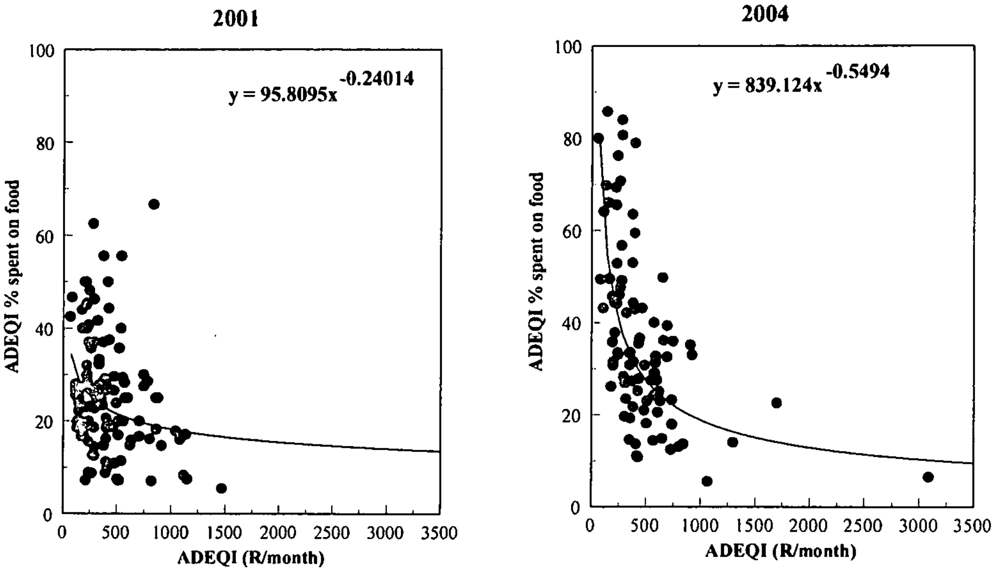

Figure 8.4 Comparison of the proportion of adult equivalent income (ADEQI) spent on food in communities in the study area during 2001 and 2004.

Secondly, most households generally have lower levels of available income and thus are barely making it, which may explain the lower proportion of income spent on food per adult equivalent in 2001. One would have expected that the value should have been higher, but due to low income availability for the household there is also a tendency to allocate lower proportions of the income available to food acquisition and the rest of the income was used to pay for other household needs (shelter, clothing, etc.). In 2004, the income available to the household seems to have increased (shift to the right) and this also resulted in an increase in the expenditure on food.

In summary, the use of the *IRWH* technique enabled the households to spend more on their food per adult equivalent than was the case in 2001. Secondly, in 2004 there was an increase in the income available to a household as well as amount and crop diversity of food produced in their homestead gardens. This can be looked at as an increase in food sufficiency status of the households. The lower levels of expenditure on food in 2001, seems to point to the fact the households were barely surviving and thus being able to only purchase just enough to meet the energy needs of the household.

In general, there was a low level of income available in 2001 than is the case in 2004. For 2001, the highest available ADEQI (R/month) was just below R1600 and of this about 40% was spent on food. In 2004, the highest available income was just below R3500 and the selected farmers had increased the proportion of income spent on food. This could be due to the increased availability of income, which implies that the *IRWH* technique provided enough income to allow the households to be able to spend more on food and still be able to purchase other household needs. However, in 2004 expenditure on food went even as high as about 80%, which may indicate that some households still had more adults per available income. Even though the income available increased, the households still had spent a considerable amount to feed its members adequately and hence use most of their available household income.

8.3.4 CHALLENGES AND CONCERNS

Generally *IRWH* has seen an increase in the number of households that apply the technique in their homestead gardens; however, there are still a number of challenges and concerns, which need to be addressed. In a recent survey, which determined the number of households using the technique in each community, it was found that in excess of 90% of the communities were successful in the application of *IRWH,* 35-90 households per community had already applied the technique. For the majority of the communities, this expansion was rapid. In one case, in excess of 40 households had already applied the technique one year after its introduction into the community. In about 10% of the communities adoption has been slow, even three seasons after introduction. This poses both a challenge and concern. There is therefore a need to study the reasons for this seeming failure of adoption and address them effectively, so as to facilitate the introduction of *IRWH* techniques in other areas.

Even though the *IRWH* technique is not applied in every household, there seems to be consensus among farmers on the need to expand from homestead gardens to the cropland in order to fight food insecurity and poverty. The farmers, nonetheless, realise that there are a number of constraints that will need to be addressed in order to facilitate this expansion. The following section of the chapter will deal specifically with these constraints.

8.3.5 CONSTRAINTS THAT NEED TO BE ADDRESSED TO FACILITATE EXPANSION TO CROPLANDS

A major constraint, which partly explains the slow expansion of *IRWH* technique to croplands is the absence of fencing on communally, owned land.

The following are considered to be important by the farmers:

(a) Because of the land tenure system the land allotted to each community is communally owned. This includes areas of potential cropland included in larger grazing areas. In all the communities there are generally no fences to protect the croplands. This problem is exacerbated when only some of the community members would like to practice *IRWH* on the cropland, and others object because the grazing area has been reduced in size.

(b) Inputs needed e.g. seeds, fertilizers, chemicals, machinery, tractor and implements.

(c) Marketing, access to markets and value adding.

(d) Fencing is necessary protect crops from damage by livestock.

As in any rural community, cooperation and trust among community members is seen as important for effective expansion of agronomic activities. There is a need to mobilise whole communities to start arable production so as to minimize the theft of crops from fields. The farmers also call for the establishment of effective administrative structures within the community and among communities that will help to unite their efforts and promote success.

8.4 CONCLUSIONS AND RECOMMENDATIONS

Farmers in the study area have become discouraged about crop production using conventional production techniques because of the high frequency of crop failures in this marginal area and the withdrawel of services post-1994.

Without efficient agricultural production and lacking alternative economic opportunities, farm households are generally poor. Results from a household survey conducted in the area showed household income to be substantially below the poverty line, and food intake to be low and lacking variety. Government transfers in the form of old age pensions and child support grants comprised the largest portion of cash income (65% of total household cash income).

From the group discussions held by the researchers and communities following participatory research principles, most community members indicated that their present circumstances (food insecurity, lack of employment opportunities, etc.) were not satisfactory and that improving agricultural production provided a potential means for more secure livelihoods. It is then that suggestions to try *IRWH* as a new production technique were discussed with the farmers. The communities have homestead gardens; cropland and communal pastures for their livestock but most of the arable land are unused.

Case studies from a number of residents indicated that:

(a) Because of the prevailing unsatisfactory living conditions in the study area the introduction of *IRWH* to boost agricultural production provided a means of improving the standard of living.

(b) Crop production in the homestead gardens can make a significant positive impact on food security through: (i) their ability to buy food with the money obtained through selling of their produce; and (ii) the cultivation of a variety of crops for own consumption. Additionally, the homestead gardens provide a simple environment for promoting the *IRWH* technique through training. However, converting the croplands into a sustainable enterprise remains the biggest challenge because at the moment they do not use the cropland productively. The attitudes, confidence and hope of people changed through these two years. All of a sudden, people started to believe in themselves and they now have hope of a better future.

(c) Results indicate that food production in homestead gardens with the *IRWH* technique contributed to household food security while production on the cropland can contribute to both food security and alleviation of poverty. It is therefore critical for people in rural areas, not only to make use of the *IRWH* technique in homestead gardens to fight food insecurity, but also to use the *IRWH* technique on the croplands in order to turn the croplands into a sustainable enterprise to fight food insecurity and poverty.

(d) An appropriate strategy is to first introduce the *IRWH* technique in the homestead gardens where training can be easily done, owners have direct control, and can gain valuable experience in applying the technique before they expand to the croplands.

(e) Comparison of the proportion of adult equivalent income (ADEQI) spent on food in communities in the study area as well as a case study of Yoxford during 2001 and 2004 indicate that, there was a shift in the adult equivalent income spent on food from the left to the right and also a general increase in the available income per adult equivalent. The increase in available income further led to an increase in the proportion of income spent per adult equivalent on food.

(f) It can thus be postulated that the use of the *IRWH* techniques had some positive ‘welfare effects’ in the study area. However, it should be noted that the data set was quite small and may not necessarily show the whole effect that was brought about (or not) by the use of the *IRWH* techniques. The findings are nonetheless important, as they show a move towards a positive trend in the in availability and proportion of income spent on food by households.

(g) The following constraints need to be addressed to facilitate the expansion of crop production using *IRWH* to croplands: The land tenure/communal land conflict and associated fencing and crop theft problem where there is any disunity in the community; the need to assistance with agricultural inputs; marketing, etc.

From this study the following recommendations can be made:

(a) Farmers and extension officers

- Firstly, apply the *IRWH* technique to obtain higher yields.
- Make optimum use of homestead gardens and croplands to fight food security and poverty.
- Demonstration plots also play an imported role in unlocking the potential of the cropland.

(b) Administrators and Policy makers

- A very good foundation has been laid for people in rural communities in the study area to become self sufficient, produce more, and to earn a good income using the *IRWH* technique. A long-term efficient extension programme should be encouraged and developed to maintain the current status and expectations.
- When new crop production techniques are introduced into rural communities it should be demonstrated in the homestead gardens where possible. These provide a suitable environment for training and close supervision by the owner. The focus should be initially be on food security.
- A second phase focus should be on the development of the croplands into sustainable enterprises.
- Education and training structures must be in place.
- Support structures in the form of the Department of Agriculture's Extension Service, and technical aid from the Agriculture Research Council and Universities need to be in place.
- Attention also needs to be given to marketing structures and strategies.
- Institutional arrangements and land tenure aspects also need attention.

(c) Researchers

- To ensure the sustained success of crop production using the *IRWH* technique in the rural communities, especially the expansion from homestead gardens to croplands, certain structures are of fundamental importance. The mechanization of the *IRWH* technique should be researched to insure that it meets the requirements of the five pillars of sustainability.
- To ensure the sustained success of crop production institutional arrangements and land tenure aspects should be researched.

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CHAPTER 9: REVIEW ON THE SUSTAINABILITY OF THE IN-FIELD RAINWATER HARVESTING CROP PRODUCTION SYSTEM

ABSTRACT

A number of studies have revealed low adoption rates of water conservation technologies or new innovations among smallholder farmers in developing areas. The reason might be that only one or two of the five pillars of sustainability were considered, instead of all five. The question that needs to be answered can be stated as follows: Is the in-field rainwater harvesting (IRWH) technique proposed by Hensley, Botha, Anderson, Van Staden & Du Toit (2000) sustainable? It was hypothesized that the IRWH technique is a sustainable crop production technique that could contribute towards enhancing food security and alleviating poverty at household level. This chapter discusses the sustainability of the IRWH technique in terms of the five pillars of sustainability namely, agronomic productivity, crop production risk, conservation of natural resources, economic viability and social acceptability.

Short-term agronomic productivity was measured with on-station trials conducted at the Glen Agricultural Institute, and on-farm trials and demonstrations on croplands and homesteads in rural communities around Thaba Nchu in the Free State Province of South Africa. In these experiments the IRWH technique was compared with normal conventional tillage (CON). Rainwater productivity (RWP) as the second indicator for agronomic productivity was determined using simulate long-term maize and sunflower yields obtained with the crop model CYP-SA and long-term rainfall data over 81 consecutive seasons. Simulated long-term crop yield data for different production techniques were used to draw cumulative probability functions (CPFs) to quantify the risk of crop failures. Runoff and sedimentation were measured under different crop production systems to quantify the influence of the production techniques on the conservation of natural resources. In addition, the carbon content of the topsoil was measured at the start and end of the experiment. Evaporation from *the soil surface (Es) and rainwater productivity (RWP_{rf}) measured over the short-term was also used as indicators for conservation of the natural resources. Enterprise budgets for the CON and IRWH techniques were linked to long-term yield data (81-years) obtained using the CYP-SA model to calculate gross margins (R ha^{-1}). CPFs of gross margins determined over the long-term were used to determine the economic viability (long-term profitability) of the two techniques. Income data from a number of farmers in rural communities were also used to determine the economic viability of the IRWH technique compared to CON. Specific "indicators" used to monitor social-acceptability of the IRWH technique included: initial number of households and communities that applied the IRWH technique after it had been demonstrated to them; the increase or decrease in application number in the following years; increases in crop diversity. Applying the named criteria to test the sustainability of the two crop production techniques in the specific agro-ecological and socio-economic environment present in the rural communities around Thaba Nchu gave the following results: long-term agro-ecological and short-term socio-economic data indicated that CON was non-sustainable and the IRWH was sustainable.*

Keywords: in-field rainwater harvesting, sustainability, agronomic productivity, crop production risk, conservation of natural resources, economic viability and social acceptability.

9.1 INTRODUCTION

Water scarcity affects rainfed crop production and directly threatens the livelihood of millions of people, particularly in developing countries, and particularly in Sub-Saharan Africa. Agriculture is generally the largest user of rainwater. In South Africa for example about seventy percent of the rainfall is used to produce food, natural fibres, and forestry products, involving large numbers of people in a productive way. Where water is scarce, the need for developing rainwater management skills to improve water use efficiency and in particular rainwater productivity is increased. Population growth necessitates an increase in food supplies, requiring the use of marginal land for food production. Rainwater harvesting can address this problem by increasing the water available to crops under rainfed conditions, and thereby increasing yields.

Developing communities are the most seriously affected by the unsatisfactory level of food security and sustainability, which prevails in areas that are marginal for crop production. In South Africa, and in other developing countries, levels and incidence of poverty tend to be disproportionately high amongst the rural population. The poorest of the rural households mostly live in semi-arid and arid areas and rely on rainfed agriculture for their livelihoods, and are often farming on marginal and fragile soils. In dry areas the lack of adequate water poses a major constraint to increasing agricultural production and attempts to develop other economic activities. However, many agricultural scientists agree that with the use of appropriate production techniques, especially those that encourage conservation of water and soil resources, it is possible to increase and sustain agricultural output in semi-arid areas (Hatibu, 2002). In relation to smallholder agricultural needs in the semi-arid regions of the Southern African Development Community (SADC), Kronen (1994) accentuates the need to develop water harvesting and water conservation techniques. She estimates that 10 million people are affected. In the Free State Province of South Africa there are a large number of households living on smallholdings under similar conditions (Department of Agriculture - Free State, 1996). In particular, various water conservation techniques, *viz.* rainwater harvesting, are seen as having the potential for increasing available water for successful crop production in semi-arid areas. While in many cases the biophysical properties of such techniques are well understood, and its ability to increase yield proven, the lack of its widespread use remains a challenge.

In central South Africa a large area east of Bloemfontein is occupied by developing farmers. There is a large population in the scattered communities and the two peri-urban towns of Thaba Nchu and Botshabelo. The area, termed the target area, is marginal for crop production because of relatively low and erratic rainfall and predominantly clay soils. This results in low and often, no yields because of high water losses due to runoff (R) and evaporation from the soil surface (Es). The in-field rainwater harvesting technique (*IRWH*), developed by Agricultural Research Council - Institute for Soil, Climate and Water (ARC-ISCW) researchers at Glen (Hensley, Botha, Anderson, Van Staden & Du Toit, 2000; Botha, Van Rensburg, Anderson, Hensley, Macheli, Van Staden, Kundhlande, Groenewald & Baiphethi, 2003b), combines the advantages of water harvesting, no-till, basin tillage and mulching on high drought risk clay soils (Figure 9.1). This innovative water conservation technique has the potential to stop ex-field runoff (R_{Ex}) completely, reduce Es significantly and increase in-field runoff (R_{In}) efficiency and therefore water redistribution, resulting in increased yields due to increased plant available water.

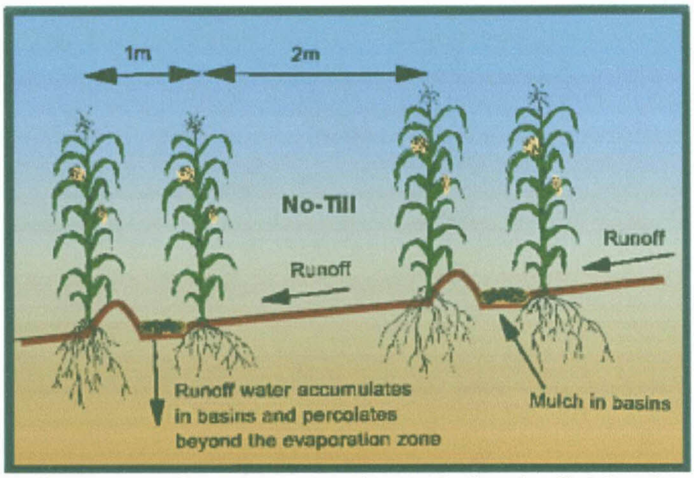

Figure 9.1 A diagrammatic representation of the in-field rainwater harvesting technique.

The technique consists of promoting runoff on a 2 m wide strip between alternate crop rows, and storing the runoff water in the basins. Water collected this way can infiltrate deep into the soil below the surface layer from which evaporation takes place. Organic material or stones can be applied to the basins and the runoff area in various combinations to facilitate the water conservation process. Mulch in the basins helps to suppress evaporation, while mulch on the 2 m wide runoff strip has a dual-purpose, firstly to reduce or suppress soil movement, and therefore promote sustainability of the land resource base, and secondly to suppress evaporation from the soil surface. Fully-grown crops may benefit especially during dry seasons from the water stored in the soil volume underneath the runoff area, which is unavailable early in the growing season. After the basins have been constructed no-till is applied to the land as a whole. Due to the absence of cultivation a crust soon develops on the runoff strip.

Intensive field experiments on clay soils on the Glen/Bonheim ecotope (on-station) and in Thaba Nchu (on-farm) demonstrated over a period of three seasons that, compared to conventional (*CON*) production techniques, *IRWH* could increase maize and sunflower yields by as much as 50%. The term ecotope defines an area of land on which the natural resources that influence yield (climate, topography and soil) are reasonably homogeneous (MacVicar, Scotney, Skinner, Niehaus & Loubser, 1974).

A number of water conservation technologies that have showed great potential for decreasing poverty and food insecurity have been develop through research over the years. Unfortunately, low adoption of these techniques occurs in rural communities. Twomlow & O'Neill (2003), claim that households' ability to adopt different crop management options depends on a range of socio-economic and biophysical factors. They further anticipate that if research and development do not take these factors into consideration, households will not adopt innovative techniques. Another angle could be that low adoption rates are directly the result of not investigating the five pillars of sustainability. Sustainability involves the appropriate use of crop systems, and agricultural inputs supporting those activities, that maintain economic and social viability while preserving the productivity of land. The requirements for sustainable crop production according to Smyth & Dumanski (1993) are improvement in agronomic productivity, reduction in production risk, conservation of the natural resource base, economic viability and social acceptability.

It was hypothesised that the *IRWH* technique is more sustainable than *CON* tillage with regard to the five pillars of sustainability in the agro-ecological and socio-economic environment present in the rural communities in the Thaba Nchu region.

9.2 MATERIALS AND METHODS

The five pillars of sustainability were used to evaluate the *IRWH* and *CON* crop production techniques.

9.2.1 AGRONOMIC PRODUCTIVITY

Agronomic productivity was measured by maize and sunflower seed yields obtained from on-station experiments, on-farm experiments and demonstration sites on croplands and homesteads in rural communities in the Thaba Nchu region, as described in Chapter 4 and 5 and results obtained from Hensley *et al.* (2000), Botha *et al.* (2003b); Botha & Van Rensburg (2004).

The on-station field experiments were conducted on a clay soil (45% clay in the A horizon) located at the Glen Agricultural Institute (28°57` S, 26°20` E), 25 km north east of Bloemfontein. The soil is classified, according to the Soil Classification Working Group (1991), as belonging to the Onrus Family of the Bonheim Form. Following the ecotope approach of MacVicar *et al.* (1974), the site was classified as the Glen/Bonheim ecotope (Chapters 2, 4 and 5). Two on-farm field experiments were conducted on black commercial farmers fields in the resettlement area between Thaba Nchu and Excelsior. These experiments were located on the farms Khumo (29°04`00`` S, 26°56`39`` E) of Mr. Thekisho (Khumo/Swartland ecotope with 17% clay in the A horizon) and Vlakspruit (29°05`37`` S, 26°54`33`` E) of Mr. Ramagaga (Vlakspruit/Arcadia ecotope with 42% clay in the A horizon). The soils are described in detail in Chapter 5. On-farm experiments results conducted in the homesteads and on the croplands of different rural communities with maize and sunflower were obtained from Botha *et al.* (2003b). On-farm experimental results from two trust farms (Sepanè 7 - 29°09`39`` S, 26°38`41`` E and Willow Park - 29°26`47`` S, 26°51`09`` E) in the target area, namely the Sepanè 7/Oakleaf with 42% clay in the A horizon and Willow Park/Katspruit ecotopes with 30% clay in the A horizon, were obtained from Botha & Van Rensburg (2004).

Results from the following treatments obtained from various experimental layouts and designs were compared:

- ***CON***,
- *IRWH* technique with a bare basin (***b***) and runoff (***b***) area (***BbBr***),
- *IRWH* technique with organic (***O***) mulch in the basins (***b***), bare (***B***) runoff (***r***) area (***ObBr***),

- *IRWH* technique with organic mulch in the basins, stones (***S***) on the runoff area (***ObSr***),
- *IRWH* technique with organic mulch in the basins, organic mulch on the runoff area (***ObOr***),
- *IRWH* technique with stones in the basins, organic mulch on the runoff area (***SbOr***).

The seed yield for maize and sunflower was determined by harvesting 36 m^2 from each replication. The seed was weighed, oven-dry and adjusted to 13% moisture content and expressed as kg ha^{-1}.

Rainwater productivity (RWP) (kg ha^{-1} mm^{-1}) is the most reliable, appropriate and acceptable way to describe the effectiveness with which rainwater is converted into grain by the different techniques. This is the most comprehensive and important effectiveness term, and essential for comparing different water conservation techniques for dryland purposes. It is based on the simple principle that the system that produces the highest yield per unit area with a certain amount of rainfall represents the best practice. The assumption is made that rainwater conserved by restricting losses (R and Es), although not directly measured, will be reflected in the higher yield obtained. $RWP_{1922/23\text{-}2002/03}$ was calculated by using Equation 4.9 with simulated long-term maize and sunflower yield data for the different production techniques on the Glen/Bonheim ecotope with the crop model CYP-SA and long-term rainfall data over 81 consecutive years.

9.2.2 RISK ASSESSMENT

Various crop models were used for the prediction of crop yields as affected by mulch combinations within the *IRWH* systems. Unfortunately, none of the models that have been used or tested were able to make satisfactory yield predictions (Hensley *et al*., 2000; Botha *et al*., 2003b). As a last resort an empirical Crop Yield Predictor for Semi-Arid Areas (CYP-SA) model for sunflower and maize was developed to enable long-term yield predictions to be made for *CON* and the complicated *IRWH* technique as affected by various mulch combinations. The model was created to cater specifically for the following production techniques: *CON*; *BbBr*; *ObBr; ObSr*; *ObOr*; *SbOr*; *IRWH* technique with stones in the basins and stones on the runoff area (*SbSr*). The inputs required by the model are drained upper limit of available water (DUL), lower limit of available water (LL), crop modified upper limit of available water (CMUL), rainfall (P), evaporative demand (E_o), and soil water content at planting (θ_p). Validation results for the short-term yield predictions were reasonable good. It was therefore concluded that CYP-SA was suitable for making long-term yield predictions for maize and sunflower with long-term climate data. The composition, development and validation of the model are described in detail in Chapter 6.

Risk assessment was achieved by developing long-term cumulative probability functions (CPFs) of maize and sunflower yields. The calibrated and validated crop model CYP-SA (Botha *et al.*, 2003b), and long-term climate data (81 year period), were used to provide long-term yield simulations. Details on the application of the model are presented in Chapter 7. CPFs were developed of simulated long-term yields for maize and sunflower on the Glen/Bonheim, Khumo/Swartland and Vlakspruit/Arcadia ecotopes planted in a ½ full profile on 17 December. Simulated yield data for the Glen/Bonheim, Khumo/Swartland and Vlakspruit/Arcadia ecotope was pooled to estimate the average long-term maize and sunflower yields in the target area. The average simulated yields for each crop were divided by the maximum yield obtained at the three experimental sites to calculate the relative yield for each crop. The simulated maximum yields for maize and sunflower were 4585 and 4236 kg ha^{-1}, respectively. The expected relative yields, independent of crop type, were taken as the average of the relative yields of maize and sunflower.

9.2.3 CONSERVATION OF NATURAL RESOURCES

Five indicators of sustainability of conservation of natural resources were used for describing the conservation of rainwater and soil, namely runoff; sedimentation loads; organic carbon (C) content; Es; and RWP.

For the conserving of rainwater, runoff was used and measured for *CON* and *IRWH* on plots laid out at the Glen/Bonheim and Glen/Swartland ecotopes (Chapter 2). To quantify the amount of in-field runoff harvested by *IRWH*, runoff was measured with automatic tipping bucket runoff meters on separate runoff plots, each 2 m long and 3 m wide. The runoff treatments were: (a) flat crusted soil surface with minimum surface storage (bare); (b) organic reed mulch covering 60% of the flat crusted runoff surface (organic mulch); and (c) inorganic stone mulch covering 60% of the flat crusted runoff surface (stone mulch). All the runoff events measured on the two ecotopes over three years (2000 - 2002) were pooled and plotted against the corresponding rainfall events. A linear function for each treatment (bare runoff area, organic and stone mulch on the runoff area) was fitted through the data to obtain equations to estimate water harvested from the 2 m runoff area. The runoff equation of Hensley *et al.* (2000) was appropriately adapted and used for predicting ex-field runoff from the *CON* treatment. These equations were used together with long-term rainfall data (81 year period) to compile CPFs of simulated runoff from the *CON* and *IRWH* production techniques. Sedimentation loads, the second indicator, were also measured during rainfall-runoff events from separate 3 x 2 m plots with the same treatments as describe above. The procedure for sediment measurement is described in detail in Chapter 2.

The organic carbon content of the top 150 mm soil layer was used as the third indicator of sustainability. Soil samples were taken prior the start of the 1999/2000 growing season at on-station field treatments (Glen/Bonheim ecotope). Samples were dried in the oven in glass bottles and then sealed and left in a cool, dry place until the end of the experiment (2002) when samples were taken again on all the treatments. The soil samples were analysed at the ARC-ISCW laboratories in Pretoria using standard procedures.

Es measurements were made for both a summer and winter period from four treatments (each 2 m x 2 m) and three replications on the Glen/Bonheim and Glen/Swartland ecotopes. The treatments were: (a) bare soil; (b) stone mulch covering 50% of the soil surface; (c) organic mulch covering 50% of the soil surface; (d) organic mulch covering 100% of the soil surface. Changes in soil water content were measured with a neutron water meter (0 - 1200 mm) and gravimetrically (0 - 300 mm). The procedure for Es measurements and the description of the two ecotopes are described in detail in Chapter 3.

RWP_n on the Glen/Bonheim (maize and sunflower); Glen/Swartland (Sunflower); Khumo/Swartland (sunflower) and Vlakspruit/Arcadia (sunflower) was calculated from short-term field experiments that were conducted over periods from two to four years as described in Chapters 4 and 5

9.2.4 ECONOMIC VIABILITY

Enterprise budgets for maize and sunflower were developed for both the *CON* and the different *IRWH* techniques on the Glen/Bonheim ecotope as described by Kundhlande, Groenewald, Baiphethi, Viljoen, Botha, Van Rensburg & Anderson (2004). The development of the enterprise budgets was based on the 1999/2000-production season data. To determine the yearly profitability (financial sustainability) over the long-term using the *CON* and *IRWH* techniques, enterprise budgets were linked to simulated long-term (81 year) yield data obtained with the yield predictor model CYP-SA. Gross margins (R ha^{-1}) over the long-term were calculated. CPFs, of gross margins (profitability) associated with the different production techniques (*CON* and *IRWH*) for the two crops on the Glen/Bonheim ecotope were constructed. The results from the analysis of the CPFs are aimed at determining the comparative long-term profitability and production risk associated with the production techniques (*CON* and *IRWH*, and among the different *IRWH* techniques). In addition, case studies (Chapter 8) of a number of farmers from different communities were conducted to investigate the economic viability of the *BbBr IRWH* technique and comparing it to *CON.*

9.2.5 SOCIAL ACCEPTABILITY

Social acceptability is, however, not as easily quantifiable as the other four pillars. The social acceptability of a new technology can only be measured over the course of time after the appearance of the new technique, and after valid and reliable indicators have been developed during comprehensive follow-up studies.

The indicators of social acceptance used in this study included: the initial number of households and communities that applied the *IRWH* technique after it had been demonstrated and explained to them; the increase or decrease in these numbers in the following three growing seasons; the increase in crop diversity planted by members of the communities and homestead owners. Technical assistants of the ARC - ISCW research group at Glen recorded the number of farmers who implemented the *IRWH* technique and the different crops planted monthly by gathering the relevant data at focus group discussions. The methodology followed is presented in Chapter 8.

9.3 RESULTS AND DISCUSSIONS

9.3.1 AGRONOMIC PRODUCTIVITY

The agronomic results are discussed in detail within the context of the water balance components in Chapters 4 and 5 and in Hensley *et al.* (2000), Botha *et al.* (2003b) and Botha & Van Rensburg (2004). However, a summary of seed yields of maize and sunflower obtained from on-station, on-farm and demonstration plots in rural communities, as affected by different treatments, are presented in Table 9.1. Generally, the results showed that the *IRWH* technique increased crop yields significantly compared to *CON*, and that the *IRWH* treatments with stone or organic mulch on the runoff area gave the best yields for maize and sunflower. The most productive *IRWH* treatment was *ObSr*, followed by *ObOr*, *SbOr*, *ObBr* and *BbBr*. It was concluded that the subsistence farmers in the semi-arid area east of Bloemfontein, South Africa, could improve maize and sunflower yields considerably by replacing the *CON* practices with *IRWH*. This would improve their level of food security (Chapters 4 and 5).

$RWP_{1922/23\text{-}2002/03}$ calculated from simulated yields varied between 2.7 and 5.1 and from 1.8 to 3.8 kg seed ha^{-1} mm^{-1} rain over the 81 consecutive seasons for maize and sunflower, respectively. The mean $RWP_{1922/23\text{-}2002/03}$ value for the *IRWH* treatments was 74 and 89% higher than *CON* for maize and sunflower, respectively. These are indications that for every 1 mm of rain that occurred during the 81 consecutive seasons the *IRWH* treatments produced 2 kg of maize grain yield per hectare and 1.6 kg of sunflower seed yield per hectare more than *CON*. This is a remarkable difference especially in a semi-arid environment where every drop of rainwater must be utilized to produce food. The superiority of the *IRWH* treatments is the result of their ability to stop R_{Ex} completely and induces in-field runoff (R_{In}) within the system and therefore utilizes every drop of rainwater far better than *CON*. Comparing the different *IRWH* treatments $RWP_{1922/23-2002/03}$ results reveal a trend of *ObSr* >*SbSr* > *ObOr* ≈ *SbOr* > *ObBr* > *BbBr* with all the *IRWH* treatments with mulch either in the basin area and or on the runoff area performing on average 14.3 and 16.7% better than *BbBr* for maize and sunflower, respectively. $RWP_{1999/00-2002/03}$ results also indicate that *ObSr*, *SbSr*, *ObOr* and *SbOr* are on average 11.4 and 16.1% more effective than *ObBr* in converting rainwater into maize and sunflower yields, respectively. These results indicate that it is more advantageous to apply mulches in the basin and on the runoff areas of the *IRWH* technique.

Table 9.1 Seed yield for maize, sunflower and dry beans as affected by different treatments

Crop	Ecotope	Season	Treatment					
			CON	*BbBr*	*ObBr*	*ObOr*	*ObSr*	*SbOr*
Maize	Glen/Swartland (Hensley *et al.*, 2000)	97/98	3187^{a}	5475^{b}	5308^{c}	-	-	-
		98/99	41^{a}	117^{a}	157^{a}	-	-	-
		Mean	**1614**	**2346**	**2733**	-	-	-
	Glen/Bonheim (Hensley *et al.*, 2000)	97/98	3133^{a}	4251^{b}	4678^{c}	-	-	-
		98/99	0^{a}	35^{a}	132^{a}	-	-	-
		Mean	**1567**	**2143**	**2405**	-	-	-
	Glen/Bonheim	99/00	3093^{a}	-	3455^{b}	3519^{b}	3962^{c}	3500^{b}
		00/01	1489^{a}	-	2543^{b}	2908^{c}	3098^{c}	2731^{b}
		01/02	1521^{a}	-	3281^{b}	3325^{b}	3607^{b}	3288^{b}
		02/03	459^{a}	-	2401^{b}	3272^{c}	3066^{d}	2952^{d}
		Mean	**1641**	-	**2920**	**3256**	**3433**	**3118**
	Sepané 7/Oakleaf (Botha & Van Rensburg, 2004)	01/02	1261^{a}	1593^{b}	1596^{b}	-	-	-
		02/03	2003^{a}	3075^{b}	3408^{b}	-	-	-
		Mean	**1632**	**2334**	**2502**	-	-	-
	Willow Park/Katspruit (Botha & Van Rensburg, 2004)	01/02	1041^{a}	1513^{b}	1576^{b}	-	-	-
		02/03	1110^{a}	2958^{b}	3344^{b}	-	-	-
		Mean	**1076**	**2236**	**2460**	-	-	-
	Yoxford (cropland)	01/02	1741^{a}	2970^{b}	-	-	-	-
	Yoxford (homestead)	01/02	409^{a}	3588^{b}	-	-	-	-
	Feloanè (cropland)	01/02	1987^{a}	3642^{b}	-	-	-	-
	Feloanè (homestead)	01/02	144^{a}	4809^{b}	-	-	-	-
	Cropland/homestead	**Mean**	**1070**	**3752**	-	-	-	-
Sunflower	Glen/Swartland	97/98	2028^{a}	2462^{b}	2558^{b}	-	-	-
		98/99	506^{a}	661^{b}	815^{c}	-	-	-
		Mean	**1267**	**1562**	**1687**	-	-	-
	Glen/Bonheim	97/98	2098^{a}	2773^{b}	2806^{b}	-	-	-
		98/99	594^{a}	651^{ab}	804^{b}	-	-	-
		Mean	**1346**	**1712**	**1805**	-	-	-
		99/00	1024^{a}	-	1879^{b}	2190^{b}	2346^{c}	2251^{b}
		00/01	582^{a}	-	1716^{b}	1971^{c}	2138^{d}	1882^{c}
		01/02	1699^{a}	-	2340^{b}	2519^{c}	2704^{d}	2622^{c}
		02/03	1025^{a}	-	2208^{b}	2490^{c}	2596^{c}	2548^{c}
		Mean	**1083**	-	**2036**	**2293**	**2446**	**2326**
	Khumo/Swartland	97/98	1216^{a}	1734^{b}	1876^{b}	-	-	-
		98/99	1096^{a}	1260^{b}	1628^{c}	-	-	-
		Mean	**1156**	**1497**	**1752**	-	-	-
		99/00	1049^{a}	-	1315^{b}	-	1578^{c}	1504^{bc}
		00/01	978^{a}	-	1362^{b}	-	1441^{b}	1345^{b}
		01/02	1829^{a}	-	2535^{b}	-	2661^{b}	2618^{b}
		Mean	**1285**	-	**1737**	-	**1893**	**1822**
	Vlakspruit/Arcadia	97/98	2134^{a}	2835^{b}	2937^{b}	-	-	-
		98/99	1045^{a}	1588^{b}	1997^{c}	-	-	-
		Mean	**1590**	**2212**	**2467**	-	-	-
		99/00	1062^{a}	-	1706^{b}	-	1944^{b}	1814^{b}
		00/01	1116^{a}	-	1506^{b}	-	1623^{b}	1498^{b}
		01/02	1389^{a}	-	2878^{b}	-	3117^{b}	3079^{b}
		Mean	**1189**	-	**2030**	-	**2228**	**2130**
	Sepané 7/Oakleaf (Botha & Van Rensburg, 2004)	01/02	1895^{a}	2758^{b}	2794^{b}	-	-	-
		02/03	1670^{a}	2206^{b}	2593^{b}	-	-	-
		Mean	**1548**	**2162**	**2694**	-	-	-
	Willow Park/Katspruit (Botha & Van Rensburg, 2004)	01/02	1265^{a}	1791^{b}	1810^{b}	-	-	-
		02/03	873^{a}	1549^{b}	1867^{b}	-	-	-
		Mean	**876**	**1449**	**1839**	-	-	-
	Paradys (cropland)	01/02	1834^{a}	2143^{b}	-	-	-	-
	Feloanè (cropland)	01/02	1680^{a}	2243^{b}	-	-	-	-
	Cropland/homestead	**Mean**	**1757**	**2193**	-	-	-	-

Different superscripts within a row refer to statistically significant differences at $P \leq 0.05$; values with similar letters are not statistically different.

Table 9.2 RWP$_{1922/23-2002/03}$ data (kg ha^{-1} mm^{-1}) for maize and sunflower on the different treatments during 81 consecutive seasons

Crop	*CON*	*BbBr*	*ObBr*	*ObOr*	*ObSr*	*SbOr*	*SbSr*	Mean *IRWH*
Maize	2.7	4.2	4.4	4.7	5.1	4.7	5.0	4.7
Sunflower	1.8	3.0	3.1	3.5	3.8	3.4	3.7	3.4

9.3.2 RISK ASSESSMENT

The relative yields of a crop planted in a ½ full profile on 17 December, using different treatments, are presented in Figure 9.2.

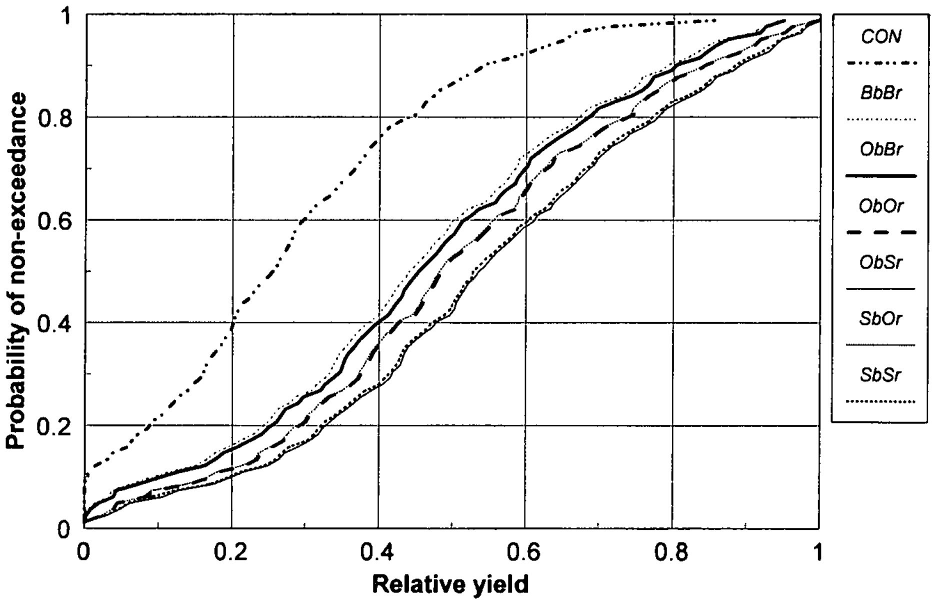

Figure 9.2 Simulated long-term relative yields of a maize or sunflower crop planted in the target area on a ½ full profile on 17 December, using different treatments.

The simulated maximum yields for maize and sunflower were 4585 and 4236 kg ha^{-1}, respectively. Results indicate a 60% chance of getting a relative yield of 0.30, 0.50 and 0.61 when using *CON*, *BbBr* and *ObSr* respectively. This indicates a 40% probability that yields of 1376 and 1271 kg ha^{-1} for maize and sunflower will not be exceeded when using *CON*. The corresponding yields when using *BbBr* or *ObSr* are 2293 and 2118 kg ha^{-1} or 2797 and 2584 kg ha^{-1}, respectively. Yields in the target area can therefore probably be increased by 67 or 103% by changing from *CON* to *BbBr* or *ObSr*, respectively. More results in terms of model development, validation and application are presented and discussed in detail in Chapters 6 and 7.

Wherever the unique combination of an ecotope is replicated anywhere in the world the potential productivity of the system will be the same. Hensley *et al.* (2000), suggested that attention must be focused on carefully selected benchmark ecotopes, to ensure efficient extrapolation of results obtained to all the others (i.e. pedotransfer actions), which will eliminates the possibility to do detailed research work on every ecotope in South Africa. Unfortunately, at this stage only a few people are making use of the ecotope concept. The reason might be that it is not correct interpreted and therefore not supplying all the information needed. Another problem is that the crop part is normally forgotten in the ecotope concept. An ecotope should be an integration of the three disciplines (agrometeorology, soil science and agronomy) and should therefore be able to supply ecotope specific information with regard to the three different dicciplines, which affects the productivity of the system. An ecotope concept is also a perfect opportunity for agrometeorologists, soil scientists and agronomists to work closer together and integrate results.

The broader national framework into which the ecotope fit has already been created for South Africa in the form of the Land Type Survey. Each land type consists of a number of soilscapes, each soilscape consists of a number of hillslopes and each hillslope consists of a number of ecotopes. The following characteristics should be included when an ecotope is described: (a) climate characterization; (b) soil and landscape characterization; (c) agronomic information. In order to reduce crop production risk in South Africa the following strategy should be followed: (1) identify and prioritize all the poverty nodes in South Africa; (2) identify the most important or common ecotopes within every poverty node; (3) select two or three-water conservation or water harvesting techniques for every poverty node according to the different ecotopes and conduct field trails to identify the best crop production technique for every node in the short-term as well as over the long-term. Thereafter pedotransfer actions should take place to similar ecotopes in the various poverty nodes.

9.3.3 CONSERVATION OF NATURAL RESOURCES

Results of long-term in-field runoff predictions within the *IRWH* system indicated that organic mulch, stone and bare treatments have an 80% probability of harvesting 22 mm, 90 mm and 156 mm into the basin area every season, respectively. Comparing the same area of *CON* tillage, it has a very high probability (80%) of losing 40 mm of rainwater every season through R_{Ex}. This implies that the organic, stone and bare runoff strip treatments of the *IRWH* conserve 62 mm, 130 mm and 196 mm of rainwater per season more than the *CON* treatment. An additional benefit for the *IRWH* treatments is that this becomes concentrated in the basin area between the 1 m spaced crop rows, and therefore ends up close to the crop roots. This has been made possible by the total stoppage of R_{Ex}, and the simulation of R_{In} through crusting of the surface (Chapter 2).

R_{Ex} was completely stopped by the *IRWH* system and hence also soil erosion. A matter of concern that influences the sustainability of the *IRWH* system is the siltation of the basins through the in-field runoff process. Sedimentation results indicate that with the *ObOr* treatment it will theoretically take 82 years to completely silt up the basins if no sediment is removed. This treatment is shown to be the most sustainable in terms of maintaining the surface storage capacity of the basin over time. *ObOr* is followed by the treatments *SbOr* (68 years), *ObSr* (23 years), *BbBr* (20 years) and *ObBr* (12 years). Sediment measurements and estimates have therefore revealed that the basins will take between 12 and 82 years to become filled if no sediment is removed. The period depends on the type of mulch on the runoff area and also in the basins. Mulch on the runoff area restricts sediment movement; depending on mulch type, while mulch type in the basin influences the capacity of the basin to absorb sediment. It is also necessary to realize that long before the basins are full of sediment, their storage capacity will be below the threshold value needed to prevent them overflowing during high intensity storms of long duration. The need for a certain amount of maintenance to the basins is therefore inevitable (Chapter 2).

The change in percentage carbon for the 0 - 150 mm layer over the period end of 1998 until 2002 for *IRWH* and *CON* is presented in Figure 9.3. Apparently, the carbon cycle processes in the soil are drastically influenced by both systems, and the system responded accordingly, with the carbon content tending towards a lower equilibrium. This was to be expected as the land was ploughed before the basins of the *IRWH* systems were constructed. However, the carbon trends predict that the no-till *IRWH* system will stabilize at a relatively higher C content than the *CON* treatment. Carbon declined by 19% over the period 1999 - 2002 for the *CON* treatment and by 10% for the *IRWH* treatments. Serious carbon degradation caused by continuous tillage in this soil type has been clearly shown by du Toit (1994). It seems therefore that the C% in the no-till *IRWH* system with organic mulches might stabilize or improve, while in the case of *CON* it will probably decline towards lower equilibrium levels. Since changes in C% are generally not sensitive over the short-term, verification of this hypothesis will require testing over a long period.

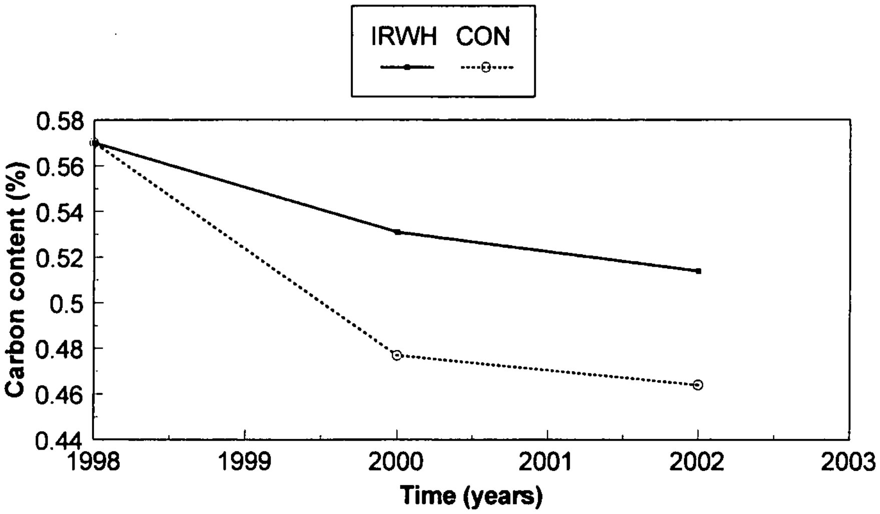

Figure 9.3 Carbon decline in the Glen/Bonheim-Onrus ecotope as affected by *IRWH* and *CON* treatments.

The reduction in Es, and therefore the beneficial effect on plant water availability of the 100% organic mulch treatment is clearly shown on both ecotopes during both the summer and winter measuring periods. The influence of the 50% organic mulch and stone treatments on Es reduction was generally very similar on both ecotopes and always far less effective than the 100% organic mulch. These results indicated that percentage cover is more important in terms of Es reduction than type of mulch. This study has shown that Es can be reduced by 8 - 20% using different mulches over long periods. The effect, however, over the short-term (8 - 16 DAS) is much greater and varied between 28 and 72%. This will give crop roots time to extract a greater portion of the rainwater and therefore use it more productively through transpiration. This would lead to less water being lost by evaporation and therefore conservation of plant available water (Chapter 3).

The Es study indicated that Es measurements should be taken for the 0 - 300 mm soil layer but preferably be taken to around 1 m for reliable results especially on duplex and clay soils. Shallower measurements are shown to be unreliable. In order to avoid any confusion with the various terminologies it is recommended to use early, intermediate and late stage of Es to replace the various terminologies used for first, second and third stage of Es, respectively. Results from the literature review and the field experiment from this study indicate from the beginning of early stage of Es through to the intermediate and the late stage E_0 dominate during the early stage and the domination gradually reduces until E_0 plays a minor but important role during the late stage. The relationship between the water content and hydraulic conductivity of the surface layer and the under laying layers play an important but minor role at the beginning of the early stage but during intermediate stage their importance gradually increases until they dominate (Chapter 3).

The α value used by Ritchie (1972) and Stroosnijder & Hoogmoed (1984) for a range of soils of 3.5 mm $d^{-0.5}$ compares well with α values obtained for the Bo and Swr soils of 3.5 and 3.0 mm $d^{-0.5}$ respectively. α Values for winter and summer periods should be determined which would be valuable information for crop models. These differences can possible be avoided by relating Es to ΣE_0 to give an ecotope specific β value as suggested by Boesten and Stroosnijder (1996). Previously it was not possible to make any simulations concerning the influence of mulching on Es with the SWAMP model. An algorithm to overcome this shortcoming was developed (r^2 = 0.99) and need to be tested with an independent data set. The benefit of this equation is that the suppressing effect of mulch on evaporation could be quantified irrespective of soil and season for any period. This equation allows the modeller to predict evaporation for a specific percentage ground cover when evaporation from the bare soil for a certain period is known as well as the percentage ground cover (Chapter 3).

The ability of *IRWH* to stop R_{Ex} completely and minimize Es was the reason for higher RWP_n values compared to *CON* (Chapters 4 and 5). The mean values of RWP_n for *CON* and *IRWH* (means of four treatments) obtained over various growing seasons for maize on the Glen/Bonheim ecotope were 3.2 and 6.3 kg ha^{-1} mm^{-1}, respectively. For sunflower produced on the Glen/Bonheim, Glen/Swartland, Khumo/Swartland, and Vlakspruit/Arcadia ecotopes, the mean RWP_n were 2.8 and 4.3 kg ha^{-1} mm^{-1}, respectively. This result clearly demonstrates the superiority of *IRWH* for growing maize and sunflower as well as the productive use of rainwater on this and similar ecotopes (Chapters 4 and 5).

9.3.4 ECONOMIC VIABILITY

CPFs of predicted long-term relative gross margins for maize and sunflower grown in the target area with *CON* and different *IRWH* techniques are presented in Figure 9.4.

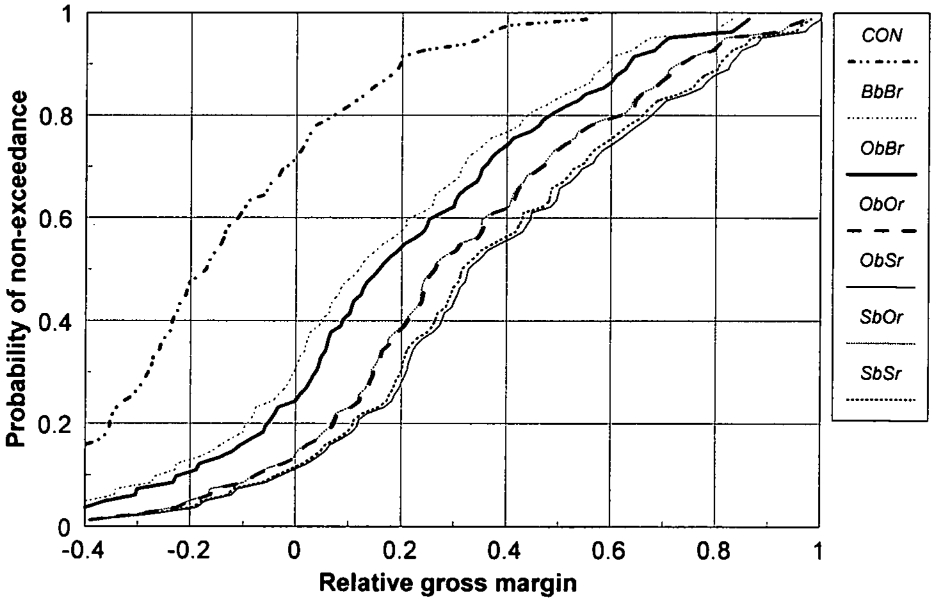

Figure 9.4 CPFs of long-term relative gross margins of a crop planted in the target area on a ½ full profile on 17 December, using different treatments.

Based on these results it can be concluded that higher profits are realized with the *IRWH* techniques compared to *CON*. Among the *IRWH* techniques, *ObSr* showed the highest increase in profits over time and the lowest production risk for both crops, followed by *SbSr*, *ObOr*, *SbOr*, *ObBr* and *BbBr*. In addition, the *IRWH* techniques reduce production risk considerably compared to *CON*. Production using *CON* is associated with a 73% probability of a loss (negative gross margin) compared to about 30% for *BbBr* and only 10% when using *ObSr* (Figure 9.4).

It has been shown in Chapter 8 that a number of farmers from the rural communities in the target area have in fact achieved higher farm profits and a reduction in production risk (economic viability) by applying *BbBr* compared to *CON* (Botha *et al.*, 2003; and Botha, van Rensburg, Anderson, Kundhlande, Groenewald & Macheli, 2003a). Crop yields obtained in these case studies indicated that production in the homesteads can make a significant impact on food security through: (i) their ability to buy food with the money obtained through selling of their produce; and (ii) the cultivation of a variety of crops for own consumption. Net profits results from case studies obtained from homestead food production with the *IRWH* technique and crop yields have indicated that food production in homesteads with the *IRWH* technique contributed to household food security, while production on the cropland can contribute to both food insecurity and alleviation of poverty. According to Botha, Groenewald, Anderson, Mdibe, Nlhabatsi, Zere & Baipethi (2006), when interviewing 240 participants from structured questionnaires, 229 respondents or 95.4% indicated that the introduction of *IRWH* (Matangwana in Sesotho) to their community had resulted in opportunities for them to earn an extra income.

9.3.5 SOCIAL ACCEPTABILITY

Community mobilization, capacity building, empowerment, human well being, self-reliance and community participation are specifically indicators for measuring the social-acceptability of techniques introduced to communities for the first time. Most of these indicators showed that the community benefited tremendously from the *IRWH* technique as described by Botha *et al.* (2003a); Botha *et al.* (2003b) and Kundhlande *et al.* (2004). There is a strong movement towards building an active learning process in farmer groups and individual farmers lower down the hierarchy. When taking account of the large study area and huge number of end-users, much time and effort was invested in empowering the end-users. The magnitude of social acceptability of the *IRWH* technique can also be described by the number of end-users applying the technique in the different communities (Figure 9.5) as well as the number of different crops they planted (Figure 9.6). In the first growing season (2001/02) six owners of homesteads in four communities applied the *IRWH* technique. By 2002/03 this number had increased to 108 and six respectively, and in 2003/04 the number had further increased to 400 homesteads and 37 communities using the technique. The number of homesteads in the communities that applied the *IRWH* technique during the 2003/04 season, varied between one and 55 families per community. Before planting time for the 2004/05 season the number had further increased to more than 1033 households in 42 communities and one trust farm. The number of households in the communities that applied the *IRWH* technique before the 2004/05 season, varied between three and 100 families per community. These results reveal a phenomenal increase, over a relatively short period, in the application of *IRWH* in homesteads. Short-term data indicate that the *IRWH* technique has a great potential to be socially acceptable. However, information over a longer-term will be needed to make a final assessment using additional criteria (Chapter 8).

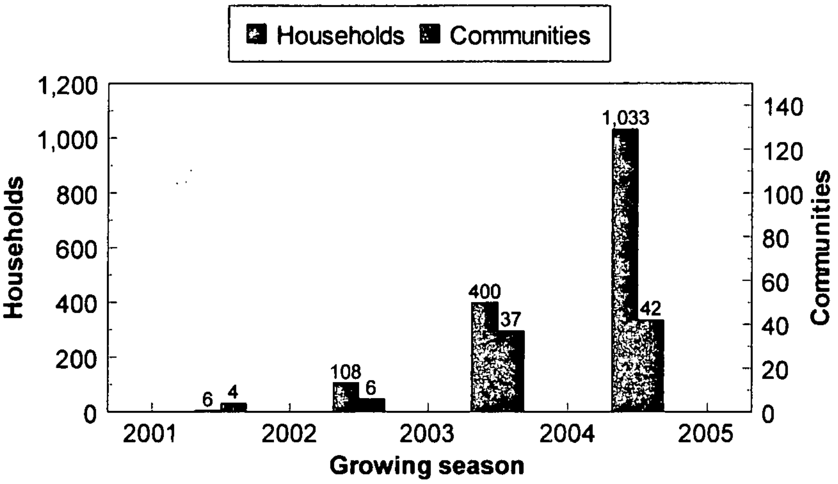

Figure 9.5 A graphical representation of the expansion of *IRWH* in different rural communities and homesteads during the 2001/02, 2002/03, 2003/04 and 2004/05 growing seasons.

The residents of the different communities planted a variety of crops as part of their *IRWH* strategy to combat food insecurity. Over the three growing seasons the variety of crops increased from three crops during 2001/02, to ten crops in 2002/03 and to 15 crops during the 2003/04 growing season (Figure 9.6).

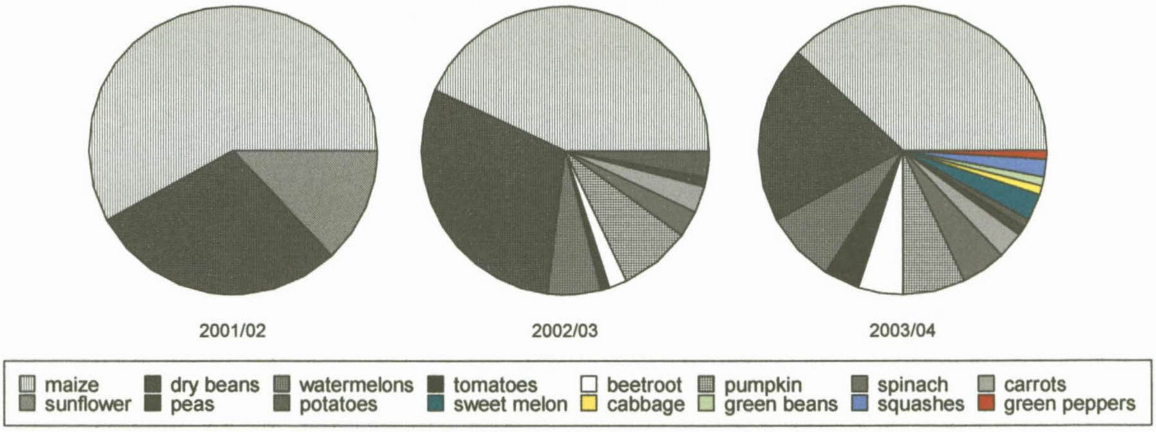

Figure 9.6 A graphical description of the expansion of different crops planted on the *IRWH* plots at homesteads in different rural communities during the 2001/02, 2002/03 and 2003/04 growing seasons.

Botha *et al.* (2006) indicated, by interviewing 240 participants (head of the household or representative) from structured questionnaires, that the coming of Matangwana to rural communities impacted households' health (84%), income (85%), food security (92%), education (83%), reduction in crime in the community (62%), and their social lives (76%), positively.

9.4 SUMMARY AND CONCLUSIONS

This is one of the rare studies where all five pillars of sustainability were measured simultaneously. It reveals important information. The overall main conclusion with long-term agro-ecological data and short-term socio-economic data indicate that the *IRWH* technique is sustainable. This applies to all the five pillars of sustainability, *i.e.* which is agronomic productivity, crop production risk, conservation of natural resources, economic viability and social acceptability. Results indicate that the *CON* treatment is non-sustainable in the agro-ecological and socio-economic environment of the study area. The *IRWH* technique is therefore a sustainable tool to empower people in rural communities to enable them to fight food insecurity and poverty. These five pillars can individually been seen as links in a chain where the chain is sustainability. It is well known that a chain is a strong as its weakest link, therefore it is important that all five pillars should be individually sound but also in balance with each other in order to form a strong chain (sustainability).

The following summarizes the findings of the study.

(a) Agronomic productivity: Results show that *IRWH* significantly increased crop yields compared to *CON* on on-station experiments, and on on-farm experiments and demonstrations in rural communities. Hensley *et al.* (2000) obtained similar results which were confirmed by Botha &Van Rensburg (2004). $\mathrm{RWP}_{1922/23\text{-}2002/03}$ results for maize and sunflower over 81 consecutive seasons indicate that the *IRWH* treatments are far more superior that *CON* in converting rainwater into grain and seed yields. $\mathrm{RWP}_{1922/23\text{-}2002/03}$ results also indicated that it is more advantageous to apply mulches in the basin and on the runoff areas of the *IRWH* technique.

(b) Risk: The newly developed and validated crop model CYP-SA and long-term climate data were used to provide long-term yield simulations (81 years) to quantify risk. Cumulative probability functions (CPFs), of simulated long-term yields indicated that where *CON* exposes farmers to a high production risk, *IRWH* techniques reduced risk considerably. The approach on determining production risk in this study is unique and needs to be used to determine risk elsewhere in South Africa. This implies the identification of suitable land for *IRWH*, identification of ecotopes, the transfer of biophysical information from existing ecotopes, research and demonstration on new ecotopes, mobilization and education of communities on crop production, establishing of socio-economic structures etc.

(c) Conservation of natural resources: Results of long-term in-field runoff predictions indicated that the *IRWH* treatments conserve more rainwater than *CON*, due to the total elimination of ex-field runoff and stimulation of in-field runoff. Sediment measurements and estimates have revealed that the basins will take between 12 and 81 years to become filled, depending on the particular treatment used, if no sediment is removed. Es results indicated that percentage cover is more important to reduce Es losses and therefore conserve plant available water than the type of mulch. This would lead to less water being lost by evaporation and therefore conservation of plant available water. RWP_n result for *CON* and *IRWH* clearly demonstrates the superiority of *IRWH* for growing maize and sunflower as well as the productive use of rainwater on this and similar ecotopes. Carbon measurements at the start and end of the experiments showed that the no-till *IRWH* treatments were more beneficial for carbon conservation than *CON*.

(d) Economic viability: Enterprise budgets for maize and sunflower revealed that greater returns are possible with *IRWH* than with *CON*. This was confirmed by long-term simulations (81 years). Farmers from a number of rural communities have shown improved economic viability in practice using *IRWH* compared to *CON*.

(e) The procedure used to assess social acceptance revealed that there is a great potential for social acceptability of the *IRWH* technique. However, only comprehensive follow-up studies in the years to come will provide more concrete evidence about the extent to which the practice has been accepted and utilized by farmers. In these follow-up studies, criteria such as the degree of mobilization of the community, capacity building, empowerment, human well-being, self-reliance and community participation need to be further developed and used. Such studies would also be useful for providing information about patterns of adoption of new technologies among small-holder farmers that can benefit other farming communities in South Africa.

(f) It is expected that socio-economic conditions will soon change as production goes beyond household food security levels. Institutional arrangements such as the Community Based Water Harvesting Interest Groups (CB:WIG), land tenure aspects, markets etc. will become important socio-economic factors determining the adoption of the technique at high production levels.

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