RESPONSE OF MAIZE TO RAINWATER HARVESTING AND CONSERVATION TECHNIQUES ON THE GLEN/OAKLEAF ECOTOPE

by

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LIST OF ABBREVIATIONS

AI = Aridity index
ANOVA = Analysis of Variance
ARC = Agricultural Research Council
ARC-ISCW = Agricultural Research Council – Institute for Soil, Climate and Water
BD = Bulk density (g. cm^{-3})
BFAP = Bureau for Food & Agriculture Policy
BM = Biomass
CMUL = Crop modified upper limit (mm)
CO_2 = Carbon dioxide
CON = Conventional
D = Deep drainage (mm)
DL = Daling pough
DAP = Days after planting (days)
DBSA = Development Bank of Southern Africa
DUL = Drained upper limit of available water (mm)
Eo = Evaporative demand (mm)
Es = Evaporation from the soil surface (mm)
ET = Evapotranspiration (mm)
Ev = Evaporation from the crop (transpiration) (mm)
FAO = Food and Agriculture Organization of the United Nations
F_p = Fallow period
FSP = Free State Province
GI = Galvanised iron
G_p = Crop growing period
Gy = Grain yield (kg/ ha^{-1})
ha = Hectare
HI = Harvest index
IRWH = In-field rainwater harvesting
k = Transpiration efficiency coefficient (g m^{-2} mm^{-1})
kg = Kilogram
LAI = Leaf area index
LL = Lower limit of plant-available water (mm)

LT = Long-term
LSD = Less significant differences
MB = Mechanized basin
MIN = Minimum
N = Nitrogen
NWM = Neutron water meter
P = Phosphorus
P = Precipitation (mm)
PAW_H = Plant available water at harvest (mm)
PAWp = Plant available water at planting (mm)
PAW_T = Plant available water at tasselling (mm)
P_f = Rainfall during the fallow season (mm)
P_p = Production period
PUE_{FG} = Precipitation use efficiency for fallow period (kg ha^{-1} mm^{-1})
PUE_G = Precipitation use efficiency for growing period (kg ha^{-1} mm^{-1})
R = Runoff (-); run on (+)(mm)
RCBD = Randomized complete block design
R_{ex} = Ex-field (mm)
R_{in} = In-field (mm)
R_p = Reproductive period
RSE = Rainfall storage efficiency
RWH = Rainwater harvesting
RWH&C = Rainwater harvesting and conservation
RWP = Rainwater productivity (kg ha^{-1} mm^{-1})
SA = South Africa
SSA = sub-Saharan Africa
SWC = Soil water content
T = Temperature (°C)
UN = United Nation
V_p = Vegetative period
$WUE_{(ET)}$ = Water use efficiency (kg ha^{-1}mm^{-1})
Y(0-2100) = Water content of the root zone (mm)
Yb = Total above-ground biomass (kg ha^{-1})
$\theta_{h(n-1)}$ = Root zone water content at harvesting of the previous crop (mm)

θm = Gravimetric soil water content (mm)

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

θv = Volumetric soil water content (mm)

$\sum P_n$ = Total precipitation over n consecutive years (mm)

ΔS = Change in soil water content (mm)

DECLARATION

I, Mardulate Motlalepula Chuene, declare this dissertation, I hereby submit an Msc (Agric) Agronomy degree at the University of the Free State. This dissertation consists of my own work and has not previously been submitted at any tertiary institution.

Signature:………………………..

Date:……………………………..

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ABSTRACT

Rainfall in semi-arid areas fluctuates constantly and it is difficult for farmers to increase crop productivity. The rainfall is insufficient, erratic and unreliable, which is associated with poor water availability due to increased water losses such as high evaporation from the soil (Es) due to rising temperatures, runoff (R) and deep drainage (D). These unproductive losses (Es, R & D) contribute to inefficient rainfall, which increases food insecurity and poverty. Crops produced in semi-arid areas under rainfed agriculture by smallholder farmers are usually produced using conventional tillage (CON). This system uses a moldboard plough, which turns and exposes the soil and therefore increases Es and R while organic matter is decreasing. In many semi-arid areas, research was conducted to improve crop production. One of these researches was conducted in South Africa at the Thaba Nchu villages where the Agricultural Research Council (ARC-ISCW) introduced an In-field rainwater harvesting technique (IRWH) to increase efficiency and use of limited water. This system was used to reduce unproductive water losses especially Es and R, to optimize rainwater productivity (RWP). This study was conducted to investigate the ability of different rainwater harvesting and conservation (RWH&C) techniques to produce higher yield in using and storing water efficiently under rainfed conditions of Glen/Oakleaf ecotope.

To test the hypothesis, a field experiment was conducted in a semi-arid area under rainfed conditions at the Glen/Oakleaf ecotope in Bloemfontein. The area is characterized by an average long-term (LT) rainfall in the growing period of 262 mm and an evaporation demand of 758 mm. Treatments used were In-field rainwater harvesting with a 2.0 m runoff strip (IRWH-2.0m), In-field rainwater harvesting with a 2.4 m runoff strip (IRWH-2.4m), Mechanised basins (MB), Minimal tillage (MIN), Darling plough (DAL) and Conventional tillage (CON). The experiment was conducted in two consecutive growing seasons (2008/09 & 2009/10) laid out in a complete block design (RCBD), with four replications and six treatments. The study was aimed to identify the most appropriate RWH&C techniques that will increase rainwater availability throughout the growing season to increase crop productivity by maximizing yield per unit of water.

The first season had 260 mm of rainfall, and was considered a dry season, the second season was a wetter season with 486 mm. rainfall. During the first growing season rainfall was 8% lower than the LT (262 mm), while in the second season it could be considered wetter as the

rainfall was 85% higher than LT. Rainfall during Vp was greater than LT during both seasons with 19% and 49% higher rainfall respectively. During the first dry season rainfall at Rp was 41% lower than LT and 160% higher during the second wet season. A short growing maize cultivar was chosen as a crop indicator, PAN 6Q-521R with a growing period of 120 days from planting to harvest.

The ecotope had a fine sandy loam soil with a depth of ± 1200 mm and a clay content of 15% in the A horizon and 30% in the B horizon. Land preparation was done by loosening up the soil to avoid compaction before implementing the different RWH&C techniques and CON treatment. Therefore, CON treatment was tilled with a moldboard plough. Only CON was ploughed during the second season and other treatments were not implemented. Evapotranspiration was calculated by using the soil water balance equation for dryland crop production. Soil water content was measured with a neutron water meter and crop water efficiencies (RSE, WUE, PUE & RWP) were calculated. Maize height, stem diameter, leaf area index and biomass were measured in four growth development stages only during the 2008/09 growing season while grain yield was measured during both seasons.

The first objective is explained in chapter 4, which was to evaluate soil water balance and different rainwater efficiency (Rainwater storage efficiency (RSE), Water use efficiency (WUE) and Precipitation use efficiency (PUE)) of various RWH&C techniques against CON tillage for possible adoption by smallholder farmers to increase crop productivity. The Plant available water at planting, tasseling and harvest were higher with RWH&C techniques compared to the CON treatment during both growing seasons. Similarly soil water content during both seasons were higher with RWH&C techniques compared to CON tillage. However, during the first growing season at 13 DAP, the soil water content of all treatments was above the DUL line of 280 mm indicating that D could have occurred. MIN treatment was shown to have the highest runoff percentage followed by CON tillage. The ET of RWH&C techniques during the dry season (2008/09) was higher than that of CON tillage, however more water was lost through Es with RWH&C techniques. During the second season RWH&C techniques excluding MIN tillage had higher ET compared to CON tillage and higher Es. RSE was not included during the first season due to late implementation of treatments. During the second season IRWH-2.0 m and IRWH-2.4 m treatments had the lowest RSE compared to MIN CON, MB and DAL treatments. The results showed that IRWH-2.0m treatment had the lowest WUE_{ET} during both seasons. During the dry season

(2008/09) WUE_{EV} based on transpiration was highest on the IRWH-2.0m treatment and during the wetter season (2009/10) CON treatment had the highest WUE_{EV}. During the 2009/10 season, RWH&C techniques excluding IRWH-2.0m showed to have greater PUE_{fg} than that of CON treatment. During the dry season the results showed a higher PUE_g with RWH&C techniques than that on CON treatment; however during the wet season PUE_g was higher with IRWH-2.4m treatment compared to that of CON treatment. For both seasons (2008/09 & 2009/10) IRWH-2.4m, MIN and MB techniques had greater RWP compared to CON tillage. Overall the results showed that RWH&C techniques collected and stored water better during the dry season than in the wet season.

The second objective of this study was to determine maize performance under the various RWH&C techniques compared to CON tillage on the Glen/Oakleaf ecotope. This objective is explained in Chapter 5. Plant height, stem diameter and LAI data were collected only during the first season and the study revealed that maize plants exposed to the CON treatment were taller and thicker compared to RWH&C techniques. During the Vp, plants exposed to the CON treatment had lower LAI than those exposed to RWH&C techniques. At 66 DAP there were no differences between the treatments, however, at 90 DAP plants exposed to the CON treatment had higher LAI. During the Vp of the first season at 30 DAP, plants exposed to the IRWH-2.4m treatment had greater biomass than all other treatments, however during the second season plant biomass exposed to the IRWH-2.0m, and MB treatments were greater than those exposed to the CON treatment. During the first season at 45 DAP plants biomass exposed to the MIN and IRWH-2.0m treatments were both greater than that of other treatments and during the second season plants exposed to the CON treatment were higher than those exposed to the RWH&C techniques. During the Rp at 66 DAP, in both seasons plants exposed to the DAL treatment produced less biomass than in all the other treatments. During the 2008/09 season at 90 DAP, plants exposed to the IRWH-2.4m, MIN and CON treatments were higher than DAL. However, in the second season at 90 DAP plants showed no difference in biomass between treatments. Grain yield differed between the two seasons due to differences in rainfall. During the dry season of 2008/09, RWH&C techniques had higher grain yield than that of CON treatment. In the wet season of 2009/10 IRWH-2.4m was the only RWH&C technique with a high yield. It was concluded that RWH&C techniques were most likely to perform better in dry conditions than during wetter conditions. During the wet season only IRWH-2.4m techniques performed better than that of CON treatments.

Keyword: Rainwater harvesting, Maize, Soil water balance, Rainfall storage efficiency, Water use efficiency, Rainwater productivity

OPSOMMING

Reenval wissel in semi ariede gebiede, wat dit moeilik maak vir boere om gewas produksie te verbeter. Die reenval is min, onvoorspelbaar en wisselvallig. Dit veroorsaak min water beskikbaarheid vir die volgende redes, verdamping (Es), verhoogde temperature, afloop (R) en diep dreinering (D). Hierdie onproduktiewe verliese (Es, R & D) dra by tot swak reenval, wat voedsel onveiligheid bevorder en sodoende armmoede tot gevolg het. Gewasse wat geproduseer word in semi ariede gebiede onder reenwater toestande, word gewoonlik op die Konvensionele Bewerkings Metode (CON) geproduseer. Hierdie sisteem gebruik gewoonlik ‘n ploegskaar, wat die grond omdop en blootstel aan die son, dit bevorder Es en R terwyl organiese materiaal in die grond verminder word. Navorsing is in baie semi ariede gebiede gedoen om te bepaal of water retensie en gewas produksie kan verbeter. Een van die gebiede is in Suid Afrika, by die Thaba Nchu nedersettings, waar die Landbounavorsings Raad (ARC-ISCW) ‘n Binneveld Reenwater Oes Tegniek (IRWH) gevestig het. Dit het die doeltreffendheid en gebruik van reenwater baie verbeter. Die sisteem word gebruik om watervermorsing as gevolg van Ese n R baie te beperk, en dit veroorsaak dat die beskikbare water geoptimaliseer word. Hierdie studie is gedoen om vas te stel of verskillende grond bewerkings tegnieke en verskillende reenwater oes metodes (RWH&C) ‘n verskil sal maak aan gewas produksie om sodoende armmoede te beveg.

Om hierdie hipotese te toets, is gebruik gemaak van ‘n semi ariede gebied wat bestuur word onder reenval toestande, die Glen/Oakleaf ekotoop net buite Bleomfontein. Hierdie gebied word gekenmerk deur ‘n gemiddelde langtermyn (LT) reenval in die groeiseisoen (262 mm) en ‘n verdampings anvraag van 758 mm. Die behandelings wat toegepas is, is Binneveld reenwater opvangs met ‘n 2 m afloop strook (IRWH-2m), Binneveld reenwater opvangs met ‘n 2.4 m afloop strook (IRWH-2.4m), Gemeganiseerde dammetjies (MB), Minimum bewerking (MIN), Daling ploeg (DAL) en Konvensionele bewerking (CON). Die eksperiment was gedoen oor twee opeenvolgende groeiseisoene (2008/09 & 2009/10), uitgele in ‘n volledige blok formasie (RCBD), met vier replikas en ses behandelings. Die studie se doel is om die beste tegniek te vind wat reenwater beskikbaarheid sal vermeerder, sodat gewas produksie kan verhoog, en daar ‘n optimale opbrengs per eenheid water sal wees.

Die eerste seisoen het 260 mm reen gehad, en was beskou as ‘n droe jaar. Die tweede seisoen was beskou as die natter jaar met ‘n reenval van 486 mm. Gedurende die eerste seisoen was

die reenval 8% laer as die LT (262 mm), terwyl die tweede seisoen se reenval 85% hoer was as LT. Reenval gedurende Vp was groter as LT in beide seisoene met 19% en 49% onderskeidelik. Gedurende die eerste droe seisoen was die reenval by Rp 41% laer as LT en in die tweede nat seisoen was dit 160% hoer. ‘n Kort groeiende mielie kultivar is gekies as die gewas aanwyser, PAN 6Q-521R, met ‘n groei seisoen van 120 dae van plant tot oes.

Die ekotoop het ‘n fyn sanderige leem grond met ‘n diepte van min of meer 1 200 mm en ‘n klei inhoud van 15% in die A horison en ‘n 30% klei inhoud in die B horison. Die land voorbereiding was gedoen deur die grond los te maak om kompaksie te vermy voor die verskillende RWH&C tegnieke geimplimenteer is. Die CON lande is met ‘n gewone ploeg behandel, net die CON lande is in die tweede seisoen ook geploeg. Die evapotranspirasie was bereken deur die grond water balans vergelyking vir droe land gewas produksie te gebruik. Die grond water inhoud was gemeet deur ‘n neutron water meter en die gewas water doeltreffendheid (RSE, WUE, PUE & RWP) is bereken. In die 2008/09 seisoen is die mielie hoogte, stam deursnee, blaar oppervlak index en biomassa gemeet in vier verskillende groei stadiums. Die gewas produksie was in altwee seisoene gemeet.

Die eerste objektief is in hoofstuk 4 verduidelik, dit was om die grond water balans en die reenwater doeltreffendheid te evalueer. Daar is gekyk na reenwater stoor tegnieke (RSE), water verbruik doeltreffendheid (WUE) en neerslag doeltreffendheid (PUE) van verskillende RWH&C tegnieke, teenoor CON tegnieke, sodat daar bepaal kan word of daar ‘n meer doeltreffende tegniek is wat aan boere voorgele kan word om gewas produksie te verbeter. Die plant beskikbare water by plant, pluimverskyning en oestyd was hoer met die RWH&C tegnieke as by die CON tegniek op dieselfde tye. Die grond water inhoud in beide seisoene was ook hoer met die RWH&C tegnieke as met die CON tegniek. Die MIN tegniek het die meeste afloop gehad, gevolg deur die CON tegniek. Die ET van die RWH&C tegnieke was hoer in die droe seisoen (2008/09) as die van die CON tegniek, alhoewel meer water verlore gegaan het deur Es in die RWH&C tegnieke. Gedurende die tweede seisoen het die RWH&C tegnieke (uitsluitend die MIN tegniek) hoer ET gehad in vergelyking met die CON tegniek, e nook hoer Es. RSE was nie ingesluit in die eerste seisoen nie as gevolg van die laat toediening van tegnieke. Gedurende die tweede seisoen het die IRWH-2m en die IRWH-2.4m die laagste RSE gehad. Die uitslae het gewys dat die IRWH-2m die laagste WUE in albei seisoene gehad het. Gedurende die droe seisoen (2008/09) was die WUE gebasseer op

transpirasie die hoogste op die IRWH-2m behandeling, en gedurende die nat seisoen (2009/10) het die CON tegniek die hoogste WUE gehad. Gedurende die 2009/10 seisoen het die IRWH&C tegnieke (uitsluitend die IRWH-2m tegniek) ‘n groter PUE gehad as die CON tegniek. In die droe seisoen het die RWH&C tegnieke ‘n hoer PUE gehad. Die algehele resultate het getoon dat die RWH&C tegnieke beter water versamel en gestoor het in die droe seisoen as in die nat seisoen.

Die tweede objektief van die studie was om te bepaal of die mielie gewas beter presteer onder ander tegnieke as die CON tegniek. Hierdie objektief is in hoofstuk 5 bespreek. Plant hoogte, stam dersnee en LAI data was versamel net in die eerste seisoen, en dit het getoon dat plante wat blootgestel was aan die CON tegniek groter en swaarder was as die plante wat aan die ander tegnieke blootgestel was. Gedurende Vp was die LAI van die plante wat aan die CON tegniek blootgestel was laer as die LAI van die plante wat aan die RWH&C tegnieke blootgestel was. By 66 DAP was daar geen verskille tussen die onderskeie tegnieke nie, maar op 90 DAP was die LAI van die plante op die CON tegniek hoer. Gedurende die Vp van die eerste seisoen, by 30 DAP, was die plant biomassa op die IRWH-2m tegniek en die plante op die MB tegniek meer as die plante op die CON tegniek.

Gewas produksie het verskil tussen die twee seisoene (2008/09 en 2009/10), as gevolg van die verskil in reenval. Gedurende die droe seisoen (2008/09) het die RWH&C tegnieke meer produksie getoon, en in die natter seisoen (2009/10) het die IRWH-2m tegniek die beste produksie gehad. Dit was bepaal dat die RWH&C tegnieke beter werk in droe jare, en dieselfde of slegter vaar in nat jare as die CON tegniek.

Sleutelwoorde: Verskillende reenwater, Mielie, Reenwater stoor tegnieke, Water verbruik doeltreffendheid, Reënwater produktiwiteit,

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

The Agricultural sector remains the source of food production and a critical component of the economic growth at global, national and local level. Global economies are developing strategies to grow and improve the agricultural sector. Almost 60% of the world's food is produced on agricultural land under rainfed conditions (Mekdaschi & Liniger, 2013; Stroosnijder, 2003). According to the United Nations (UN), the Millennium Development Project in countries over the world that are experiencing poverty, are those in arid and semi-arid climatic zones.

Over 60% of the total population in Sub-Sahara Africa (SSA) depends highly on rainfed agriculture, which generates about 30% - 40% of the GDP (World Bank, 2000). Consistent and sufficient rainwater supplies are critical under these conditions to prevent crop failure. Rainfall in most SSA countries is insufficient, erratic and unreliable or falls in high intensity, thereby increasing soil water loss such as runoff (R), evaporation from the soil (Es) and deep drainage (D). Unreliable rainfall and high R, Es and D conditions tend to have a huge negative impact on farmers that depend on rainfed agriculture. Botha (2006) indicated that every drop of rainwater wasted contributes to the problem of food insecurity.

Improved agricultural practices could help to alleviate malnutrition, poverty and unemployment, especially in poor rural areas in most SSA countries. The total agricultural land available in South Africa is 122.8 million ha, with approximately 80% lying in arid and semi-arid climates (Bennie and Hensley, 2001). It was also estimated by DBSA (2005) that over twenty two million people in South Africa live below the poverty line. The majority of the poorest communities in South Africa lives in rural areas and makes a living from rainfed crops. In arid and semi-arid areas the lack of adequate water poses a major constraint to crop production, and low crop productivity in these communities leads to poverty and food insecurity (Hensley *et al*., 2000). Only 12% of the land can be classified as arable (Department of Agriculture, 2007). Due to this limited availability of arable land it is important to make use of soil and water conservation management practices to improve food production. Baiphethi & Jacobs (2009) reported that agricultural production is important for food security in South Africa, as it is a source of food for the majority of rural communities.

Among the nine Provinces in South Africa, the Free State, which covers about 10.62% of South Africa's total area, is considered the breadbasket of South Africa. Almost 92% of the Free State is used for agricultural production (Tekle, 2004). The Province is largely semi-arid and is dominated by rural a population that relies heavily on agriculture for household food security. It is therefore important to improve infield water management and conservation strategies for optimum crop production. The Department of Agriculture of the Free State (2006) estimated that 31% of the population in the Free State Province (FSP) lives in poverty and are unemployed (Botha, 2006).

Lack of adequate soil moisture is not only caused by low and poor distribution of rainfall but also by high water losses through R, D and Es (Boer *et al*., 1986). Precipitation (P) and Temperature (T) plays important role in semi-arid areas, where P is low and erratic and T is high, leading to high evaporation rates (Es). According to Botha (2006) deep drainage (D) in clay soil and all coarser textured soil with an impermeable layer within the root zone, is negligible, whereas Es and R are the main mechanisms through which soil water is lost. Bennie & Hensley (2001) reported that between 50% and 75% of the annual precipitation was lost in South Africa Es, while results obtained by Botha (2006) revealed that 70% of rainfall was lost through R. In addition, Raisuba (2007) reported that close to 30% of the rainfall in rainfed agriculture contributes to crop growth, while 70% is lost through as Es, R and D contributing to crop failure.

Many agricultural scientists agree that with the use of water conservation, soil resources and improved harvesting techniques, crop production might improve. Innovative water conservation and harvesting techniques have the potential to eliminate R from the field and reduce Es resulting in potentially increased yields due to increased plant available water (PAW). By using these techniques it is possible to increase and sustain agricultural output in semi-arid areas (Hatibu & Mahoo, 2000). Improving PUE is also important to sustain production in semi-arid areas (Hensley & Snyman, 1991).

Rainwater harvesting (RWH) is an age old practice used worldwide in water scarce rainfed crop production. It is used to reduce unproductive water losses, particularly Es and R, and optimize rainwater productivity (RWP) (Nhlabatsi, 2010). Rainwater harvesting and conservation techniques are useful systems in semi-arid areas, were irrigation is not available or is too costly to be used. The techniques collect surface runoff and concentrate it into the root zone area of crops, this leads to increases in yield. According to Ngigi *et al.* (2005) rainwater harvesting is one of the viable technologies for reducing high seasonal risk of soil water scarcity. Anschutz & Nederlof (1997) declared that rainwater harvesting techniques increased crop production by 50 - 100% depending on the system used, soil type and land husbandry.

In order to improve crop production in areas with a continuous water scarcity and attempting to overcome food insecurity, the Agricultural Research Council (ARC-ISCW) introduced the In-field rainwater harvesting technique (IRWH). This increases the efficiency and use of limited rainfall. The IRWH technique was studied on the small plots of different ecotopes. However, soil parameters were measured and the agronomical parameters of the technique were not fully investigated. For example Botha *et al.* (2003) conducted research to reduce crop failure in the FSP rural communities around Thaba Nchu and Botshabelo and found RWH&C techniques such as IRWH proved to increase household food production. The study was conducted on croplands which had been abandoned for many years due to continuous crop failure. The technique dealt with the challenge of coping with water scarcity by increasing rainwater use efficiency and it also indicated good water management and resulted in increased crop productivity. On the Glen/Bonheim and Glen/Swartland ecotopes maize and sunflower yield increased between 30 and 50% using IRWH compared with conventional tillage (Botha, 2006). Other techniques used to improve rainwater use efficiently are daling plough (DL), mechanized basin (MB) and minimum tillage (MIN). It was decided to compare all of the techniques (RWH&C) with conventional tillage (CON) in order to determine which would give the best agronomical performance on the Glen/Oakleaf ecotope.

This study aimed to investigate various RWH&C techniques against conventional tillage on the Glen/Oakleaf ecotope in the Free State Province of South Africa. The production of food, using limited water supplied by rain under rainfed conditions in arid and semi-arid areas is exaggerated by climatic changes as temperatures increase and decrease in rainfall distribution. These losses can be mitigated by using various methods of soil and water conservation to increase food production.

1.2 OBJECTIVES

The objectives of the study is as follows:

- To evaluate the soil water balance and rainfall storage efficiency of various rainwater harvesting and conservation techniques against conventional tillage for possible adoption by farmers.
- To determine maize performance under the various tillage techniques on the Glen/Oakleaf ecotope.
- To identify the most appropriate technique that will result in improved water-use efficiency for recommendation to farmers.

CHAPTER 2

LITERATURE REVIEW

2.1 THE EFFECT OF CLIMATE VARIABILITY ON CROP PRODUCTION

Water scarcity is primarily an issue in semi-arid countries like South Africa and according to climate change projections, water shortage will be more critical in the future (Mancosu *et al*., 2015). Botha (2006) reported that scarcity of water is one of the many factors limiting food production, hence food security will remain a serious problem in the future. It was projected that the South African population is likely to increase from 5349100 in 2015 to 56665000 in 2025 respectively. According to Schultz *et al*, (2006) this projection of population growth and increases in the standard of living might possibly influence the rate of increases in food production. Since an increasing population requires an increased food production, more efficient use of rain in rainfed agricultural conditions is necessary (Botha, 2006).

Rainfed agriculture dominates in most arid and semi-arid parts of South Africa. It covers about 80% of South Africa's agricultural land and it produces 60% of the food (Woyessa *et al*., 2006). Most regions operating under rainfed agriculture are exposed to low, variable and unreliable rainfall. This resulted in crop failure, which may increase food prices, intensifying food insecurity. According to Botha (2006), if food insecurity is to be reduced, the focus should be on the needs of the people. The majority of people in the rural areas of South Africa depend on rainfed agriculture, where roughly 80% of poor communities grow their own food. Most of the communities have a low production of food due to lack of adequate water. An increase in water availability in the soil could lead to an improved crop yield, thereby reducing the level of poverty, a problem faced by the most vulnerable citizens in most African countries; South Africa included. Many researchers believe that the use of water and soil conservation management practices could possibly sustain and increase crop production in dryland regions.

South Africa is a relatively dry country with an average annual rainfall of about 464 mm, 30% of the country receives less than 300 mm, and almost 60% less than 500 mm per annum ((Schulze & kunz 1993), (Ortman & Machethe 2003)) (Figure 2.3). The rainfall is insufficient to meet basic water requirements for crop production. Botha (2006) reported that South Africa's problem is exacerbated by an increase in potential evaporation from east to west, which is higher than the rainfall. Furthermore, most of the rainfall is poorly distributed during the growing season and often occurs in big drops which increase runoff. Low annual rainfall is associated with a high annual potential evapotranspiration, resulting in more than 80% of the country having a semi-arid and arid climate (Bennie & Hensley, 2001). Another factor, associated with poor rainfall distribution, is the frequent occurrence of mid-season dry spells that consequently result in poor soil water availability during the growing season (Rockstrom, 2000). Inadequate rainfall is the main reason for the relatively small portion of South Africa considered to be suitable for rainfed crop production (Bennie and Hensley, 2001). To sustain crop production in the current climate conditions, researchers should seek alternative ways such as water and soil conversation management practices to increase rainwater productivity (RWP).

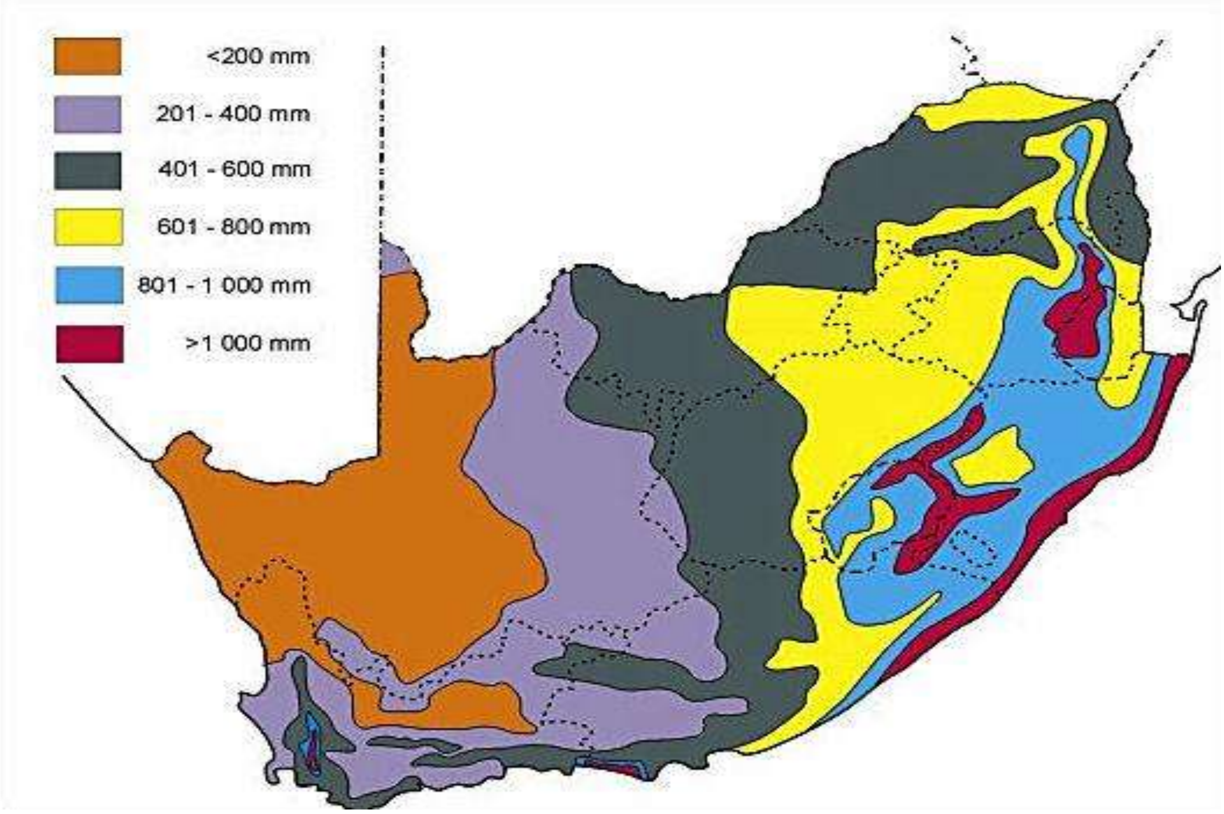

Figure 2. 1Average annual rainfalls (mm) of South Africa.
(http://www.hoeckmann.de/karten/afrika/suedafrika/index-en.htm)

2.2 MAIZE PRODUCTION

Maize (*Zea mays* L) is a dominant crop worldwide with its origin in Mexico. In Mexico maize is grown in summer with favourable conditions as in South Africa. Maize is the most important cereal in the world after wheat and is also one of the main primary crops planted in South Africa (Fanadzo *et al*., 2010), contributing significantly to South Africa's economy. It is also the largest locally produced field crop and is the most important source of carbohydrates as referred in Figure 2.1. Its grain, stalk, leaves, cobs, tassels and silk all have commercial value. Furthermore maize can be used to manufacture all kinds of products, from syrups to fuels (Oladejo & Adetunji, 2012). Moriri *et al*. (2010) reported that maize is the priority crop to most farmers because it is a staple food in many communities of Southern Africa.

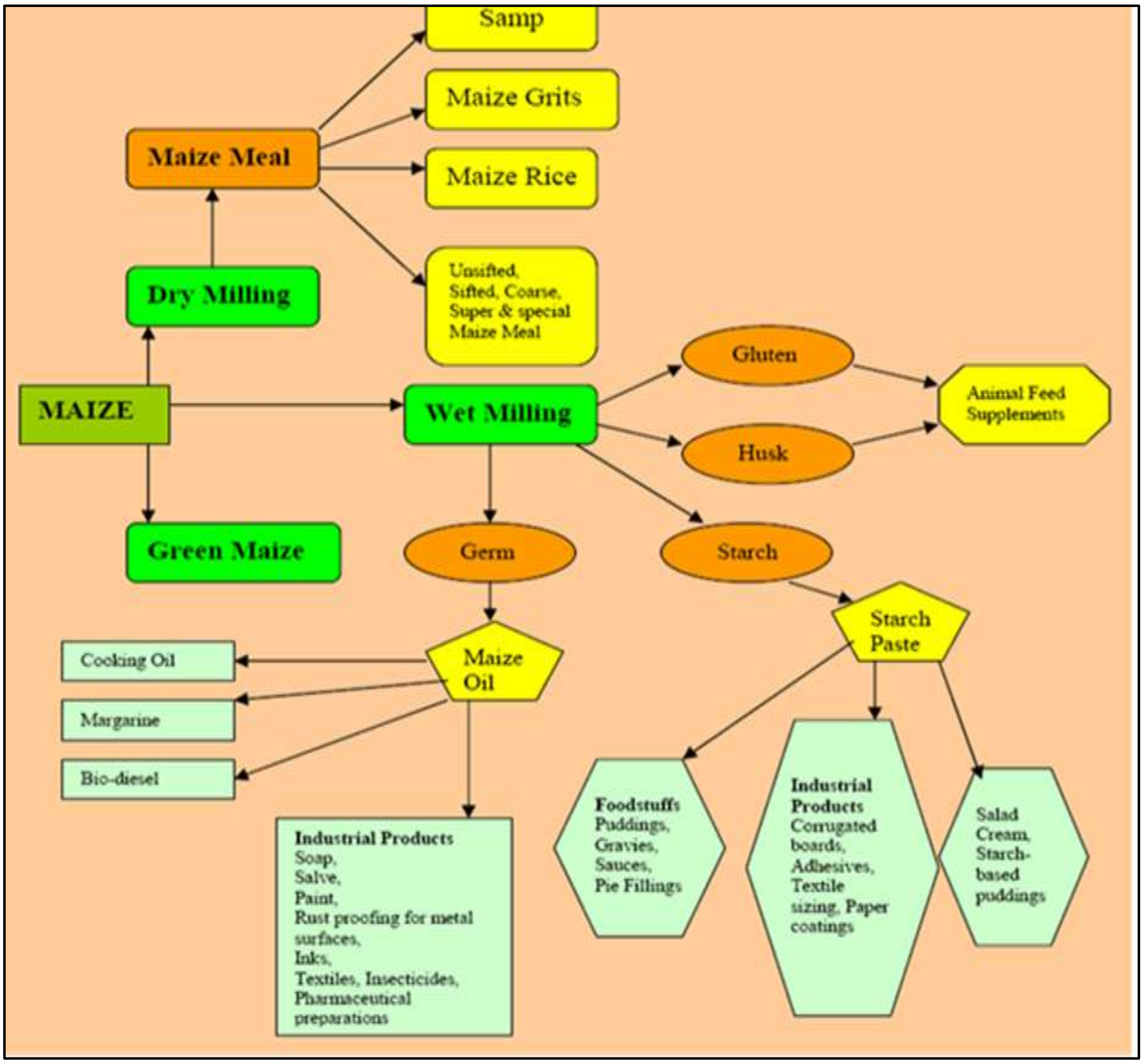

Figure 2. 2 Functions and the importance of maize in South Africa

Maize is regarded as one of the key drivers of food inflation in South Africa (BFAP, 2007). The Maize Tariff Working Group (2004) and Dredge (2011) reported that maize is the second most valuable agricultural product in South Africa. In the Free State Province of South Africa maize is produced in larger quantities than in the other eight Provinces. Figure 2.2 show that the Free State Province alone contributes approximately 40% of the total production of maize in South Africa (Department of Agriculture, Forestry and fisheries, 2010). Out of 122.8 million total land of South Africa, the Free State Province occupies only 12.9 million ha. However, potential arable land in the Free State Province is approximately 3.82 million ha (Department of Agriculture, Forestry and Fisheries, 2010). Arable land is a challenge in the Free State Province, however the most important limiting factor for maize is the scarcity of water in the Province.

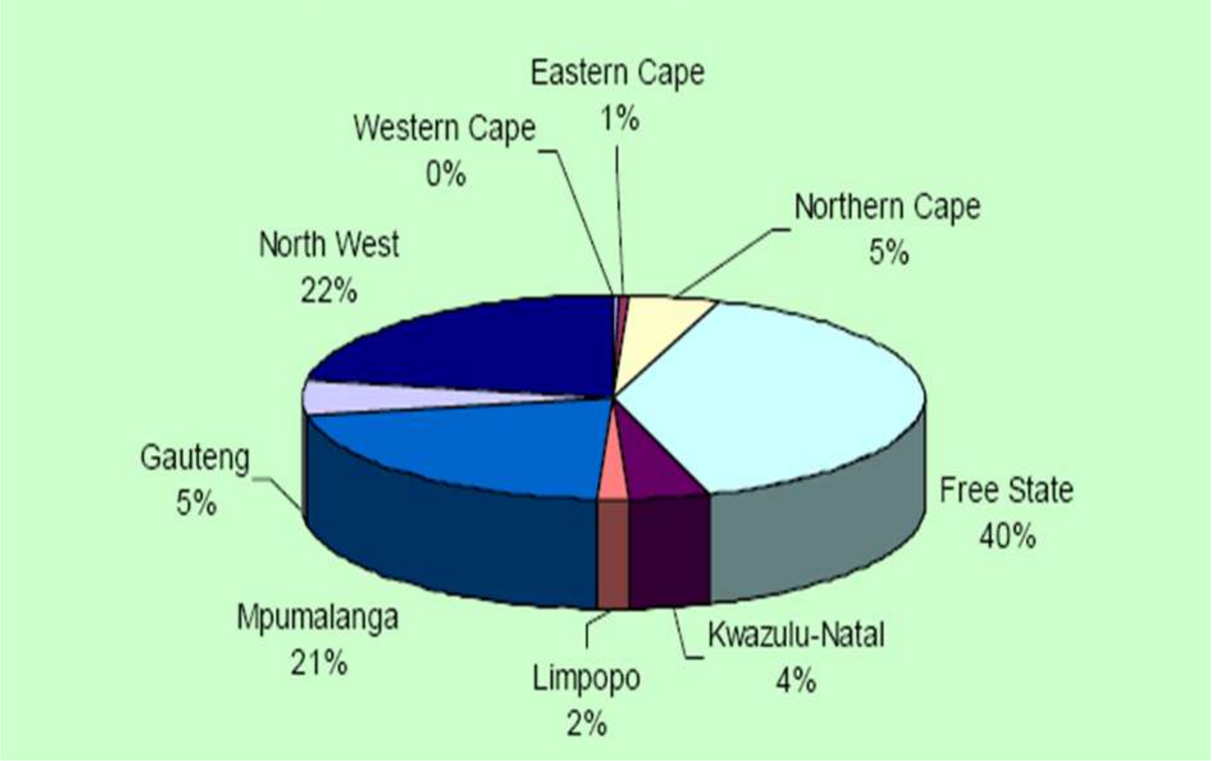

Figure 2. 3 Total production of maize in S A Provinces 2009/10 (Department of Agriculture, Forestry and Fisheries, 2010

2.3 SOIL WATER BALANCE

The soil water balance is important for crop production in dryland regions to identify water availability in the soil. It is used to determine the amount of water that enters the soil profile and the amount of water that exits in the soil profile. The following equation adapted from Botha (2006) is used:
Water for yield = water gains – water losses

$$Ev = (P \pm \Delta S) - (Es + R + D) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. (2.1)$$

Where:

Ev is evaporation from the crop (transpiration) (mm)
P is the precipitation (mm)
ΔS is the change in volumetric water content of the root zone between the start and end of the growing season (mm)
Es is the evaporation from the soil surface (mm)
R is the runoff (mm)
D is the deep drainage (mm)

The problem of low and erratic rainfall in semi-arid regions is intensified by soil water losses such as R, Es and D (Figure 2.). Runoff (R) occurs due to rainfall occurring in the form of high intensity thunderstorms and rainfall exceeding the final infiltration rate of the soil. Furthermore runoff occurs when raindrops strike bare soil, their energy, preventing aggregation of dispersion and this results in crust development (Unger and Howell, 1999). Various South African researchers have found that losses of R can be between 6% and 30% of the annual rainfall on various tilled soil Bennie *et al*., 1998, Zere, 2003, Botha 2006, Mzezewa and Van Rensburg, 2011).

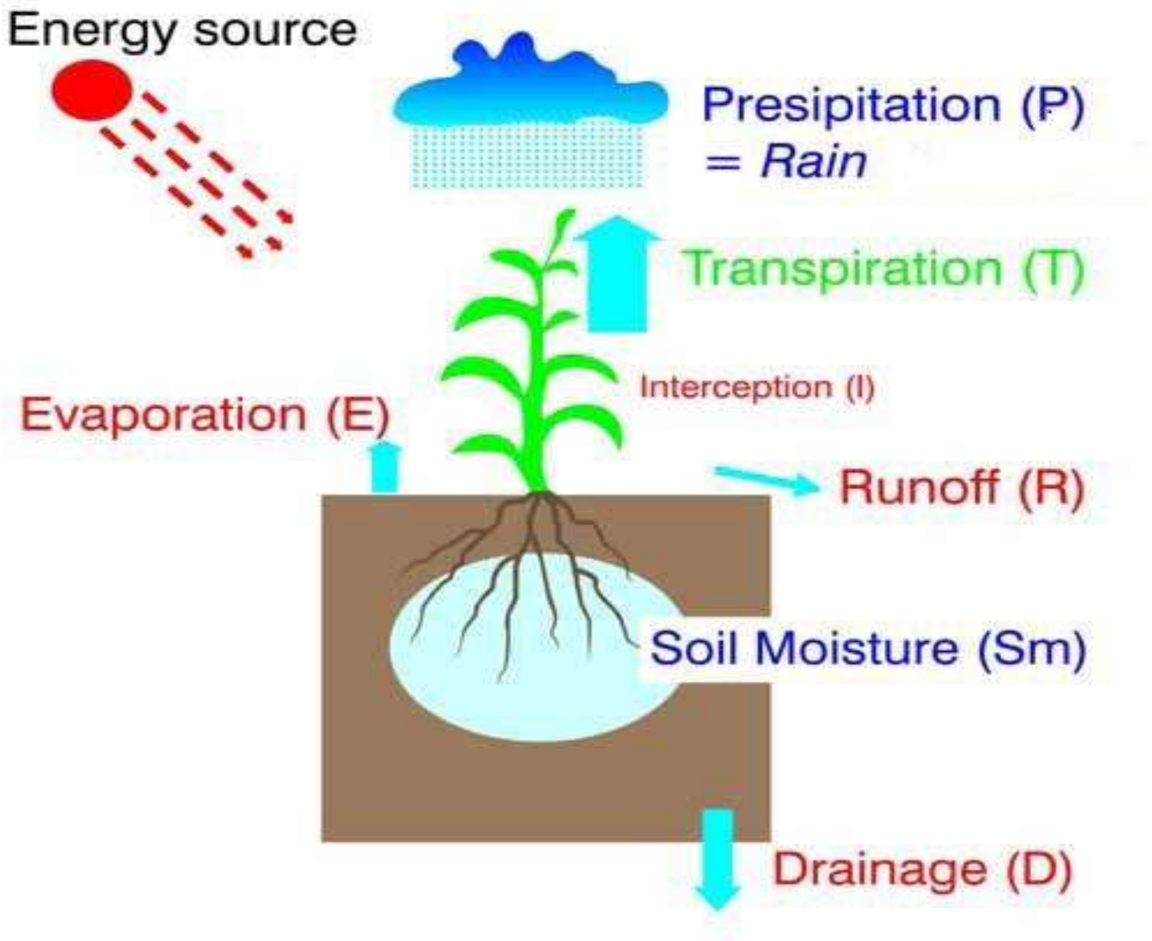

Figure 2. 4 Components of the soil plant atmosphere continuum showing water balance Procedure for dryland crop production (www.senwes.co.za).

Evaporation from the soil (Es) is the process by which water in the soil is changed to vapor (Van der Watt and Van Rooyen, 1995 cited by Botha, 2006) and lost to the atmosphere. Bennie *et al*. (1994) claimed that in semi-arid areas of South Africa 60% - 85% of rainfall is lost through Es before contributing to crop production. However, Wallace (2000) states an Es of 30-35% is estimated in rainfed agriculture. This indicates that in semi-arid areas operating under rainfed agriculture, significantly more water evaporates from the soil surface than what is used by the growing crops. It was indicated by Botha (2006) that Es is a complex process that involves intensive dynamic interaction between factors such as the evaporation demand, conditions of the soil and soil water content.

Deep drainage (D) is generally negligible on duplex and clay soils and all coarser textured soils underlain by an impermeable layer within the root zone (Botha 2006). The loss of R, Es and D can be minimized by efficient use of water available in the soil profile. Rockstrom *et al*. (2000) reported that in semi-arid areas between 60-85% of the rainfall can be lost by Es, R and D without making any contribution to the crop production. Furthermore Gregory *et al*. (2000) claims that crops will likely experience water stress if there is no balance between the atmospheric demand and water supply in the soil. Improving soil water regimes can be achieved by increasing the amount of water stored in the root zone by reducing R, Es and D. Innovative systems which will improve and sustain crop production are required to optimize Precipitation Use Efficiency (PUE).

Little can be done about the amount of rainfall and the number of rainfall events received. This makes soil and water management practices the key factors in enhancing agricultural production in rainfed crop production. These management practices can increase plant available water (PAW) resulting in improved yield and a reduction of water losses (R, Es and D). Runoff can be reduced by increasing rain water efficiency (RSE). Runoff could also be reduced by use of alternative classification systems for rainwater harvesting methods categorized in ex-field (R_{ex}) (Outside farmland) and in-field (R_{in}) (within the farm) runoff. In the study conducted by Du Plessis & Mostert (1965) cited by Joseph (2007) R_{ex} of 4.4%, 8.5%, 10.3% and 31.9% of annual rainfall was reported on red sandy loam soil with a 5% slope at Glen. This R_{ex} was obtained from natural veld, bare tilled plots and bare untilled surfaces respectively. Runoff of 30%, 47% and 47% of annual rainfall of 479, 544 and 591 mm was recorded on bare Glen/Boeheim soil respectively. This indicates that runoff is one of the major losses of water in rainfed agriculture. Bennie & Hensley (2001), claim that Es is the main process responsible for soil water loss in dryland crop production. Under semi-arid climatic conditions in South Africa evaporation from bare soils during the fallow period can amount to 60–75% of the rainfall in the driest summer crop areas (Bennie *et al.*, 1994). In the study conducted by Botha (2006) Es of 150 mm was reported on bare soil during the growing season. Managing received precipitation to enhance crop water productivity and water use efficiency (WUE) in crop production is therefore important in rainfed agriculture. This can be achieved by increasing the effective use of rainfall and water storage by use of rainwater harvesting techniques. Moeletsi and Walker (2011) believed that by knowledge of the length and probable dates of the onset and cessation of the rainy season can help farmers to choose the right cultivar suitable for their location reducing crop failure. However, this would be difficult as a farmer's land has no weather stations close by. But with rainwater harvesting farmers timing rainfall is not that important, water from the runoff surface is captured and is stored or utilized.

2.4 RAINWATER HARVESTING TECHNIQUES

Rainwater harvesting in agriculture is defined as the process of concentrating rainfall as runoff from a large area (catchment area) to be used productively in a target area (Oweis *et al.*, 1999). Rainwater harvesting can be classified as macro-catchment, micro-catchment and domestic micro catchment (Figure 2.7). Macro-catchment rainwater harvesting is water which is collected from locations far from and external to the crop area. It is mostly used in natural rangeland, steppe or mountainous areas. The catchment area is usually not cultivated and rainwater from macro-catchments are either applied to the crop or stored to be used later (Mwenge-Kahinda *et al.*, 2007). The disadvantages about these catchments are that mostly they are located outside the farm, and farmers do not have full control over them (Oweis *et al.*, 1999).

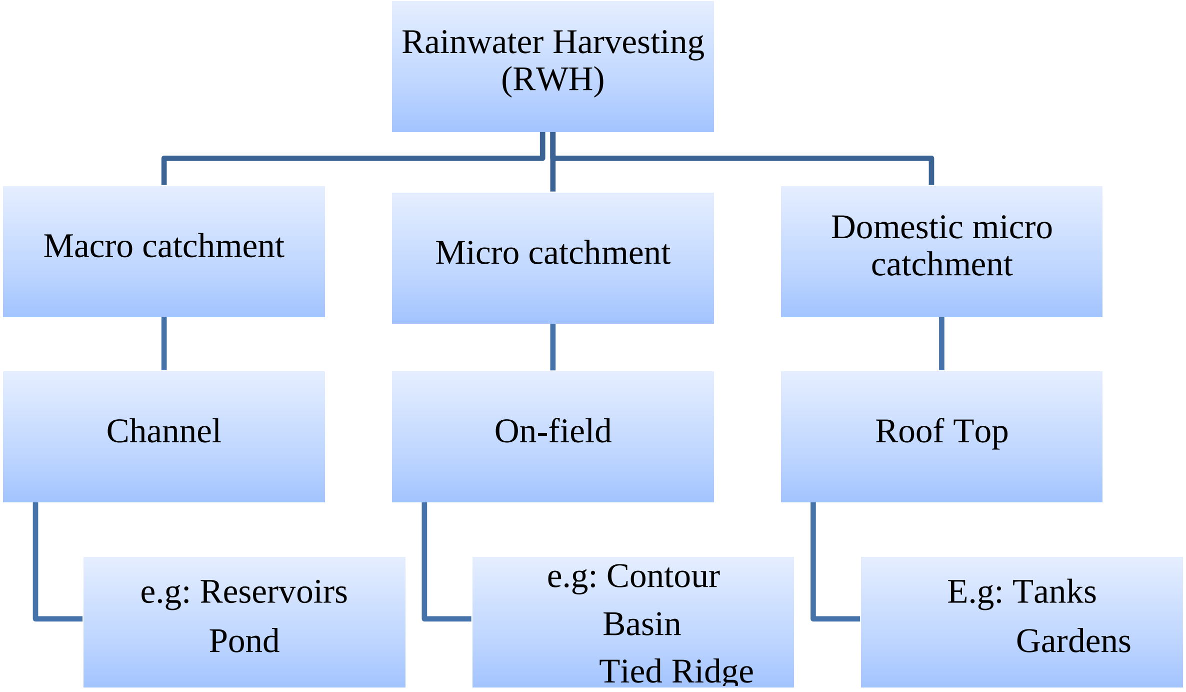

Figure 2. 5 Rainwater harvesting classification demonstration and its examples (Mekdaschi & Liniger, 2013).

In micro-catchment rainwater harvesting (RWH) surface water runoff is collected from short runoff strips, to be stored in the root zone or used instantly by crops depending on plant water availability. With this type of catchment, water is retained in the soil to be used by the roots. (Ibraimo and Munguambe, 2007). The advantage of this system is the catchment area, storage facility of the system and the area which is targeted are all within the planted land. Oweis *et al*. (1999) reported that micro-catchment has higher runoff efficiency than macro-catchment and soil erosion is more controlled. Domestic micro rainwater harvesting is the collection of water from rooftops, compacted, or treated surfaces, which is stored in tanks and used for domestic purposes (Award, 2009). This study is focusing on the investigation of micro-catchment rainwater harvesting (RWH).

The meaning of the term rainwater harvesting is broad, but for agricultural purposes it can be defined as a method of collecting, storing, managing and utilizing rainwater for productive purposes such as crops, fodder, pasture or tree production, livestock and domestic water supplies in arid and semi-arid areas (Ngigi *et al*., 2005). Boers and Ben-Asher (1982) reviewed literature on rainwater harvesting and conservation techniques and established a common definition. They defined it as a method to induce, collect, store, and conserve local surface runoff for agriculture use in arid and semi-arid regions... It is a practice to supply additional water for crops with an insufficient amount of rainfall for optimum yield production (Kronen, 1994). The system was first introduced in India, Sri Lanka, and the United Kingdom, by means of utilizing the erratic rainfall for crops and conserving runoff for drinking and recharging purposes (Sivanappan, 2006).

Rainwater harvesting and conservation techniques (RWH&C) are mainly implemented in arid and semi-arid regions (Ibraimo and Munguambe, 2007), where runoff and evaporation is usually high. In these regions the little amount of water stored in the root zone is below crop water requirements. Furthermore it is also useful in all areas where rainfed agriculture practices and water shortages are prevalent during the growing stages of crops (Welderufael *et al*., 2012). The aim of RWH is to increase the infiltration capability of the soil, prolong duration of soil moisture availability and to store surface runoff for later use (Ngigi *et al*., 2005). RWH is also aimed at minimizing soil water loss (R, Es and D) by maximizing water storage in the root zone for increasing crop production. Crop production is mostly under rainfed conditions, most of which is marginalized by water stress (Welderufael *et al*., 2012). There are different types of rainwater harvesting and conservation techniques that can be adopted, however, in this study the focus is on the following in-field rainwater harvesting techniques (IRWH), Daling plough (DAL), mechanized basin (MB) and minimum tillage (MIN).

2.4.1 In-field rainwater harvesting and crop response

The Department of Soil, Climate and Water of the Agricultural Research Council (ARC-ISCW) of South Africa has developed in-field rainwater harvesting (IRWH) systems for communal farmers with the objective of harnessing rainwater for crop production (Hensley et al., 2000). This technique combines the advantages of rainwater harvesting, no tillage and basin tillage to stop ex-field runoff (R_{ex}) completely on high clay soils (Botha *et al*., 2003; Hensley *et al*., 2000). Ibraimo (2011) reported that another planting configuration like IRWH, was found in certain regions of West Africa, where main crops were seeded in the upslope side of the ridge between the top of the ridge and the furrow. In this planting configuration, it is recommended that approximately 65% of the plant population make use of rainfed cultivation, so that the plants can have more water available in years of low rainfall (Critchley & Siegert, 1991)

In South Africa IRWH was first introduced by Hensley *et al*. (2000) to improve yield in rainfed agriculture of the semi-arid areas and further investigations was done by Botha *et al*. (2003) and Botha, (2006) (Figure 2.7). However, plant height, stem diameter, LAI and plant biomasses at different growth stages were little investigated. The study conducted by Botha, 2006 and Botha *et al*. (2003) investigated different mulch applications, however, most farmers have a shortage of residue due to animals feeding on them. The initial system consists of a 2 m runoff strip and a 1 m wide basin to capture and store water, the runoff strip can be adjusted. This system improves plant available water (PAW) by moving water closer to the root zone. The depth of the basin is 100 mm to store runoff during large, high intensity rain events (Van Rensburg & Zerizghy, 2008). The system collects water from the sensitive zone in the basin where infiltration is maximized to eliminate evaporation from the soil. The role and function of the basin area is to stop ex-field runoff, maximize infiltration and store the harvested water in the soil layer (Hensley *et al*., 2000). The basin area of the IRWH technique acts as a surface storage medium where the loss can be converted into a gain. Water is temporally stored in the basin until the infiltration process is completed (Mzezewa & Van Rensburg, 2011).

Several studies were conducted based on the physical ability to improve yields and the socio economical sustainability of the technique, however, investigation into agronomic aspects were limited. In the study conducted at Thaba Nchu in FSP by Botha *et al*. (2003) the results showed potential increases in the yields of maize and sunflower of about 30% to 50% respectively, in the long-term, compared to conventional tillage. The technique was again tested on maize, sunflower and beans on the Glen duplex clay soil, which resulted in significantly increased yields compared to conventional tillage (Hensley *et al*., 2000) and (Botha *et al*., 2003). In a study conducted at Hatfield experimental farm of the University of Pretoria where IRWH and Tied ridge were tested against conventional tillage, it showed that during the dry season the IRWH technique showed a bigger success, compared to Tied ridge and conventional tillage. In addition, the study conducted by Mzezewa & Van Rensburg (2011) showed that smallholder farmers in the Limpopo Province of South Africa had a significantly better yield of sunflower and cowpea in IRWH than in conventional tillage. The results shows that single stand sunflowers and cowpea produced higher yields at a lower water use than intercropping (Mzezewa & Van Rensburg 2011).

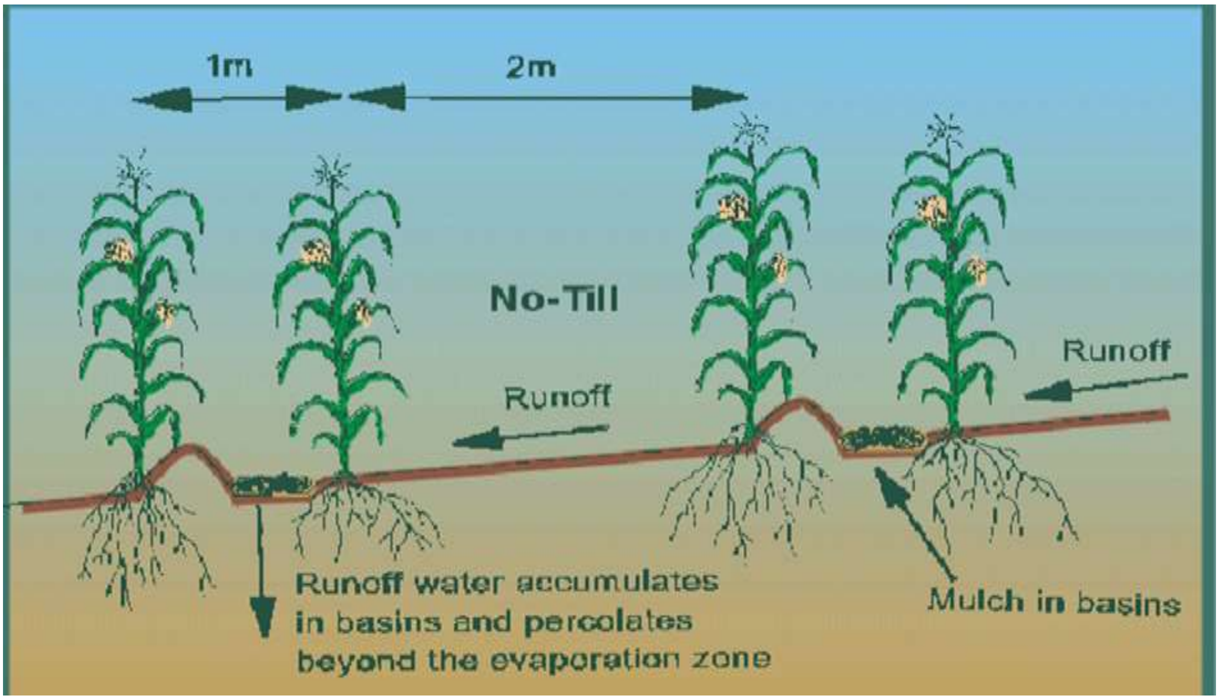

Figure 2. 6 Diagramed sketch of In-field rainwater harvesting technique (Botha *et al*. 2003).

IRHW consists of a runoff area and a runoff basin to collect and channel rainfall in the basin close to the root zone. The runoff area is designed to promote in-field runoff and to act as a storage medium for the water. In-field runoff is the transportation of water over the 2 m area, while ex-field runoff (R_{ex}) occurs over an area of a much greater size and is usually associated with erosion (Botha *et al*., 2003). Hensley *et al*. (2000) measured in-field runoff from 2 m untilled runoff strips on the Glen/Bonheim and Glen/Swartland ecotopes. It was found that between 30% and 35% of the mean annual rainfall was collected in the basin. This study was expanded by adding mulches in various combinations on the runoff and basin areas to minimize evaporation losses, stone (60% surface coverage) and organic mulches (maize residue covering 60% of soil surface). In the study conducted on Kenilworth Bainsvlei ecotope by Tesfahuney (2012) indicated the effect of different runoff strips together with mulch. The results obtained indicated higher maize yield and biomass in the smaller runoff strips of 1 m. However, the study conducted by Tesfahuney (2012) indicated that a selection of 2 m for IRWH was different. Also the study conducted by Mavimbela and Van Rensburg (2012) at Paradys Experimental farm of the University of the Free State showed 1 m runoff strips of IRWH had higher ET, biomass, grain yield and less drainage compared to 2 and 3 m runoff strips.

Welderufael, *et al*. (2012) indicated that many types of water harvesting and conservation techniques show significant crop yield increases, but the in-field rainwater harvesting technique gave the best results in semi-arid areas of South Africa. The disadvantage of the in-field rainwater harvesting techniques is the soil movement from the runoff area into the basin. The basin may need regular maintenance. In the case of small rainfall events the small amount of runoff may not reach the basins. The technique requires intensive labor to initially construct the basins. This is based on the previous implementation of manual practices.

2.4.2 Daling plough

The Daling plough (DAL) in South Africa was introduced and constructed by Mr. Dirk Daling from Settlers in Limpopo Province who practices rainwater harvesting on a commercial scale since 1997. Mr. Dirk Daling created two runoff areas with a basin in the middle, making the runoff area shorter to collect water even from the smaller rainfall events (Anderson *et al*., 2003). A tiller is connected directly to the three point linkage of the tractor and then the basin plough follows behind. With this technique the field is ploughed and runoff and basins are created simultaneously. The tiller is used to loosen the soil before basins are created. Furthermore it is inexpensive, easy to transport and does not take too much of the topsoil away (Anderson *et al.*, 2003). A slight disadvantage of the Daling plough is that soil movement can occur from the runoff area into the basin, thereby reducing the water holding capacity of the basin. There is limited scientific research on the Daling plough.

Another RHW technique similar to the Daling plough is negarim micro catchments, which is regular square earth bands mostly used on orchard trees Figure 2.8. Negarims are made up of 45 degree turned soil from the contour, to concentrate surface runoff at the lowest corner of the square where infiltration occurs. The shape of the infiltration pit can be a circular or square shape, with dimensions varying according to the catchment size (Critchley & Siegert, 1991).

For crop production negarims were altered to be called Daling ploughs. The technique is constructed of a 1 m runoff area and 1 m basin creating a V shaped flattish basin (Figure 2.8). In South Africa there was little research conducted on DAL for rainwater management and conservation.

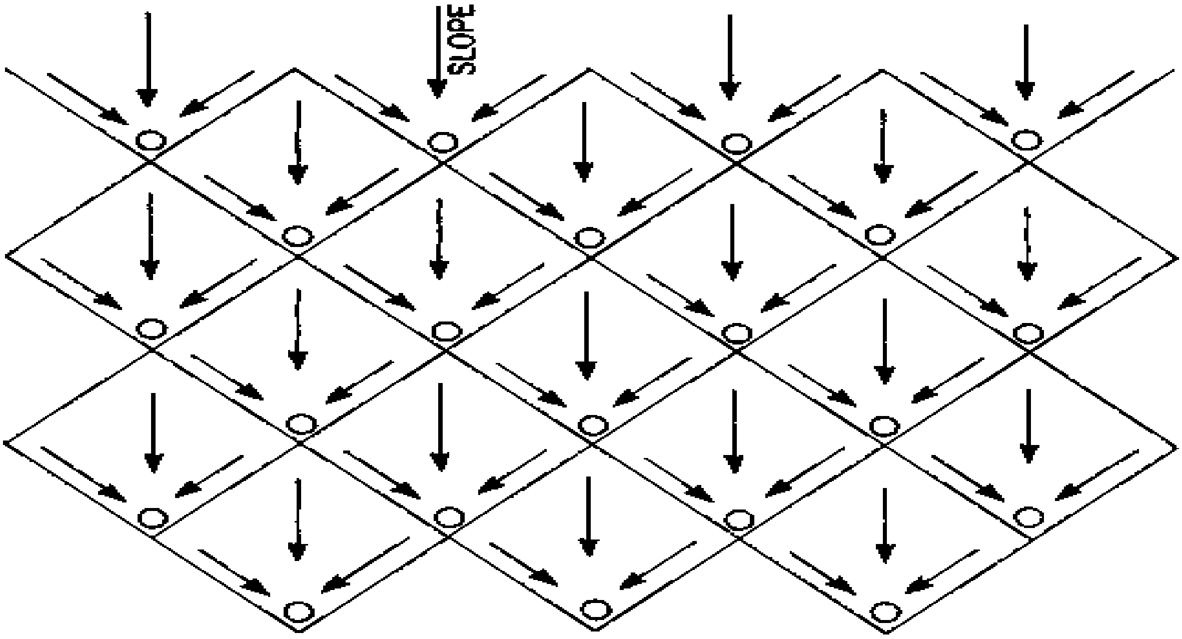

Figure 2. 7 Diagrammatic sketches of negarims (Critchley & Siegert, 1991).

2.5 CONSERVATION TILLAGE AND CROP RESPONSE

Soil conservation is defined as a set of management strategies for prevention of soil erosion, soil becoming chemically altered by overuse, salinity, acidity or other forms of chemical soil contamination (Botha *et al.*, 2003). The system involves combining minimum soil disturbances to improve soil organic matter and at least 30% of the soil surface is covered by residue after planting. This creates a suitable environment for growing a crop. With conservation tillage the soil and water is conserved and less energy is consumed through a reduction in the intensity of tillage. Conservation tillage maintains a ground cover with less soil disturbance than traditional cultivation, thereby reducing soil and water loss and energy use while maintaining crop yields and quality. Soil loss through water erosion is greatly reduced when crop residue is left on the soil surface and it also improves the organic matter and moisture content of the soil (Nelson, 2002). The crop residue or mulch protects impact from rain and wind and lessens the overall production cost (Broller & Hanif, 2004).

In the past 15 years, successful adoption of conservation agriculture methods was practiced by sugar farmers in Kwa Zulu Natal, as well as grain farmers in the Western Cape and Free State, but has remained rather slow in other production areas of South Africa (BFAP, 2007).
Conservation farming practices have been studied by many researches; however, for the purpose of this study only minimum tillage and Mechanized basin were used. Conservation tillage requires careful farm management practices to be successful. With conservation tillage weeds are not ploughed into the soil, where it is easy for weeds to compete with the main crop for the available water and nutrients. Insects and diseases are also easily carried over from crop residues (Boller & Hanif, 2004).

2.5.1 Mechanized basin

Mechanized basin (Figure 2.9) configurations are similar to furrow diking or tied ridge, where small basins are created between ridges and there are no runoff strips. The advantage of this system is, the basins are used to store rainwater, promoting infiltration and decreasing surface runoff and improving PAW. The disadvantage of the system, as described by Ibraimo (2011), is that weed control requires the application of herbicides, germination of the crops planted on the top of the ridge might be slower than on normal flat land and the ridge might dry out faster and take longer to get wet. The furrow diking was first introduced in the U.S.A in 1931 by Peacock, a former wheat farmer. Jone & Baumhardt, (2003) indicated that crop yield responses in furrow diking are highly variable under dryland crop conditions. This technique is effective on heavy soil, once constructed, the ridges remain for a period of six seasons, depending on the crop grown by the farmer (Ibraimo, 2011).

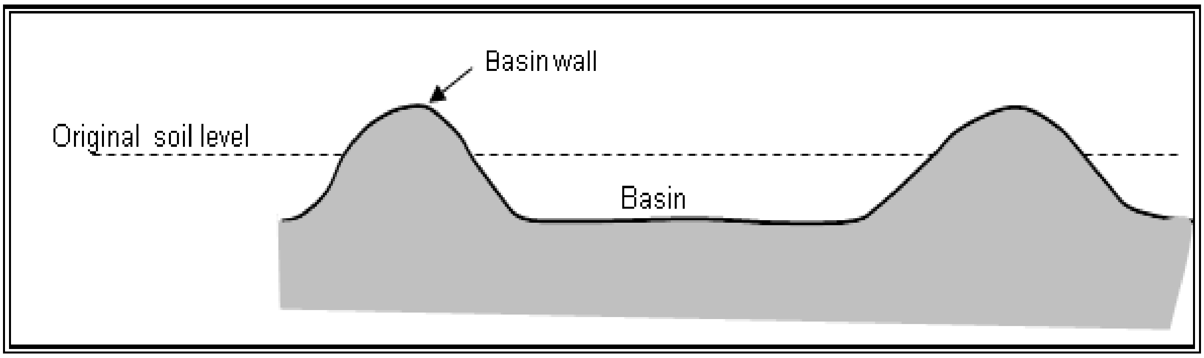

Figure 2. 8 An example of a mechanized basin in traversing directions (Van der Merwe & Beukes, 2006)

Figure 2. 9 An example of a land implemented mechanized basin filled with water after Rainfall (Jone & Baumhardt, 2003).

Mechanized basins may be created manually or mechanically, however in this study we concentrate on mechanically constructed basins. The basins are created by a scraper blade and a tied ridge forms between the basins. A mechanized basin has been used successfully for runoff control on field slopes of less than 5%. Basin tillage implements consist of small paddles or a set of disk blades installed behind a cultivator shaft. The implement drags loose soil from between the crop rows for a preset distance, often 2 m, and deposits it across the row middle, creating a small dam. The area upslope from the dam becomes a small water storage basin. Hensley *et al*. (2000) indicated that mechanized basin tillage was the most effective method to retain runoff, thereby improving soil water storage. Mechanized basins is a conservation technique that is suitable in arid and semi-arid areas where water scarcity is a challenge.

The study conducted at Kanana Experimental Trial (Bafokeng area) and Zimbabwe, Mudzi district in Mashonaland Province showed that the use of mechanized basins increased the soil water storage and yield of sunflower and maize compared to conventional tillage (Van der Merwe & Beukes, 2006; Motsi *et al*., 2004). With the mechanized basin technique water is stored throughout the rainy season. A mechanized basin is an advantage to retaining runoff and improves soil water storage, however, a disadvantage is that planting must be accurate and an experienced tractor driver is essential. According to Jone & Baumhardt, (2003) negative crop responses caused from the use of mechanized basins are usually due to poor weed control or retention of excessive water on the soil surface, which causes aeration problems.

2.6.2 Minimum tillage

There are three types of reduced tillage: reduced cultivation, direct drilling and minimum tillage. For this research minimum tillage was used. Minimum tillage is the minimum amount of cultivation or soil disturbance done to prepare a suitable seedbed. With minimum tillage crops are planted with just sufficient tillage to allow placement and coverage of the seed for germination and emergence (Phillips *et al*., 1991). In many studies it was shown that minimum tillage, where crop residues remain on the soil surface, decreases evaporation losses, increases rainfall infiltration and reduces water runoff as compared to conventional tillage where crop residues are incorporated into the soil (Griffith *et al*., 1984). It has been found that minimum tillage in comparison with conventional tillage increased the concentration of plant nutrients like nitrogen, phosphorus and potassium in the surface soil layer (Ismail *et al*., 1994).

Minimum tillage is widely recognized for its role in conservation of both soil and water (Uri, 1999). It retains at least 30% of crop residue evenly distributed on the soil surface and this protects the soil against potential rainfall energy by decreasing crust formation and water runoff (Uri, 1999). A comparison of conventional tillage with minimum tillage on highly erodible land showed that minimum tillage reduced soil erosion by 50% and more (Philips *et al*., 1991). BFAP, (2007) reported that minimum or reduced tillage is described as the second best option for conservation tillage, although it was reported that minimum tillage performs better compared to conventional tillage in low rainfall years (Maali & Agenbag, 2003).

The advantage of minimum tillage is that it allows for better timing of crop establishment as there is no need to wait for suitable conditions in order to prepare land. Soil erosion tends to be reduced, as residual vegetative matter is generally present. Minimum tillage improves water retention in the soil due to the presence of residual vegetative matter at the surface. It also allows the use of marginal lands, as there is little soil disturbances. Minimum tillage contributes to the reduction in land preparation costs (Astatke & Jabbar, 2001).

Disadvantages of minimum tillage include weed infestation which can become a major problem. Some pests increase due to a greater opportunity for shelter. Due to the decrease in soil disturbance there is less movement of nutrients into the soil. In the smallholder farming sector all crop residues are consumed in winter. Maize is an important crop in South Africa, however under conventional tillage in the North West Province it can lead to soil losses of 20 tons ha^{-1} per annum which exacerbates the province’s soil degradation problem (Van Zyl *et al*., 1996).

2.4 CONVENTIONAL TILLAGE AND CROP RESPONSE

Conventional tillage is a system which attempts to cover most of the residue, leaving less than 30% of the soil surface covered with residue after planting (Berry & Mallett, 1988). This system usually implies a plough action or an intensive range of cultivations. It is usually regarded as moldboard ploughing followed by disking one or more times to obtain a loose and easy crumbled seedbed (Phillips *et al.,* 1991). The majority of crop production in South Africa is subjected to intense and frequent ploughing practices, referred to as conventional tillage (Berry & Mallett, 1988).

The advantages of conventional tillage are familiar to most farmers and machinery is widely available. Conventional tillage incorporates manure without specialized equipment. This allows earlier planting and is a plus for poorly-drained soils. Conventional tillage destroys pest shelters and disrupts their lifecycles. The tillage distributes soil nutrients throughout the soil and it controls weeds (FAO, 1993).

The disadvantages of conventional tillage are that more equipment is needed than with reduced tillage systems. Low residue levels make soil vulnerable to crusting and erosion by wind and water (Figure 2.5). Tillage stimulates weed growth and reduces levels of organic matter on the soil surface. Working in wet soil may cause compaction and the development of plough pans. During the growing season, high evaporation resulting from lack of residue can reduce crop yields. Conventional tillage might be more expensive compared to minimum tillage especially with the rising fuel prices. It also disrupts the lifecycle of beneficial soil organisms (Pfiffner & Madder, 1997).

Figure 2. 10 Example of erosion on field under conventional tillage after rainfall.

CHAPTER 3

METERIAL AND METHODS

3.1 STUDY SITE

The study was conducted under dryland conditions at the Glen Experimental Station in the Free State Province of South Africa (Figure 3.1). The Glen Experimental Station (28°57' S, 26°20' E) is situated 25 km north east of Bloemfontein, falls within the semi-arid region of South Africa and receives an average annual rainfall of 542 mm with evapotranspiration of approximately 1 500 mm(Le Roux & Hensley, 2012).

Figure 3. 1 Location of the study area (Le Roux & Hensley, 2012).

3.2 SOIL CHARACTERISTICS

The Glen/Oakleaf soil is one of the dominant soil types in the Glen area, belonging to the Dipene family. The soil has a terrain slope of 2% that is sufficient to implement RWH&C techniques. The soil has a depth of 2 100 mm, with a clay content of 15% in the A horizon and 30% in the B horizon, with no mechanical limitations in the profile (Soil classification, 1991). The clay content is sufficient for effective water storage capacity (Land Type Survey Staff, 2002). The soil component of Glen/Oakleaf ecotope consists of a non-bleached orthic A horizon, with a smooth transition at about 300 mm to a luvic, red, neocutanic B horizon, with a fine sub-angular, blocky structure (Apendix 1). No occurrence of lime or mottles is visible throughout the profile. The Glen/Oakleaf soil form occurs on a concave foot slope with a 1% south-westerly slope with a fine sandy loam texture (Zere *et al.,* 2012). Typical Oakleaf soil from profiles is shown in Figure 3.2, while a description of the soil profile on which the experiment was conducted is given in Table 3.1.

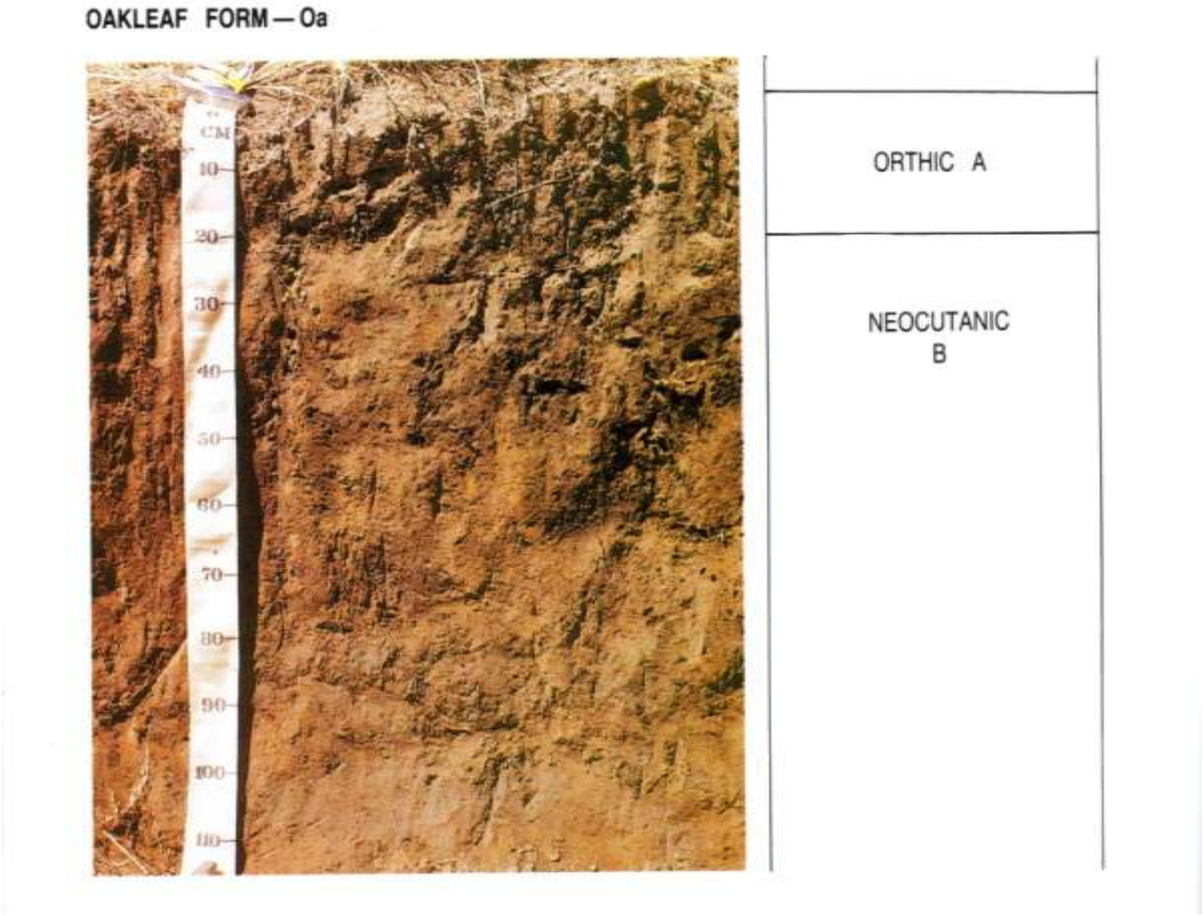

Figure 3. 2 Top soil and subsoil of Glen/Oakleaf soil form (Soil classification working Group, 1991).

Table 3. 1 Description of the soil profile on Glen/Oakleaf soil

Horizon	Diag. Horizon	Depth (mm)	Colour	Clay (%)	BD^{*1} (g. cm^{-3})
Orthic	A	300	Yellowish-red	16	1.66
Neo-cutanic	B	2100	Red	34	1.66

BD^{*1} = bulk density

3.3 EXPERIMENTAL DESIGN AND DESCRIPTION OF TREATMENTS

The experiment consisted of six treatments (Conventional tillage (CON), In-field rainwater harvesting with a 2.0 m runoff strip (IRWH-2.0m), In-field rainwater harvesting with a 2.4 m runoff strip (IRWH-2.4m), Mechanised basins (MB), Minimal tillage (MIN) and Darling plough (DAL). The gross plot consisted of twelve rows with an area of 20 m x 30 m and the net plot was 180 m^2. The experiment was laid out on 1.4 ha using a randomised complete block design (RCBD) with four replications. The spacing between replications was 4 m and between treatments 10 m to enable a tractor to turn when implementing treatments, with an estimated Plant population of 18 000.

- **Conventional tillage (CON)**

This is the traditional tillage method using primary and secondary cultivation as the major means of seedbed preparation and most of the crop residue is incorporated. The conventional treatment was disked and ploughed before planting and harrowed to produce a fine seedbed. Cultivation depth was approximately 20 cm to 30 cm. Figure 3.3 represents four of twelve rows laid out in each Plot of CON treatment.

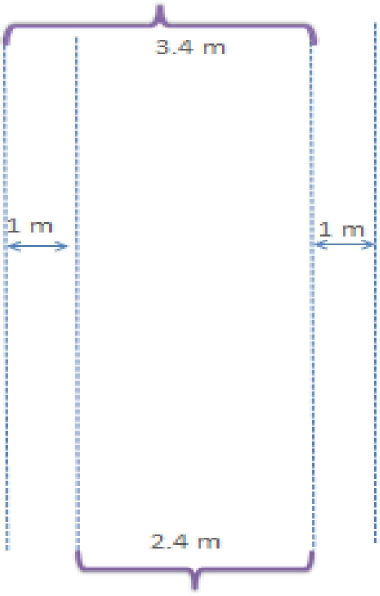

Figure 3. 3 Schematic representation of the row spacing in the conventional treatment.

- **Minimal tillage (MIN)**

The soil was ripped to a depth of 35 mm and the row spacing was 1.5 m. Thereafter chisel ploughing was used to provide minimum disturbance of the soil surface and leave 15% to 30% of the plant residue on the soil surface before planting.

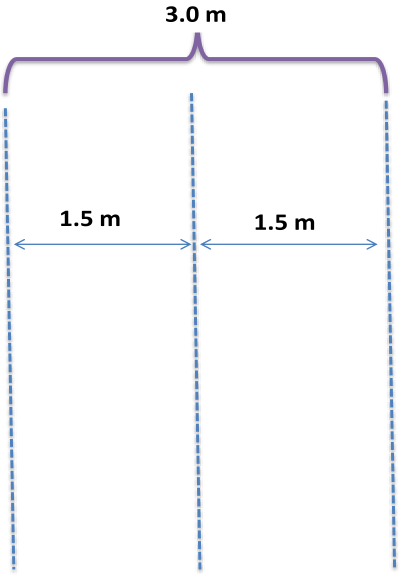

Figure 3. 4 Schematic representation of minimum tillage showing spacing between rows.

- **In-field rainwater harvesting (IRWH)**

The IRWH treatments had runoff strips with a width of 2.0 m or 2.4 m, respectively, both with 1 m basin areas where water was stored. This treatment required two tillage operations, one with ridge plough as a primary tillage activity to construct ridges and the second using a puddler plough to create basins (Figure 3.5 and Figure 3.6). The runoff strip directs water into the basin.

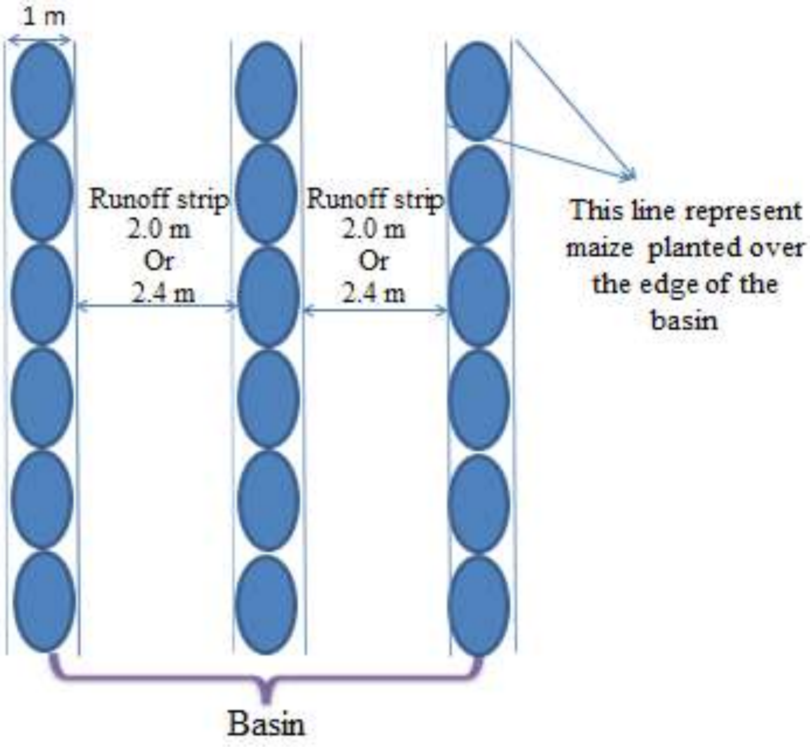

Figure 3. 5 Schematic representation of the row spacing in the IRWH treatments.

Figure 3. 6 Demonstration of ridge plough and the puddler plough all developed by Bramley Engineering in Bloemfontein (Bothma, 2009).

- **Mechanised basin (MB)**

A mechanised basin was created by the plough described by Van der Merwe (2005). It had a basin attachment which pivots on the rear of a three-point hitched ripper. The scraper at the rear of the attachment creates a basin 1 m wide and 15 cm deep and the space between basins is 1 m. A ripper tine operates directly in front of the attachment to break up compacted soil. Chains were used to enable the tractor to lift the whole machine clear of the ground, though it limits downward movement of the attachment. When the ripper tine is engaged, the diamond-shaped control wheel controls the movement of the scraper blade, resulting in a row of basins being created (Figure 3.7).

Figure 3. 7 Demonstration of mechanised basins implement.

- **Daling plough tillage (DL)**

The plough was developed by Mr Daling from Settlers in Limpopo. A chisel plough is connected directly to the tractor and the basin plough then follows behind. It works on contour and creates flattish basin areas and a runoff area of 1.8 m. The chisel plough loosens the soil before the basins are constructed in the same direction (Figure 3.8).

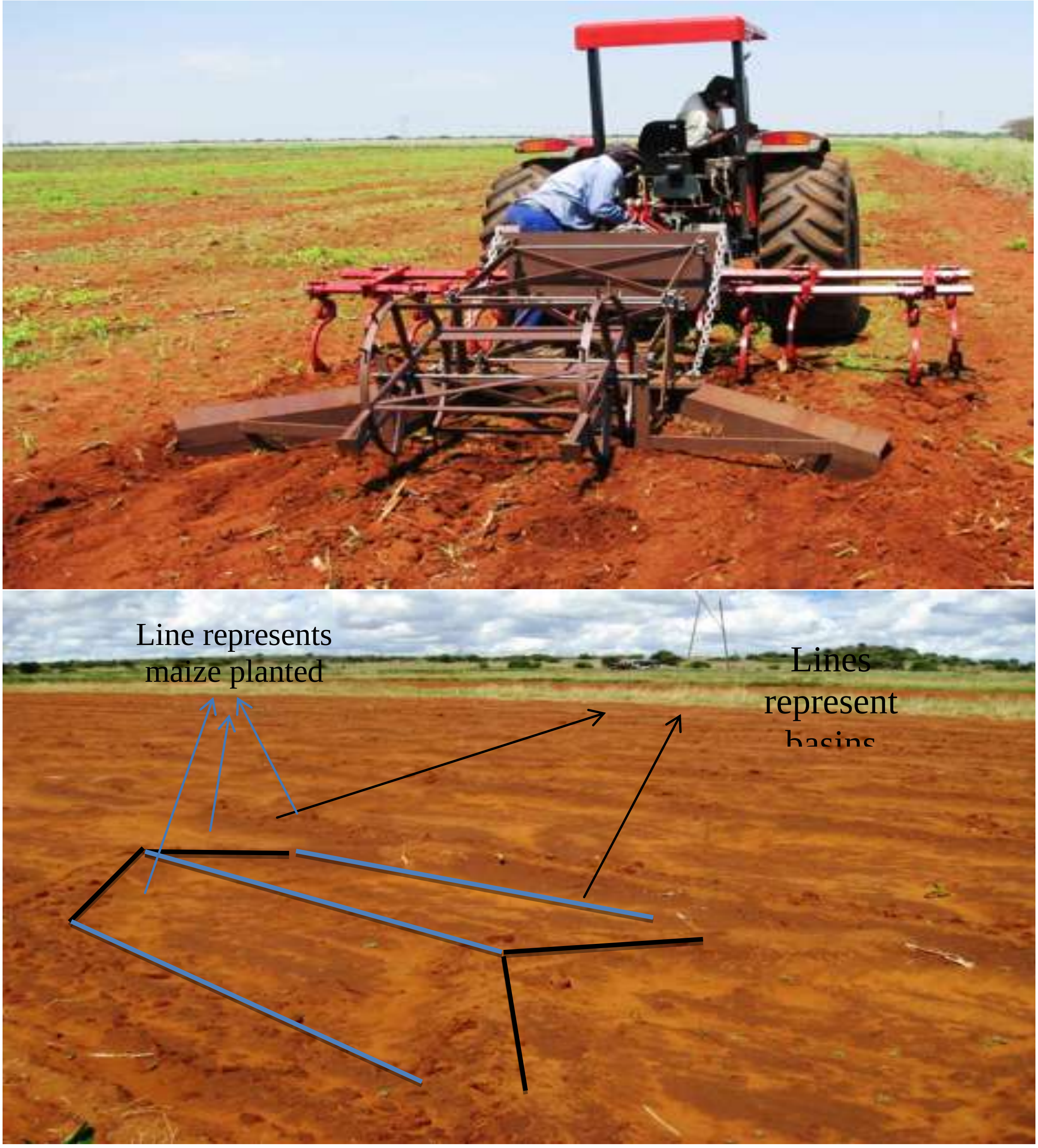

Figure 3. 8 Demonstration of the Daling plough design by Dirk Daling

Planting during the 2008/09 and 2009/10 seasons took place during mid-January and early December, respectively. During the first growing season (2008/09), land was tilled with a mouldboard plough to loosen soil prior to the implementation of different treatments. During the second season (2009/10), only CON was ploughed and soil on the IRWH, DL and MB treatments was loosened up with a disk and chisel plough. Land was then disked to obtain a fine, level seedbed. Basins were then constructed and a neutron access tube inserted.

The short-growing maize cultivar, PAN 6Q-521R, with a growing period of 120 days from planting to harvest was used. Information on plant population and fertilizer application as well as planting and harvesting dates is presented in Table 3.3. Fertilizer was applied based on soil analyses (Apendix 2). Fertilizer as applied during the 2008/09 season (25.2 kg N ha^{-1}, 7.2 kg P ha^{-1} and 3.6 kg K ha^{-1}) and the 2009/10 season (25.6 kg N ha^{-1}, 8.5 kg P ha^{-1} and 4.3 kg K ha^{-1}). However, during the second season (2009/10) the maize showed symptoms of nitrogen deficiency and a further 50 kg N ha^{-1} in the form LAN was added as a top dressing.

Weeds were controlled mechanically, chemically or a combination of mechanical and chemical control, depending on the treatment. In the conventional treatment, weeds were controlled mechanically with a tiller during early growth stages and hand hoeing as the season progressed. Only chemical weed control was applied in all other treatments. Due to the weed spectrum in the field, no pre-emergence herbicide was used during the 2008/09 season, while a mixture of atrazine and terbuthylozine (Combo- Zine 600SC) at a rate of 0.81 kg a ί ha^{-1} was applied during the 2009/10 season. Glyphosate (Roundup ready plus) was applied at a rate of 972 g a ha^{-1} to control weeds that emerged later. When glyphosate could not be used due to the maize being in a sensitive stage bromoxynil was applied at a rate of 337.5 g a ha^{-1}.

3.4 DATA COLLECTED

3.4.1 Long-term climatic data

Long-term climatic data (rainfall, temperature and class A-pan evaporation), which were recorded over a period of 52 years (1958-2010) were used to characterise the climate (Figure 3.9). Climatic data during the trial period were collected from an automated weather station situated approximately 1 km from the trial. Climatic characteristics of the Glen/Oakleaf ecotope indicate that the area is semi-arid with an average annual rainfall of 542 mm. It is also associated with high atmospheric evaporative demand with relatively low, unreliable and erratic rainfall.

Normally the maize-growing season in the Glen/Oakleaf ecotope extends from November to March, with an average rainfall of 262 mm. However, during the winter season, approximately 5% of the average annual rainfall occurs. During the summer months, March seems to experience high rainfall intensity with the additional advantage of low evaporation demand. The aridity index (AI) during the month of March was the highest with a value of 0.4 due to consistency of rainfall events from January to March. Arora (2002) indicates that AI can be used to obtain an estimate of annual evapotranspiration and estimates to the rainfall for the next season. AI was calculated with the equation below:

$$AI = \frac{R}{Eo} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

Where:

R = Rainfall mm

Eo = Evaporative demand mm

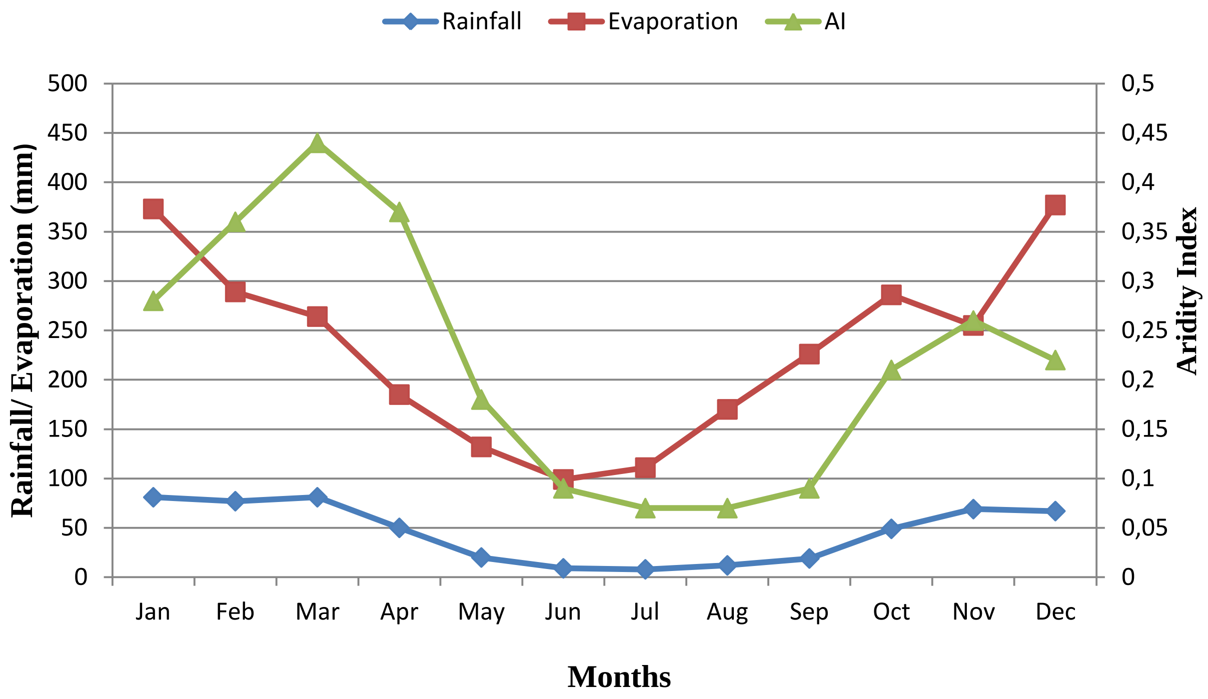

Figure 3. 9 Long-term monthly rainfall, evaporation and aridity index from Glen Meteorological station (ARC-ISCW) for the period of 1958-2010.

3.4.2 Soil parameters

Soil water content (SWC) represents the depth ratio of soil water and the depth of water per depth soil. To monitor soil water content of the root zone, two aluminium access tubes were installed per treatment and measured at a depth of 150 mm, 450 mm, 750 mm and 1 050 mm. An auger was used to make holes where access tubes will be inserted. Two access tubes were inserted per treatment, preferably in the middle of the plot. On RWH&C treatments one access tube was inserted in the basin and the other in a catchment area. Soil water content was measured every two weeks, using a neutron water meter or neutron probe (NWM) (Figure 3.10). The NWM was calibrated by using gravimetric soil water measurements, Hensley *et al*. (2000) describe bulk densities of the soil, and the procedure used to calibrate.

Figure 3. 10 Neutron water meter used to measure soil water content.

Deep drainage (D) is defined as the loss of water from the deepest soil layer of the root zone, and therefore out of reach of crop roots and is one of the water loss processes in water balance components. D only occurs when the soil water content of the deepest soil layer exceeds the drained upper limit of the soil. Thus, water is held by gravity and it can be removed by crops or through evaporation from the soil. This indicates the ability of crops to extract water from the soil while the water is moving through the soil profile. Soil water content between saturation and drainage in the upper limit (DUL) is called the Crop Modified Upper Limit (CMUL). DUL is the highest field measure water content of a soil after it has been thoroughly wetted and allowed to drain until drainage becomes practically negligible (Ratliff *et al*., 1983). Water holding capacity of the root zone is determined by DUL or water holding capacity of plant water availability (PWA).

It is the point on the drainage curve where the drainage rate is equal to the evapotranspiration (ET). D can be estimated by interpreting soil-water extraction diagrams during the growing season in relation to the drainage curve of the on-station experiments. Ratliff *et al.* (1983) reported that DUL exists when the water content in the profile of specific soil decreases to less than 0.1-0.2% per day.

Drainage was determined according to the method described by Botha (2006). The 4 m x 4 m level plots of 700 mm deep were dug around the levelled plots and galvanised iron (GI) was inserted in the channel to isolate the monolith from the soil. The channel was filled with soil around the outside of the GI sheet so that it was pressed as firmly as possible against the side of the monolith. Smectite-rich clay slurry was poured into the gap between the GI sheet and the sides of the monolith to prevent leakage of water downwards through this gap. The purpose of the GI sheet was to prevent lateral water movement, which is especially prone to occur at transitions between the A and the less permeable B horizons. A low earth wall was made around the area to prevent runoff water from entering. The water content of the entire profile was measured before any addition of water. A water cart was used to fill the plots with water, and to keep them full until continuous NWM readings show that the wetting front had reached the bottom of the root zone. The addition of water was then discontinued. The plots were covered with a plastic sheet and allowed to drain over a period of one month.

To measure ex-field (R_{ex}) and in-field (R_{in}) runoff plots were constructed next to each experimental plot to resemble different treatments. Measurements were made throughout the course of the experiment. R_{ex} was estimated using the equation from Hensley *et al.* (2000) (Equation 3.11). It was assumed that R_{ex} would be regarded as zero with precipitation less than 8 mm. The runoff plots were demarcated with corrugated iron sheets and a flat piece of aluminium sheeting was laid down at the down slope bottom end that collects and channels the runoff into 210 ℓ drums (Figure 3.11). The water was pumped out into calibrated plastic drums after each rainfall event and the volume recorded. Maize was planted on the runoff plots in order to give a true reflection of what was happening in the trial plot and weeds were chemically controlled with the same chemicals as in the trial.

$$R_{ex}\ (mm) = [(0.473xP) - 2.17]x\ 0.4 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

Figure 3. 11 Runoff strip with installed tipping bucket.

Water balance processes in Equation 3.7 play an important role in the functioning, productivity and stability of the soil-plant-atmosphere continuum. The procedure proposed by Tanner & Sinclair (1983) was used to separate evapotranspiration (Ev) into its two components, transpiration from the crop (ET) and evaporation from the soil surface (Es). Transpiration efficiency coefficient (k) values for the selected crops were used to separate Es and Ev. The k value of 9.5 g m^{-2} mm^{-1} suggested by Tanner & Sinclair (1983) was used for maize. To implement the procedure

Change in the soil water = water in – water out

$$Ev = (P \pm \Delta S) - (Es + R + D) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.7)$$

Drainage curves helped to estimate Plant Water Availability (PWA) in the root zone by subtracting the LL from the DUL values (Hensley *et al*., 2000).

$$PAW = L - DUL\ (mm) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.8)$$

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

$$RSE = \frac{\theta\rho(n) - \theta\eta(n-1)}{pf} * 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (3.9)$$

Where:

$\boldsymbol{\theta\rho(n)}$ = root zone water content at planting of the current crop (mm)

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

$\boldsymbol{pf}$ = rainfall during the fallow season (mm)

Water use efficiency (WUE_{ET} and WUE_{Ev}) in the various treatments was calculated after the final grain yield had been determined. It was used to measure the efficiency with which a particular crop converted the water available during the growing season (Hillel, 1972; Tanner & Sinclair, 1983; Botha *et al.*, 2012; Botha *et al.*, 2003). WUE_{ET} and WUE_{Ev} were determined with a slightly modified version of Hillel (1972), Singh *et al.* (2007) & Tanner and Sinclair (1983) as follows:

$$WUE_{ET}\ (kg\ ha^{-1}mm^{-1}) = \frac{GY}{ET} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (3.10)$$

$$WUE_{Ev}\ (kg\ ha^{-1}mm^{-1}) = \frac{GY}{Ev} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \ldots\ldots (3.11)$$

Where:

$\boldsymbol{WUE_{ET}}$ = water use efficiency in terms of total evapotranspiration (ET) in mm.

$\boldsymbol{GY}$ = grain yield

Precipitation use efficiency (PUE) was calculated using Equation 3.12. For fallow and growing periods, PUE was determined as a simple way to describe the efficient use of rainwater available for dryland crop production (Hensely *et al.*, 2000).

$$PUE(kgha^{-1}mm^{-1}) = \frac{GY}{P} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (3.12)$$

Where:

$\boldsymbol{P}$ = precipitation during fallow period or growing season

Rainwater productivity (RWP) was taken as the ratio of rainfed yield (total grain yield) to rainwater (Botha, 2006).

$$RWP_n\ (kg\ ha^{-1}mm^{-1}) = \frac{\Sigma Yg_n}{\Sigma P_n} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (3.12)$$

Where:

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

$\boldsymbol{\Sigma Ygn}$ = Total grain yield over n consecutive years (kg ha^{-1})

$\boldsymbol{\Sigma P_n}$ = Total precipitation over n consecutive years (mm)

3.4.2 Crop parameters

Yield and yield component measurements

The height (cm) and stem diameter (cm) of 12 randomly selected maize plants were measured at 30, 45, 66 and 90 days after planting (DAP). A plant that was selected was tagged to ensure that data was collected from the same plant throughout the growing season. The arithmetic meaning of the measured heights and stem diameter was determined to give a representative plant height and stem diameter for the plot. Data for plant height stem diameter and leaf area index were only collected during the 2008/09 season, while yields, and biomass data were collected during both the 2008/09 and 2009/10 seasons.

Leaf areas (LA) from twelve randomly selected plants per treatment were measured during the first growing season. Leaf area index (cm) determines LA on plant per treatment at 30, 45, 66 and 90 DAP. LAI was calculated using the following equation, Watson (1958):

$$LAI = \frac{Leaf\ area}{Land\ area} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3.2)$$

The aerial biomass (BM) of 12 randomly selected maize plants per treatment was determined at 30, 45, 66 and 90 DAP. Sampled plants were cut at the soil surface and fresh mass determined. Fresh material was then dried at 65ºC for seven days before being weighed again to obtain dry mass. The biomass was calculated as:

$$BM(kgha^{-1}) = \frac{plant\ population\ ha^{-1}\ X\ dry\ mass\ of\ plant\ dried}{12\ plants\ sampled} \dots\dots\dots\dots\dots\dots.. (3.3)$$

The grain yield (kg/ ha^{-1}) was determined at biological maturity by harvesting. Three double rows each 20 m long were harvested on each plot. The grain was oven dried to adapt to 13% water content and expressed as the yield in kg/ ha^{-1}.

$$GY(kg\ ha^{-1}) = \frac{mass\ seed\ (kg)}{area\ harvested} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3.4)$$

Harvest index (HI) was calculated as the ratio of grain or seed yield to the total above ground biomass yield (Bennie *et al.*, 1998).

$$HI = \frac{GY\ (kg\ ha^{-1})}{BM\ (kgha^{-1})} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3.5)$$

Where:

HI = harvest index

GY = grain yield (kg/ ha^{-1})

BM = total above-ground biomass (kg/ ha^{-1})

3.5 DATA ANALYSIS

Data were analysed using the general linear model procedure of SAS (Ver. 9.3) for personal computers ($SAS_{0.05}$). Treatment means of parameters indicating significant differences were separated using Turkey's least significant different test as described by Steel & Torrie (1980).

CHAPTER 4

EVALUATION OF VARIOUS TILLAGE TECHNIQUES ON SOIL WATER BALANCE AND RAINFALL STORAGE EFFICIENCY

4.1 INTRODUCTION

The low and erratic rainfall in the semi-arid areas of South Africa limits crop production under rainfed conditions. The problem is exacerbated by a high evaporative demand (Eo) and high runoff due to high rainfall intensity and clay and duplex soils. These losses hamper the efficient use of available water for crop production, and need to be minimised to optimise rainwater productivity (Botha *et al*., 2003). It is also important to increase the amount of water available to crops, which may lead to improved maize yields in these areas. Botha (2006) reports that every drop of rain is important for improving crop production. Soil and water management practices can be used to increase plant available water for crop production (Gupta, 1995).

A number of South African researchers report that the in-field rainwater harvesting (IRWH) technique improves grain yields compared to conventional tillage (CON) Hensley *et al*. (2000), Botha *et al*. (2003) and Botha (2006). IRWH, using 2 m-wide runoff strips and 1 m-wide basins implemented by hand were introduced by Hensley *et al*. (2000) as a suitable tillage practice for summer crops (maize, sunflower and beans). The technique implemented by hand using spades and rakes was tested in detail on the Glen/Bonheim and Glen/Swartland ecotopes on small plots as well as in homestead gardens and demonstration plots of subsistence farmers in the Thaba Nchu and Botshabelo areas. It was successful in producing much higher crop yields. The technique resulted in yield improvements of between 30% and 50% compared to CON during an average rain season (Botha *et al*., 2003; Botha, 2006). As a result, smallholders in these areas adopted this technique. The technique was later mechanised by Bramley Engineering works in Bloemfontein, to improve productivity of smallholders (Bothma, 2009). A number of mechanised rainwater harvesting and conservation (RWH&C) techniques are available, but they have not yet been studied and compared in detail regarding yields, soil water balance and efficiencies.

Van der Merwe & Beukes (2006) compared mechanised basin (MB) with CON tillage on a vertic soil with a high clay content at Kanana Experimental Farm in the Bafokeng District. The technique tested on sunflower and cotton resulted in higher yields and soil water contents. Mr. Dirk Daling, a farmer from Settlers in the Limpopo Province, built the Daling plough. He has been conducting rainwater harvesting on a commercial scale since 1997 (Anderson *et al.*, 2003). These various techniques have not been compared with one another on similar environmental conditions.

The objective of the study was therefore to compare the soil-water balance components, water availability, water use, storage efficiency and water productivity of selective RWH&C techniques with CON tillage on the Glen/Oakleaf ecotope.

4.2 RESULTS

4.2.1 Climatic conditions

The climate data of the two seasons (2008/09 and 2009/10) were divided into three periods according to crop growth. These divisions were the fallow period (Fp), vegetative growth period (Vp) and the period of reproductive growth (Rp). Combining Vp with Rp gave the crop growth period (Gp), while the Fp and Gp combination resulted in the overall production period (Pp). Weather data for the rainfall, evaporation demand and aridity index for the growing period divisions are given for both seasons in Table 4.1.

From Table 4.1 it can be seen that the long-term average rainfall (LT) of the Glen/Oakleaf ecotope is 519 mm during the Pp, and that there was a variation of 229 mm between LT and the second season, confirming the finding by Botha *et al.* (2012) that rainfall on this ecotope is highly variable. The Production period (Rp) of the first season (2008/09) was not included as there was no fallow period and this season was considered a dry season with rainfall 1% lower than the LT during Gp, while the second season (2009/10) could be considered as a wet season, as the rainfall was 44% higher than LT during Rp. Rainfall during the Vp was greater than that of LT, during both seasons with 19% and 49% higher, respectively. During the first season (2008/09), rainfall during Rp was 41% lower than LT and 160% higher during the second season (2009/10). There was less than 1% variation in rainfall during the Gp for the first season, while the second season received 85% more rainfall during the Gp than the LT.

Consequently, the first season can be considered representative of an average rainfall year, while the second season represents a wet season. However, due to the amount of rainfall during Rp the first season was considered a dry year due to its very low rainfall during the critical Rp (Cakir, 2004).

Table 4. 1 Rainfall, evaporative demand and aridity index for the two growing seasons in relation to the mean of long-term data of the Glen/Oakleaf ecotope

Parameter	Season	Period*				
		F_p	V_p	R_p	G_p	P_p
Rainfall	2008/09	-	209	51	260	-
(mm)	2009/10	257	262	224	486	748
	LT Mean	**257**	**176**	**86**	**262**	**519**
Evaporative	2008/09	-	433	235	663	-
demand	2009/10	1048	559	374	933	1978
(mm)	**LT Mean**	**1324**	**490**	**268**	**758**	**2082**
Aridity index	2008/09	-	0.48	0.22	0.39	-
(AI)	2009/10	0.25	0.47	0.60	0.52	0.38
	LT Mean	**0.19**	**0.36**	**0.32**	**0.39**	**0.26**

*Fp = Fallow period, Vp = Vegetative period, Rp = Reproductive period, Gp = Growing period and Pp = Production period.

Lost water from the soil surface during the first season might have been 14% lower than LT and 19% higher than LT due to the higher Eo during both growing seasons, indicating a lower effectiveness of rainfall. According to Botha *et al.* (2003), approximately 70% of the annual rainfall is lost due to evaporation from the soil in semi-arid areas. During theVp of both seasons, rainfall was less than Eo with 69% and 53% respectively. Evaporation demand during the Rp of the first growing season (2008/09) exceeded the rainfall by 78%. During the second season (2009/10), the evaporation demand during this Rp was 66% lower than the rainfall for the same period (Table 4.1).

The aridity index (AI) is a numerical indicator of the degree of dryness of the climate at a given location (Thornthwaite, 1948, cited by Mzezewa *et al*., 2010). The AI represents climatic aridity and is used to determine the adequacy of rainfall in satisfying the water needs of the crop (Tsiros *et al*., 2008). The overall rainfall condition for the Gp for the 2008/09 season with 260 mm was 1% lower than LT with a high Eo of 663 mm, implying a dry season. During 2009/10, the rainfall for Gp was high with 486 mm 86% greater than LT, giving a wet season. The aridity index of the first season on Fp was not included, however during the second season the Fp was 32% above LT average. During the Vp of both seasons, rainfall was more than LT contributing to favourable AI of 0.48 and 0.47 respectively. Low rainfall during the Rp during 2008/09 contributed to a low AI of 0.22 and high rainfall during the second season (2009/10) contributed to a high AI of 0.60. A favourable AI during the 2009/10 season was attributed to high rainfall and slightly lower Eo. In the research conducted by Botha *et al*. (2012) over a three-year trial, good cropping conditions was indicated by higher AI values attributed to lower Eo's rather than good rains.

4.2.2 Drainage characteristics

Drained upper limit (DUL) is the highest field-measured water content of a soil and allowed to drain until drainage becomes negligible (Ratliff *et al.*, 1983). Although the effective root zone was considered to be 2100 mm, soil water content measurements were only done to a depth of 1200 mm. According to Botha *et al*. (2012), the DUL of the Glen/Oakleaf ecotope with a reading depth of 1200 mm was 280 mm. Botha *et al*. (2003) indicating that the occurrence of drainage occurs only if soil water content exceeds DUL in the deeper layer DUL ($_{900\text{-}1200\ \text{mm}}$). Drainage can occur only when the soil water content is above the crop modified upper limit (CMUL).CMUL occurs when plants extract water from the soil while the water is moving through the soil profile at soil water content between saturation and DUL.

4.2.2.1 Plant availability water

Plant available water (PAW) is the soil water content between the lower limit (LL) and DUL in the soil profile. The lower limit (LL) is the lowest field-measured water content of a soil after plants no longer extract water and are at or near premature death, or have become dormant because of water stress (Ratliff *et al*., 1983). The procedure for the determination of PAW is described by Botha *et al*. (2003). Although soil water changes constantly with time, plant-available water was calculated for three growth stages of maize; at planting (PAW_P), tasselling (PAW_T) and at harvest (PAW_H) during both growing seasons (Table 4.2).

During the 2008/09 season, the results of PAW_P showed no significant difference between treatments. However, RWH&C (MIN, IRWH-2.0m, IRWH-2.4m, DAL & MB) techniques recorded to have better PAW_p compared to CON with 108, 105, 103, 96, 95, 89 mm, respectively. Out of RWH&C techniques, the best performing treatment was MIN, which showed to contain more water, probably due to less soil disturbance and high surface plant residues, which helped to retain soil moisture. During the second season, only IRWH-2.0m and DAL treatment from RWH&C techniques had significantly higher PAW_p than CON. The rest of the RWH&C treatments (MIN, IRWH-2.4m, & MB) were 75, 84, 75 mm higher than CON treatment but differences were not significant.

During the 2008/09 season, the low value of PAW_T showed that water shortage during the tasselling stage was probably detrimental to yield components (ear and kernel number) when the potential number of kernels is determined. During the dry season (2008/09), RWH&C techniques (MIN, IRWH-2.0M, IRWH-2.4, MB, DAL) had higher PAW_T than the CON treatment 27, 57, 60, 43, 46 mm respectively. The PAW_T values of RWH&C techniques were significantly higher than that of CON tillage excluding MIN. Even during the wet season (2009/10) RWH&C techniques (MIN, IRWH-2.0M, IRWH-2.4,) had significantly higher PAW_T than CON, excluding MIN.

During the first season (2008/09), RWH&C techniques had higher PAW_H values compared to CON treatment. The soil on IRWH-2.0m and IRWH-2.4m techniques showed significantly higher PAW_H than that of CON treatment. Treatments during the second season (2009/10) had higher PAW_H than the first season (2008/09). This suggested that the level of water stress during 2008/09 Rp was more than that of the 2009/10 season. The higher AI on Gp of the second season supports these results, compared to the first season with 0.52 and 0.39, respectively. During both seasons, IRWH-2.0m and IRWH-2.4m treatments had a significantly greater PAW_H than the CON, MB and MIN treatments. This is explained by the ability of the IRWH technique to collect rainfall from the runoff and channel it to the potential rooting zone.

Table 4. 2 Plant available water at planting (PAW_P), tasselling (PAW_T) and harvest (PAW_H) for the root-zone of different treatments on the Glen/Oakleaf ecotope over two maize-growing seasons (2008/09 & 2009/10)

PAW (mm)	Season	Treatment						LSD $_{(T0.05)}^{a}$
		CON	**MIN**	**IRWH-2.0m**	**IRWH-2.4m**	**MB**	**DAL**	
Planting	2008/09	87	107	104	103	95	96	Ns
	2009/10	68b	75ab	92a	84ab	75ab	89a	18.5
	Mean	**78**	**91**	**98**	**94**	**85**	**93**	
Tasselling	2008/09	25c	27cb	57a	60a	43ab	46ab	17.3
	2009/10	40c	50bc	81a	81a	70ab	70ab	22.9
	Mean	**33**	**39**	**69**	**57**	**57**	**58**	
Harvest	2008/09	10b	13b	42a	36a	19b	13b	15.9
	2009/10	24d	34cd	88a	91a	53bc	72ab	28.2
	Mean	**17**	**24**	**65**	**64**	**36**	**43**	

*Different letters within a row indicate significant differences ($p<0.05$), between treatments.

*ns – not significant.

4.2.3 Soil water balance

4.2.3.1 Soil water content

Soil water content (Figure 4.1) has been coupled with rainfall, volumetric water content and available soil water. Figure 4.1 illustrates the change in the soil water content of the various treatments implemented during the two growing seasons to a depth of 1 200 mm. The information on these two graphs (Figure 4.1) assisted in explaining yield differences between treatments and water balance data. Data in Figure 4.1 shows the vegetative (Vp) and reproductive (Rp) phase of the maize growing period.

Soil water content is the quantity of water contained in the soil profile. Water scarcity during Vp during the season usually results in smaller plants, which in turn results in lower potential yield (Du Plessis, 2003). During water shortage, plants undergo a physiological alteration that affects plant growth. The study conducted by Thimme *et al*. (2013) shows that water requirements for maize plants during the vegetative stage increase throughout the vegetative period. During the first season Vp, good rainfall of 209 mm and low Eo of 433 mm compared to LT, Vp resulted in well-developed maize plants, which may have contributed to high potential yield. The highest rainfall events occurred at 13 and 42 days after planting (DAP) with amounts of 50 mm and 42 mm, respectively (Figure 4.1). Ten well-distributed rainfall events of 50, 10, 10, 9, 9, 10, 13, 11, 10, and 14 mm, respectively during Vp added to PAW. The small rainfall events below 10 mm, which were followed by more rainfall events, have a positive impact on crop production. The rest of the rainfall events were below 10 mm, which is prone to be lost immediately due to evaporation from the soil surface (Botha, 2006). The soil water contents of all the treatments at Vp were far above 10 mm during 2008/09, which indicted high water content and ensured that plants were not subjected to water stress.

There was no significant difference in soil water content between the different treatments during Vp of the 2008/09 season. However, the soil water content of MIN treatment was at DUL at planting. This was possibly due to less disturbance of the soil surface during land preparation whereby moisture was retained in the soil and planting while plant residues were available. All the treatments responded well to the 50 mm rainfall event at day 13 after planting by increasing soil water content to above DUL. At this stage, no drainage occurred from the soil profile as water was lost due to plants absorbing water and while Es occurred to reduce the soil water content as well. Between 18 and 21 DAP the soil water content of CON, MIN and DAL treatments dropped below DUL, while that of the MB treatment remained close to DUL. Occurrences of rainfall from 28 to 41 DAP continuously kept the soil water content of IRWH-2.0m and IRWH-2.4m treatments above DUL, which might possibly have contributed to the risk of deep drainage. Towards the end of the vegetative period, the soil water content of all the treatments dropped below DUL due to lower rainfall occurrence and greater soil water extraction by plants. Although the soil water content of all the treatments dropped, IRWH-2.0m and IRWH-2.4m consistently had the highest soil water content, while the MIN and CON treatments had the lowest soil water content of all the treatments.

During the second season (2009/10), the Oakleaf ecotope received 486 mm of rain during the Gp with 48% of the rainfall falling during the Vp. RWH&C techniques (DAL, IRWH-2.0m, IRWH-2.4m, MIN & MB) throughout Vp (2009/10) had higher soil water content, compared to the CON treatment. IRWH-2.0m showed to be the treatment with the highest soil water content. The Vp 2009/10 received 262 mm of rainfall, which was 49% more than LT. With this amount of rainfall, no treatments had soil water content above DUL. This indicates that no drainage occurred at that stage. Well-distributed rainfall between 48 and 54 DAP increased the soil water contents of all the treatments, IRWH-2.0m and IRWH-2.4m switched with DAL becoming the best treatments. During this period soil water content the RWH&C techniques (IRWH-2.4m, IRWH-2.0m, DAL, MB and MIN) increased with 41, 37, 24, 22 and 16 mm respectively compared to CON with 12mm. This indicated that IRWH had the advantage of collecting water from the runoff and the in-situ conservation techniques (MB & MIN) had the advantage of capturing and storing water where it was going to be utilised. At 61 DAP all treatments dropped and MIN switched from being the second last to becoming the lowest water content treatment.

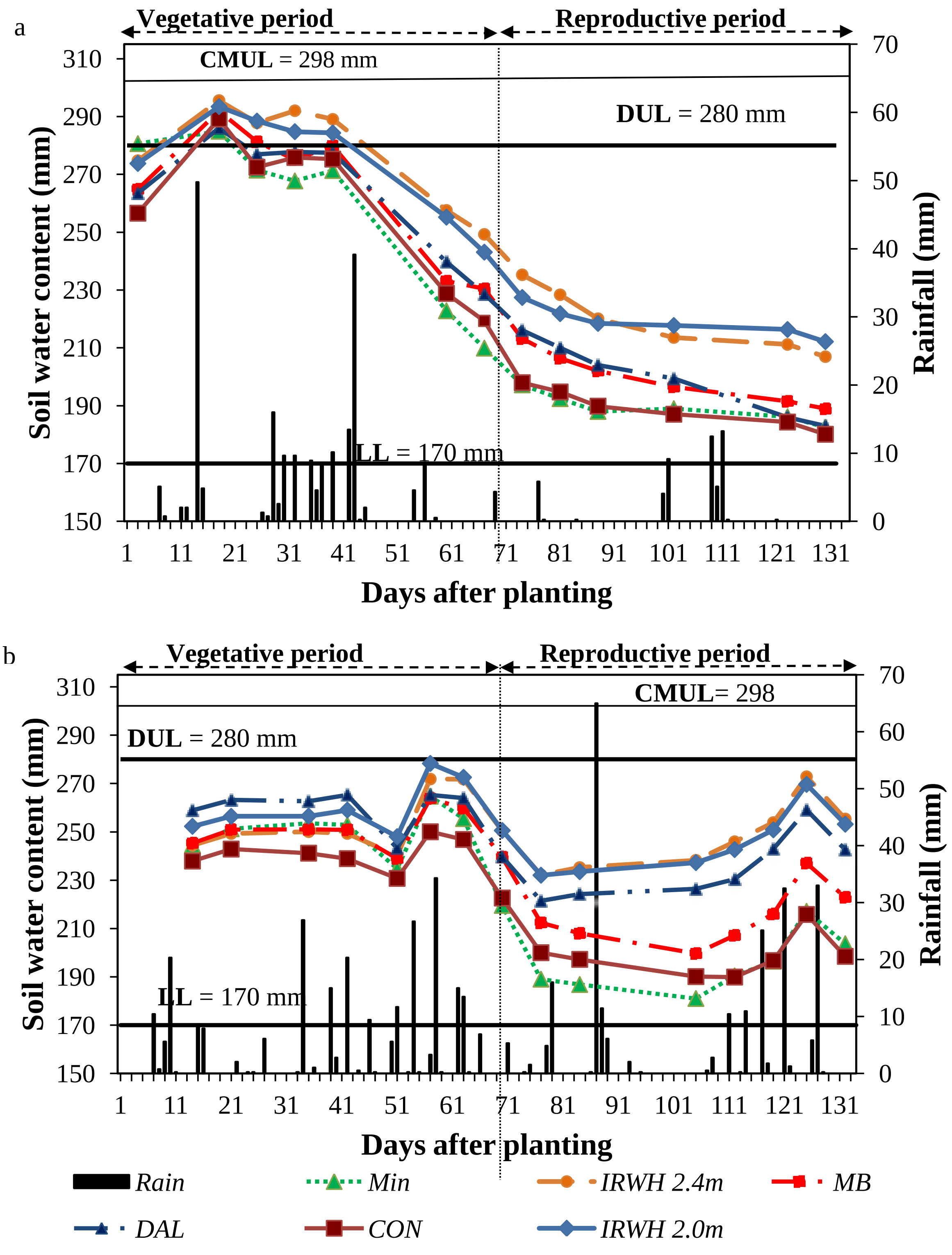

Figure 4. 1 Change in soil water content of roots zone (0-1200 mm) during the 2008/09 (a.) and 2009/10 (b.) growing seasons.

Shortage of water during the reproductive growth stage of maize is detrimental to the process of flowering and grain filling (Aslam *et al*., 2012). This can cause less grain yield due to a reduction in the number of kernels per cob and lower kernel weight. The first season was regarded as a dry season due to rainfall of 51 mm during Rp, which was 41% less than the LT. During this stage, ten rainfall events occurred with only three higher than 10 mm. During the 2008/09 season Rp constantly decreased due to plants extracting water and a long dry period with small rain events, resulting in decreased soil water content of all treatments. As a shortage of rainfall is common in the Glen/Oakleaf ecotope, soil water content during Rp dropped down, however not below the LL line. This decline in soil water content drastically affected grain yield. Water stress probably affected flowering and kernel formation (65-81 DAP) negatively and at this critical stage maize depends heavily on water conserved in the soil profile. When rainfall is not sufficient to meet crop water requirements, stored water in the soil profile is used to make up the deficit (FAO, 1991). Rainfall showers that occurred between 98 and 111 DAP kept the soil water content of IRWH-2.0m, MB, CON and MIN treatments at a constant level until late Rp, while the soil water content of IRWH-2.4m and DAL treatments decreased. With this shortage of rainfall, the RWH&C techniques (IRWH-2.0m, IRWH-2.4m, DAL and MB) were shown to be better at both capturing and storing of rainfall, compared to the MIN and CON treatments.

Weather conditions during the second season (2009/10) were favourable throughout the Rp with rainfall of 224 mm, 160% more than LT. The decrease of soil water content at 65 DAP of the root zone may contribute to rapid plant water extraction. During the tasselling stage, the soil water content declined after 7 mm of rain at 65 DAP. At the beginning of kernel formation (74 - 77 DAP) a low rainfall event below LL recharged the soil and there was a slight increase in soil water content of the IRWH-2.0m, IRWH-2.4m and DAL treatments. This phenomenon once again confirms the advantage of the RWH (IRWH and DAL) techniques to make better use of rainfall compared to the other treatments through their ability to harvest additional water from the runoff strips. Soil water content on MIN, MB and CON treatments increased responding to rainfall of 3, 10, 11, 25, 2, 33, 6 and 33 mm respectively between 107 and 127 DAP, possibly due to less water extraction.

Generally, the soil water content of the IRWH-2.0m and IRWH-2.4m treatments remained higher than other treatments during both growing seasons. During the first season (Figure 4.1a), the soil water content of the root zone (0-1200 mm) of all the treatments was above the

DUL from 12 to 21 DAP, indicating that drainage could have occurred and drainage might have continued on IRWH-2.0m and IRWH-2.4m treatments until 40 DAP. However, the soil water content of all the techniques was below CMUL, while no drainage occurred. CMUL occurs when plants extract water from the soil while the water is moving through the soil profile at soil water content between saturation and DUL (Botha *et al.*, 2012). It occurs on the drainage curve where the drainage rate is equal to evapotranspiration (ET). During the second season (Figure 4.1b), the soil water content of all the treatments was below DUL, which indicates that no drainage occurred. However, the soil water content of the CON, and MIN treatments remained lower than those of the other treatments.

The soil water content of all treatments in both seasons decreased gradually at the end of Vp towards Rp, but remained constant at the end of the 2008/09 season, while during the 2009/10 season, the soil water content of all treatments increased towards the end of the season. Although the soil water content for the first season was above LL throughout the season, low rainfall during Rp affected yield negatively. The results of higher PAW at planting and harvest supported the fact that RWH&C techniques constantly had high water available in the root zone compared to CON (Section 4.1.2.1). RWH&C techniques had higher soil water contents at the end, contributing to a high pre-plant water advantage over the CON with the onset of the 2009/10 growing season. According to Van Rensburg *et al.* (2012), water collected and conserved by RWH&C techniques contributes directly to reaching the yield potential of a crop.

4.2.3.2 Runoff

Runoff is classified into two types, namely Ex-field (R_{ex}) runoff and In-field (R_{in}) runoff (Table 4.3). R_{ex} refers to the water running out of the planted field, which is water lost for production performance. This type of runoff occurs under CON, MIN, MB and DAL treatments. R_{in} refers to the runoff in the planted field and it is only found on the runoff strips in the IRWH treatment where this water is directed into the basin. Hensley *et al.* (2000) and Botha (2006) indicated that no ex-field runoff occurs from the IRWH treatments. This water from R_{in} is therefore not lost from crop production performance, but rather collected and used by the plants. Runoff measurements were made during the 2009/10 season on plots next to each treatment. Rainfall occurring during 2009/10 was higher than that of the long term with higher intensity showers and the raindrops collapsed the soil aggregates, resulting in more runoff.

Table 4. 3 Runoff of different treatments on the Glen/Oakleaf ecotope

Event no:	Rain	CON		MIN		IRWH-2.0m		IRWH-2.4m		MB		DAL	
		mm	%	mm	%	mm	%	mm	%	mm	%	mm	%
1	10,4	1,1	10,3	1,7	16,2	1,7	16,7	2,7	25,9	0,7	6,4	0	0
2	20,3	3,9	19,1	4,2	20,6	4,8	23,9	6,7	33,1	1	5	1,2	5,9
3	8,6	0,6	6,6	1,2	14,3	1,2	13,6	2	22,8	0,6	7	0	0
4	26,9	5,7	21,4	5,9	21,8	6,9	25,7	9,4	34,9	1,2	4,6	2,3	8,4
5	15	2,4	15,8	2,9	19	3,2	21,2	4,6	30,4	0,8	5,5	0,4	2,3
6	20,3	3,9	19,1	4,2	20,6	4,8	23,9	6,7	33,1	1	5	1,2	5,9
7	9,4	0,8	8,4	1,4	15,2	1,4	15,1	2,3	24,3	0,6	6,7	0	0
8	11,7	1,4	12,3	2	17,2	2,1	18,3	3,2	27,5	0,7	6,1	0	0
9	26,7	5,7	21,3	5,8	21,8	6,9	25,7	9,3	34,9	1,2	4,6	2,2	8,4
10	34,3	7,8	22,9	7,7	22,5	9,2	26,9	12,4	36,1	1,5	4,4	3,5	10,1
11	15	2,4	15,8	2,9	19	3,2	21,2	4,6	30,4	0,8	5,5	0,4	2,3
12	13,5	2	14,5	2,5	18,3	2,7	20,1	4	29,3	0,8	5,7	0,1	0,8
13	16	2,7	16,6	3,1	19,4	3,5	21,8	5	31	0,9	5,4	0,5	3,2
14	51,6	12,7	24,7	12,1	23,5	14,7	28,4	19,4	37,6	2,1	4,1	6,2	12,1
15	11,4	1,4	11,9	1,9	17	2,1	18	3,1	27,2	0,7	6,1	0	0
16	10,4	1,1	10,3	1,7	16,2	1,7	16,7	2,7	25,9	0,7	6,4	0	0
17	10,9	1,2	11,1	1,8	16,6	1,9	17,4	2,9	26,6	0,7	6,2	0	0
18	15,5	2,5	16,2	3	19,2	3,3	21,5	4,8	30,7	0,8	5,4	0,4	2,8
19	25,1	5,2	20,9	5,4	21,5	6,4	25,3	8,7	34,5	1,2	4,7	2	7,9
20	32,5	7,3	22,6	7,3	22,4	8,7	26,7	11,7	35,9	1,4	4,4	3,2	9,7
21	5,8	0	0	0,5	9	0,3	5	0,8	14,2	0,5	8,6	0	0
22	22,4	4,5	20	4,7	21,1	5,5	24,6	7,6	33,8	1,1	4,8	1,5	6,9
Total	413.7	76,3		83,9		96,2		134,6		21		25,1	
%P			17,1		18,8		21,6		30,2		4,7		5,6

The occurrence of R_{ex} depends on climatic factors such as rainfall amount and intensity within the season and is an unproductive water loss, which may reduce yield. MIN treatment had higher R_{ex} during growing seasons compared to CON, MB and DAL treatment with 18.8, 17.1, 4.7 and 5.6%, respectively. This might possibly be due to the MIN treatment having about 15% - 30% of plant residue left on the soil surface, which affected the infiltration of water. Most often, runoff occurs when rainfall intensity exceeds the infiltration of water into the soil. Mzezewa *et* al. (2011) indicated that an increase in water runoff is caused by a decrease in infiltration. On the DAL treatment, rainfall less than 12 mm recorded lower runoff on rain event number 1, 3, 7, 8, 15, 16, 17 and 21. At the highest rain event, number 10, MB obtained the lowest runoff of 4.4 %, whereas CON had the highest runoff at 22.9%. However, event number 21 was low with 5.8 mm and recorded no runoff on CON treatment.

R_{in} is referred to as runoff within the planted field area. Water harvested and collected by the basin in IRWH treatments. R_{ex} then becomes zero. The result shows that the IRWH-2.5m treatment collected more rainwater than the IRWH-2.0m treatment with 30.2% and 21.6% respectively. This might possibly be because when rainfall occurs, more water flows into the basins on longer runoff strips.

4.2.3.3 Drainage

Drainage was calculated from the soil-water balance equation. Drainage is the loss of water from the deepest soil layer of the root zone and it is calculated by using the soil water balance equation (see Chapter 3, equation 3.7). During the first growing season at 13 DAP, the soil water content of all treatments was above the DUL line of 280 mm indicating that D could have occurred. After zero rainfall between 15 and 24 DAP, the soil water content of CON, MIN, MD and DAL treatments decreased below DUL. However, soil water content of the IRWH-2.0m and the IRWH-2.4m treatments continued to stay above the DUL line between 41 and 45 DAP, then the water content started to drop. As a result, the D value on IRWH-2.0m and IRWH-2.4m treatment in Table 4.4 were higher with 62 mm and 37 mm, respectively. The possible reason is that IRWH-2.0m and IRWH-2.4m treatments had more water directed and collected into the basins through runoff strips therefore R_{ex} is zero. During the second growing season (2009/10), the soil water content of all the treatments was below the DUL line indicating no occurrence of drainage.

Table 4. 4 Calculated drainage possibility during the 2008/09 and 2009/10 growing Seasons on the Glen/Oakleaf ecotope

Parameter (mm)	**Season**	**Treatment**					
		CON	**MIN**	**IRWH-2.0m**	**IRWH-2.4m**	**MB**	**DAL**
Drainage	08/09	9	7.5	61.8	37.3	18	9
	09/10	0	0	0	0	0	0
	Mean	**4.5**	**3.8**	**30.9**	**18.6**	**9**	**4.5**

4.2.3.4 Evapotranspiration

The ET, Es and Ev for all treatments of the two growing seasons (2008/09 & 2009/10) are summarised in Table 4.5. Evapotranspiration (ET) was calculated using the soil water balance equation presented in Section 3 (equation 3.7). ET is a combination of two processes, namely evaporation of water from the soil surface and transpiration of water through the stomata of leaves. For the purpose of this study, ET was separated into evaporation from the soil (Es) and transpiration (Ev). Es represents the unproductive water loss from the soil surface and Ev is the water that contributes to plant growth. The ET for the various treatments was significantly different for both seasons. There were significant differences between treatments; ET on the CON treatment was significantly lower than that in all other treatments during the first season, except MIN and MB treatments during the first season. During the second season, ET on MIN treatments were significantly lower than that on IRWH-2.0m and IRWH-2.4m treatments, however not significantly lower than CON, MB and DAL treatments. Botha (2006) obtained similar results with higher ET values on the IRWH treatments compared to CON. Generally, the IRWH-2.0m technique had higher ET than other treatments and MIN had lower ET than other treatments.

The Ev values of the first growing season (2008/09) were lower than that of the second growing season (2009/10) due to weather condition factors such as temperature, wind and rainfall. The second season had a higher rainfall, which could have contributed towards a higher crop yield. There were no significant differences between treatments in the first season, although the highest Ev was found with MIN, due to the less disturbed soil and high amount of crop residues on the soil surface. During the second growing season, there were significant differences in Ev between treatments. The highest Ev values were obtained on the IRWH-2.4m technique, it was significantly more than that on the DAL, with 121 mm and 95 mm, respectively. There were no significant differences in Ev between any of the treatments. Generally, the mean values of Ev on IRWH-2.4m, MIN and MB treatments show that plants growing toward biomass and yield probably used more water for transpiration. Less water has transpired on DAL and IRWH-2.0m treatments compared to CON.

Table 4. 5 Transpiration (Ev), evaporation from the soil surface (Es) and evapotranspiration (ET=Es+Ev) over two maize-growing seasons (2008/09 & 2009/10) for various treatments on the Glen/Oakleaf ecotope

Parameter	Season	Treatment						LSD $_{(T0.05)}^{a}$
		CON	MIN	IRWH-2.0m	IRWH-2.4m	MB	DAL	
ET (mm)	2008/09	303a	312a	395b	373b	318a	316a	25.17
	2009/10	457a	443a	650b	589b	477a	473a	14.55
	Mean	**380**	**378**	**523**	**481**	**398**	**395**	
Ev (mm)	2008/09	79	85	65	79	70	80	ns
	2009/10	105ab	106ab	104ab	121a	116ab	95b	23.28
	Mean	**92**	**96**	**85**	**100**	**93**	**88**	
Es (mm)	2008/09	224c	227c	330a	294b	247c	236c	26.91
	2009/10	352cd	337d	546a	468b	360cd	378c	27.20
	Mean	**288**	**282**	**438**	**381**	**304**	**307**	
Es/ET (%)	2008/09	74bc	73c	84a	79ab	78abc	75bc	0.06
	2009/10	77b	76b	84^{a}	80ab	76b	80ab	0.05
	Mean	**76**	**75**	**84**	**80**	**77**	**78**	

*Different letters within a row indicate significant differences (p=0.05), between treatments.

*ns – not significant.

Incorporation of different levels of mulch were found to help reduce Es in most of the research conducted on RWH&C techniques. In the study conducted by Botha (2006) bare soil and low mulch treatments indicated higher Es values. For this study, no extra mulch was added and maize stover of previous seasons' crops served as mulch for the MIN treatment. During both growing seasons, the RWH&C techniques had higher than expected Es values, due to inefficient canopy cover that could have shaded the soil. The soil surface was also wet for a longer period of time (Figure 4.1). This was due to the ability of RWH&C techniques to capture and conserve rainwater better. Furthermore, the values during the 2009/10 season were much higher than the 2008/09 season due to a high amount of good rainfall received, water evaporates when soil is wet for a longer period.

It is difficult to measure Es in a cropped field as the process involves dynamic interaction between a number of factors such as atmospheric evaporative demand (Eo) and soil water content. During the first season, the Es on IRWH-2.0m plots was significantly higher compared to the other treatments followed by IRWH-2.4m treatment. During the second season, the Es on the IRWH-2.0m treatment was significantly higher than that on the CON and MIN treatments. This study obtained higher Es values during the second growing season compared to the study conducted by Botha (2006). The Es on RWH&C techniques was significantly higher in both growing seasons compared to CON. Comparing the RWH&C techniques, IRWH-2.0m had lost more water, followed by DAL, MB, IRWH-2.4m, and MIN. It is not surprising to observe MIN with the low Es among RWH&C techniques. This could be attributed to the maize stubble on the soil surface that acted as effective mulch that prevented water loss.

Es/ET shows the portion of water lost through Es, which is an unproductive loss. The Es/ET value during the first season indicated that IRWH-2.0m treatments lost significantly more water to surface evaporation than MIN. However, Es on CON, MB, MIN and DAL treatments did not differ significantly from one another. During the second growing season, the Es was significantly higher on IRWH-2.0m treatments than other treatments; however, not significantly more than the DAL treatment, with a total of 494 mm. Overall, the Es/ET value on IRWH-2.0m, MB and DAL treatments was higher than all the other treatments (CON, MIN, MB and IRWH-2.4m).

4.2.4 Rainwater efficiencies

4.2.4.1 Rainwater storage efficiency (RSE)

A summary of rainwater storage-efficiency (RSE) results for maize crop production with RWH&C compared to CON during the second growing seasons (2009/10) is presented in Table 4.6. These efficiencies were calculated using equations described in Section 3.3.4.2. RSE is an indication of the treatment to store and conserve water in the soil profile during the fallow period (Fp) for the next growing season. In the first season (2008/09), the treatments were implemented just before planting so there was no fallow period to collect and store water. Therefore, RSE could not be calculated for the first season and no mean value will be discussed.

Table 4. 6 Rainwater storage efficiency (RSE) for various treatments during on the Glen/Oakleaf ecotope for the 2009/10 maize growing season

Parameter	**Season**	**Treatment**						**LSD $_{(T0.05)}$ ^{a}**
		CON	**MIN**	**IRWH-2.0m**	**IRWH-2.4m**	**MB**	**DAL**	
RSE (%)	2009/10	26	28	22	22	25	30	ns

*Different letters within a row indicate significant differences ($p<0.05$), between treatments.

The Fp prior to the 2009/10 planting season received 257 mm of rain, with less Eo of 1048 mm. The amount of water consumed during the first cropping season affected the RSE of the second cropping season. RSE of DAL treatment was 30% higher than that of CON, MIN, IRWH-2.0m, IRWH-2.4m, and MB treatments, however not significantly so. Results indicated that the IRWH-2.0m and IRHw-2.4m treatments had the lowest RSE values of 22%. Among RWH&C techniques the DAL technique conserved more water than MIN, IRWH-2.0m, IRWH-2.4m, and MB treatments during Fp.

4.2.4.2 Water use efficiency and Precipitation use efficiency

Water use efficiency (WUE) and Precipitation use efficiency (PUE) results for maize crop production using various RWH&C practices compared to CON during both growing season are presented in Table 4.7.

WUE refers to the unit increment in yield per unit of water use. WUE in terms of evapotranspiration evaluates the outcome and environmental processes operating over the life of maize to determine both yield and ET. During the first season, there were significant differences in WUE_{ET} between treatments. The MIN treatment had significantly higher WUE_{ET} than that of the IRWH-2.0m and IRWH-2.4m treatments, but not significantly higher than CON, MB and DAL treatments. During the second season, the WUE_{ET} in the CON, MIN, IRWH-2.4m and MB treatments were significantly higher than that of the IRWH-2.0m treatment, but not significantly higher than that of the DAL treatment. The results may be due to high growing period rainfall of 494 mm during the 2009/10 growing season, which is considerably more than what is normally received at Glen. During 2009/10 the IRWH-2m treatment showed significantly lower WUE_{ET} than that of CON, MIN and IRWH-2.4m treatments, due to a higher Es. The mean values showed that MIN was the most efficient in the use of water as a function of evapotranspiration, followed by the CON, DAL, MB and IRWH-2.4m treatments.

Table 4. 7 Water use efficiency and precipitation use efficiency for the various treatments on the Glen/Oakleaf ecotope over the two growing seasons (2008/09 & 2009/10)

Parameter	**Season**	**Treatment**						**LSD $_{(T0.05)}$ ^{a}**
(kg ha^{-1mm-1})		**CON**	**MIN**	**IRWH-2.0m**	**IRWH-2.4m**	**MB**	**DAL**	
$WUE_{(ET)}$	2008/09	18.7ab	19.6.a	11.9c	15.0bc	16.0abc	18.0ab	4.30
	2009/10	14.1a	14.8a	9.9b	12.6ab	15.0a	13.0ab	2.8
	Mean	**16.4**	**17.2**	**10.9**	**13.8**	**15.5**	**15.5**	
$PUE_{(fg)}$	2008/9	-	-	-	-	-	-	
	2009/10	5ab	4bc	3c	6a	4bc	4bc	0.8
$PUE_{(g)}$	2008/09	5.3b	7.5ab	7.3ab	8.1a	5.8ab	6.9ab	2.6
	2009/10	6.3ab	5.9ab	5.4b	7.0a	5.9ab	5.3b	1.3
	Mean	**5.8**	**6.7**	**6.4**	**7.6**	**5.9**	**6.1**	

*Different letters within a row indicate significant differences ($p<0.05$), between treatments.

*ns – not significant.

PUE results based on rainfall over the fallow and growing period (PUE_{fg}) are presented in Table 4.7. According to Joseph (2007), PUE is the simplest way to express the efficiency of converting rainwater into maize biomass. It is also the most comprehensive and important in comparing the ability of RWH&C techniques to conserve water and reduce water losses in dry areas. There were significant differences among treatments during the 2009/10 season. The values for the 2009/10 season ranged between 3 and 6 kg/ $ha^{-1}mm^{-1}$. IRWH-2.4m treatment had a significantly higher PUE_{fg} compared to CON and IRWH-2.0m treatments with 6, 5 and 3 kg/ ha^{-1} mm^{-1}, respectively. The variation in precipitation use efficiency was due to the RSE of the second season (2009/10).

Looking at the precipitation use efficiency based on annual rainfall for the growing season (PUE_g) in Table 4.7, the results of PUE_g were significantly different among treatments during both growing seasons. During the first season, regarded as a dry season, all RWH&C techniques showed a high PUE_g, but only IRWH-2.4m technique had a higher PUE_g than CON. During the wetter second season, the PUE_g of the IRWH-2.4m technique was significantly greater than the IRWH-2.0m technique. In this case, the mean values of PUE_g indicated that the RWH&C techniques were higher than that of the CON treatment. This indicates that during the wet season CON can equally convert water into grain yield just as the RWH&C techniques.

4.2.5 Rainwater productivity

Rainwater productivity (RWP) over the two growing seasons (2008/09 & 2009/10) is presented in Table 4.8. Botha (2006) indicates that the most reliable, appropriate and acceptable way to describe the effectiveness with which rainwater is converted into grain is by using RWP. The results of RWP over the two seasons indicate no significant difference among treatments. However, two of the RWH&C techniques had higher RWP values than that of the CON treatment. This indicates that the MB, IRWH-2.4m and MIN treatments converted rainwater more effectively into grain than the CON treatment.

Table 4. 8 Rainwater productivity (kg $ha^{-1}mm^{-1}$) of two maize-growing seasons (2008/09 & 2009/10) on the Glen/Oakleaf ecotope

Parameter	**Treatment**						**LSD $_{(T0.05)}$ ^{a}**
	CON	**MIN**	**IRWH-2.0m**	**IRWH-2.4m**	**MB**	**DAL**	
$RWP_{(2008/09\ \&\ 2009/10)}$	6.89	7.80	6.72	8.07	9.24	6.71	ns

*Different letters within a row indicate significant differences ($p<0.05$), between treatments.

[a]ns = not significant.

4.3 DISCUSSION

The objective of this chapter was to evaluate soil water balance and rainwater efficiency on various RWH&C techniques against CON for possible increased crop productivity. The maize water requirement depends strongly on the climate conditions. Maize originated in Mexico, mostly grown in warm temperatures and humid to sub-tropical regions. However, in this study, maize was grown under semi-arid conditions on the Glen/Oakleaf ecotope, where water is a limiting factor for crop production. The Glen/Oakleaf ecotope has highly variable rainfall patterns and high Eo creating unfavourable conditions for maize production (Table 4.1). The plant requires about 450-500 mm of water during the growing season depending on plant population. However, during both seasons (2008/09 & 2009/10) studied, the ecotope received 260 and 486 mm of rainfall respectively, during the growing period. Rainfall during both seasons were almost similar during the vegetative period (Vp) with 209 and 262 mm respectively. However, during the reproductive period (R_p), the first season had 51 mm and the second season 224 mm rainfall. In this regard, the first season was considered a dry year and the second season a wetter year.

Soil water content was measured at depths of 150 mm, 450 mm, 750 mm and 1050 mm to compare the effect of the treatment to collect and use water throughout the season. During the V_p of the dry (2008/09) and wetter (2009/10) season, it could be observed from Figure 4.1 (graph a & b) that RWH&C techniques had a higher soil water content compared to CON excluding MIN, contributing to high PAW at planting (Table 4.2). The soil water content on MIN treatments decreased during the dry season (Figure 4.1 a) at 25 DAP. All treatments responded well to the 50 mm rainfall event on day 13 after planting by increasing the soil water content of all treatments above the DUL line (Figure 4.1). At that stage, water use increased rapidly because of the growth of the maize plant. Plants absorbed water and Es occurred, reducing soil water content among treatments; however, IRWH remained above the DUL line.

The reproductive period of maize, i.e. grain filling is very sensitive to water shortage and any water deficiency during the vegetative period is critical, resulting in reduced grain yields. The total rainfall of 51 mm during the R_p of the dry season (2008/09), caused the soil water content to decrease drastically, minimising the yield potential. However, RWH&C techniques continued to have higher soil water content. This might be due to the technique of collecting and storing water in the soil profile. Between days 45 to 110 after planting, 12 rainfall events occurred. However, only 2 rainfall events were above 10 mm.

There was a decrease in soil water content at the beginning of the reproductive period in the 2009/10 growing season, indicating a maximum extraction of water by plants. As usual, semi-arid climate conditions can change over a short period. This was supported by low values of PAW_T. Rainfall recharged the soil profile on day 90 with 51.2 mm, increasing the water content of IRWH-2.0m, IRWH-2.4m and DAL treatments only. The soil water content followed the same trend as PAW_T. Botha *et al*. (2012) reports high water content in IRWH treatments compared to CON over four growing seasons. In addition, Joseph (2007) also indicated high water content on the IRWH treatment containing mulch in the basin and runoff area and an equal water level in the soil profile between IRWH with a bare basin and a runoff area, and CON.

Over the two seasons (2008/09 & 2009/10), RWH&C techniques showed to have higher soil water content in the soil profile. Especially in IRWH treatments, this was due to the collection of runoff water into basins close to the plant. However, CON and MIN treatments showed lower soil water content. The fact that IRWH is designed in such a way that no runoff losses occurs in the cropping area, drainage may be a problem, especially during high rainfall periods. Similar results were found in the study conducted in semi-arid areas by Ibraimo (2011), Botha (2006), Tesfuhuney (2012) and Joseph (2007). These results confirmed the advantage of RWH&C techniques compared to CON in terms of reducing R_{ex}.

Runoff was measured during the 2009/10 season where MIN treatment showed to have high R_{ex} compared to all other treatments. This was due to less soil disturbance through cultivation, meaning that less soil aggregates are disturbed, resulting in a decrease in aeration and the rate of residue mineralisation. Among treatments were R_{ex} occured, DAL recorded no runoff at occurrence of rain less than 12 mm, and CON recorded no runoff at event number 21. According to Munodawafa (2011), runoff is directly dependent on rainfall amount and intensity. The results were similar to those in the study conducted by Botha (2006), Joseph (2007), Mzezewa and Van Rensburg (2011), were the CON treatment was observed to have a higher R_{ex} than that on IRWH treatments. There is limited information (if any) regarding the influence of MB and DAL on R_{ex} $_{and}$ R_{in} and that poses a challenge, as little can be said to support or contradict the current results.

In this study, the maize stubble from the previous season was left on the soil surface and added as natural mulch. For this reason, the ET, Es and Ev results of those obtained by Botha *et al*. (2012), Joseph (2007) and Tesfuhuney (2012) were different from the findings in this study. ET is a complex process, which is influenced by many factors including the climate of the production areas. During the dry 2008/09 season, the RWH&C techniques had higher ET values compared to CON. However, only IRWH-2.4m, MB and DAL were significantly higher than CON. The ET values of the 2009/10 season were higher than that of the 2008/09 season. This could be due to higher rainfall and Eo during the second season.

The ET was separated into two components, namely Es and Ev. The Es is influenced by evaporation demand, soil water content, crop canopy and climate. As indicated in Table 4.1, the Eo of both growing seasons (2008/09 & 2009/10) was higher than the rainfall and a high Es was expected, with more water lost through Es. According to Aydin *et al*. (2013), potential evaporation is related to the evaporation demand of the atmosphere, and actual evaporation from bare soil depends not only on atmospheric conditions, but also on soil properties and wetness. Throughout both growing seasons (2008/09 & 2009/10), the RWH&C techniques had sufficient soil water content that might be transported equally at the rate of Eo. These results were supported by the climatic data results in Table 4.1 where Eo was higher than the rainfall received during the growing period.

Es is one of the most important components of the soil water balance, which can be a major contribution to the reduction of maize growth development and grain yield. Botha *et al*. (2003) indicates that in semi-arid areas most of the rain received from rainfall events that provide small amounts of water will evaporate without contributing towards yield. In row crops like maize, Es is estimated to be as high as 50% of ET under full cultivation (Tesfuhuney, 2012). During the 2008/09 and 2009/10 growing seasons, Es was high on the RWH&C treatment. This was due to the sufficient amount of water content collected and stored in the soil profile of the RWH&C techniques. MB had the highest Es during the 2008/09 season, because the water is exposed to the atmosphere by the basins. Also during the 2009/10 growing season, IRWH-2.0m showed a higher Es. During the 2008/09 season, CON had the lowest Es, due to the full canopy cover of the plant population and because this treatment had no runoff strip between rows. The other reason for low Es in CON is associated with high R_{ex} during both growing seasons, which decreases PAW for evaporation to occur.

In general, RWH&C techniques had high Es due to the fact that the treatments had high soil water content and PAW at planting, tasselling and harvest in RWH&C techniques, which made water available throughout both seasons (2008/09 & 2009/10). In the studies conducted by Joseph (2007), Botha *et al*. (2012) and Tesfuhuney (2012), which investigated the ability of mulch to reduce the Es, it is indicated that treatments with bare runoff strips and basins have higher Es. Botha (2006) illustrates that Es occurs in stages and in the first phase Es occurs rapidly and steadily, depending on the water transported to the surface and climate conditions.

Research results indicate that the RWH&C techniques had the lowest RSE values during the 2009/10 season. This may be probably due to water consumed by plants during the previous cropping season. During the 2009/10 season the RSE of only MIN was higher than CON. Results from this study were different from what Botha (2006) obtained.

The WUE was calculated to indicate yield production in relation to water consumption. According to Sinclair *et al*. (1983), it is difficult to determine crop transpiration accurately under field conditions. WUE can be expressed in terms of ET, which combines the two water loss processes, namely Ev and Es. According to Kranz (2008), about 70% -80% of crop water use result from plant transpiration. During the dry season (2008/09), only 260 mm of rainfall were recorded, but RWH&C techniques have demonstrated its ability to use water more efficiently than CON. The values of $WUE_{(ET)}$ were less than those obtained by Tesfuhuney (2012). The reason might be the high Es that occurred during both growing seasons (2008/09 & 2009/10), which affected WUE $_{(ET)}$ negatively.

Precipitation use efficiency (PUE$_{fg}$) was calculated in terms of the use of rainwater through the fallow and growing period. During the dry season of 2008/09, RWH&C techniques showed higher PUE$_{fg}$ and PUE$_{g}$ values compared to CON. The highest PUEfg and PUEg values were found on IRWH-2.4m technique followed by MIN then IRWH-2.0m, MB and DAL. During the wetter season of 2009/10, the highest PUEfg and PUEg values were obtained on the IRWH-2.4m treatment and the other RWH&C techniques were below CON. These results were different from those obtained by Tesfuhuney (2012) where IRWH with a narrow runoff strip of 1.5m had higher PUE$_{fg}$ values.

These results indicate that during dry seasons, RWH&C techniques were better at converting rainwater into maize grain compared to CON. However, during wetter seasons, RWH&C and CON treatments performed almost similar. According to Botha (2006) he suggested that to investigate conversion of rainwater into grain yield, RWP could be used as an appropriate measure. Therefore, an increase in rainwater productivity could lead to improving reliability of the production. The RWP efficiency of converting rainwater into yield over two years appeared to be lower than those that Botha (2006) and Joseph (2007) obtained. This was possibly due to additional mulch applied to the study of Botha (2006) and Joseph (2007).

4.4 CONCLUSION

The aim of the study was to investigate the ability of RWH&C techniques (MIN, IRWH-2.0m, IRWH-2.4m, DAL & MB) in terms of water balance components, water availability, water use, storage efficiency and water productivity under rain fed conditions. The indicator was PAW at planting, tasselling and harvest, soil water content, ET partitioned into Ev and Es, RSE, PUEfg, PUEg WUE$_{ET}$, WUE$_{Ev}$ and RWP. Based on the results, RWH&C techniques indicated the ability to collect and store more rainwater compared to CON. RWH&C treatments had higher PAW$_{P,}$

PAW_T, PAW_H and soil water content during the vegetative and reproductive period. RWH&C techniques also had higher seasonal ET during both seasons, compared to the CON treatment. However, in this study it was found that RWH&C had higher Es than CON treatment, even though water was collected through the R_{in} process on IRWH-2.0m, and IRWH-2.4 treatments. When evaluating the PUE for the fallow and the growing period during a dry season (2008/09), RWH&C techniques used precipitation more efficiently than CON and during the second season, only IRWH-2.4m used precipitation more productively than other techniques. RWP proved to be the best indicator to be used to get an indication of the effectiveness of a production technique to convert water into food. The values of RWP indicated that RWH&C techniques have the potential to increase yield under dryland conditions.

CHAPTER 5

MAIZE PERFORMANCE AFFECTED BY VARIOUS RAINWATER HARVESTING AND SOIL TILLAGE PRACTICES UNDER DRYLAND CONDITIONS

5.1 INTRODUCTION

South Africa is classified as a semi-arid country, with 7% of the country receiving less than 800 mm of rain per annum, 60% receiving less than 500 mm and 23% receiving less than 200 mm (De Villiers *et al*., 2003). Rainfall ranges from less than 125 mm on the west coast to more than 800 mm on the east coast (Schulze, 2006). Rainfall is therefore insufficient to meet crop water requirements in many areas. Insufficient crop water availability combined with low potential soils and climate variability, results in the low crop yields obtained in rainfed agriculture in many areas of the country, particularly under low input agricultural conditions (Hensley *et al*., 2006).

In the semi-arid parts of South Africa low rainfall is aggravated by high evaporative demands of the atmosphere. Schulze (2006) showed an increase in annual rainfall from less than 15 mm along the west coast to more than 800 mm on the eastern seaboard of South Africa. The Free State Province located in central South Africa, is a fair representative of the country, with an annual rainfall that varies from 200 mm to 800 mm (Schulze, 2006). The Provinces' seasonal rainfall differs a lot, occurring from November to March with a clear north-eastward gradient, and with the lowest values of less than 200 mm (Moeletsi & Walker, 2011). Often rainfall is highly erratic, and most of the rain falls in intensive convective storms with spatial and temporal rainfall variability. As a result, the Province has a high risk of drought and annual dry spells. These dry conditions have a serious effect on crop yield, particularly if it occurs during water sensitive growth stages, for example during flowering and tasseling (Tesfuhuney, 2012).

Most farmers in South Africa grow maize as a staple food crop, relying on rainfall for production yield (Gouse et al., 2006). Maize productivity is highly dependent on water availability (Elda *et al*., 2003), particularly during the reproductive or flowering stage (Tesfuhuney, 2012). Payero et al. (2006) report a positive linear relationship between plant water use and yield. The total amount of water required by a crop to perform its physiological functions and achieve maximum yields is defined as the crop water requirement (Aslam *et al*., 2012). The crop water requirement for maize is reported as ranging from 500 mm to 800 mm during the growing period, depending on temperature, humidity, sunshine, and wind speed conditions (FAO, 1991).

Evapotranspiration is the sum of evaporation from the soil surface and transpiration from the crop. The water availability to the plant is stored in the soil and must be absorbed by the plant roots (Kramer, 1995). Therefore, any practice that can increase the amount of water available to the crop, will improve crop production, and should be followed. This is particularly true in arid and semi-arid regions, where rainfall is the limiting factor for crop production. The only way of doing this is to increase the amount of water that is stored in the soil profile.

The objective of this study was to compare the effect of various soil tillage and rainfall harvesting techniques on the performance of maize on the Glen/Oakleaf ecotope.

5.2 RESULTS

5.2.1 Growth and development

5.2.1.1 Plant height and stem diameter

Plants grown on the CON tillage plots were significantly taller than those of the IRWH-2.0m plots. These plants being significantly shorter during the vegetative (30 & 45 DAP), the reproductive phase (66 & 90 DAP) and growth phase. Plant height from the MIN, IRWH-2.4m, and MB and DAL treatments did not differ significantly through the vegetative and reproductive periods (Table 5.1).

Table 5. 1 Plant height and stem diameter of maize plants during the 2008/09 growing season

Parameter	DAP[b]	Treatment						LSD $_{(T0.05)}$[a]
		CON	**MIN**	**IRWH-2.0m**	**IRWH-2.4m**	**MB**	**DAL**	
Plant height (cm)	30	117.9a	109.4bc	103.4c	110.3bc	106.6bc	109.0bc	6.44
	45	140.5a	132.6ab	120.4c	133.9ab	134.8ab	126.98bc	8.51
	66	200.6a	188.2ab	178.2b	192.7ab	192.7ab	198.8ab	21.45
	90	210.6a	195.1ab	184.1b	202.7a	202.7a	208.8a	17.69
	Mean	**167.4**	**156.3**	**146.5**	**159.9**	**159.2**	**160.9**	
Stem diameter (cm)	30	3.7a	3.5a	3.0b	3.6a	3.6a	3.5a	0.27
	45	3.8ab	3.7ab	3.4c	3.9a	3.8ab	3.7b	0.18
	66	4.0a	4.0a	3.5b	3.9a	3.9a	3.8a	0.23
	90	4.1a	4.0a	3.6b	4.0a	4.0a	3.9a	0.25
	Mean	**3.9**	**3.8**	**3.4**	**3.9**	**3.9**	**3.7**	

*Different letters within a row indicate significant differences (p=0.05), between treatments.

[b] DAP = Days after planting; 30 – 45 = Vegetative period; 66 - 90 = Reproductive period.

Stem diameter did not present a consistent pattern between treatments and varied throughout the growing season. However, stem diameter of plants from the IRWH-2.0m treatment was constantly lower than that of other treatments and it was significantly lower than that of all treatments at 90 DAP (Table 5.1)

5.2.1.2 Leaf area index (LAI)

This parameter also varied throughout the season with no consistent pattern among treatments emerging. At 30 DAP plants from IRWH-2.0m treatment had significantly greater LAI than those from the DAL treatment (Table 5.2). Fifteen days later plants from the MIN and DAL treatments had the greatest LAI, significantly greater than that of plants on CON plots. No significant differences in LAI were found at 66 DAP, but 90 DAP the LAI of plants in the CON and MIN treatments was significantly larger than that of plants in the IRWH-2.0m treatment.

Table 5. 2 Leaf area index (LAI) of maize plants during the 2008/09 season

DAP[b]	**Treatment**						**LSD $_{(T0.05)}$**[a]
	CON	**MIN**	**IRWH-2.0m**	**IRWH-2.4m**	**MB**	**DAL**	
30	0.095ab	0.098ab	0.102a	0.095ab	0.097ab	0.092b	0.01
45	0.188b	0.238a	0.230ab	0.207ab	0.234ab	0.246a	0.05
66	0.294	0.273	0.276	0.285	0.296	0.286	Ns
90	0.320a	0.310a	0.265b	0.286ab	0.301ab	0.289ab	0.04
Mean	**0.22**	**0.23**	**0.22**	**0.22**	**0.23**	**0.283**	

*Different letter within a row indicate significant differences (p=0.05), between treatments.

[a] ns = not significant.

[b] DAP = Days after planting; 30 – 45 = Vegetative period; 66 – 90 = Reproductive period.

5.2.2 Above ground biomass production

Total above ground biomass for the two growing season (2008/09 and 2009/10) at 30, 45, 66, and 90 days after planting is shown in Figure 5.1. Generally, RWH&C techniques are expected to enhance biomass production as Botha (2006) reported that there are techniques to stop runoff from the field completely, induce in-field runoff, influence plant water availability at planting, and reduce Es.

5.2.2.1 Vegetative growth stage (30 & 45 DAP)

There was a variation of results in maize biomass at the vegetative growing stage during both seasons (Figure 5.1). The results in the 2008/09 season indicated that plants on the IRWH-2.4m plots had significantly greater biomass than those on MIN, MB and DAL at 30 DAP (graph a). During the 2009/10 season data indicated that the biomass of plants from IRWH-2.0m, IRWH-2.4m and MB treatments were significantly greater than that on CON (graph b). At 45 DAP during 2008/09 plants at MIN, IRWH-2.4m and CON were significantly higher than that on IRWH-2.4m, MB and DAL (graph c). However, during 2009/10 at 45 DAP plants CON treatment was significantly higher than that on IRWH-2.4m and MB treatments (graph d).

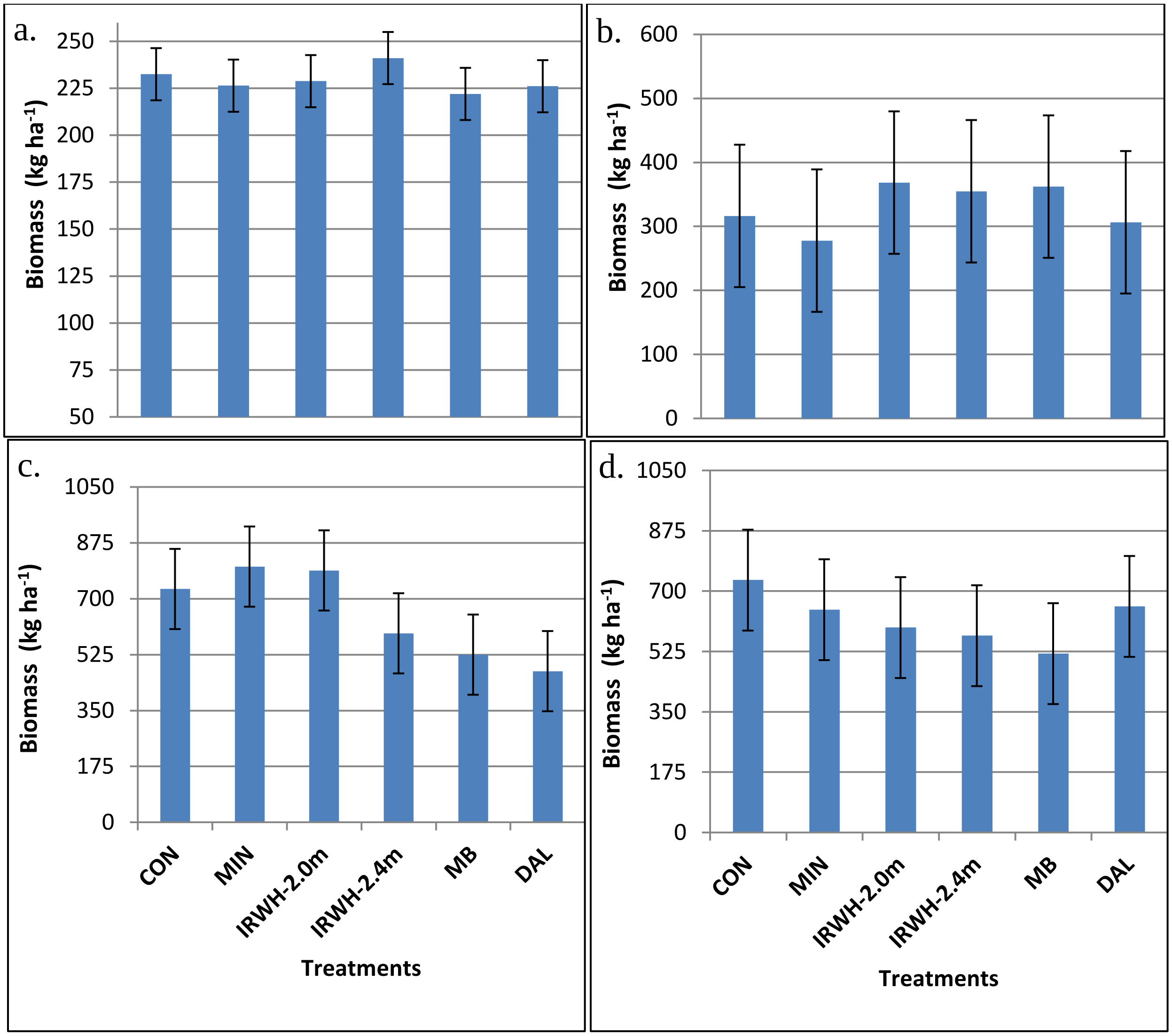

Figure 5.1 Maize biomass on various treatments during the vegetative growth stage 2008/09 (a & c) and 2009/10 (b & d).

*Bars indicate the LSD$_{(T0.05)}$ value.

*a & b = 30 DAP.

*c & d = 45 DAP

5.2.2.2 Reproductive growth stage (66 & 90 DAP)

During the 2008/09 season plants from the DAL treatment produced significantly less biomass than that on CON, MIN, IRWH-2.0m, IRWH-2.4m and MB treatments Figure 5.2a. In the 2009/10 season, plants from the CON treatment had greater biomass than those on DAL Figure 5.2b. During the 2008/09 season at 90 DAP plants on IRWH-2.4m, MIN and CON treatments were significantly higher than DAL Figure 5.2c. However, by 2009/10 at 90 DAP no significant difference in biomass between treatments were found Figure 5.2d.

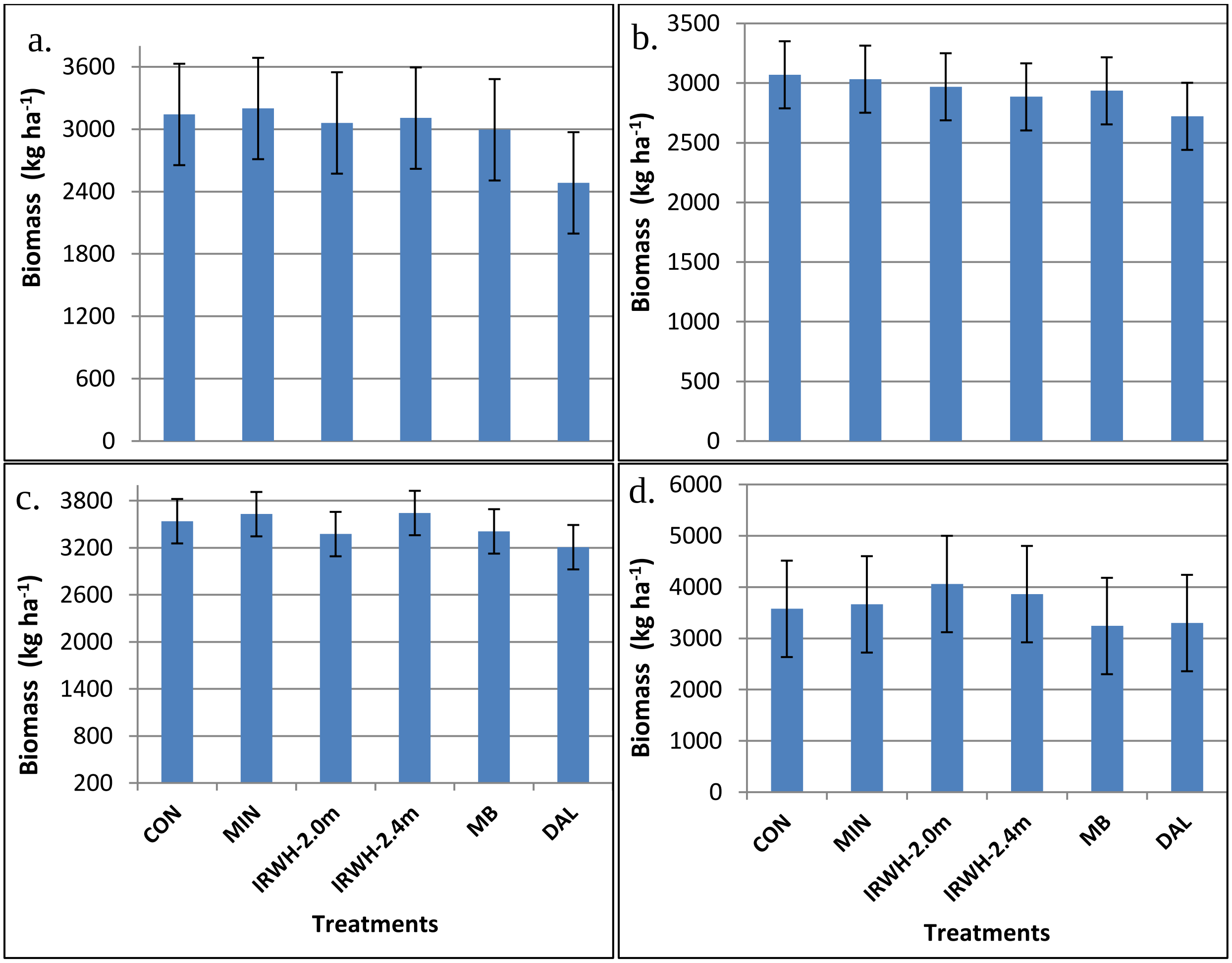

Figure 5.2 Maize biomass on various treatments at reproductive growth stage 2008/09 (a & c) and 2009/10 (b & d).

*Bars indicate the LSD$_{(T0.05)}$ value.

*a & b = 66 DAP.

*c & d = 90 DAP.

5.2.3 Yield response

The results of grain yield for the two growing seasons are presented in Table 5.3. Grain yield showed a significant difference between the two growing seasons probably due to the variation in rainfall (Table 5.3). Maize plants cultivated using the MIN technique obtained significantly higher grain yield than that from the CON treatment during the 2008/09 season. During the 2009/10 season the IRWH-2.4m plot had a significantly higher grain yield than that on IRWH-2.0m and DAL plots. The data did not show consistent yield results due to the difference in plant spacing per treatment (Table 3.2). The data was then calculated into grams per plant to try and obtain a clear conclusion. Calculated yield per plant did not follow similar trends as yield/ ha^{-1}, during the 2008/09 season plants on IRWH-2.4m had significant higher yields than those on CON. Plants on IRWH-2.4m had significantly higher yields than those on the DAL plot in the 2009/10 season. The results indicated that RWH&C techniques are more effective in dry conditions.

During the first growing season, biomass at harvest showed no significant difference between treatments in Table 5.4. However, during the second season plants on IRWH-2.4m had significantly higher biomass than those on DAL. During 2008/09 plants on the MB plot showed significantly higher biomass than plants on the CON, MIN, IRWH-2.0m and DAL plots. Plants on IRWH-2.4m during 2009/10 showed significantly higher biomass than those on DAL plots.

There is a small variation in HI data ranging from 0.32 to 0.53 during both seasons. HI values are lower during the dry season (2008/09) compared to the wet season (2009/10). During the dry season HI indicated that RWH&C techniques have the potential to increase maize yields in areas with insufficient rainfall in Table 5.5. During the wet growing season CON showed the highest HI due to sufficient rainfall received.

Table 5. 3 Maize grain yields for different treatments in 2008/09 & 2009/10

Parameter	Season	Treatment						LSD $_{(T0.05)}$ ^{a}
		CON	MIN	IRWH-2.0m	IRWH-2.4m	MB	DAL	
Grain yield (kg ha^{-1})	2008/09	1770.8b	2677.3a	2346.3ab	2633.5ab	1956.5ab	2279ab	871.7
	2009/10	3368.3ab	3139.3abc	2669.3c	3385.8a	3056.0abc	2725.8bc	646.1
	Mean	**2569.5**	**2908.3**	**2507.8**	**3009.7**	**2506.3**	**2506**	
Grain yield (g $plant^{-1}$)	2008/09	99.56b	149.7ab	148.8ab	163.7a	136.3ab	121.7ab	56.95
	2009/10	225.28ab	220.80ab	179.33ab	236.35a	202.58ab	175.58b	60.16
	Mean	**162.42**	**185.25**	**164.07**	**200.03**	**169.44**	**148.64**	

*Different letter within a row indicate significant differences (p=0.05), between treatments.

Table 5. 4 Maize biomass at harvest for different treatments in 2008/09 & 2009/10 seasons

Parameter	Season	Treatment						LSD $_{(T0.05)}$ [a]
		CON	**MIN**	**IRWH-2.0m**	**IRWH-2.4m**	**MB**	**DAL**	
Biomass harvest (kg ha^{-1})	2008/09	5700.5	6112.0	4691.0	5666.0	5073.8	5734.0	ns
	2009/10	6412.3ab	6471.5ab	6312.8ab	7350.8a	7083.5ab	5800.5b	1412.1
	Mean	**6056.4**	**6291.8**	**5501.9**	**6508.4**	**6078.7**	**6442**	
Biomass harvest (g plant^{-1})	2008/09	319.90b	303.70b	312.86b	338.92ab	420.46a	243.80b	93.01
	2009/10	429.85ab	460.43ab	424.63ab	511.40a	467.95ab	372.90b	131.59
	Mean	**374.88**	**382.07**	**368.75**	**425.16**	**444.21**	**308.35**	

*Different letter within a row indicate significant differences (p=0.05), between treatments.

[a] ns = not significant.

Table 5. 5 Maize harvest index for different treatments in 2008/09 & 2009/10 seasons

Parameter	DAP	Treatment						LSD $_{(T0.05)}$ ^{a}
		CON	MIN	IRWH-2.0m	IRWH-2.4m	MB	DAL	
Harvest index	2008/09	0.32c	0.44ab	0.50a	0.45ab	0.39bc	0.40bc	0.09
(HI)	2009/10	0.53a	0.48b	0.42d	0.46bc	0.43cd	0.46bc	0.04
	Mean	**0.43**	**0.43**	**0.45**	**0.47**	**0.42**	**0.44**	

*Different letter within a row indicate significant differences (p=0.05), between treatments.

5.2.3.1 Calculated biomass at various maize growth stages per plant

5.2.3.1.1 Biomass at different growth stages (30, 45, 66 & 90 DAP)

RWH&C techniques were further investigated by calculating maize biomass at different stages during the growing season in Figure 5.3. At the early vegetative period (30 DAP) during the 2008/09 season, plant biomass on MB treatments were significantly higher than that on MIN and DAL. The plant biomass for the 2008/09 season at 45 DAP (graph b) indicated on IRWH-2.0m was significantly greater than MB, IRWH-2.4m and DAL. However, no significant differences were found between treatments at 30 or 45 DAP analysis during 2009/10. At 30 DAP of the 2009/10 season, plants on the IRWH-2.0m treatment had greater biomass compared to other treatments and at 45 DAP plants on IRWH-2.4m treatments had better biomass compared to other treatments.

During the 2008/09 season at the two reproductive period stages (66 & 90 DAP), plants on MB treatments were significantly higher than those on the DAL plots. However, during the 2009/10 season, plants on the IRWH-2.0m plots were significantly higher than those on DAL treatments in both 66 and at 90 DAP, no significant difference of plant biomass where found between other treatments.

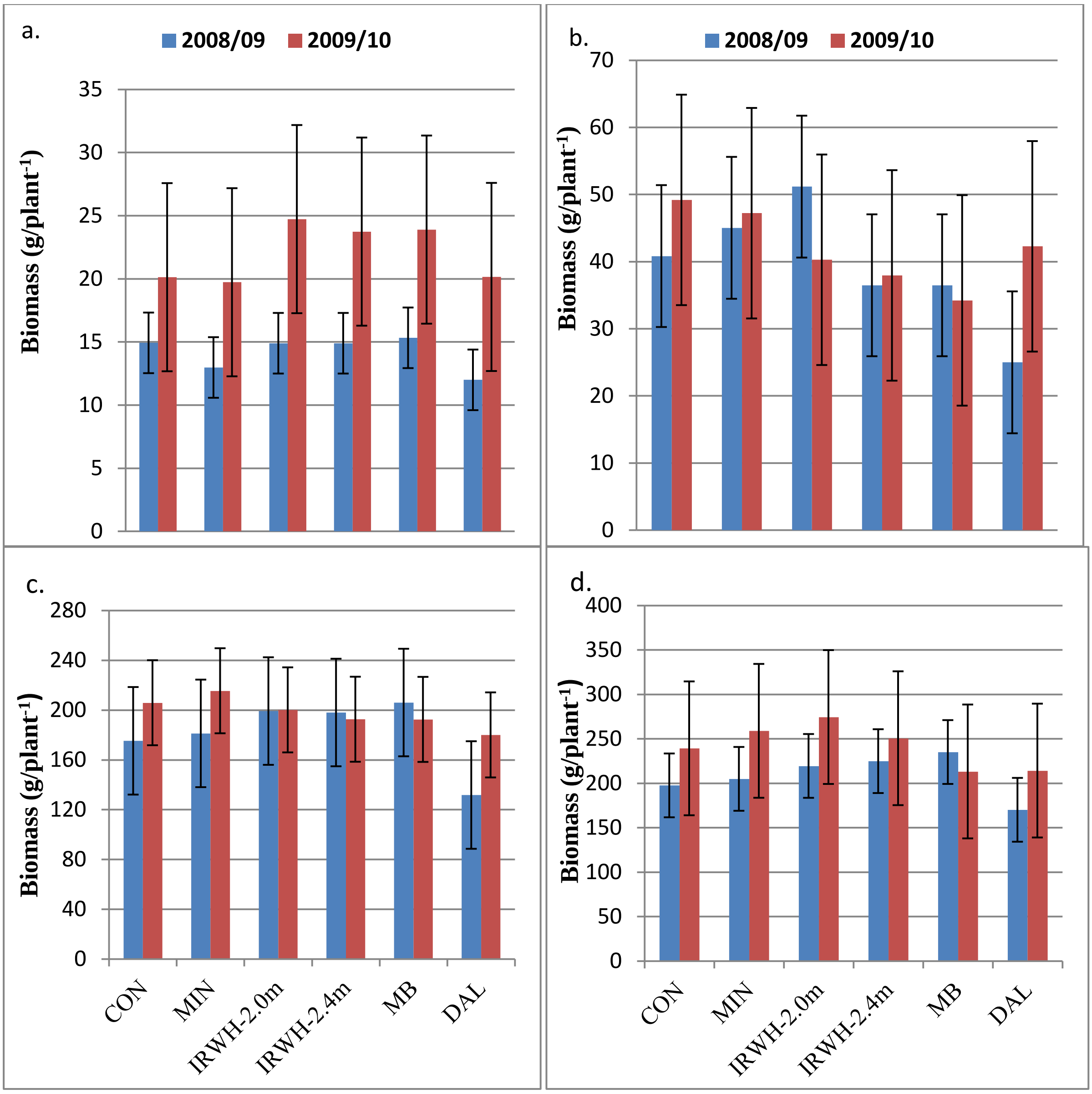

Figure 5.3 Calculated biomass of various treatments per plant for 2008/09 & 2009/10 growing season on different growing stage on Glen Oakleaf ecotope.

*Bars indicate the LSD$_{(T0.05)}$ value.

*a = 30 DAP

*b = 45 DAP

*c = 66 DAP

*d =90 DAP

5.2.4 Grain yield

The results for grain yield, in kg/ ha^{-1} and g/ $plant^{-1}$ for both seasons are given in Figure 5.4. RWH&C techniques (MIN, IRWH-2.0, IRWH-2.4, MB, & DAL) increased yield (kg/ ha^{-1}) by 34%, 24%, 32%, 10% and 22% respectively, compared to CON treatment during the 2008/09 season. During this growing season (2008/09) grain yield in g/ $plant^{-1}$ was higher in IRWH-2.0m, IRWH-2.4m and MB techniques, compared to grain yield kg/ ha^{-1}. On other treatments, the pattern of grain yield (kg/ ha^{-1}) was higher than grain yield (g /$plant^{-1}$).

During the 2009/10 growing season CON treatment produced better yields (kg/ ha^{-1} and g/ $plant^{-1}$) than all other treatments, excluding IRWH-2.4m where these yields increased by 1% and 5% respectively over that of the CON treatment. All RWH&C techniques and CON treatments indicated higher yield per gram per plant. The reproductive period is a critical stage, as water stress at flowering can drastically reduce both kernel set and grain yield (Zinselmeier *et al.*, 1999). This was confirmed by the results obtained from this trail during both growing seasons. During the dry season (2008/09) RWH&C techniques showed the ability to harvest water to promote grain yield. However, during the wet season (2009/10) CON treatment produced the highest yield, due to sufficient rainfall being received during the critical period. Rhoads & Bennett (1990) also indicated that a reduced soil water level resulted in low daily ET’s, especially during the grain filling stage, hence reducing the rate of photosynthetic supply to the seeds, which is critical for optimum seed filling.

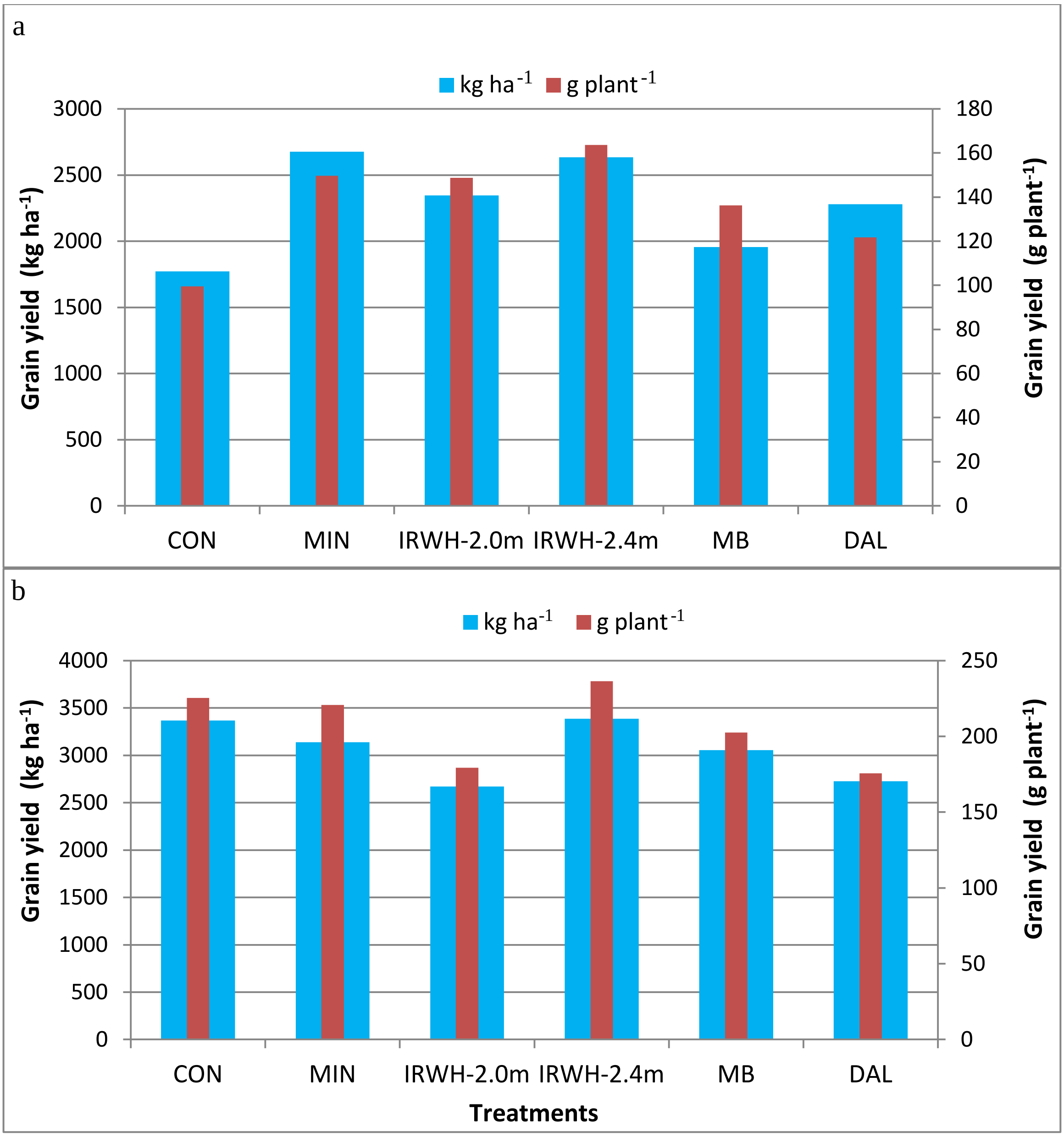

Figure 5.4 Summary of maize grains yield in both growing seasons for different treatments (top 2008/10 season, bottom 2009/10 season).

5.2.5 The relationship between growth and development of maize plants

The graphs below (5.5 and 5.6) indicate the correlation equations for biomass and LAI, and biomass and plant height. The correlation was applied to measure the degree of linear growth between biomass and LAI at different maize growth stages during the 2008/09 season (Figure 5.5). The correlation between biomass and LAI had a strong positive correlation between the two parameters in all treatments. MIN treatment had the highest positive correlation between biomass and LAI followed by CON, IRWH-2.4m, IRWH-2.0m, MB and DAL with R^2 = 0.8755, 0.8553, 0.8359, 0.7541 and 0.7216 respectively. The regression line indicated increasing LAI, and there was a corresponding increase in biomass.

The correlation pattern between biomass and plant height was a significant strong positive, MIN treatment had the lowest correlation, compared to the rest of the treatments with R^2 = 0.6121 (Figure 5.6). IRWH-2.4m, MB and DAL had R^2 values close to 10, indicating that maize biomass and plant height increased simultaneously. The correlation coefficient between biomass and LAI and Plant height indicated a higher and positive regression, due to this reason during 2009/10 plant height, Stem diameter and LAI measurements were discontinued.

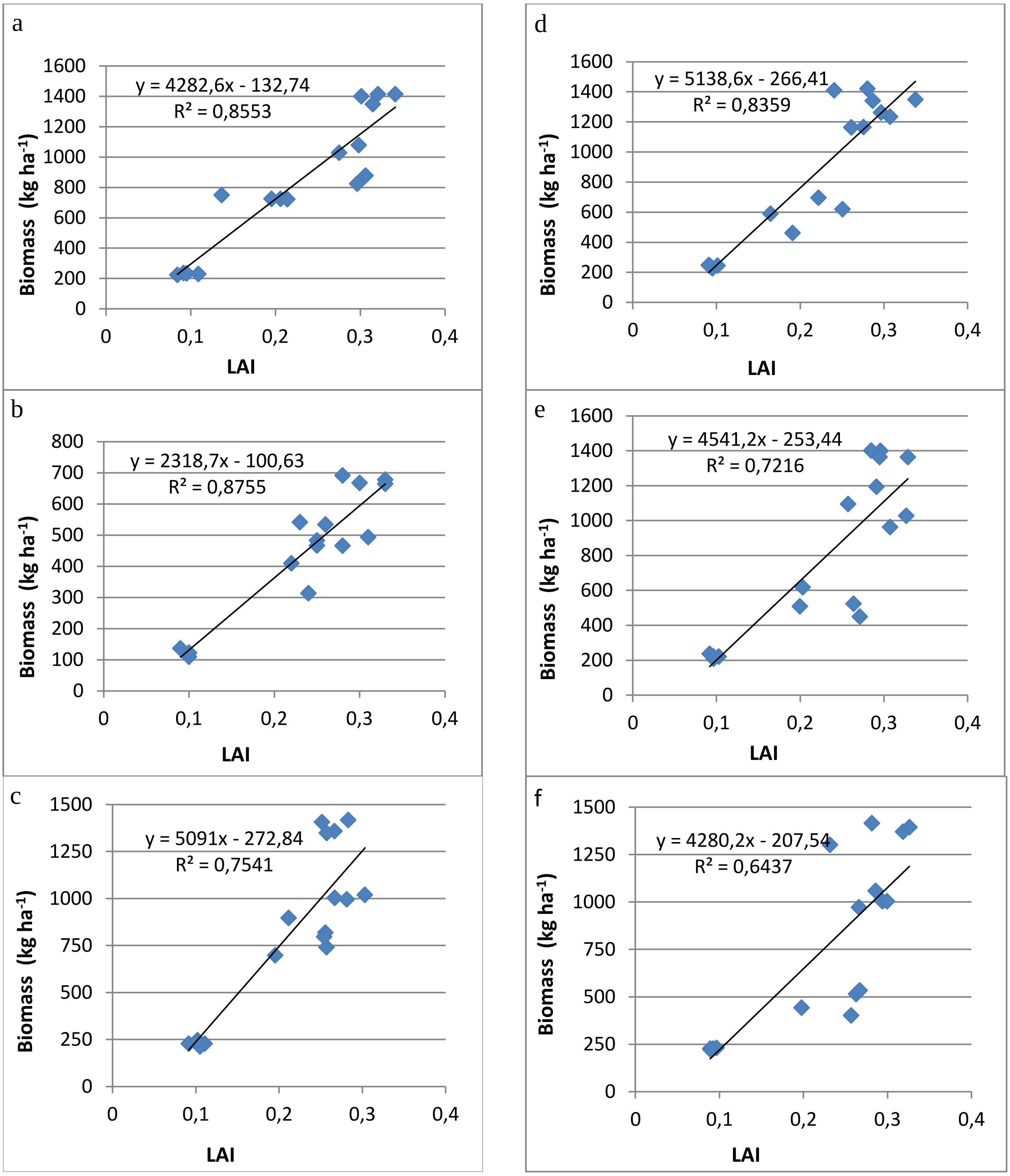

Figure 5.5 Relationships between plant biomass and LAI for the 2008/09 growing seasons on Glen/Oakleaf ecotope.

a= CON, b= MIN, c= IRWH-2.0m, d=IRWH-2.4m, e= MB, f= DAL

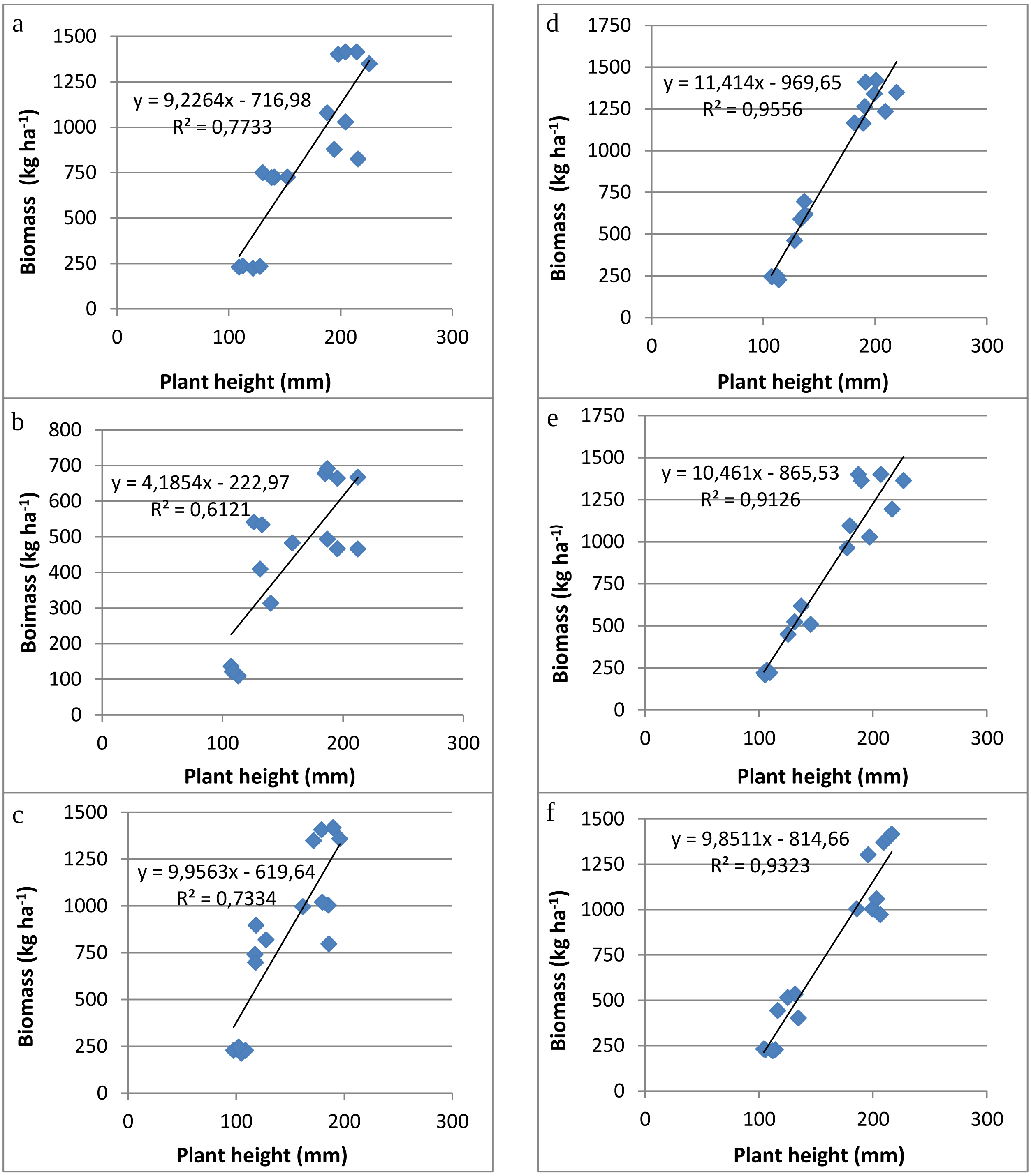

Figure 5.6 Relationships between plant biomass and plant height for 2008/09 growing seasons on Glen/Oakleaf ecotope.

a= CON, b= MIN, c= IRWH-2.0m, d=IRWH-2.4m, e= MB, f= DAL

5.3 DISCUSSION

Many studies have been conducted with IRWH, concentrating only on yield and soil parameters and not plant growth parameters. The results for RWH&C techniques showed the overall positive effect of managing and conserving water to improve maize production in a semi-arid area. The results however, were affected differently by runoff strip width in IRWH, the basins, row spacing and climatic variation.

Du Plessis (2003) reported that maize requires approximately 450 - 600 mm of water during the growing season. In this study, during the first season, only 260 mm of rainfall was received, far below the reported water requirement. This was 1% below the LT average of the growing period (Gp) for this area. During the second season (2009/10), 486 mm of rainfall at Gp was received, which is 85% higher than the LT average. This difference could explain the low yields obtained during the 2008/09 season compared to those of the 2009/10 season. The rainfall received during the vegetative growth period (VP) during both seasons was greater than the LT average with 15% and 32% respectively. However, during the first season, the rainfall received during the reproduction period (Rp) was 41% lower than the LT, and 160% higher during the second season.

The plant height, stem diameter and LAI were measured only during the 2008/09 growing season, at four developmental stages 30, 45, 66, & 90 DAP, to show maize growth performance over the season. During Vp (30 and 45 DAP) plants from the CON treatment were taller than those from the RWH&C techniques treatments. The results observed indicated that with rainfall greater than LT there was less variation between plants from the CON and RWH&C treatments. This was due to the rainfall distribution during Vp and less competition for soil moisture. During Rp rainfall was scarce with a total of 55 mm. Plants from IRWH-2.0m at 66 and 90 DAP were smaller than those in all other treatments. The plant height results are contradictory to those found by Ibraimo (2011) at Hatfield Experimental farm in Pretoria, where IRWH with a 2.0m runoff strip had taller plants than conventional tillage and tied ridges throughout the 2007/08 growing season. This may possibly be due to soil, rainfall, cultivar and plant population differences with the total rainfall of 810 mm.

During the Vp at 30 and 45 DAP plants from the CON, MIN, IRWH-2.4m, MB and DAL treatments had a greater plant height and stem diameter than those on IRWH-2.0m. Although at 45 DAP plants on the IRWH-2.4m treatment were thicker than those of other treatments (CON, MIN, IRWH-2.0m, MB and DAL). Plants on the IRWH-2.0m treatment remained small and thin. This was due to water loss through Es and the wide row spacing between plants. During Rp (66 and 90 DAP) plants from the IRWH-2.0m continued to be thinner than those of the other treatments. The results were contradictory with those of Karrar (2012) who found that plants from rainwater harvesting techniques were thicker than those on CON tillage. This can be explained by the higher rainfall of 511.4 mm and 543.4 mm, cultivar, plant population and differences and variations in climatic factors. The plant height and stem diameter of plants from IRWH-2.0m treatments had shorter and thinner plants throughout the season, probably due to the fact that plants on IRWH-2.0m treatments had wide row spacing, which reduced competition among plants for water, nutrients and light. This indicated great light interception to plants improving occurrence of photosynthesis. The results agrees with those of Riahinia and Sayed (2008) who found that light interception in maize is improved with wide row spacing between plants.

The LAI determine total light interception and this is affected by physiological processes and environmental conditions. The highest value of LAI during Vp (30 and 45 DAP) was obtained from plants on the IRWH-2.0m technique. During the Rp only 51 mm of rain fell and this was poorly distributed throughout the period. At 66 DAP plants on MB treatment indicated a larger LAI than those from other treatments. However, at 90 DAP plants on CON treatment had larger LAI than those on other treatments and plants on the IRWH-2.0m treatment had the lowest LAI. The results were, however, different from the findings obtained by Ibraimo, (2011) in the study conducted at Hatfield experimental farm, University of Pretoria, on sandy clay loam, where the results indicated high LAI in IRWH techniques as compared to tied ridges and CON throughout the growing season.

There was a good distribution of rainfall during the 2008/09 season, adding value to plant water availability. At 30 DAP during the first season, plants from the IRWH-2.4m were heavier than those on the other treatments. This is due to the long runoff strip of 2.4 m, which managed to collect more water into the basin. This would have resulted in plants having more water available, and so being able to grow better than those in the other treatments. At 45 DAP of the first season, plants on the IRWH-2.4m technique weighed in second heavier, after

MIN treatments. During Vp of the second season, (30 DAP) plants from the MIN treatment were lighter than those from other treatments. This was due to a decrease in soil disturbance in the MIN treatment and narrow row spacing, resulting in less movement of water in the soil, suppressing maize growth. The results agreed with those obtained by Hamidi *et al*. (2010), where there was biomass decrease due to an increase in number of plants per unit area. However at 45 DAP plants from the MIN treatment were heavier than those from IRWH-2.0m, IRWH-2.4 and MB treatments. The second season Vp received good rainfall distribution, where soil water content increased slightly, indicating water availability to plants.

There was a steady increase in plant biomass during the Rp of 2008/09 at 66 DAP on RWH&C plots. This was due to 14 mm less rainfall. Plants in the MIN tillage were heavier than those on CON, IRWH-2.0m, IRWH-2.4m, MB and DAL treatments. If there is less soil disturbance through cultivation, it means that less soil aggregates are disturbed and a decrease in aeration might possibly contribute to the difference in plant mass. The plants from the IRWH-2.4m treatment had a higher biomass than those on other treatments. However, plants from MIN treatment had the second best weight. During the wet season of (2009/10) plants on CON treatment were heavier than those on RWH&C treatment at 66 DAP. This is due to a good rainfall distribution of 126 mm that was received, increasing availability of water to plants during 66 DAP. However, during 90 DAP, plants from IRWH-2.0m were heavier, compared to those of other treatments. Plants in the CON treatment had a higher biomass than those in MB and DAL treatments and less than those from other treatments (MIN, IRWH-2.0m and IRWH-2.4m). This is due to a decrease in rainfall of 93 mm.

Kernel formation in maize production is inhibited by water stress due to insufficient plant turgor and lack of assimilation. This was shown by the low grain yield values obtained during the dry season of (2008/09) compared to the wetter season of (2009/10). In the first season, the average rainfall of 55 mm in Rp generated higher yield from the RWH&C technique plots compared to the CON tillage plot. The results agreed with those obtained by Reshid *et al.* (1987). High rainfall at the beginning of the growing period, and its absence at later stages of crop growth and development, significantly reduces the yield. The results were supported by low PAW at planting, tasseling and harvest in CON treatment. There was an increase in grain yield during the second season, due to a good distribution of rainfall throughout the season. The results showed increased yield on CON, MIN, IRWH-2.0m, IRWH-2.4m, MB and DAL with 47%, 15%, 12%, 1%, 36%, and 16% respectively. Only plants in the IRWH-2.4m treatments produced better grain than those from other treatments. However, plants from the CON treatment produced better grain than those in MIN, IRWH-2.0m, MB and DAL treatments, excluding the IRWH-2.4m treatment. The results obtained during the 2008/09 season in this study (Glen/Oakleaf ecotope) were not similar to the one obtained where IRWH was tested on clay and duplex soils in the semi-arid area of the Glen/Duplex ecotope. Maize grain yield was reported to have increased between 25% and 50% as compared to CON with the average rainfall of 538 mm from the 99/00 to the 01/02 season (Botha *et al*., 2003; Hensley *et al*., 2000). The results from the 2009/10 season were different from what Botha *et al*., (2003) and Hensley *et al*., (2000) had reported from Glen/ Bonheim and Glen/Swartland ecotopes. Furthermore, in the study conducted by Joseph (2007) on the Fort Hare/Oakleaf ecotope increases in the grain yields of IRHW treatments of 26% and 36% compared to CON treatment with the average rainfall of 201 mm were seen. It is difficult to compare these results with those reported by other researchers, due to a variation in rainfall, ecotope and population. However, with soil and climate not being similar, it was surprising that results on IRWH-2.0m treatment produced lower grain yield during the second season. This may be due to wide inter row spacing between the plants. The possible reason for reduction in grain yield results of IRWH-2.0m may be due to low rainwater productivity and high Es throughout the season. To verify the grain yield results, yield was calculated on a plant basis, and the results followed similar trends to grain yield kg/ ha^{-1}, where yield on IRWH-2.4m techniques tend to have higher grain yield than that CON treatment during both seasons.

During the first season biomass at harvest showed the same trend as mean grain yield where plants on IRWH-2.4m treatment had better biomass than the other treatments. Although the plants from the IRWH-2.4m treatment were short and thin, they produced better grain yield than those on CON, MIN, IRWH-2.0m, MB and DAL. Plants on IRWH-2.0m were shown to have used the available water effectively as the plants weighed less than those of other treatments. A study conducted at Paradys Experimental Farm of the University of the Free State investigated IRWH under three water regimes (dryland, supplemental and full irrigation) and evaluated on three runoff strips (1m, 2m and 3 m) (Mavimbela & Van Rensburg, 2012). The results obtained on the 2 m runoff strip showed a 19% higher biomass than the 1 m runoff strip with 18% increase. Furthermore, biomass decreased with an increase in the runoff strip length in the dryland regime with an average rainfall of 282 mm.

These results suggested that an IRWH-2.4m runoff strip might be the best option. In the study conducted by Xiaolong *et al*. (2008), the effect of RWH testing furrow and ridge system were evaluated and resulted in an increase in maize biomass of 83% in the 230 mm of rainfall and 11% at 400 mm. This indicates that RWH&C techniques are more effective in a drier area than in a high rainfall area. The study conducted by Hensley *et al*. (2000) and Joseph (2007) reported no significant difference in biomass between IRWH techniques and CON treatments in both Glen Bonheim and Fort hare ecotope. The calculated biomass per plant had different trends, where plants from the MB treatment had a biomass higher than plants on CON, MIN and DAL treatments during the 2008/09 season. During the 2009/10 season, plants from IRWH-2.4m had a higher biomass than those on the DAL treatment. These results are not clear as to which treatment performed best in the overall conditions.

The harvest index of the treatments over the two seasons varied between 0.32 and 0.53. During the drier 2008/09 season however, the HI on CON treatment was 0.32 lower than those in the RWH&C treatments, this was in line with the low seasonal rainfall. During the wetter 2009/10 season however, plants on CON treatment had a higher HI value compared to those on the RWH&C technique plot and this was in line with higher seasonal rainfall, compared to the first season. The results were supported by those obtained by Botha (2006) where CON tillage had a higher HI during the 1999/2001 season where a 479 mm rainfall was received.

Variation in rainfall affected total biomass and yield, which did not reflect on the growth performance between treatments. Data was calculated on an individual plant basis. After 30 days from planting, biomass results showed that plants on Vp MIN, MB, IRWH-2.0m and IRWH-2.4m treatments had higher biomass than those on CON treatment during the first season. This is due to a high soil water content at planting on MIN, MB, IRWH-2.0m and IRWH-2.4m techniques than on CON tillage (section 4.1.3), which contributed to good plant growth. However, at this stage there was an increase in soil water content of all treatments above drainage upper limit, indicating high PWA. This resulted in a decrease in maize growth morphology, causing a reduction in root activity and respiration. Fifteen days later, only plants in IRWH-2.0m and MIN treatments showed higher biomass than those in the CON treatment. The reason might be due to the occurrence of six good distributions of rainfall of more than 10 mm and there was a steady decrease in soil water content among the treatments. This caused CON treatment to have sufficient water to sustain maize growth development.

Plants in the MB, IRWH-2.0m, DAL, and IRWH-2.4m treatments had a higher biomass than those in the CON treatment at 30 DAP during the second season. The results followed similar trends to soil water content and they were supported by plant available water at planting (Table 4.2). However, plant biomass in the CON treatments was greater than those on RWH&C techniques treatments at 45 DAP. This was due to the good distribution of rainfall of about 76 mm and four of those rain events were above 10 mm, contributing to plant available water.

At the onset of the Rp in the first season (66 DAP) plants on the MIN, MB, IRWH-2.0m and IRWH-2.4m treatments had a higher biomass than those on CON treatment. At 90 DAP, the results followed the same trend, plants in the MIN, MB, IRWH-2.0m and IRWH-2.4m treatments having a higher biomass than those in the CON treatment. This was due to a decrease in soil water content caused by low rainfall of about 14 mm and 11 mm at 66 and 90 DAP, respectively. This was further supported by high PAW at tasseling in RWH&C techniques. At Rp of 66 DAP during the second season plants from the MIN treatment had a higher biomass than those on the CON treatment. This was due to rainfall of about 118 mm, five of the rainfall events were above 10 mm contributing positively to PAW in CON treatments. However, at 90 DAP plants in the MIN, IRWH-2.0m and IRWH-2.4m treatments had a heavier biomass than those in the CON treatment. The reason might be poor distribution of rainfall of 99 mm, only three rainfall events were above 10 mm. This resulted in a decrease in soil water content between all treatments. At this stage plants from MIN, IRWH-2.0m and IRWH-2.4m were using water stored in the soil profile.

These results are however, not conclusive as the fallow period of the 2008/09 season was not included as implementation of treatments only occurred at planting. Taking this into account the IRWH-2.4m treatment offered the best water management and conservation of all techniques. The fallow period was included in the 2009/10 season, and the rainfall prior to planting was therefore stored in the soil and this was not the case in the 2008/09 season.

5.4 CONCLUSION

The results for plant height, stem diameter, LAI and biomass at different growth stages (vegetative and reproductive) were inconsistent and did not show a clear trend as to which treatment performed best. The study revealed that the RWH&C techniques worked best to improve yield during a dry season (2008/09), on the Glen/Oakleaf ecotope. However, the results of yield per plant in both growth seasons indicated the IRWH-2.4m as the best treatment during both dry and wet seasons. The results were confirmed by calculated biomass and grain yield per plant where the RWH&C techniques performed best in the 2008/09 season. Higher yield under CON was observed during the second season. These results are due to the difference in rainfall between the two seasons.

CHAPTER 6

6.1 SUMMARY AND RECOMMENDATIONS

All farmers in semi-arid areas of South Africa depend on sufficient rainfall to produce sustainable maize crops under rainfed conditions. The challenge in these areas are the ability to use low, uneven and poorly distributed rainfall efficiently, to increase maize productivity. To combat these challenges RWH&C techniques can be used to maximize PWA for increased production. This study has three objectives, which each form the basis of the summary.

1) **Evaluation of Soil Water Balance - The first objective** was to evaluate the soil water balance and rainwater storage efficiency of various RWH&C techniques against CON tillage for possible adoption by farmers. The result of soil water balance during the 2008/09 season showed that the values of ET were high in the RWH&C techniques (IRWH-2.0m, IRWH-2.4m, MB, DAL and MIN) compared to CON treatment. However, during the second wetter season (2009/10) MIN treatment had significantly lower ET, whereas other RWH&C techniques were higher than CON treatment. This is due to the lower Soil water content in the MIN treatment from 69 to 110 DAP. Less soil aggregates are disturbed and a decrease in aeration occurred, which resulted in better water adsorption. IRWH-2.0m and IRWH-2.4m treatment plots had high Es during both growing seasons, followed by MB and DAL treatment plots. This indicated that more water was lost to the atmosphere in these treatments. Measures to suppress Es should be applied on RWH&C technique plots, especially IRWH-2.0m, IRWH-2.4m, MB and DAL to reduce water loss. The trend in Es/ET percentage during the first dry season was IRWH-2.0m > IRWH-2.4m > MB > DAL > CON > MIN. The Es/ET shows that the portion of water lost through Es was significantly higher on the IRWH-2.0m technique compared to all other RWH&C treatments (IRWH-2.4m , MB, DAL, MIN) while CON treatment plots lost less water. This is due to the unprotected runoff areas on these plots. However, during the second wetter season the trend in Es/ET percentage was IRWH-2.0m > DAL > IRWH-2.4m CON > MIN > MB. The RSE during the first season was not recorded, however during the second season in the DAL treatment, significantly more rainwater

was collected compared to the IRWH-2.0m and IRWH-2.4m treatments but not significantly more than CON, MIN and MB treatments.

2) **Maize Performance - The second objective** was to determine maize performance under the various tillage techniques on the Glen/Oakleaf ecotope. The results of plant growth (plant height, stem diameter and LAI) were only collected during the 2008/09 growing season. During the Vp, plant height and stem diameter were significantly higher on plants in the CON plots compared to those in the RWH&C technique plots. Plant height from the CON treatment was significantly greater at 30 DAP, but stem diameter was not significantly different when compared to plants in the IRWH-2.4m, MB, MIN and DAL treatments. As soil water content decreased, plant height and stem diameter in the CON treatment was negatively affected. The LAI from plants in the RWH&C technique plots were greater than those of plants in the CON treated plots at 30 and 45 DAP. A lack of rain during the reproductive period (51 mm) was encountered and impacted negatively on plants. At 66 DAP plants in CON treatment plots were taller and thicker than in the RWH&C technique plots, however not significantly so than those in IRWH-2.4m, MB, MIN and DAL treatment plots. The results at 90 DAP followed the same trend as at 66 DAP, but the growth of plants on IRWH-2.0m plots improved to such an extent that they had caught up to those in the CON treatment plots. At 30 and 45 DAP during Vp of the first season, plants on IRWH-2.0m treatment plots had higher LAI than those of the other treatments. This was due to wide row spacing, resulting in greater light interception to plants, improving photosynthesis. A lack of rainfall (24 mm) during Rp at 66 DAP resulted in plants in the IRWH-2.0m treatment plots being second last, however there was no significant difference between treatments. The results at 90 DAP showed that plants in the CON and MIN treatment plots grew significantly higher in LAI than the plants in IRWH-2.0m. This was probably due to a drastic decrease in rainfall (4 mm).

Rainfall was well distributed throughout Vp of the 2008/09 season. This resulted in a positive effect on the plants in the IRWH-2.4m treatment where their biomass at 30 DAP was as high as but not significantly higher than the plants in the CON treatment plots. At 45 DAP a decrease in soil water content had no effect on plants in the MIN treatment plots where plants had a heavier biomass than those in the CON treatment plots. During the second season at 30

DAP, rainfall was well distributed, resulting in a positive effect on plants in the IRWH-2.0m, IRWH-2.4m, MB and DAL technique plots where they had a greater biomass compared to those in the CON treatment plots. During 45 DAP rainfall was well distributed, increasing soil water content, resulting in plants from the CON treatment having better biomass than those in the RWH&C technique. A lack of rainfall during Rp of the 2008/09 season was encountered, however, at 66 DAP plants in the MIN technique had a heavier biomass than those in the CON treatment, but not significantly so. At 90 DAP, plants in the IRWH-2.4m and MIN treatment plots had the highest biomass, but not significantly so, compared to those in the CON treatment plots. During Rp of the 2009/10 season soil water content dropped, however, plants in the CON treatment plots had a higher biomass at 66 DAP. At 90 DAP plants in all the treatments showed no significant difference in biomass.

During the dry season of (2008/09) results on soil and agronomical components led plants on RWH&C techniques to have a heavier biomass than those on CON treatments. During the wetter season of (2009/10) only plants in the IRWH-2.4m technique plots had a higher biomass than those on CON tillage, however, not significantly so. There was no significant difference between the plants biomass at harvest during the 2008/09 season, however during the 2009/10 season plants in the IRWH-2.4m treatment plots were heavier. The harvesting index during the dry season was higher for the RWH&C techniques than on CON tillage. However, during the wet season CON treatment plots had significantly higher HI than RWH&C techniques plots. The yield trend during the first dry season was MIN > IRWH-2.4m > IRWH-2.0m > DAL > MB > CON and the trend for the second wet season was IRWH-2.4m > CON > MIN > MB > DAL > IRWH-2.0m.

3) **Best Technique - The third objective** was to identify the most appropriate technique that will result in improved water-use efficiency, for recommendation to farmers. The results during both the 2008/09 season and the 2009/10 season showed MIN treatment had a higher $WUE_{(ET)}$ value. During the first season the value was significantly higher than IRWH-2.0m and IRWH-2.4m treatment excluding CON, MB and DAL. However, during the second season the value of $WUE_{(ET)}$ in the MIN treatment was significantly less than on IRWH-2.0m treatments only. The results of $PUE_{(fg)}$ were only calculated for the second season (2009/10) due to no recorded data for the fallow period during the first season (2008/09). The IRWH-2.4m treatment plots obtained significantly higher $PUE_{(fg)}$ compared to MIN, IRWH-2.0m, MB & DAL treatment

plots, however not significantly higher compared to the CON treatment. The results showed that during the drier season (2008/09) RWH&C techniques showed better PUE $_{(g)}$ than CON treatments. However, during the wetter season (2009/10) only IRWH-2.4m treatment plots had higher PUE $_{(g)}$ than CON treatment plots. This indicates that IRWH-24m treatment might be a better treatment to convert water into grain than CON treatment plots during wet seasons. The results showed that the use of RWH&C techniques for growing maize in this dry area can improve RWP and grain yield.

In conclusion, the results obtained from the growth and development of maize, and the gain yield of crops, generally indicated that rainfed agriculture could be improved by the use of rainwater harvesting systems under dry conditions. Even though soil water balance results, indicated the average ET to be higher under RWH&C techniques during both seasons. This indicated more transpiration because there is more water available. During both drier and wetter seasons more water was lost through Es from IRWH-2.0m and IRWH-2.4m treatments plots compared to other treatment plots. This could have resulted from bare runoff strips, however application of mulch will be vital to suppress Es. These techniques have shown the capability of collecting rainwater, storing the water in the soil to reduce R_{ex} but to increase R_{in}. The mean values of grain yield indicated that IRWH-2.4m techniques might possibly be the best treatment, as it obtained the highest grain yield, better than CON treatments during both dry and wet seasons.

Based on the result obtained the following recommendations were made:

- The results found in this study were different from the results obtained by Mavembela and Van Rensburg (2012), Tesfuhuney, (2012), Joseph, (2007), Botha (2006), Botha *et al*, (2003) and Hensley *et al*, (2000) this was due to ecotope differentials. The authors investigated rainwater management and conservation of IRWH, negating the critical aspect of crop production. The combination of soil parameters and crop parameters were consistent but RWH&C techniques (IRWH-2.0m, IRWH-2.4m, MB, DAL and MIN) would improve productivity during the dry season compared to CON tillage. However, increasing IRWH-2.0m to IRWH-2.4m proved a better option of managing rainwater than CON tillage.

- In the study conducted by the Authors mentioned, they indicated a total decrease in Es on RWH&C techniques compared to CON tillage, however, in this study higher Es was obtained on RWH&C technique plots compared to CON tillage. The use of mulch in runoff strips of IRWH-2.0m, IRWH-2.4m would be advisable to reduce water loss due to high Es associated with row spacing in RWH&C techniques.

- More research is required focusing on agronomic aspects (plant height, stem diameter, LAI, etc.) on IRWH, MB and DAL techniques, using a constant plant population. Such research should also include rainwater management and conservation on MB and DAL techniques.

- A long term study in R_{ex} should be further investigated on RWH&C techniques as it was not clear what causes high R_{ex} in MIN, MB and DAL treatments..

REFERENCES

ANDERSON, J. J., SEBOLAI, E. & BOTHA, J. J. 2003. Mechanization, commercialization and up scaling of the in-field rainwater harvesting techniques in the Thaba Nchu area. Agricultural Research Council Institution of Soil, Climate and Water. Bloemfontein, Glen, South Africa.

ANSCHUTZ, J. & NEDERLOF, M. 1997. Water harvesting and soil moisture retention. Agrodok-series No 13. Wageningen, Netherlands. Agromisa.

AYDIN, M., JUNG Y.S., YANG J.E., & HYUN-IL, L. 2013. Long-term water balance of a bare soil with slope in Chuncheon, South Korea. *Journal of Agriculture and Forestry* 37.

ARORA, V.K. 2002. The use of the aridity index to assess climate change effect on annual runoff. *Journal of Hydrology* 265: 164-177.

ASLAM, M., IKRAM, M., HASHMI, N. I., & MAJID, A. 2000. Dry matter accumulation and water requirements of maize (*Zea mays L*). *Pakistan Journal of Agriculture* 16: 99-114.

ASTATKE, A. & JABBAR, M. 2001. Low-cost animal-drawn implements for Vertisol management and strategies for land-use intensification. In: Syers, J. K., Penning de Vries, F., Nyamudeza, P. (Eds.), The Sustainable management of Vertisols. publishing in association with the International Water Management Institute.

ASSOCIATION FOR WATER & RURAL DEVELOPMENT (AWRD). 2009. Techniques of Rainwater Harvesting. www.award.org.za/themes/theme_landing.asp. Accessed 06/06/2014.

BAIPHETHI, M. N & JACOBS, P. T. 2009. The contribution of subsistence farming to food security in South Africa. *Agrekon* 48:4.

BENNIE, A. T. P. & HENSLEY, M. 2001. Maximizing precipitation utilization in dryland agriculture in South Africa- a review. *Journal of Hydrology* 241: 124-139.

BENNIE A. T. P., HOFFMAN J. E., COETZEE M. J. & VREY H. S. 1994. The storage and use of rain water in soil for stabilizing crop production in semi-arid areas. WRC Report No. 227/1/94. Water Research Commission, Pretoria, South Africa 208 pp.

BENNIE, A. T. P., STRYDOM, M. G. & VREY, H. S. 1998. The use of computer models or agricultural water management on ecotope level. Water Research Commission report, TT 122/98, Pretoria, South Africa.

BERRY, W. A. J. & MALLETT, J. B. 1988. The effect of the tillage: Maize residue interactions upon soil water storage. *South African Journal of Plant and Soil*. 5: 57-64.

BLUM, A. 2011. Plant breeding for water limited environments. *Springer Science*.

BOERS, T. M. & BEN-ASHER, J. 1982. A Review of rainwater harvesting. *Agricultural Water Manage* 5: 145-158.

BOER, T.M., ZONDERVAN, K & BEN-ASHER, J. 1986. Micro-catchment water harvesting (MCWH) for arid zone development. *Agricultural water management* 12: 21-39.

BOTHA, J. J., VAN RENSBURG, L. D., ANDERSON, J. J., VAN STADEN, P. P., & HENSLEY, M. 2012. Improving maize production of in-field rainwater harvesting technique at Glen in South Africa by the addition of mulching practices. *Irrigation and Drainage* 61: 50-58.

BOTHA, J. J. 2006. Evaluation of maize and sunflower production in a semi-arid area In-field rainwater harvesting. PhD thesis, university of Free State, Bloemfontein, South Africa.

BOTHA, J. J., VAN RENSBURG, L. D., ANDERSON, J. J., HENSLEY, M., MACHELI, M. S., 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. WRC Report No. 1176/1/03, Water Research Commission, Pretoria, South Africa.

BOTHMA, C. B. 2009. In-field runoff and soil water storage on duplex soil at Paradys experimental farm. Msc thesis at University of Free State, Bloemfontein, South Africa.

BRADY, N. C. & WEIL, R. R. 1999. The nature and properties of soils. 12th edition. Prentice- Hall. 449-453.

BROLLER, E. & HANIF, L. 2004. Ecological infrastructures, Idea Book on Functional biodiversity at the farm level, Switzerland.

BFAP (BUREAU FOR FOOD & AGRICULTURE POLICY). 2007. Policy brief on the national biofuel strategy: prepared for the national agricultural marketing council. www.bfap.co.za Accessed 08/04/2011.

CAKIR, R., 2004. Effect of water stress at different development stages on vegetative and Reproductive growth of corn. *Field Crops Research* 89: 1-16.

CRITCHLEY, W. & SIEGER T, K. 1991. A manual for the design and construction of water harvesting schemes for plant production. Food and Agriculture organization of the United Nations- FAO, bulletin 64. Rome.

DEPARTMENT OF AGRICULTURE. 2007. Sectoral overview and performance. strategic plan. http://www.nda.agric.za/docs/StratPlan07/07sectoral.

DEPARTMENT OF AGRICULTURE, FORESTRY AND FISHERIES, 2010. Trends in the Agricultural sector. South Africa, Pretoria.

DEPARTMENT OF AGRICULTURE-FREE STATE. 2006. Annual performance plan 2006-2009. Department of Agriculture –Free State, Glen, South Africa.

DBSA (DEVELOPMENT BANK OF SOUTHERN AFRICA). 2005. Development Report Overcoming Underdevelopment in South Africa’s Second Economy.

DE VILLIERS, M.C., NELL, J.P., BARNARD, R.O. & HENNING, A. 2003. Sat-affected Soil: South Africa. Paper for FAO.

DREDGE, R.D. 2011. Crop estimates committee. Department of Agriculture, Forestry and Fisheries, Republic of South Africa. www.daff.gov.za/doadev/cropestimates/media Accessed 24/07/2010.

DU PLESSIS, J. 2003. Maize production. Compiled by Directorate Agricultural Information Services Department of Agriculture in Cooperation with ARC-Grain Crop Institute. Pretoria, South Africa.

DU PLESSIS, M.C.F. & MOSTERT, J.W.C., 1965. Runoff and soil loss at the Agricultural Research Centre, Glen. [Afr.]. *South African Journal of Agriculture Science* 8: 1051-1060.

ELDA, M.C., CARLOS, A.B., FERNANDO, H.A. & RONALDO, J.S. 2003 AZOSPHILLUM-Inoculated maize plant responses to irrigation restraints imposed during flowering. *Cereal Research Communication* 31: 3-4.

FANADZO, M., CHIDUZA, C. & MNKENI P. N. S. 2010. Effect of inter-row spacing and plant population on weed dynamics and maize (*Zea mays L.*) yield at Zanyokwe irrigation scheme, Eastern Cape, South Africa. *Journal of Agricultural Research* 5: 518-523.

FAO (FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS), 1991. Water harvesting. Natural Resources Management and Environment Department, AGL/MISC/17/91.

FAO (FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS), 1993. Soil Tillage in Africa. Needs and Challenges. FAO Soil Bulletin No 69.

GREGORY, P. J., SIMMONDS, L. P. & PILBEAM, C. J. 2000. Soil type, climatic regime and the response of water use efficiency to crop management. *Agronomy Journal* 35:217-226.

GOUSE, M., PRAY, C., SCHIMMELPFENNIG, D. & KIRSTEN, J. 2006. Three seasons of subsistence insect-resistant maize in South Africa: Have Smallholder benefited. *Journal of Agro biotechnology Management and Economics* 9.

GUPTA, G. N. 1995. Rainwater management for tree planting in the Indian Desert. *Journal of Arid Environments* 31: 219–235.

GRIFFITH, L.W., SCHUMAN, G. E., RAUZI, F. & BAUMGARTHER, R. E. 1984. Mechanical renovation of short grass prairies for increased herbage production. *Journal of Range Management*. 38(1): 7-10.

HAMIDI, A., KHODABANDEH, N. & MOHAMMADY-NASAB, A.D. 2010. Plant density and nitrogen effects on some traits of maize (*Zea mays* L). *Plant Ecophysiology* 2: 47-52.

HATIBU, N. & MAHOO, H.F., 2000. Rainwater harvesting for natural resources management: A planning guide for Tanzania. RELMA-SIDA, Nairobi.

HENSLEY M., LE ROUX P. A. L., DU PREEZ C. C., VAN HUYSSTEEN C. W., KOTZE E. & VAN RENSBURG L. D. 2006. Soil: The Free State agriculture base. *South African Geographical Journal* 88: 11-21.

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. WRC Report No. 878/1/00, Water Research Commission, Pretoria, South Africa.

HENSLEY, M., LE ROUX, P.A.L., GUTTER, J. & ZERIZGHY, M.G., 2006. A procedure for an improved soil survey technique for delineating land suitable for rainwater harvesting. Report No. TT311/07, Water Research Commission, Pretoria.

HENSLEY, M. & SNYMAN P. J. 1991. Wheat yield probabilities on the Glen/Shorrocks ecotope with different soil water contents at planting. *South African Journal Plant and Soil* 8: 194-199.

HILLEL, D. 1972. The Field Water Balance and Water Use Efficiency. Optimizing the soil physical environment towards greater crop yields: Academic Press: London.

HIRICH, A., RAMI, A., LAAJAJ, K., CHOUKR-ALLAH, R., JACOBSEN, ES.E., EL YOUSSFI L., & EL OMARI, H. 2012. Sweet corn water productivity under several deficit irrigation regimes applied during vegetative growth stage using treated wastewater as water irrigation source. *Journal of Medical and Biological Sciences* 6.

IBRAIMO, N. A. 2011. Rainwater harvesting: management strategies in semi-arid areas. MSc thesis, University of Pretoria.

IBRAIMO, N. & MUNGUAMBE, P. 2007. Rainwater harvesting technologies for small scale rain fed agriculture in arid and semi-arid areas. Department of rural engineering, Faculty of Agronomy and Forestry Engineering, University Eduarodo Mondlane.

ISMAIL, I., BLEVINS R. L. & FRYE, W. W. 1994. Long–term no tillage practices on Soil temperature and thermal Properties. *Journal of Soil Science 58*: 193-198.

JONES, O. R. & BAUMHARDT, R. L. 2003. Furrow dikes. *Encyclopedia of Water Science*.

JOSEPH, L. F. 2007. Maize response to in-field rainwater harvesting on the fort hare/Oakleaf ecotope. Msc thesis at University of Free State, Bloemfontein, South Africa.

KARRAR, A.B., MOHAMED, H.I., ELRAMLWAI, H.R., SAEED, A.B & IDRIS A.E. 2012. Effect of some in-situ water harvesting techniques on soil moisture and sorghum (Sorghum bicolor (L.) Moench) production in Northern Gedaref State. *Global Journal of Plant Ecophysiology* 2: 54-66.

KRAMER, P.J. 1995. Water relations of plants and soil. Elsevier science. Academic Press.

KRANZ, W. L. 2008. Irrigation management for corn. Institute of Agriculture and Natural Resources at the University of Nebraska–Lincoln.

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

LAND TYPE SURVEY STAFF, 2002. Land Type Survey Database. ARC-ISCW, Pretoria.

LE ROUX, P. A. L. & HENSLEY, M. 2012. Petrological aspects of land evaluation for in-field rainwater harvesting in South Africa. *Irrigation and drainage Journal* 61: 129-137.

MAALI, S. H. & AGENBAG, G. A. 2003. Effects of soil tillage, crop rotation and nitrogen application rates on soil mineral-N levels in the Swartland wheat producing area of South Africa. *South African Plant and Soil*. 20, 119-126.

MAIZE TARIFF WORKING GROUP. 2004. Submission of Maize Tariff Working Group to the International Trade Administration Commission of South Africa (ITAC). http://www.grainmilling.org.za/maize_tariff.htm.

MANCOSU, E. &. GAGO-SILVA, A., BARBOSA, A., DE BONO, A., IVANOV, E., LEHMANN, A. & FONS, J. 2015. Future land-use change scenarios for the black sea catchment. *Environmental Science and Policy* 46: 26-36.

MATHEWS, O.R. & ARMY, T.J. 1960. Moisture storage on fallowed wheat land in the Great Plains. *Soil Science Society of America.* 24: 414-418.

MAVIMBELA, S. S. W. &VAN RENSBURG, L. D. 2012. Integrating micro-flood irrigation with in–field rainwater harvesting: maize yield and water use efficiency. *Irrigation and drainage* 61:70-81.

MEKDASCHI, S. R. & LINIGER, H. 2013. Water Harvesting: Guidelines to Good Practice. Centre for Development and Environment (CDE), Bern; Rainwater Harvesting Implementation Network (RAIN), Amsterdam; MetaMeta, Wageningen; The International Fund for Agricultural Development (IFAD), Rome.

MOELETSI, M. E. & WALKER, S. 2011. ENSO and implications on rainfall characteristics with reference to maize production in the Free State Province of South Africa. *Physics and Chemistry of the Earth* 775-781.

MORIRI, S., OWOEYE, L. G. & MARIGA I. K. 2010. Influence of component crop densities and planting patterns on maize production in dry land maize cowpea intercropping systems. *African Journal of Agricultural Research* 5:11.

MOTSI, K. E., CHUMA, E. & MUKAMURI, B.B. 2004. Rainwater harvesting for sustainable agriculture in communal lands of Zimbabwe. Department of Soil Science and Agricultural Engineering, University of Zimbabwe, Mount Pleasant, Harare, Zimbabwe.

MUNODAWAFA, A. 2011. The effect of rainfall characteristics and tillage on sheet erosion and maize grain yield in semiarid conditions and granitic sandy soils of Zimbabwe. *Applied and environmental soil science*.

MWENGE-KAHINDA, J. M., ROCKSTROM, J., TAIGBENU, A. E. & DIMES, J., 2007. Rainwater harvesting to enhance water productivity of rainfed agriculture in the semi-arid Zimbabwe. *Physics and Chemistry of the Earth.* 32:1068-1073.

MZEZEWA, J., MISI, T. & VAN RENSBURG, L. 2010. Characterization of rainfall at a semi-arid ecotope in the Limpopo Province (South Africa) and its implications for sustainably crop production. *Water South Africa* 36:1.

MZEZEWA, J., & VAN RENSBURG, L.D. 2011. Effect of tillage on runoff from a bare clayey soil on a semi-arid ecotope in the Limpopo Province of South Africa. *Water South Africa* 37: 165-172.

NELSON, R.G. 2002. Resource assessment and removal analysis for corn stover and wheat straw in the eastern and Midwestern united states-rainfall and wind-induced soil erosion methodology. *Biomass and Bioenergy* 22: 348-363.

NGIGI, S. N., SAVENJIE, H. H. G., THOME, J. N., ROCKSTROM, J. & PENNING DE VRIES, F. W. T. 2005. Agro-hydrological evaluation of on-farm rainwater storage systems for supplemental irrigation in Laikia District, Kenya. *Agricultural Water Management* 73: 21-41.

NHLABATSI, N. N. 2010. Soil surface evaporation studies on the Glen/Bonheim Ecotope. PhD thesis, University of Free State, Bloemfontein, South Africa.

OLADEJO, J. A. & ADETUNJI, M. O., 2012. Economic analysis of maize (*Zea mays L*) production in Oyo state of Nigeria. *Agricultural Science Research Journals* 2: 77-83.

ORTMAN G & MACHETHE C. 2003. Problems and opportunities in South African agriculture. In: Nieuwoudt WL & Groenewald JA (Eds), The Challenge of Change: Agriculture, Land and the South African Economy. University of Natal Press, Pietermaritzburg 47-62.

OWEIS, T., HACHUM, A., & KIJNE, J. 1999. Water harvesting and supplemental irrigation for improved water use efficiency in the dry areas. SWIM Paper 7. Colombo, Sri Lanks: International Water Management Institute.

PAYERO, J. O., MELVIN, S. R., IRMAK, S. AND TARKALSON, D. 2006. Yield response of corn to deficit irrigation in a semiarid climate. *Biological Systems Engineering: Papers and Publications* 52.

PFIFFNER, L. & MADER, P. 1997. Effects of biodynamic, organic and conventional production systems on earthworm populations. *Biology Agriculture and Horticulture*, 12:14.

PHILLIPS, M. C., FRY, G. J. & HARRIS, D. 1991. Measurement of water use by four common weeds of Botswana in competition with sorghum. In: Proceedings of the Second Annual Scientific Conference, and Mbabane, Swaziland.

RAISUBA, T. C. 2007. Water budget allocation, water use efficiency in agriculture in Olifants catchment. MSc Dissertation. University of the Witwatersrand, South Africa.

RATLIFF, L.F., RITCHIE, J.T. & CASSEL, D.K. 1983. Field-measured limits of soil water availability as related to laboratory-measured properties. *Soil Science. Society. America. Journal* 47: 770-775.

RESHID, K., GETAHUN & JAMA, B. 1987. The influence of rainfall distribution on the yield of maize under Leucaena leucocephala alley cropping at Mtwapa, Coast Province, Kenya. *Journal of Meteorology and Agroforestry* 383-389.

RHOADS, F.M. & BENNETT, J.M. 1990. Irrigation of agricultural crops. Madison, Wisconsin 569-596.

RIAHINIA, S.P &SAYED, M.D. 2008. Row spacing effects on light extinction coefficients, leaf area index, leaf area index affecting in photosynthesis and grain yield of corn (*Zea may* L.) and sunflower (*Helianthus annuus* L.). *Journal of Biological Science* 8(5):954-957.

ROCKSTRÖM, J., BARRON, J. & FOX P. 2000. Rainwater management for increased productivity among smallholder farmers in drought prone environments. *Physics and Chemistry of the Earth*, 27: 949-959.

SCHULZE, R.E. (Ed.), 2006. South African Atlas of climatology and agro hydrology. WRC Report 1489/1/06. Water Research Commission, Pretoria, RSA.

SCHULZE, R. E. & KUNZ, R. P. 1993. Global climate change and agricultural productivity in Southern Africa. *Global Environmental Change* 3: 29-349.

SINCLAIR, T. R., TANNER, C. B. & BENNETT, J. M. 1983. Water-Use efficiency in crop production. *Journals of Biological Sciences* 34:36-40.

SINGH, J.B., PRADEEP, B. & YADAVA, R. B. 2007. Water relations current science. *Current Science*. 93(1): 17-19.

SIVANAPPAN, R. K. 2006. Rain water harvesting conservation and management strategies for urban and rural sectors. *Rainwater Harvesting and Water Management* 11-12.

SOIL CLASSIFICATION WORKING GROUP. 1991. Soil classification a taxonomic system for South Africa. Soil and irrigation research institute. Department of Agricultural Development: Pretoria, South Africa.

STEEL, R.G. & TORRIE, J. H. 1980. Principles and procedures of statistics. McGraw Hill Book Co. New York.

STROOSNIJDER, L. 2003. Technologies for improving rainwater use efficiency in semi-arid Africa. In: Proceedings of the Symposium and Workshop on Water Conservation

Technologies for Sustainable Dryland Agriculture in Sub-Saharan Africa (WCT). Eds. D. Beukes, M de Villiers, S. Mkhize, H. Sally & L van Rensburg. Bloemfontein, South Africa.

TANNER, C. B. & SINCLAIR, T. R. 1983. Efficient water use in crop production. In: T.R. Jordan & H.M. Taylor (Eds.). Efficient water use in crop production. *America Society of Agronomy*. Inc., Madison, Wisconsin, USA.

TEKLE, S. A. 2004. A soil scape survey to evaluate land for In-field rainwater harvesting in the Free State province, South Africa. MSc Dissertation, University of Free State, Bloemfontein, South Africa.

TESFUHUNEY, W. A. 2012. Optimizing runoff to basin rations for maize production with In-Field rainwater harvesting. PhD thesis in the Faculty of Natural and Agricultural Sciences, Department of Soil, Crop and Climate Science, University of the Free State, Bloemfontein, South Africa.

THIMME, G. P., MANJUNATHTHA, S. B., YOGESH, T. C. & SATYAREDDI S. A. 2013. Study on water requirement of maize (*Zea mays L*) using CROPWAT Model in Northern Transitional zone of Karnataka. *Journal of Environmental Science, Computer Science and Engineering and Technology* 2:105-113.

THORNTHWAITE C.W. 1948. An approach toward a rational classification of climate. *Geographical Review* 38: (1) 55-94.

TSIROS, E., KANELLOU, E., DOMENIKIOTIS, C. & DALEZIOS, N.R. 2008. The role of satellite derived vegetation health index and aridity index in agro climatic zoning. *Geophysical Research Abstracts 10*.

UNGER, P.W, & HOWELL, T. A. 1999. Agriculture water conservation- A global perspective. *Journal of Crop Production* 2: 2.

URI, N.D. 1999. Conservation tillage in U.S. Agriculture: Environmental, economic and policy Issues. Food Products Press, New York.

VAN DER MERWE, G. M. E. 2005. The use of water harvesting techniques on vertisols to provide stable crop production on rural farms in Bafokeng district of the North West province. Agricultural Research Council- Institution of Soil, Climate and Water.

VAN DER MERWE, G. M. E. & BEUKES, D. J. 2006. Water conservation with the use of a basin plough on commercial scale to stabilize crop production in Bafokeng, North West Province, South Africa. SADC Land and Water Management Scientific Symposium 1: 50-59.

VAN DER WATT, H.V.H. & VAN ROOYEM, T.H. 1995. Aglossary of soil science. Second edition. Soil Science Society of South Africa, Pretoria.

VAN RENSBURG, L.D., BOTHMA, C.B., FRAENKEL, C.H., L. LE ROUX A.P. & HENSLEY, M. 2012. In-field rainwater harvesting: mechanical tillage implements and scope for upscaling. *Journal of Irrigation and Drainage* 61: 138-147.

VAN RENSBURG, L. D. & ZERIZGHY, M. G. 2008. The BEWAB + Computer program for irrigation scheduling. Department of Soil Crop ang Climate Science, University of Free State, Bloemfontein, South Africa.

VAN ZYL, J., KIRSTEN, J. F., & BINSWANGER, H. P. 1996. Agricultural land prices. Department of Agricultural Economics, Extension and Rural Development, University of Pretoria.

WANI, S. P., SREEDEVI, T. K., ROCKSTROM, J & RAMAKRISHNA, Y. S., 2009. Rain fed Agriculture past trends and future prospects. International Crops Research for Semi-arid Tropics (ICRISAT), Patancheru, Andhra Pradesh, India.

WALLACE, J.S. 2000. Increasing agricultural water use efficiency to meet future food production. *Agriculture, Ecosystems and Environment* 82: 105–119.

WELDERUFAEL, W. A., LE ROUX, P. & HENSLEY, M., 2012. Quantifying rainfall-runoff relationships on the Mieso Hypo Calcic Vertisol ecotope in Ethiopia. *Water South Africa* 3: 423-435.

WORLD BANK. 2000. Spurring agricultural and rural development. In: Can Africa Claim the 21st Century? Washington, DC, USA.

WOYESSA, Y. E, PRETORIUS, E., VAN HEERDEN, P. S., HENSELY, 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. Report Commissioned by the International Water Management Institute.

XIAOLONG, R., ZHIKUAN, J., XIAOLI, C., QINGFANG, H., & LI, R. 2008. Effects of a rainwater-harvesting furrow/ridge system on spring corn productivity under simulated rainfalls. *Acta Ecologica Since Journal* 28(3): 1006-1015.

ZERE, T. B., VAN HUYSSTEEN, C. W. & HENSLEY, M. 2012. Development of a simple empirical model for predicting maize yields in a semi-arid area. *South African Journal of Plant and Soil* 22: 07.

ZINSELMEIER, C., JEONG, B., &BOYER, J.S., 1999. Starch and the control of kernel number in maize at low water potentials. *Plant Physiology*: 121, 25–36.

Appendix

Appendix 1 Profile description of the Glen/Oakleaf ecotope.

Land Type No	Ea 39	**Soil Form**	Oakleaf
Climate zone	Semi-arid	**Soil Family**	Dipene 1220
Terrain unit	Lower 3	**Surface rockiness**	None
Slope	2%	**Surface stoniness**	None
Slope shape	Straight	**Occurrence of flooding**	None
Aspect	North	**Wind erosion**	None
Micro relief	None	**Water erosion**	Slight
Parent material solum	Weathered Schale	**Vegetation / Land use**	Cultivated land
Weathering of underlying material	Chemical/weak	**Described by**	C.H. Fraenkel
Water table	None		

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0 – 300	Moist colour: yellowish red, 5YR4/6; mottles: none; structure: fine, massive apedal; consistence (dry): loose; consistence (moist): loose; wet-stickiness: non-sticky; macro pores & cracks: no cracks and few fine pores; cementation of horizon: none; free lime: none; slickensides: none; coarse fragments: none; cutans: none; roots: many roots; transition: gradual transition: smooth	Orthic
B	300 - 2100	Moist colour: dark red, 2.5YR3/6; mottles: None sub angular block; consistence (dry): hard; consistence (moist): slightly hard; wet-stickiness: slightly sticky; macro pores & cracks: medium fine pores and no cracks; cementation of horizon: moderate; free lime: none; slickensides: moderate; coarse fragments: none; cutans: moderate; roots: many roots; transition: smooth.	Neocutanic

Appendix 2 Physical and chemical analysis of the Glen/Oakleaf ecotope.

Physical and chemical analysis of the Glen/Oakleaf ecotope as in January 2009

Horizon	**Depth** (mm)	**Diagnostic horizon**	**Exchangeable Cations** (mg kg^{-1})				**Phosphorus** (Bray 1) (mg kg^{-1})	**Carbon** (%)	**Resistance** (ohm)	**pH** (H_2O)	**Particle Size Distribution** (%)						
											Sand				Silt		Clay
			Potasium	Calsium	Magnesium	Sodium					2 - 0.5 mm	0.5 - 0.25 mm	0.25 - 0.106 mm	0.106 - 0.05 mm	0.05 - 0.02 mm	0.02 - 0.002 mm	< 0.002 mm
A	0 - 300	Orthic	174	1989	278	3.6	13.18	0.36	210	7.83	2.42	7.75	44.81	20.75	5.04	2.92	14.45
B	300 - 1200	Neocutanic	195	1454	907	19.0	4.06	0.40	460	6.94	0.10	4.89	38.19	13.65	4.43	2.90	33.96

Chemical analysis of the Glen/Oakleaf ecotope as in January 2009

Horizon	**Depth** (mm)	**Site**	**Exchangeable Cations** (mg kg^{-1})				**Phosphorus** (Bray 1) (mg kg^{-1})	**Resistance** (ohm)	**pH** (H_2O)
			Potasium	Calsium	Magnesium	Sodium			
A	0 - 250	Block 1	173	665	319	3.5	3.06	150	5.53
A	0 - 250	Block 2	196	507	196	2.5	4.56	160	5.36
A	0 - 250	Block 3	203	510	221	6.3	3.23	60	5.47
A	0 - 250	Block 4	179	492	216	3.2	5.42	80	5.0

Chemical analysis of the Glen/Oakleaf ecotope as in October 2009

Horizon	**Depth** (mm)	**Treatment**	**Exchangeable Cations** (mg kg^{-1})				**Phosphorus** (Bray1) (mg kg^{-1})	**Resistance** (ohm)	**pH** (H_2O)
			Potasium	Calsium	Magnesium	Sodium			
A	0 - 250	*CON*	232	583	214	2.7	52.5	2770	6.8
A	0 - 250	*MIN*	204	474	230	3.2	15.2	3440	6.34
A	0 - 250	*IRWH*, *MB*, *DAL*	184	456	217	2.6	20.3	3350	6.38