EVALUATING RAINWATER HARVESTING AND CONSERVATION TECHNIQUES ON THE TOWOOMBA/ARCADIA ECOTOPE

by

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DECLARATION

I declare that the mini-dissertation hereby submitted to the University of Limpopo, for the degree of Master of Science in Agriculture (Agronomy) has not previously been submitted by me for a degree at this or any other university; that it is my work in design and in execution, and that all material contained herein has been duly acknowledged.

_________________ **31 MARCH 2015**

NGWEPE, M.R (MR) **DATE**

DEDICATION

This valuable work is dedicated to my late father Mr. Kwena Calvin Ngwepe and my beloved family, for their encouragement, support and understanding, my mother Mrs. Johanna Moloko Ngwepe, my brothers and sisters, who laid down the foundation of my education which made me who I am today. This work is also dedicated to my wife and my son whose courage and love was the source of inspiration for undertaking this work.

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ABSTRACT

The changes in climate, especially poor rainfall patterns and distributions are key issues posing major agricultural challenges for food security and threaten the rural livelihoods of many communities in the Limpopo Province. Rainfall (P) is low and limited. These limited P is mostly lost through runoff and evaporation, which result in low soil moisture availability and possible crop failure. Therefore, techniques that reduce these water losses are important for improving dryland crop production and rainwater productivity (RWP). The objectives of this study were to determine the potential and effectiveness of rainwater harvesting and conservation techniques (RWH&CT's) to conserve and improve plant available water (PAW) for dryland maize production and also determine the efficiency of the RWH&CT's to improve dryland maize yield and RWP compared to conventional tillage (CON). The study was conducted over a period of two growing seasons (2008/09; 2009/10) using maize as indicator crop at the Towoomba Research Station of the Limpopo Department of Agriculture in the Limpopo Province of South Africa, on an Arcadia ecotope. The experiment was laid out in a randomized complete block design, with four replications and five treatments. The five treatments used in the study were; conventional tillage (CON), No-till (NT), In-field rainwater harvesting (IRWH), Mechanized basins (MB) and Daling plough (DAL). The IRWH and DL were classified as rainwater harvesting techniques (RWHT's), whilst MB and NT were classified as water conservation techniques. Two access tubes were installed at each treatment to measure the soil water content (SWC) at four different soil depths of 150, 450, 750 and 1050 mm using the neutron water meter. The data collected included climatic data, soil and plant parameters. The data were subjected to analysis of variance through NCSS 2000 Statistical System for Windows and GENSTAT 14th edition. Mean separation tests were computed using Fisher's protected least significant difference test. The SWC of IRWH, DAL and MB were about 510 and 490 mm higher compared to CON and NT treatment during the 2008/09 and 2009/10 seasons, respectively. The PAW_T of the IRWH, MB and DAL was significantly different from the CON treatment during the 2008/09 season. For both seasons the biomass yield of the IRWH treatment was significantly different from the NT treatment, producing 23 and 50% more biomass in the 2008/09 and 2009/10 growing seasons, respectively. The grain yield under IRWH was significantly different from the NT treatment during both 2008/09 and 2009/10 seasons. The highest maize grain yield of IRWH was achieved during the 2009/10 season with 56% higher grain yield than the NT treatment. RWP from various RWHT's were significantly different from the NT treatment. These results indicate that IRWH and DAL were 12 and 2% more effective in converting rainwater into harvestable grain yield than the CON treatment. R^2 values of 68.6 and 78.4% for SWC and transpiration (Ev) were obtained when correlated with maize grain yield respectively. This indicates the importance of moisture conservation for improved dryland maize production under low P areas. Therefore, the use of appropriate RWHT's by small-scale farmers maybe crucial to improve dryland maize production. IRWH outperformed all other treatments in terms of the soil parameters and plant parameter measured during the period of this study. Therefore, these results suggest IRWH has potential of sustaining maize yields under low rainfall conditions.

Key words*:* Rainwater harvesting, conservation techniques, ecotope, rainwater productivity, maize yield, precipitation use efficiency.

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LIST OF ABBREVIATIONS

AI	Aridity index (%)
ARC-ISCW	Agricultural Research Council Institute of Soil, Climate and Water
BD	Bulk density (g cm^{-3})
Ca	Calcium
CA	Conservation agriculture
CON	Conventional tillage
D	Deep drainage (mm)
DAL	Daling plough
DUL	Drained upper limit (mm)
ERD	Effective rooting depth (mm)
Es	Evaporation from the soil surface (mm)
ET	Evapotranspiration (mm)
ETo	Reference evapotranspiration (mm)
Ev	Transpiration (mm)
FANRPAN	Food, Agriculture and Natural Resources Policy Analysis Network
FAO	Food and Agricultural Organization
F_p	Fallow period
G_p	Crop growing period
GDP	Growth Domestic product
HI	Harvest index
ICRISAT	International Crops Research Institute for the Semi-Arid-Tropics
IFPRI	International Food Policy Research Institute
IPCC	Intergovernmental Panel on Climate Change
IRWH	In-field rainwater harvesting
K	Potassium
Kc	crop coefficient
LL	Lower limit (mm)
LT	Long-term
MB	Mechanized basins
Mg	Magnesium
Na	Sodium

NT	No-till
NWM	Neutron water meter
P	Annual rainfall (mm)
P_f	Rainfall during the fallow period (mm)
P_g	Rainfall during the growing period (mm)
P_p	Production period
PAW	Plant available water (mm)
PAW_p	Plant available water at planting (mm)
PAW_{PM}	Plant available water at physiological maturity (mm)
PAW_T	Plant available water at tasselling (mm)
P_n	Total rainfall over n consecutive years (mm)
PUE_{gp}	Precipitation use efficiency during the growing period (kg ha^{-1} mm^{-1})
R	Runoff
R6	Reproductive stage 6 of maize
R_p	Reproductive period
RCBD	Randomized complete block design
R_{EX}	Ex-field runoff (mm)
RSE	Rainwater storage efficiency (%)
RWH	Rainwater harvesting
RWH&CT's	Rainwater harvesting and conservation techniques
RWHT's	Rainwater harvesting techniques
RWP	Rainwater productivity (kg ha^{-1} mm^{-1})
RWP_n	Rainwater productivity over a period of n consecutive years (kg ha^{-1} mm^{-1})
SA	South Africa
SADC	Southern African Developing Community
SPAC	Soil-plant-atmospheric continuum
SSA	Sub-Saharan Africa
SWC	Soil water content (mm)
t	Time after saturation (hours)
TESW	Total extractable soil water (mm)
V5	Vegetative stage 5 of maize
V12	Vegetative stage 12 of maize

V_p	Vegetative period
Vs	Volume of dry soil (cm^3)
WRC	Water Research Commission
Ws	Weight of dry soil (g)
WUE	Water use efficiency (kg ha^{-1} mm^{-1})
$Y_{(0-1200)}$	Water content of the rootzone (mm)
Y_b	Total above-ground biomass (kg ha^{-1})
Y_g	Grain yield (kg ha^{-1})
Yg_n	Total grain yield over n consecutive years (kg ha^{-1})
Zn	Zinc
$\theta_{h(n-1)}$	Rootzone water content at harvesting of the previous crop (mm)
θ_m	Gravimetric soil water content (mm)
$\theta_{p(n)}$	Rootzone water content at planting of the current crop (mm)
θ_v	Volumetric soil water content (mm)
$\sum P_n$	Total rainfall over *n* consecutive years
ΔS	Change in soil water content (mm)
$\sum Yg_n$	Total grain yield over *n* consecutive years

CHAPTER 1

1 INTRODUCTION

1.1 BACKGROUND

Maize in South Africa is the most important field crop and a staple food for the majority of the population in the country. Maize production contributes to the economic development of the country, through exports and trade. Therefore, production of maize requires innovative intervention which will ensure sustainable dryland production, due to challenges posed by climatic change and erratic rainfall distribution. Rainfall (P) is one of the most important factors affecting agricultural productions, especially in the arid and semi-arid regions. Akpalu *et al.* (2009) indicated that maize yields are determined more by the level of P than by the presence of irrigation. Water from rainfall must be captured and retained in soil and used efficiently for optimum yield production (Morell *et al.,* 2011).

Soil water availability is the major limiting factor in any dryland crop production. Water deficit caused by low, erratic rainfall and high evaporative demand limits dryland crop production in most parts of South Africa, particularly in the Limpopo Province (FANRPAN, 2010). Innovative approaches and practices of soil and water conservation and management can increase crop water use efficiency, thus increasing yields and reducing the likelihood of crop failure. FAO (2009) reported that the most global agricultural challenge of the 21st century is to produce 70% more food by the year 2050 to feed a projected increased population. While change in long-term mean climate will have significant effect on global food production dryland crop production may require ongoing adaptation. The greater risks to food security may be posed by changes in year-on-year variability and changes in weather conditions, results in high temperature and low annual P. Historically, many of the largest falls in crop productivity have been attributed to anomalously low rainfall (P) events (Sivakumar *et al.,* 2005). However, even small changes in mean annual rainfall can impact on productivity. The current agricultural production practices require implementation of sustainable production methods which are tailored to respond to these changing climatic conditions and low mean annual P.

This study introduced techniques which have the potential of enhancing sustainable soil moisture conservation and its availability throughout the crop growing season. The techniques involve creation of in-field basins, which encourage more water infiltration, and limit ex-field runoff (R_{EX}), reducing potential soil erosion and are termed rainwater harvesting techniques (Oweis *et al.,* 2001). Other practices such as the no-till systems, involve reduction of disturbing the surface soil as a way of limiting excessive evaporation (Es), whilst conserving soil moisture. Rainwater harvesting and conservation techniques (RWH&CT's) are climate smart techniques which are important and well suited for dryland farming conditions, especially in areas with low annual P.

1.2 PROBLEM STATEMENT

In the semi-arid areas of Africa particularly the Sub-Saharan Africa water and soil fertility are the main factors limiting dryland crop production (Ramaru *et al.,* 2000). A large population in the Limpopo Province live in rural areas and solely depend on dryland agriculture for their livelihoods (FANRPAN, 2010). These areas are characterized by poor soil fertility, low annual P and poor crop yields (Ramaru *et al.,* 2000). However, the fertiliser application is very much dependent on P, so that P becomes the most important factor influencing dryland crop production. This limited rainwater is mostly lost through R_{EX} and Es, which result in low soil moisture availability and leading possible crop failure. Therefore, R_{EX} and Es are two major causes of poor maize production in the Limpopo Province. As water resources shrink and competition from other sectors grows, agricultural production will continue to face dual challenges of producing more food with less water. Increasing water use efficiency and reducing surface runoff water is important for a sustainable dryland crop production and provision of food security to the rural livelihoods. Techniques that reduce/limit these water losses are important for improving dryland crop production and rainwater productivity (RWP) in these areas. Therefore, management of this limited rainwater in small-scale farming systems can provide a positive solution for improving crop production and food security. The impact of moisture conservation techniques that reduce surface runoff and encourage infiltration on dryland maize performance have not fully been tested in the Province.

1.3 MOTIVATION OF THE STUDY

Maize is a staple food crop for majority of people living in the rural area of Limpopo Province. RWP plus the change in soil water content (SWC) of the rootzone proved to be a valuable parameter for comparing the level of P utilization by different production or management practices for dryland crop production (Botha, 2006). This study intended to determine the potential ability of RWH&CT's as a way of increasing soil moisture availability, and improving RWP of maize. The major emphasis of the techniques is to retain, store and utilize highly scarce and variable P. There are soil- and crop-water-management practices that can reduce the impact of prolonged droughts in these dryland crop production systems. Several technologies and strategies have been developed that clearly demonstrate efficient utilization of the limited and erratic P in dryland areas to contribute to increased crop yield. Studies show that the RWH&CT's have the potential of increasing dryland maize production. Botha (2006) reported 30% yield increase of maize planted under in-field rainwater harvesting (IRWH) when compared to conventional tillage systems.

1.4 PURPOSE OF THE STUDY

1.4.1 Aim

The aim of the study was to evaluate different RWH&CT's as alternative methods to conventional tillage for increasing maize production, by improving plant available water under dryland crop production.

1.4.2 Objectives

The objectives of the study were to:

i. Determine the effectiveness of RWH&CT's for improved plant available water for dryland maize production.

ii. Determine the effectiveness of RWHCT's for improved maize yield and RWP under dryland production.

iii. To make recommendations for small-scale farmers about appropriate RWH&CT's for increased plant available water and improved maize yields.

1.4.3 Hypotheses

i. There are no differences between RWH&CT's and conventional practices in plant available water for maize production.

ii. There are no differences in yield and RWP of maize under different RWH&CT's compared with conventional practices.

CHAPTER 2

2 LITERATURE REVIEW

2.1 INTRODUCTION

Agriculture plays a key role in economic development and poverty reduction (World Bank, 2005), with evidence indicating that increase in agricultural yields can translate to a decrease in the percentage of the absolute poor (Thirtle *et al*., 2002). Agricultural production systems are expected to produce food for a global population that will amount to 9.1 billion people in 2050 and over 10 billion by the end of the century (UNPFA, 2011; and IFPRI, 2011). IPCC (2007) projected that by 2020 yields from dryland agriculture in some African countries could be reduced by up to 50% due change in climate conditions resulting in increased rise in temperature. With agricultural production and access to food adversely affected, malnutrition and hunger will increase. In addition to changing patterns to P amounts, the P events may become more intense (IPCC, 2007). This may affect incidences of flooding and droughts, making the supply of both freshwater for human consumption and crop water requirement even more unreliable. In order to secure and maintain food security, agricultural systems need to increase production capacity and stability of small-scale agricultural production.

Africa remains the region with the highest prevalence of undernourishment, with more than one in five people estimated to be undernourished, and that more than 50% of the population in SA lives below the poverty line (Statistics SA, 2014). The scarcity of arable land, erratic P and frequent dry spells are contributing to low crop productivity, which leads to food insecurity. Without better water management in agriculture the following development goals: (i) poverty alleviation, (ii) hunger, (iii) sustainable environment and (iv) economic growth will not be met. Statistics SA (2014), further indicated that levels of poverty differ significantly across the provinces, with Limpopo (63,8%), Eastern Cape (60,8%) and KwaZulu-Natal (56,6%) displaying the highest levels of poverty.

South Africa is a water scarce country with very low P at an average of about 500 mm per annum which varies seasonal and it’s highly irregular in its occurrence (Oosthuizen, 2005). Water scarcity is the main cause of insufficient soil moisture availability for crop growth (Rosegrant *et al.,* 2002). The country is characterized by spatial and temporal P variability, which is often accompanied by heavy thunders and storms (SIWI, 2001). The occurrence of droughts and dry spells are manifested in a reduction in P, which affects the amount of crop water availability in the plant rooting zone. Rockström (2000) indicated that rainwater productivity has to increase dramatically over the next generations if food productivity is to keep pace with the human population growth and its food demand. Dryland agriculture is practiced worldwide on 80% of the agricultural area and most countries in the world depend primarily on dryland agriculture for their grain food crops (Wani *et al.,* 2011). However, in many parts of the water scarce countries, the yield of maize from dryland agricultural production is low, oscillating around 1000 kg ha^{-1} (Rockström, 2000).

The small-scale farming sector in rural areas are faced with a range of challenges from poor soil quality, poor rainfall distribution, lack of resources (inputs and water for irrigation), which often results in poor or zero crop yields. These challenges result in the need for the small-scale farmers to enhance water productivity of dryland agriculture by mitigating intra-seasonal dry spells through the adoption of new technologies such as rainwater harvesting techniques (RWHT's) (Kahinda *et al.,* 2007). Increasing rainwater productivity in agriculture may play a vital role in easing competition for scarce water resources, prevention of environmental degradation and provision of food security (Molden *et al*., 2007).

2.2 PRINCIPLES OF RAINWATER HARVESTING SYSTEMS

The first step in any RWHT's involves methods that increase the amount of water stored in the soil profile. The principle of rainwater harvesting is based on depriving a certain area its share of rainwater, which would have been non-productive and diverting its share to another part of the land to make it more useful (Oweis *et al.,* 2001). This may involve small movements of rainwater as surface runoff in order to direct and concentrate the rainwater near the growing plants. Rainwater harvesting (RWH) describes a number of different practices which all work towards harvesting and conserving rainwater, for sustainable moisture supply to the growing crops. Reij *et al.* (1988) gave the following definition: RWH makes use of and even induces surface runoff, whereas in-situ rainwater conservation aims at preventing runoff and retaining P where it falls. These techniques are mainly applied in arid and semi-arid regions to minimize R_{EX} (Boers & Ben-Asher, 1982). The rainwater conservation can mainly be achieved by increasing the SWC through increasing the infiltration rates/tempo and reducing the surface R_{EX} water. R_{EX} constitutes one of the major water losses from dryland cropping areas causing the loss of valuable water, soil and nutrients (Schiettecatte *et al.,* 2005). This water becomes less valuable to crop production. Hatfield *et al.* (2001) indicated that improved water and precipitation use efficiencies (PUE) in crop production are key factors for dryland cropping systems. The RWHTs has the ability to reduce R_{EX} to zero and reduce Es to a considerable extent, resulting in increased crop yields (Botha, 2006).

RWHT's provide water catchments through the basins on the surface soil, which maximises water infiltration and increase SWC for crop uptake during the growing season. When rainwater is trapped in the basins R_{EX} is reduced or minimized. RWH&CT's are innovations for dryland farming systems (Oweis *et al.,* 2001), however, they are also applicable over a wide range of conditions in areas where seasonal average rainfall is insufficient to meet the crop water requirements. In many localities, direct rainfall is insufficient to meet crop water requirement (Oweis & Hachum, 2006). Therefore, increasing the amount of water available through RWHT's seems to be the most appropriate way of ensuring sustainable dryland crop production. RWHT's aim to alleviate the most limiting crop production factors, which are water and soil fertility (Kronen, 1994).

Better utilization of P through RWHT's can greatly increase agricultural productivity, improve food security and alleviate poverty. Several studies have been carried out with the aim of determining the potential of RWH&CT'S to improve land productivity. The study of rainwater harvesting dates back many decades, and is consisted of different methods or techniques which were aimed at improving soil moisture availability for the growing crops, under dryland production. Dagga & MaCartney, (1968) in Tanzania conducted several experiments to determine the effect of tied ridges as soil water harvesting technique on different soil types including red, ash and black soils. Their results of physiological observation of maize indicated that, on the red soils maize showed signs of moisture stress at tasseling. Whereas on the ash soils, moisture stress apparently was the lowest at the time of tasseling. They concluded that, ridges made on black soils conserved the largest amount of moisture followed by those on the red soils. The ridges made on the ash soils conserved the least amount of moisture. They further concluded that, tied ridges were also found to be effective in controlling runoff and increasing the infiltration period.

Mzirai & Tumbo (2010) conducted a study using macro-catchment systems of RWH, and their results showed that, in macro-catchment RWH systems increased water use efficiency (WUE) to more than 20 kg ha^{-1} mm^{-1} compared to dryland system without micro-catchment of RWH. WUE of systems without micro-catchments hardly reached 3 kg ha^{-1} mm^{-1} (Mzirai & Tumbo, 2010). Hatibu & Mahoo (2000) investigated the effects of modified cropping system for maize, which aims to reduce the risk drought through RWH. Their results of macro-catchment RWH resulted in more benefits compared to cultivation without rainwater conservation techniques. Mutekwa & Kusangaya (2006) reported that successful adoption of RWHT's lead to higher agricultural productivity, household income and soil erosion control.

Nyamangara *et al.* (2013) studied two conservation agriculture (CA) practices, planting basins (Basins) and ripper tillage (Ripper), in comparison with conventional tillage (CON) on sandy soils. They concluded that, the basins produced 59% more maize grain yield when compared to CON. Van der Merwe & Beukes (2006), conducted a study on the use of MB at Kanana experimental farm, South Africa and reported that the method increases surface water retention in the basins and ultimately increasing the time for water to infiltrate into the soil. According to the definition of RWH by Oweis *et al*. (2001) the MB treatment is a water conservation technique, because it does not cater for the additional collection of rainwater as runoff (R), but it conserves the rainwater that falls in the basins only. Whilst IRWH and DAL are RWHT's due to the created runoff areas that directs the additional water into the basins. Therefore, these studies indicate the extent to which RWHT's can contribute to various agricultural production improvements, especially on field crops which are staple food for majority of people living in rural areas.

2.3 COMBINING RWHT'S AND FERTILIZER APPLICATION

The two major bio-physical problems of dryland crop production are insufficient soil moisture availability and low or poor soil fertility. Kahinda *et al.* (2007) argued that water is not the only limiting factor to crop growth, but indicated that these two bio-physical problems should be addressed simultaneously to ensure sustainable dryland crop production. Mugwe *et al*. (2009) indicated that poor soil fertility is also of the greatest bio-physical constrains to increasing agricultural productivity and also threatening food security in the Sub-Saharan region. Rockström *et al*. (2003) indicated that fertilizer application by small-scale farmers is lower than 20 kg ha^{-1} $year^{-1}$ in Sub-Saharan Africa. Hence plants suffer from both nutrient deficiency and moisture stress due to low fertilizer application and insufficient soil moisture availability.

Experiments conducted on soil moisture conservation and fertilizer applications indicate that combined use of RWHT's and fertilizer application resulted in increased dryland crop production. Anderson *et al.* (2006) conducted a study on the application of nitrogen fertilizer on maize and compared maize yield from IRWH and CON. Their results indicated that the IRWH plots produced 50% higher yields than the CON. However, in terms of absolute yield, the combination of moisture conservation and use of fertilizer application of IRWH gave the highest yield of maize compared to CON (Anderson *et al.,* 2006).

Whilst, Kahinda *et al.* (2007) conducted a study using Agricultural Production Simulator Model on seven different treatments (Control, RWH, Manure, Manure + RWH, Inorganic Nitrogen and Inorganic Nitrogen + RWH) for 30 years on alfisol deep sand, they indicated that combined use of inorganic fertiliser and RWH treatment had more productivity when compared to other treatments. Therefore, Kahinda *et al.* (2007) results indicate the importance of RWH and nutrient management in agricultural production. The results of Rockström *et al.* (2010) showed that soil fertility management and increase in proportion of soil moisture availability is one of the most important management practices to improve yields of dryland crop production. The average grain yield increases ranged from 75 to more than 145% compared to the traditional CON practice depending on soil type, slope, P and the type crop planted (Rockström *et al.,* 2010).

2.4 CONSERVATION AGRICULTURE

Soil and water conservation practices can be described as the activities that reduce water losses by R and evapotranspiration (ET), while maximizing soil-moisture storage for improved crop production. A range of agronomic practices have been reported to have an impact on the performance of conservation agriculture (CA) and often determine its performance in relation to CON. These practices include practices such as ridging, bench terraces and addition of manure (FAO, 2002; Hatibu & Mahoo, 1999). FAO (2002) described CA as any tillage practice that ensures about 30% of mulch or crop residues cover is left in the field throughout the fallow period. CA leads to increased infiltration and enhanced water holding capacity from crop residues left on the soil surface. The more the mulch is retained on the soil surface the more the organic matter increases (FAO, 2002).

Rockström & Falkenmark (2000) stated that when organic material is increased on the soil surface soil erosion is decreased. Gowing & Palmer (2008) indicated that CA can only improve food security if farmers have access to herbicides and fertilizers. The primary importance of such conservation practices is to limit R_{EX} water, with the purpose of maximizing infiltration. The longer the water is held on the soil surface and infiltrates into the soil, more water is made available in rootzone for crop root absorption. ICRISAT (2009) conducted a study on CA and concluded that this technology contributes to increased yields across all agro-ecological zones and can thus make a major contribution to household food security. Mazvimavi *et al.* (2008) reported 10 to more than 100% of grain yield increases when practicing CA and further indicated that these is depended on input levels and the experience of the farmers.

2.5 CONVENTIONAL TILLAGE

The CON tillage practices are believed to encourage more water infiltration, by destroying any layers of crust on the soil surface. Ploughing with the mouldboard buried the plant residues deep into the soil, which is contrary to the NT as the plant residues serve as the soil cover against evaporative loss and control of erosion (OISAT, 2005). These operations are expensive and require high farm labour supply

(OISAT, 2005). Seeding was done similarly as it was done in the NT treatment. The mechanization and intensification of the traditional, tillage-based system of agriculture (CON) has often been accompanied by numerous adverse impacts on soil systems. The CON treatment leaves the soil bare, and when it is pulverized excessively and exposed to wind and rain, most of the R_{EX} carries the topsoil causing soil erosion and degradation (Hobbs *et at.,* 2008). Maize in SA is mostly produced under CON practices. Small-scale farmer practice CON tillage on less than 2 ha and the yields are very low under CON often less than 1000 kg ha^{-1} (Rockstrom, 2001.).

2.6 SOIL WATER CONTENT

The plant growth stage, ET, R and deep drainage (D) affect the availability of water in the soil. Therefore, during poor rainfall distribution, the RWH&CT's is likely to enhance water infiltration and contribute to increased SWC, and later improving plant available water (PAW). Under low SWC the plants suffer from moisture stress and these leads to potential crop failure (Mutekwa & Kusangaya, 2006). PAW defined as the difference between the lower and the upper limit of SWC, is an important plant requirement to limit water stress and maximize crop production. Ratliff *et al.* (1983) defined the lower limit of PAW (LL) as the lowest field-measured water content of a soil after plants have stopped extracting water and are at or near premature death, or have become dormant as a result of water stress. Whilst the drained upper limit of PAW (DUL) is defined as the highest field-measured water content of a soil after it has been thoroughly wetted and allowed to drain until D becomes zero (no water movement), was measured using the drainage curve systems (Ratliff *et al.,* 1983).

Water balance is based on the law of conservation of mass: any change in the water content of a given soil volume during a specified period must equal the difference between the amount of water added to the soil volume and the amount of water withdrawn from it (Zhang *et al.*, 2002). In other words, the water content of the soil volume will increase when additional water from outside is added by infiltration or capillary rise, and decrease when water is lost through ET or deep D.

2.7 WATER USE EFFICIENCY

WUE is defined as the yield of harvested crop product achieved from the water available to crop through P, irrigation and the contribution by soil moisture availability (Hatfield *et al.,* 2001). Improving WUE in agriculture requires an increase in crop water productivity and reduction in water losses from the plant rooting zone (Hensley *et al.,* 2011). This is a critical zone where adequate storage of moisture and nutrients are required for optimized crop production. Increasing WUE particularly in arid and semi-arid areas with erratic rainfall patterns is important. Under dryland conditions, soil water can be lost from the soil surface through Es or through R and D from the soil profile. When soil moisture availability meets the transpiration demand the plant growth is improved and significantly increasing crop yield.

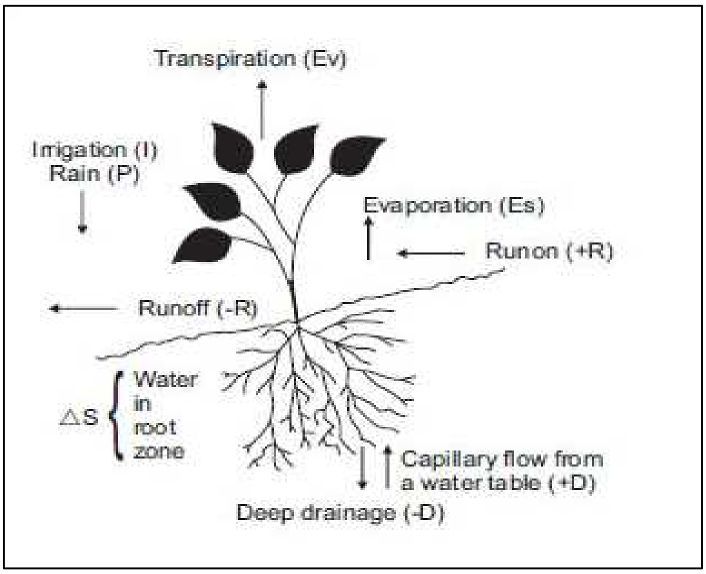

Figure 2.1 The soil-plant-atmosphere continuum (SPAC) showing the water-balance processes (Hensley *et al.,* 2011).

Es is one of the main causes of water loss in dryland agricultural production, mainly in the first periods of high temperature when the crop is at the initial phenological stages, with low soil coverage. Both surface R and Es coincide with the period when the soil surface is not completely covered by the crop. ET may decrease overtime as SWC decreases. Figure 2.1 illustrate the soil-plant-atmosphere continuum (SPAC) by Hensley *et al.* (2011) and further illustrate six process of the soil water balance as described by Bennie *et al.* (1998) in Equation 3.

The change in the SWC is as a result of P, (adding the SWC), losses occurring through R, D, Es and during Ev utilization when soil water is absorbed by the plant roots. Stewart & Steiner (1990) indicated that in years of below-average P, the threshold amount of ET may not be met or only exceeded by a small amount, therefore little or no grain is produced. They further concluded that just a small amount of additional water can increase yields dramatically once the threshold amount has been reached. Sorghum grown in semi-arid regions requires about 100 mm of seasonal ET before any grain is produced (Stewart & Steiner, 1990). About 15 kg ha^{-1} of sorghum grain can be produced for every additional millimetre of ET (Stewart & Steiner, 1990).

Through RWH&CT's the concepts PUE and RWP are measures determining the production increases through the efficiency of the techniques in conserving rainwater when compared to CON in kg ha^{-1} mm^{-1}. This concept of RWP was found to be the most appropriate measure of determining the efficiency of the techniques to improve dryland crop yield (Botha, 2006). PUE is defined as the amount of harvestable product produced per unit of P received. RWP is the yield per unit of water used (Oweis & Hachum, 2006). In dry areas more soil water will be available to the crops when rainwater harvesting is used.

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CHAPTER 3

3 RESEARCH METHODOLOGY

3.1 DESCRIPTION OF THE STUDY SITE

The experiment was conducted at the Towoomba Research Station of Limpopo Department of Agriculture, which is located on the southern part of the Springbok flats, approximately 4 km south east of Bela-Bela in the Limpopo Province (28°21'E, 24°25'S; 1 184 m above sea level). Towoomba Research Station is situated in the summer rainfall area with a long-term average annual rainfall of 620 mm per annum (Towoomba weather station data). The rainfall distribution during the season is highest from November to February and lowest during May to August. The annual rainfall distribution is erratic, and rain often occurs in short bursts of high intensity, associated with thunderstorms and lightning.

3.2 RESEARCH DESIGN

The experiment was based on RWH&CT's, using maize as the indicator crop, over two growing seasons (2008/09 and 2009/2010). The experiment was laid out in Randomized Complete Block Design (RCBD). Five treatments were used in the experiment, which were replicated four times. The treatments were: 1. Mechanized basins (MB), 2. In-field rainwater harvesting (IRWH), 3. Daling plough (DAL), 4. No-till (NT), and 5. Conventional tillage (CON). The experiment occupied a total area of 330 m x 105 m = 34650 m^2 as illustrated in Figure 3.1. The total area for each plot was 21 m x 75 m = 1575 m^2. The treatments were 1.5 m apart. The grain yield was harvested from 6 rows of 10 m long from the middle of each plot. Figure 3.1, A-E presents the treatments used in the experiment whereby A= MB, B=IRWH, C= DAL, D=NT and E=CON; 1- 40 indicate the access tubes within each treatment.

MAIZE										
C	1.5m	**A**	1.5m	**E**	1.5m	**B**	1.5m	**D**	Rep 1	75m
31&32		33&34		35&36		37&38		39&40		
									↕10m	
A	1.5m	**D**	1.5m	**B**	1.5m	**C**	1.5m	**E**	Rep 2	75m
21&22		23&24		25&26		27&28		29&30		
									↕10m	
C	1.5m	**B**	1.5m	**A**	1.5m	**D**	1.5m	**E**	Rep3	75
19&20		17&18		15&16		13&14		11&12		
									↕10m	
D	1.5m	**C**	1.5m	**B**	1.5m	**A**	1.5m	**E**	Rep 4	75m
9&10		7&8		5&6		3&4		1&2		
↔21m	↔21m		↔21m		↔21m		↔21m			
105 m										

Figure 3.1 The experimental layout for maize on the Towoomba/Arcadia ecotope.

3.3 DESCRIPTION OF THE TREATMENTS

The study was based on the RWH&CT's which were compared to CON. The treatments were classified into three categories based on their mechanisms of operation and application: (i) RWHT's = IRWH and DAL, (ii) Conservation techniques = MB and NT treatments and (iii) the control conventional tillage (CON). IRWH and DAL are classified as RWHT's because they offer runoff area, where additional rainwater is harvested. MB conserve the rainwater were it falls but does not provide runoff area to harvest additional water. NT conserves the rainwater through soil surface cover with plant residues or mulch and the mechanism of not disturbing the soil surface. CON treatment encompassed the activities of cultivating the land, disking the soil, and use of tillage implements to level the soil during the preparation of seed bed.

3.3.1 The rainwater harvesting techniques

IRWH and DAL were classified as the RWHT's because they have the ability to collect additional rainwater as the water runs down the slope (runoff strip) into the created basins.

3.3.1.1 In-field rainwater harvesting

The IRWH technique is a system of RWHT's; it combines the advantages of RWH, no-till and basin tillage. Firstly, the slope of the field was identified for the purpose of implementing the basins to face the opposite direction of runoff water in order to maximize runoff water capturing (Figure 3.2 and 3.3) (Botha *et al.,* 2007). The IRWH technique consists of a runoff promoting area of 2.4 m wide strip called the runoff area between alternate crop rows, and storing the runoff water in the basins (Figure 3.3). The 2.4 m runoff areas of the IRWH were not disturbed which then provide the advantages of no-till system (Figure 3.2c and Figure 3.3).

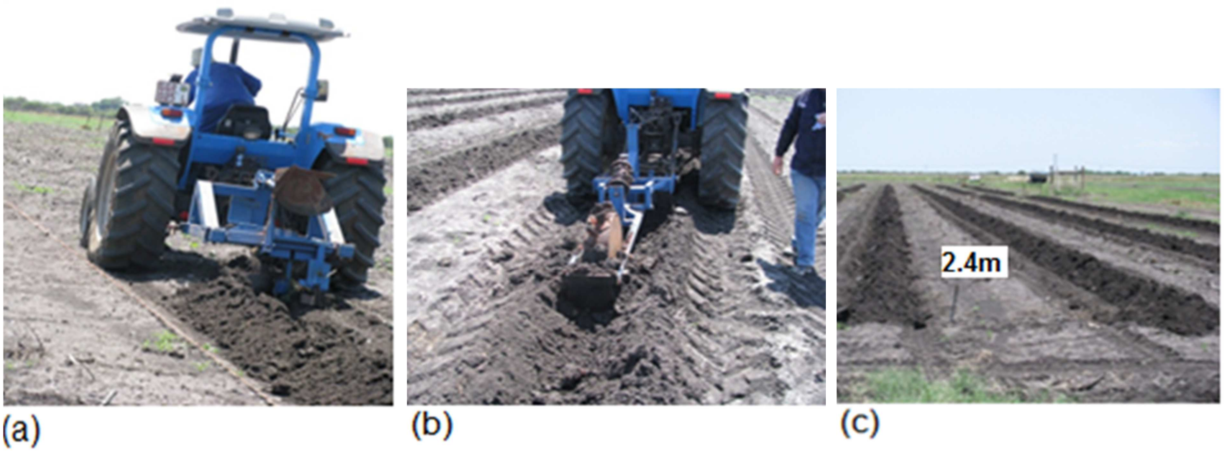


Figure 3.2 The IRWH implements; furrow plough (a), basin maker (b) and created basins (c).

Creation of the basins encompasses a single mouldboard plough (Figure 3.2a) called the furrow plough which creates a 20 cm high contour ridge and 15 cm deep furrow, this is followed by a basin maker (Figure 3.2b) that was driven inside the furrow and creates the inter-ridges to form basins which are 1 m long and 0.6 m wide to cater for a 90 cm inter-row planting space. A 2.4 m runoff strip was left between each row of furrows, where the water is allowed to run into the basins created inside the furrows (Figure 3.2c).

Two rows of maize were planted on both sides of the furrow, one row in the side of runoff direction and the other row on the opposite site as illustrated in Figure 3.3.

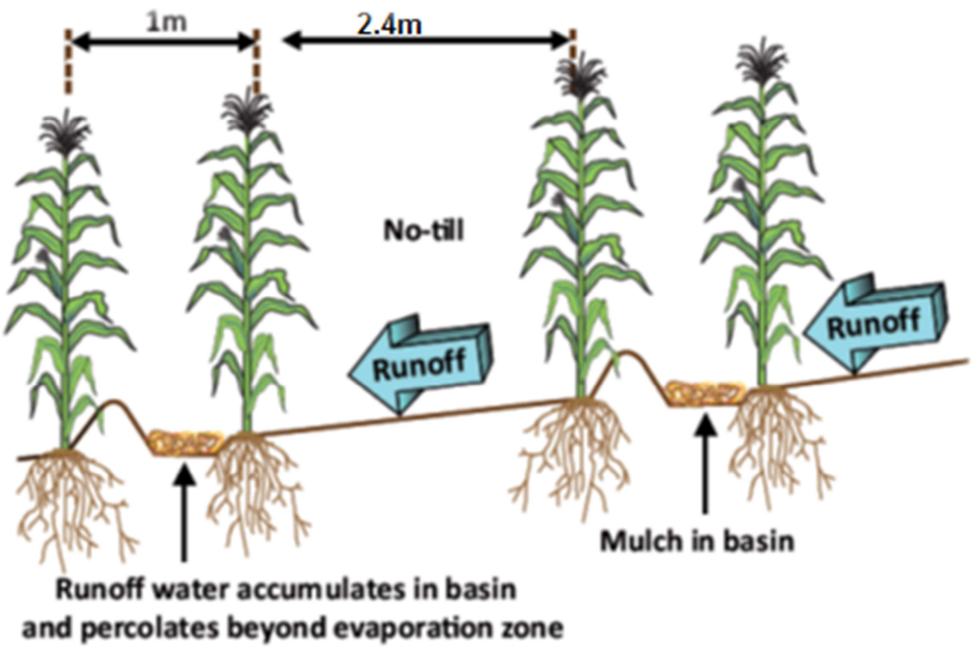


Figure 3.3 The in-field rainwater-harvesting technique with a no-till runoff, with mulch in the basins (Botha *et al.,* 2007).

3.3.1.2 Daling plough

The DAL is another treatment of the RWHT's. This plough, named after its inventor, Mr. Dirk Daling. A small planter adaptation has been used extensively in the Settlers area of the Waterberg district, Limpopo Province, SA as a method of RWH. The DAL consists of three joint implements which work simultaneously: (i) the tiller (chisel plough) which is in front with linkages to the tractor (lifts and top-link), (ii) the arc-shape basin plough mounted behind the tiller and the off-centre wheel (Figure 3.4 a). The tillers loosen the soil and the basin plough is continuously lifted up by the off-centre wheel (Anderson & Botha, 2009). The basins plough creates flattish V-shaped basins, which are continuously joined together to all the sides. The principle of the DAL technique ensures zero R_{EX}. The water collected in the basins can only flow to the next basins when the upper basins are full of water. The basins are wide open being 1.8 m wide and 2 m in length (Figure 3.4 b). The 1.8 m width of the basins allows one row of maize to be planted on the edge of the basins and the second row is planted in the middle of the basin.

(a)

(b)

Figure 3.4 The Daling plough (a) and signs of water harvested in Daling plough basins after a rainfall event (b).

3.3.2 The rainwater conservation techniques

MB and NT treatments were classified as the water conservation techniques as they do not provide additional water catchments, but they conserve the rainwater were it falls through the basins of MB and residue cover of NT.

3.3.2.1 Mechanized basins

The MB implement consists of two sets of paddles, with two rippers mounted in front of each paddle (Figure 3.5a). The rippers mounted in front rip the soil and loosen the soil for ease of creation of the basins, whilst breaking any possible plough pans which also lead to improved infiltration. The paddles are lifted up and down by the pivoting rear wheel hitched on the front ripper, and the scraper at the far back of hitched wheels create two rows of basins which are similar in shape (Anderson &

Botha, 2009). The implement was pre-set at 1.8 m wide and created 1 m long and 0.75 m wide basins (Figure 3.5b). The maize was planted in alternate rows of the basins at a pre-set plant inter row space of 90 cm, to ensure no damages were done on the basins, as the tractor was driven on the outer side of the ridges (Figure 3.5b).

The ridges all around the basin prevent this technique from harvesting additional rainwater as R (Figure 3.5b). The rainwater is conserved as illustrated in Figure 3.5 b after a rainfall event.

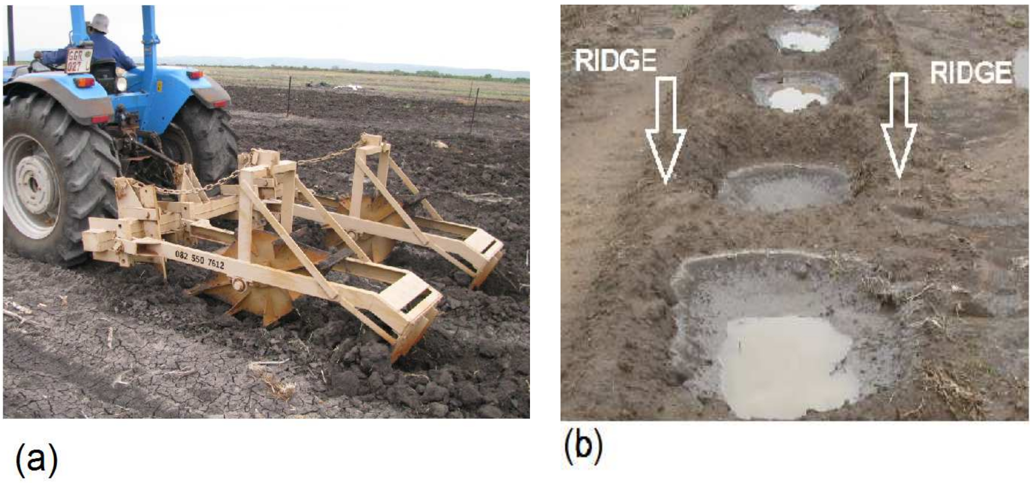


Figure 3.5 The mechanized basins implement (a); signs of water harvested in mechanized basins after a rainfall event (b).

3.3.2.2 No-till

In situ water conservation technologies aim at conserving the rainfall where it falls in the planted area. NT conserves water in the soil profile since the soil is not tilled and exposed to the evaporative elements of the atmosphere. The moisture is retained within the soil profile. The primary importance of such technologies is to reduce in-field runoff, increase the amount of water available within the root zone and reduce soil erosion. Mulches also protect the soil surface from extreme temperatures and greatly reduce Es, which is particularly important. The NT practices offers the advantages of conserving soil, water and reduces capital investment in machinery, but most important to many producers, NT can improve maize yields. NT requires dedicated weed management as over time the weeds become resistant to chemical control.

The implementation of the NT treatment used in this study was to chemically control the weeds using herbicides at pre-planting and post emergence application. The maize seed was planted without any form of cultivation of the land in order to maintain the plant residues on the soil surface. The Monosen planter used in this study was adapted to plant maize in NT treatment, with its front steel plates that penetrated through the crop residues into the undisturbed soil below. The soil was disturbed only where the seed was deposited at a depth of 7 cm, the rear wheels of the planter pressed the seed to maximize seed-soil moisture contact to ensure seed germination.

3.3.3 Conventional tillage

CON is mainly characterised by intensive primary and secondary tillage systems to prepare seedbed and control weeds. CON tillage used in this study included disking of the plots after harvesting of the previous crops, ploughing after the first rain with a mouldboard and harrowing, to produce a fine seedbed that allowed seed to be planted easily at a suitable moist soil depth.

3.4 AGRONOMIC INFORMATION

Planting was done with a two row Monosen planter for the maize crop. The planter was calibrated at 90-100 cm inter-row depending on the treatment for a plant population of 18 000 plants ha^{-1}. The seed was planted at the depth of 7 cm. The maize cultivar PAN 6995B was planted on the 16/01/2009 for 2008/2009 season and PAN 6P-563R was planted on the 25/11/2009 for 2009/2010 growing season (Appendix 1). The cultivar PAN 6P-563R is a Roundup ® cultivar and it was used as a result of increasing weed control efficiency during the second season.

The weeds were controlled at pre-planting using the Roundup ® (glyphosate) herbicide. Roundup ® (glyphosate) herbicide had an active ingredient of 480 g l^{-1}

and was applied at 5 l ha^{-1} before planting. A follow up spraying was done to ensure maximum crop benefits to minimize crop-weed competition at 2.5 l ha^{-1} during the crop growing stage. The weeds were also controlled manually for the non-roundup ready cultivar during the 2008/09 season. The pesticide (Bull-dock) for controlling the stalk-borer was used. All the herbicides and pesticides were applied using a calibrated boom sprayer according to the product label recommendation.

Systemic soil sampling procedure was used to collect the soil samples at the depth of 0 to 15 cm topsoil and 15 to 30 cm during the fallow period. The soil samples were collected and analyzed for both pH and nutrient elements using the: water solution method for pH and Bray1 method for Phosphorus (McLean, 1982; Bray & Kurtz, 1945) (Appendix 3). Potassium (K), calcium (Ca), magnesium (Mg) and sodium (Na) were analyzed using Ammonium acetate extraction, (McLean, 1982) for the purpose of fertilizer recommendation. Fertilizer application was done simultaneously at planting according to the soil analysis results (Appendix 3) using the fertilizer limestone ammonium nitrate and superphosphate fertilizer. N and P were applied at 45 and 40 kg ha^{-1} respectively. The banding method of fertilizer application was used, placing the fertilizer mixture 5 cm to the side and below the seed.

3.5 ECOTOPE CHARACTERIZATION

3.5.1 Soil profile description

The term ecotope according to Ingegnoli (2002), refers to the smallest landscape unitary multi-dimensional element that has all the structural and functional characters which are relatively homogeneous, that influence crop yield (climate, topography, and soil). A profile pit was dug and different master horizons were delineated and the soil was described and classified according to the Soil Classification Working Group (1991) prior to the implementation of the experiment and treatments.

3.5.2 Bulk density

A site was demarcated next to the experimental site to determine the bulk density of the soil. The bulk density (BD) is defined as the weight of dry soil per unit of volume and is expressed in g cm^{-3} (Cresswell & Hamilton, 2002). The BD was determined by collecting a known volume of soil for each soil layer in the root zone using a core sampler pressed into the soil (intact core), and determining the weight after oven drying (McKenzie *et al.*, 2002). The sample was oven dried until a constant weight was recorded. BD is an indicator of soil compaction and soil health. It affects infiltration, rooting depth/restrictions, available water capacity, soil porosity, plant nutrient availability, and soil micro-organism activity, which influence key soil processes and productivity. The BD values were also required for the calibration of the neutron water meter (NWM). The equation describing the bulk density is represented in Equation 1 (Blake, 1965).

$$BD = \frac{Ws}{Vs} \qquad \text{(Equation 1)}$$

Where:

BD = bulk density (g cm^{-3})

Ws = weight of dry soil (g)

Vs = volume of dry soil (cm^3)

3.6 CLIMATE

An automatic weather station was installed at the experimental site, which measured minimum and maximum temperatures (^{0}C), wind speed and direction, and rainfall (P) data. P was also measured manually using the rain gauge, to validate the data provided from the automatic weather station. Climatic data was used to calculate some of the important parameters that influence the SWC of the Towoomba/Arcadia ecotope. These parameters are important for the purpose of calculating the ET of the ecotope. To analyse P and ET of the two growing seasons, the rainfall distribution was divided into three periods of rainfall, (i) fallow period (F_p) which is the period from harvesting of the previous crop to the date of planting of the new or current crop, (ii) vegetative period (V_p) which is the period from planting to flowering; (iii) reproductive period (R_p) which is the period from flowering to physiological maturity. The total growing period (G_p) was calculated as the sum of vegetative period and reproductive period ($V_p + R_p = G_p$). These periods of rainfall were then compared to the long-term (LT) climatic data records of the Towoomba Research Station.

3.6.1 Long-term climate data

The LT climatic data from the year 1973 to 2009 for the Towoomba/Arcadia ecotope was provided by the South African Weather Services (Appendix 4). This was used to compare the climatic data of the 2008/09 and 2009/10 experimental seasons with the LT average.

3.6.2 Aridity Index

The aridity index (AI) is an indicator of the degree of dryness of the climate at a given location (Thornthwaite, 1948). The AI of this study was determined using Equation 2, proposed by UNESCO (1979).

$$\mathrm{AI} = \frac{P}{ET_O} \qquad \text{(Equation 2)}$$

Where:

AI = Aridity index (%)

P = Mean annual rainfall (mm)

ETo = Reference evapotranspiration (mm)

3.7 SOIL PARAMETERS

Bennie *et al.* (1998) list the six water balance processes for dryland crop production which play an important role in the functioning, productivity and stability of the soil-plant-atmospheric continuum (SPAC) (Equation 3).

Water for yield (mm) = water gains (mm) - water losses (mm)

$$Ev = (P \pm \Delta S) - (Es \pm R + D) \qquad \text{(Equation 3)}$$

Where:

Ev = evaporation from the crop (transpiration) (mm)

P = rainfall (mm)

ΔS = change in soil water content (mm)

Es = evaporation from the soil surface (mm)

R = runoff (-); run on (+) (mm)

D = deep drainage (mm)

3.7.1 Drainage, drained upper limit and lower limit

The drainage (D) curve for the Towoomba/Arcadia ecotope was determined by constructing a drainage plot of 3 m X 3 m during the winter months to avoid possible water additions by P. The Wilcox method by Miller & Aarstad (1972) was used to determine the drainage behaviour of the Towoomba/Arcadia ecotope. Corrugated iron sheets were installed around the drainage plot to isolate the monolith from the surrounding soil or ensure no lateral water movement was possible. A water cart was used to fill the drainage plot with water. The SWC of the whole profile was regularly measured before and after addition of water, in order to determine whether the soil is saturated. The addition of water was then discontinued and the soil was allowed to drain. Five aluminium access tubes were installed in the drainage plot, one access tube was placed in the middle of the plot and the remaining four were placed 1 m away from the middle access tube. The access tubes were installed 1100 mm deep into the soil, same as those used in the crop field. The drainage plot was covered with a black plastic, to limit any possible Es and water losses or any water accessing the plot. SWC was measured at the depth of 150, 450, 750 and 1050 mm using NWM. SWC was measured hourly for the first 7 days, thereafter once a day for a period of 100 days in order to plot the drainage curve.

Through the drainage determination, the drained upper limit (DUL) and Lower limit (LL) of the Towoomba/Arcadia soil was measured. The equation describing the drainage is presented in Equation 4.

$$Y_{(0-1200)} = -1.433\, Ln(t) + 535.62 \qquad R^2 = 0.85 \qquad \text{(Equation 4)}$$

Where:

$Y_{(0-1200)}$ = water content of the root zone (mm)

t = time after saturation (hours)

3.7.2 Soil water content

The SWC was measured periodically with NWM model (CPN 503DR) at four soil depths, (150, 450, 750 and 1050 mm). The NWM was calibrated for every soil layer by using gravimetric SWC (θm) and the bulk density of the soil (Robinson & Hubbard, 1990). The SWC was measured by lowering the probe into the aluminium access tube to the desired soil depth. The soil water extraction characteristics for the field crops were determined by installing two access tubes in the middle of each treatment. One access tube was installed in the basin between the paired rows of maize and the second access tube was installed on the runoff area outside the basins. The access tubes fitted on the CON and NT treatments were all placed 1 m apart from each other, with one of the access tubes installed between the paired rows of maize. The soil around the access tube was carefully pressed to ensure maximum contact with the soil. The access tubes were covered with lids to avoid water entering inside the access tubes. A total of 40 access tubes (resulting from 5 treatments X 4 replications X 2 access tubes per treatment) were installed during the two experimental seasons (2008/09 and 2009/10). The access tubes were installed to a depth of 1100 mm into the soil. The change in the SWC of each treatment was measured to determine the efficiency of the treatments to increase SWC. These changes in the SWC were also related to crop growing stages in order to determine the PUE and RWP.

3.7.3 Runoff

In this study R water from CON and NT treatments was classified as R_{EX} (ex-field runoff - water losses from production area) and was calculated using Equation 5 as developed by Anderson (2007) on the Glen/Bonheim ecotope.

$R_{EX} = 02678P – 2.5298$ (Equation 5)

Where:

R_{EX} = Ex-field runoff (mm)

P = rainfall (mm)

3.7.4 Evapotranspiration

Evapotranspiration (ET) is the loss of water from a vegetative surface through the combined processes of plant Ev and Es (Allen *et al.,* 1998). The most known and used technique to estimate ET is based on the crop coefficient (Kc) approach (Allen *et al.,* 1998). The Climatic variables for calculating the evaporative demand (ETo) were measured with an automatic weather station at the experimental site. For a specific period, ET was obtained from the soil water balance equation (Equation 3) (Botha *et al.,* 2012). ET was separated into its components of transpiration (Ev, mm) and soil water evaporation Es (mm). Ev was estimated using the procedure of Tanner and Sinclair (1983) which includes a transpiration efficiency coefficient (k) for maize of 9.5 $gm^{-2}mm^{-1}$ (Equation 6). Ogola *et al. (*2007) indicated that the value of (Kc) for maize has been found to vary little. For example, in Sonning, England, values of 8.4 to 10.5 Pa were obtained (Ogola *et al.*, 2002). To implement the procedure, the mean saturation deficit during daylight hours for each growing season was determined using data obtained from the automatic weather station. With ET and Ev known, Es was obtained by subtracting Ev from ET.

ET = Kc x ETo (Equation 6)

Where:

Kc = Crop coefficient

ETo = Reference evapotranspiration

3.7.5 Plant available water

The change in the SWC is an important factor determining the growth pattern and yield potential of the growing crop. The SWC of the Towoomba/Arcadia ecotope during the two growing seasons were calculated using two categories: (i) the plant available water at the maize tasselling stage (PAW_T) and (ii) the plant available water at physiological maturity (PAW_{PM}) of maize.

3.7.6 Rainfall storage efficiency

Rainfall storage efficiency (*RSE*) is defined as the change in SWC over the potential rooting depth divided by P during the fallow period. *RSE* was calculated using Equation 7 as proposed by Mathews & Army (1960).

$$RSE = \frac{\theta_{p(n)} - \theta_{h(n-1)}}{P_f} * 100 \qquad \text{(Equation 7)}$$

Where*:*

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

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

P_f = rainfall during the fallow period (mm)

3.8 PLANT PARAMETERS

3.8.1 Plant height

Plant height is an important crop growth parameter and is positively correlated to maize grain yield (Tenaw, 2000). The higher the plant height the higher the potential yield of the maize crop. Maize plant height was measured using a 2.5 m ruler from the soil surface to the tip of the maize plant. The plant height was measured at 15, 45 and 120 days after planting (DAP) during the two maize growing seasons (2008/09 and 2009/10). A total of 12 plants with tag numbers were selected from two paired rows of maize around the access tube areas, in order to measure plant height.

3.8.2 Stem diameter

The stem diameter was measured above the first node of the maize plant from the soil surface, using a vainer calliper, from the same plants which were used for the measurement of plant height. The stem diameter was measured at 15, 45 and 120 days after planting (DAP) during the two maize growing seasons (2008/09 and 2009/10). Stem diameter is an important plant parameter which was measured to determine maize growth in relation to SWC conserved by different treatments used in this study.

3.8.3 Biomass

Biomass yield was determined from a total of 36 plants per treatment at maize physiological maturity and expressed as oven dry mass in kg ha^{-1}. The plants were cut above-ground and dried in the over until a constant weight was measured at a temperature of 60 ^{0}C. The biomass at physiological maturity was also used for the calculation of harvest index (HI).

3.8.4 Grain yield

Maize was harvested at physiological maturity in order to determine the grain yield by harvesting a statistically representative area of 6 rows of 10 m long from the middle of each treatment. The cobs were harvested manually then later threshed using a threshing machine. The grain yield was recorded in kg ha^{-1} at 13% grain moisture for all the treatments. The grain yield data was also used for calculating HI and RWP.

3.8.5 Harvesting index

HI was calculated as the ratio of grain yield (Y_g) to the total above-ground biomass yield (Y_b) (Bennie *et al.,* 1998) as shown in Equation 8.

$$HI = \frac{Yg}{Yb} \qquad \text{(Equation 8)}$$

Where:

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

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

3.8.6 Precipitation use efficiency

The precipitation use efficiency during the growing period (PUE_{gp}) measures the efficiency of the techniques in converting P into harvestable yield. PUE takes into consideration the total grain yield, total rainfall, and the difference in the SWC at planting and harvesting of the previous crop (Equation 9).

$$PUEgp = \frac{Yg}{Pg + (\theta p(n) - \theta h(n))} \qquad \text{(Equation 9)}$$

Where:

PUE_{gp} = precipitation use efficiency (kg ha^{-1} mm^{-1})

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

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

P_g = rainfall during the growing period (mm)

3.8.7 Rainwater productivity

The equation of the RWP is represented in Equation 10 (Botha, 2006) which is the ratio of total grain yield produced over a number years to the total rainfall received during those production years.

$$RWP_n = \frac{\sum Yg_n}{\sum P_n} \qquad \text{(Equation 10)}$$

Where:

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

$\sum Yg_n$ = total grain yield over consecutive years (kg ha^{-1})

$\sum P_n$ = total rainfall over n consecutive years (mm)

3.9 DATA ANALYSIS

The data was subjected to analysis of variance using the NCSS 2000 Statistical System for Windows (Hintze, 1996) and GENSTAT 14th edition (GENSTAT, 2014). Mean separation tests were computed using Fisher's protected least significant difference test at 5% level of probability.

CHAPTER 4

4 RESULTS AND DISCUSSION

4.1 ECOTOPE CHARACTERISATION

Table 4.1 summarises the results of the soil properties of the Towoomba/Arcadia ecotope. The Towoomba/Arcadia ecotope is classified as belonging to the Lonehill Family of the Arcadia Form (Soil Classification Working Group, 1991). The detailed soil profile description and chemical analysis of the Towoomba/Arcadia ecotope are presented in Appendix 2 and Appendix 3, respectively.

Table 4.1 Soil properties of the Towoomba/Arcadia ecotope

Profile detail						Soil water extraction properties		
Horizon	**Diagnostic Horizon**	**Colour**	**Depth** (mm)	**Clay** (%)	**BD** (g cm^{-3})	**DUL** (mm)	**LL** (mm)	**TESW** (mm)
Ap	Vertic	Black	300	70	1.40	135	70	65
A_1		Black	600	70	1.39	144	99	45
A_2		Black	900	70	1.24	124	104	20
A_3		Black	1200	70	1.16	122	102	20
Total						525	375	150

BD = bulk density; DUL = drained upper limit of plant available water; LL = lower limit of plant available water; TESW = total extractable soil water.

According to Botha *et al.* (2014) the soil is characterized as a black clay, Vertic A-horizon rich in smectitic clay minerals. The soil profile has an effective rooting depth (ERD) of approximately 1200 mm. ERD is defined by Van der Watt & Van Rooyen (1990) as the depth of soil material that plant roots can penetrate readily to obtain water and plant nutrients. The Towoomba/Arcadia ecotope possesses a suitable ERD for the production of dryland maize. The soil has a high clay content of more than 70% and has a well-developed structure. This indicates that the Arcadia soil has high water holding capacity due to its high clay content. The high clay content found on the Towoomba/Arcadia ecotope results in the soil shrinking when dry and swells when wet, this occurs in response to moisture changes (Botha *et al.*, 2014).

The BD gives an indication of the porosity and structure of the soil which influences oxygen and water movement in the soil profile. From Table 4.1 it can be seen that the bulk density of the Towoomba/Arcadia ecotope is low, ranging from 1.16 to 1.40 g cm^{-3} and it decreases with increasing soil depth from 0 – 1200 mm. A soil with a high BD can restrict seed germination and root development which will affect the total plant growth and reduce grain yield. Goodman & Ennos (1998) studied the effect of BD on maize and sunflower root growth, and found that soils with a low BD had a significantly lower penetration resistance (118±4-4 kPa) than soils with high BD (325±12-2 kPa). In the case of the Towoomba/Arcadia ecotope, with the low BD, the soil may not have an effect on root growth and yield of the maize crop. It will provide a good soil health condition where the plant root growth will be maximized and the microbial activities will be enhanced.

The DUL and LL of SWC are useful in determining the total extractable soil water (TESW). TESW is given by the difference between the DUL and LL. From Table 4.1 the TESW is found to be higher at the upper 300 mm depth with 65 mm of available soil water and lower at the lower horizons 900 and 1200 mm at 20 mm. The higher TESW in the top horizons indicate that the soil has the ability to hold water for a significant period of time at the upper horizons. The 0 – 300 mm layer hold 43% of the TESW of the whole profile. Therefore, this signifies crops grown on the Towoomba/Arcadia may have an ample provision and access to soil water for plant root uptake, provided rainfall is well distributed.

4.2 CLIMATE

The climatic data for P, ETo and AI for the two growing seasons (2008/09 and 2009/10) and their relation to the corresponding LT are represented in Table 4.2. To calculate P, ETo and AI the results were divided into three production periods, i.e. (i) F_p, (ii) V_p and (iii) R_p. G_p was calculated as the sum of vegetative period and reproductive period. These periods of rainfall were then compared to the LT climatic data records of the Towoomba Research Station.

Table 4.2 Rainfall (P), reference evapotranspiration (ETo) and aridity index (AI) over two growing seasons (2008/09 and 2009/10) and in relation to the long-term (LT) means for maize production on the Towoomba/Arcadia ecotope

Parameters	Season	Periods				
		F_p	**V_p**	**R_p**	**G_p**	**P_p**
P (mm)	2008/09	*	374	23	397	*
	2009/10	253	426	50	476	729
	Mean	*****	**400**	**37**	**437**	*****
	$LT_{(2008/09)}$	*	321	152	427	*
	$LT_{(2009/10)}$	34	159	260	419	452
	Mean	*****	**240**	**206**	**423**	*****
ETo (mm)	2008/09	*	264	197	461	*
	2009/10	681	305	261	566	1246
	Mean	*****	**285**	**229**	**514**	*****
	$LT_{(2008/09)}$	*	270	186	457	*
	$LT_{(2009/10)}$	352	237	222	458	810
	Mean	*****	**254**	**204**	**458**	*****
AI	2008/09	*	1.42	0.11	0.86	*
	2009/10	0.37	1.40	0.19	0.84	0.58
	Mean	*****	**1.41**	**0.15**	**0.85**	*****
	$LT_{(2008/09)}$	*	1.19	0.81	1.03	*
	$LT_{(2009/10)}$	0.10	0.67	1.17	0.91	0.56
	Mean	*****	**0.93**	**0.99**	**0.97**	*****

F_p = fallow period; V_p = vegetative period; R_p = reproductive period; G_p = crop growing period; P_p = production period and * = data not available.

The 2008/09 growing season had 17% less P for the G_p compared to the 2009/10 season, and was also 6% lower compared to LT mean for $G_{p.}$ P results during 2008/09 experimental period indicated that maize received approximately 17% more P during V_p and 85% less rainfall during the R_p as compared to $LT_{(2008/09).}$ Comparing the ETo values during 2008/09 growing season of V_p, R_p and G_p *vs*. $LT_{(2008/09)}$ show that climatic conditions in terms of ETo were slightly favourable during V_p, but unfavourable during R_p and very similar during G_p than the $LT_{(2008/09)}$. AI results for the 2008/09 season indicated that very favourable climatic conditions occurred during V_p, where AI was 19% better than $LT_{(2008/09)}$ whereas very unfavourable conditions occurred during the critical R_p with AI 86% lower than $LT_{(2008/09)}$. The very favourable climatic conditions during V_p contributed to the highest biomass yields at physiological maturity during (2008/09) over the two growing seasons. The very unfavourable conditions that occurred during the critical R_p hampered grain yield and contributed to the lower grain yield (2008/09) as compared to the 2009/10 growing seasons.

The 2009/10 climatic results indicate that rainfall during F_p, V_p and R_p was 644% (219 mm) more, 40% higher and 81% lower than $LT_{(2009/10)}$, respectively. The 2009/10 growing season was characterized by high P during the F_p and $V_{p.}$ P was extremely low during the R_p compared to the LT data. The P during F_p contributed 35% of the total P of the 2009/10 growing season, which indicated that more water was received during this F_p. High P values during F_p result in poor PAW if there are no mechanisms to conserve the valuable P during the F_p. This indicates that implementation of the treatment during the F_p is vital in order to conserve enough soil moisture prior to the planting of the crops. The V_p contributed to 58% of the total P during the 2009/10 growing season.

The higher P during the Fp and Vp and low P during Rp indicate that during the Rp, lack of soil moisture would have resulted in crop stress and this would have affected the maize grain yield. SIWI (2001) indicated that, water stress during crop growth, even during short periods of a couple of weeks, is a major cause of yield reduction in dryland areas. The purpose of the RWH&CT's ensures soil moisture availability is maximized to limit potential effects of moisture stress on crop growth. When the techniques are efficient in conserving rainwater, the demand for evapotranspiration and crop water requirement are likely to be met.

ETo results for the 2009/10 season indicated that during F_p, V_p and R_p, ETo was 93, 29 and 18% higher than $LT_{(2009/10)}$, respectively. Although ETo during F_p and V_p was higher than $LT_{(2009/10)}$, the higher P during the same periods contributed to increased moisture availability from plant roots absorption. The low P and high ETo during the R_p resulted in high AI of 84% less favourable as compared to the $LT_{(2009/10)}$. If it was not for the very favourable climatic conditions that occurred during F_p and V_p the extremely dry and unfavourable R_p could have had serious yield implications due to low moisture availability. This indicates that moisture conservation especially in dryland crop production areas should be an all year round activity.

4.3 SOIL WATER BALANCE

4.3.1 Drainage

The results of the drainage characteristics of the Toowoomba/Arcadia ecotope for rooting zone (0 - 1200 mm), is presented in Figure 4.1. The drainage curve is a model used to determine the mode of water movement in any given soil profile. The rate of water movement in a particular soil is determined by the soil characteristics or properties of that particular soil.

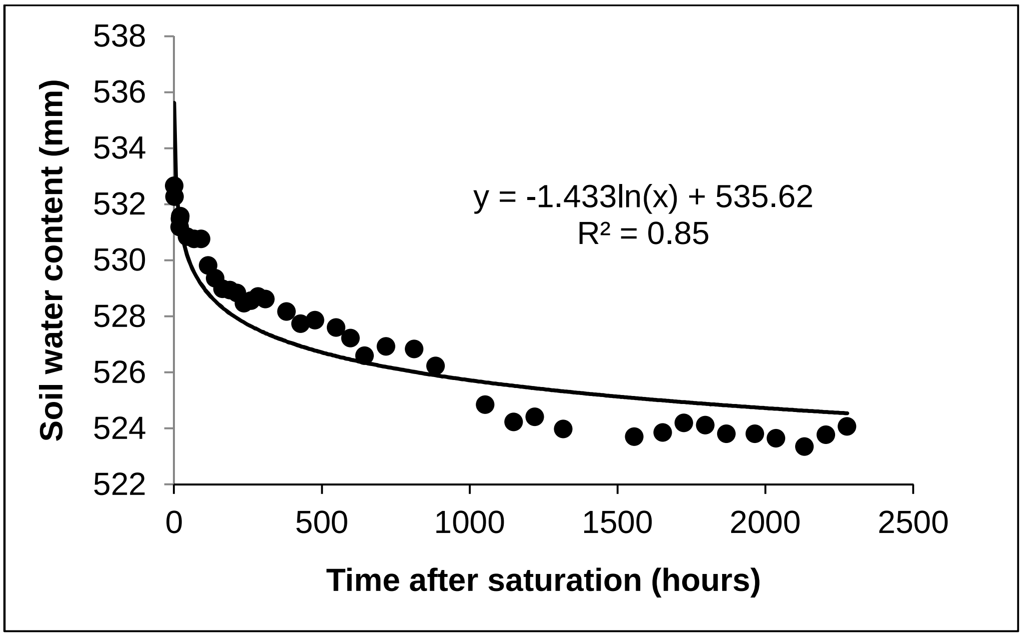


Figure 4.1 Drainage curve for the Toowoomba/Arcadia ecotope (0 – 1200mm).

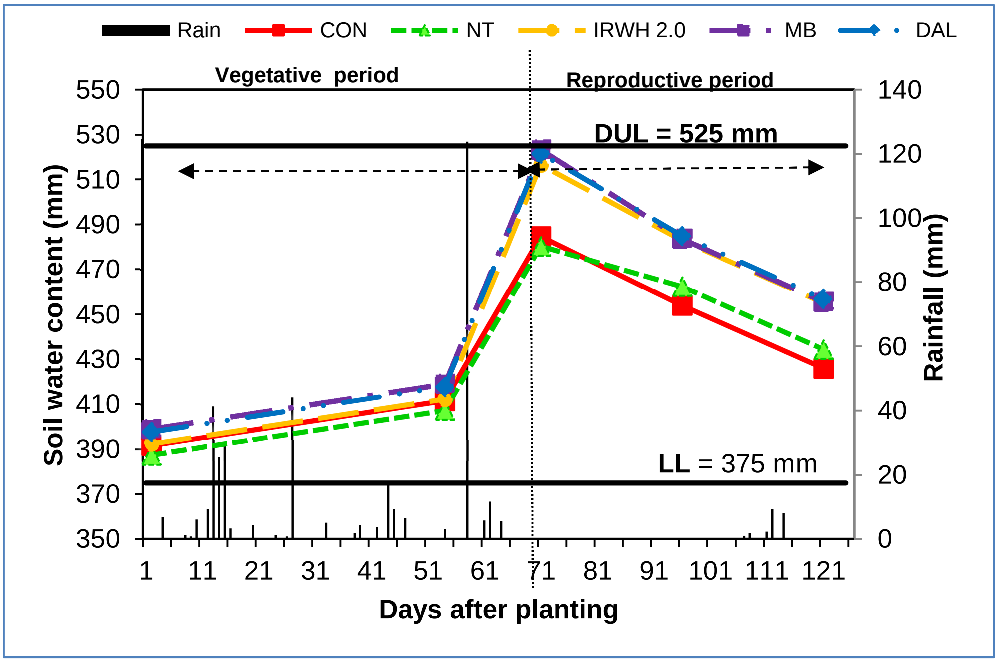
The drainage curve served as a measure of the drainable porosity, DUL, rate of change of drainage, and permeability of the horizon to the underlying horizons and lateral movement of water in the same horizon. The Arcadia soil form under the discussion is described by high clay content (70%) and is presumably having low infiltration rate. At zero hours after the profile was fully saturated the SWC was 532 mm, lowered to about 525 mm after 95 days of internal drainage. The SWC rapidly lowered for the first 36 days after saturation, this indicates the internal drainage processes of D. The SWC stabilized from 48 to 95 days after saturation. This indicates that the soil has the ability of retaining more SWC at about 525 mm on average for about 40 days after saturation. Because of the high clay content and slow infiltration rate of the Towoomba/Arcadia ecotope, more rainwater will likely be lost through R_{EX} water, under CON. This might also occur under NT treatment if the plant residues are not enough to prevent any runoff water movement on the soil surface. Therefore, the basins of RWHT's would limit or reduce the R_{EX} and increase PAW for plant root uptake.

4.3.2 Soil water content

The results of the measured changes in the SWC of the rootzone during the 2008/09 and 2009/10 growing seasons are illustrated in Figure 4.2. The measured changes are vital for the purpose of determining the water balance data and explaining yield differences for all the treatments. The water management boundaries of PAW, DUL and LL are also included in the graphs, as these are critical in determining the variations in the PAW for plant root uptake, provided by different treatments.

The results for both seasons had a similar trend and all the treatments responded positively towards rainfall events. The experiment was implemented during the 2008/09 growing season where all the treatments had low SWC. The SWC of all the treatments was between 390 and 410 mm, close to LL at planting. The LL of PAW for the Towoomba/Arcadia ecotope is 375 mm (Figure 4.2). The SWC slightly increased with the rainfall events which were mostly received between 11 and 15 DAP during the 2008/09 season.

a) 2008/09 Season



b) 2009/10 Season

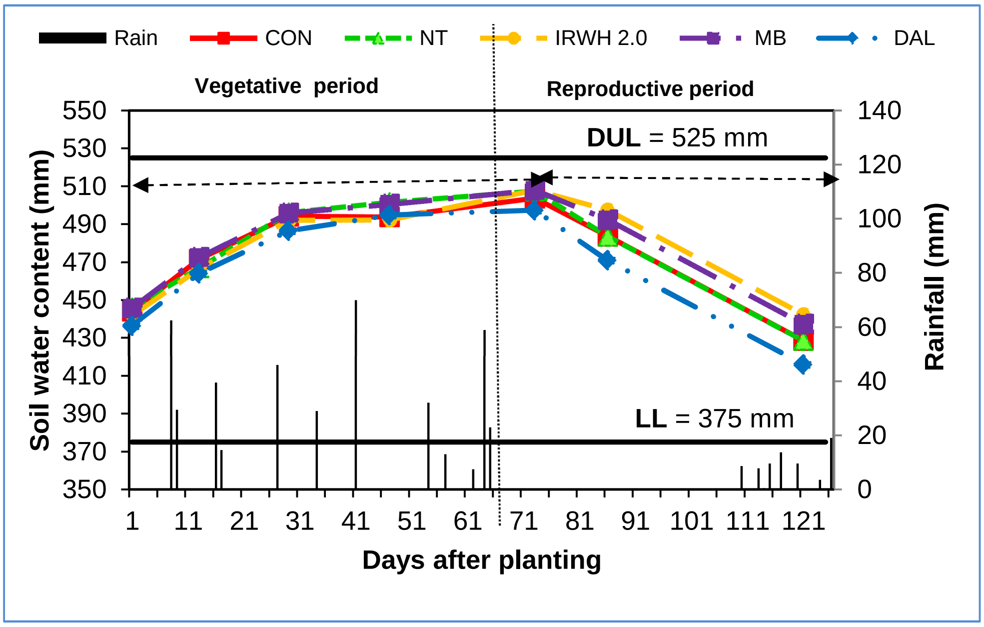


Figure 4.2 Changes in soil water of the rootzone (0 - 1200 mm) during the two maize growing seasons (2008/09 and 2009/10) on the Towoomba/Arcadia ecotope.

At 58 DAP a high rainfall event of 120 mm was received and the SWC of all treatments increased. The SWC of IRWH, DAL and MB treatment were highest at 510 which is near DUL of the Towoomba/Arcadia ecotope. The SWC of IRWH, DAL and MB increased by about 100 mm compared to the SWC of CON and NT treatment which only increased by about 70 mm. The low increase in SWC increase of CON and NT was possibly be due to the loss of rainwater through R_{EX}. Whilst the high increase in SWC of the RWHT's and MB would be attributed to the ability to harvest and conserve rainwater in the basins compared to CON and NT. During the R_p a total P of 23 mm was received and SWC of all the treatments decreased sharply after DAP 71 in a similar pattern as a result of the soil water extraction by the maize crops. The lack of P during R_p would be the cause of low grain yield during the 2008/09 season. Soil moisture availability during the R_p is critical to meet the maize water requirement in order to complete its grain filling stage.

During the 2009/10 season the SWC of all the treatments was higher and was characterized by a fairly well-distributed P during the Vp. All the treatment had a positive response to the P events, but DAL treatment had a slightly lower SWC at 71 DAP. Similarly in 2009/10 season no rainfall was received during Rp until 111 DAP.

This lead to sharp decrease in the SWC during the Rp, and this indicates that the crop relied heavily on the stored SWC. There was no D from all the treatments during both 2008/09 and 2009/10 growing seasons. The DUL of the Towoomba/Arcadia ecotope of 525 mm was no exceeded by the SWC of any of the treatment (Figure 4.2).

4.3.3 Runoff

Table 4.3 represents the results of R_{EX} which was calculated from the CON and NT treatments from the two maize growing seasons 2008/09 and 2009/10 on the Towoomba/Arcadia ecotope.

Table 4.3 P (mm) and R_{EX} (mm) from CON and NT over two growing seasons (2008/09 and 2009/10) for maize production on the Towoomba/Arcadia ecotope

Parameters	Seasons	Periods				
		F_p	**V_p**	**R_p**	**G_p**	**P_p**
P (mm)	2008/09	*	374	23	397	*
	2009/10	253	426	50	476	729
	Mean	*****	**400**	**37**	**437**	*****
R_{EX} (mm)	2008/09	*	61	0	61	*
	2009/10	45	84	1	85	131
	Mean	*****	**73**	**1**	**73**	*****
R_{EX}/P (%)	2008/09	*	16.3	0	15.4	*
	2009/10	18	19.7	2.5	17.9	18
	Mean	*****	**18.1**	**1.3**	**16.7**	*****

F_p = fallow period; V_p = vegetative period; R_p = reproductive period; G_p = crop growing period; P_p = production period, * = no data available.

It was assumed that R_{EX} was zero on IRWH, MB and DAL treatments and that R_{EX} only occurred from NT and CON. R_{EX} from NT and CON was calculated with the equation that was developed on the Glen/Bonheim ecotope for the Toowoomba/Arcadia ecotope of Anderson (2007) (Equation 5). The mean results indicated that R_{EX} amounted to 73 mm which is 17.9% of the total P during the G_p for CON and NT. This resulted in the loss of valuable rainwater that could have been utilized to produce higher maize yields, especially in a semi-arid environment where every drop of rainwater must be utilized efficiently and effectively for increasing crop yields. More P was received during the 2009/10 V_p, therefore this led to the higher ex-(R_{EX})/P value of 19.7% compared to low value during the R_p which was 2.5%.

4.3.4 Evapotranspiration

ET, Ev and Es results from individual treatments are presented in Table 4.4 Ev defines the loss of water via the stomata of the plant canopy, whilst Es defines loss of water from the soil surface. The ET is the major loss of water in semi-arid areas and it is directly related to the grain yield of the crop. The RWH&CT's are designed with the possibility of reducing the impact of R_{EX} and ensuring the water is converted into grain production.

Table 4.4 Transpiration (Ev), evaporation from the soil surface (Es) and evapotranspiration (ET), over two maize growing seasons (2008/09 and 2009/10) for various treatments on the Towoomba/Arcadia ecotope

	Parameters							
	Ev (mm)		**Es (mm)**		**ET (mm)**		**Es/ET (%)**	
Treatments	2008/09	2009/10	2008/09	2009/10	2008/09	2009/10	2008/09	2009/10
CON	67.4^{ab}	94.5^{ab}	233.6^{ab}	311.4^{a}	301.0^{a}	405.9^{a}	77.70^{a}	76.61^{a}
NT	59.8^{a}	70.4^{a}	228.5^{a}	337.6^{ab}	288.3^{a}	408.0^{a}	79.21^{a}	82.64^{a}
IRWH	73.4^{b}	105.4^{b}	260.3^{bc}	370.0^{bc}	333.7^{b}	475.4^{b}	78.01^{a}	77.78^{a}
MB	68.6^{ab}	92.4^{ab}	271.4^{c}	392.0^{c}	340.0^{b}	484.3^{b}	79.61^{a}	80.87^{a}
DAL	68.4^{ab}	94.8^{ab}	268.8^{c}	401.4^{c}	337.2^{b}	496.3^{b}	79.72^{a}	80.88^{a}
Significant	*	*	*	*	*	*	ns	ns
$LSD_{0.05}$	12.4	27	31.5	56.8	30.7	56.6	-	-
CV $_{(\%)}$	5.9	6.6	11.2	9.2	11.3	12.1	-	-

CV= coefficient of variation. * = significant at P≤0.05. The values with similar superscripts are not significantly different (P≤0.05) within a column.

The results from Table 4.4 indicate that the Ev of the IRWH treatment was significantly different from the NT treatment for both 2008/09 and 2009/10 growing season. Significant differences were not found between the RWHT's and the CON treatment, but IRWH induced a higher Ev for both growing seasons compared to all the other treatments. The higher the Ev values the more productive the crop become, as a result of more water utilization by the crops during photosynthesis. The high water losses via Ev positively correlate to the crop yield. IRWH induced 9 and 12% more Ev values compared to CON during both 2008/09 and 2009/10 seasons, respectively. MB and DAL also induced high Ev values than CON during 2008/09 season, though the margins were minimal, at about 2 and 1% respectively. The NT treatment was the poorest in improving efficient moisture supply to enhance Ev of the maize crop, at an average 24% lower Ev values for both seasons.

The Es of IRWH was significantly different from the NT treatment, but not significantly different from other treatments. Measures to reduce Es, will ensure water became available for Ev. The higher Ev value means that more water transpired through the crop, contributing to yield increases. MB and DAL had higher Es values than CON and NT treatments during both seasons, this indicates that MB and DAL contribute to higher water losses through Es, which is critical to reducing crop yield. The high Es values of IRWH, MB and DAL treatments would be as a result of higher SWC which was conserved through the basins, therefore more water was made available to meet both Ev and Es demands. Whilst the lower Es values of both CON and NT treatments during both growing seasons, was as a result of low SWC, which would results in lower supply of the Ev and Es demands.

The Es/ET percentage value determines the total contribution of Es value to the total ET. The higher the Ev values to the total ET the higher the potential of crop yield. The importance of water conservation is to ensure that more water transpires through the crop canopy which leads to high photosynthetic assimilation and high yield potential. But there were no significance difference amongst all the treatments during both the 2008/09 and 2009/10 seasons (Es/ET). The CON treatment which was envisaged to result into higher Es/ET percentage, due to the ploughing and exposing the top soil to high intensive light, had lowest average mean of Es/ET for both seasons when compared to all treatments. But the low Es/ET would be as a result of low SWC which reduced the Es value. Therefore, the treatment that increases Ev values and reduces Es water losses is critical when practicing dryland maize production in order to sufficiently meet and supply the Ev water demand for the purpose of increasing water for production than water for losses.

4.3.5 Plant available water

4.3.5.1 Plant available water at tasselling

Figure 4.3 represents the results of PAW_T induced by different RWH&CT's and CON treatment. Water availability at maize tasselling stage is critical, moisture stress can lead to delayed silking and this will hamper the fertilization synchrony of the maize crop. When fertilization synchrony of the maize is affected this leads to poor crop yield.

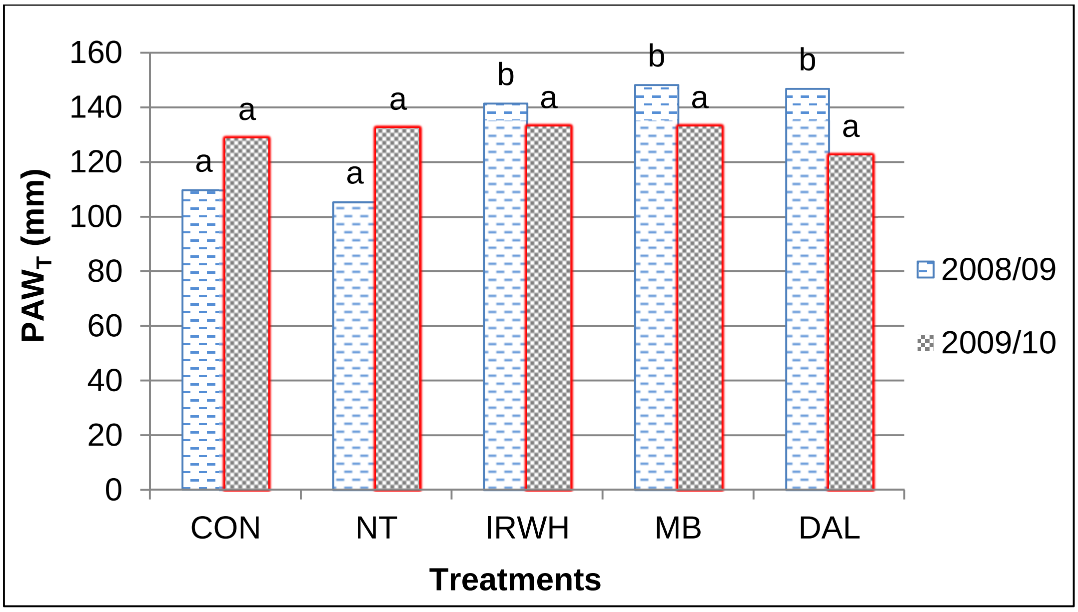


Figure 4.3 Plant available water at tasselling (PAW_T) over two maize growing seasons (2008/09 & 2009/10) on the Towoomba/Arcadia ecotope.

The PAW_T for the IRWH, MB and DAL during the 2008/09 season were significantly higher from the CON and NT treatments. Although IRWH, MB and DAL were not significantly different, the MB treatment had slightly higher PAW_T than IRWH and the DAL techniques (Figure 4.3). The treatments that provide high PAW_T minimize the water stress effect on the fertilization process and grain filling of the maize. If water stress is high during tasseling stage the silking process is delayed, and fertilization process will be affected. The pollen is likely to be shed earlier than the silking process and this will affect the yield of the crop. SIWI (2001) indicated that, water stress during crop growth, even during short periods of a couple of weeks, is a major cause of yield reduction in dryland areas. IRWH, MB and DAL had higher PAW_T during the 2008/2009 growing season compared to CON and NT treatments. There were no significance differences amongst all the treatments during the 2009/10 growing season. The DAL had the lowest PAW_T of all the treatments during the

2009/10 season. The 2009/10 growing season was characterized by better rainfall distribution compared to the 2008/09 season. The high rainfall events prior to tasseling would likely be the cause of no significant differences amongst the treatments during the 2009/10 season.

4.3.5.2 Plant available water at physiological maturity

Figure 4.4 presents the results of PAW_{PM} induced by different RWH&CT's and CON treatment. The plant water requirement reduces with the grain filling of maize, slightly after fertilization of the silks has taken place, and becomes zero at physiological maturity, as the plant cells die.

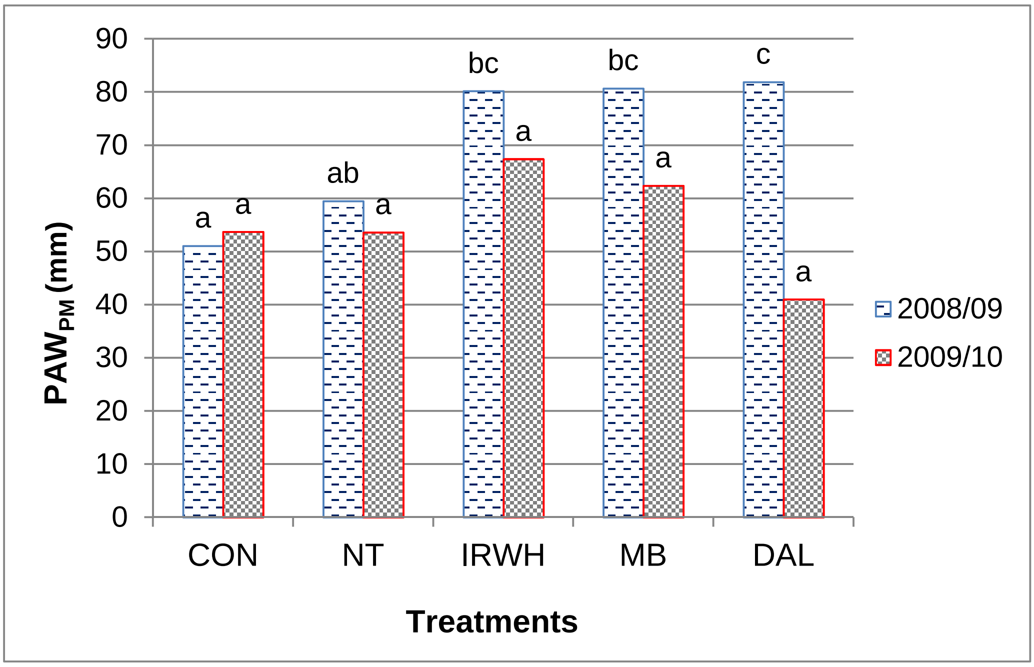


Figure 4.4 Plant available water at physiological maturity over two maize growing seasons (2008/09 &2009/10) on the Towoomba/Arcadia ecotope.

PAW_{PM} during the 2008/2009 growing season for the IRWH, MB, and DAL were significantly higher from the CON treatment. IRWH, MB and DAL had on average 28 mm more PAW_{PM} than the CON treatment. Therefore this indicated that IRWH, MB, and DAL were efficient in conserving rainwater under such poor P distribution experienced of 2008/09 growing season compared to CON. The CON and NT treatment lost more water through R_{EX} during both seasons (2008/09 and 2009/10). DAL treatment was significantly different from both CON and NT treatments during the 2008/09 growing season.

Although IRWH, MB and DAL were not significantly different, the DAL treatment induced the highest mean of PAW_{PM}. The higher PAW_{PM} of DAL treatment would be as a result of total limitation of the R_{EX} compared to the MB which does not cater for additional collection of the R water into the basins. But a different scenario was encountered during the 2009/10 season where DAL had the lowest average mean of PAW_{PM} as compared to all other treatments. This would be as a result of the scrapper removing the top soil when making ridge and leaving the subsoil bare and exposing it to high intensive temperature which increased Es. This is also evident by the highest Es value of DAL during the 2009/10 season (Table 4.4). All other treatments had lower PAW_{PM} when comparing 2008/09 and 2009/10 season.

The PAW_{PM} of the RWH&CT's for the 2009/10 growing season were not significantly different from the CON treatment. However, the IRWH had higher PAW_{PM} than all the treatments. IRWH contributed about 28 and 15 mm more than CON treatment during both 2008/09 and 2009/10 seasons, respectively. The very small insignificant higher PAW_{PM}, provided a higher yield and yield components of maize during 2009/10 growing season. This indicates the effectiveness of the techniques in converting P into harvestable yield.

4.3.6 Rainfall storage efficiency

The results of RSE are represented in Table 4.5 for the Towoomba/Arcadia ecotope. The RSE measures the treatment's ability to conserve and store rainwater on a specific soil profile during the F_p.

Table 4.5 Rainfall storage efficiency as induced by the different treatments on the Towoomba/Arcadia ecotope

Seasons	Treatments					
	CON	**NT**	**IRWH**	**MB**	**DAL**	**Mean**
2008/09	*	*	*	*	*	*
2009/10	3.55	8.41	10.21	9.83	8.31	***8.06***
Mean	*	*	*	*	*	*****

* indicate there was no fallow period data for 2008/09 season.

RSE for the 2008/09 season was not calculated because there were no SWC values for the fallow period of 2008/09 season. Equation 7, used in this study requires the SWC at harvesting of the previous crop, therefore only the results of 2009/10 were used. The 2008/09 season was the first year of the experiment and treatment were implemented closer to the planting date of maize during the 2008/09 season.

From Table 4.5 the IRWH, MB, NT treatments induced the highest RSE values, which were 188, 177 and 137 % more than the CON treatment. The highest RSE values of the IRWH and MB treatments positively correlate to the highest SWC measurement of the two treatments (IRWH and MB) during the two maize growing seasons (2008/09 and 2009/10). The low RSE values of the CON treatment would be as a result of lack of water conservation mechanism of the treatment, more water was lost through the R_{EX} and Es. The high Es water loss from CON treatments is likely caused by the tillage practices whereby the soil is exposed to high temperature during seedbed preparation and F_p weed control. Van Donk *et al.* (2010) argued that the net effect over a season on a total Es is expected to be greater from cultivated bare soil.

4.4 PLANT PARAMETERS

4.4.1 Plant height

Table 4.6 presents the results of maize plant height during the two growing seasons (2008/09 and 2009/10) on the Towoomba/Arcadia ecotope. The plant height (cm) was measured during three growing stages, the V5, V12 and R6. The detailed statistical analyses for the plant height during both the 2008/09 and 2009/10 seasons are presented in Appendix 5 and Appendix 6.

Table 4.6 Plant height (cm) of maize for different treatments during two maize growing seasons (2008/09 and 2009/10) on the Towoomba/Arcadia ecotope

	Growth stage					
	V5		**V12**		**R 6**	
Treatments	2008/09	2009/10	2008/09	2009/10	2008/09	2009/10
CON	44.1^{ab}	44.9^{a}	113.1^{a}	110.8^{a}	207.1^{a}	220.8^{b}
NT	41.3^{a}	43.0^{a}	110.7^{a}	110.8^{a}	205.9^{a}	222.6^{bc}
IRWH	45.6^{b}	46.9^{a}	115.9^{a}	110.2^{a}	211.5^{a}	227.6^{c}
MB	43.3^{ab}	45.7^{a}	113.9^{a}	116.3^{a}	207.4^{a}	217.3^{ab}
DAL	46.0^{b}	46.7^{a}	109.4^{a}	106.1^{a}	210.0^{a}	213.9^{a}
Significant	*	ns	ns	ns	ns	*
$LSD_{0.05}$	3.161	-	-	-	-	5.907*
CV $_{(\%)}$	4.7	-	-	-	-	2.0

V5 = vegetative leave stage 5, V12 = vegetative leave stage 12, R6 = reproductive stage 6. CV= coefficient of variation. * = significant at P≤0.05. ns = no significant difference. The values with similar superscripts are not significantly different (P≤0.05) within a column.

Plant height of IRWH and DAL during V5 was significantly higher from the NT but not significantly different from MB and CON during the 2008/09 season. There were no significant differences amongst all the treatments during V5 of the 2009/10 season, but IRWH had higher plant height measurement than all the treatments during both seasons (2008/09 and 2009/10). During the V12 growing stage, there were no significant differences amongst all the treatments for both 2008/09 and 2009/10 growing seasons.

There were no significance differences at R6 of the 2008/09 season but there were significance differences during the 2009/10 season. The plant heights at R6 for IRWH and NT treatments were significantly higher to the DAL but not significantly different to the CON and MB treatments during the 2009/10 season. IRWH induced higher plant height averages for 2008/09 and 2009/10 season at both V5 and R6. The differences in the plant height measurements between the 2008/09 and 2009/10 season would be as a result of the difference in growing ability between the two cultivars used during the study period. MB induced the highest plant height measurement during the V12. The higher plant heights of both the IRWH and MB treatments would be as a results of high SWC during the critical reproductive period of maize where water requirements were higher. The higher plant height also contributed to the significant yield increases of the IRWH, which is attributed to the water conservation ability of the IRWH treatment (Table 4.6). All the treatments followed similar patterns of plant height measurements. DAL had the lowest plant height during the R6 growing stage of maize, this would be as a result of low SWC results of DAL during the 2009/10 season as shown in Figure 4.2.

4.4.2 Stem diameter

The results of stem diameter (cm) of maize from all the treatments used during the two maize growing seasons are represented in Table 4.7. The detailed statistical analyses for the stem diameter during both the 2008/09 and 2009/10 seasons are presented in Appendix 7 and Appendix 8.

Maize stem diameter results were only significantly different during the V12 stage of the 2008/09 season. The MB treatment was significantly higher to the NT treatment during the 2008/09 season at V12 growing stage of maize. There were no significant differences amongst all the treatments during the V5 and R6 growing stages for both 2008/09 and 2009/10 seasons.

Table 4.7 The results of stem diameter of maize from different treatments of during the two maize growing seasons (2008/09 and 2009/10) on the Towoomba/Arcadia ecotope

	Growth stages					
	V5		**V12**		**R 6**	
Treatments	2008/09	2009/10	2008/09	2009/10	2008/09	2009/10
CON	1.12[a]	1.08[a]	2.27[a]	2.31[a]	2.51[a]	3.04[a]
NT	1.18[a]	1.11[a]	2.21[a]	2.32[a]	2.65[a]	3.11[a]
IRWH	1.09[a]	1.12[a]	2.33[ab]	2.43[a]	2.71[a]	3.06[a]
MB	1.16[a]	1.09[a]	2.47[b]	2.36[a]	2.72[a]	3.12[a]
DAL	1.14[a]	1.09[a]	2.20[a]	2.26[a]	2.62[a]	3.10[a]
Significant	ns	ns	*	ns	ns	ns
$LSD_{0.05}$	-	-	0.1833	-	-	-
CV $_{(\%)}$	-	-	5.2	-	-	-

V5 = vegetative leave stage 5, V12 = vegetative leave stage 12, R6 = reproductive stage 6. CV= coefficient of variation. * = significant at P≤0.05. The values with similar superscripts are not significantly different (P≤0.05) within a column.

The results show that maize of CON treatment had the lowest stem diameter measurement during the R6 growing stage compared to all the treatments during both 2008/09 and 2009/10 season. The 2009/10 season had on average higher stem diameter measurements during all the three growing stages, this would be as a result of the higher rainfall received during the 2009/10 season or due to the variation in the growth ability of the different cultivars used in the study. The effect of higher rainfall received during the 2009/10 season was also the probable cause of higher SWC measurement as compared to the 2008/09 season. This high SWC of 2009/10 would be the cause of higher stem diameter measurement compared to 2008/09.

4.4.3 Biomass

Biomass yields for different treatments are summarized in Table 4.8. The detailed statistical analyses for the biomass yields during both the 2008/09 and 2009/10 seasons are presented in Appendix 9 and Appendix 10.

Biomass production plays an important role in the grain yield of maize. For both seasons IRWH treatment was significantly higher to the NT treatment, producing 23 and 50% more biomass in the 2008/09 and 2009/10 growing seasons, respectively than NT treatment. The IRWH treatment was not significantly different to other treatments including the CON for both 2008/09 and 2009/10 seasons. The IRWH had the highest biomass production of 6530 and 6856 kg ha^{-1} for the 2008/09 and 2009/10 growing seasons, respectively, than all other treatments.

Table 4.8 Maize biomass yield (kg ha^{-1}) under different RWH&CT's over two growing seasons (2008/09 and 2009/10) on the Towoomba/Arcadia ecotope

	Biomass		
Treatments	**2008/09**	**2009/10**	**Mean**
CON	5997^{ab}	6144^{ab}	6071
NT	5320^{a}	4578^{a}	4949
IRWH	6530^{b}	6856^{b}	6693
MB	6100^{ab}	6007^{ab}	6054
DAL	6085^{ab}	6168^{ab}	6127
significant	*	*	-
$LSD_{0.05}$	1202.9	1501.7	-
$CV_{(\%)}$	5.9	11.3	-

LSD=Least Significant Difference, CV= coefficient of variation,* = significant at P≤0.05. The values with similar superscripts are not significantly different (P≤0.05) within a column.

The increase in biomass production of the IRWH would be attributed to the efficient P distribution of the 2009/10 season compared to the 2008/09 season, and the efficiency of the system to conserve and encourage more water infiltration. The

2009/10 season had 79 mm more P than the 2008/09 during the G_p, this increase in P collates to the increase in biomass yield of all the treatments except NT treatment. IRWH, DAL and CON treatments had a higher biomass production compared to NT and MB, with NT having a reduction in biomass yield of more than 740 kg ha^{-1} from the 2008/09 to the 2009/10 season despite the good P distribution during the 2009/10 season. This biomass yield reduction of NT is in contrast with the increase in the measured SWC, where the NT SWC during 2009/10 was 20 mm more than 2008/09 season, which was expected to result in positive biomass yield. The decrease in biomass yield of NT treatment would be probably linked to surface sealing of the Arcadia soil due to high clay content. NT treatment lost more water was lost through R_{EX} and possibly due to inefficiency of weed control through both hand hoeing and chemical weed control. Other factors such as the difference in yielding ability of the two cultivars used in the study might have contributed to the low NT biomass yield.

4.4.4 Grain yield

Table 4.9 represent the maize grain yield results of different RWH&CT's and CON treatment for the 2008/09 and 2009/10 growing seasons. The detailed statistical analyses for the grain yield during both the 2008/09 and 2009/10 seasons are presented in Appendix 11 and Appendix 12.

The IRWH grain yield was significantly higher from the NT treatment. The IRWH produced 26 and 56% more maize grain yield during the 2008/09 and 2009/10 respectively than the NT treatments. IRWH was not significantly different from other treatments including CON. The IRWH had the highest grain yield of 2089 and 2614 kg ha^{-1} for the seasons 2008/09 and 2009/10, respectively. Although there were statistical differences, IRWH produced over 11 and 13% higher yields during the 2008/09 and 2009/10 season compared to the CON treatment. These results conform with Hensley *et al.* (2000), who found that the maize yield of IRWH were about 50% more compared to the CON system. From a four year experiment, Botha *et al.* (2003) also concluded that IRWH outperformed CON with regard to maize grain yield which is an indication of the efficiency of the IRWH to conserve rainwater and increase dryland maize production. Botha *et al.* (2014) reported 31% higher maize grain yield of IRWH when compared to CON on the Fort Cox/Valsrivier ecotope. With the MB plough tested by Botha *et al.* (2014) on the Glen/Oakleaf ecotope, they found a 3% yield increase of maize when compared to the CON. The water conserved in the basins infiltrates deeper into the soil, below the evaporation layer.

Table 4.9 Maize grain yield under different RWH&CT's over two growing seasons (2008/09 and 2009/10) on the Towoomba/Arcadia ecotope

	Grain yield		
Treatments	**2008/09**	**2009/10**	**Mean**
CON	1879^{ab}	2319^{ab}	2099
NT	1661^{a}	1686^{a}	1674
IRWH	2089^{b}	2614^{b}	2352
MB	1967^{ab}	2276^{ab}	2122
DAL	1934^{ab}	2328^{ab}	2131
significant	*	*	-
$LSD_{0.05}$	366.8	630.3	-
CV	6.3	11.8	-

LSD=Least Significant Difference, CV= coefficient of variation,* = significant at $P \leq 0.05$. The values with similar superscripts are not significantly different ($P \leq 0.05$) within a column.

This increase in P resulted in the yield increase of all the treatments, but maize grain yield under IRWH increased by 25% from 2008/09 to 2009/10 season. The positive increase of grain yield of IRWH would be attributed to the well P distribution of the 2009/10 compared to the 2008/09 growing season, and the efficiency of the system to conserve and enhance water infiltration. An increase in rainwater conservation of the treatments, leads to higher PAW, which was evident under IRWH, DAL and MB treatments. Although there were not significant differences, the average grain yield of DAL and MB were higher than CON at about 1 and 2% more grain yield. Botha *et al.* (2014) from a study conducted on the Glen/Swartland ecotope, reported that DAL produced 6% more maize grain yield when compared to CON. Both DAL and MB treatment produced 27% higher grain yield than the NT treatment during the two seasons (2008/09 and 2009/10). This indicates that the high moisture content difference between the treatment leads to higher grain yield.

4.4.5 Harvesting index

Figure 4.5 illustrate the results of the HI for the two growing season (2008/09 and 2009/10) on the Towoomba/Arcadia ecotope.

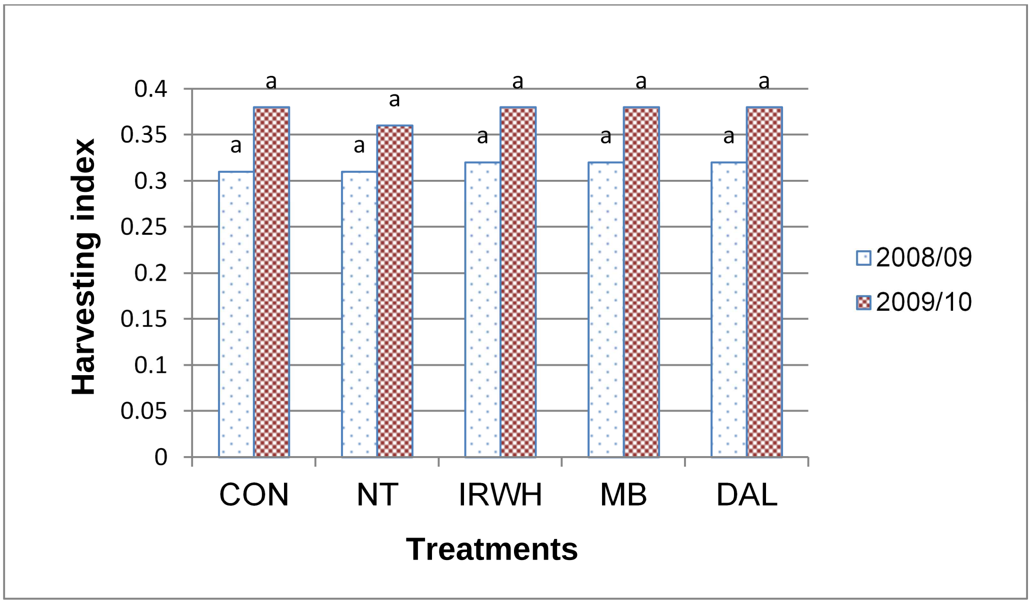


Figure 4.5 Harvesting index for different treatments over the two maize growing seasons (2008/09 and 2009/10) on the Towoomba/Arcadia ecotope.

Figure 4.5 show that there were no significance differences in the HI for all the treatments during both the 2008/09 and 2009/10 growing seasons. The HI of the 2009/10 season was slightly higher than that in the 2008/09 season for the treatments, due to slightly higher grain yield of 2009/10 compared to 2008/09 season. This would also be attributed to the difference in the yielding potential of the two different cultivars used in the experiment. Although the were no significant difference, the HI of IRWH, DAL and MB, were slightly higher than for the CON and

NT treatments during the 2008/09 season. Similar results were found by Botha (2006), that there were no significant differences in HI between RWH&CT's, but the HI of the RWHT's and MB were higher than the CON treatment.

The HI of the NT treatment was the lowest in the 2009/10 season as the grain yield of NT treatment was also the lowest. This would have resulted in more soil water extracted by the weeds, due to delayed weeding, as compared to the other treatments which are complemented by mechanical weed control during the implementation of the treatment. The HI of all the RWHT's, MB and CON were 3 and 5% higher than the HI of the NT treatment during the 2008/09 and 2009/10 growing season, respectively.

4.4.6 Precipitation use efficiency

The PUE_{gp} results for the various treatments over two maize growing seasons (2008/09 and 2009/10) are represented in Table 4.10.

Table 4.10 Precipitation use efficiency (kg ha^{-1} mm^{-1}) from various treatments over two maize growing seasons (2008/09 and 2009/10) on the Towoomba/Arcadia ecotope

	Precipitation use efficiency		
Treatments	2008/09	2009/10	**Mean**
CON	4.74^{ab}	4.87^{ab}	**4.54**
NT	4.18^{a}	3.54^{a}	**3.53**
IRWH	5.27^{b}	5.49^{b}	**5.29**
MB	4.96^{ab}	4.78^{ab}	**4.63**
DAL	4.88^{ab}	4.89^{ab}	**4.79**
Significant	*	*	-
$LSD_{0.05}$	0.91	1.41	-
CV (%)	11	13	-

LSD=Least Significant Difference, CV= coefficient of variation, * = significant at P≤0.05. The values with similar superscripts are not significantly different (P≤0.05) within a column.

PUE during the two growing seasons was useful in determining the effectiveness of the techniques in converting a given amount of P into maize grain yield. Table 4.10 shows for the two growing seasons that IRWH was significantly higher from NT treatment, but not significantly different from the other treatments. Botha (2006) indicated that PUE is based on a simple principle that the system that produces the highest yield per unit area represents the best practice in any dryland crop production. IRWH had higher PUE_{gp} values for both growing seasons, than all the treatments.

This indicates the efficiency of the IRWH technique to convert rainfall into harvestable yield. IRWH had higher PUE_{gp} values which were also found in a study by Hensley *et al.* (2000). Mzezewa *et al.* (2011) concluded that PUE under IRWH on sunflower was consistently higher than under CON system but varied between the cropping seasons. In this study the IRWH induced 1.09 and 1.95kg ha^{-1} mm^{-1} for the 2008/09 and 2009/10 growing season respectively when compared to the NT treatment. This higher PUE_{gp} induced by IRWH is attributed to the technique's ability to limiting R_{EX} compared to NT. The NT systems produced the lowest PUE_{gp} for both season with the lowest mean being in the 2009/10 growing season with PUE_{gp} of 3.54. MB and Dal had 32 and 35% more PUE_{gp} than NT treatment. This is also supported by the high biomass and grain yield of the MB and DAL treatment when compared to the NT treatment. Comparing MB and DAL treatment to CON the difference in biomass and grain yield were marginally higher, and this is evident with PUE_{gp} than MB and DAL slightly contributed to better PUE_{gp} than CON throughout the study period.

4.4.7 Rainwater productivity

Figure 4.6 represents RWP of maize for the two growing seasons. RWP is an important indicator that determines the efficiency of the technique in converting the rainwater into harvestable grain yield over consecutive years. RWP measures the efficiency of the system to produce a certain amount of grain yield per a given amount of rainfall, which is measured as kg ha^{-1} mm^{-1}. Therefore, for long-term studies RWP will be a better indicator than PUE which measures the efficiency of a treatment intra-seasonally, whilst RWP considers the total average yield and rainfall of all the study period.

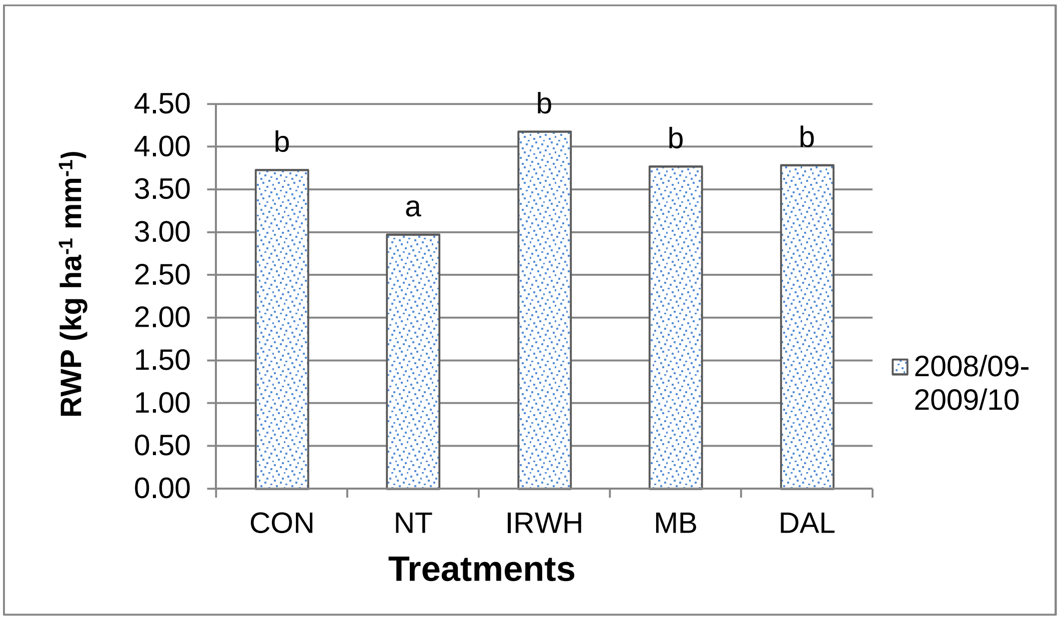


Figure 4.6 Rainwater productivity as induced by different treatments over the two maize growing seasons (2008/09-2009/10) on the Towoomba/Arcadia ecotope.

From Figure 4.6 it can be seen that the results of RWP from various RWHT's were significantly different to the NT treatment, but were not significantly higher to the CON and MB treatment. The IRWH induced the highest RWP which was 41% more than the NT treatment. Results indicate that IRWH and DAL were 12 and 2% more effective in converting rainwater into harvestable grain yield than the CON treatment. These indicate that for every 1 mm of P received IRWH and DAL will produce 12 and 2% more yield than CON. In this study the average yield difference of both seasons (2008/09 and 2009/10) when planting maize under IRWH was 250 kg ha^{-1} than the CON treatment. These results are also comparable to those found by Botha (2006), who concluded that the IRWH technique produced 22% higher RWP value than the CON treatment. Botha (2006) also stated that more water in the basin means more water available for plant root uptake. Hence, for the results above they would likely be attributed to the efficiency of the techniques in narrowing the total potential R_{EX}

and conserving and directing the water where it is mostly required for the purpose of increasing PAW for the plant root extraction.

4.5 THE SOIL-PLANT ATMOSPHERIC CONTINUUM

Figure 4.7 illustrates the results of the soil-plant-atmospheric continuum (SPAC) correction for the two growing season (2008/09 and 2009/10) on the Towoomba/Arcadia ecotope.

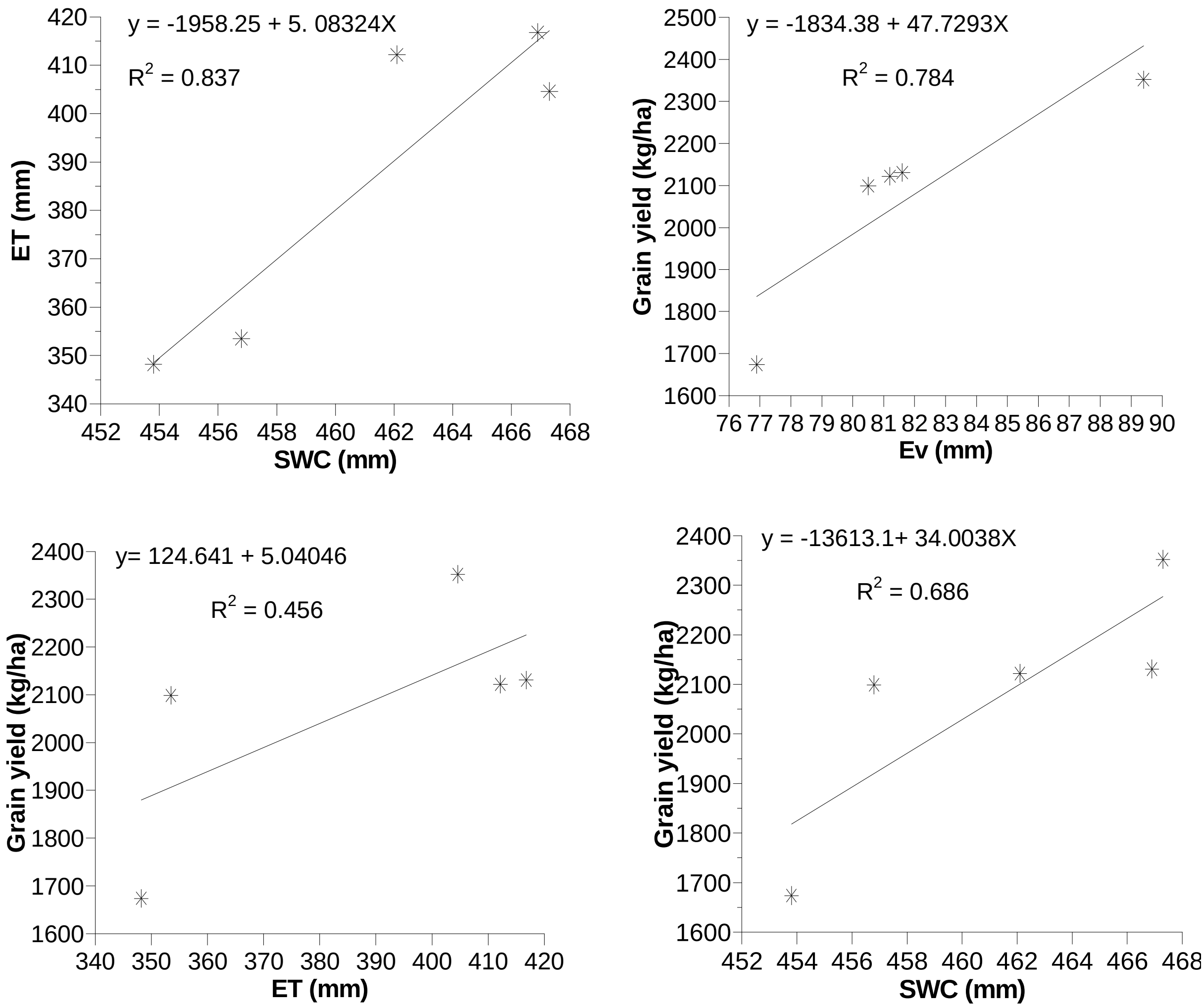


Figure 4.7 The relationship of the soil water content, evapotranspiration, transpiration and maize grain yield for the two growing seasons.

The SWC is a major important driver of the ET and grain yield of the maize crop. A high R^2 value of 83.7% was obtained when SWC was correlated with ET. This indicates that the high SWC leads to the high Es and Ev values. An R^2 value of 45.6% was obtained when correlating ET and maize grain yield. Keller (2005) on the study of yield-ET relationship indicated, there is little correlation between yield and ET. He concluded that the apparent lack of correlation between yield and ET is due primarily to two factors: 1) difference seasons' saturation vapour pressure deficit and 2) variability in the Es component of ET. Keller (2005) found that there is a high correlation shown between maize yield and Ev, with Es explaining most of the remaining variability in the maize yield-ET relationship. Therefore in this study a high R^2 value of 78.4% was obtained when correlating Ev and maize grain yield. Therefore, when the SWC meet the Ev demand for the maize crops, more water is made available for the process of photosynthesis leading to increased crop yield. Therefore, the lower R^2 value would be attributed to high Es mean values, resulting from more water made available to evaporate from the soil than to Ev from the maize canopy. An R^2 value of 68.6% was obtained when correlating SWC and the maize grain yield. This indicates that increasing the SWC in the soil profile, the PAW for absorption will be increased which will increase maize grain yield.

4.6 GENERAL DISCUSSION OF THE MAIN FINDINGS

Results indicated that CON and NT resulted in average R_{EX} amounting to 61 and 85 mm during G_p for the 2008/09 and 2009/10 season, respectively. These R_{EX} values were 15.4 and 17.9% of the total P received during the $G_{p,}$ this was also evident by the low SWC of CON and NT during this study. These water losses contributed to low grain yield of maize under CON and NT treatments. The reduction in R_{EX} and Es contribute to higher SWC which increases the PAW. Higher PAW lead to a sustainable moisture supply to the crop to meet its Ev demand. When Ev demand is met plant growth is enhanced and total biomass production increases. For both seasons the biomass yield of the IRWH treatment was significantly different from the NT treatment, producing 23% and 50% more biomass in the 2008/09 and 2009/10 growing seasons, respectively. The IRWH, MB, NT treatments induced the highest RSE values, which were 188, 177 and 137% more than the CON treatment, respectively. The low RSE value for CON treatment would be as a result of lack of water conservation mechanisms of the treatment and more water was lost through the R_{EX} and Es.

The significance in yield was measured as a product of both plant parameters (growth and biomass yield) and efficiency parameters (RSE, PUE and RWP). RWHT's and MB constantly had higher values of production parameters than CON and NT treatment. Although not significantly different at all times, the ability of the treatments (RWHT's and MB) to conserve rainwater measured from SWC, higher RSE, high Ev values, high PUE and RWP indicates that these are major factors contributing to increased dryland crop production. The average maize grain yield of IRWH, DAL and MB treatments were 2200 kg ha^{-1} compared to 1887 kg ha^{-1}, the average of CON and NT treatment. IRWH produced about 250 kg ha^{-1} of maize grain more than CON. The highest significant grain yield of 56% more under IRWH was achieved during the 2009/10 season than the NT treatment.

CHAPTER 5

5 CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

The extreme variation of rainfall (P) is one of the difficulties that the majority of small-scale farmers, practicing dryland farming are faced with. Rainwater harvesting techniques (RWHT's) are potential climate smart technologies for adoption in areas with increased rainfall variability and distribution, which are ultimate causes of poor dryland crop production. Nevertheless, no system can provide all the solutions as a standalone technology, but rather be more effective when complemented by other management practices. The techniques that reduce water losses through evaporation (Es) and ex-field runoff (R_{EX}) are important for improving dryland crop production.

Hypothesis one of this study stated that: there are no differences in soil moisture retention between RWH&CT's compared to conventional treatment (CON). This null hypothesis was rejected, since the research findings of the study revealed that there were significant differences in plant available water (PAW) when comparing RWHT's, to CON, mechanized basins (MB) and no-till (NT). The PAW_T and PAW_{PM} of in-field rainwater harvesting (IRWH), MB and Daling plough (DAL) were on average 30 and 20 mm more compared to the CON and NT treatments respectively, during the 2008/09 season. There were no significant difference in plant available water at tasselling (PAW_T) and plant available water at physiological maturity (PAW_{PM}) during 2009/10 season, amongst all the treatments. But the soil water content (SWC) of IRWH and MB were slightly higher than all CON, NT and DAL.

The second hypothesis of the study stated that: there are no significant differences in yield and rainwater productivity (RWP) of maize under different RWH&CT's compared with CON treatment. This hypothesis was also rejected because there were significant differences in grain yield and RWP of different treatments. The IRWH grain yield was significantly different from the NT treatment, with more than 400 and 900 kg ha^{-1} respectively for the 2008/09 and 2009/10 seasons. The IRWH produced over 11 and 13% higher yields during the 2008/09 and 2009/10 season compared to CON treatment, respectively. The average grain yield of 2008/09 and

2009/10 seasons from IRWH, MB and DAL (2201 kg ha^{-1}) their yields were higher than the average grain yield of CON and NT (1886 kg ha^{-1}) treatments. These yield increases were attributed to the treatments' ability to limit R_{EX} and effectively provide the conserved rainwater during the critical stage of maize water requirement.

The parameters used to evaluate the performance of the various treatments included: PAW, transpiration (Ev), yield, RWP and precipitation use efficiency (PUE). The high values attained from the IRWH, MB and DAL showed that yield is influenced by high SWC (PAW), Ev, and possibly the quality of seed and management practices associated with this production. IRWH, DAL and MB constantly achieved higher values of production parameters. This indicates that moisture conservation especially in dryland crop production areas should be an all year round activity. Therefore, the overall inference that can be drawn from the study based on soil-plant-atmospheric continuum (SPAC) is that, there is a linear relationship between the SWC, the processes of ET and crop yields.

5.2 RECOMMENDATIONS

Improved PAW in dryland production is a key factor that needs to be addressed, which can result in increased yields and enhanced food security. A major strategy for increasing yields in dryland regions should be to reduce R_{EX} and Es during both the fallow and crop growing periods.

Based on the research findings, the following recommendations are made in order to improve dryland maize production in the semi-arid areas:

RWH&CT's should be applied in areas with considerable slope that will induce sufficient runoff, where the basins will collect the water and encourage more water infiltration.

- Implement RWH&CT's during the fallow period and maintain the basins during the growing season to maximize the PUE and RWP. Well-constructed RWH structure will ensure maximum water collection and higher SWC for improved crop growth and higher grain yield.

- Conservation of plant residues on the soil surface is required, to minimize Es. This though is likely to be a challenge in the small-holder farming sector in South Africa where livestock depend on crop residues for winter feed. New management systems such as fencing may have to be instituted if these water harvesting techniques are to be taken advantage of.
- Encourage small-scale farmers to implement appropriate RWH&CT's, especially in areas where insufficient rainfall is the most limiting factor for crop production. This will also improve household food security status. The RWH&CT's are climate smart technologies which contribute to conservation of natural resources (conserve soil moisture, reduces runoff water) and increase yield of dryland condition. Traction services to build these water harvesting structures on farmers' fields will have to be provided at affordable cost if small-holder farmers are to adopt them.
- Raise awareness and provide training to farmers and extension officers on all aspects of a sustainable crop production, *viz*. soil, seedbed preparations, implementation and application of the appropriate RWH&CT's. A programme of demonstrations, both on-station and on-farm can achieve this.
- Conduct research on fertilizer use efficiency under RWH technologies. Due to the nature of the physical layout of the IRWH technique, the crops are concentrated on one third of the crop area, still maintaining the same plant population ha^{-1} as in the case for CON practices. This phenomenon as well as high yields obtained induces huge pressure on the natural resource base to provide N, P and K through mineralization process. The IRWH technique optimises RWP through better control of the water balance processes. The higher the amount of PAW for crop production should therefore be taken into account with a nitrogen management programme. This could be combined by use of early and medium maturity 3-way hybrids which are more adaptable to low rainfall conditions.
- It is recommended that small-scale farmers should implement IRWH on clay soils similar to the Towoomba/Arcadia ecotope. This IRWH technique outperformed all the other techniques and will contribute to higher yield, food security and poverty alleviation.

CHAPTER 6

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APPENDICES

Appendix 1 Detailed agronomic information for the two maize growing seasons on the Towoomba/Arcadia ecotope

Crop	**Season**	**Cultivar**	**Plant population** (plants ha^{-1})	**Planting date**	**Harvesting date**
Maize	2008/09	PAN 6995B	18 000	16/01/09	27/07/09
	2009/10	PAN 6P-563R	18 000	25/11/09	25/05/10

Appendix 2 Detailed description of the Towoomba/Arcadia ecotope

Latitude & Longitude	$24^0$55'70 & $28^0$20'63	**Soil Form**	Arcadia
Land Type No	Ea1	**Soil Family**	Lonehill
Altitude	1111	**Surface rockiness**	None
Terrain unit	Foot slope	**Surface stoniness**	None
Slope	1	**Occurrence of flooding**	None
Slope shape	Straight	**Wind erosion**	None
Aspect	North	**Water erosion**	None
Micro relief	None	**Vegetation / Land use**	Cash crops
Parent material solum	Single	**Water table**	None
Weathering of underlying material	Physical and Weak	**Described by**	LF Joseph

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0 - 1200	Dry colour: black, moist colour: black; 7.5YR3/0, mottles: none; structure, size & type: strong; coarse & angular blocky; consistence (dry): hard; consistence (moist): very firm; wet-stickiness: very sticky; macro pores & cracks: common fine pores and very coarse cracks; cementation of horizon: none; free lime: none; slickensides: many; coarse fragments: none; cutans: none; second(s); roots: many roots	Orthic

Appendix 3 Physical and Chemical analysis of the Towoomba/Arcadia ecotope

Horizon	**Depth** (mm)	**Diagnostic Horizon**	**Exchangeable Cations** ($mg\ kg^{-1}$)				**Phosphorus** (Bray 1) ($mg\ kg^{-1}$)	**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
Ap	0 - 300	Vertic	297	8435	1138	183	1.3	340	8.26	0.1	5	10	7	6	11	59
A1	300 - 1200	Vertic	303	7408	1184	179	2.1	370	8.18	0.1	2	7	5	8	9	67

Appendix 4 Long-term (1973 - 2009) monthly and annual climate data from the Towoomba - Bela-Bela climate station (SAWS data)

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual total* / Monthly mean
Rain	119	92	81	33	16	9	7	9	19	56	98	123	662*
ETo	170	143	139	110	89	72	80	105	131	160	161	171	1530*
Evap	207	172	169	136	133	106	121	166	215	237	216	229	2107*
AI	0.57	0.53	0.48	0.24	0.12	0.08	0.06	0.05	0.09	0.24	0.45	0.54	0.29
T_H	24	24	22	19	24	12	13	16	19	22	22	23.5	20
Tx	31	30	29	27	24	21	22	25	28	30	29	30	27
Tn	17	17	15	11	7	3	3	6	10	14	15	17	11
RH	56	57	57	55	50	48	44	41	41	47	51	55	50
RHx	81	82	83	82	76	74	67	61	60	69	75	80	74
RHn	31	32	32	29	24	24	21	21	22	25	28	30	27
Rs	8.65	8.73	8.41	8.27	8.95	9.16	9.24	9.61	9.39	9.17	8.55	8.66	8.90

Appendix 5 The results of plant height for maize during the V5 growing stage on the Towoomba/Arcadia ecotope

Source	**DF**	**SS**	**MS**	**F**	**P**
Block	3	15.81	5.27	1.25	
Treatment	4	58.432	14.608	3.47	0.042
Error	12	50.52	4.21		
Total	19	124.762			

Appendix 6 The plant height results during the R6 of maize on the Towoomba/Arcadia ecotope 2008/09 season

Source	**DF**	**SS**	**MS**	**F**	**P**
Block	3	304.18	101.39	6.9	
Treatment	4	431.47	107.87	7.34	0.003
Error	12	176.38	14.7		
Total	19	912.02			

Appendix 7 The stem diameter results during the V5 stage of maize on the Towoomba/Arcadia ecotope 2008/09 season

Source	**DF**	**SS**	**MS**	**F**	**P**
Block	3	0.0715	0.02383	1.68	
Treatment	4	0.19983	0.04996	3.53	0.04
Error	12	0.16993	0.01416		
Total	19	0.44126			

Appendix 8 The stem diameter results during the 12 stage of maize on the Towoomba/Arcadia ecotope 2008/09 season

Source	DF	SS	MS	F	P
Block	3	0.0715	0.02383		
Treatment	4	0.19983	0.04996	3.53	0.04
Error	12	0.16993	0.01416		
Total	19	0.44126			

Appendix 9 Maize biomass yields for the 2008/09 season on the Towoomba/Arcadia ecotope.

Source	DF	SS	MS	F	P
Block	3	1869534	623178		
Treatment	4	3045237	761309.3	1.24	0.0334745
Error	12	9183267	612217.8		
Total	19	14098038			

Appendix 10 Maize biomass yield for the 2009/10 season on the Towoomba/Arcadia ecotope

Source	DF	SS	MS	F	P
Block	3	1869534	623178		
Treatment	4	11161430	2790357	2.31	0.0105617
Error	12	18129300	1208620		
Total	19	31160264			

Appendix 11 Maize grain yield for the 2008/09 season on the Towoomba/Arcadia ecotope.

Source	DF	SS	MS	F	P
Block	3	214050	71350		
Treatment	4	395676	98919	1.66	0.02114
Error	12	894087	59606		
Total	19	1503813			

Appendix 12 Maize grain yield on the 2009/10 season on the Towoomba/Arcadia ecotope.

Source	DF	SS	MS	F	P
Block	3	1044385	348128		
Treatment	4	1847529	461882.2	2.27	0.0110064
Error	12	3053287	203552.4		
Total	19	5945201			

Appendix 13 Peer reviewed paper presented as an oral paper at the Combined Congress held at George, Western Cape, South Africa, 19 - 23 January 2015.

EVALUATING RAINWATER HARVESTING AND CONSERVATION TECHNIQUES ON THE TOWOOMBA/ARCADIA ECOTOPE

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INTRODUCTION

In the semi-arid areas of the Sub-Saharan Africa water and soil fertility are the main factors limiting dryland crop production. These areas are characterized by low and poor rainfall distribution. This limited rainwater is mostly lost through runoff and evaporation, which result in low soil moisture availability and possible crop failure. Therefore, techniques that reduce these water losses are important for improving dryland crop production and rainwater productivity (RWP). The objectives of this study were to determine the effectiveness of the rainwater harvesting and conservation techniques (RWH&C) to increase plant water availability (PAW) and maize grain yield as compared to conventional practices (CON) for small-scale farmers working under these conditions.

MATERIALS AND METHODS

A field trial was conducted at the Towoomba Research Station during the 2008/09 and 2009/10 growing seasons. The experiment was conducted as a randomized complete block design with five tillage treatments [1. Conventional (CON), 2. No-till (NT), 3. Daling plough (DAL), 4. In-field rainwater harvesting (IRWH) and 5. Mechanized basins (MB)] and replicated four times. Maize was used as the indicator crop at 18 000 plants ha^{-1}. A total of 40 neutron water meter access tubes (2 access tubes per treatment) were installed to a depth of 1100 mm in order to measure the soil water content (SWC) at four depths (150, 450, 750 and 1050 mm). The other parameters used were PAW, RWP and grain yield. Data was analysed using Genstat 14.0 and treatment means were separated at 5% level of probability.

RESULTS AND DISCUSSION

PAW during the 2008/09 growing season for the IRWH, MB, and DAL were significantly different from CON, with no significant difference during the 2009/10 growing season. The SWC of the RWH&C techniques was higher than CON. The IRWH treatment produced 23 and 50% significantly more biomass than the NT treatment, with during the 2008/09 and 2009/10 growing seasons, respectively. IRWH grain yield was only significantly different from the NT treatment. IRWH induced 26 and 56% more grain yield during 2008/09 to 2009/10 respectively, than the NT treatment. IRWH produced 22% higher RWP than CON.

CONCLUSION

The results revealed that rainwater harvesting techniques significantly increased SWC, maize grain yield and RWP when compared to CON treatment.

KEYWORDS: *Plant available water, Rainwater harvesting, maize, yield.*