MAIZE RESPONSE TO IN-FIELD RAINWATER HARVESTING ON THE FORT HARE/OAKLEAF ECOTOPE

By

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Date: May 2007

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TABLE OF CONTENTS

Declaration

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

Lesoetsa Frans Joseph

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Date: May 2007

Place: Bloemfontein, Republic of South Africa

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LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS AND SYMBOLS

AI	Aridity index
ARC-IAE:	ARC-Institute for Agricultural Engineering
ARC-ISCW:	ARC-Institute for Soil, Climate & Water
AUC	Area under the curve
BbBr	Bare runoff area and bare basin area
BD	Bulk density (g cm^{-3})
C_c	Clay content
C (%)	Organic carbon percentage
Ca	Calcium
CEC	Cation Exchange Capacity
CON	Conventional tillage
DOY	Day of the year
DRC	Democratic Republic of Congo
DUL	Drained Upper Limit (mm)
Dg	Deep drainage (mm)
E_s	Soil surface evaporation (mm)
E_v	Transpiration (mm)
EC	Eastern Cape Province
E_o	Reference evaporation (mm)
ΣE_s	Cumulative soil surface evaporation
ET	Evapotranspiration (mm)
f	Fallow period
FAO	Food and Agriculture Organization

g	Growing season
H_2O	Water
HI	Harvest index
I_f	Final infiltration rate (mm)
IRWH	In-field Rainwater Harvesting
k	transpiration efficiency coefficient ($gm^{-2}mm^{-2}$)
K	Pottassium
LL	Lower limit of plant available water (mm)
LTMR	Long–term mean rainfall (mm)
Mg	Magnesium
MAE:	Mean absolute error
MAR	Mean annual rainfall (mm)
MC	Morin & Cluff
mm	Millimetres
MNCRF	Mini-catchment runoff farming
MRDSP	Mean rainfall during study period
Na	Sodium
NT	No-tillage
NWM	Neutron Water Meter
ObSr	Organic mulch in the basin area and stone mulch on the runoff area
OrOb	Organic mulch on the runoff area and in the basin area
P	Precipitation (mm)
P_i	Rainfall intensity (mm)
PAW	Plant Available Water (mm)

pH	Soil acidity
PUE	Precipitation Use Efficiency (kg ha^{-1} mm^{-1})
r^2	correlation coefficient
R_a	Runoff after (mm)
R_b	Runoff before (mm)
R_{ex}	Ex-field runoff (mm)
R_{in}	In-field runoff (mm)
Rain	Rainfall (mm)
RH_{min}	Minimum relative humidity (%)
RH_{max}	Maximum relative humidity (%)
RMSE:	Root mean square error
$RMSE_s$:	Root mean square error systematic
$RMSE_u$:	Root mean square error unsystematic
RSA	Republic of South Africa
RSE	Rainfall storage efficiency (%)
RT	Reduced tillage
RTS	Reservoir Tillage System
RWP	Rainwater Productivity (kg ha^{-1} mm^{-1})
SD_{max}	Surface storage and detention for the soil (mm)
S-value	Total basic cations
ΔS	Change in soil water content (mm)
SbOr	Stone mulch in the basin area and organic mulch on the runoff area
SI	Supplementary Irrigation
SS	Sub-soiling

Sun	Sunshine hours
SWC	Soil water content (mm)
T_{ave}	Average of mean temperature (°C)
T_{max}	Maximum temperature (°C)
T_{min}	Minimum temperature (°C)
TSP	Theoretical saturation point
WCT	Water Conservation Technologies
WRC	Water Research Commission
WUE_{Ev}:	Water use efficiency based on transpiration (kg ha^{-1} mm^{-1})
WUE_{ET}	Water use efficiency based on evapotranspiration (kg ha^{-1} mm^{-1})
Y_b	Total biomass (kg ha^{-1})
Y_g	Grain yield (kg ha^{-1})
Zn	Zinc
γ crust	Soil coefficient related to aggregate stability during formation (mm^{-1})

ABSTRACT

The majority of rural households in the Eastern Cape Province struggle to meet basic needs especially in terms of household food security. Recent studies done in the Province indicate that agriculture contributes little to solve this problem especially in the villages around Alice. Despite poverty, most households rely on purchasing food from urban markets instead of producing food themselves. Crops are usually produced under dryland conditions by using mouldboard plough (conventional tillage) as the primary cultivation method. Research on clayey soils in semi-arid ecotopes showed that in-field rainwater harvesting technique (IRWH) has potential to increase maize grain yield by up to 50% compared to conventional tillage (CON). The question was whether IRWH will also perform better than CON in the Alice district using Fort Hare/Oakleaf as a benchmark ecotope.

The main aims of this study were to characterize important climate, soil properties and soil processes related to maize production on the selected ecotope and to compare the influence of IRWH treatments and CON on; (i) maize grain yield (ii) soil water balance components and (iii) crop-water related efficiencies. The ecotope was characterized in detail with respect to slope, long-term climate and soil characteristics. Long-term (27 years) climate data was used to analyze climate parameters which are related to maize production. A profile pit was dug next to the experimental plot and the soil was described in detail and classified using the South African Classification System. To compare the influence of IRWH treatments and CON on maize grain yield, a fully randomized complete block design experiment was used in 2004/05 and 2005/06 growing seasons. The three treatments viz. IRWH (with mulch), IRWH (without mulch) and CON were *replicated three times. Maize cultivar PAN 6480 was planted at a population of 22 000 plants* ha^{-1}*. Since planting was done by hand, 32.5 g of fertilizer mixture 3:2:3 (22) + 0.5% Zn was applied per hole to supply 60 kg N* ha^{-1}*, 40 kg P* ha^{-1} *and 60 kg K* ha^{-1}*. Evapotranspiration was calculated by using the soil water balance equation which depended on rainfall (measured with rain gauge), drainage (by comparing soil water measurements with drained upper limit), runoff (calculated) and change in soil water content (measured with neutron water meter). Grain yield was measured and crop-water related efficiencies were calculated. The results were used to compare maize response to three different treatments in terms of grain yield, soil water balance components and crop-water related efficiencies.*

The long-term climate data indicates that the ecotope qualifies as semi-arid due to high evaporative demand (1611 mm) and low rainfall (583 mm). The soil was classified as an Oakleaf form of the Ritchie family. The mean grain yield indicates that IRWH (with mulch) and IRWH (without mulch) produced 25 and 19% more grain than CON, respectively. The grain yield ranged from 2066 to 4373 kg ha^{-1} *over the two seasons. IRWH treatments had higher ET than CON at the end of both seasons. The low* E_s *at the end of both growing seasons for CON was ascribed to the higher ex-field runoff that decreased the available water for evaporation considerably. Crop-water related efficiencies' results followed the same trend as grain yield. It can be concluded that Fort Hare/Oakleaf ecotope is suitable for in-field rainwater technique due to its climate and soil properties. IRWH treatments were compared to CON and as hypothesized IRWH treatments performed better than CON in terms of to grain yield and crop-water related efficiencies. Mulch application increased grain yield by 25% compared to CON, while IRWH (without mulch) increased grain yield by 19%*

compared to CON. Results showed that IRWH technique was able to harvest and store more rainwater than the CON due to the total stoppage of ex-field runoff.

CHAPTER 1

1 INTRODUCTION

1.1 MOTIVATION

Poverty and food insecurity are characteristics of 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. National Treasury (2003) and the Human Sciences Research Council (2004) estimated that more than 14 million people in South Africa are vulnerable to food insecurity. The majority of rural households in the Eastern Cape Province struggle to meet basic needs especially in terms of food security. According to Maxwell (2000) food security can be defined as a strategy to provide access to food needed for healthy life. More than 90% of the households in the rural villages in the Eastern Cape earn below the poverty line which makes them highly vulnerable to poverty and food insecurity (Monde, 2005). One of the reasons for these households living below the poverty line is the low income they earn while others depend on social grants for survival. Recent studies conducted in the Eastern Cape Province indicate that agriculture contributes little to solving this problem. Households rely on purchasing food from urban markets instead of producing food themselves. Above 40% of the income earned is spent on food bought from the urban market (Monde, 2005).

Crop production is usually under dryland conditions and this also contributes to some constraints due to erratic rainfall in this Province. Kronen (1994) emphasizes the need to develop water harvesting and water conservation techniques to address the problem of food insecurity in many rural villages. Following the success of the rainwater harvesting projects in the Free State Province, the Water Research Commission (WRC) funded a similar project in Alice town in the Eastern Cape Province. The villages around the town of Alice were selected as the benchmark ecotopes for implementation of water conservation techniques (WCT).

Conventional tillage *(CON)* is risky and unsustainable under dryland due to high losses of water through runoff and soil surface evaporation (Hensley *et al.,* 2000). Hence the solution lies in the Water Conservation Technologies (WCT). Hensley *et al.* (2000) analyzed the problem of low and erratic rainfall in semi arid areas of South Africa with duplex soils, and then conceptualized the in-field rainwater harvesting *(IRWH)* technique to overcome the biophysical limitations in crop production. The technique consists of a two-meter wide, no till area that promotes runoff through natural surface crusting and a 1-meter basin area for collecting the runoff water.

The *IRWH* has been compared with *CON* and has performed significantly better agronomically. The *IRWH* technique improved water use efficiency (WUE) by more than 50% when compared to *CON* (Hensley *et al.,* 2000). Botha (2006) developed a crop model called Crop Yield Predictor for Semi Arid areas (CYP - SA) for predicting crop yield produced with *IRWH* technique. The model was applied to simulate long-term yields in similar ecotopes. The problem is that the ecotopes in the Eastern Cape Province identified for crop production differ from the original ecotopes used for *IRWH* in the Free State Province. Due to the empirical nature of the CYP-SA model, it is not valid to apply the model for the Eastern Cape ecotopes as most of them differ. Therefore it was decided to conduct an on-farm experiment at Fort Hare University to evaluate the *IRWH* technique. There are certain questions or uncertainties on whether

IRWH developed in the Free State Province will perform significantly better than *CON* under different soils and climate in the Eastern Cape. It was hypothesized that *IRWH* will perform significantly better than *CON.* The hypothesis was made considering the higher rainfalls experienced in the Eastern Cape Province compared to Free State Province.

1.2 OBJECTIVES

The objectives of the study were:

- To characterize important climate and soil properties and processes related to maize production on the Fort Hare/Oakleaf ecotope (Chapter 3).
- To compare the influence of *IRWH* and *CON* tillage on maize grain yield (Chapter 4).
- To compare the influence of *IRWH* and *CON* on soil water balance components and crop-water related efficiencies (Chapter 4).

CHAPTER 2

2 LITERATURE REVIEW

2.1 Introduction

Rainfall in arid and semi-arid areas is generally insufficient to meet basic needs for crop production. It is poorly distributed over the growing season and often comes in thunderstorms and usually it cannot support economically viable crop farming. Annual rainfall for arid areas is generally less than 300 mm and comes mainly in sporadic, unpredictable storms. Even this water is mostly lost through evaporation (mm per year) and runoff (mm), leaving frequent dry periods during the growing season. In the semi-arid areas of South Africa, scarce water supply is one of the main factors limiting food production. There is now increasing interest in alternative water and soil conservation techniques, generally referred to as "Water harvesting" that can improve food production (Hensley & Bennie, 2003).

2.2 Soil and water conservation for crop production

The water balance equation presented in Equation 2.1 is adapted from Hillel (1982) to suit cropping in areas sufficiently dry to warrant the application of WCT.

$$E_v = (P_g \pm \Delta S_g) - (R_g + D_g + E_s) \quad \text{.........................(2.1)}$$

where: E_v = Transpiration (mm)

P_g = Precipitation during the growing season (mm)

ΔS_g = Change in soil water content (mm)

R_g = Runoff during the growing season (mm)

D_g = Deep drainage (mm)

E_s = Evaporation from the soil surface (mm)

The equation describes the conditions prevailing under dryland crop production and conventional tillage. In this equation it is also assumed that there are no special methods to stop ex-field runoff and the soil water losses are through ex-field runoff and deep drainage. The subscript *g* refers to the growing season; E_v is transpiration; P_g is precipitation; ΔS is change in soil water content of the root zone; Dg is the deep drainage; R_g is the ex-field runoff and E_s represents soil surface evaporation. The bracket on the extreme right of the equation contains all the components of the water balance that constitute non-productive losses of water to the soil system. WCT involves minimizing these losses, thereby maximizing E_v, yield and precipitation use efficiency (PUE). PUE is the parameter that is used to compare the efficiency with which different water conservation techniques conserve water or the ability to turn rainwater into food (Hensley *et al.*, 2000).

The majority of soils cultivated for annual crop production in South Africa, especially in semi-arid areas have sandy topsoils with clay contents lower than 25%. The plant available water (PAW) storage capacity for these soils varies between 120 and 200 mm (Bennie *et al.*, 1994). The parameter PAW for these soils is important for WCT applications. As values decrease below about 100 mm, soils in dry areas become increasingly more unsuitable for WCT (Hensley & Bennie, 2003). It is essential to include ΔS_g in the definition of PUE;

$$\text{PUE} \ \ (\text{kg ha}^{-1}\text{mm}^{-1}) = \frac{\text{Y (kg ha}^{-1})}{\text{P}_g \text{ - } \Delta\text{S}_g \text{ (mm)}} \text{..................................} 2.2$$

It is important to include ΔS_g because in most cases the growing season is preceded by a fallow period lasting from harvesting of the previous crop until planting of the present crop. During this period precipitation is stored in the soil and is therefore available for plant uptake during the growing season. Storage of precipitation also occurs where natural vegetation or perennial crops become dormant during the winter. In such cases, Hensley *et al.* (1990) suggested that precipitation during fallowing period (P_f, mm) should also be included in the definition of PUE_{fg} to account for rain storage efficiency during the fallow period. The equation thus becomes:

$$\text{PUE}_{fg} \ (\text{kg ha}^{-1}\text{mm}^{-1}) = \frac{\text{Y (kg ha}^{-1})}{\text{P}_f + \text{P}_g \text{ - } \Delta\text{W}_{fg} \text{ (mm)}} \text{...............................} 2.3$$

where, ΔW_{fg} is the soil water content in the root zone at the end of the previous growing season minus the water content over the same depth at the end of the current season.

An alternative classification system for rainwater harvesting techniques has been proposed by Van Rensburg *et al.* (2004) whereby rainwater harvesting methods are characterized simply as ex-field (outside farm-land boundaries), in-field (within the farm-land) (R_{in}) or non-field (e.g. rooftops), according to location of the catchment area. Ex-field runoff (R_{ex}) is another process of water loss from the soil and therefore reduces the water available to plants. In a study on a red sandy loam soil with a 5% slope at Glen with mean annual rainfall of 545 mm, Du Plessis & Mostert (1965), measured runoff and soil loss for 18 years from runoff plots. They reported mean annual R_{ex} losses of 4.4%, 8.5%, 10.3% and 31.9% of the mean annual rainfall (MAR) from natural veld, continuous maize, bare tilled plots and bare untilled surface, respectively. In a study under similar soil conditions for 27 years in Pretoria (MAR = 730 mm), Hayllett (1960) reported runoff losses as a percentage of MAR ranging from 4.2% on natural veld to 49.4% on bare soil. Runoff is affected by several factors. Allen (1998) indicated that the amount of water lost by runoff depends on rainfall intensity, slope of the land, hydraulic conductivity of the soil, initial water content of the soil, as well as land use and land cover. Crust formation is a major factor controlling the reduction of infiltration rate and hence increasing runoff in dry areas. Research has shown that reduction in runoff will result from practices that successfully increase the infiltration capacity of the soil, increase the contact time and /or reduce surface sealing. It is generally accepted that covering the soil with mulch will reduce runoff (Allen, 1998).

Soil surface evaporation (E_s) is the process whereby liquid water is converted to water vapour and removed from the evaporating surface (Jalota & Prihar, 1990). In dryland crop production, E_s is the main process responsible for soil water loss in semi-arid areas (Bennie & Hensley, 2001). It may account for soil water loss of up to 70% of the annual rainfall (Jalota & Prihar, 1990; Hoffman, 1997). Bennie *et al.* (1994) reported that in semi-arid areas of South Africa, E_s from bare soils during the fallow period could amount to 60-75% of the rainfall in the driest summer cropping areas. Hoffman (1997) used micro-lysimeters to measure the E_s from a wide range of South African soils with silt-plus-clay contents ranging from 4 to 66% under similar evaporative demand conditions. He found that the cumulative E_s increased with increasing silt-plus-clay contents or water holding capacities. He also determined that a minimum of 80% shading is required to ensure significant decreases in the cumulative evaporation within the first 10 days after wetting under dry climatic conditions.

Substantial increase in crop yields can be realized if the amount of water used for E_v could be increased. Transpiration contributes to yield and can be regarded as positive loss of water from the soil since the water is used by the plant (Hensley & Bennie, 2003).

On bare land, when the root zone water content exceeds drained upper limit (DUL), following a heavy rainstorm for example, soil water starts to drain below the root zone. This is referred to as deep percolation (D). In dryland crop production D may cause a considerable water loss, especially in coarse textured soils. The quantification of D using the field measurements is difficult. In South Africa, Bennie *et al.* (1994) reported values of D ranging from 0 to 20% of the seasonal rainfall under semi-arid conditions. The values were measured on well-drained sandy aeolian soils. Less D occurred in soils with clayey horizons in or below the root zone, the values were found to be between 0 and 8% of the mean seasonal rainfall.

Bennie & Hensley (2001) reported that the magnitude of D depends on initial water contents, the amount of rain or irrigation water added, and the water holding capacity of the soil. Factors limiting water available for E_v should therefore be eliminated as much as possible to maximize PUE. It is necessary to clarify the difference between PUE and WUE. Several definitions of WUE have been given but the most common definition used is the amount of dried matter produced per unit of water used. The total biomass (Y_b, kg ha^{-1}) produced per unit area is directly related to the amount of water taken up during the corresponding period (Tanner & Sinclair, 1983). WUE based on E_v is very critical and very important in WCT's since it only includes productive water loss, E_v, which is water used by plants. WUE based on E_v can thus be calculated as follows (De Wit, 1958 cited by Hanks & Rasmussen, 1982):

$$WUE_{Ev}\ (\text{kg ha}^{-1}\text{mm}^{-1}) = \frac{Y_b\ (\text{kg ha}^{-1})}{E_v\ (\text{mm})} \ldots\ldots\ldots\ldots\ldots\ldots 2.4$$

where: Y_b and E_v represent total biomass and transpiration respectively.

WUE and PUE are very important concepts in evaluating the ability of a crop to convert available water into grain yield and the ability of water conservation techniques to convert available precipitation into grain yield, respectively. However, mathematically speaking the use of the term "efficiency" is not exactly appropriate (Passioura, 2006). 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". Because of these considerations it is concluded that the most reliable, appropriate and acceptable way to describe the effectiveness with which rainwater is converted into grain yield is by using Equation 2.5, rainwater productivity (RWP) (Botha, 2006) with experimental data over a number of consecutive seasons.

$$RWP_n \cdot (\text{kg ha}^{-1}) = \frac{\sum Yg_n(\text{kg ha}^{-1})}{\sum P_n(\text{mm})} \ldots\ldots\ldots\ldots\ldots\ldots (2.5)$$

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)

RWP is probably the simplest and most comprehensive way of expressing the productivity of converting rainwater into grain yield.

2.3 Rainwater harvesting techniques for crop production

There are different types of rainwater harvesting techniques that have been adopted and implemented, some of these rainwater harvesting techniques are discussed below.

2.3.1 Nature and role of rainwater harvesting techniques

Rainwater harvesting is a term used to describe a number of different practices that have been used for centuries in dry areas to collect and use rainfall more efficiently. Rainwater harvesting is defined as "the process of concentrating rainfall as runoff from a larger area (catchment area) to be used productively in a target area (Oweis *et al.,* 1999). The catchment area can be as small as few square meters or several square kilometers (Oweis *et al.,* 2004). Rainwater harvesting practices are the key solution in making better use of rainwater for agriculture production. Rainwater harvesting practices increase the amount of water available per unit of cropping area, reduce the impact of drought, and use runoff beneficially.

Instead of R_{ex} being left to cause erosion, it is harvested and utilized, thus being a directly productive form of soil and water conservation. Both the yields and the reliability of production can be significantly improved with this method. Runoff may be harvested from roofs and ground surfaces and uses include domestic use and agricultural production. According to Oweis *et al.* (1999) and Siegert (1993), rainwater harvesting methods are classified in several ways, mostly based on the type of use or storage, but the main classification is based on the catchment size (Figure 2.1).

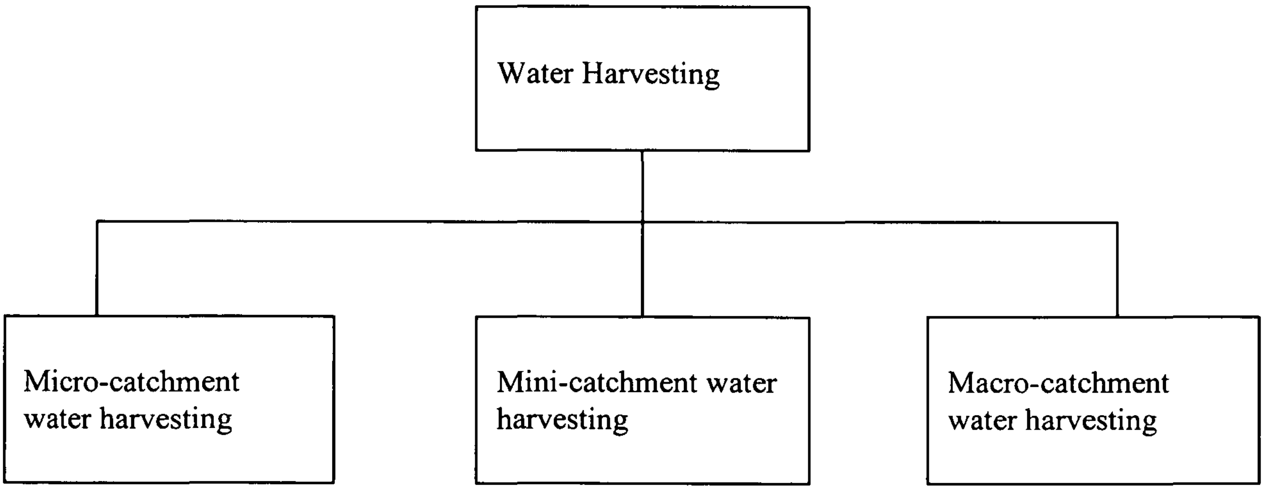


Figure 2.1 Proposed classification of water harvesting techniques (Oweis *et al.*, 1999).

According to Oweis *et al.* (1999), micro-catchment systems are those in which surface runoff is collected from a small catchment area with mainly sheet flow over a short distance. After runoff water has been harvested, it is either stored in the root zone and used directly by plants, or stored in a small reservoir for later use (days or weeks). The land catchment surfaces may be natural, or cleared and treated in some way to induce runoff. Other catchment surfaces include the rooftops of buildings and other impermeable structures. The relevant term for the present study is "mini-catchment runoff farming" (MNCRF) in Figure 2.1. This term will be considered as equivalent to the term "*IRWH*". Macro-catchments and floodwater-harvesting systems are characterized by having runoff water collected from a relatively large catchment and often the catchment is a natural range, the steppe, or mountainous areas. These are sometimes referred to as water harvesting from long slopes or as "harvesting from an external catchment" (Oweis *et al.*, 1999). Further-more water harvesting methods can be subdivided according to the sources of water *viz.* water in the air, runoff water, ground-water and to the kind of storage applied, i.e. above-ground and under-ground (Palmier, 2003).

The main objective of WCT is to minimize soil water losses by R_{ex}, D and E_s, and maximize water storage in the root zone (ΔS) for increased crop production. Rainwater harvesting technologies that minimize R_{ex} beneficially by means of in-field water harvesting are shown to generally increase yields considerably (Hensley *et al.*, 2000). The most important aspect for WCT is that they are crop-ecotope specific; therefore a detailed ecotope characterization is needed (Hensley & Bennie, 2003). MacVicar *et al.* (1974) defined an ecotope as an area of land on which the natural resources (climate, soil and topography) are homogenous.

2.3.2 Overview of different micro water harvesting techniques

Although several micro rainwater harvesting techniques are being practiced in the world, only few will be discussed below.

2.3.2.1 Ridging

Two types of ridging *viz.* contour ridging and contour ridging with bunds are discussed below.

2.3.2.1.1 Contour ridges

These are bunds or ridges constructed along the contour (Figure 2.2), usually spaced between 5 and 20 - 40 m apart. The first 1 - 2 m above the ridge is for cultivation, whereas the rest serves as a catchment area. The height of each ridge varies from 0.15 - 0.4 m (Oweis *et al.,* 2001), slope's gradient and the expected depth of the runoff water retained behind it. Ridges may be reinforced with stones, especially on sandy soils, which are susceptible to erosion. Ridges may be constructed on a wide range of slopes, 1 –5 0% (Oweis *et al.*, 2001). The ridges should be located as precisely as possible along the contour, otherwise the water will flow along the ridge and accumulate at the lowest point, break through and destroy the whole down-slope system.

There are some advantages and limitations with this technique; it is advantageous in that farmers can be taught to construct the ridges themselves. Its limitations include breaking of ridges when high rainfall intensities occur and its unsuitability for uneven or eroded land.

Figure 2.2 An example of contour ridging (FAO, Land and Water Digital Media Series 26; 2004).

2.3.2.1.2 Contour ridging with cross bunds

These are contour ridges where bunds are constructed across the contour ridge, stone or soil could be used. Cross bunds prevent runoff water from breaking the ridges during high rainfall intensities. Stone bunds are permeable structures which serve to slow down sheet flow and promote infiltration (Oweis *et al*., 2001). The use of stones as cross bunds has limitations in terms of labour, especially when people have to collect stones from long distances.

2.3.2.2 Trenching

Trenching is one of the WCT's that have been practiced over the years. It is either practiced as deep trenching or shallow trenching.

2.3.2.2.1 Shallow trenching

Trenching is a very old technique whereby circular trenches or pits are dug to collect rainfall water as illustrated in Figure 2.3a. It is an excellent method for rehabilitating degraded agricultural lands. According to Wright (1985) trenches are 0.1 - 0.3 m in diameter and 50 - 150 mm in depth while the spacing between them is 0.5 - 1 m. These measurements are also confirmed in Figure 2.3b. Wright (1985) and Oweis *et al.* (2001) reported that trenching could be applied in combination with bunds to conserve runoff, which is slowed down by the bunds. Different organic materials can be mixed with soil and put into the pits. However if trenches are dug on flat instead of sloping ground, they may be regarded more as an *in situ* moisture-conservation technique than as a water harvesting technique (Oweis *et al.*, 2001).

2.3.2.2.2 Deep trenching

As reported by Stellamaris (2003) on Mma Tshepo's homestead, the trenches are dug manually up to 1.2 m deep. The trenches can also be dug until a hard layer is reached at the bottom of the profile. The trench can then be filled with organic materials and anything that is not organic is removed e.g. plastics. Earth bunds are constructed which surround the dug area. Top-dressing can also be done by digging a shallow hole of up to 200 mm (Stellamaris, 2003) and fill the hole with organic materials, which are left to decompose and then finally mixed with soil. The earth bunds constructed protect the water from spilling out.

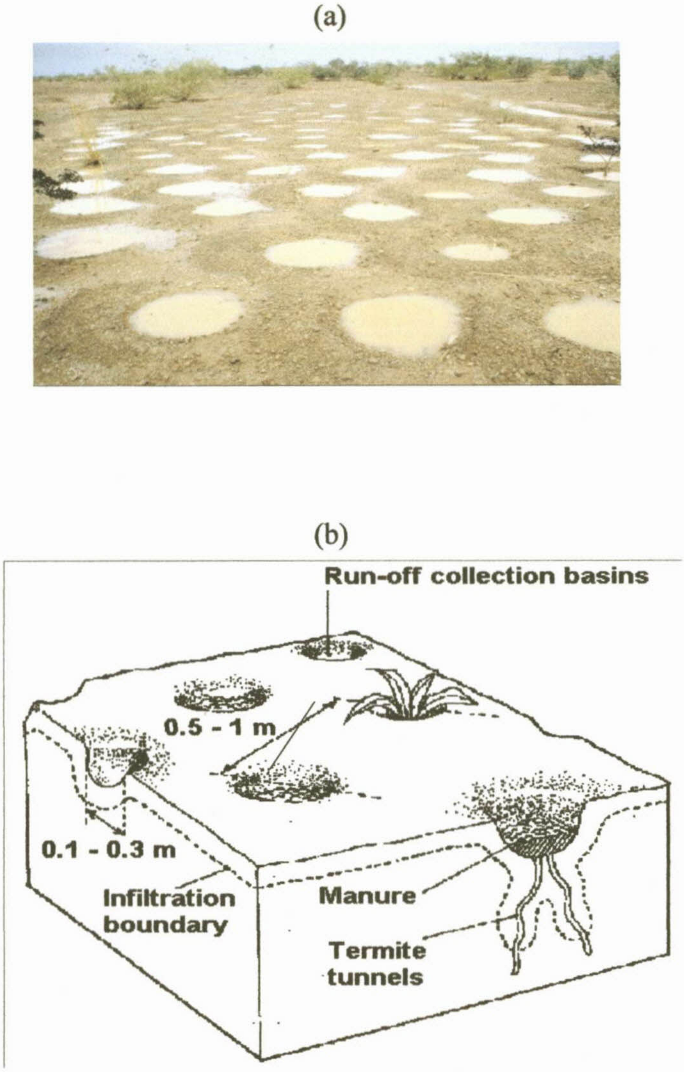


Figure 2.3 Example of shallow trenching using pits to improve surface storage of water as illustrated in (a) and (b) (FAO, Land and Water Digital Media Series 26; 2004).

Both shallow and deep trenching improve soil fertility due to organic material application and improved soil structure. Their limitation is that they are labour intensive during the first year (Reij *et al.,* 1988).

2.3.2.3 Basin tillage

Basin tillage can either be done manually or mechanically with implements specially designed for that purpose. Both types of basin tillage are discussed below.

2.3.2.3.1 Manual basin tillage

Basin tillage consists of small diamond or rectangular shaped structures surrounded by low earth bunds (Figure 2.4). They are orientated in such a way that the runoff flows to the lowest corner, where the plant is placed. Small runoff basins can be constructed on almost any gradient, with the precaution that the bund height must be adapted to soil long-term runoff patterns and characteristics (Oweis *et al.*, 2001).

If the catchment is well maintained, 30 - 80% of rainfall can be harvested and used by the crop (Oweis *et al.*, 2001). Once the system is constructed, it lasts for years with little maintenance. If the tillage is done on crusting soils, a high runoff coefficient may be achieved. Runoff can also be induced if the soil is not crusted. Limitations include control of weeds by ploughing as this may be impractical due to small space of the basins, weeding is therefore done by hand or with chemicals. Although much runoff water can be harvested, labour demand is very high (Oweis *et al.*, 2001).

Figure 2.4 An example of basin tillage (FAO, Land and Water Digital Media Series 26; 2004).

2.3.2.3.2 Mechanized basin tillage

This mechanized basin tillage is done using a basin plough. One such plough was designed by ARC-Institute for Agricultural Engineering (ARC-IAE). For a detailed description of how the basin plough operates, see report by Van der Merwe (2004).

2.3.2.4 Runoff strips

In this technique, the farm should be divided into alternating strips along the contour. The upper strip is used as a catchment area while the lower strip is used as target area where crops are planted (Figure 2.5). According to Oweis *et al.* (2001) the technique is suitable for gentle slopes and the downstream should not be too wide one to three meters, while the catchment width depends on amount of water required. The cropped strips are cultivated every year and compaction may be needed to improve runoff. This technique is advantageous in that it is fully mechanized. However, limitations include non-uniform distribution of water in the target area where planting of crops takes place and soil erosion may occur in the target area during high rainfall intensities (Oweis *et al.*, 2001). Another limitation includes its high labour intensity when it is done manually (Oweis *et al.*, 2001).

Figure 2.5 An example of runoff strips (FAO, Land and Water Digital Media Series 26; 2004).

2.3.2.5 In-field rainwater harvesting

A diagrammatic representation of the surface layout of the *IRWH* system as suggested by Hensley *et al.* (2000) is presented in Figure 2.6. Two distinct areas can be seen from the diagram, *viz.* a two-meter runoff strip and a one-meter basin. Maize is planted in tramlines (one meter wide) along the basins as indicated on the diagram.

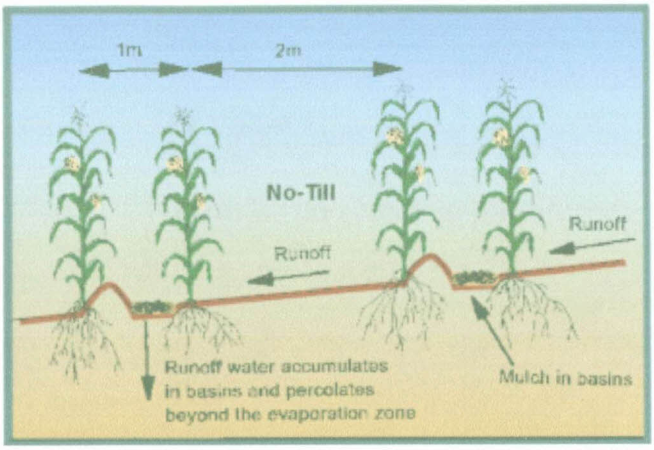


Figure 2.6 Diagrammatic representation of the *IRWH* technique (Botha *et al.*, 2003).

The runoff area is sloped towards the basins to direct the surface water into the basins. Runoff created in this way is called in-field runoff (R_{in}), which differs significantly from R_{ex} that occurs on *CON* prepared fields. In-field runoff can be utilized positively and used to enhance agronomic production and conservation. *IRWH* technique can conserve natural resources by reducing soil erosion due to total stoppage of R_{ex}. It is known that raindrop impact can cause surface compaction and it therefore contributes to the formation of soil crusts, which stimulate in-field runoff. No-till is practiced on the runoff strip to maintain a smooth surface.

The capacity of the basin must be sufficient to hold the runoff from the largest rainstorm. The capacity might change with time depending on the amount of sediment that accumulates in the basins. Runoff experiments at Glen Agricultural College experimental fields revealed that mulches on the runoff area and in the basin could significantly influence the sedimentation of the basins and hence maintenance of the basins. According to Botha *et al.* (2003) estimates showed that the basins would take between 12 and 81 years to fill up if no sediment is removed. The filling period depends on the type of mulch on the runoff area and in the basin area. The mulch on the runoff area restricts sediment movement into the basin. However, it should be noted that *IRWH* system need yearly maintenance.

2.3.2.5.1 Role and function of runoff and basin area within *IRWH* system

The runoff area and basin area in the *IRWH* system have different functions which are discussed in detail below.

2.3.2.5.1.1 Basin area

The basin area has three functions, *viz.* to (i) stop R_{ex}, completely (ii) maximize infiltration and (iii) store the harvested water in the soil profile (Kundhlande *et al.*, 2004). The stoppage of R_{ex} is a very important characteristic which directly explains yield advantages that could be obtained from the *IRWH* technique in comparison to *CON.* Ex-field runoff is one of the major processes responsible for unproductive water losses in crop production. The basin area in the *IRWH* technique acts as a surface storage medium where the "loss" can be converted into a "gain" (Figure 2.7). The water is temporarily stored in the basin until the infiltration process is completed. The infiltration rate depends on the soil surface conditions of the basin as well as the internal drainage characteristics of the soil profile.

2.3.2.5.1.2 Runoff area

The runoff area has two functions in the *IRWH* technique. Firstly, it promotes R_{in} and secondly it acts as a storage medium for water (Kundhlande *et al.*, 2004). Hensley *et al.* (2000) started with preliminary trials to investigate R_{in}. They measured R_{in} from two meter untilled runoff strips located on the Glen/Bonheim and Glen/Swartland ecotopes for a short period. They found R_{in} to be 30 and 35% of the mean annual rainfall, respectively.

This initial study was expanded to include mulch treatments, viz. stone (60% surface coverage) and organic mulches (reeds) (60% of soil surface) (Botha *et al.*, 2003). Results from this three-year experiment indicated that the average in-field runoff from the bare plots amounted to 43 and 39% of the annual rainfall for the Glen/Bonheim and Glen/Swartland ecotopes, respectively. Runoff from the runoff plots on the Glen/Bonheim and Glen/Swartland covered with stones amounted to 25 and 20%, respectively and in the plots covered with organic mulch, runoff amounted to 6 and 4% respectively (Botha *et al.*, 2003). This is a clear indication that mulch type on the runoff area influences runoff on the *IRWH* plots. Long-term predictions revealed that organic mulch, stone mulch and bare treatments had an 80% probability of harvesting 22, 90 and 156 mm rainwater every year, respectively. On the other hand, the predictions for ex-field runoff from the *CON* treatments indicated a loss of 40 mm annually from the bare plots (Botha *et al.*, 2003). This amounted to 43 and 39% of the annual rainfall for the Glen/Bonheim and Glen/Swartland ecotopes, respectively.

Figure 2.7 In-field rainwater harvesting technique immediately after rainfall event (Botha *et al.*, 2003).

2.4 Guidelines for application of micro water harvesting techniques

Table 2.1 indicates guidelines for application of various rainwater harvesting techniques, the term variable in this case means the clay content varies. It must be noted that the sign (-) means that values were not provided in the literature. It can be concluded from this table that the clay content can be up to 60%, while the slope can be about 50% and at least 500 mm soil depth is required.

Table 2.1 Application guidelines for micro water harvesting technique (Hensley *et al.*, 2000; Stellamaris, 2003, Theodore, 2003; Oweis *et al.*, 2001)

Technique	**Crop type**	**Soil properties**		
		Depth (mm)	**Texture (%)**	**Slope (%)**
Contour ridging	Trees, vegetable & veld	1000+ 500-1000+	Variable	4-12
Tied ridging	Various crops	500-1000+	Variable	1-50
Contour ridging with bunds	Various crops	500-1000+	Variable	1-50
Shallow trenching	Various crops	500-1000+	Variable	<4
Deep trenching	Trees, various crops & vegetables	1000+ 500-1000+	Variable	<4
Basin tillage	Various crops Trees	500-1000 1000+	Variable	4-12 < 4
Pot-holing	Veld Trees Various crops	> 1000 500-1000 500-1000	Variable	4-12
Runoff strip	Various crops	500-1000	Variable	2-4
IRWH	Various crops	>700	20-60	1-7*

* suggested slopes but not confirmed yet with research (Personal communication, Hensley, 2005, Dept. Soil, Crop and Climate Sciences, University of the Free State, Bloemfontein).

Soil depth is very important for *IRWH* since depth is needed for adequate water holding capacity. Slope is also important for runoff collection, however, it depends on the type of technique being applied. Some techniques induce soil erosion rather than runoff water harvesting on steep slopes. Soil structure is also important since poorly structured soil results in easy dispersal of aggregates upon wetting. When aggregates are dispersed the surfaces seals and runoff takes place before the profile is saturated.

2.5 Technical evaluation of water harvesting techniques (Case studies)

Several cases in Table 2.2 were studied in different countries with various climatic zones (semi-arid, sub-humid and arid) in terms of WCT and their efficiency. Long-term mean annual rainfall ranged from 144 to 1000 mm and average rainfall during the study period was between 199 and 505 mm. Different countries used various soil water balance components and crop parameters *i.e.* seed yield and crop height to evaluate the efficiency of a particular WCT. It must also be noted that every country had a specific objective for their research, for example in DRC the main objective was to evaluate the WCT in terms of runoff reduction and on the other hand in RSA (Glen) the main objectives included reduction of runoff, minimizing E_S, increasing crop yield and water use efficiencies. The case studies will be analyzed further in terms of soil and water conservation in the following sections.

Table 2.2 Case studies of infield rainwater harvesting

Country	Author	Crop	Climatic zone	LTMR	MRDSP	C_c	D	R_b	R_a	E_s	E_v	ET	ΔS	SI	Y	PUE	WUE	Evaluation parameter
DRC	Theodore, 2003	-	Semi arid	670-1000	-	-	-	+	+	-	-	-	-	-	-	-	-	Runoff
RSA*^{1} (EC)	Mandiringana, *et al.* (2003)	Maize	Semi arid	703	505	-	-	-	-	-	-	-	-	-	+	+	-	Crop height
RSA*^{2} (EC)		Maize	Semi arid	570	445	-	-	-	-	-	-	-	-	-	+	+	-	Crop height
RSA (Glen)	Botha, *et al.* (2003) & Hensley *et al.* (2000)	Maize	Semi arid	545	+	+	+	+	+	+	+	+	+	+	+	+	+	Yield (seed)
Central Mexico	Ventura *et al.* (2003)	Beans	Semi arid	-	-	60	-	-	-	-	-	-	-	-	+	-	-	Yield (seed)
Mexico (Texcoco)	Ventura *et al.* (2003)	Maize	Semi arid	-	464	-	-	-	-	-	-	-	-	-	+	+	-	Yield (seed)
Libya	Razzaghi *et al.* (2003)	Shrubs	Arid	144	199	-	-	-	-	-	-	-	-	-	+	-	-	Height
China	Gabriels *et al.* (2003)	Maize, peanuts and wheat	Sub humid to arid	560-864	-	14	+	-	+	+		+	+	-	+	+	+	Yield (seed)

Where: C_c: Clay content (%), D: Drainage, EC: Eastern Cape Province, E_s: Evaporation from the soil surface, E_v: Transpiration, ET: Evapotranspiration LTAR: Long term mean rainfall (mm), MRDSP: Mean rainfall during study period (mm), R_a: Runoff after study period (%), R_b: Runoff before study period (%).RSA: Republic of South Africa, ΔS: Change in soil water storage (mm), SI: Supplementary irrigation (mm), Y: grain yield (kg ha^{-1}), +: Parameters measured, -: Parameters not measured, RSA*^{1}: Middledrift, RSA*^{2}: Peddie.

2.5.1 Soil conservation

In the DRC case study, runoff was used as a parameter for evaluating contour tillage technique as water conservation. Contour tillage significantly reduced runoff from 17% to 6% (Theodore, 2003). In Central Mexico a mechanized basin tillage called Reservoir Tillage System (RTS), which creates basins or pits to hold water allowing it to infiltrate into the soil was evaluated. Reservoirs were created with a specialized commercially available tillage machine. To evaluate the RTS, simulated rainfall laboratory and field experiments were done. According to the results, runoff started just 15 minutes after simulation in the *CON*, while in RTS runoff only started 20 minutes later. The time before runoff can start is very important since the longer it takes before runoff commences, the more water infiltrates into the soil. After 90 minutes of simulation, RTS had 35 mm of runoff while conventional system had 50 mm. The soil erosion after 35 minutes of simulation was 8 g of soil m^{-2} min^{-1} for RTS compared to 24 g of soil m^{-2} min^{-1} for conventional system. RTS was then evaluated in the field and was compared with *CON*, RTS increased infiltration rate from 5.5 mm h^{-1} (*CON*) to 17 mm^{-1} (Ventura *et al.*, 2003).

2.5.2 Water conservation

Unfortunately only two of the eight case studies measured the soil water balance components. In Central Mexico case study, infiltration rate for RTS was 17 mm h^{-1} compared to 5.5 mm h^{-1} for *CON*. Soil moisture content of the topsoil (0 - 400 mm) for both treatments was measured after harvesting. The results showed that RTS had higher soil moisture content than *CON*. RTS had 42% of volumetric soil moisture content while *CON* had 22%. In RSA (Glen) case study, from 1996/97 – 1998/99 seasons, ΔS and T were higher in *IRWH* than in *CON* (Table 2.2). ΔS for *IRWH* ranged from 44 to 82 mm; whereas *CON* ranged from 28 to 80 mm for three seasons. In the first season 96/97 there was no significant difference between the two treatments where ΔS was 80 mm (*CON*) and 82 mm (*IRWH*) respectively. However, in 98/99 season ΔS of *IRWH* (66 mm) was twice higher than the 33 mm on *CON*. Generally, E_s was lower in *IRWH* compared to *CON*, however, the difference was not significant.

The treatments in China's case study were reduced tillage (RT), sub-soiling (SS), no tillage (NT) and *CON*. The trials ran from August 1999 to April 2001, the first year was August 1999 to May 2000 and the second year was from May 2000 to April 2001. At the end of the fallow period of the first year, cumulative reduction in water storage was highest for the RT followed by *CON*; the values were –9.5 mm and –6.5 mm, respectively. The lowest reduction in storage was in SS and NT where the values were –2.7 mm and –1.2 mm, respectively. Total amount in E_s was lowest for NT (48.3 mm); SS (53.2 mm) that resulted in highest water storage at the beginning of the crop-growing season for these two treatments (Gabriels *et al.,* 2003).

2.5.2.1 Water use efficiency

In RSA^{*1} and RSA^{*2} (Table 2.3) case studies, tie ridge had high precipitation PUE, followed by pothole and ripping. The values were 6.5 and 6.4 kg ha^{-1} mm^{-1} for pothole and ripping respectively, whereas control (mould-board plough), had 5.3 kg ha^{-1} mm^{-1}

(Mandiringana, *et al.,* 2003). In Mexico (Table 2.2) mulching resulted in 18.74 kg ha^{-1} mm^{-1} compared to 15.87 kg ha^{-1} mm^{-1} for non mulching treatment (Ventura *et al.,* 2003). The *IRWH* technique improved water use efficiency by more than 50% when compared to conventional tillage systems (Hensley *et al.*, 2000). WUE_{ET}, WUE_{Ev} and PUE_g were all generally higher in *IRWH* compared to *CON.*

In the second year (China) cumulative increase in ΔS was higher for SS (123 mm) and RT had the lowest value (70 mm). NT (101 mm) and *CON* (101 mm) showed intermediate results at end of fallow period. During subsequent winter season, reduction in soil moisture content was highest for SS due to high ET that was observed during that season. ET was lowest on the RT plot (315 mm) due to relatively low soil moisture content at the beginning of the winter wheat season. Highest value was observed in SS (400 mm), NT (360 mm) and *CON* (366 mm) showed intermediate results. The large difference in ΔS and ET between first and second season was partly due to a difference in measuring period. In the first season, the measurements only started in the last month of the rain season whereas in the second season, the whole season was covered (Gabriels *et al.*, 2003).

2.5.3 Agronomic productivity

2.5.3.1 Growth and yield response

Table 2.3 Yield, precipitation and PUE of maize at RSA*[1] and RSA*[2] (Mandiringana, *et al.*, 2003)

Technique	**RSA*[1] (Middledrift)**			**RSA*[2] (Peddie)**		
	Yield (kg ha^{-1})	P (mm)	PUE (kg ha^{-1} mm^{-1})	Yield (kg ha^{-1})	P (mm)	PUE (kg ha^{-1} mm^{-1})
Control	2680	505	5.3	2467	445	5.6
Tie ridge	3268	505	6.5	2621	445	5.9
Pothole	3220	505	6.4	2563	445	5.8
Rip	2813	505	5.6	2387	445	5.4

Rainwater harvesting techniques increased yield in almost every case study that was studied even though some increases were not significant. In the Eastern Cape (RSA*[1]), tie ridge gave 3268 kg ha^{-1}, pothole 3220 kg ha^{-1} and rip 2813 kg ha^{-1} whereas *CON* produced 2680 kg ha^{-1} of maize yield (Table 2.3), (Mandiringana, *et al.,* 2003). In this case study crop height was used as an indicator for crop performance (Table 2.4). According to Table 2.4 *CON* resulted in high crop heights throughout the measurement periods, while seed yield was lower than in the soil and water conservation treatments. This indicates that parameters like crop height are not a good indicator for evaluating cultivation techniques as it only reflects the vegetative stage of the crop growth. In RSA*[2] (Eastern Cape) the differences were not significant (Mandiringana, *et al.*, 2003). RT system resulted in 100% yield improvement, from 450 kg ha^{-1} (*CON*) to 900 kg ha^{-1} for beans in Central Mexico.

Table 2.4 Average crop height of different treatments (Razzaghi *et al.*, 2003)

Technique	**RSA*[1]**			**RSA*[2]**		
	Height (cm)			Height (cm)		
	10 days after germination	At tasseling	At harvesting	10 days after germination	Before tasseling*	At harvesting
Control	53	138	160	51	82	177
Tie ridge	53	120	155	55	81	175
Pothole	52	124	152	55	80	176
Rip	48	124	157	47	69	165

* Crops were replanted and were not yet at tasseling stage at time of sampling

In Libya, Artriplix shrubs were planted using two rainwater harvesting techniques (contour ridges and basin tillage) and control (no rainwater harvesting technique) from 1997 to 2001. The results indicate that both techniques performed better than control, contour ridges were the best among all treatments. The volume of biomass for basin tillage and contour ridges was higher by 2.3 and 11 times as compared to control respectively (Razzaghi, *et al.*, 2003).

The *IRWH* technique system performed better in all times (except in 1996/97 season) compared to *CON* in crop production. The difference in 1996/97 season was not significant and this is due to the fact that it was the beginning of the experiment and *IRWH* had no pre-plant water content advantage over *CON*. The two treatments started with the same volume of water in the profile. On average *IRWH* produced 2186 kg ha^{-1} compared to 1805 kg ha^{-1} for *CON*. Although all the techniques showed an improvement in yield, the long-term production risks were not calculated in most of the case studies, except in *IRHW* technique. *IRWH* production risk has been established using long-term

(81 years) data as an input for the Crop Yield Prediction for Semi Arid areas (CYP-SA) model (Botha *et al.*, 2003). The results in Table 2.5 indicated that maize production risk was significantly reduced where the *IRWH* technique was applied as an alternative to conventional tillage.

Table 2.5 Grain yield (kg ha^{-1}) for maize as affected by different treatments on Glen/Swartland, Glen /Bonheim, Sepanè 7/Oakleaf, Willow Park/Katspruit, Yoxford (cropland), Yoxford (homestead), Feloanè (cropland), Feloanè (homestead) (Botha, 2006)

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	-	-	-
			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	-	-	-
			1567	**2143**	**2405**	-	-	-
	Glen/Bonheim (Botha *et al.*, 2003)	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
			459^a	-	2401^b	3272^c	3066^d	2952^d
			1641	-	**2920**	**3256**	**3433**	**3118**
	Sepanè 7/Oakleaf (Botha *et al., 2003*)	01/02	1261^a	1593^b	1596^b	-	-	-
		02/03	2003^a	3075^b	3408^b	-	-	-
		Mean	**1632**	**2334**	**2502**	-	-	-
	Willow Park/Katspruit (Botha *et al.*, 2003)	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**	-	-	-	-

Different superscripts within a row refer to statistically significant differences at P = 0.05; values with similar letters are not statistically different.

2.6 The effect of mulching

In Mexico, a case study was done to determine the influence of mulching and water harvesting technique (contour ridges) on water conservation in maize production. The trials ran from 1999 to 2002, however, 1999 data was not included since it was assumed that the first crop cycle was in 00. It was found that mulching treatment had higher PUE than non-mulching treatment with 18.7 kg $ha^{-1}mm^{-1}$ and 15.9 kg $ha^{-1}mm^{-1}$, respectively (Limon-Ortega & Sayre, 2003).

The effect of mulching on R_{in} was studied on Glen/Bonheim ecotope and Glen/Swartland ecotopes. Three mulching treatments, *viz.* bare, stone and organic mulching were studied on a 2 x 3 m runoff area for three seasons (1999/00, 2000/01 and 2001/02). On the Glen/Bonheim ecotope bare treatment had higher runoff, which amounted to 43% of the total annual rainfall, whereas organic mulch induced 4% runoff. The stone treatment had an average of 25% runoff. The average rainfall for three seasons was 479 mm, 544 mm and 591 mm. On the Glen/Swartland ecotope the same trend was observed, bare treatment had 39% runoff of the annual rainfall, while stones and organic mulch had 20% and 4% runoff, respectively. The average rainfall was 489 mm, 544 mm and 567 mm for three seasons (Botha *et al.*, 2003).

The amount of sediment collected in the basins can also be used to evaluate *IRWH* in terms of soil conservation. The mulching treatments were also used to determine the best combination for conservation of the natural resource base. The experiment was conducted on the Glen/Bonheim ecotope. The results show that bare treatment had high sediment collection followed by stone and organic mulch. The average values were 3724 g m^{-2} per season, 1958 g m^{-2} per season and 551 g m^{-2} per season for 2000/01 and 2001/02, respectively. Different treatment combinations were also used and it was found that *IRWH* with organic mulch in the basin and on the runoff strip (ObOr) treatment is the most sustainable in terms of maintaining the surface storage capacity of the basin over time. It was followed by *IRWH* with stones in the basin and organic mulch on the runoff strip (SbOr), organic mulch in the basin and stones on the runoff strip (ObSr), *IRWH* with no mulch in the basin and on the runoff strip (BbBr), stones in the basin and on the runoff strip (SbSr) and *IRWH* with organic mulch in the basin and no mulch on the runoff strip (ObBr). Reij *et al.* (1998) also reported that organic mulches reduce runoff velocity, and they are therefore very effective in reducing the sediment load.

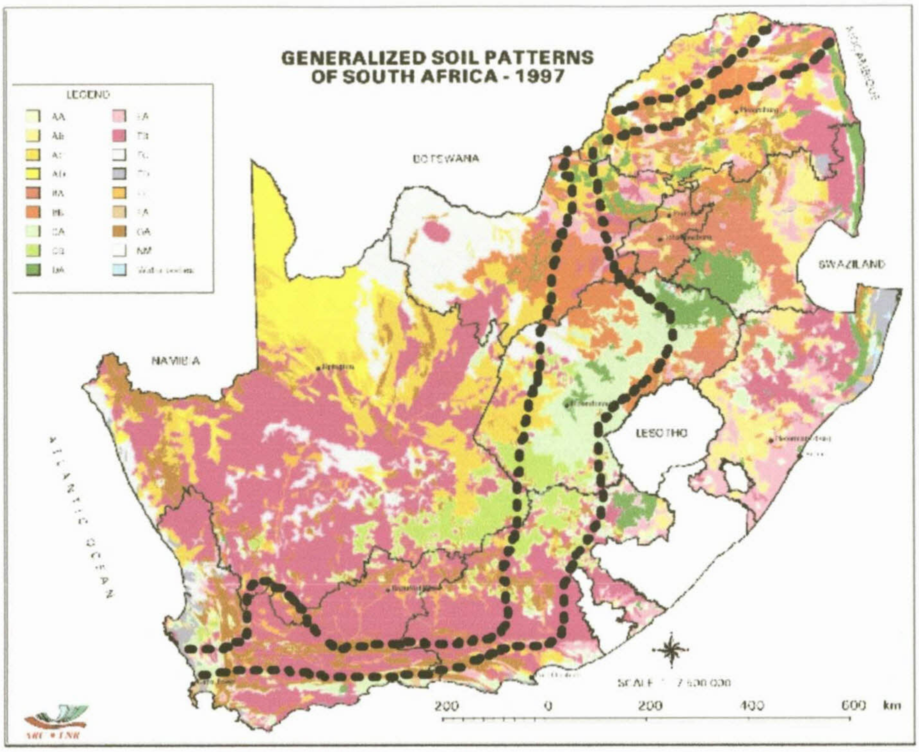
CHAPTER 3

CHARACTERIZATION OF SELECTED CLIMATE AND SOIL PROPERTIES ON THE FORT HARE/OAKLEAF ECOTOPE

3.1 Introduction

Natural resources, climate and soils are seen as national assets. The importance of climate and soils as natural resources in South Africa has reached a special peak with the completion of the Land Type Survey in 2002 (ARC-Institute for Soil Climate & Water, 2005). About 7200 Land Types and 3000 climate zones were identified during this task which took several decades to complete. Tekle *et al.* (2004) used the information to identify the areas where *IRWH* could be potentially applied. As a first approximation they suggested an area which falls within a narrow strip where the arid and semi-arid zones merge in the interior of the country. The strip is shown on the Broad Soil Groups Map (1:250 000) of South Africa (Figure 3.1).

The strip in Figure 3.1 stretches from the West Coast, just north of Cape Town, through the Western Cape, Eastern Cape, Free State, Northern Cape and Gauteng to reach the Limpopo Province in the North. The demarcated land in Figure 3.1 indicates proposed area for potential application of *IRWH* techniques. The area includes many of the Broad Soil Types emphasizing the great "diversity" of the Broad Soil Groups encountered (Soil Survey Staff, 2002). Much more variation could be expected in the soil types and climate at ecotope level within the strip (Tekle *et al.*, 2004). Such diversity demands research to ensure sustainable use of natural resources, especially where relatively new techniques are to be introduced (Beukes *et al.,* 1998).



AA Red and yellow soils with a humic horizon

AB Red and yellow, massive or weak structured soils with low to medium base status

AC Red, massive or weak structured soils with high base status

AD Red, excessively drained sandy soils with high base status. Dunes present

SOILS WITHIN A PLINTHIC CATENA

BA Red, yellow and greyish soils with low to medium base status

BB Red, yellow and greyish soils with high base status

SOILS WITH A STRONG TEXTURE CONTRAST

CA Soils with a marked clay accumulation, strong structure and a non-reddish colour. In addition one or more vertic, melanic and plinthic soils could be present

CB Soils with a marked clay accumulation, strong structure and a reddish colour

SOILS WITH A HIGH CLAY CONTENT

DA Black and red, strongly structured clayey soils with high base status

EA Soils with minimal development, usually shallow on hard or weathering rock, with or without intermittent diverse soils. Lime rare or absent in the landscape

EB Soils with minimal development, usually shallow on hard or weathering rock, with or without intermittent diverse soils. Lime generally present in part or most of the landscape

EC Red and yellow, sandy well drained soils with high base status

ED Greyish, sandy, excessively drained soils

EE Soils with negligible to weak profile development usually occurring on recent flood plains

PODZOLIC SOILS

FA Soils with a sandy texture, leached and with subsurface accumulation of organic matter, iron and aluminium oxides, either deep or on hard or weathering rock

ROCKY AREAS

GA Rock with limited soils

NM Not mapped

☐ Water bodies

*Legend for Figure 3.1

Figure 3.1 Map indicating diverse soil groups in South Africa and potential areas for implementation of *IRWH.* (Map courtesy of ARC-ISCW)

The importance of sound research on soil and climate properties related to the sustainable application of rainwater harvesting is generally ignored. In a recent literature study (van Rensburg *et al.*, 2004) it was found that only three of the eight rainwater harvesting case studies reviewed used soil and climate properties to evaluate the performance of the systems. Grain yield response was used as the sole indicator of the performance (Mandiringana *et al.*, 2003 and Ventura *et al.*, 2003). Apart from yield, Hensley *et al.* (2000) and Botha *et al.*, (2003) studied various properties such runoff, soil surface evaporation (E_s), internal drainage and deep percolation and showed the importance thereof in terms of explaining yield response. For example, van Staden (2003) determined that ex-field runoff (R_{ex}) causes water losses which amount to 43 and 39% of the annual rainfall. The measurements were made on two clayey ecotopes in the Central Free State. Botha (2006) revealed that during an eight-month fallow period E_s amounted to about 69% of the annual rainfall. Climate played a dominant role in the suggested *IRWH* strip as it is involved in the supply and demand side of the hydraulic cycle. Therefore properties such as rainfall, rainfall intensity, temperature, wind and humidity are regarded as a necessity in ecotope evaluation Bennie *et al.* (1994) & Walker *et al.* (2005). Another advantage is that most of the information gained during the analysis can be transferred to similar ecotopes elsewhere.

The aim of this chapter is to characterize climate and soil properties related to the soil water balance components of the Fort Hare/Oakleaf ecotope as part of the baseline information required to evaluate maize production under *IRWH*. The ecotope falls in the potential *IRWH* strip indicated in Figure 3.1 and is located in the Eastern Cape Province near Alice.

3.2 Materials and methods

The ecotope at Fort Hare was characterized in detail with respect to slope, long-term climate data and soil characteristics. An ecotope can be defined as an area of land on which the natural resources (climate, soil and topography) are homogenous (MacVicar *et al.,* 1974).

3.2.1 Profile description

A profile pit was dug next to the experimental plot and the soil was described in detail and classified using the South African Classification System (Soil Classification Working Group, 1991). The profile pit was about 1500 mm in depth. The slope was determined by using dumpy level.

3.2.1.1 Location

The experimental site is situated at University of Fort Hare Research Farm in Alice (32°47'46"S/ 26°50'52"E) in the Eastern Cape Province. The area in the Eastern Cape Province is indicated on the map in Figure 3.2.

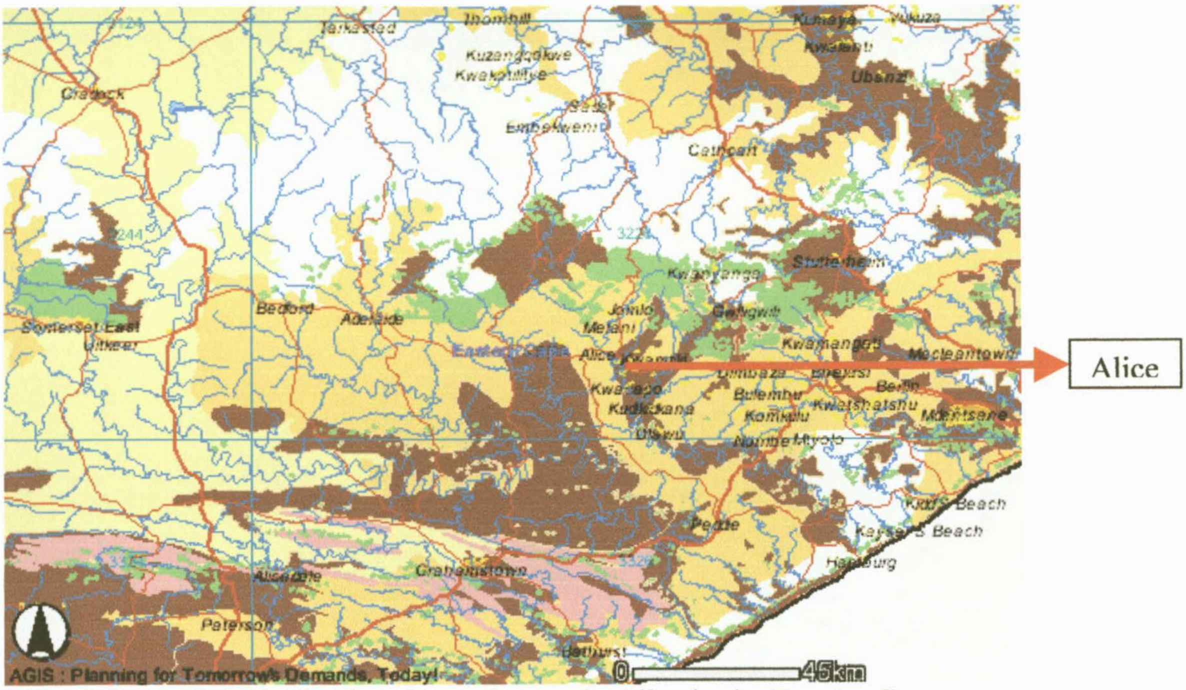


Figure 3.2 Map indicating the study area in Alice in the Eastern Cape.

3.2.2 Climate characterization

Weather parameters *viz.* minimum and maximum temperature, evaporation (Class A - pan), and rainfall were analyzed at the University of Fort Hare Research Farm's meteorological station, which is about 500 m from the experimental site. The station is maintained and monitored by ARC – ISCW.

3.2.3 Soil characterization

3.2.3.1 Internal drainage

Ratliff *et al.* (1983) defined the drained upper limit of plant available water (DUL) as the highest field measured water content of a soil after it has been thoroughly wetted and allowed to drain until drainage becomes practically negligible. Therefore, an internal drainage experiment was conducted on an area of 4 m x 4 m. The area was levelled and a low earth wall coupled with zinc plates was made around the area to prevent runoff water from entering. Five neutron water meter (NWM) access tubes spaced at about 0.75 m from one another were installed to a depth of 1350 mm in the middle of the area.

The plot was filled with water until NWM readings showed that the transition zone of infiltration had reached about 1200 mm, the bottom of the root zone. Addition of water was then discontinued when there was no more change in the readings at 1050 mm depth. The plot was then covered with a plastic sheet to prevent rainwater from entering the plot. Silicon was used to ensure that there was good seal around the protruding access tubes and the plastic to prevent wetting by rain. 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 with NWM. Soil water content measurements were taken at 300 mm intervals at the following depths, *viz.* 150, 450, 750, and 1050 mm. The water content of the root zone plotted against time after saturation describes the drainage curve. Previous research has shown that at saturation, percentage of porosity filled with water ranges between 0.75 and 0.95 for sandy to clay soils respectively (personal communication, Hensley, 2006, Dept. Soil, Crop and Climate Sciences, University of the Free State, Bloemfontein). The theoretical saturation point (TSP) was calculated by using Equation 3.1; the procedure was followed for all soil layers and the root zone. This procedure was followed because the soil was too wet to take initial gravimetric soil water content samples.

$$\text{TSP (mm)} = \frac{1 - BD}{2.64} \times 0.9 \times layer \text{ ....} 3.1$$

where: BD represents bulk density and layer represents the depth of different layers from 300 to 1200 mm.

Deep drainage (D) or percolation is defined as the loss of water from the deepest soil layer of the root zone, and therefore out of reach of roots. D occurs when the soil water content of the deepest layer exceeds the DUL. The internal drainage experiment will provide insight into the drainage process of the individual soil horizons and the whole profile.

3.2.3.2 Evaporation characteristics

An evaporation curve was determined on the same plot used for the internal drainage experiment. The soil water content was then measured with the NWM. The gravimetric soil water content samples for calibration were also taken at the same time as NWM readings were taken. The soil water content was measured at the following depth intervals; 150, 450, 750, 1050 and 1350 mm. The loss of water contributed to evaporation from the soil. The procedure of Black *et al.* (1969) as applied by Botha (2006) was used to determine the α-value in Equation 3.2.

$$\Sigma E_s = \alpha t^{1/2} \quad \text{..........} \quad 3.2$$

where: α (alpha) = parameter characterizing the E_s process (mm d^{-1})

t = time after preceding of stage 2 of evaporation (d)

The α-value is derived from a mathematical relationship between ΣE and time over a medium to long drying period.

3.2.3.3 Runoff characteristics

To measure runoff from the land (ex-field runoff, R_{ex}) runoff plots (3 x 2 m) were laid out at the study area. The runoff plots were replicated twice. An automatic tipping bucket was installed to measure the amount of R_{ex} during a rainfall event. A computerized data logger was connected to the automatic tipping bucket to record whenever the tipping bucket discarded the runoff water. The data from the data logger was downloaded with a computer.

The PutuRun model developed by Walker *et al.* (2005) was used to predict the R_{ex} during the same period as measured R_{ex}. To predict R_{ex} using the PutuRun model, rainfall intensity (P_i) was first generated from daily rainfall using the procedure described by Tsubo *et al.* (2005). R_{ex} was then estimated using the Morin & Cluff (1980) (MC) runoff model incorporated in PutuRun. The measured R_{ex} was compared with the predicted R_{ex} and it was found that the former values were far below the predicted values. It was concluded that the low values were probably due to failure of the data logger resulting in some R_{ex} not being recorded. These measurements were therefore abandoned and an alternative procedure for obtaining R_{ex} was adopted.

It was decided to use the area under the curve (AUC) procedure described by Walker *et al.* (2005) to estimate R_{ex}. In this procedure it is assumed that R_{ex} will occur whenever P_i exceeds the final infiltration rate (I_f) of the soil. Therefore to estimate R_{ex}, P_i (mm h^{-1}) was plotted against time (minutes) for each rainfall event. The horizontal I_f line was also plotted on the graph. The area above the I_f line represents R_{ex}. It was determined using a computerized procedure and these results were termed "measured R_{ex}". The graphs are presented in Appendix 3. The acceptability of the "measured R_{ex}" values was then tested using the MC runoff model. Half of the rain events were used to calibrate the model and validation was done with the rest of the rain events.

The MC runoff model was calibrated by repeatedly changing the model parameters *viz.* soil coefficient related to aggregate stability during crust formation (γ, mm^{-1}), surface storage and detention for the soil (SD_{max}, mm). Final and initial infiltration rates were estimated to be 10 mm h^{-1} and 20 mm h^{-1}, respectively (Hensley 2007, personal communication, Department of Soil, Crop & Climate Science, University of the Free State). The latter values were kept constant. The model was then run a number of times, each time changing γ and SD_{max}. The R_{ex} values per rainfall event were compared with the "measured R_{ex}" value for the each rainfall event. This procedure was repeated until the comparison between "measured R_{ex}" values and predicted R_{ex} values agreed satisfactorily using the Willmott (1982) statistical test. The best parameter combination was found to be; $\gamma = 0.6$ mm^{-1} and $SD_{max} = 0.1$ mm. The results are presented in Figure 3.3.

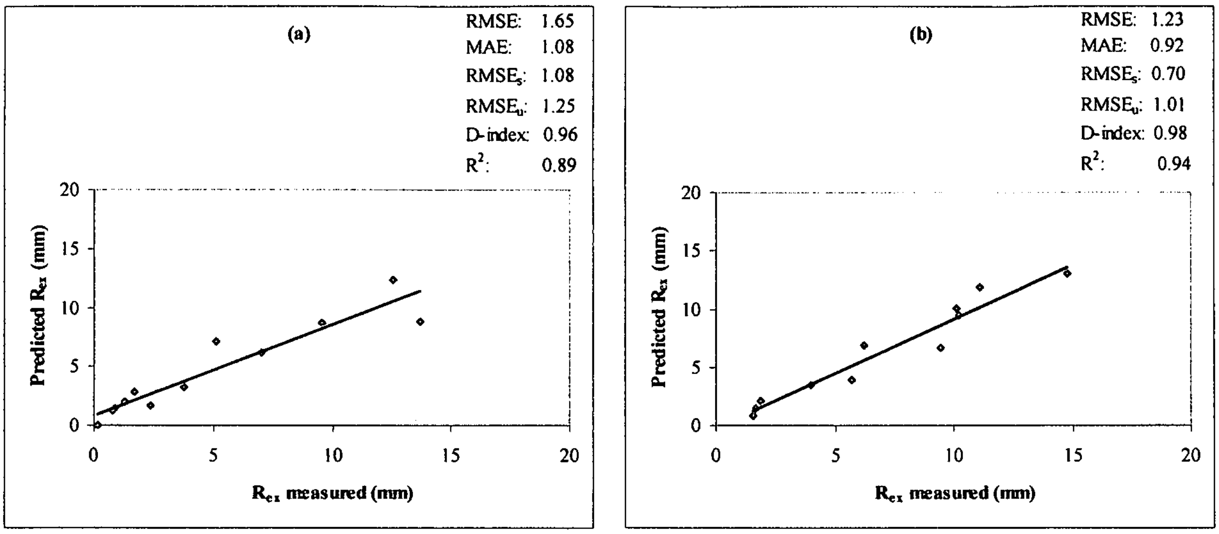


Figure 3.3 Predicted R_{ex} vs. measured R_{ex} for calibration (a) and validation (b) of the study area.

where: RMSE: the root mean square error

$RMSE_S$: the root mean square error systematic

$RMSE_u$: root mean square error unsystematic

MAE: mean absolute error

r^2: coefficient of variation

D-index: index of agreement

3.2.3.4 Bulk density

The soil samples were taken at the following depths, *viz.* 150, 450, 750, 1050 and 1350 mm using the core sampler method (Blake & Hartge, 1986). The samples were dried for 24 hours at 105^0C before they were weighed. The volume of the cylinder was 6.5 cm^3. Three replications from each depth were taken.

3.3 Results and discussions

3.3.1 Slope

The experimental plot is located on a straight terrain unit with a 1.5% slope in the northerly direction. According to the literature study, in-field rainwater harvesting techniques can be done on the slopes between 1 and 7%. The slope (1.5%) in this ecotope is also in agreement with the literature study.

3.3.2 Climate

Long-term monthly and annual averages of rainfall, evaporation (class A evaporation pan), temperature (minimum and maximum) and aridity index for the period of 27 years (1979-2006) are summarized in Table 3.1. The ecotope qualifies as semi-arid due to high evaporative demand (1611 mm) and low rainfall (583 mm). According to UNESCO (1977) as cited by Reij *et al.* (1988), the area is classified as semi-arid when aridity index (AI) is between 0.2 and 0.5. The aridity index (AI) is calculated by dividing annual precipitation (P) by annual reference evaporation (E_o). The long-term AI of the study area is 0.36 and qualifies as semi-arid area.

Table 3.1 Long-term monthly and annual climate data from University Fort Hare meteorological station (ARC-ISCW data) for 27 years (1979-2006)

Key	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Evap	190	157	133	105	99	90	102	116	127	148	157	185	1611
Rain	63	65	65	49	20	20	18	26	38	60	87	72	583
AI	0.33	0.41	0.48	0.46	0.19	0.22	0.18	0.23	0.30	0.41	0.55	0.39	0.36
T_{max}	28.2	28.5	27.0	25.0	23.1	20.6	20.7	21.6	23.1	24.2	25.3	27.2	
T_{min}	16.2	16.5	15.0	11.7	8.2	5.3	5.0	6.9	8.9	11.2	13.2	14.9	
T_{ave}	22.2	22.5	21.0	18.3	15.7	12.9	12.9	14.2	16.0	17.7	19.3	21.1	

AI: Aridity index, Evap: Evaporation (mm/month), Rain: Rainfall (mm/month, T_{min}: Minimum temperature (°C), T_{max}: Maximum temperature (°C), T_{ave}: Mean temperature (°C) (Tmax+Tmin/2)

The coldest months are June and July during winter with an average long-term temperature of 13 °C and the warmest month is February during summer with average long-term temperature of 23 °C. June and July also have the lowest long-term maximum temperature of 21 °C while February has the highest long-term maximum temperature of 29 °C. Maritz (2004) analyzed the climate by using a weather station 40 km (32.68°S and 27.13°E) from the ecotope and found that the frost season lasts for 124 days, starting on 13 June and lasting until 15 October. Frost is defined as a day with temperature below 0 °C. It was reported that 6 frost days occur per season and the most frost days occur during July (Maritz, 2004).

The ecotope receives mean annual rainfall of 583 mm and November receives the highest rainfall (87 mm) followed by December month with 72 mm (Table 3.1). June and July receive the lowest amounts of rainfall with only 2 mm difference between them.

Rain days are defined as days with at least 1 mm of rainfall (Maritz, 2004). The days were calculated using rainfall data from 1979 to 2006 by excluding rainfall events of less than 1 mm. According to Figure 3.4, November has highest number (9) of rain days followed by January, October and December with 8 rain days. July has the lowest number (3) of rain days. Rain days follow the same trend as amount of rainfall for November and July. November receives the highest amount of rainfall and July receives the lowest amount of rainfall (Table 3.1). Although January has a higher number of rain days than both February and March, it receives less rainfall compared to February and March. Both months receive 65 mm of rainfall compared to 63 mm for January. According to both rain days and rain amount, November and December months are recommended as planting months for this ecotope.

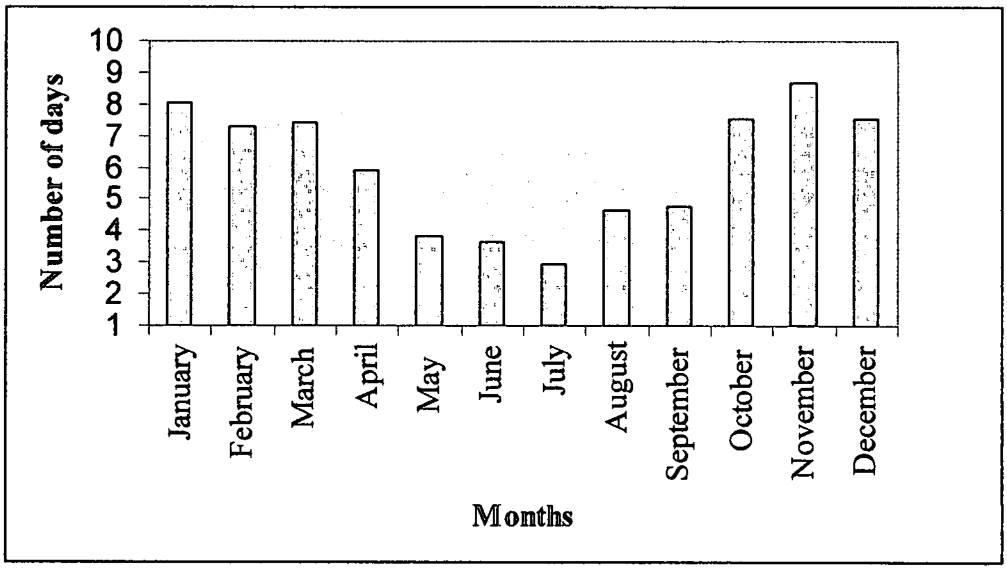


Figure 3.4 Rain days at the Fort Hare/Oakleaf ecotope.

3.3.3 Soil classification

The profile was described up to 1200 mm since there were no evident changes from 600 mm to 1500 mm in terms of diagnostic horizons. The effective rooting depth was estimated to be 1500 mm. The soil was classified as an Oakleaf form of the Ritchie family according to South African soil classification system (Soil Classification Working Group, 1991). The detailed profile description and analytical data are presented in Appendix 1 and Appendix 2, respectively. Important features are summarized in Table 3.2. The soil profile is remarkably homogenous with respect to colour, texture, structure and bulk density. The colour of the soil is generally dark brown to dark yellowish brown in the dry state. The sand grade of the profile is fine with loam texture of clay content between 21 and 24% both in the topsoil and subsoil. The topsoil (0-300 mm) and the subsoils (600 – 900 and 900 –1200 mm) are structureless while the subsoil (300 – 600 mm) has sub-angular blocky structure. The bulk density varies from 1.6 g cm^{-3} in the topsoil (150 mm) to an average of 1.5 g cm^{-3} in the subsoil (450 – 1050 mm). Sum of the exchangeable cations (S-value) varies from 10 cmol (+) kg^{-1} soil in the topsoil to 11 cmol (+) kg^{-1} soil in the subsoil.

Table 3.2 Soil properties of the Fort Hare/Oakleaf-Ritchie ecotope

Diagnostic horizon	**Depth (mm)**	**Colour (Dry)**	**Clay (%)**	**Structure**	**BD (g cm^{-3})**
Orthic A	0 - 300	Dark brown (10YR3/3)	21	Apedal	1.6
Neocutanic B	300 - 600	Very dark greyish brown (10YR3/2)	22	Sub-angular blocky	1.6
Neocutanic B	600 - 900	Dark yellowish brown (10YR4/6)	24	Apedal	1.4
Neocutanic B	900 - 1200	Reddish brown (5YR5/3)	21	Apedal	1.5

3.3.4 Drainage characteristics

According to Ratliff *et al.* (1983), DUL is reached when water content decrease is about 0.1 to 0.2% per day. The volumetric soil water content (θ) time series graphs for the different B-horizon layers are presented in Figure 3.5.

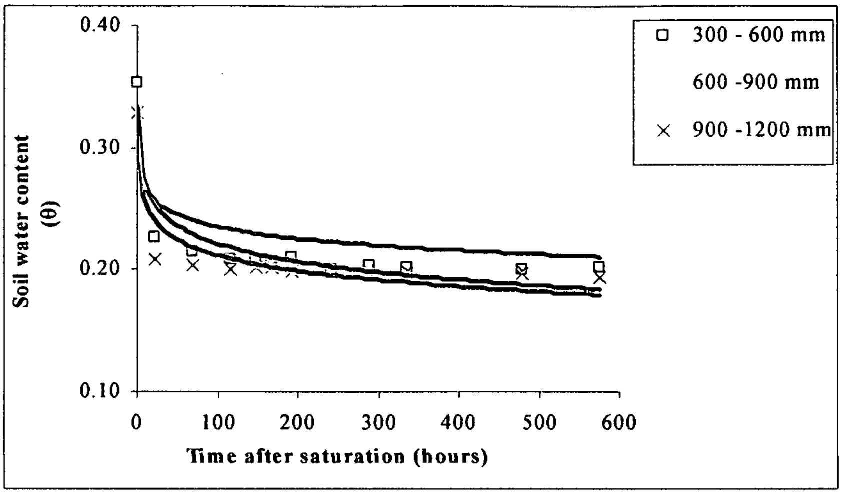


Figure 3.5 Drainage curves for 300 – 600, 600 – 900 and 900 – 1200 mm layers of the Fort Hare/Oakleaf ecotope.

Firstly, it is clear from the graphs that the profile was uniformly wetted at the onset of the experiment. Secondly, the shape of the curves reflects the internal drainage process, which seems remarkably similar amongst layers. The wetness diminishes approximately at the same rate over the measuring period of 25 days. This can be attributed to the homogeneity in soil texture and bulk density of the layers. Under such homogenous conditions it is possible to obtain depth-average soil water content – time relationship through fitting the data to a mathematical function depicted in Equation 3.4. The internal drainage process of the A-horizon was also characterized and plotted in Figure 3.6. The r^2 of both functions justify the application of Equation 3.3.

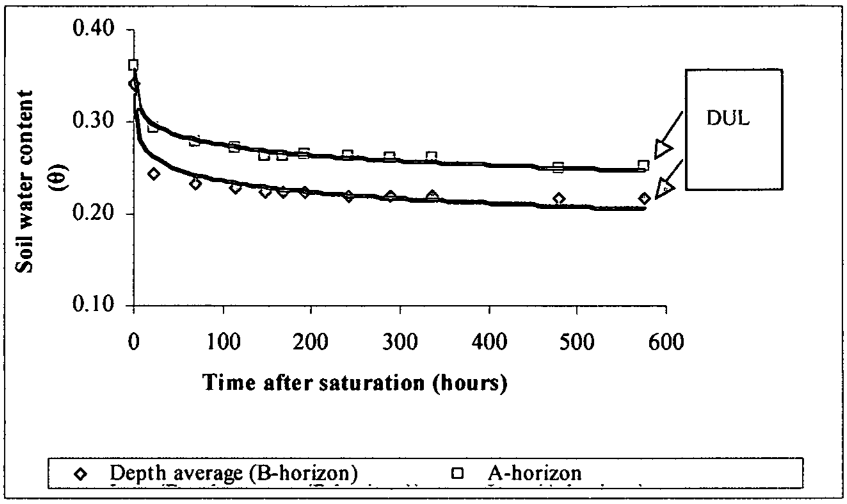


Figure 3.6 θ – time relationship of the B-horizon and A-horizon during the internal drainage on the Fort Hare/Oakleaf ecotope.

$$\theta_A = -0.02\text{Ln}(t) + 0.35 \ldots\ldots (r^2 = 0.99) \ldots\ldots (3.3)$$

$$\theta_B = -0.02\text{Ln}(t) + 0.32 \ldots\ldots (r^2 = 0.93) \ldots\ldots (3.4)$$

where: θ = soil water content (θ) depth average of B-horizon (subscript B) and A-horizon (subscript A)

t = time (hours) after field saturation

On the other hand, downward flux (q_b) through any plane at depth z_b can be calculated with the following equation;

$$q_b = \frac{dw}{dt} = -z_b \frac{d\theta}{dt} \ldots\ldots (3.5)$$

Equation 3.5 was used to calculate q values for a range of θ values at 1-day intervals. Following the suggestion of Hillel (2004) that under internal drainage conditions for homogenous deep soil the hydraulic conductivity (K) equals the downward flux (Equation 3.6). Equation 3.7 was derived from Equation 3.6 assuming that the matrix suction gradient $(\frac{\partial \varphi}{\partial z})$ is negligible, leaving the gravitational force $(\frac{\partial z}{\partial z} = 1)$ to be the main driver in the internal drainage process.

$$q \quad = \quad \frac{-K(\theta)(\partial(-\varphi - z)}{\partial z} \quad \ldots\ldots(3.6)$$

$$q \quad = \quad K(\theta) \quad \ldots\ldots(3.7)$$

Equation 3.7 indicates that K relates to q at a given soil water content. By using Equation 3.5 it is possible to calculate K at daily time interval drainage by applying the θ – time related functions (Equation 3.3 and 3.4). The corresponding K – θ values for depth average B-horizon and A-horizon are plotted Figure 3.7. The functions are presented in Equation 3.6 and Equation 3.7 for B-horizon and A-horizon, respectively.

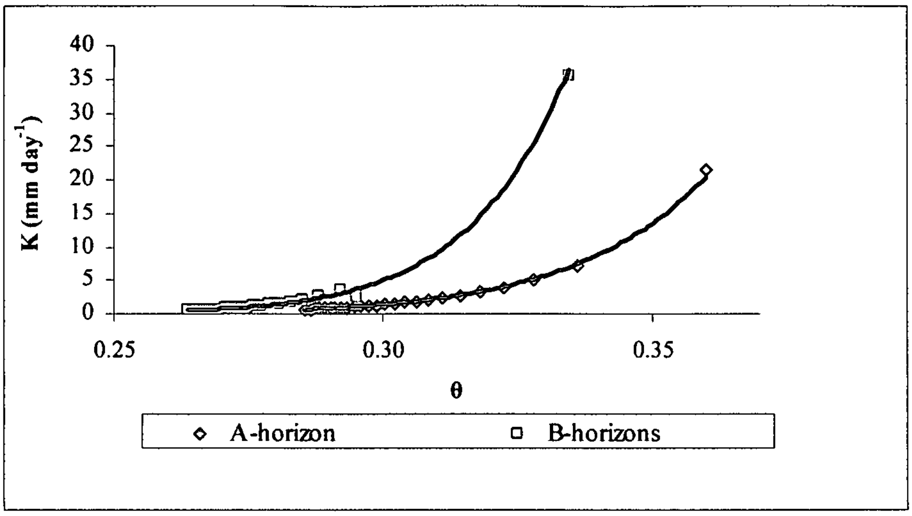


Figure 3.7 Relationship between hydraulic conductivity and θ between field saturation and the DUL of both A and B-horizons.

$$K_B = 10^{10} \times \theta^{18} \ldots\ldots (r^2 = 0.99) \ldots\ldots (3.8)$$

$$K_A = 6 \times 10^7 \times \theta^{14.6} \ldots\ldots (.r^2 = 1.00) \ldots\ldots (3.9)$$

Figure 3.7 represents soil water content between field saturation and DUL. When Equation 3.7 is applied to the field, it is possible to calculate the daily percolation from the depth-average soil water content, if the soil water content is above the DUL. According to Ratliff *et al.* (1983) DUL can be taken at any point where the internal drainage becomes negligibly low *viz.* 0.1 – 0.2% lower than initial K. The θ points were chosen to be 0.25 and 0.22 for the A and B-horizons, respectively. The corresponding K-values for A and B-horizons were 0.09 and 0.14 mm day^{-1}, respectively. Taking into account the thickness of the pedological layers, the DUL for the A-horizon and the three successive B-horizons is 75, 60, 66 and 57 mm/300 mm, respectively. Hence, the amount of water stored in the profile to a depth of 1200 mm is 258 mm. For the same depth, Botha *et al.* (2003) reported the DUL values of 456 and 385 mm on Glen/Bonheim and Khumo/Swartland ecotopes, respectively.

3.3.5 Evaporation characteristics

The procedure proposed by Ritchie (1972) was used to determine α value using E_s data presented in Figure 3.8. The α-value for Fort Hare/Oakleaf ecotope was found to be 4 mm $d^{1/2}$. Botha (2006) reported α-winter values of 4 and 3 mm $d^{0.5}$ on Glen/Bonheim-Onrus and Glen/Swartland-Rouxville ecotopes, respectively. The alpha value is very valuable information for crop models that predicts E_s.

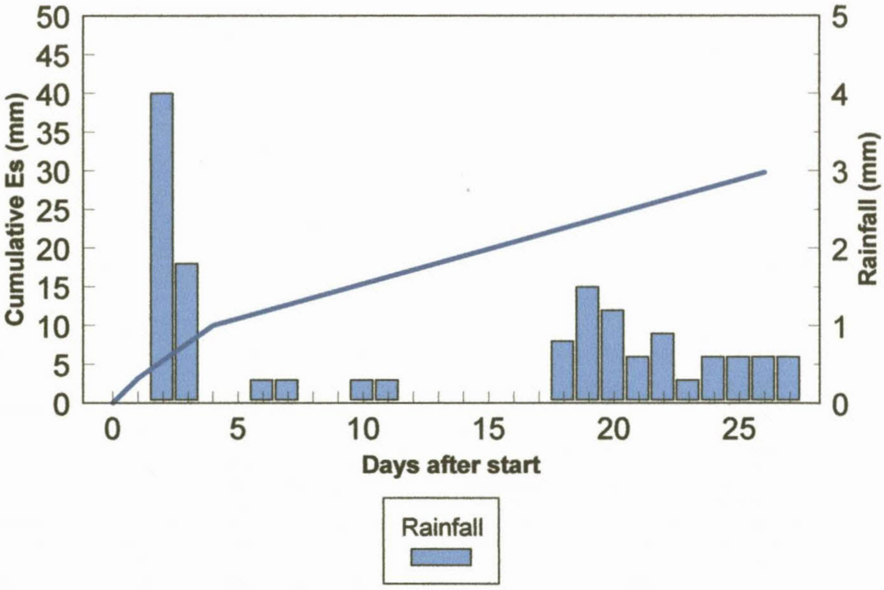


Figure 3.8 Cumulative soil surface evaporation graph for 0-1200 mm.

As mentioned in Section 3.2.3 change in soil water content was measured by using the NWM. Figure 3.8 illustrates cumulative E_s determined with NWM. The cumulative E_s over 27 days was 40 mm. According to Figure 3.8, the first four days E_s was rapid which explains the first stage of evaporation where evaporation is rapid and steady.

3.3.6 Runoff characteristics

According to Morin & Cluff (1980) R_{ex}. in arid and semi-arid areas consists mainly of overland flow and surface crusting is the dominant factor in causing the overland flow. This overland flow starts when the following conditions are met; the rainfall intensity is higher than final infiltration rate and maximum surface storage and detention are satisfied. The total measured R_{ex} for two growing seasons was found to be 92 and 130 mm for 2004/05 and 2005/06 growing season, respectively. R_{ex} amounted to 36 and 38% of the rainfall during 2004/05 and 2005/06 growing seasons respectively. R_{ex} increased linearly with the amount of rainfall (Figure 3.9) with a coefficient of determination of 0.86.

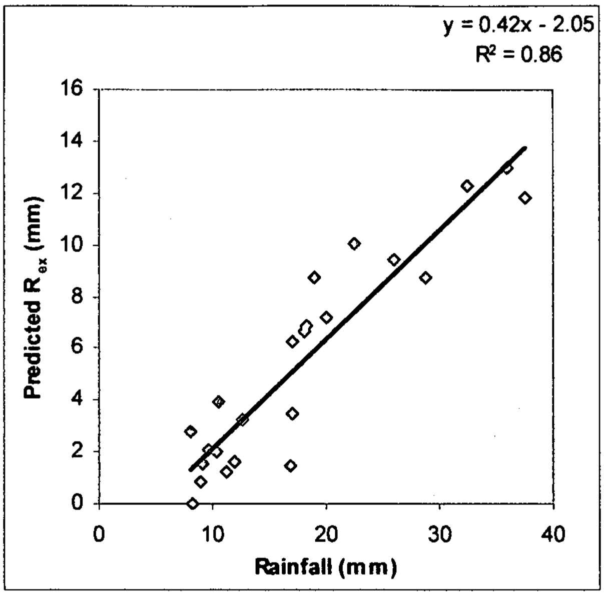


Figure 3.9 Relationship between predicted R_{ex} and rainfall for two growing seasons on Fort Hare/Oakleaf ecotope.

The Equation in Figure 3.9 can be used with reasonable confidence to predict R_{ex} from rainfall event in this ecotope. The Equation can also be used in similar ecotopes with the same rainfall characteristics. This is also very helpful in modeling the long-term soil water balance and therefore, long-term yield prediction for the similar ecotopes. The relationship between "measured R_{ex}" and predicted R_{ex} in Figure 3.10 was found to be satisfactory with the coefficient of determination of 0.91. The model predicted R_{ex} fairly well and this shows that MC runoff model can be used to predict R_{ex} in the semi-arid areas with reasonable confidence.

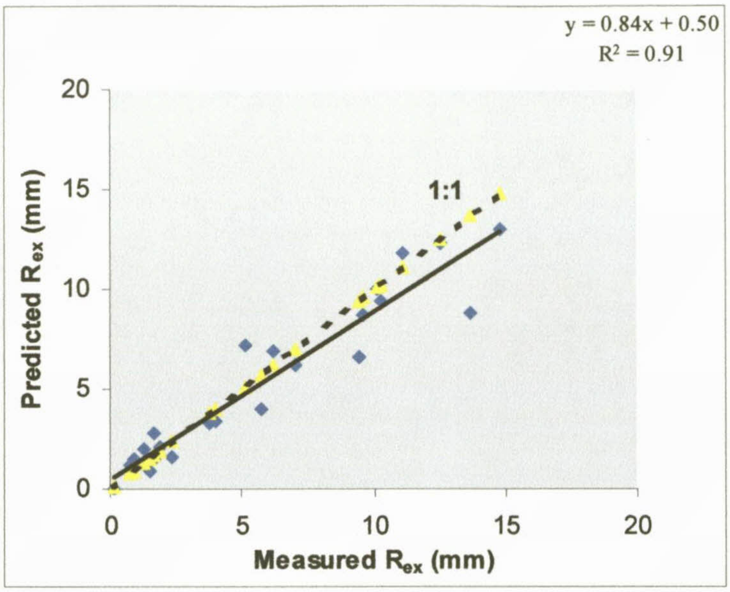


Figure 3.10 Relationship between predicted R_{ex} and measured R_{ex} on Fort Hare/Oakleaf ecotope.

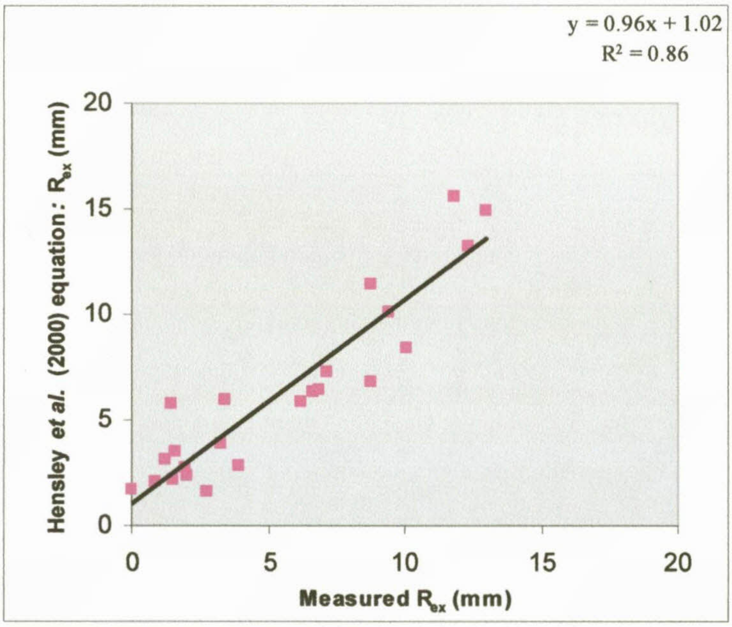


Figure 3.11 Comparison of calculated R_{ex} using Hensley *et al.* (2000) equation and measured R_{ex} on Fort Hare-Oakleaf ecotope.

The measured R_{ex} was also compared with R_{ex} calculated by using Hensley *et al.* (2000) equation. The equation was developed for Glen and Thaba-Nchu soils in the Free Sate province and it was assumed that R_{ex} would occur when rainfall was more than 8 mm (Hensley *et al.*, 2000). The "measured R_{ex}" was similar when compared with R_{ex} Hensley *et al.* (2000) equation with the coefficient of determination of 0.86 (Figure 3.11). According to the results in Figure 3.11, R_{ex} Hensley *et al.* (2000) equation could also be used to calculate R_{ex} in similar ecotopes where there is lack of resources to determine R_{ex}.

3.4 Conclusion

It was possible to characterize important climate and soil properties of the Fort Hare/Oakleaf ecotope near Alice in the Eastern Cape Province. The ecotope's climate is typically of semi-arid zone, normally with very high evaporativity conditions during mid-summer (December and January) followed by a sharp decrease during late summer (February) towards mid-autumn (April). The evaporation conditions are low during winter until they start to increase during September - October. Although the rainfall is typical of that expected of the semi-arid zone, very erratic and unpredictable, the long-term analysis indicates more than 7 rainfall days per month over summer cropping months (October to March). In addition, the long-term annual rainfall is 41 mm higher than the ecotopes at Glen where experiments showed that *IRWH* is sustainable even in a harsher climate.

The soil was classified as the Oakleaf form of Ritchie family with clay content of 21% in the A-horizon. The neocutanic B-horizons were identified with different colours, but with very uniform clay content (21 – 24%) and bulk densities (1.4 – 1.6 g cm^{-3}). The uniformity was reflected in the internal drainage of the B-horizon. A single $K(\theta)$ relationship was developed to describe drainage in the subsoil (Equation 3.4) Although the A-horizon is of similar texture class as the B-horizon it exhibits a different $K(\theta)$ response (Equation 3.3). It seems as if the retention of water is slightly better than B-horizon, probably due to naturally high organic matter associated with the topsoils. The evaporation characteristics of the A-horizon were determined by using the Ritchie (1972) method and the α-value was found to be 4 mm $day^{1/2}$. Observed runoff data from the runoff plots seems to be unreliable due to instrumental failures and installation problems. Runoff was therefore estimated with the combination of PutuRun and MC models. It was concluded that the models were able to predict runoff from the land reasonably when compared to that of the two Glen ecotopes.

CHAPTER 4

IN SITU EVALUATION OF IN-FIELD RAINWATER HARVESTING TECHNIQUE FOR MAIZE PRODUCTION ON THE FORT HARE/OAKLEAF ECOTOPE

4.1 Introduction

Theoretical maize yield estimations based on soil and water properties characterized in Chapter 3, suggested that in-field rainwater harvesting (*IRWH*) will perform better than mouldboard ploughing, here described as conventional tillage (*CON*) on Fort Hare/Oakleaf ecotope. The aim of this chapter is to test the theory in the field using a randomized complete block experimental design. The most suitable tillage practice soil and crop is influenced by many factors *viz.* climate, topography, soil types and soil properties such as texture, structure, depth, colour, the presence of permeable layer etc. (Bennie, 2003). Broad guidelines for tillage practices based on these factors are available for South Africa (Bennie, 2001). A recent socio-economic survey confirmed that maize farmers from the Alice district prefer mouldboard plough as primary tillage method (conventional) to prepare their crop fields (Monde, 2005). Recently Hensley *et al* (2000) introduced the in-field rainwater harvesting (*IRWH*) as a tillage practice to produce mainly summer field crops. It consists of a 2 m wide runoff strip along the slope of the land and 1m basin area (Figure 2.6).

Hensley *et al.* (2000), Botha *et al* (2003) and Botha (2006) tested the *IRWH* technique on clay and duplex soils in the central Free State and found that the *IRWH* technique resulted in maize yield improvements of between 30 and 50% in comparison to the mould board plough (*CON*) tillage. Botha (2006) determined that rainwater productivity on *IRWH* technique was high on *CON*, however, at least data for four seasons is needed to make good conclusions. Although in-field rainwater harvesting practices are not currently present in the Alice district, it is not total new concept in the target area. Mandiringana *et al.* (2003) from University of Fort Hare in Alice compared two in-field rainwater harvesting techniques *viz.* tied ridge and potholing against *CON* on two sites each about 30 km from Alice. The results indicated that both in-field rainwater harvesting techniques had significantly higher maize yield (up to 21%) than *CON.* However, the results were not inclusive as they represented one growing season which are probably too few to convince the farmers to adopt the technique. Based on the climate and soil properties characterized in chapter 3 and the theory of *IRWH* to conserve water during crop production two aims were formulated. Firstly, to estimate the agronomical sustainability of maize production on the ecotope for both the *IRWH* and *CON* methods. Secondly, to verify the influence of *IRWH* and *CON* on (i) maize grain yield and (ii) soil water balance components and crop-water related efficiencies (in situ experiment).

4.2 Materials and methods

4.2.1 Yield modelling

The following procedure was adopted to estimate the maize yield by *IRWH* compared to *CON.* Since R_{ex} is reduced to zero in *IRWH,* an increased yield can be expected because more water is available for ET. An estimate of combination of these two components is provided by the R_{ex} measured over two growing seasons. R_{ex} amounted to 222 mm for both growing seasons. It is necessary to have an estimate of the fraction of extra water that will be used for increasing yield, in this case used specifically for ET. The extra water can be considered to consist of two components. Firstly, the R_{ex} from *CON* which has been reduced to zero and secondly, the extra runoff which has been induced by that crusted no-till surface of the *IRWH* runoff strip. The results obtained by Hensley *et al.* (2000) & Botha (2006) for field experiments comparing the *IRWH* and *CON* with maize on the Glen/Bonheim ecotope, over seven growing seasons were employed to estimate this fraction of water. The following information was extracted for each growing season:

(i) R_{in} from the BbBr treatment;

(ii) difference in water used for ET on BbBr compared to *CON* ($ET_{BbBr} - ET_{CON} = \Delta ET$);

(iii) ratio of $\frac{\Delta ET}{R_{in}}$

4.2.2 In situ experiment

4.2.2.1 Experimental layout

A randomized complete block design experiment with three treatments replicated three times was employed on Fort Hare/Oakleaf ecotope. The three treatments were as follows:

- BbBr = *IRWH* with a bare basin area and bare runoff area.
- ObOr = *IRWH* with organic mulch in the basin and organic mulch on the runoff area. Reeds were used as organic mulch to cover the whole surface (Figure 4.1).
- *CON* = Conventional tillage

Figure 4.1 Illustration of ObOr, BbBr and *CON* treatments (left to right).

CON in this case is defined as ploughing of the land with a tractor using mould-board plough and then maize was planted in tramlines (2 x 1 m). There were no secondary cultivation activities and the land was left bare. No raking on the two-meter area took place as it was the case with BbBr. The mulch (reeds) was packed to cover 100% of runoff area and basin area. Each replicated treatment was 90 m^2. The experimental layout is presented in Figure 4.2.

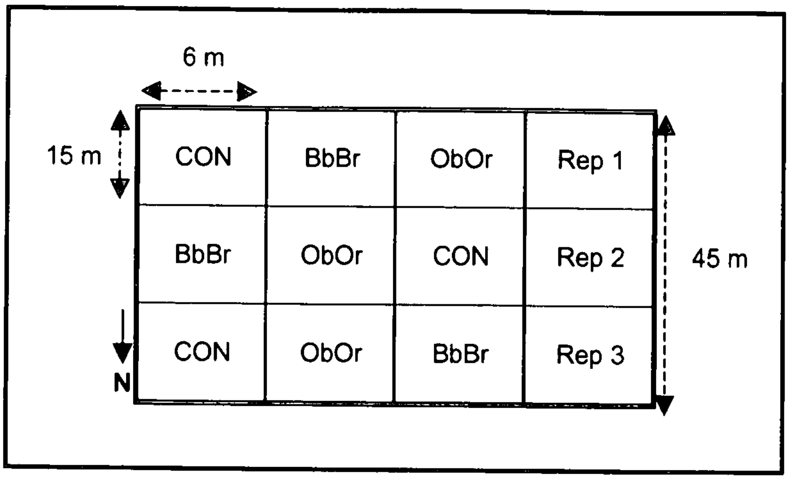


Figure 4.2 Experimental layout on Fort Hare/Oakleaf ecotope illustrating various treatments and replications.

4.2.2 2 Agronomic practices

Land preparation: A mouldboard plough was used as primary tillage to cultivate the land. The land was then disked to get a fine seedbed and the basins were then constructed for *IRWH* treatments.

Planting: The maize cultivar PAN 6480 as recommended by local agronomists was planted on 09/01/2005 for the first experiment and on the 22/11/2005 for the second experiment. Planting was done by hand at plant population of 22 000 plants ha^{-1}. Three seeds per planting hole were planted by hand in the one-meter wide area. After emergence the other two plants were thinned out, this was to ensure that the correct plant population of 22 000 plants ha^{-1} was achieved. The rows were one meter apart and the plants were 30 cm apart from each other. Since planting was done by hand, 32.5 g of fertilizer mixture 3:2:3 (22) + 0.5% Zn was applied per plant to supply 60 kg N ha^{-1}, 40 kg P ha^{-1} and 60 kg K ha^{-1} during planting. The quantity of fertilizer was based on soil analysis data. No top-dressing was done during the growing season.

Weeds, insects and pests control: The weeds were controlled by both mechanical and chemical methods. During, the growing season the weeds were controlled mechanically and during fallow period both methods were used. This was done due to the fact that some of the weeds were of the grass family and using chemicals to control them would also kill the maize plants since they are of the same family. Bulldock was used to control insects and pests. The mixture was prepared by adding 20 ml of bulldock in 20 litres of water (0.1% concentration). Knapsack sprayers were used to wet the plants whenever it was necessary.

4.3.3 Yield measurements

Biomass (Y_b): Twelve plants per replication in each treatment were cut just above the soil surface on 22/06/2005 for the first growing season and on 21/04/2006 for the second growing season. Since the roots were not sampled, the biomass represents only above ground component. The plants were chopped and then put in an oven at 65 ^{0}C for seven days. The biomass was calculated as follows:

$$Y_b\ (\text{kg ha}^{-1}) = \frac{22\,000\ \text{plants ha}^{-1} \times \text{mass of oven dried plants}}{12\ \text{plants}} \qquad \text{..................(4.1)}$$

The total Y_b at harvest was calculated by adding both the dry matter (above-ground biomass) and grain.

Grain yield: The grain yield of maize was determined by harvesting 6 rows, each 4 m in length from each replication on the same dates specified for biomass. The grain was oven-dried, weighed and adjusted to 13% water content and expressed as kg ha^{-1}.

Harvest index: The harvest index (HI) was calculated as the ratio of seed yield to the total above-ground biomass yield (Bennie, Strydom & Vrey, 1998).

4.3.4 Soil water balance components

4.3.4.1 Precipitation

Precipitation was measured by using the automatic rain gauge at the weather station which is about 1 km from the experimental plot.

4.3.4.2 Drainage

Drainage was calculated by using the soil water balance; Equation 2.1.

4.3.4.3 Runoff

The procedure described in Section 3.2.3.3 was used to calculate $R_{ex.}$

4.3.4.4 Transpiration

Transpiration (E_v) was calculated by using the transpiration coefficient of 9.5 g m^{-2} mm^{-1} as applied by Botha (2006) and Hensley *et al.* (2000).

4.3.4.5 Evaporation from the soil surface

Soil surface evaporation (E_s, mm) during the fallow period was calculated by using the α-value determined in Section 3.3.5. The soil water balance equation was used to calculate E_s for the growing period

4.3.4.6 Soil water content of the root zone

To determine the soil water content in the root zone, Neutron Water Meter (NWM) access tubes were installed until 1200 mm. The lower ends of the access tubes were sealed with aluminium plugs and silicon to prevent water from entering the tubes. Measurements were taken at the following depth intervals, i.e. 150, 450, 750 and 1050 mm. This ensured that all the different pedological layers were well represented. The NWM was calibrated for 0 – 300 mm, 300 – 600, 600 – 900 and 900 – 1200 mm layers using gravimetric soil water measurements and the bulk density of each layer. The gravimetric soil samples for calibration purposes were taken in the vicinity of the access tubes using an auger. The soil samples were taken and weighed in the field and then oven-dried for 48 hours at 105 °C. After oven-drying, the samples were weighed and gravimetric soil water content was calculated. The volumetric soil water content (%) was calculated by multiplying gravimetric soil water content of each layer by its bulk density. To calculate volumetric soil water content in mm, the volumetric soil water content (%) was multiplied by the depth layer.

An equation representing count ratio (CR) of NWM against volumetric soil water content (%) at different depths was derived to convert CR into volumetric soil water content (mm). The CR is calculated by dividing the reading obtained in the soil by the Standard reading obtained with the instrument in the shield. The CR was used due to advantages ascribed to this procedure by Gardner (1965) as applied by Hensley (1984). The Standard readings were taken before taking the soil measurements and again after taking the soil measurements to get the average reading. The same procedure was followed every time when taking the soil measurements.

The NWM soil water content measurements were taken at planting, during vegetative growth, at harvest and during the fallow period. However, it must be noted that during the first growing season (2004/05), gravimetric soil water content measurements were taken at planting. This was due to the fact that the access tubes were not yet installed at that time.

4.3.5 Plant available water

The lower limit (LL) of plant available water is the lowest field measured water content of soil after plants have stopped extracting water and are at or near premature death or have become dormant as a result of water stress (Hensley *et al.*, 2000). Hensley (1980) used field and laboratory methods to determine DUL and LL on Fort Hare/Oakleaf ecotope, LL value for 0 – 1200 mm from these findings was also taken for this study. The LL was calculated at –1500 kPa and was taken as preliminary LL for the purpose of this study.

The drained upper limit (DUL) was determined using the procedure described in Section 3.2.3.1. The difference between the DUL and LL for the root zone of 1200 mm was taken as the plant available water.

4.3.6 Crop-water related efficiencies

4.3.6.1 Water use efficiency

Water use efficiency (WUE, $\text{kg ha}^{-1}\ \text{mm}^{-1}$) based on E_v was calculated by using Equation 2.4.

4.3.6.2 Precipitation use efficiency

Precipitation use efficiency (PUE, $\text{kg ha}^{-1}\ \text{mm}^{-1}$) for the growing seasons was calculated by using Equation 2.2.

4.3.6.3 Rainfall storage efficiency

Rainwater storage efficiency (RSE, %) was calculated using Equation 4.2;

$$RSE = \frac{\theta_{p(n)} - \theta_{h(n-1)}}{P_f} * 100 \quad \text{.....(4.2)}$$

where:

$\theta_{p(n)}$ = root zone water content at planting of the current crop (mm)

$\theta_{h(n-1)}$ = root zone water content at harvesting of the previous crop (mm)

P_f = rainfall during the fallow season (mm)

4.3.6.4 Rainwater productivity

Rainwater productivity (RWP, kg ha^{-1} mm^{-1}) was calculated by dividing cumulative grain yield by cumulative rainfall (Equation 4.3).

$$\mathrm{RWP} = \frac{\sum \text{Grain Yield (kg ha}^{-1}\text{)}}{\sum \text{Rainfall (mm)}} \quad \text{.....(4.3)}$$

4.3.7 Statistical analysis

All data for yield was analysed using the NCSS 2000 Statistical System for Windows to determine the difference between various treatments (NCSS, 1998).

4.4 Results and discussions

4.4.1 Yield response

The results of grain and biomass yields are summarized in Table 4.1. *IRWH* treatments (BbBr and ObOr) increased grain yield by 26 and 34%, respectively during the first season compared to *CON*. In the second season *IRWH* treatments (BbBr and ObOr) increased grain yield by 14 and 20%, respectively. The effect of mulch application on ObOr treatment showed improvement in grain yield production when compared to BbBr. ObOr increased grain yield by 6 and 5% in the first and second seasons, respectively when compared to BbBr. The application of mulch contributes in suppression of E_s thus further minimizing unproductive soil water losses. Although *IRWH* treatments increased grain yield, there was no significant difference ($P \leq 0.05$) between treatments in terms of grain yield and biomass (ANOVA tables are presented in Appendix 13 and 14). Hensley *et al.* (2000) also reported no significant differences between *IRWH* and *CON* during the first growing season on the Glen/Bonheim ecotope. In both cases the first season did not include a full fallow period as in the case of the second growing season. Therefore the two seasons are not the same and could not be statistically compared.

Table 4.1 Yield parameters as affected by various treatments

Parameter		Treatments		
	Season	*CON*	BbBr	ObOr
Grain yield (kg ha^{-1})	04/05	2066^a	2611^a	2775^a
	05/06	3619^a	4177^a	4373^a
	Mean	**2843**	**3394**	**3574**
Total above-ground biomass (kg ha^{-1})	04/05	5528^a	5883^a	6323^a
	05/06	7609^a	8289^a	8996^a
	Mean	**6569**	**7086**	**7660**
Harvest index	04/05	0.37^a	0.41^a	0.47^a
	05/06	0.48^a	0.50^a	0.49^a
	Mean	**0.43**	**0.46**	**0.48**

The same superscripts in rows means that there is no significant difference between treatments at $P \leq 0.05$

The mean grain yield indicates that ObOr and BbBr produced 19 and 25% more grain yield than *CON*, respectively. The higher yields for both ObObr and BbBr compared to *CON* was also expressed in the total biomass.

4.4.2 Soil water balance components

The soil water balance components of the root zone are summarized in Table 4.2 (for the first growing season (2004/05) and Table 4.3 for the second growing season (2005/06) for all treatments. The soil water balance components include the change in soil water content (ΔS, mm), precipitation (P, mm), ex-field runoff (R_{ex}, mm), evapotranspiration (ET, mm), evaporation from the soil surface (Es, mm) and deep drainage or percolation (D, mm). The components were computed for intervals during the season that correspond with the soil water measuring dates. The totals of the various components of the three main periods, *viz*. the two growing seasons and the fallow period are also listed in Table

4.2 (for the first growing season (2004/05) and Table 4.3 for the second growing season and fallow period (2005/06). The following sections cover the discussion on the effect of various treatments on the soil water balance components.

4.4.2.1 Runoff

Two types of runoff are dealt with, *viz.* ex-field runoff (R_{ex}) and in-field runoff (R_{in}). The term R_{ex} refers to runoff from the crop field and is regarded as a water loss to crop production. On the other hand, R_{in} refers to runoff inducement practices where rainwater is harvested from a runoff area and collected in a basin as explained in Chapter 1 for *IRWH* treatments. R_{ex} becomes zero where the basin area can sufficiently store water during rain events. It should be mentioned that the basins did not break under any rain event over the measuring period. R_{ex} on CON was estimated with the method explained in Section 3.2.3.3. It amounted to 92, 95 and 130 mm for the first growing season, the fallow and the second growing season, respectively. Runoff expressed as a percentage of the corresponding total rainfall of the main periods results in values of 36, 37 and 38%, respectively.

The higher yields of *IRWH* are attributed to the stoppage of R_{ex} and improved storage of runoff water in the basins. Improved storage can be clearly witnessed in the difference in the soil water contents between BbBr and *CON* after the 81 mm rain shower on DOY 310 in 2005 (Figure 4.3). The soil water level of the BbBr was considerably higher than the *CON*. The arithmetic mean of the soil water content of the two access tubes; one represents the runoff area of 2 meters and one represents the basin area of 1 meter tends to normalise the data and in a way masks the in-field runoff process. A detailed analysis of the individual tubes should give a better reflection on the actual impact of runoff inducement. For example, the soil water content of the basin area, just after the 81 mm rain event, was 38.5 mm higher than the access tube in the runoff area.

A similar trend was observed in the mean soil water contents of the second growing season where the *IRWH* completed a full production cycle (fallow and growing period cycles). The soil water content of the basin was considerably higher than the runoff area (Appendix 4 to Appendix 12). Mulching on the runoff area, as practiced with the ObOr treatment, tends to reduce runoff inducement considerably. It impacts differently on the *IRWH* system and gives a more uniform distribution of water in the runoff area and basin area. For example, the soil water content of the two access tubes were 271 mm in the runoff area versus 273 mm in the basin area (Appendix 8). Comparing the mean for the second growing seasons reveals that the soil water content did not differ significantly between the two areas (Appendix 4 to Appendix 12).

4.4.2.2 Drainage

In this study drainage was calculated by using the soil water balance equation and not with the K(θ) relationships. The reason for this is that the time span between soil water content measurements was in most cases too long for the internal drainage method to be applied. The internal drainage method gives the best results where soil water content is measured directly after a rain event. The soil water content – time series graph in Figure 4.3, indicated that the risk for drainage was very low for the first growing season and large part of the fallow period until about DOY 300. During this period the soil water content fall far below the drained upper limit of 258 mm, indicating that drainage was low or zero. The drainage increased considerably following the series of rain events prior to planting, especially for the *IRWH* treatments that responded positively to water storage.

The risk of drainage in the basin area is higher than on the runoff area due to the concentration of infield runoff in the basin area. Fortunately for the BbBr treatment, the soil water content of the basin area did not rise above the DUL threshold, which confirms the result on zero drainage obtained during the period DOY 291-313. The soil water content-time series graph (Figure 4.3) shows clearly that the water content of the ObOr treatment moved above the DUL threshold value during the period following the 81 mm rain event. Accordingly, drainage was calculated to be 32 mm in total (Table 4.3). The accuracy of the value depends heavily on the accuracy of E_s estimations. However, it seems that drainage can become a risk on this ecotope due to the relatively good permeability of the subsoil and deeper layers (Section 3.3.4).

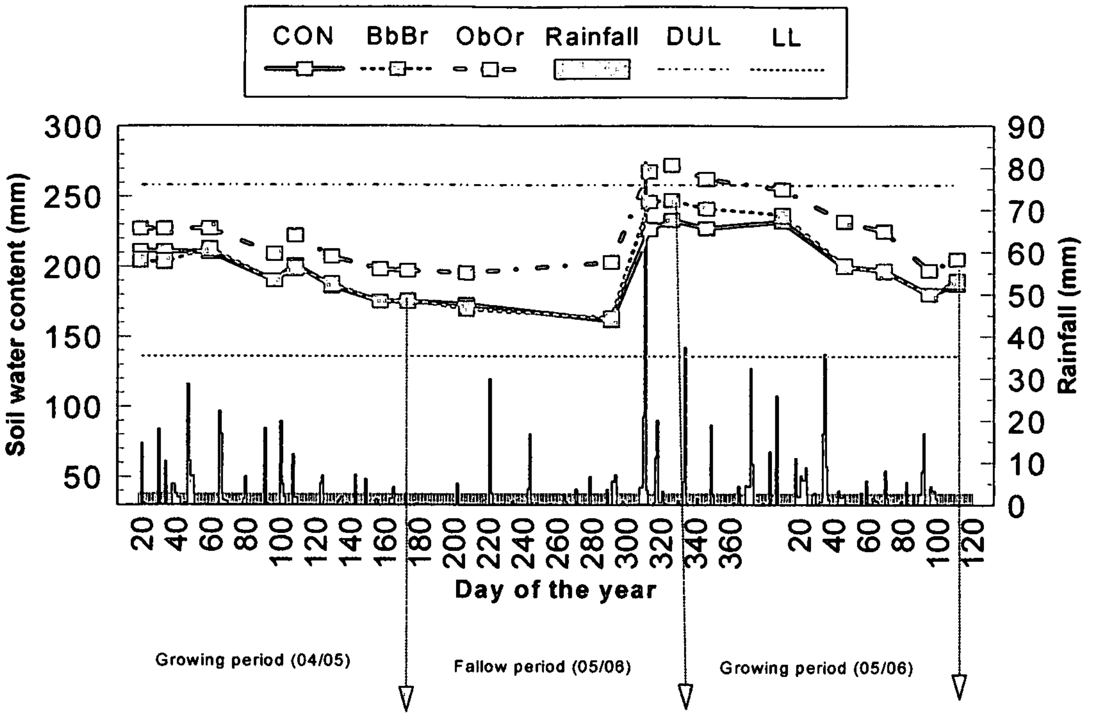


Figure 4.3 Change in soil water content during 2004/05, 2005/06 growing seasons and fallow period.

4.4.2.3 Evapotranspiration

The daily and seasonal water balance components for the two growing seasons are summarised in Table 4.2 for the first growing season (2004/05) and Table 4.3 for the second growing season (2005/06). The mean soil water content and rainfall distribution over the entire experimental period are presented in Figure 4.3. The corresponding mean daily transpiration (E_v) and reference potential evapotranspiration (E_o) are plotted in Figure 4.4. The transpiration (E_v) at the end of the season was calculated by using procedure described in Section 4.3.4.4 and soil water balance equation was then used to calculate seasonal evapotranspiration (ET).

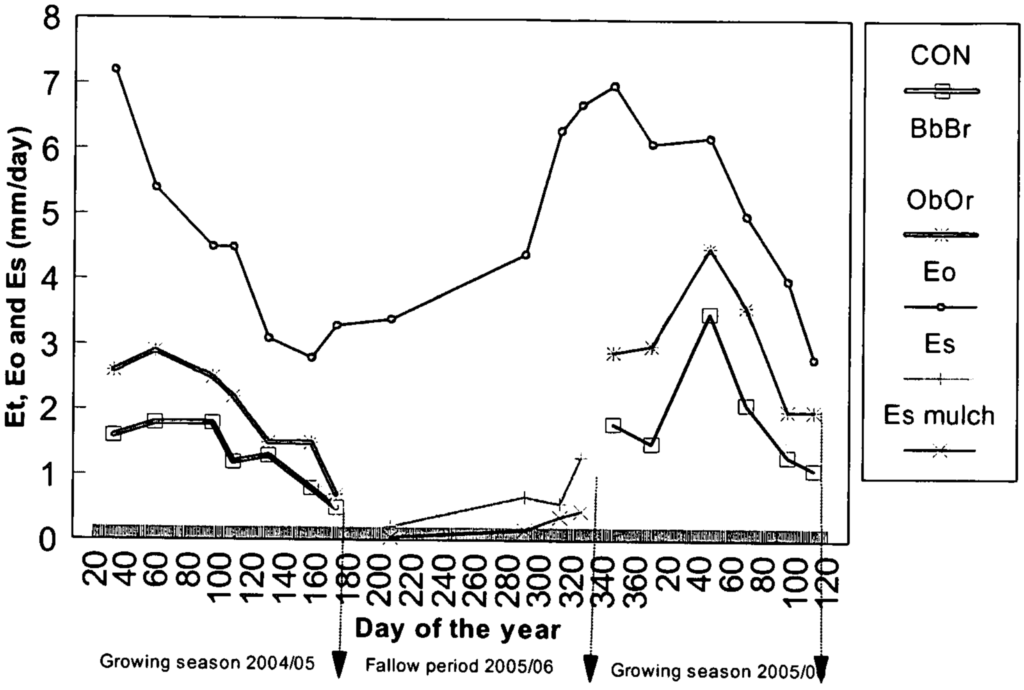


Figure 4.4 ET and E_o during 2004/05, 2005/06 growing seasons and E_s during the fallow period.

First growing season (04/05): Maize was planted very late during the first growing season under high evaporative demand conditions (Figure 4.4). E_o declined sharply during the growing season following the natural decline for the area as indicated in Table 3.1. Crop growing conditions were ideal until milk growth stage of the crop (DOY 108). During this period the cumulative E_o amounted to 464 mm while rainfall was 213 mm. Figure 4.3 indicates the rainfall events were well distributed over the period which resulted in aridity index of 0.46.

The generally good growing conditions of the period are also reflected on in the mean daily ET of the crop and soil water contents (SWC's) of the root zone. The SWC's graphs show that the water levels were relatively stable during the first part of the period (up to

DOY 60) under discussion indicating that the supply of water to the crop and the atmospheric demand were in balance. In the second part of the period (DOY 60 - 108) the ET increased, probably due to bigger leaf area. The water supply through rainfall was low for meeting the demand, therefore the atmospheric deficit was extracted from the soil as it can be seen by decrease in SWC's (Figure 4.3). It is interesting to note that ET for *CON* remained lower than the two *IRWH* treatments despite generally good climatic conditions.

Climatic conditions deterioted from DOY 108 to harvest (DOY 173) which represents a large portion of the reproductive growth phase. Rainfall amounted to 39 mm over this period, while the corresponding E_o was 194 mm (aridity index = 0.2). These unfavourable conditions in the supply of water are reflected in the sharp decrease of SWC's of all treatments (Figure 4.3). However, the E_o also decreased sharply during the same period and had a negative impact on the seed filling of the crop in all treatments. This explains the generally lower yields than expected. At the end of the season there was still 39, 40 and 61 mm plant available water left in the root zone for *CON,* BbBr and ObOr, respectively. Seasonal ET amounted to 205, 337 and 297 mm for *CON,* BbBr and ObOr, respectively. Separating ET into components reveals that E_v amounted to 70, 80 and 84 mm for *CON,* BbBr and ObOr, respectively, while E_s resulted in 135, 256 and 223 mm, respectively. The higher E_s on *IRWH* treatments is attributed to availability of soil water relative to *CON.* A large proportion of the water did runoff on the *CON* as explained in Section 3.3.6. Mulching in the *IRWH* treatments did not result in significantly higher yield, probably due to the climatic conditions explained.

Second growing season (05/06): The *IRWH* treatments had pre-plant soil water advantage over *CON* at the beginning of 05/06 season. The maize was planted late in November. From planting to milk stage (DOY 326 to DOY 36) crop growth conditions were favourable and the rainfall was well distributed. The rainfall amounted to 188 while cumulative E_o amounted to 484 mm (aridity index = 0.38). The generally good growing conditions are also reflected in the mean daily ET (Table 4.3 and Figure 4.4) of the crop. The SWC's of the root zone was also relatively stable during this period (plating to milk growth stage). This indicates that the water supply to the roots and atmospheric demand processes were in balance. After this period the water use increase due to increased leaf area of the crop.

After DOY 36 ET increased due to increased leaf area of the crop. The water supply through rainfall was not enough to meet the atmospheric demand as it can seen by sharp decrease in SWC's of the root zone for all treatments (Figure 4.3). To meet the atmospheric demand, the water was extracted from the soil. ET also decreased sharply during this period (Figure 4.4). The same trend was also observed in 04/05 growing season. DOY 36 to DOY 111 represent the reproductive stage of the crop. This is a very crucial stage since the actual yield is depended on water supply and demand conditions during this stage. Unfavourable climatic conditions can result in lower yields. During this period the total rainfall was 155 mm and cumulative E_o amounted to 316 mm. The favourable conditions during the entire season in comparison to 04/05 season resulted in higher grain yields. At the end of the season there was still 51, 54 and 69 mm of plant available water left for *CON,* BbBr and ObOr, respectively. The plant available water was higher by 31, 35 and 13% for *CON,* BbBr and ObOr in comparison to 2004/05 season. Seasonal ET amounted to 306, 471 and 475 mm for *CON*, BbBr and ObOr, respectively. Separating ET into its components reveals that E_v amounted to 127, 137 and 149 mm for *CON*, BbBr and ObOr respectively. The E_s amounted to 157, 334 and 348 mm for *CON*, BbBr and ObOr, respectively. The higher E_s values were attributed to higher soil water content in *IRWH* treatments.

4.4.2.4 Evaporation from the soil surface during the fallow period

Evaporation from the soil surface occurred during the fallow period as well as the two growing seasons. Two approaches were used to estimate E_s during the fallow period. Firstly, the soil water balance equation method ($Es = \Delta S + P - Rex$) was applied on all plots where drainage was negligibly low or zero, assuming that transpiration is also zero (no weeds or crops on the land). In the cases where drainage occurred on the ObOr treatment, E_s was calculated to be 21% of the corresponding BbBr treatment. The 21% reduction in ET due to mulching was derived from the mean reduction in E_s during the DOY 173-207 period and DOY 207-291 period of ObOr in comparison with BbBr. This methodology used to calculate E_s on ObOr seems reasonably accurate, because similar magnitudes in E_s reduction were measured at the Glen/Bonheim and Glen/Swartland ecotopes. The total E_s for the different treatments amounted to 93, 174 and 138 mm for *CON*, BbBr and ObOr, respectively. The low E_s of *CON* was ascribed to the higher ex-field runoff which decreased the available water for evaporation considerably. These two losses (E_s and R_{ex}) will always influence each other directly under *CON* because the risk for percolation is generally low.

Table 4.2 Soil water balance components as affected by various treatments during 2004/05 growing season

Season	Treatment	DOY	S (mm)	ΔS (mm)	P (mm)	R_{ex} (mm)	D (mm)	$ET_{(d)}$ (mm/day)	$ET_{(p)}$ (mm)	$E_{o(d)}$ (mm/day)	$E_{o(p)}$ (mm)	$E_{s(SWB)}$ (mm)
Growing season 2004/05	*CON*	19	211									
		33	210.8	0.2	33.2	11.9	0	1.6	22.7	7.2	100.4	
		59	210	0.8	72.8	28.5	0	1.8	46.8	5.4	141.4	
		95	190.1	19.9	68.6	26.8	0	1.8	63.4	4.5	163.1	
		108	200.8	-10.7	39	14.3	0	1.2	15.1	4.5	59.1	
		129	185.9	14.9	14	3.8	0	1.3	26.3	3.1	64.1	
		157	174.6	11.3	16.2	4.8	0	0.8	23.5	2.8	78	
		173	174.8	-0.2	8.8	1.6	0	0.5	7.4	3.3	52.1	
	BbBr	19	204									
		33	203.5	0.5	33.2	0	0	2.6	36.3	7.2	100.4	
		59	212.7	-9.2	72.8	0	0	2.5	66	5.4	141.4	
		95	190.9	21.8	68.6	0	0	2.6	92.9	4.5	163.1	
		108	198.1	-7.2	39	0	0	3.6	46.5	4.5	59.1	
		129	188.3	9.8	14	0	0	2.7	55.7	3.1	64.1	
		157	174.8	13.5	16.2	0	0	1.1	30.8	2.8	78	
		173	175.7	-0.9	8.8	0	0	0.5	8.5	3.3	52.1	
	ObOr	19	227									
		33	226.8	0.2	33.2	0	0	2.6	35.8	7.2	100.4	
		59	227.3	-0.5	72.8	0	0	2.9	75.1	5.4	141.4	
		95	209.2	18.1	68.6	0	0	2.5	88.9	4.5	163.1	
		108	222.4	-13.2	39	0	0	2.2	28	4.5	59.1	
		129	207.4	15	14	0	0	1.5	31.5	3.1	64.1	
		157	197.9	9.5	16.2	0	0	1	26.6	2.8	78	
		173	196.8	1.1	8.8	0	0	0.7	10.6	3.3	52.1	

DOY: Day of the year, S: soil water content of the root zone, ΔS: change in soil water content of the root zone, P: precipitation, R_{ex}: ex-field runoff, D: deep drainage or percolation, $ET_{(p)}$: evapotranspiration for measuring period, $ET_{(d)}$: daily evapotranspiration, $E_{o(p)}$: reference potential evapotranspiration for measuring period, $E_{o(d)}$: daily reference potential evapotranspiration, $E_{s(SWB)}$: soil surface evaporation using soil water balance, $E_{s(Ritchie)}$: soil surface evaporation using Ritchie's procedure

The second approach for estimating E_s was based on the procedure of Ritchie (1972) as discussed in Section 3.3.3.2 and is applicable to both the *CON* and BbBr treatments. The reduction of E_s due to mulching was also taken as 21% of the BbBr treatment. The results indicate that the total E_s values are 125, 125 and 98 mm for the *CON*, BbBr and ObOr treatments, respectively. The Ritchie method over estimates E_s in conditions where successive rain events give rise to alternating phase 1 and 2 of evaporation.

Table 4.3 Soil water balance components as affected by various treatments during fallow and growing season (2005/06)

Season	Treatment	DOY	S	ΔS	P	R_{ex}	D	$ET_{(d)}$	$ET_{(p)}$	$E_{o(d)}$	$E_{o(p)}$	$E_{s(SWB)}$	$E_{s(Ritchie)}$
			(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
Fallow period 2005/06	*CON*	173	174.8										
		207	172.9	1.9	5.8	0.4	0	-	-	3.4	-	7.3	23.3
		291	161.3	11.6	73.1	28.7	0	-	-	4.4	-	56.1	63.7
		313	226.3	-65	130.2	52.6	0	-	-	6.3	-	12.6	14.9
		326	232.9	-6.6	36.6	13.3	0	-	-	6.7	-	16.7	22.6
	BbBr	173	175.7										
		207	169.2	6.5	5.8	0	0	-	-	3.4	-	12.3	23.3
		291	163.5	5.7	73.1	0	0	-	-	4.4	-	78.8	63.7
		313	246	-82.5	130.2	0	0	-	-	6.3	-	47.7	14.9
		326	247.2	-1.2	36.6	0	0	-	-	6.7	-	35.4	22.6
	ObOr	173	196.8										
		207	195.4	1.4	5.8	0	0	-	-	3.4	-	7.2	18.4
		291	203	-7.6	73.1	0	0	-	-	4.4	-	65.5	50
		313	264.5	-61.5	130.2	0	31	-	-	6.3	-	37.7	11.8
		326	272.1	-7.6	36.6	0	1.1	-	-	6.7	-	27.9	17.8
Growing season 2005/06	*CON*	326	232.9										
		346	227.1	5.8	46.2	17.4	0	1.8	36.4	7	139.2		-
		10	231.7	-4.6	77.1	30.3	0	1.5	43.8	6.1	175.6		-
		46	199.7	32	80	31.6	0	3.5	125.6	6.2	223.7		-
		69	197.4	2.3	72.1	28.2	0	2.1	48.1	5	114.6		-
		95	179.6	17.8	22.7	7.5	0	1.3	34.3	4	103.9		-
		111	187	-7.4	40	14.8	0	1.1	17.9	2.8	44.3		-
													-
	BbBr	326	247.2										
		346	240.7	6.5	46.2	0	0	2.8	55.4	7	139.2		-
		10	237.1	3.6	77.1	0	0	2.9	83.5	6.1	175.6		-
		46	200.8	36.3	80	0	0	5.1	181.8	6.2	223.7		-
		69	196.1	4.7	72.1	0	0	3.5	80.3	5	114.6		-
		95	180.4	15.7	22.7	0	0	1.5	40	4	103.9		-
		111	190	-9.6	40	0	0	1.9	30.4	2.8	44.3		-
													-
	ObOr	326	272.1										
		346	262.3	9.8	46.2	0	0	2.9	58.8	7	139.2		-
		10	255	7.3	77.1	0	0	3	87.3	6.1	175.6		-
		46	231.5	23.5	80	0	0	4.5	162	6.2	223.7		-
		69	224.6	6.9	72.1	0	0	3.6	82.6	5	114.6		-
		95	196.5	28.1	22.7	0	0	2	52.8	4	103.9		-
		111	205	-8.5	40	0	0	2	31.5	2.8	44.3		-
													-

DOY: Day of the year, S: soil water content of the root zone, ΔS: change in soil water content of the root zone, P: precipitation, R_{ex}: ex-field runoff, D: deep drainage or percolation, $ET_{(p)}$: evapotranspiration for measuring period, $ET_{(d)}$: daily evapotranspiration, $E_{o(p)}$: reference potential evapotranspiration for measuring period, $E_{o(d)}$: daily reference potential evapotranspiration, $E_{s(SWB)}$: soil surface evaporation using soil water balance, $E_{s(Ritchie)}$: soil surface evaporation using Ritchie's procedure

4.4.3 Crop- water related efficiencies

The crop- water related efficiencies (Table 4.4) were calculated using equations described in Section 4.3.6. In rainfed agriculture, crop-water related efficiencies are very important parameters to compare different water conservation techniques. WUE_{Ev} measures the efficiency in which a particular crop can convert water available to it during that particular growing season into yield. WUE_{Ev} (where E_v represents transpiration) is more efficient to use since it excludes E_s that is not directly related to the crop's ability to convert water into yield. The WUE_{Ev} results indicate that there was no significant difference between all treatments for both seasons. The mean WUE_{Ev} for the first season was 31.7 kg $ha^{-1}mm^{-1}$ and it was 30.3 kg $ha^{-1}mm^{-1}$ for the second season. The mean WUE_{Ev} for the three treatments followed the trend; ObOr > BbBr>*CON*.

PUE is probably the simplest way of expressing the efficiency of converting rainwater into food. It is based on the simple principle that the system that produced the highest yield per unit area represents the best practice (Hensley & Bennie, 2003). Again there was no significant difference observed in PUE_g between all treatments irrespective of the season. The mean PUE_g for the experiment amounted to 10.77 kg $ha^{-1}mm^{-1}$, while the trend ObOr > BbBr>*CON*.

Table 4.4 Crop-water related efficiencies as affected by various in-field rainwater harvesting techniques and conservation tillage treatments

Crop- water related efficiencies		Treatments		
	Season	*CON*	BbBr	ObOr
WUE$_{(Ev)}$ (kg ha^{-1}mm^{-1})	04/05	30^{a}	33^{a}	33^{a}
	05/06	31^{a}	31^{a}	29^{a}
	Mean	**29**	**32**	**33**
PUE$_{g}$ (kg ha^{-1}mm^{-1})	04/05	8^{a}	10^{a}	11^{a}
	05/06	11^{a}	12^{a}	13^{a}
	Mean	**9**	**11**	**12**
RSE (%)	05/06	17^{a}	21^{a}	28^{a}
RWP (kg ha^{-1}mm^{-1})	05/06	10^{a}	11^{a}	12^{a}

The same superscripts in rows means that there is no significant difference between treatments at $P \leq 0.05$

Rainfall storage efficiency (RSE) describes the ability of the soil to store water in the profile during the fallow period. Bennie *et al.* (1994) did an extensive research on rain storage efficiency under dryland crop production in South Africa and reported pre-plant rain storage efficiency varying between 2 and 37%. As expected, a similar trend was also observed for the three treatments, ObOBr had higher RSE (28%) than BbBr (21%) and *CON* (17%), while BbBr had higher RSE than *CON.*

To determine crop-water related efficiencies over a long-term period, Botha (2006) suggested the concept Rainwater Productivity (RWP) would be more appropriate. The results in Table 4.4 indicate ObOr had higher values than both BbBr and *CON.* A similar trend as in other crop-water related efficiencies was observed, ObOr > BbBr > *CON.*

4.4.4 Yield modelling

The average value of $\frac{\Delta \mathrm{ET}}{\mathrm{R}_{\mathrm{in}}}$ over seven seasons was 0.62 (Welderufael, 2006). The estimated value for ΔET on Fort Hare/Okleaf ecotope due to employing *IRWH* compared to *CON* is therefore obtained as follows; 91.74 mm x 0.62 = 56.89 mm and 129.7 mm x 0.62 = 80.4 mm for 05 and 06 growing seasons, respectively. The multiplication of this ΔET by average $\mathrm{WUE}_{\mathrm{ET}}$ of 12.75 kg ha^{-1} mm^{-1} measured over two growing seasons gives an estimate of the increase in yield to be expected from *IRWH.* On average, the yield increase was estimated to be 875 kg ha^{-1} of maize grain yield when using *IRWH.*

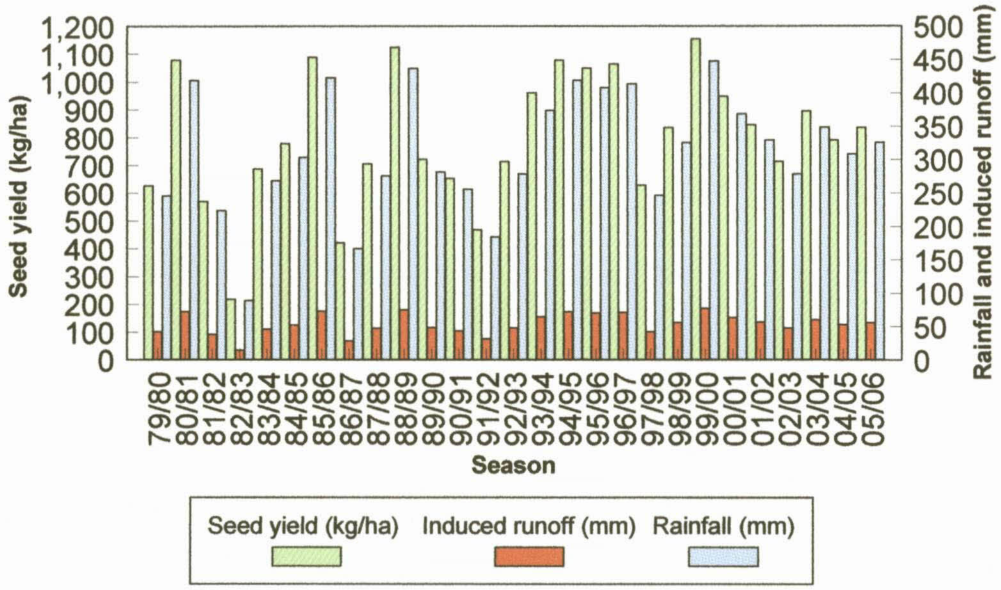


Figure 4.5 Long-term rainfall, induced runoff and estimated grain yield during the growing seasons on Fort Hare/Oakleaf ecotope.

Assuming a growing period of December to end of April grain yield estimations based on methodology suggested by Welderufael (2006) indicates that runoff inducement could have contributed to 219 and 1154 kg ha^{-1} yield above *CON* over the 27 year period (Figure 4.5). Application of mulches can further increase the yield potential in the *IRWH* system. Mulch on the runoff area reduces in-field runoff significantly in comparison to *IRWH* treatment without mulch. These phenomena impacts on the uniformity of water distribution in the system. Soil water was uniformly distributed in the basin and runoff area. On the contrary, it was found that soil water content was always higher in the basin area than in the runoff area in *IRWH* without mulch.

4.5 Conclusion

IRWH treatments were compared to *CON* and as hypothesized *IRWH* treatments performed better than *CON,* in terms of total biomass yield and grain yield. The average grain yield for the two growing seasons were 3574, 3394 and 2843 kg ha^{-1}, for ObOr, BbBr and *CON,* respectively. Mulch application increased grain yield by 25% compared to *CON,* while BbBr increased grain yield by 19% compared to *CON.* The models were also used to predict the potential water harvested in the basin area within *IRWH* system where the surface was assumed to be bare. However, accurate field data on runoff on different roughness indexes is needed in order to verify the estimations. It can be concluded that sufficient runoff can be induced to increase the yield between 219 to 1154 kg ha^{-1}.

IRWH treatments had higher ET than *CON* at the end of both growing seasons. The average ET for ObOr was 50% more than *CON,* while BbBr amounted to 58% compared to *CON.* The low E_s at the end of both growing seasons for *CON* was ascribed to the higher R_{ex} that decreased the available water for evaporation considerably. Results showed that *IRWH* technique was able to harvest and store more rainwater than the *CON* due to the total stoppage of runoff. Water conserved during the growing period led to higher maize yields, ET and water production efficiencies. Despite the obvious savings in water, none of the *IRWH* treatments seems to be significantly better than *CON* in terms of the various crop-water related efficiencies, except RSE. All the efficiencies (WUE_{Ev}, PUE_g, RSE and RWP) followed the same trend; ObOr > BbBr > *CON*. The means of the experiment were 31.3, 10.8 and 10.9 kg $ha^{-1}mm^{-1}$for WUE_{Ev}, PUE_g, and RWP, respectively. Botha (2006) found that RWP is a better indicator of crop-water related efficiencies, however more than four years of data is required. Therefore it is concluded that the experiment should continue as it is of national importance to convince farmers, extension and managers of the unique mechanisms of water conservation provided by *IRWH*.

CHAPTER 5

APPLICATION, SUMMARY AND RECOMMENDATIONS

5.1 Potential application of *IRWH*

A socio-economic study conducted in Guquka and Khayalethu villages of the Alice district in the Eastern Cape (Figure 5.1) revealed that the level of poverty in these villages ranges from poor to "ultra-poor". Ultra-poor people were defined as those who live far below the poverty line (Monde, 2005). Hebinck (2000) also studied the overview of livelihoods in Guquka and Koloni villages and categorised sources of income in three groups, *viz.* exchange of labour for income, income from governmental grants and pensions and incomes from arable land. Hebinck (2000) concluded that livelihoods in these villages was hardly based on agricultural production, but relied on incomes through exchange of labour for wages and from the governmental grants and pensions. Recent socio-economic studies conducted by Monde (2005) in Guquka and Khayalethu villages indicate that the situation in terms of poverty has not changed.

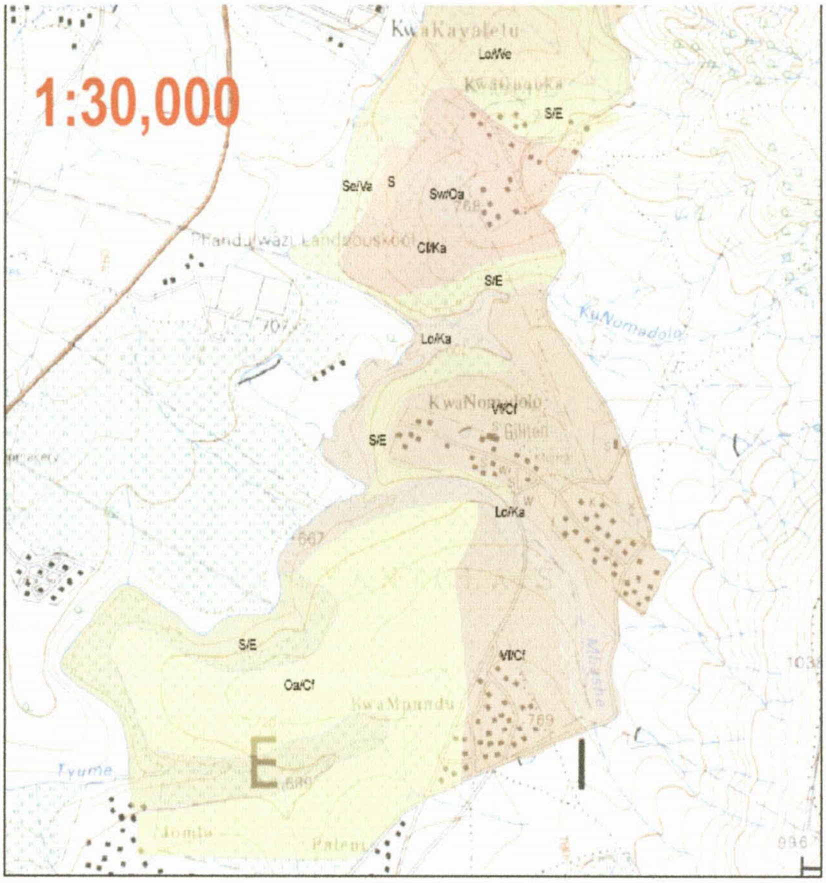
On the other hand Monde (2005) observed that there was a serious under utilization of crop fields in these villages. A survey was then done in the form of structured interviews to find out the reasons why the crop fields are under utilization. Monde (2005) concluded that the main reason was frequent crop failures and this led to lack of interest in crop production. Crop failures in these areas can be attributed to erratic rainfall and the use of the mould-board conventional tillage (*CON*) system. Monde (2005) concluded that implementation of rainwater harvesting techniques in the crop fields could be one of the tools that can alleviate poverty in these villages.

Following the success with *IRWH* in Thaba Nchu villages in the Free State Province and results obtained through research, it is recommended that *IRWH* should be implemented in those villages with similar ecotopes to that used in this research.

5.1.1 Pedotransfer

Evaluation of suitable land for crop production should primarily be based on the ecotope concept. Ecotope characterization is very important since it incorporates the three natural resources that affect productivity of the land. Therefore to maximize research efficiency, Hensley *et al.* (1997) recommended that benchmark ecotopes should be identified and characterized in detail in terms of climate, soil and topography and production potential.

A soil survey was conducted by Potgieter (2005) in Alice district. The following soil forms were found to be dominant; Cartref (Cf), Wasbank (Wa), Vilafontes (Vf), Oakleaf (Oa) and Longlands (Lo) and its distribution is demarked on the map provided in Figure 5.1 (Potgieter, 2005). It is clear from the findings that the Oakleaf soil form found on Fort Hare/Oakleaf ecotope also forms part of the dominating soil forms in these villages.



Map unit	Dominant soil forms and families
Vf	**Vilafontes 1120**
Oa	**Oakleaf 2220**
Wa	**Cartref 1100**
Lo	**Longlands 1000**
Ka	**Katspruit 1000**
Swa	**Swartland 1112**
Cf	**Cartref 1100**
Wa	**Wasbank 1000**
We	**Westleigh 1000**

*Legend Figure 5.2 (The number indicates soil family)

Figure 5.1 Map indicating villages and dominating soil forms in Alice district (Potgieter, 2005).

There were eight ecotopes found *viz.* Mpundu/Oakleaf, Mpundu/Cartref, Gilton/Vilafontes, Gilton/Cartref, Guquka/Longlands, Guquka/Westleigh and Khayalethu/Longlands Khayalethu/Westleigh. Soil texture was estimated by field method. The most important soil properties for implementation of *IRWH* are summarised in Table 5.2.

Table 5.1 Applicable soil and climate properties (Potgieter, 2005; Maritz, 2004) for implementation of *IRWH*

Village	Soil depth (mm)	Clay content (%)	Mean annual aridity index
Mpundu	400 - 900	18 - 25	0.39
Gilton	700 - 1000	15 - 25	
Guquka	750 – 1100+	15 - 30	
Khayalethu	700 – 1200+	18 - 42	
*Fort Hare/Oakleaf	1200+	21 - 22	0.36

*Fort Hare/Oakleaf ecotope where field experimentation was done

The soil depth in these ecotopes ranged from 400 to more than 1200 mm. Soil depth is very important since it determines profile soil water storage capacity. The clay content ranged from 18 to 42%. Potgieter (2005) reported that most areas on these ecotopes have slopes of less than 7%.

5.2 Summary

The technical information obtained from Chapters 3 and 4 provides a scientific basis to encourage farmers to replace mouldboard ploughing (*CON*), here defined as conventional tillage practices with *IRWH.* The average maize yields improved by 21 and 28% for BbBr and ObOr, respectively compared to *CON* over the two growing seasons. Such improvements will have positive impact on the water productivity as reflected on crop-related water production efficiencies (Table 4.4). The main reasons for the improvements are attributed towards total stoppage of R_{ex}, runoff inducement on the 2 m mini-catchment area and suppression of E_s by mulches. Long-term estimations on in-field runoff based on the 27 years of available climatic data reveal that between 35 and 181 mm runoff can be expected to be harvested in the basin area of *IRWH* systems.

Many other socio-economic constraints such as poverty, lack of appropriate tools and implements and lack of crop farming skills are ignored most of the time by researchers. The optimal use of technical information plays a huge role in communicating the underlying principles of *IRWH.* The ecotope provides a practical basis for pedo-transfer of technical information as it presents the smallest land unit with a unique set of soils, climate and slope related to specific crop production techniques (MacVicar *et al.,* 1974). Although an ecotope seems to be unique, much of the procedures, principles and information gathered can be transferred to other similar ecotopes. Hence, a summary of the important agronomic properties related to climate and soil of the Fort Hare/Oakleaf ecotope is presented in Table 5.2.

Table 5.2 Summary of important yield parameters, crop-water related efficiencies and soil properties of the Fort Hare/Oakleaf ecotope obtained during field experimentation

Treatment	Means	Parameters measured						
		Yield		Crop-related water efficiencies		Soil water balance components during growing seasons		
		Grain yield	Harvest index	RWP	RSE	ET	R_{ex}	P
		(kg ha^{-1})		(kg ha^{-1} mm-^{1})	(%)	(mm)		
CON	**Mean**	**2843**	**0.43**	**7**	**17**	**230**	**111**	**300**
BbBr	**Mean**	**3394**	**0.46**	**8**	**21**	**343**	**0**	**300**
ObOr	**Mean**	**3574**	**0.48**	**9**	**28**	**349**	**0**	**300**

5.3 Recommendations

5.3.1 Researchers

Following the intensive research conducted on *IRWH* in the Free State Province on various Glen ecotopes, there is huge scope for research in terms of *IRWH* on different ecotopes found in villages around Alice. Due to differences in soil and climate properties between these ecotopes, the starting point for research could be on the following:

5.3.1.1 Plant population

Following the success of 22 000 plants ha^{-1} on the Glen/Bonheim and Glen/Swartland ecotopes in the Free State Province, it is necessary to carry out research on plant population on other ecotopes with different soil and climate properties. The long-term (80 years) annual mean rainfall for the Glen ecotopes is 543 mm compared to 583 mm (27-year rainfall data) on Fort Hare/Oakleaf ecotope. The plant population was adapted for the climatic and soil properties on Glen ecotopes, therefore, higher plant population should be exploited due to difference in annual rainfall between Glen ecotopes and Fort Hare/Oakleaf ecotope. Results in Chapter 4 indicate that the plant population on Fort Hare/Oakleaf ecotope might be too low.

5.3.1.2 Drained upper limit

Drained upper limit is one of the most important soil properties that should be determined for each ecotope. Drained upper limit threshold value will assist to quantify whether deep percolation occurred during high rainfall events or not.

5.3.1.3 Deep percolation

Quantification of deep percolation needs to be taken into consideration especially when mulch is applied. Research done on Glen ecotopes (high clay content) indicates that deep percolation was never experienced for the duration of the studies (Hensley *et al.,* 2000). Preliminary results show that whenever there is high precipitation, deep percolation might occur on ObOr treatment on Fort Hare/Oakleaf ecotope. This is illustrated in Figure 3.5 where the soil water content of ObOr treatment was higher than the DUL.

5.3.1.4 Runoff studies

Runoff results in this study were determined by using Area Under the Curve (AUC) procedure developed by Walker *et al.,* 2005. However, one of the shortcomings was that the procedure uses rainfall intensity that is generated by the PutuRun model. The PutuRun model was only calibrated for Pretoria and Glen conditions. In this instance AUC procedure might have over-estimated the runoff on Fort Hare/Oakleaf ecotope. Therefore, accurate field measurements for at least three years for both ex-field (*CON*) and in-field runoff (*IRWH* treatments) should be taken.

5.3.1.5 Evaporation from the soil surface

Evaporation from the soil surface is one of three unproductive water losses. In order to quantify E_s qualitatively, it is recommended that further measurements for both winter and summer months on *IRWH* treatments and *CON* be taken with different instruments on the Fort Hare/Oakleaf ecotope.

5.3.1.6 Crop model

A crop model for maize needs to be developed for Fort Hare/Oakleaf ecotope in order to extrapolate the results to similar ecotopes. An efficient *IRWH* adapted crop model would likely make a valuable improvement on rainfed crop production.

5.3.2 Extension

It is recommended that the extension officers around Alice acquire knowledge and skills of *IRWH* in order to teach and guide farmers/families with application of *IRWH.* It is also recommended that *IRWH* application be part of the extension officer's programme as well as their training.

5.3.3 Farmers

It is recommended that the farmers implement *IRWH* in order to improve crop yields. Depending on the availability of organic mulches, mulch can be applied either on both runoff and basin area or only in the basin area of the *IRWH* system. Application of mulch minimizes evaporation from the soil surface. It is also recommended that farmers plant during November if rainfall allows due to higher number of rain days compared to other planting months.

As mentioned in the guidelines (Table 2.1), it is recommended that the soil depth should be at least 700 mm for optimum soil water storage and the slope should be less than 7% on the non-erodible soils. A fallow period of at least five months for summer crops could also be useful. Lack of weed control during the fallow and growing season will always result in low crop yields or even total failure during drought spells or during below average rainfall years. Therefore effective weed control either mechanically or chemically during the fallow and growing season and is essential to ensure higher crop yield. Farmers should also be aware that D might occur during high rainfall events under mulch treatment.

6 References

Allen, R.G., Pereira, L.S., Raes, D. & Smith, M., 1998. Crop evapotranspiration - Guidelines for computing crop water requirements. FAO Irrigation and drainage. Paper 56. FAO, Rome.

Baiphethi, M.N, Viljoen, G., Kundhlande, G., Botha, J.J., & van Rensburg, L.D., 2006. Quantifying the impact of in-field rainwater harvesting (*IRWH*) production techniques on household food security for communal farmers in Thaba Nchu, Free State Province.

Bennie, A.T.P., 2001. Grondbenutting vir droeland kontantgewasproduksie. Department of Soil, Crop and Climate Sciences.

Bennie, A.T.P., 2003. Effect of conservation farming on physical processes and properties. Paper presented at Combined Congress in Stellenbosch.

Bennie, A.T.P. & Hensley, M. 2001. Maximizing precipitation utilization in dryland agriculture in South Africa- a review. *J. Hydrol.* 241: 124-139.

Bennie, A.T.P., Hoffman, J.E., Coetzee, M.J. & Vrey, H.S., 1994. Storage and utilization of rain water in soils for stabilizing crop production in semi arid areas] [Afr]. Report No. 227/1/94. Water Research Commission, Pretoria.

Bennie, A.T.P., Strydom, M.G. & Very, H.S., 1998. The use of computer models on agricultural water management on ecotope level [Afr]. Water Research Commission, Report No. TT 102/98, Pretoria, South Africa

Beukes D.J., Bennie A.T.P. & Hensley, M., 1998. Optimization of soil water use in the dry crop production areas of South Africa: A review. pp 1 - 20. *In*: van Duivenbooden, D., Pala, M., & Bielders., C.L. (eds.). *Proceedings of the Optimizing Soil Water Use (OSWU) consortium workshop, Sadore, Niger, 26 April* -1 May 1998.

Black, T.A., Gardner, W.R. & Thurtell, G.W., 1969. The prediction of evaporation, drainage, and soil water storage for a bare soil. *Soil Sci. Soc. Amer. Proc.,* 33: 655-660.

Blake, G.R. and Hartge, K.H., (1986). Bulk density. 363-376. *In*: Campbell, GS, Jackson R.D., Mortland M.M., Nielsen, D.R. and Klute, A. (eds.). Methods of Soil Analysis. Part 1: Physical and Mineralogical Methods. Agronomy Monograph No 9 (2nd Ed) American Soc. Agron. Inc., Madison, Wisconsin, USA.

Botha, J.J., 2006. Evaluation of maize and sunflower production in a semi area using in-field rainwater harvesting. PhD. Thesis, University of the Free State, Bloemfontein.

Botha, J.J., van Rensburg, L.D., Anderson, J.J., Hensley, M., Macheli, M., van Staden, P.P., Kundhlande, G., Groenewald, D.G. & Baiphethi, M.N., 2003. Water conservation techniques on small plots in semi-arid areas to enhance rainfall use efficiency, food security, and sustainable crop production. Report No. 1176/1/03. Water Research Commission, Pretoria, South Africa.

Du Plessis, M.C.F. & Mostert, J.W.C., 1965. Runoff and soil loss at the Agricultural Research Centre, Glen [Afrikaans with English summary]. S. *Afr. J. Agric. Sci.* 8: 1051-1061.

FAO. 2004. Training course on water harvesting. Land and Water Digital Media Series 26. CD format. FAO, Rome.

Gabriels, D., Schiettecatte, W., Cornelis, W.M., Ouessar, M., Wu, H., Cai, D., Verbist, K., & Hartmann, R., 2003. Water Harvesting in Southern Tunisia and effect of soil tillage on the soil water balance in the semi-arid zone of the loess plateau of Northern China. *Proceedings of XI th International conference on rainwater catchment systems. Mexico,* 25-29 August 2003.

Hanks, R.J. & Rasmussen, V.P., 1982. Predicting crop production as related to plant water stress. *Adv. Agron.* 35: 193-215.

Haylett, D.G., 1960. Runoff and soil erosion studies at Pretoria. *S. Afr. J. Agric. Sci.* 3: 379-394.

Hebinck, P., 2000. Overview of Livelihoods in Guquka and Koloni. pp 28-33. *In*: Van Ranst, E., Verplancke, H., van Averbeke, W., Verdoodt, A. & Bonroy, J. (eds.). *Rural* *livelihoods in the Central Eastern Cape: Extended Abstracts of the International Workshop,* 20 - 22 June 2000, Ghent, Belgium: The Laboratory of Soil Science, University of Ghent.

Hensley, M., 1980. A comparison of two methods for determining plant available water in a soil profile. Agrochemophysica, 12: 39 – 43.

Hensley, M., 1984. The determination of profile available water capacities of soils. Ph.D. Thesis, University of Fort Hare, Alice.

Hensley, M., Anderson, J.J., Botha, J.J., van Staden, P.P., Singels, A., Prinsloo, M & du Toit, A., 1997. Modelling the water balance on benchmark ecotopes. Report No. 508/1/97. Water Research Commission, Pretoria, South Africa.

Hensley, M. & Bennie, A.T.P., 2003. Application of water conservation technologies and their impacts on sustainable dryland agriculture in sub-Sahara Africa. pp 2-17. *In*: Beukes, D., de Villiers, M., Mkhize., S., Sally, H. & van Rensburg L. (eds.). *Proceedings of the symposium and workshop on water conservation technologies for sustainable dryland agriculture in sub-Saharan Africa (WCT), Bloemfontein, South Africa,* 8 - 11 April 2003. Agricultural Research Council, Pretoria, South Africa.

Hensley, M., Botha, J.J., Anderson, J.J., van Staden, P.P. & du Toit, A., 2000. Optimizing rainfall use efficiency for developing farmers with limited access to irrigation water. Report No. 878/1/00. Water Research Commission, Pretoria, South Africa.

Hensley, M., Snyman, P.J. & Potgieter, H.L.J., 1990. A parameter for describing the efficiency of water use in rainfed cropping. pp 12-13. *In.* R.C. Muchow and J.A. Bellamy (eds). Climatic risk in crop production. Models and management in the semi-arid tropics and sub-tropics. CSIRO. Brisbane, Australia.

Hillel, D., 1982. Infiltration and surface runoff. pp 211-234. *In* D. Hillel (ed). Introduction to Soil Physics. Academic Press, New York.

Hillel, D., 2004. Introduction to environmental soil physics. Academic Press, New York.

Hoffman, J.E., 1997. Quantification and prediction of soil water evaporation under dryland crop production [Afrikaans]. Ph.D. Thesis, University of the Free State, Bloemfontein, South Africa.

Human Sciences Research Council (HSRC), 2004. Food security in South Africa: Key policy issues for the medium term. Report prepared for the Integrated Rural and Regional Development Program, South Africa by the Human Science Research Council.

Jalota, S.K & Prihar, S.S., 1990. Bare–soil evaporation in relation to tillage. *Adv. Soil Sci.* 12: 187-212.

Kronen, M., 1994. Water harvesting and conservation techniques for smallholder crop production systems. *Soil and Tillage Research* 32: 71-86.

Kundhlande, G., Groenewald, D.C., Baiphethi, M.N., Viljoen, M.F., Botha, J.J., van Rensburg L.D., & Anderson, J.J., 2004. Socio-economic study on Water Conservation Techniques in semi-arid areas. Report No. 126/1/04. Water Research Commission. Pretoria, South Africa.

Limon-Ortega, A. & Sayre, K.D., 2003. Dry land wheat production on narrow raised beds; a promising option. *Proceedings of XI th International conference on rainwater catchment systems. Mexico,* 25-29 August 2003.

MacVicar, C.N., Scotney, D.M., Skinner, T.E., Niehhaus, H.S. & Loubser, J.H., 1974. A classification of land (climate, terrain form, soil) primarily for rainfed agriculture. S. Afr. J. Agric. Ext. 3: 21-24.

Mandiringana, O.T., Mabi, M. & Simalenga, T.E., 2003. The potential of three water conservation technologies for adoption and use by communal farmers in the Eastern Cape. pp 56-59. *In*: Beukes, D., de Villiers, M., Mkhize, S., Sally, H. & van Rensburg L.D. (eds.). *Proceedings of the symposium and workshop on water conservation technologies for sustainable dryland agriculture in sub-Saharan Africa (WCT), Bloemfontein, South Africa,* 8 - 11 April 2003. Agricultural Research Council, Pretoria, South Africa.

Maritz, L., 2004. Climate Profile and Crop Suitability for Guquka, Khayaletu, Gilton, Sompondo and Mpundu villages. Report No. GW/A/20/86.

Maxwell, S., 2000. The evolution of thinking about food security. *In:* Devereaux & Maxwell, S eds. Food security in sub Saharan Africa. London. ITDG Publishers.

Monde, N., 2005. Sustainable techniques and practices for water harvesting and conservation and their effective application in resource-poor agricultural production: A situation analysis of Guquka and Khayalethu at Nkonkobe district Municipality, Eastern Cape. Deliverable No 3 for Water Research Commission Project No. K5/1477, Pretoria, South Africa.

Morin, J. & Cluff, C.B., 1980. Runoff calculation on semi-arid watersheds using a rotadisk rainulator. *Water Resour. Res.* 16: 1085-1093.

National Treasury, 2003. Intergovernmental Fiscal Review, 2003. Pretoria: Government Prints.

NCSS, J. 1998. NCSS help system: Multiple regression. Jery Hintze, Kaysville, Utah.

Oweis, T., Hachuum, A. & Bruggeman, A., 2004. Indigenous water-harvesting systems in West Asia and North Africa. International Centre for Agricultural Research in the Dry Areas. (ICARDA), Aleppo, Syria.

Oweis, T., Hachum, A. & Kijne, J., 1999. Water harvesting and supplementary irrigation for improved water use efficiency in dry areas. IWMI contribution (no 7) to System-Wide

Initiative on Water Management (SWIM). International Water Management Institute, Colombo, Sri Lanka.

Oweis, T., Prinz, D. & Hachum, A., 2001. Water harvesting: Indigenous knowledge for the future of the drier environments. International Centre for Agricultural Research in the Dry Areas. (ICARDA), Aleppo, Syria.

Passioura, J.B., 1983. Roots and drought resistance. *Agric. Water Management* 7: 265-280.

Passioura, J.B., 2006. Increasing crop productivity when water is scarce-from breeding to field management. *Agric. Water Management* 80: 176-196.

Potgieter, L.J.C, 2005. Soil survey of the Khayaletu, Sompondo, Guquka, Gilton and Mpundu Villages in the Eastern Cape Province in the Alice District. Report No. GW/A/2005/50.

Ratliff, L.F., Ritchie, J.T. & Cassel, D.K., 1983. Field-measured limits of soil water availability as related to laboratory-measured properties. *Soil Sci. Soc. Amer. J.* 47, pp 770-775.

Razzaghi, M.A., Rabti, M.A., Taleb, H., & Abulkhair, S., 2003. Evaluation of Atripx shrubs growth in semi-arid area using rainwater harvesting systems. *Proceedings of XI* th *International conference on rainwater catchment systems. Mexico,* 25-29 August 2003.

Reij, C., Mulder, P. & Begemann, L., 1988. Water harvesting for plant production. World Bank Technical Paper No. 91. The World Bank, Washington, DC, USA.

Ritchie, J.T., 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resources Res. Vol 8. No. 5: 1204 - 1211

Siegert, K., 1993. Introduction to water harvesting: some basic principles for planning, design and monitoring. *In*: Water harvesting for improved agricultural production. FAO report. Proceedings of the FAO expert consultation. Cairo, Egypt, 21 - 25 November 1993; Water Reports (FAO), no. 3 / FAO, Rome (Italy). Land and Water Development Div. 1994.

Soil Classification Working Group, 1991. Soil Classification - A taxonomic system for South Africa. Soil and Irrigation Research Institute, Department of Agricultural Development, Pretoria.

Soil Survey Staff, 1972-2002. *Generalized soil patterns of South Africa.* ARC-ISCW, Pretoria.

Stellamaris, S., 2003. Identify and estimate the quantities of water supplies and uses on Plot 66, Dewangsdrift of Mrs MaTshepo Khumbane. M.Sc. Thesis. University of Pretoria.

Tanner, C.B. & Sinclair, T.R., 1983. Efficient water use in crop production: Research or Re-search? *In* H.M. Taylor & W.R. Jordan (eds). Limitations to efficient water use in crop production. Am. Soc. of Agron:1-27. Madison, Wisconsin.

Tekle, S.A., Hensley, M & le Roux, P.A.L., 2004. Soilscape survey for planning in-field rainwater harvesting in Thaba Nchu, Central Free State.

Theodore, M., 2003. Current water conservation practices used by farmers in the Zambezian dryland areas of the southern Democratic Republic of the Congo: pp 37-44. *In:* Beukes, D., de Villiers, M., Mkhize, S., Sally, H. & van Rensburg L.D. (eds.). *Proceedings of the symposium and workshop on water conservation technologies for sustainable dryland agriculture in sub-Saharan Africa (WCT), Bloemfontein, South Africa,* 8 - 11 April 2003. Agricultural Research Council, Pretoria, South Africa.

Tsubo, M., Walker, S & Hensley, M., 2005. Quantifying risk for water harvesting under semi-arid conditions. Part I. Rainfall intensity generation. *Agric. Water Management.* 76: 77 – 93.

UNESCO, 1977. Map of the world distribution of arid zones. Man and Biosphere Technical Notes No 7.

Van der Merwe, G.M.E., 2004. The use of water harvesting techniques on vertisols to provide stable crop production on rural farms in the Bafokeng district of North West Province: 2nd Progress Report to the Department of Agriculture. ARC-ISCW Report No.GW/A/2004/25. Agricultural Research Council, Pretoria, South Africa.

Van Rensburg, L.D., Botha, J.J., Anderson, J.J. & Joseph, L.F., 2004. A review on the technical aspects of rainwater harvesting for crop production. Poster presented at SANCID 2004 Symposium, Fish River Sun, 16 – 19 November 2004, South Africa.

Van Staden, P.P., 2003. The effect of runoff-storage relations on rainwater utilization by maize on clay soils with high drought risk. M.Sc. Thesis, University of the Free State, Bloemfontein

Ventura, E., Darrell -Norton, L., Ward, K., Lopez-Bautista, M. & Tapia-Naranjo, A, 2003. "In Situ" Water harvesting for crop production in semi-arid regions. *Proceedings of XI th International conference on rainwater catchment systems. Mexico,* 25-29 August 2003.

Walker, S., Tsubo, M., & Hensley, M., 2005. Quantifying risk for water harvesting under semi-arid conditions. Part II. Crop yield simulation. *Agric. Water Management.* 76: 94 – 107.

Welderufael, W.A., 2006. Quantifying rainfall-runoff relationships on selected benchmark ecotopes in Ethiopia: A primary step in water harvesting research. PhD. Thesis. University of the Free State, Bloemfontein.

Willmott, C.J., 1982. Some comments on the evaluation of model perfomance. *Bull. Am. Metereol. Soc.* 63: 1309-1313.

Woyessa, Y.E., Pretorius, E., van Heerden, P.S., Hensley, M. & van Rensburg, L.D., 2006. Impact of Land Use on River Basin Water Balance: A Case Study of the Modder River Basin, South Africa.

APPENDICES

Soil Profile Description: University of Fort Hare

NATIONAL SOIL PROFILE NO:
Map / photo:
Latitude & Longitude: -32°47'46"/ 26°50'52"
Land type No:
Climate zone:
Altitude: 520 m
Terrain unit: Footslope
Slope: 1.5%
Slope shape: Straight
Aspect: North
Micro relief: None
Parent material solum: Alluvium
Underlying material: Old alluvium

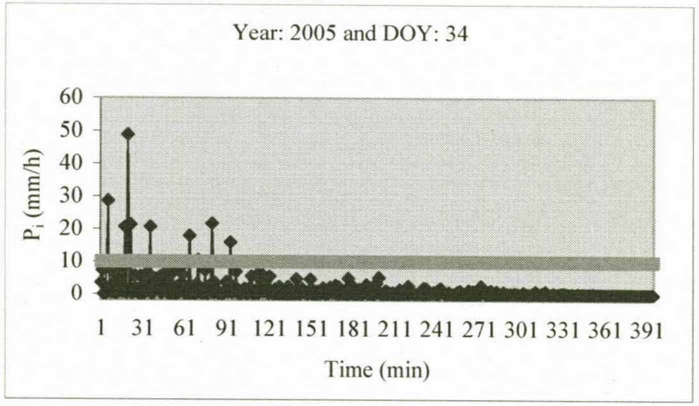
Soil Form: Oakleaf
Soil Family: Ritchie
Surface rockiness: None
Surface stoniness: None
Occurrence of flooding: None
Wind erosion: None
Water erosion: None
Vegetation / Land use: Agronomic Cash Crops
Water table: 0 mm
Described by: L.F. Joseph
Date described: November 2005
Weathering of underlying material: Strong physical and weak chemical
Alteration of underlying material:

Horizon	Depth (mm)	Description	Diagnostic horizons
A	0 - 300	Dry colour: dark brown 10YR3/3; moist colour: very dark brown 10YR2/2; loam; structure: apedal, consistence (dry): soft; consistence (moist): friable; wet-stickiness: non-sticky; common fine pores; water absorption: 3 second(s); many roots; gradual transition.	Orthic
B1	300 - 600	Dry colour: very dark greyish brown 10 YR 3/2; moist colour: very dark grey 10YR3/1; loam, structure: sub-angular blocky; consistence (dry) slightly hard; consistence (moist): slightly firm; wet-stickiness: slightly-sticky, many fine pores; water absorption: 3second(s); few roots; gradual transition	Neocutanic
B2	600 - 900	Dry colour: dark yellowish brown 10YR 4/6; moist colour: dark yellowish brown 10 YR 4/4; loam; structure: apedal, consistence (dry): friable; consistence (moist): friable, many fine pores; water absorption: 3second(s), gradual transition.	Neocutanic
B3	900 - 1200	Dry colour: reddish brown 5YR 5/3; moist colour: dark reddish brown 5 YR 3/4; loam; structure: apedal, consistence (dry): friable; consistence (moist): friable, many fine pores; water absorption: 3second(s), gradual transition	Neocutanic

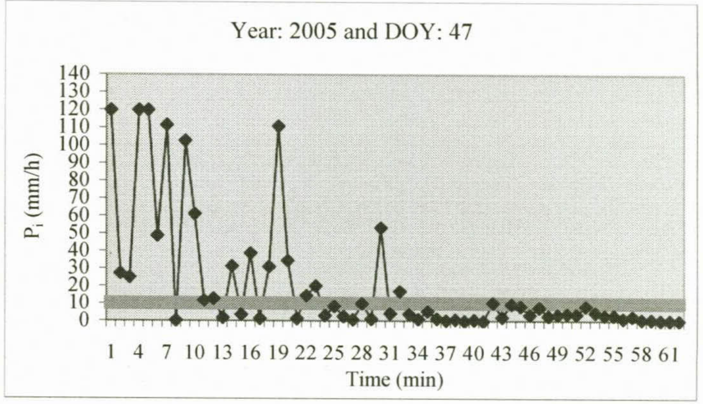
Soil analytical data Fort Hare/Oakleaf ecotope

Horizon	A	B1	B2	B3
Depth (mm)	0-300	300-600	600-900	900-1200
Lab no	M467	M468	M469	M470
Particle size distribution (%)				
Coarse sand: (2-0.5 mm)	0.21	0.21	0.00	0.20
Medium sand:(0.5-0.25 mm)	1.91	0.63	0.62	0.60
Fine sand: (0.25-0.106 mm)	12.00	11.45	10.37	9.93
Very fine sand:(0.106-0.05 mm)	15.50	18.38	17.97	16.54
Coarse silt: (0.05-0.02 mm)	31.95	30.30	30.08	14.09
Fine silt: (0.02-0.002 mm)	15.82	15.44	15.30	16.41
Clay: (>0.002 mm)	20.86	22.01	23.67	40.53
Texture class	Loam	Loam	Loam	Clay
Sand grade	Fine	Fine	Fine	Fine
Chemical analysis				
C (%)	1.05	0.65	0.47	0.33
pH (H_2O)	6.41	7.16	7.74	7.52
Extractable cations cmol(+)/kg soil				
Na	0.23	0.41	0.56	0.51
K	0.42	0.17	0.18	0.18
Ca	6.38	7.51	7.49	7.19
Mg	2.64	2.59	2.81	2.79
S-value	9.68	10.68	11.04	10.66
CEC	16.02	15.17	13.92	13.25

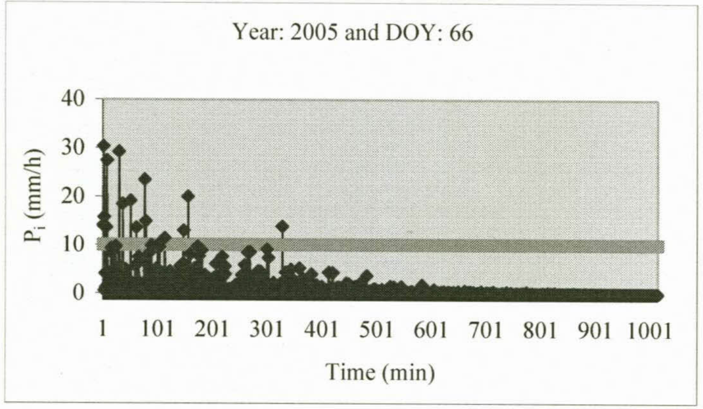
Appendix 3.1



Appendix 3.2



Appendix 3.3



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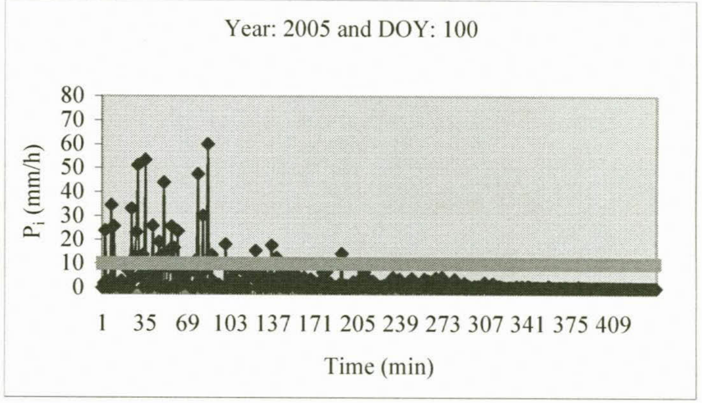
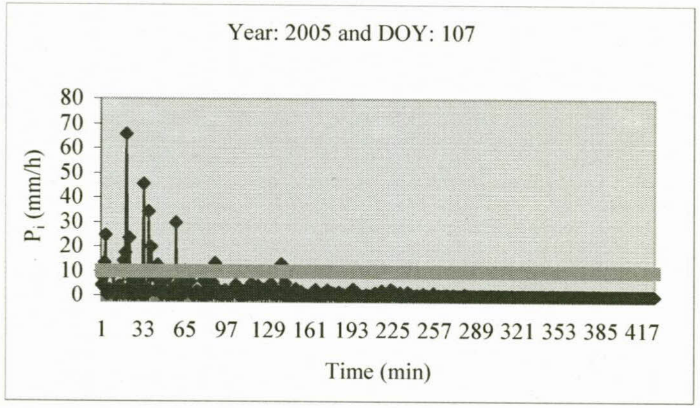


Appendix 3.5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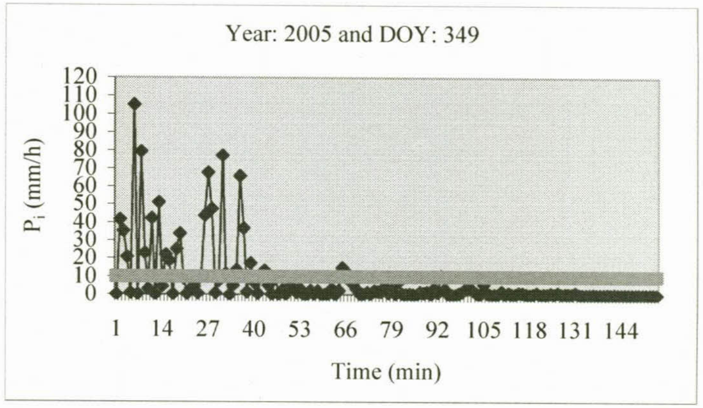
Appendix 3.6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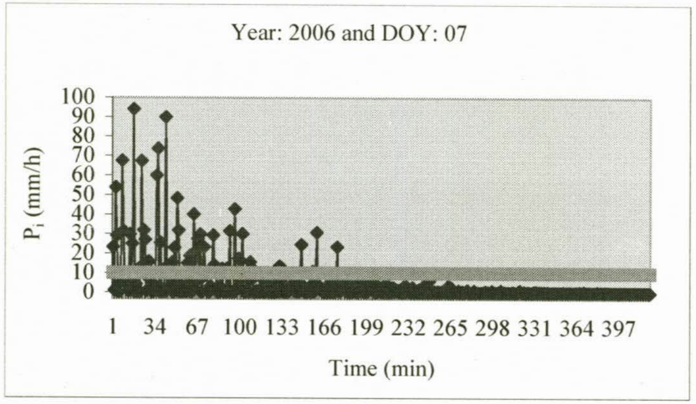
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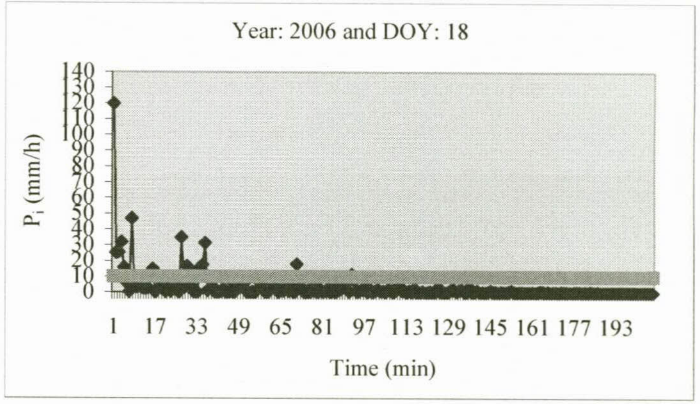
Appendix 3.8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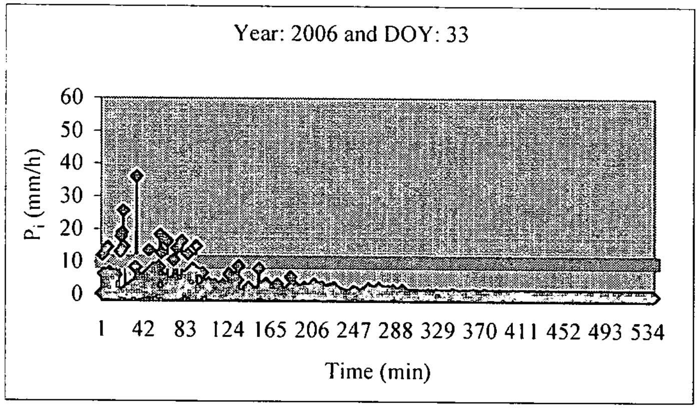
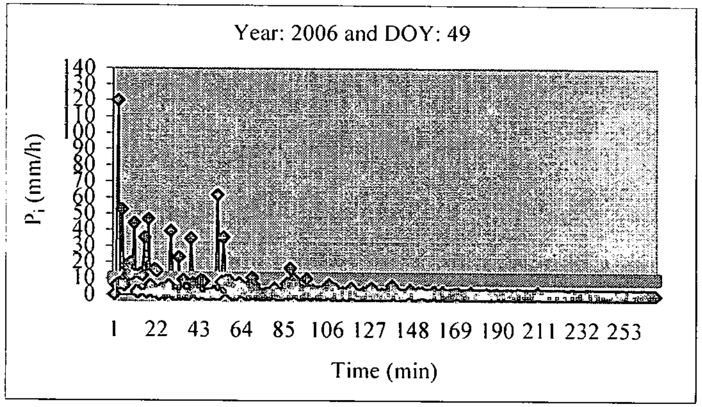
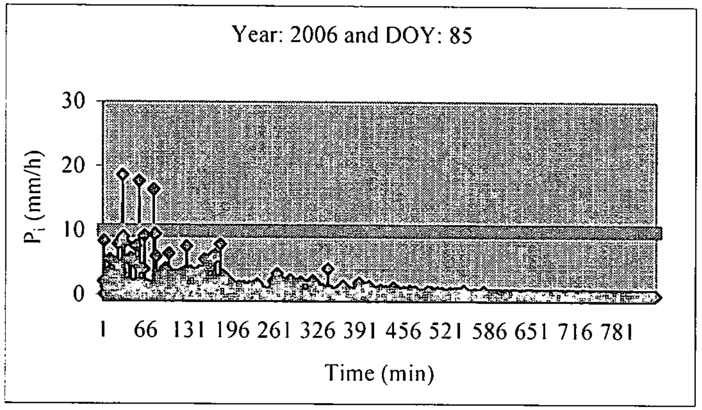
Appendix 3.9



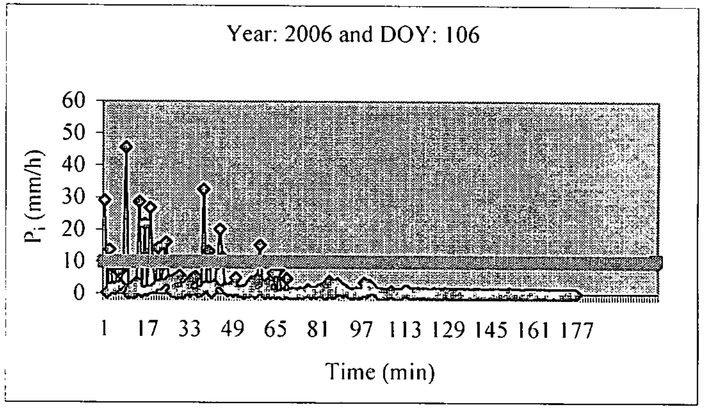
Appendix 3.10

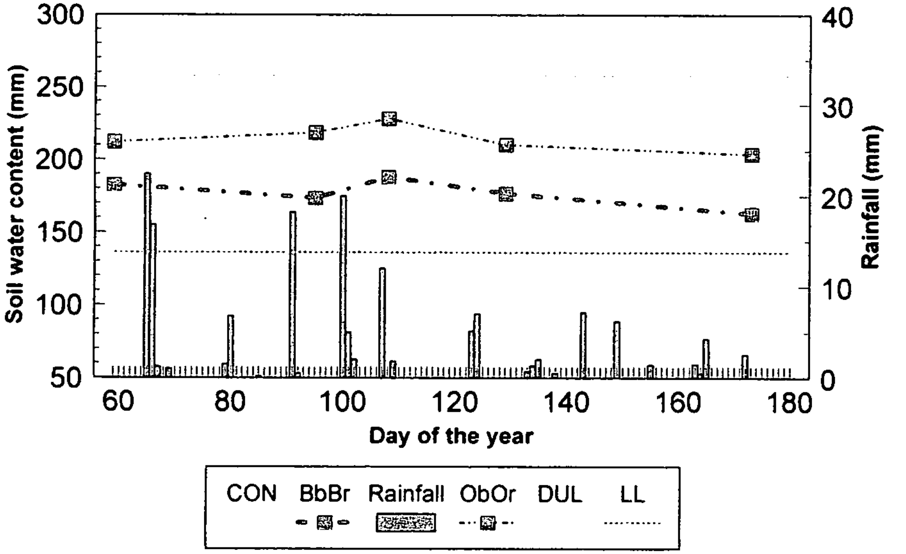


Appendix 3.11

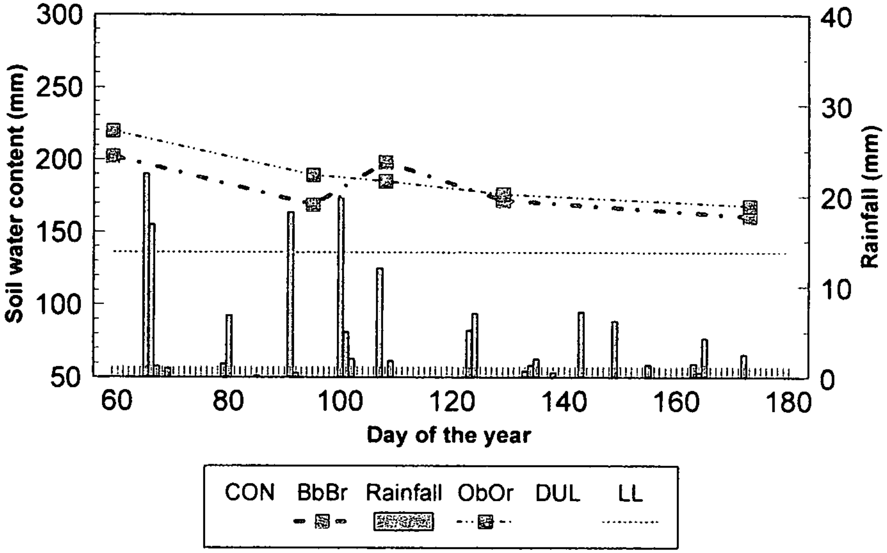


Appendix 3.12

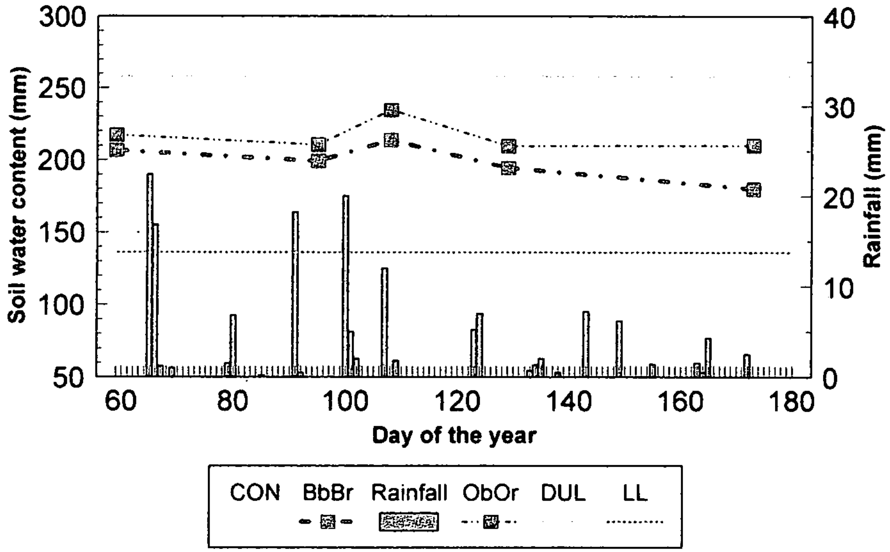




(a) Soil water content on the Runoff area (Rep1) during 04/05 growing period



(b) Soil water content in the Basin area (Rep1) during 04/05 growing period



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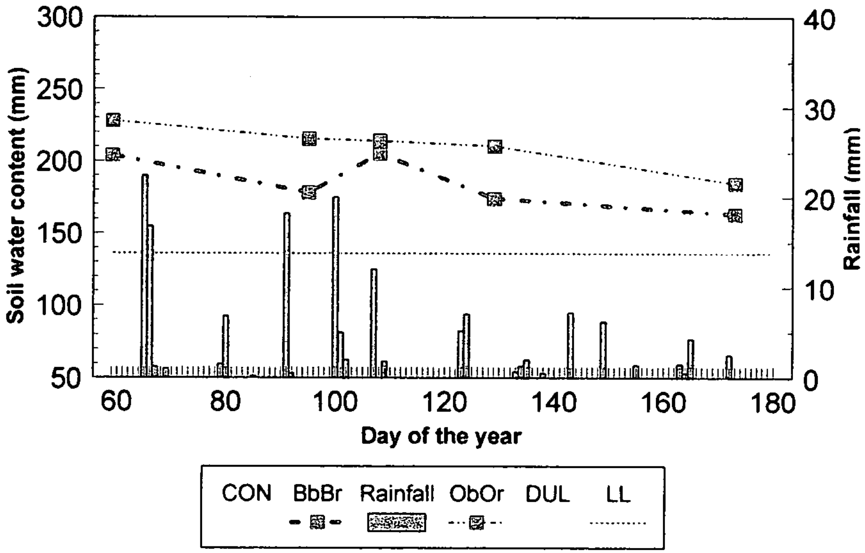

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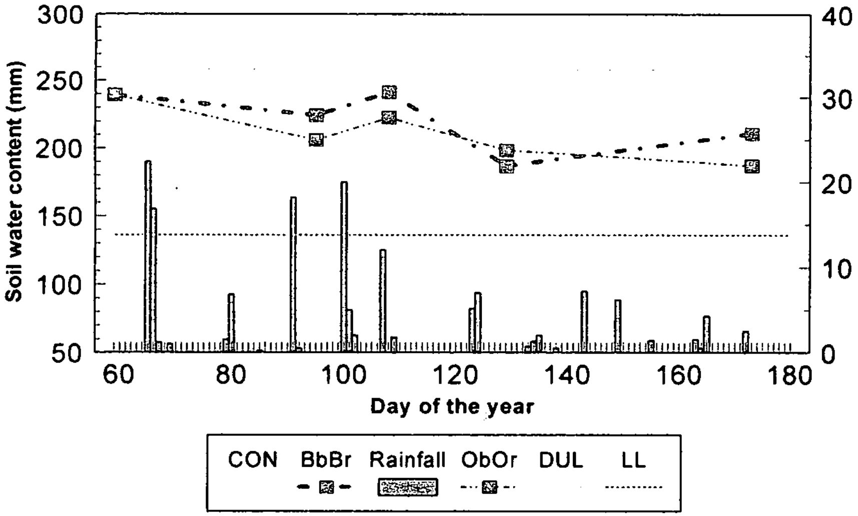

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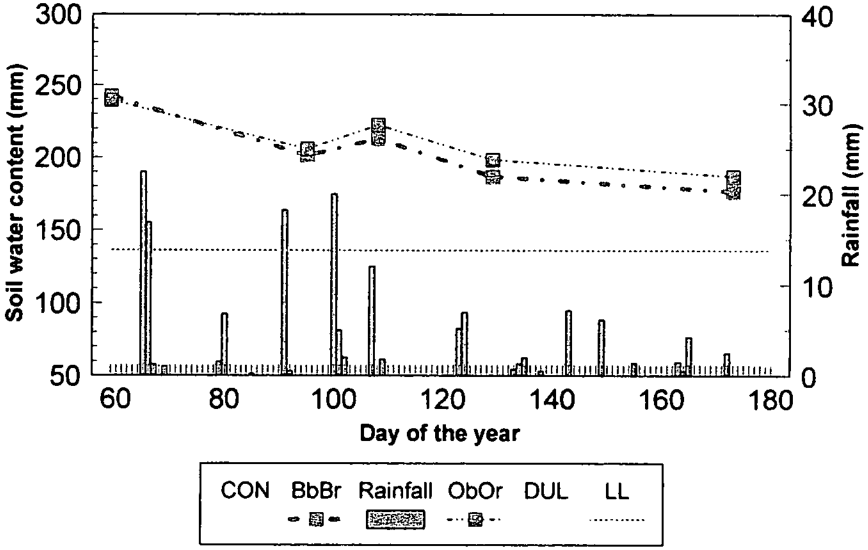

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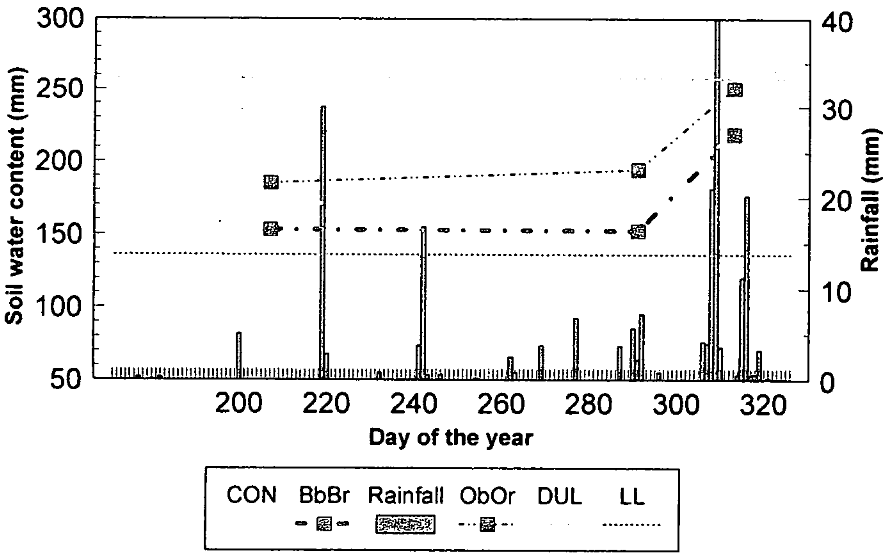
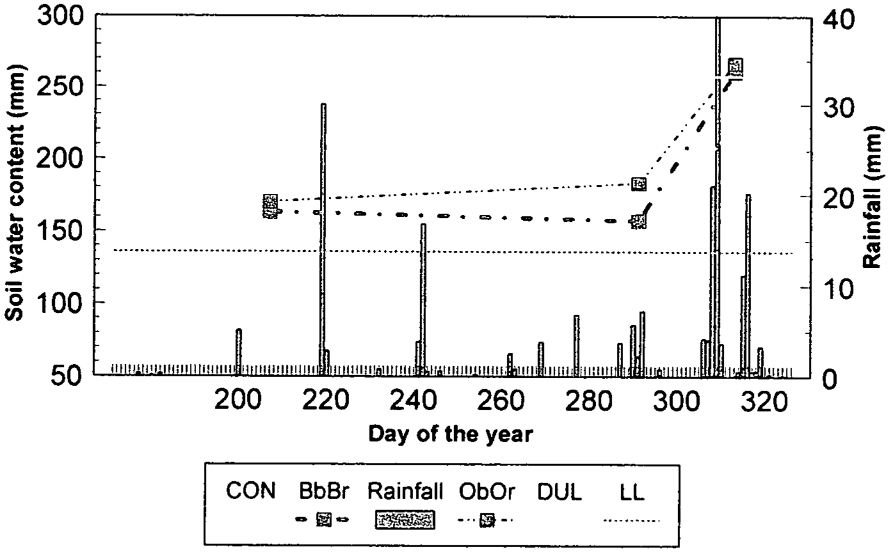


(a) Soil water content on the Runoff area (Rep 1) during 05/06 fallow period



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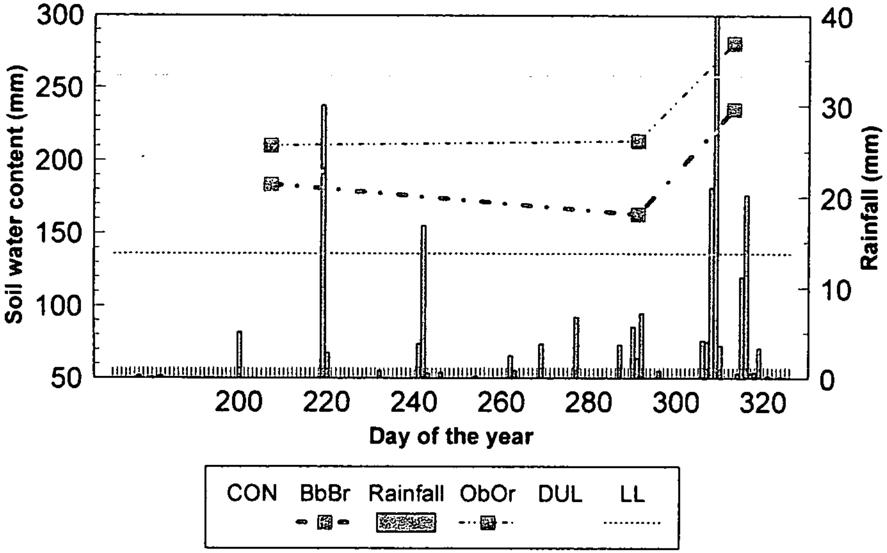

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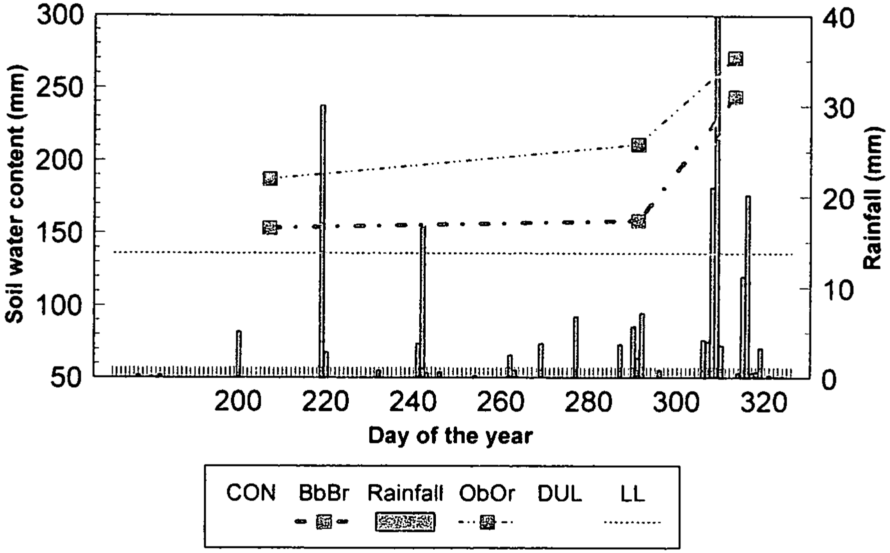

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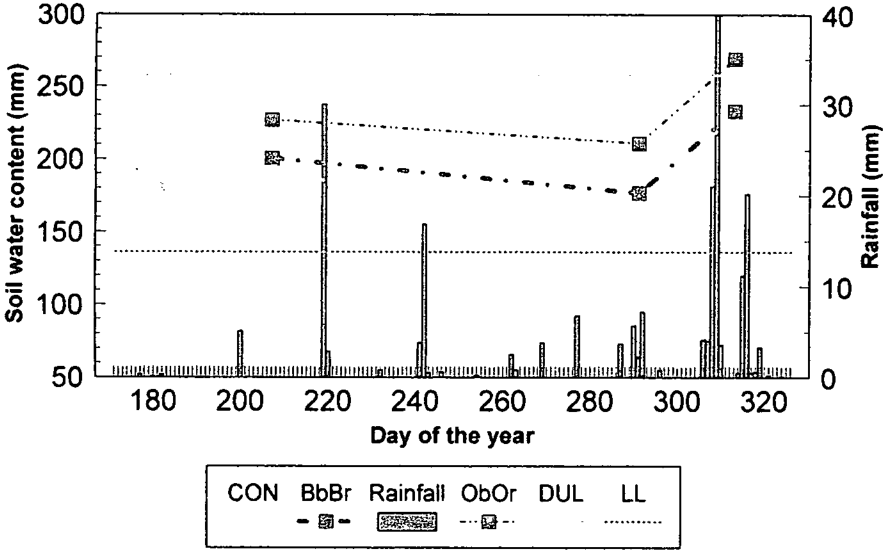

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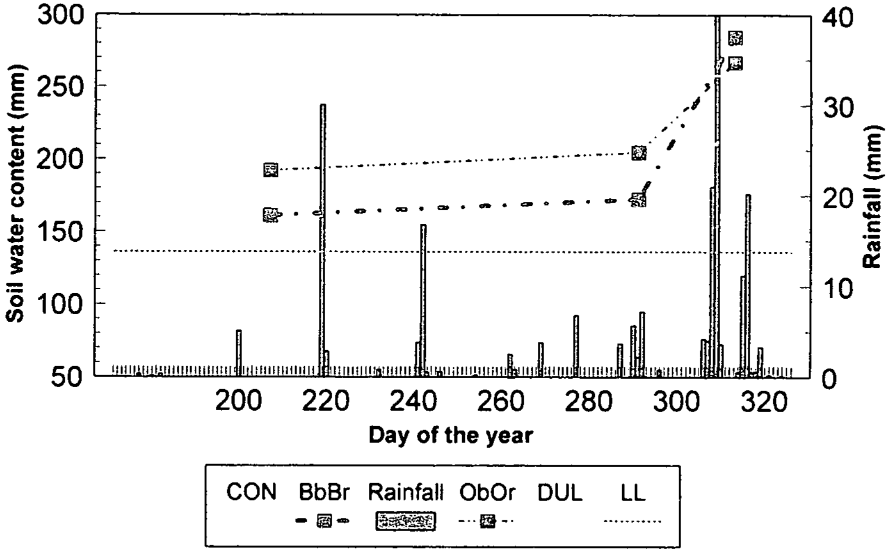

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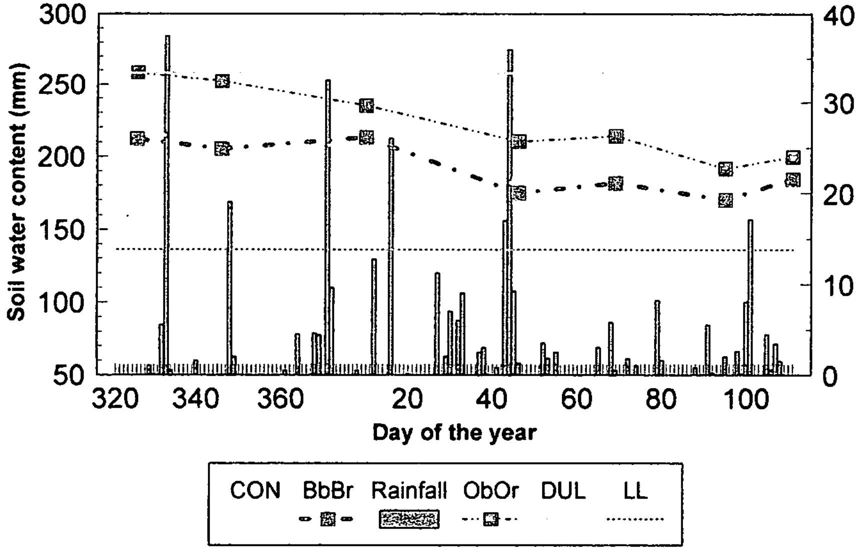
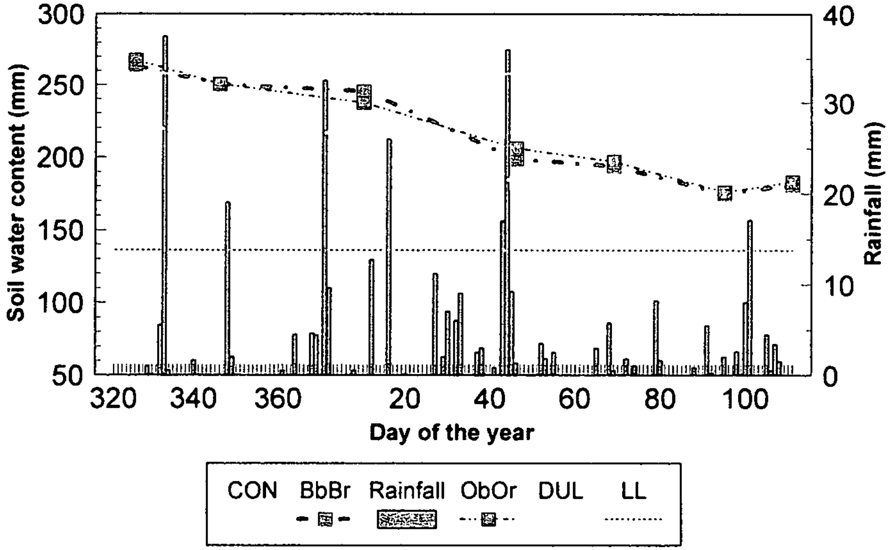


(a) Soil water content on the Runoff area (Rep 1) during 05/06 growing period



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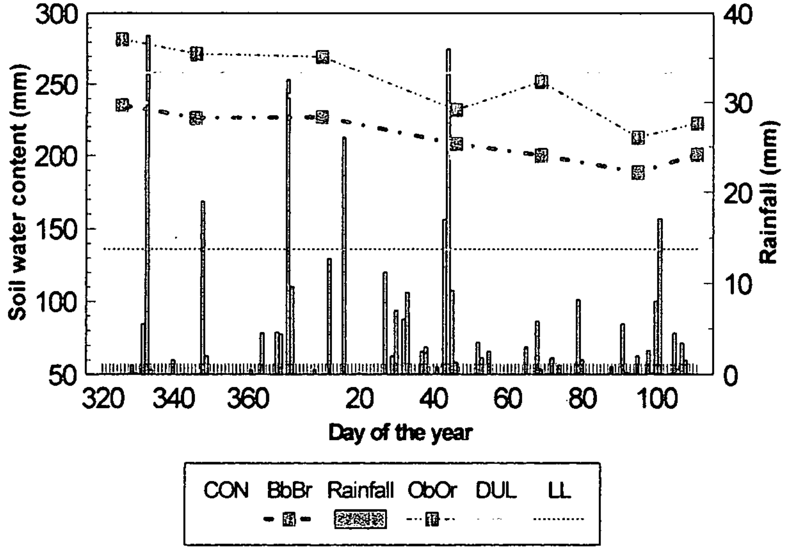

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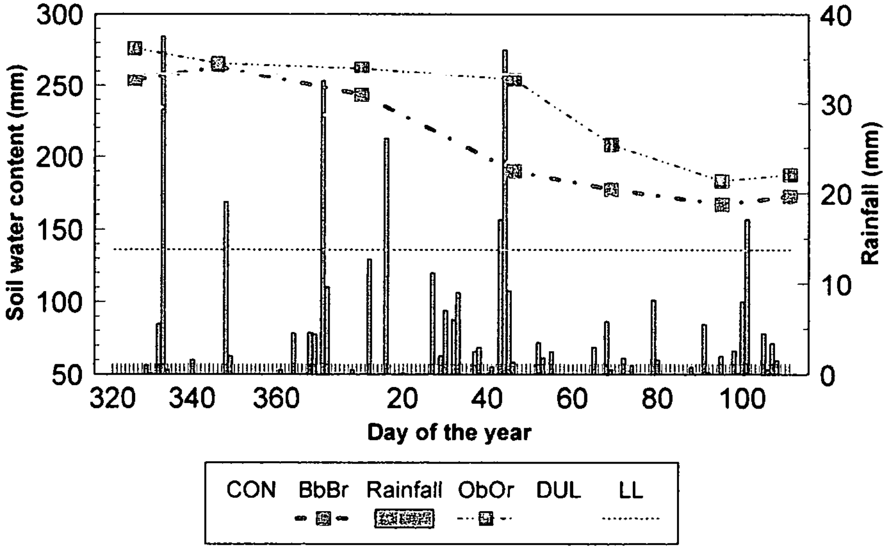

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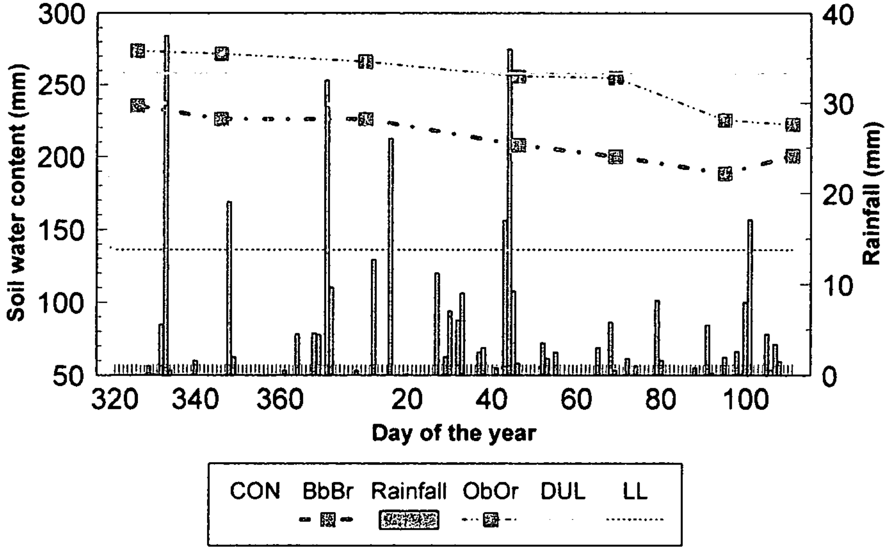
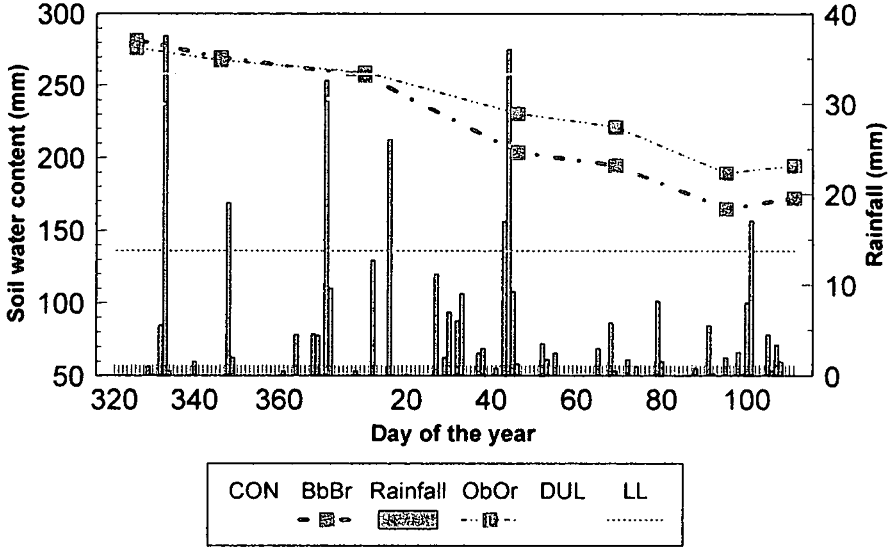


(a) Soil water content on the Runoff area (Rep 3) during 05/06 growing period



(b) Soil water content in the Basin area (Rep 3) during 05/06 growing period

ANOVA for grain yield (2004/05 season)						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	828275	2	414137	2.24	0.19	5.14
Within Groups	1111536	6	185256			
Total	1939811	8				

ANOVA for biomass (2004/05 growing season)						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	950793	2	475397	0.73	0.52	5.14
Within Groups	3909115	6	651519			
Total	4859908	8				

ANOVA for grain yield (2005/06 growing season)						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	265852	2	132926	1.59	0.28	5.14
Within Groups	503161	6	83860			
Total	769013	8				

ANOVA for biomass (2005/06 growing season)						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2616730	2	1308365	4.24	0.07	5.14
Within Groups	1852693	6	308782			
Total	4469423	8				