Optimising rainfall utilisation in dryland crop production: A case of shallow-rooted crops

by

Ambroise Ndayakunze

Submitted in fulfilment of the requirements for the degree

MSc (Agric) Agronomy

In the Faculty of Natural and Agricultural Sciences

University of Pretoria

Supervisor: Prof. J.M. Steyn

Co-Supervisor: Prof. J.G. Annandale

March 2014

TABLE OF CONTENTS

DECLARATION

I hereby declare that this dissertation is my own work, except where duly acknowledged. I also certify that no plagiarism was committed during the write-up of this dissertation.

Signature: Ambroise Ndayakunze

ACKNOWLEDGEMENTS

I would like to address many thanks and heartfelt gratitude to my supervisors, Professor JM Steyn (supervisor) and Professor JG Annandale (co-supervisor), both from the Department of Plant Production and Soil Science of the University of Pretoria, for their invaluable assistance, mentorship, guidance and inspiration during the course of this study. Special gratitude goes to Professor JM Steyn who did not give up providing me with financial support and moral encouragement when this program has miraculously stretched beyond the assigned period. Most importantly, Prof, this work should not have been completed without your full supervision.

I am deeply thankful to the Department of Plant Production and Soil Science of the University of Pretoria, for having offered me this opportunity to study in this well-known institution. I sincerely acknowledge Professor JG Annandale for it was in his capacity as the Head of the Department that this was possible. In addition, his constructive critics and priceless contribution in reviewing this manuscript were highly appreciated.

I owe too much appreciation to the staff and colleagues from the Department of Plant Production and Soil Science of the University of Pretoria. The study and research activities should hardly have been successful without their frank collaboration and unconditional assistance. Particular thanks go to Mme J Herman and her husband Mr J Herman for their parental care when I was close to throwing in the towel. Mme N Ibraimo, without your boundless generosity in assisting me in every stage of this work, I doubt it should have come to its completion.

My sincere recognition also goes to other staff and students from the different departments of the University of Pretoria, for their unreserved and unconditional personal or official assistance during my stay at the university. I gratefully acknowledge, among others, the help of Dr M Nolte (Student Affairs), Dr J Shelembe (Food Science) and Mr D Mesay (IT).

I profoundly appreciate the field insight and experience contributed by the members of the technical team of the Hatfield Experimental Farm of the University of Pretoria: Mrs GEB

Cillie, JH Marneweck and ML Nonyane. Your well deserved thanks also go to the farm casual and permanent workers who are your right hands.

Finally, I must recognize Mme P Michelle, Mrs CD Hertzog, PC De Jager and JT Vahrmeijer for the experience, support, understanding and encouragement while I was assisting in the Soil and Plant Analysis Laboratory of the Department of Plant Production and Soil Science of the University of Pretoria.

ABSTRACT

In drought-prone arid and semi-arid areas, limited plant available water exerts a tremendous negative effect on crop production, leading to undesirable low crop productivity, untold food insecurity, and never-ending poverty. In-field rainwater harvesting (IRWH or In-field RWH) is specifically designed to trap rainfall within the field and optimise its use to benefit crop yield and quality, and improve water use efficiency (WUE) in these regions. Two RWH-crop field experiments were established in the semi-arid area of the Hatfield Experimental Farm, University of Pretoria, South Africa. The first RWH-potato experiment was conducted during the 2009/2010 growing season while the second RWH-Swiss chard experiment was carried out during the 2010/2011 growing season. Three cropping systems were involved: (1) conventional tillage (CT), (2) tied-ridges (TR), and (3) IRWH with three different design ratios of runoff area to cropping area (1:1, 2:1 & 3:1). The runoff area of each design ratio was either bare (B) or plastic-covered (P) and this resulted in six IRWH treatments. Therefore, there were a total of eight treatments: CT, TR, 1:1B, 1:1P, 2:1B, 2:1P, 3:1B and 3:1P. For both growing seasons, the total plot area yields and WUEs of TR and CT were in general higher than those of the IRWH treatments. This is because TR and CT had more plants per plot than the IRWH treatments and the rainfall recorded for the specific seasons were sufficient, so there was little advantage in collecting/harvesting additional water. In terms of yields and WUEs expressed on the net cropped area, the IRWH treatments had higher yields and WUE than CT and TR because they captured more runoff than the latter treatments. Field trials are expensive, laborious and time consuming, therefore models were developed to predict potential runoff and crop growth and yield of different RWH techniques or design ratios. During the current investigation, runoff models such as the linear regression, curve number (CN) and Morin and Cluff (1980) models were used to describe and simulate runoff generation from this ecotope. The empirical rainfall-runoff linear regression model indicated that runoff efficiency declined as runoff length increased. The statistics revealed that the CN and Morin and Cluff (1980) models simulated runoff very well. Moreover, the use of a generic crop growth Soil Water Balance model (SWB) showed potential to simulate crop growth and yield for different RWH techniques and design ratios. During the present study, the SWB model was modified by incorporating linear runoff simulation models in order to predict the soil water balance and crop yield under different RWH design scenarios. Field data collected on the study ecotope contributed to the parameterization and calibration of the SWB model for the crops involved. The SWB model was in general, successfully calibrated for the potato crop, while the calibration for the Swiss chard crop was generally not as successful, most probably because of the continuous growing and harvesting system followed (approach for pastures). The scenario simulation results for potato suggested that for the study ecotope, if land is limiting, CT, TR and smaller design ratios (1:1) are the best options in terms of yield per total plot area. However, if land is not limiting, larger design ratios (2:1 and 3:1) are better options, according to the yields per net cropped area outcomes. The SWB model shows promise as a useful tool to assist in the selection of the best RWH strategy and the ideal planting date under specific conditions with minimal input requirements. However, there is a need to upgrade it to a 2D SWB model for better accuracy under a range of conditions.

Keywords: Semi-arid cropping, conventional tillage, cropped area, design ratios, in-field rainwater harvesting (IRWH), plastic-mulch, potato, rainwater harvesting, runoff, SWB model, Swiss chard, tied ridges.

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

AI Aridity index

AM Ante Meridiem

AMC Antecedent moisture content

ANOVA Analysis of variance

a_n Leaf absorptance of near infrared radiation (NIR) (0.7 – 3 µm)

a_p Leaf absorptance of PAR

ARC Agricultural Research Council

ARC-IAE ARC Institute for Agricultural Engineering

a_s Leaf absorptance of solar radiation

b The number of times that a rain day with a certain rain depth range occurred

B Bare

BP_1 Potato cultivar

c Constant in cumulative infiltration (Ic) and infiltration rate (It) equations

Ca Calcium

CDM Canopy dry matter production (kg)

CN Curve number

Co. LTD. Corporation limited

CO_2 Carbon dioxide

CROPSYST Cropping System Simulation Model

CT Conventional treatment

cv. Cultivar

CV Coefficient of variation (%)

CWSI Crop water stress index

d A given dry spell duration (days)

D Deep drainage (mm) (also for Willmott (1982) index of agreement)

DAP Days after planting

DAT Days after transplanting

DF Degree of freedom

DL Drylands

DM Dry matter production (kg m^{-2})

DMi Daily increment of total dry matter (kg m^{-2})

DWR Vapour pressure-corrected dry matter/water ratio (Pa)

E Actual evaporation (mm)

Ec Radiation conversion efficiency (kg MJ^{-1} day^{-1})

Ef Model efficiency

Eq(s). Equation(s)

ET Actual crop evapotranspiration (mm)

ETo FAO reference crop evapotranspiration (mm day^{-1})

ETo/2 Half ETo (mm day^{-1})

F Fisher F distribution most commonly used in analysis of variances (ANOVA) or the F test (to determine if two variances are equal)

FAO Food and Agriculture Organization of the United Nations

Fe Iron

FI Fractional interception

FI$_{PAR}$ Fractional interception of photosynthetically active radiation

GDD Growing day degrees (d ^{o}C)

GWUE Green water (soil water in the root zone from infiltrated rainfall) use efficiency (kg ha^{-1} mm^{-1})

H_2O Water

Hc Crop height (m)

HDM Harvestable (tuber) dry matter (kg m^{-2})

HDMi Harvestable (tuber) dry matter increment (kg m^{-2})

HI Harvest index (%)

I Irrigation amount (mm)

i Number of the given intervals per rainfall event (i = 1, 2, 3 . . .)

i-1 Previous interval

Ic Cumulative infiltration (mm)

$Id_{\Delta ti}$ Potential infiltration during any time segment Δt_i (mm)

I_i Rainfall intensity (mm hr^{-1})

IRWH In-field rainwater harvesting

It Soil infiltration rate (mm hr^{-1})

I_{tf} Final infiltration rate of the soil (mm hr^{-1})

I_{ti} Initial infiltration rate of the soil (mm hr^{-1})

k Constant in Ic and It equations

K Potassium

k^{-1} Constant related to Ic derivation

K_{bd} Canopy radiation extinction coefficient for black leaves with diffuse radiation

Kc Crop factor

KCl Potassium chloride

Kc_{max} The maximum value of the crop factor (Kc) following rain or irrigation

K_{PAR} Canopy extinction coefficient of photosynthetically active radiation

K_S Canopy extinction coefficient of total solar radiation

LAI Leaf area index (m m^{-2})

LAN Limestone ammonium nitrogen

LDM Leaf dry matter (kg m^{-2})

LINTUL-POTATO Light INTerception and UtiLisation

LSD Least significant difference

m.a.s.l. Meters above sea level

Ma Mass of tubers in air (kg)

MAE Mean absolute error (%)

MC Micro-catchment

MCRWH Micro-catchment rainwater harvesting

MDGs Millennium development goals

Mg Magnesium

Mw Mass of tubers in water (kg)

N Nitrogen (also for the total number of items) n Total number of days in a given month

NEPAD New partnership for Africa’s development

NIR Near infrared radiation (0.73 µm)

NPK Nitrogen:phosphorus:potassium

ns Non significant

^{o}C Degrees Celsius

^{o}Cd Day degree

P Phosphorus (also for plastic-covered or probability)

PAR Photosynthetically active radiation (0.4 – 0.7 µm)

PART Stem-leaf partitioning parameter (m^{2} kg^{-1})

PET Potential evapotranspiration (mm)

pH Hydrogen potential

PM Post Meridiem

PRFRH Plastic-covered ridges supplied with water from a furrow rainfall harvesting system

P-T Parched-Thirst crop model

PUE Precipitation use efficiency (kg ha^{-1} mm^{-1})

q Number of times that a dry spell of a given duration (in days) occurred

R Rainfall (precipitation) (mm)

R0 Runoff for CT (mm)

R_0 Threshold rainfall (mm)

R^2 Coefficient of determination

R_a Extraterrestrial radiation (MJ m^{-2} day^{-1})

RCBD Randomized complete block design

RD Root depth (m)

RDLFTI Relative day length factor for tuber initiation

RE Runoff efficiency (%)

R_i Cumulative rainfall over interval i (mm)

R_{i-1} Cumulative rainfall in the previous interval i-1 (mm)

RMSE Root mean square error

R_n net radiation (MJ m^{-2} day^{-1})

Roff Runoff (mm) (also for runoff depth (mm) or runoff volume (L))

$Roff_b$ Runoff from a bare runoff area (mm)

$Roff_i$ Runoff during segment i of the rainfall (mm)

$Roff_p$ Runoff from a plastic-covered runoff area (mm)

RPA Runoff producing area (m^2)

RRA Runoff receiving area (m^2)

R_S Total solar radiation (MJ m^{-2} day^{-1} or W m^{-2})

RUE Radiation use efficiency (kg MJ^{-1} day^{-1})

RWH Rainwater harvesting

RWUE Rainwater use efficiency (kg ha^{-1} mm^{-1})

S Sulfur (also for soil storage in the root zone (mm))

s Soil surface storage and retention for the time segment t_i (mm)

SAS Statistical analysis software

SCS Soil conservation service

SCS- USDA SCS-United States Department of Agriculture

SCS-CN SCS-curve number

SDM Stem dry matter (kg m^{-2})

SG Specific gravity

Simpotato Crop simulation model for potato

s_{i-1} Soil surface storage and retention for the previous time segment t_{i-1} (mm)

SLA Specific leaf area (m^2 kg^{-1})

s_m Maximum soil surface storage and retention (mm)

SPAC Soil-plant-atmosphere continuum

SPAD Soil plant analysis development

SUBSTOR Simulate Underground Bulking Storage Organs

SWB Soil Water Balance model

SWD Soil water deficit (mm)

T Actual transpiration (mm)

t Time segment (hr or min) (also for the upper limit of a rain depth range (mm))

t_{-1} Previous time segment (hr or minutes) (also for the lower limit of a rain depth range (mm))

TDM Total dry matter production (kg m^{-2})

t_i Time from the beginning of rain (hr)

TR Tied ridges

UN United nations

UNCCD UN-Convention to combat desertification

UNEP UN-Environment program

UNESCO United Nation Educational Scientific and Cultural Organisation

USA United States of America

USDA United States Department of Agriculture

USDA-CN USDA-curve number

USDA-SCS USDA-Soil Conservation Service

VPD Vapour pressure deficit (Pa)

WASAL World Arid and Semi-Arid Lands

WMO World Meteorological Organization

WU Water use (mm)

WUE Water use efficiency (kg ha^{-1} mm^{-1})

WUE_{ET} Evapotranspirational WUE (kg ha^{-1} mm^{-1})

WUE_T Transpirational WUE (kg ha^{-1} mm^{-1})

Y Yield (kg ha^{-1} or t ha^{-1})

Y1 – Y7 Harvest 1 – harvest 7 (kg ha^{-1} or t ha^{-1})

Yr Period of years

Y_{T7} total (seasonal) yield (kg ha^{-1} or t ha^{-1})

γ (Γ) Empirical soil parameter representing surface aggregate resistance to dispersion (mm^{-1})

ΔS Changes in soil water storage in the root zone (mm)

Δt_i Time segment (hr)

1:1B Design ratio 1:1 of the IRWH with a bare runoff area

1:1P Design ratio 1:1 of the IRWH with a plastic covered runoff area

1 m x 5 m	Bare runoff plot of 1 m long and 5 m wide
2 x 5P	Plastic covered runoff plot of 2 m long and 5 m wide
2:1B	Design ratio 2:1 of the IRWH with a bare runoff area
2:1P	Design ratio 2:1 of the IRWH with a plastic covered runoff area
2D SWB	Two-dimensional SWB model
2 m x 5 m	Bare runoff plot of 2 m long and 5 m wide
3:1B	Design ratio 3:1 of the IRWH with a bare runoff area
3:1P	Design ratio 3:1 of the IRWH with a plastic covered runoff area
3 m x 5 m	Bare runoff plot of 3 m long and 5 m wide

CHAPTER 1

GENERAL INTRODUCTION

1.1 Background and problem statement

Nearly 30% of the terrestrial surface of our planet is arid and semi-arid land and about half the nations of the world are situated wholly or partly in dry regions (Bruins *et al*., 1986). In these areas, rainfall is extremely temporally and spatially variable and generally occurs as storms of high rainfall intensity which negatively affect the productivity of rainfed agriculture. According to the statistics, semi-arid regions experience severe crop reductions caused by intra-seasonal dry spells, which occur once to twice every five years, and total crop failure caused by annual droughts occur once in a decade (Bruins *et al*., 1986; Rockström, 2000). Moreover, the vast majority of developing countries in these areas experience a general shortage of financial and technological resources, which constitute another massive barrier to agricultural production (Bruins *et al*, 1986; FAO, 2009).

A new green revolution to improve growth in the agricultural sector has become an utmost necessity to achieve the Millenium Development Goals (MDGs) of eradicating hunger and poverty (Falkenmark & Rockström, 2004). According to the literature, in an effort to ensure food security and sustainable economies, food production will have to double over the coming 20-30 years, especially in parts of Africa and Asia, where malnourishment and food insecurity are rife (UN Millenium Project, 2005). However, it was reported that water to irrigate world-wide crops, especially in dryland regions, is decreasing rapidly. Therefore, it is imperative to increase agricultural productivity in arid and semi-arid areas by optimising the yield per unit of water used or the water use efficiency (WUE) in order to keep food production abreast of population growth (Rockström, 2002).

One potential solution to the challenge of unreliable rainfall and low WUE in dryland cropping systems is rainwater harvesting (RWH) which consists of systems that can collect rainwater runoff for agricultural use (Hatibu *et al*., 2003; FAO, 2009). According to the size ratio and the transfer distance between the runoff-producing area (RPA) and the runoff-receiving area (RRA), RWH techniques can be classified into three major categories: (1)

macro-catchment RWH, (2) micro-catchment (MC) RWH, and (3) *in-situ* RWH (Hatibu *et al*., 2003; Hatibu & Mahoo, 2009). Due to their relative simplicity in design and implementation, MCRWH and *in-situ* RWH have been identified as suitable for small-scale rainfed agriculture. MCRWH systems consist of collecting surface runoff from a small catchment area (runoff area) and storing it in the root zone of an adjacent infiltration area (run-on area) (Haile & Merga, 2002; Senkondo *et al*., 2004). *In-situ* RWH or soil and water conservation, involves the use of methods that increase the amount of water stored in the soil profile by trapping or holding rainfall where it falls (Hatibu & Mahoo, 1999; Stott *et al*., 2001).

Several MCRWH techniques are used to satisfy the local conditions of water harvesting projects (Kunze, 2000; Haile & Merga, 2002; Senkondo *et al*., 2004). An example of an on-farm type MCRWH is the In-field Rainwater Harvesting (IRWH) technique, which has been implemented in dry areas around Bloemfontein, South Africa (Botha *et al*., 2003). The technique consists of the following characteristics: a runoff area, which produces in-field runoff and a cropping basin, which stops the produced runoff, maximises its infiltration and stores it in the soil layers beyond the sensitive evaporation zone (Botha *et al*., 2003). The design of such structures, which involves manipulation of the ratio between the runoff area and the cropping area, is affected by several factors, including rainfall intensity and amount, ground slope, soil factors, crop factors and surface treatments on the runoff area (Oweis *et al*., 1999; Prinz & Malik, 2002). Thus, the design of MC structures is liable to spatial and temporal variability. One advantage of selecting the best MC structure design is the fact that it can avoid excessive or insufficient runoff production on the catchment area, which will otherwise result in a negative effect on crop growth and yields (Critchley & Siegert, 1991). In addition, it helps farmers to maximise the use of arable land for crop production, since the runoff area uses potentially arable land.

Farmers in arid and semi-arid areas have mostly been using MC and *in-situ* RWH technologies which are specifically designed to trap rainfall within the field for ultimate plant benefits (Mzirai *et al*., 2002). Yet field trials for assessing these technologies were proven to be laborious, time consuming and costly; therefore, models were introduced to address many practical issues arising from their planning, design, implementation and management (Walker & Tsubo, 2003). Simulation models can contribute to our understanding of interactions between soil behaviour and crop responses in highly changing climates (Connolly, 1998). With regard to rainfed agriculture, several models of water harvesting and comprehensive models of rainfall-runoff-yield systems have been developed (Gould & Nissen-Petersen, 1999; Young *et al*., 2002). These include but are not limited to: (1) the simple empirical (for example USDA-SCS (1985) curve number (CN)) of daily rainfall to daily runoff that is the simplest method for estimating daily runoff (Budyko, 1974; Hensley *et al*., 2000); (2) the conceptual rainfall-runoff models that can be used to simulate overland flow (surface runoff) (Horton, 1940; Morin & Cluff, 1980); (3) the runoff-crop integrated models such as PUTURUN (Walker & Tsubo, 2003) or Parched-Thirst model (Young *et al*., 2002) that can be utilized in the prediction of runoff and crop yields, and; (4) the Soil Water Balance (SWB) model, which is a user-friendly tool in soil water management. The SWB model makes use of weather, soil and crop databases to provide a mechanistic description of the soil-plant-atmosphere continuum (SPAC) (Annandale *et al*., 1996a).

1.2 Hypotheses

1. The rainfall-runoff relationship can satisfactorily be established using the rainfall and runoff data of a growing season;

2. The mechanistic Morin and Cluff (1980) model can provide more accurate runoff predictions than the linear regression and CN models, since it makes use of rainfall intensity input data;

3. Use of RWH will result in increased crop yields, WUEs and reduced soil erosion on the study ecotope, compared to CT;

4. There will be limited benefits to IRWH technique for the study ecotope in Pretoria which is a wet sub-humid area, but more benefits are expected in more arid areas;

5. The SWB model can successfully be calibrated for the crops involved (*Solanum tuberosum* cv. BP1 and *Beta vulgaris* cv. Fordhook Giant);

6. The selection of the ideal RWH technique and the optimal design ratio for the study ecotope will be dictated by the rainfall amount expected for the specific rainy season.

1.3 Objectives

The main objective is to investigate whether RWH can achieve the full potential of dryland crop production to ensure food security and improve the livelihoods of the people of drought/hunger-stricken areas through higher yields and improved WUEs.

Specific objectives

- To characterize the agro-climatic conditions of the study ecotope;
- To develop a rainfall-runoff relationship for the study ecotope;
- To calibrate the Morin and Cluff (1980) model for the site;
- To determine the effects of RWH on plant growth, yields, WUEs and soil erosion reduction;
- To determine the soil and crop specific parameters in order to calibrate the SWB model for the crops involved (*Solanum tuberosum* cv. BP1 and *Beta vulgaris* cv. Fordhook Giant).

CHAPTER 2

LITERATURE REVIEW

2.1 Aridity

Arid and semi-arid regions experience inadequate and extreme spatial and temporal fluctuations in the variability of the plant available water necessary for agricultural production. Moreover, rainfall in these regions often proves to be of short duration and high intensity leading to flash flooding, soil erosion and degradation, and agricultural failure (Bruins *et al.*, 1986; Fisher *et al.*, 1995; Rockström, 2000). Aridity denotes a severe lack of available water, to the extent of hindering or preventing the growth and development of plant and animal life (UNEP, 1992). Aridity, in drylands of the world, is omnipresent for water shortage persists through most of the year. Aridity is assessed on the basis of climate variability (aridity index, AI), or number of days when the water balance is favourable for plant growth (length of growing season). According to NEPAD (2003), the term semi-arid refers to conditions where the average annual rainfall ranges from 350 to 800 mm, and/or potential evapotranspiration (PET) exceeds rainfall most of the time and/or the rainfall regime is highly variable in quantity, timing and distribution (Oweis *et al.*, 1999; NEPAD, 2003). As a result, periodic droughts and different associations of poor soils and vegetative cover become imminent (Oweis *et al.*, 1999).

Wallen (1967) declared that a major climatological difficulty is the lack of generally accepted definitions and methods to approach the aridity concept. However, in an effort to define aridity and in classifying the arid or semi-arid areas of the world, the following approaches were considered: (1) a classical approach, which makes use of the fundamental study of various climatic parameters in their relation to vegetal or agricultural conditions, to detect those parameters with particular significance in defining aridity; (2) an index approach, which entails different standard indices which have been developed from earlier classical studies over the years and including one, two or more climatic parameters; and (3) a water balance approach, which involves the application of the generally determined or calculated concept of water balance by means of formulas. Nevertheless, according to Keyantash and Dracup (2002), the term drought or aridity can be classified in three ways: (1) meteorological drought resulting from a shortage of precipitation; (2) hydrological drought defined as a deficiency in the volume of water supply; and (3) agricultural drought related to a shortage of available water for plant growth.

Studies in many drought-prone environments have shown that meteorological dry spells are important causes of low yield (Rockström *et al*., 2002; McHugh *et al*., 2007). Even in the course of high seasonal rainfall, if the interval between consecutive rain events is too long it may cause total pasture and crop failure (Tilahun, 2006; Araya, 2005). The impact of drought stress on crop productivity is particularly severe when the drought coincides with the water sensitive stage of the crop and if farmers have no alternative management to overcome the problem (FAO, 2002). Moreover, plant drought stress is known to relate to soil conditions. For example, the risk of drought in sub-Saharan Africa is also linked to the degradation of soil physical attributes such as depth and water holding capacity (Stroosnijder & Slegers, 2008).

The map of world distribution of arid regions uses the ratio of the mean value of annual precipitation (R) and the mean annual potential evapotranspiration (PET), i.e. R/PET, to define the various aridity indices (AI) of arid zones on a global level (Budyko, 1974; UNESCO, 1979; UNEP, 1992, 1997; UNCCD, 1994; Le Houérou, 1996; Zhang *et al*., 2001). PET and R must be expressed in the same units, e.g., in mm per month (annum). In this case, the boundaries that define various degrees of aridity and the approximate areas involved are shown in Table 2.1. The level of bioclimatic aridity is dependent on the balance between rainfall gains and water losses. If for a given period, the cumulative rainfall is less than the cumulative atmospheric evaporative demand, then it is very likely that growth will be negatively affected. According to Kafle and Bruins (2009), a drier or wetter climate in bio-climatic or agricultural terms is not just a matter of only rainfall (input), but also of PET (output), in which temperature is an important factor. If temperature increases then PET also increases, reducing the R/PET ratio when R remains the same, and vice versa.

The area of land covered by hyper-arid, arid and semi-arid climates in total represents about one-third of the earth's surface area. However, if dry sub-humid zones are taken into account, this area would represent over 47% of the land area of the planet. The expression 'desert', denoting 'true desert' or 'climatic desert' is herewith equivalent to the hyper-arid zone. Likewise, the term 'drylands (DL)' denotes the hyper-arid, arid, semi-arid and dry sub-humid zones, while the term 'World Arid and Semi-Arid Lands (WASAL)' omits the dry sub-humid zones (Kafle & Bruins, 2009). Humid areas consist of wet sub-humid, humid and hyper humid regions.

Table 2.1: The dryland and humid zones, according to the respective values of the R/PET index, as defined by UNEP (1992, 1997), UNCCD (1994) and Le Houerou (1996).

Classification		**Area (10^3 km^2)**	**R/PET (AI)**
Dryland areas	Hyper-arid	9781	< 0.05
	Arid	15692	0.05 – 0.20
	Semi-arid	23053	0.20 – 0.50
	Dry sub-humid	12947	0.50 – 0.65
Humid areas	Wet sub-humid	25843	0.65 – 0.75
	Humid & hyper-humid	42811	≥ 0.75

Table 2.1, which shows the bioclimatic classification of the world regions, can approximately indicate the climatic expanse in which RWH agricultural production is both possible and sensible. The hyper-arid zone (AI < 0.05) is generally too dry for viable RWH farming. The sub-humid zone (AI 0.5 – 0.75) is too wet for RWH farming, so that normal rainfed farming may be implemented regularly. The RWH farming zone is mainly located in the arid zone (AI 0.05 – 0.2) and to some extent also in the semi-arid zone (AI 0.2 – 0.5). Therefore, this extended zone covers the span of AI 0.05 – 0.50. For instance, the historical RWH farming region in the Negev has at present arid AI values of 0.04 – 0.09 (UNESCO, 1979). Whilst, in South Africa, most dryland crop production is practiced in the semi-arid zones where the AI fluctuates in the range of 0.2 – 0.5 and which can be split into winter and summer rainfall belts (UNESCO, 1977).

2.2 Water use efficiency (WUE)

Food production and water productivity are closely linked processes and, as competition for water intensifies, water must be used more efficiently in food production worldwide (Zhang *et al.*, 2008). Water use efficiency (WUE) is the ratio of crop yield per unit water use (Sinclair, 1984; Kijne, 2003). It is a ratio which reflects the relative magnitude of an output to the input (driver). WUE is used exclusively to denote the amount or value of product over volume of water depleted or diverted. According to Sharma *et al*. (2010), rainfed agriculture is practiced on 80% of the world's agricultural land area, and generates nearly 70% of the world's staple foods (Molden *et al*., 2007). WUE in rainfed agriculture will have to increase dramatically over the next generation if food production is to keep pace with population growth (Rockström *et al*. 2002), which is estimated to reach 8 billion in 2025 (United Nations Population Reference bureau, 2004). Many researchers suggest that the low productivity in rainfed agriculture is more due to sub-optimal performance related to management aspects than to low physical potential. For instance, Rockström and Falkenmark (2000) reported that in many arid and semi-arid areas between 60% and 85% of the rainfall evaporates from the soil surface before making any contribution to production (Figure 2.1). In addition, there is a need for a green-green revolution (green for rapid production increase and green for environmental sustainability) which focuses more strongly on environmental sustainability of soil, crop and water resources (Conway, 1997). Furthermore, a triple green revolution (green-green plus green for focus on all green water flows) is in fact required, as the major hotspots in terms of food insecurity also coincide with the world's savannahs (Falkenmark & Rockström, 2004). These are hydroclimatic regions subject to extreme rainfall variability, water scarcity and a large dependence on green water flows, i.e., soil water in the root zone from infiltrated rainfall that contributes evapotranspiration (ET) flow in rainfed farming systems.

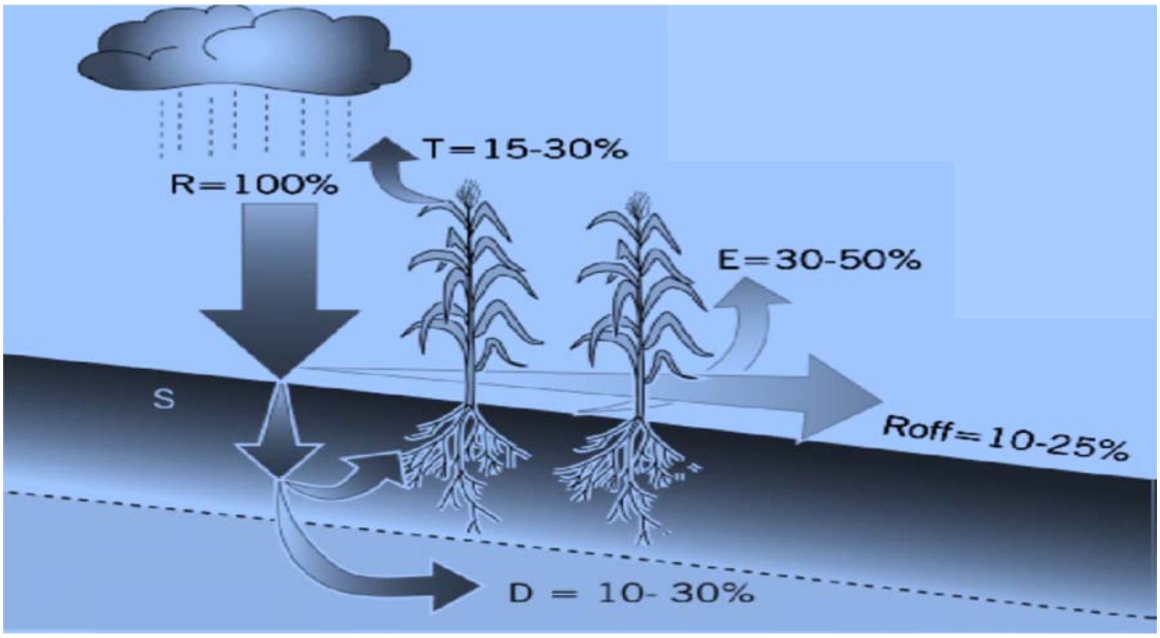


Figure 2.1: General overview of rainfall partitioning in farming systems in the semi-arid tropics of sub-Saharan Africa. R = rainfall, E = evaporation from interception and soil, Roff = surface runoff, S = soil moisture storage and D = deep percolation (Rockström & Falkenmark, 2000).

WUE is expressed as the ratio between the crop yield (Y) and the water consumed. Since the crop growth is directly governed by transpiration (T), it is more appropriate to consider the transpirational WUE (WUE_T) given by:

$$WUE_T = \frac{Y}{T} \qquad \text{(Eq. 2.1)}$$

However, since it is difficult to separate E and T, it is common to focus on evapotranspirational WUE (WUE_{ET}):

$$WUE_{ET} = \frac{Y}{(E+T)} \qquad \text{(Eq.2.2)}$$

It has been reported, however, that for a given species and location, there is a clear relationship between the amount of biomass produced and the amount of water transpired. In terms of WUE, it is more convenient to use the concept of green water (soil water in the root zone from infiltrated rainfall) use efficiency (GWUE), expressed as the fraction transpiration/precipitation. GWUE in dryland systems in sub-Saharan Africa is in the range of 5 to 15%. Stroosnijder and Hoogmoed (1984) found for a millet crop that soil E made up 80% of the actual seasonal ET. In East Africa, GWUE may reach 20%, but in a comparable climate in the USA the GWUE may be above 50%. The latter improvement is caused by a better control of soil E. For example, Pimentel *et al.* (2004) found in a USA study that maize T made up 75% of actual seasonal ET.

2.3 Rainwater harvesting (RWH)

2.3.1 Introduction

Cropping systems in dryland regions are characterized by rainfall patterns which are spatially and temporally highly unreliable (Hatibu *et al*., 2003; FAO, 2009). One potential solution to this enigma is RWH. This term describes systems that induce, collect, store, and conserve rainwater for agricultural use. According to Pandy *et al.* (2003), runoff rainwater harvesting was already practiced for agricultural purposes during the Neolithic Age in southern Jordan, as early as 9000 years ago. According to the size ratio and the joining distance between the runoff-producing area (RPA) and the runoff-receiving area (RRA), RWH techniques are classified in three major categories: Macro-catchment RWH, micro-catchment (MC) RWH, and *in-situ* RWH (Table 2.2) (Hatibu *et al*., 2003; FAO, 2009). Figure 2.2 shows the principle of RWH, which is common for the different classifications, except *in-situ* (no runoff) systems which capture rainfall where it falls (Pacey & Cullis, 1986; FAO, 2009).

Table 1.2: Characteristics of the three types of RWH tested in the North-East of Tanzania (Hatibu *et al*., 2003).

Characteristic	***In-situ***	**Micro-catchment**	**Macro-catchment**
Flow distance	Few centimetres	Several metres	Several kilometres
Flow type	Sheet	Sheet/rill	Channel
Location of RPA	Within crop	Within farm	Outside farm
Typical RPA: RRA	1: 1	>1: 1	>>10: 1
Division between RPA: RRA	Indistinct	Distinct	Distinct
Risk of erosion	Reduced	Reduced	Increased
Potential problems	Produces insufficient runoff	Leaving land uncultivated	Erosion, water allocation
Typical techniques	'*Ngoro*' pits (Tanzania)	*Meskat* (Tunisia) and *Negarim* (Israel)	*Caag* systems (Somalia)

2.3.2 Macro-catchment (external) RWH

External catchment RWH systems involve the collection of runoff from a large RPA which is much larger than the RRA (RPA : RRA >>10: 1) (Hatibu *et al*., 2003; FAO, 2009). In general, the two do not lie within a single farmer's land, given an appreciable distance separating them (Table 2.2). The RPA and RRA will often be very different in character and the transfer distance may be in the range of a few hundred meters to several kilometres. Macro-catchment size varies from 1000 m^2 to 200 ha. The type of catchment areas includes an overflow system or spillway and a catchment slope that varies from 5 to 50 percent. The water collected in these large catchment areas is normally used to irrigate crops located in terraces or in flat fields (Prinz & Malik, 2002). In this system, the catchment has to be established based on crop water requirement, RPA : RRA ratio, design rainfall, runoff coefficient and collection efficiency factor (SWCB, 1997a). Examples include: semi-circular bunds, trapezoidal bunds, road runoff harvesting into basins and into retention ditches (SWCB, 1997a), contour stone bunds (FAO, 2009), hillside systems such as the *Majaluba* system in Tanzania (Meertens *et al*., 1999); stream-bed systems or earth bunds (Van Dijk & Ahmed, 1993); and stream diversion systems such as the *Caag* system in Somalia (Reij, 1991).

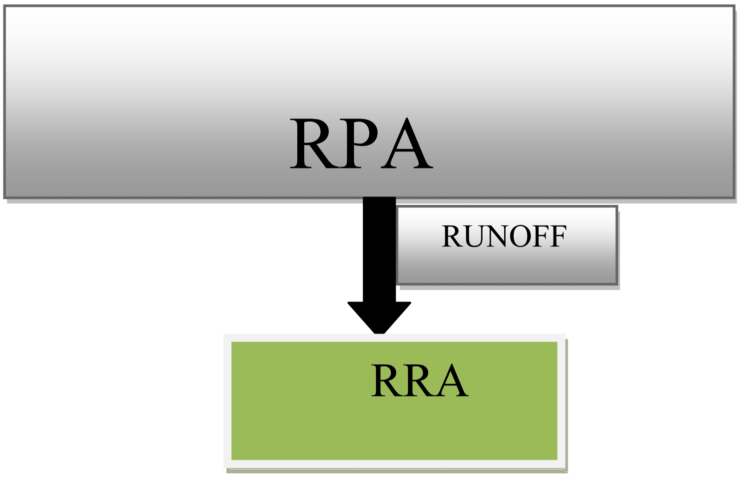


Figure 2.2: The principle of RWH (FAO, 2009): RRA = runoff receiving area and RPA = runoff producing area.

According to transfer distance, the size of catchments and, therefore, the amount of runoff produced, this technology can further be subdivided into large external catchments and small external catchments (Hatibu *et al*., 2003; Hatibu & Mahoo, 2009; FAO, 2009).

In the case of the large external catchments, a heavy runoff amount is generated and then deviated from waterways (e.g. gullies and ephemeral streams) to be conveyed into cropland, i.e. spate irrigation. Among these there exist: (1) hillside sheet/rill runoff utilization (Figure 2.3); (2) floodwater harvesting within the stream bed (Figure 2.4a); and (3) ephemeral stream diversion (Figure 2.4b). In the case of system (1), runoff which occurs on hill-tops (with stone outcrops), sloping grounds, grazing lands or other compacted areas, flow and naturally collect in low lying flat areas. In many areas, farmers grow their crops on the wetted part of the landscape and use the runoff without any further manipulation or management. In the case of system (2), barriers such as permeable stone dams are used to block the water flow and spread it on the adjacent plain and promote infiltration. The wetted area is then used for crop production. In the case of system (3), water is diverted from its natural ephemeral stream and conveyed to cropping areas.

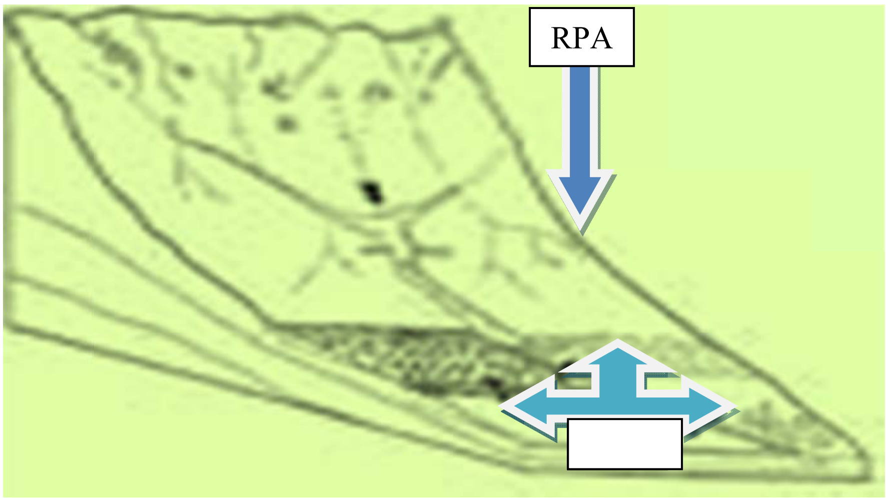


Figure 2.3: Runoff farming system using steep slope catchment areas and field cropping areas (Prinz & Malik, 2002).

Small external catchments refer to a form of small-scale flood or runoff diversion and spreading either directly into cropland or pasture through a series of water retention structures (contour bunds, terrace channels). The runoff is transported by means of natural waterways, road drainage or diversion/cutoff drains. In parts of Kenya (Machakos and Laikipia), road/footpath runoff harvesting is an outstanding model of small external catchments. Flood water from road/footpath drainage is conveyed either to storage for supplemental irrigation or into croplands (wild flooding, contour bunds, deep trenches with check-dams to improve crop yields). Another tangible instance of this type of catchment was identified in south-western Uganda, where runoff from gullies, grazing land, or road drainage is diverted into banana plantations (Kiggundu, 2002).

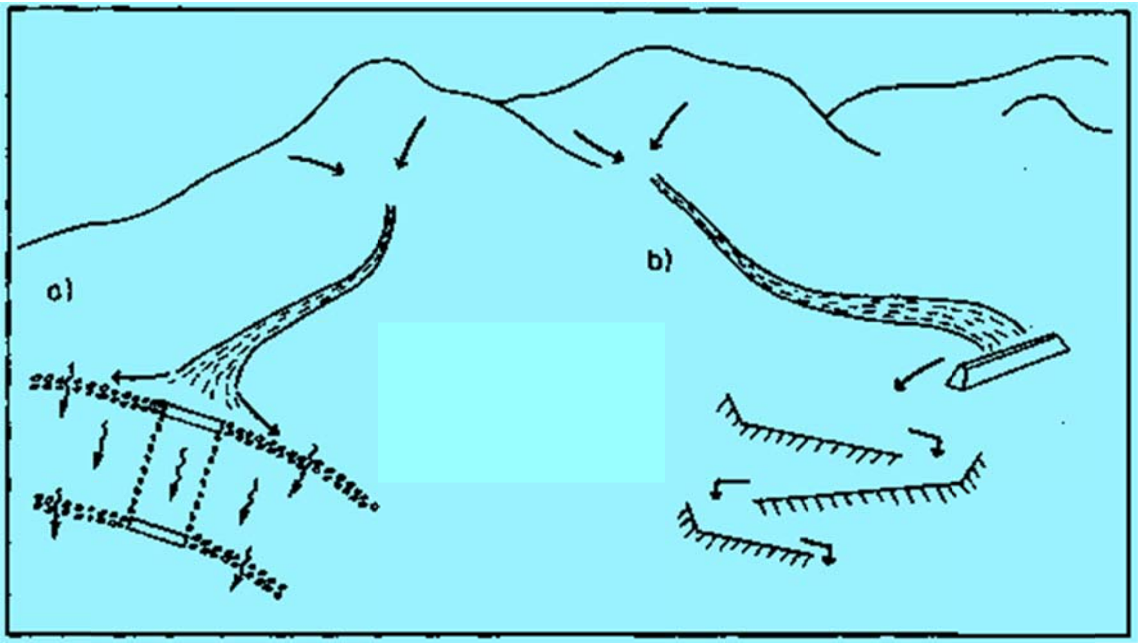


Figure 2.4: Floodwater farming systems: a) spreading within a channel, b) diversion system (FAO, 2009).

2.3.3 Micro-catchment (MC) RWH

For MC systems there is a distinct division between a catchment area and a cropping area. This involves runoff generation within the farmer's field and subsequent concentration on either a single crop especially fruit trees, a group of crops, or row crops with alternating catchment and cropped areas mainly along contours. The transfer distance is typically in the range of less than 100 m, usually 5 – 50 m and both areas will typically lie within a single farmer's land (Table 2.1) (Boers & Ben-Asher, 1982; Ngigi, 2003; Hatibu & Mahoo, 2009). Catchments are either square/rectangular, or circular, though longitudinal MC following the contour lines to enable mechanization are often preferred for field crops (Hatibu & Mahoo, 2009). A number of within-field RWH systems are grouped under this technology, in which crop land is subdivided into MCs that supply runoff either to single plants or a number of plants. For example, *Negarims* (Figure 2.5) for a single tree in Israel and in Kenya, or for a number of plants in the case of *Chololo* pits in Tanzania (Evenary *et al*, 1982; Ngigi, 2003), the *Meskat* system of Tunisia (El Amami, 1977), the ridge and furrow RWH system in the semi-arid loess areas of China (Figure 2.6) (Wang *et al*., 2005) or the in-field rainwater harvesting (IRWH) technique at Glen, South Africa (Figure 2.7) (Botha *et al*., 2003).

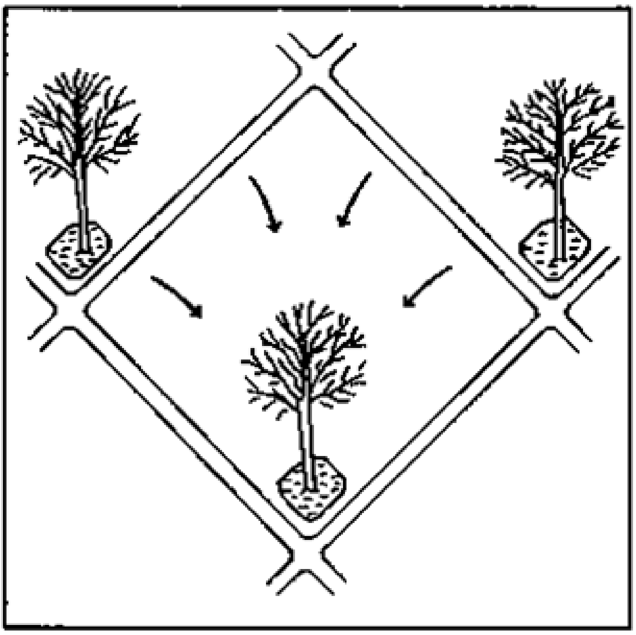


Figure 2.5: Negarim MC rainwater harvesting (FAO, 2009).

A water harvesting system should have the following four components: (a) runoff producing area, (b) runoff receiving area, (c) runoff storage facility, and (d) cultivated or cropped area (Oweis *et al*., 1999). There is a general agreement that the first two components are found in all water harvesting systems. The runoff producing area is the most important component in a water harvesting system, which is responsible for the quantity and quality of water from runoff collection. In addition, catchments vary widely in soil surface treatments and characteristics resulting in very large differences in catchment efficiency (Frasier, 1980). Many surface treatments (mechanical, surface covering, etc.) have been proposed and tested throughout the arid and semi-arid regions of the world (USDA, 1975; Dutt *et al*., 1981; Evett & Dutt, 1985). However, no surface treatment is suitable for all applications. It depends on local rainfall characteristics (amount, duration, intensity and distribution), construction materials, site conditions, installation methods, and labour cost. Therefore, water harvesting techniques do not always transfer well from one set of conditions to another (Ojasvi *et al*., 1999), and most of these use trial-and-error for the design of water harvesting catchments (Suleman *et al*., 1995).

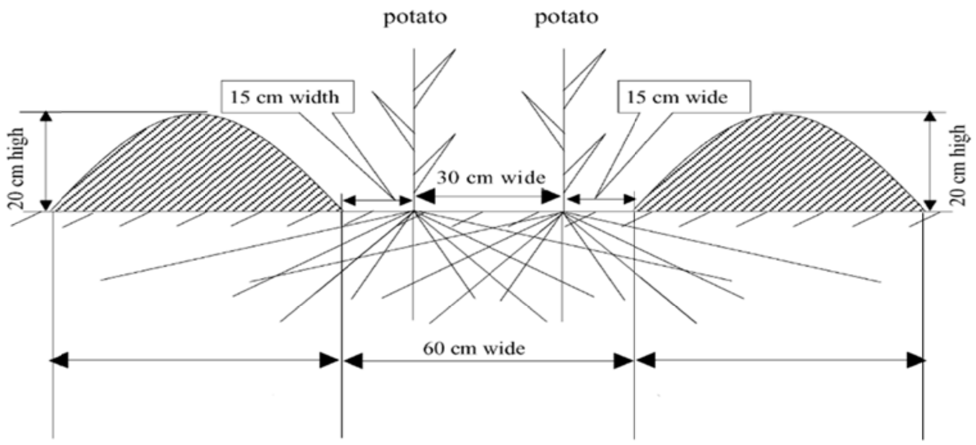


Figure 2.6: A schematic diagram showing a ridge and furrow rainfall harvesting system (after Wang *et al*., 2005).

The advantages of the MC systems include relatively high runoff efficiencies and a relatively low risk of soil erosion. In many cases, however, this form of RWH involves leaving part of a field unplanted. As a result, even though yields on the RRA may be higher, overall production may decrease when measured over the total land area (RPA plus RRA). It is a well-known fact that because of reduced infiltration losses, the percentage of runoff increases with decreasing catchment size (Amerman & McGuiness, 1968). Small watersheds can produce runoff amounting to 10 – 15% of the annual rainfall and for a MC this can be even higher.

The design of an MC affects water use efficiency, crop yield, erosion hazard, earth works, and farm operations (Gardner, 1975; Shanan & Tadmor, 1976). The first design factor to consider is the size. In experiments, MC size has ranged from roughly 0.5 m^2 (Aldon & Springfield, 1975) to 1000 m^2 (Evenari *et al*., 1968) for trees, shrubs, and row crops with average annual rainfall ranging from 100 mm (Evenari *et al*., 1982) to 650 mm (Anaya & Tovar, 1975).

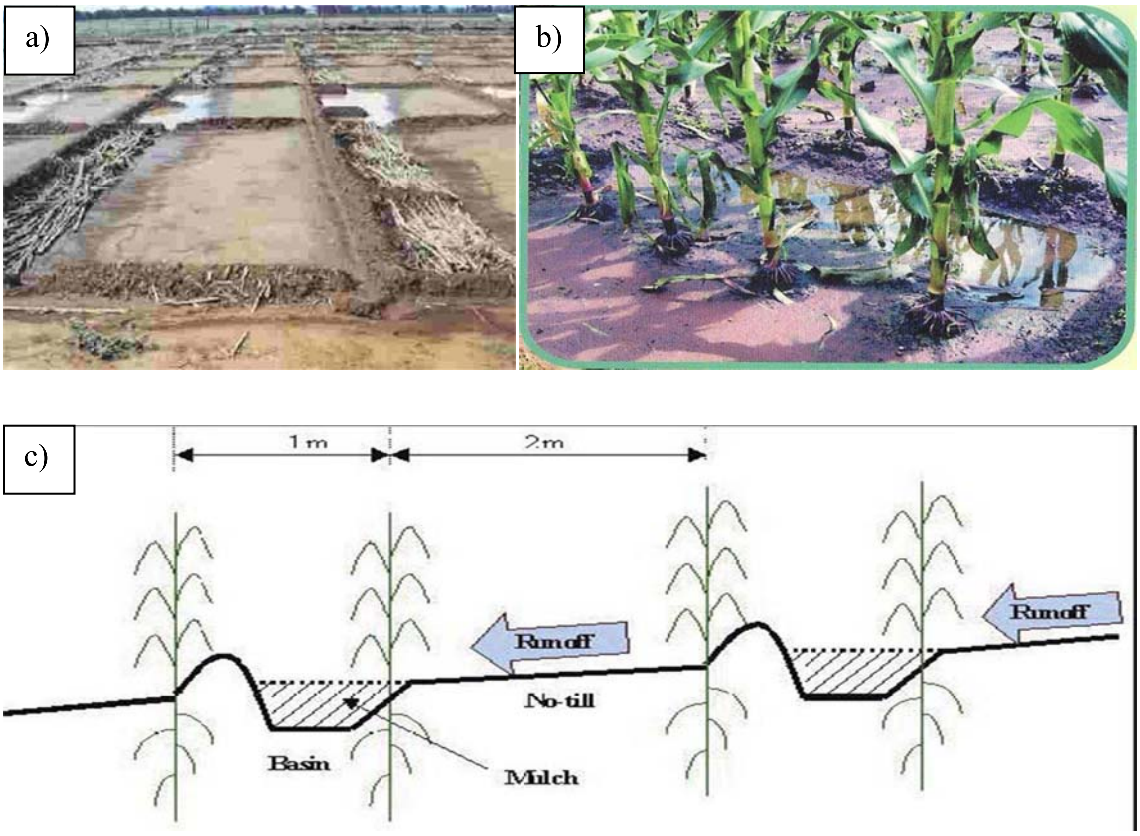


Figure 2.7a), b) and c): On-farm Application of In-Field Rainwater Harvesting Techniques on small plots in the Central Region of South Africa (Botha *et al*., 2003).

Many MCRWH techniques have been tried and trusted in many areas of the world. For instance, in Israel *negarim* MCs (Figure 2.5) are popular for growing fruit trees. These types of MCRWH are square or diamond shaped basins surrounded by low earth ridges on all sides. These ridges keep rainfall and runoff in the mini-basin. Runoff water is directed to the lowest point and stored in an infiltration pit. Another example is plastic-covered ridges supplied with water from a furrow rainfall harvesting (PRFRH) system (Figure 2.6). The system was first tried in China to examine the yield promotion of potato crops. The PRFRH technique increased temperature and availability of nutrients in the ridges, and maintained soil water in ridges. This technique markedly improved potato yield as well as WUE. In South Africa, an instance of MCRWH technique was presented as IRWH (Figure 2.7). This technique involves a catchment area or RPA, and a cropping area or RRA. The former promotes on-field runoff generation, while the latter enables the produced runoff to stop and subsequently infiltrate and be stored in the soil layers beyond the evaporation zone. Ridges are made directly below each cropping area to enable better conservation of water in the soil profile. Mulch is also placed in the cropping area to minimize evaporative losses. The ratio between the catchment area and the cropping area, according to field experience with crops in semi-arid areas, is about 2:1 (van Rensburg *et al*., 2003). The IRWH system combines the advantages of water harvesting, no-till and basin tillage to collect as much runoff as possible (Hensley *et al*., 2000).

MCRWH systems have the potential to prevent soil erosion. Since they are a useful measure in soil and water conservation, by capturing and storing runoff during heavy rainstorms, they can directly contribute to the reduction of soil erosion (UNEP, 2003). The systems can effectively increase productivity of flat rainfed land because of increased water availability (Prinz & Malik, 2002). In addition, their implementation has created labour group formation among farmers, which allows them to share tools, labour and ideas (Rosegrant *et al*., 2002). However, there also exist drawbacks associated with the application of MCRWH systems such as high demand for labour, waterlogging, high cost of investment, etc. (Haile & Merga, 2002; Rosegrant *et al*., 2002; Senkondo *et al*., 2004; Prinz & Malik, 2002).

2.3.4 *In-situ* RWH (soil water conservation)

Also called soil water conservation technologies, *in-situ* RWH technologies, are the systems which do not involve runoff generation areas but instead aims at capturing and conserving the rainfall where it falls in the cropped areas or pasture. A model of these technologies is conservation tillage which aims at maximizing the amount of soil water within the rooting zone. A number of cultural water conservation practices such as mulching, tied-ridges, addition of manure/compost, *ngoro* pit (Tanzania), no-till, etc. could fall under this category (Ngigi, 2003). Given its origin, simplicity, cost, and flexibility in use, *in-situ* rainwater conservation technology is by far the most practiced (Reij *et al*, 1996; LEISA, 1998; Rockström, 2000). *In-situ* RWH comprises a group of techniques that prevent runoff over more than a few centimetres and promote infiltration (Table 2.1) (Rockström, 2000). In Malawi for example, tied-ridges is one such technique that is being promoted to conserve rainwater in farmers’ fields (Jones & Stewart, 1990; Wiyo *et al*., 2000). In tied-ridges, ridge furrows are blocked with earth ties spaced a fixed distance apart to form a series of MC basins in the field (Figure 2.8a, b, c). The created mini-basins then retain surface runoff within the field.

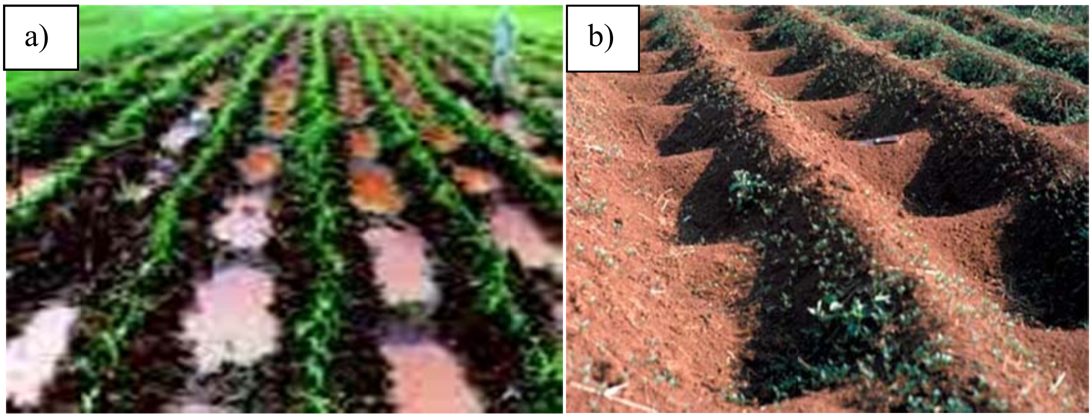


Figure 2.8: Tied-ridges rainwater harvesting.

(a) Tied-ridges for water conservation (http://www.infonet-biovision.org/default/ct /254/ soilFertilityManagement);

(b) Graded contour ridges with cross ties lower than the main ridges to retain water between the cross ties, but allow excess rainwater to flow between the main ridges rather than spill over or break them (http:www.fao.org/docrep/006/y4690e/y4690e09.htm).

In essence, tied-ridges are *in-situ* RWH technologies since they harvest rainwater where it falls. They are one of the conventional approaches to soil and water conservation, conceived to improve infiltration of rainwater into the soil. These techniques are known to be the most successful of the RWH technologies in semi-arid areas. For instance, they have been successfully used in semi-arid West Africa to enhance soil water conditions and physical properties with marked gains for cotton, maize, cowpeas, millet and sorghum growers. Compared with the conventional or open-ridged fields, tied-ridges resulted in yield increases of nearly 40% in maize trials with improved varieties. Similar increases in grain yield of about 63% were observed with a maize variety produced with tied-ridges in Ethiopia (http://www. africanexecutive.com/ modules/magazine/articles.php?).

According to the literature, in the case of tied-ridges, yields have been found to vary depending on the amount and distribution of rainfall, soil type and crop growth cycle (El-Swaify *et al*., 1985). In a semi-arid context, especially with a coarse-textured soil with high hydraulic conductivity, *in-situ* conservation may offer little or no protection against poor rainfall distribution. Tied-ridges, for example, often lead to little or no surface runoff during normal storms. In severe storms, however, tied-ridges can lead to overtopping, ridge failure, waterlogging and total loss of the crop.

2.4 Surface sealing and runoff generation

2.4.1 Soil crusting and infiltration

Infiltration is the process by which water enters the soil pore spaces and becomes soil water (Brady & Weil, 2002), and the maximum infiltration rate (infiltrability) (It) is the rate at which water can enter the soil (Brady & Weil, 2002; Horton, 1940; Morin & Cluff, 1980). Infiltration rate is one of the key parameters needed in the design and evaluation of irrigation systems, watershed modelling and prediction of surface runoff (Zerihun *et al*., 1996; Oyonarte *et al*., 2002; Idike, 2002). Cumulative infiltration is the total amount of water that penetrates into the soil in a given time. In mathematical lingo, it is the integral over time of the infiltration rate. Quantitatively, It is the flux or volume of water entering the soil per unit area per unit time. The following are major factors affecting infiltration rate:

1. Soil surface and sub-surface physicochemical properties such as texture, structure, organic matter, soil crusting, soil compaction, formation of hard pans or hardsettings, hydraulic conductivity, soil water content, pore size distribution, swelling and shrinking, and the type and nature of clay mineralogy;
2. Rainfall characteristics such as amount, intensity and duration; and
3. Surface features such as slope, vegetation, surface storage and runoff.

Crop production in arid and semi-arid areas is greatly limited by water scarcity. Furthermore, the degradation of the structure of the topsoil under rainfall can cause a drastic decrease in the infiltration rate of agricultural soils, especially under conventional tillage (Morin & Benyamini, 1977; Boiffi, 1984; Casenave & Valentin, 1989). As a result, considerable amounts of rainfall are lost through runoff in arid and semi-arid areas due to surface sealing and crusting. Soils of these areas are mostly characterized by soil sealing which is the main cause of low infiltration rates. Broadly, the origin of the feature of these soils is their exposed surface and therefore their susceptibility to damage from raindrop impact. Actually, when high energy raindrops directly lash bare soils, they break down aggregates and compact a thin surface layer, resulting in seal or crust formation (Loch, 1994). Crusting is sometimes used to depict surface seals that have dried, but more often is used interchangeably with sealing. Surface sealing and crusting are different from hardsetting in that seal or crust formation requires rainfall impact, while hardsetting needs no external influence.

A soil crust (dried seal) is a thin hard layer formed on the surface of the soil due to dispersive forces in raindrops or irrigation water followed by drying (Epstein & Grant, 1973; Morin *et al*., 1983). McIntyre (1958a, b) showed that a crust consists of two parts: a 0.1-mm-thick upper skin seal, due to compaction by raindrop impact, and a 2-mm-thick deeper zone of low porosity due to fine-particle movement and accumulation. Moreover, two types of crusts have been identified. Structural crusts are formed in the upper soil layer when aggregates break down and coalesce under raindrop impact, resulting in the reduction of soil porosity. Sedimentary crusts are formed from the deposition of sediments and micro-aggregates. Sedimentary crusts depend on flow and surface conditions which affect sedimentation. Runoff rate, flow velocity, and micro topography strongly influence the spatial distribution of sedimentary crusts. Generally, sedimentary crusts are found in depressions and micro-depressions, whereas structural crusts are associated with soil mounds (Figure 2.9).

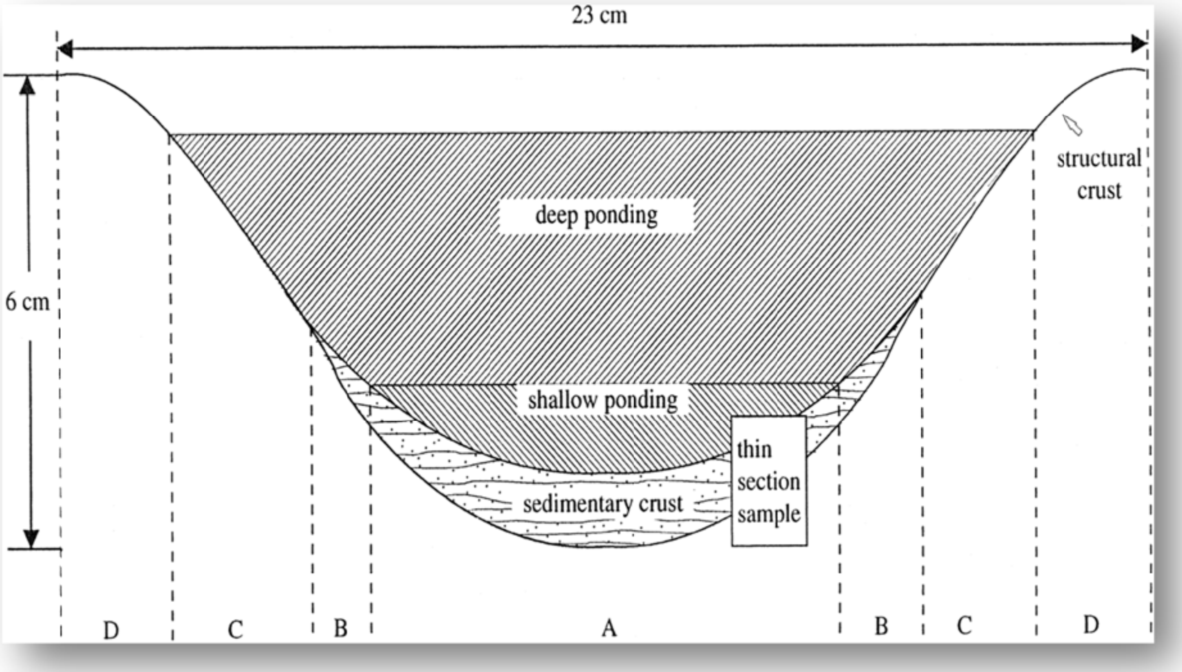


Figure 2.5: Schematic representation of soil surface depression showing the approximate configuration of the sedimentary and structural crusts and the location of the thin section samples (Fox *et al.*, 1998): A = shallow ponding, B = sedimentary crust, C = deep ponding and D = structural crust.

Surface sealing and crusting significantly decreases infiltration and increases runoff with the potential of accelerating erosion. According to McIntyre (1958a), the presence of only a 0.1 mm thick crust may reduce the infiltration rate from 800 cm/day to 70 cm/day. This infiltrability reduction exercises an adverse impact on rainfall or irrigation efficiency. At the same time, surface runoff increases with subsequent soil erosion (Hoogmoed & Stroosnijder, 1984). Investigations have proven that the infiltration rate is less for pre-wetted surfaces than for dry surfaces due to the full development of the surface seal caused by the breakdown that occurred earlier during pre-wetting (Le Bissonais & Singer, 1992).

In an effort to demonstrate the vital role played by soil crusting in the infiltration process, Morin and Benyamini (1977) developed an infiltration model that highlights soil susceptibility to crust formation (Equation 2.3). According to their field experiment conducted on a Hamar soil (13% clay and 2% silt) in Israel under different soil water regimes, it was revealed that soil crusting played the key role in determining the final infiltration rate (I_f), rather than the antecedent soil moisture (Table 2.3). This was corroborated by Morin *et al.* (1983) throughout a study conducted in the Sha'ar Hanegev region of southern Israel on a Calcic Haploxeralf soil (FAO classification) (Table 2.4). Nonetheless, in the absence of a soil crust, the antecedent soil water content impacts on the infiltration rate. This is more likely in the first few hours of infiltration. In this framework, Hoogmoed and Stroosnijder (1984) reported that for permanently crusted soils the effect of different soil water content on infiltration was only on the time between initial infiltrability (I_{ti}) and final infiltrability (I_{tf}).

$$\boxed{I_t = I_{tf} + (I_{ti} - I_{tf}) * \exp(-\gamma * I_i * t_i)} \qquad \text{(Eq.2.3)}$$

where I_t = instantaneous infiltration rate (mm hr^{-1}), I_{tf} = final infiltration rate of the soil (mm hr^{-1}), I_{ti} = initial infiltration rate of the soil (mm hr^{-1}), I_i = rain intensity (mm hr^{-1}), t_i = time from the beginning of rain (hr), and γ = empirical soil parameter representing surface aggregate resistance to dispersion (mm^{-1}).

Table 2.2: Values of initial infiltration rate (I_{ti}), final infiltration rate (I_{tf}) and soil particle aggregate stability (γ) for the various drying regimes (after Morin & Benyamini, 1977).

Drying regime	**I_{ti} (mm h^{-1})**	**I_{tf} (mm h^{-1})**	**γ (mm^{-1})**
Dry soil, first rainfall[1]	320	8	0.106
Wet soil, second rainfall[2]	50	5	0.70
Six days after first rainfall	160	8	0.16
Eleven days after first rainfall	170	8	0.16

[1] –Prepared seedbed and [2] – twenty-four hours after first rainfall.

From Table 2.3 and 2.4 can be observed that a higher value for final infiltration rate was reached before the crust was produced. Thereafter, the final infiltrability value stabilized at different antecedent soil water conditions. In another development, infiltration rate values ranging from 6 to 7 mm per hour were found during several studies, for example, Hoogmoed and Stroosnijder (1984) in the Sahel (West Africa) and Hensley *et al.* (2000) at Glen (South Africa). In the first case, the soil was a loamy fine sand (5% clay and 20% silt) with a wet crust, whilst in the second, the study area was a semi-arid ecotope with a clay soil. Likewise, Zere *et al.* (2005) predicted a final infiltration value of 5 mm hr^{-1} and 10 mm hr^{-1} on bare untilled and maize cropped treatments at the Glen ecotope, respectively.

Table 2.3: Values of initial infiltration rate (I_{ti}), final infiltration rate (I_{tf}) and soil particle aggregate stability (γ) for the different experimental soils (after Morin *et al*., 1983).

Soil conditions	**Alumim loess (36% silt & 17% clay)**			**Alumim loess + gypsum**			**Ruhama loess (47% silt & 17% clay)**		
	I_{ti}	I_{tf}	γ	I_{ti}	I_{tf}	γ	I_{ti}	I_{tf}	γ
Dry, friable, 1st storm on wheat seedbed	50	4	0.080	50	7	0.043	77	8	0.095
Dry, crusted, 7 days after preceding storm	18	2	0.137	43	5	0.054	35	5	0.114
Wet, crusted, 24th after preceding storm	5	1.5	0.149	15	5	0.097	35	5	0.420

The γ letter in the infiltration model (Equation 2.3) and in Tables 2.3 and 2.4, illustrates the aggregate stability, i.e. resistance to the dispersion of the crust particles due to raindrop impact. Tables 2.3 and 2.4 present high γ values after 24-hour rainfall and this shows the strength of the crust when it is relatively wet; since high γ values are linked to a more stable crust. Usually, the γ values of the dry crust are low and exhibit a constant trend as it appears in Table 2.3. However, the γ values are considered to change according to the state of the soil surface. From Table 2.4 can be seen that I_{tf} values increased when gypsum was added to the Alumim loess soil (36% silt and 17% clay). In effect, adding gypsum resulted in lower γ and higher I_{tf} values than no gypsum at all.

2.4.2 Surface treatment and runoff efficiency

The runoff producing area is the most important element of any water harvesting system, for it is responsible for the amount and quality of water collection. However, runoff generation varies due to several factors, including soil surface state and treatment, which affect the required sizes of both the catchment and storage facilities (Frasier, 1980). As such, many RWH catchment surface treatments for increasing runoff have been tried in many arid and semi-arid areas of the world (USDA, 1975; Dutt *et al*., 1981; Evett & Dutt, 1985). These watershed treatments include mechanical treatments (compacting and smoothing), colloidal dispersion methods (slaking), hydrophobic applications (water repellents), surface binding materials (cementing and sealing) as well as surface covering (asphalt, rubber and plastic) (Tadmor & Shana, 1969). For example, sodium dispersed, compacted earth micro-watersheds had been tested and applied to the USA (Frasier, 1983); roaded catchments in Australia

(Coles *et al*., 2004), and plastic-covered in China (Li *et al*, 2004) and South Africa (Ibraimo, 2011). Nevertheless, there is no surface treatment which is appropriate for all applications. It is conditioned by local features, installation methods, and labour cost. Consequently, RWH techniques do not always transfer well from one site to another (Ojasvi *et al*., 1999), and this has often led to resorting to the use of trial-and-error for the design of water harvesting catchments (Suleman *et al*., 1995). Moreover, among the treatments introduced above, it is likely that only the cheapest treatments such as clearing, smoothing and compacting are economical for crop production (Evett & Dutt, 1985). Figure 2.10 illustrates six different runoff inducement treatments tested and reported by Li *et al* (2004). These surface treatments are referred to in the last paragraph of this section. In addition, other factors involving catchment size, field gradient and soil surface depth have also been reported to affect all aspects of runoff (Boers, 1997).

Fink *et al* (1979) defined threshold retention of a catchment as the quantity of precipitation required to initiate runoff, and runoff efficiency of a catchment as the ratio of runoff volume to precipitation volume. Runoff efficiencies have been expressed as annual averages to discount variability due to storm characteristics. Several reports on rainwater harvesting in arid and semi-arid areas confirmed that runoff volume varies with the capacity of the catchment to collect runoff (Karnieli *et al*., 1988, Li *et al*., 2006, Ibraimo, 2011). For instance, the report on runoff trial (1982 – 1998) from Yair and Raz-Yassif (2004), carried out at spatial scales varying from a few hundreds of m^2 up to 0.3 km^2, showed a decrease in runoff as the slope length increased. This is because the longer the catchment area (and the time available for runoff water infiltration), and the higher the lost surface runoff (Myers, 1974; Sharma *et al*., 1986). In conformity with Li *et al*. (2006), runoff depth and runoff efficiency were significantly higher in smaller MCs than in the larger micro-watersheds. This was corroborated by Ibraimo (2011), declaring that runoff volume for the runoff plots with bare surface increased with an increase in plot length, while runoff efficiencies decreased (with length) in general.

Figure 2.6: A photograph of an experimental plot layout showing different surface treatments with the concrete plot in the front, followed by a natural loess slope, gravel covered plastic film, and other treatments (*Li et al*., 2004).

In order to understand the response of runoff to the status of the soil surface, Wang *et al.* (2009) carried out a study in the semi-arid region of China. Treatments consisted of compacted and plastic-mulched ridges. In this trial, the rainfall threshold (minimum rainfall necessary to generate runoff) was 2.8 mm for compacted ridges, while the range of rainfall threshold for plastic-mulched ridges varied from 0.23 to 0.47 mm. Likewise, the runoff efficiency of the compacted ridges varied from 25 to 29%, whereas the efficiency of the plastic-covered ridges fluctuated between 91 and 94%. The reason behind these results was that the smooth and waterproof plastic sheet did not allow any water infiltration, and the rainfall was only lost through evaporation which took place before the runoff was collected by buckets. Conversely, the compacted ridges were characterized by high infiltration, and runoff was generated only under high rainfall intensities. Runoff was produced only when rainfall intensities exceeded the soil infiltration rates (Wilcox *et al*., 1997).

In the experiment reported by Li *et al.* (2004) on shallow sandy loam soils of a semi-arid region of China, six different surface treatments on plots with a 19.8 m^2 (3.3 m x 6 m) area were investigated. The treatments were as follows: concrete, plastic film, gravel covered plastic film, asphalt fibreglass, cleared loess slope, and a natural loess slope. In the course of this study, the average monthly or annual runoff efficiency was calculated by dividing the monthly or yearly total volume of runoff by the corresponding total volume of rainfall (Table 2.5 & 2.6). Monthly runoff efficiency was higher and varied between 31% and 76% for the concrete, and 60% and 88% for the asphalt fibreglass as compared to 3% and 94% for the plastic film. Monthly runoff efficiency was low for the cleared loess slope (3 – 23%) and the natural loess slope catchments (1 – 30%). The large runoff efficiency variation for the plastic film and the gravel-covered plastic film was attributed to the fact that plastic film deteriorated by weathering after 5 months. Gravel cover extended the longevity of the plastic film by 1 – 2 months.

Table 2.4: Monthly runoff (mm) and runoff efficiency (%) and the annual average (runoff and runoff efficiency) for the surface treatments in 1998 (the values in parentheses are runoff efficiencies calculated as percent of rainfall).

Treatment	May	June	July	August	September	October	Annual
Natural loess slope	8.1 (15)	2.2 (10)	5.4 (10)	10.5 (11)	0.2 (1)	1.3 (9)	27.7 (11)
Cleared loess slope	9.0 (17)	2.2 (10)	6.1 (11)	13.1 (14)	0.5 (3)	2.1 (15)	32.9 (13)
Concrete	27.7 (51)	10.5 (46)	22.6 (40)	43.9 (48)	4.2 (31)	8.0 (57)	116.9 (46)
Plastic film	46.3 (86)	18.5 (82)	49.1 (87)	28.4 (31)	0.9 (7)	0.6 (4)	143.9 (57)
Gravel-covered plastic film	-	-	44.4 (79)	50.1 (55)	7.9 (57)	8.5 (60)	110.9 (56)
Asphalt fiberglass	43.7(81)	17.2(76)	49.5 (88)	54.9 (60)	10.6 (77)	12.0 (85)	187.9 (74)

Table 2.5: Monthly runoff (mm) and runoff efficiency (%) and the annual average (runoff and runoff efficiency) for the surface treatments in 1999 (the values in parentheses are runoff efficiencies calculated as percent of rainfall).

Treatment	April	May	June	July	August	September	October	Annual
Natural loess slope	4.6 (30)	6.1 (9)	3.7 (6)	15.0 (11)	0.1 (0)	0.2 (1)	0 (0)	29.6 (9)
Cleared loess slope	3.5 (23)	5.0 (23)	5.0 (8)	24.3 (17)	0.8 (3)	1.2 (5)	0 (0)	39.8 (12)
Concrete	6.6 (45)	47.0 (72)	46.7 (76)	105.5 (74)	13.8 (57)	12.9 (48)	4.0 (45)	236.5 (69)
Plastic film	10.3 (69)	57.0 (87)	57.9 (94)	126.2 (89)	7.7 (32)	2.4 (9)	0.3 (3)	261.8 (76)
Gravel-covered plastic film	7.2 (48)	55.6 (85)	54.4 (88)	123.1 (87)	16.5 (68)	7.0 (26)	0.4 (4)	264.2 (77)
Asphalt fiberglass	9.5 (64)	52.6 (80)	51.0 (83)	117.6 (83)	19.5 (81)	22.2 (82)	6.5 (74)	279.0 (81)

2.5 Crop, runoff and crop growth-surface runoff integrated models

2.5.1 Crop models

Risk analysis has become an integral part of every decision made in management. Managers are constantly faced with uncertainty, ambiguity and variability. In addition, even with the access to unprecedented information, realistically predicting the future still remains a puzzle. Simulation models can overcome some of these challenges. In the agricultural field, simulation models are mathematical equations that can, for example, represent the phenomena that occur within the plant and the interactions between the plant and its environment. Owing to the complexity of the system and the incomplete status of present knowledge, it seems impossible to completely represent real agricultural systems in mathematical terms. Moreover, unlike in the fields of physics and engineering, universal models do not exist within the agricultural sector. Therefore, models are built for specific purposes and the level of complexity is adapted accordingly. Inevitably, different models are designed for different subsystems and several models may be built to simulate a particular crop or a particular aspect of the production system (Kumar & Chaturevdi, 2009).

In general, with crop simulation models, input data of the soil-plant-atmosphere continuum (SPAC) help to simulate daily water requirement. These models make use of weather data to predict plant growth and development, from which the water requirement and soil water balance are computed. Some models give the user the possibility to update inputs during the season, say, canopy cover or soil water content. Among these, certain scheduling models currently available in South Africa include PUTU, BEWAB and SWB (Steyn & du Plessis, 2003). SWB is a mechanistic, real time, crop growth irrigation-scheduling model; and it covers a wide range of crops, including potato (Steyn, 1997; Annandale *et al*, 1999) and Swiss chard (Annandale *et al.*, 1999). More detail on this model is given in Chapter 7.
In the case of potato crop production, simulation models include but are not limited to the following:

- A temperature-driven LINTUL-POTATO (Light INTerception and UtiLisation) model has been developed to simulate potential dry matter production in different environments through the relative effect of thermal time on different growth stages

(Kooman & Haverkort, 1995). Moreover, the model takes into account the effects of both photoperiod and physiological time on crop development rate from the vegetative to the tuber initiation stage and potential tuber dry matter production. The LINTUL-POTATO model estimates the total crop dry matter production which is determined by the length of the growth cycle, water supply and radiation.

- The growth and phenology elements of the SIMPOTATO potato model (Hodges, 1992) were integrated into the CROPSYST (Stockle & Nelson, 1994) crop simulation model. CROPSYST is a multi-year and multi-crop simulation model. Its structure allows the simulation of diverse crops in a rotation and therefore the assessment of the water, carbon and nitrogen dynamics in the whole production system. The updated CROPSYST-SIMPOTATO model can be used to simulate the growth and production of potatoes using input parameters derived from a field study. The predicted yields under different N management practices can be compared with measured yields from the field experiment. The water percolating and the N leaching below the rootzone can be predicted using this model.
- Ritchie *et al*. (1995) developed a model called SUBSTOR (Simulate Underground Bulking Storage Organs), where the timing of tuber initiation is a function of cultivar response to both temperature and photoperiod. They established that cultivars differ in the threshold photoperiod above which tuber initiation is inhibited. This idea was incorporated in SUBSTOR, where a relative day length factor for tuber initiation (RDLFTI) was developed.

2.5.2 Rainfall-runoff models

Runoff models came to light in the late 1960’s and early 1970’s (Madsen *et al*., 2002). Most of these runoff models consisted of two types: on one hand, the infiltration model used to disaggregate rainfall into runoff and infiltration, on the other hand, models used to simulate just runoff (Horton, 1940; Morin and Cluff, 1980; Morin *et al*., 1983; Madsen *et al*., 2002; Chahinian *et al*., 2005; Xuefeng & Marino, 2005). Recently, the runoff models have been combined with several physical and conceptual infiltration models developed in this regard. These latter include among others: Green and Ampt (1911), Horton (1940), Philip (1957), USDA – Soil Conservation Service (SCS) (1972), Morel-Seytoux (1978) and Morin and Cluff (1980). Besides Philip (1957) and Morel-Seytoux (1978) which are physical models, the others are either conceptual or empirical models (Chahinian *et al*., 2005). Mathematical models have simple structures, but employ sophisticated methods for parameter or error estimation (Bruggeman & Oweis, 1998). Physically-based models use differential equations to compute infiltration, surface runoff and channel flow at any particular point in a catchment area. Nevertheless, it is difficult to use such models for practical purposes, because the necessary parameters cannot be evaluated with the required spatial and temporal accuracy (Naef, 1981). Meanwhile, unit hydrographs and linear regression models are also commonly used for rainfall-runoff prediction (Walker *et al*., 2005).

Since the choice of any model depends on many factors including the objective of the study, in the following sections, it was decided to further discuss some of the runoff models that are useful for this RWH study.

A. Simple empirical models

The linear regression of daily rainfall to daily runoff appears the simplest method for estimating daily runoff (Budyko, 1974; Hensley *et al*., 2000). In general, the linear regression model (Boers, 1997; Bruggeman & Oweis, 1998) can be expressed as:

$$\boxed{Roff = RE(R - R_o)} \quad (R > R_o) \qquad \text{(Eq. 2.4)}$$

$$\boxed{Roff = 0} \quad (R < R_o)$$

where Roff = daily runoff (mm); R = daily rainfall (mm); and RE and R_o = constants. The constant R_o is the rainfall threshold above which runoff occurs (mm), and RE is the runoff efficiency after the rainfall threshold has been exceeded (%).

In simple linear regression procedures, daily observed runoff is regressed against daily rainfall to obtain the constants RE and R_o (Asante & Stephenson, 2006). It should be noted that even though these simple models estimate surface runoff from rainfall volumes only, their implementation becomes more reliable when they are applied to the site of their parameterization or other sites with similar soil characteristics. Moreover, owing to the high variability in both infiltration rates and surface retention, there exists immense spatial and temporal fluctuations in RE and R_o for specific surfaces.

In order to test the rainfall-runoff linearity assumption, the USDA-SCS (United States Department of Agriculture-Soil Conservation Service) (1985) conducted small watershed experiments and collected data which led to the development of the empirical rainfall-runoff relationship used in the USDA-SCS method of estimating direct runoff from storm rainfall. The USDA-SCS (1985) utilized the USDA-SCS-CN (1972) version to denote empirical relationships between the depth of direct runoff and the depth of precipitation after runoff inception:

$$\boxed{Roff = (R - 0.2 * s)^2 / (R + 0.8 * s)} \quad (R > 0.2*s) \qquad \text{(Eq. 2.5)}$$

$$\boxed{Roff = 0} \quad (R < 0.2*s)$$

where: Roff = runoff (mm), R = precipitation (mm) and s = initial abstraction (soil surface storage and retention) (mm).

This equation has been modified according to Woodward *et al*. (2003) to better simulate runoff from corresponding rainfall. The modified model makes use of an initial abstraction of 0.05 in lieu of 0.2. The initial abstraction value thus declines, resulting in earlier runoff generation for a given rain event. This earlier runoff production is favourable for RWH in arid and semi-arid regions with high frequencies of small rainfall events. The conversion between $s_{0.05}$ and $s_{0.2}$ is:

$$\boxed{s_{0.05} = 1.33 * s_{0.2}^{1.15}} \qquad \text{(Eq. 2.6)}$$

s is computed as:

$$\boxed{s = (1000 / CN) - 10} \qquad \text{(Eq. 2.7)}$$

where CN is the dimensionless curve number. CN is determined from antecedent soil moisture content (AMC), which is an index of soil wetness for different hydrological soil groups in the USA. The CN could vary in the range of 0 – 100 (Mishra & Singh, 2003). A low CN gives the response expected from a field with good infiltration, while a high CN denotes the response from a field with a fairly uniform soil with a low infiltration capacity. 1000 and 10 are arbitrarily selected constants with the same units as s (in. or mm; 1 in. = 25.4 mm). With the s equation it is possible to express CN:

$$\boxed{CN = 1000/(s+10)} \qquad \text{(Eq. 2.8)}$$

A CN of 100 indicates a condition of zero potential retention (s = 0), thus an impermeable catchment. Conversely, a CN of 0 represents a theoretical upper limit to the potential retention (s = ∞), therefore an infinitely abstracting catchment.

The popularity of this method created in 1954 lies in its convenience, its simplicity, its predictability, its stability, its reliance on only one parameter, and its responsiveness to major runoff-producing watershed properties: soil type, land use/treatment, surface condition and antecedent condition (Ponce & Hawkins, 1996). However, the intrinsic drawbacks of this approach render it a little awkward. Among these drawbacks can be cited its marked sensitivity to CN, the absence of clear guidance on how to deal with antecedent condition, and the fixing of the initial abstraction ratio at 0.2, pre-empting regionalization based on geologic and climatic setting (Ponce & Hawkins, 1996; Pilgrim & Cordery, 1993). In addition, the choice of an adequate antecedent moisture condition (AMC) (CN selection) becomes more difficult when applying the model outside of the USA.

B. Conceptual models

(1) The Morin & Benyamini (1977) infiltration model was derived from the Seginer & Morin (1970) model which accounts for the influence of crust creation and the rain drop size on the soil infiltration rate. Since measuring rain drop size appeared quite impractical, Morin & Benyamini (1977) introduced a model (Eq.2.3) using the aggregate rainfall in the place of the rain drop size.

(2) The Morin & Cluff's (1980) model is based on the Morin & Benyamini (1977) model. Morin & Cluff developed a conceptual model which enables calculation of runoff from any storm, segment by segment, over the total storm duration. The model is:

$$\sum Roff_i = \sum_{i=1}^{n} (I_i * \Delta t_i + s_{i-1} - Id_{\Delta ti} - s_m) \qquad \text{(Eq. 2.9)}$$

where $Roff_i$ = the surface runoff during segment i of the rainfall event (mm); I_i = the rainfall intensity (mm hr^{-1}); Δt_i = any time segment (hr); s_{i-1} = the surface storage and retention for the previous time segment t_{i-1} (mm); $Id_{\Delta ti}$ = the potential infiltration during any time segment Δt_i (mm); and s_m = the maximum surface storage and retention (mm).

The integration of the Morin and Benyamini (1977) equation over time resulted in $Id_{\Delta ti}$ (Morin & Cluff, 1980):

$$\boxed{Id_{\Delta ti} = I_{tf} * \Delta ti \frac{(I_{ti} - I_{tf})}{-\gamma * I_i} * [\exp(-\gamma * R_i) - \exp(-\gamma * R_{i-1})]} \qquad \text{(Eq. 2.10)}$$

$$\boxed{R_i = \sum I_i * \Delta ti} \qquad \text{(Eq. 2.11)}$$

where R_i = the cumulative rainfall over interval i (mm); R_{i-1} = the cumulative rainfall in the previous interval i-1 (mm); I_{ti} and I_{tf} = the soil initial and final infiltration rates (mm hr^{-1}); and γ = the soil factor, which is an empirical soil parameter representing surface aggregate stability or resistance to reorientation (mm^{-1}).

The total amount of Roff (mm) per rainfall event is the sum of runoff amounts over the whole period (all time intervals):

$$\boxed{Roff = \sum_{i=1}^{i=n} Roff_i} \qquad \text{(Eq. 2.12)}$$

The model was tested and verified in experiments carried out at Tucson, Arizona, USA (Morin & Cluff, 1980) and the Sha'ar Hanegev Region, Israel (Morin *et al.*, 1984), by comparing predicted results with observed experimental data. They found $R^2 > 0.98$ between the measured and model predicted runoff for both places. The places where the experiments were carried out are found in the semi-arid regions and the soils are characterized by crust formation. Even if in both study places the model was tested with a minimum data set, it showed a good performance in simulating the runoff from a rainfall intensity record which was arranged on a minute intensity basis. In addition, the model also showed that in semi-arid regions where the soils are most susceptible to crust formation and rainfall is characterized by high intensity, I_f is rather more dependent on the soil crust physical morphology than the antecedent soil moisture.

2.5.3 Crop growth-surface runoff integrated models

Quite recently, researchers such as Walker and Tsubo (2003) developed a model known as PUTURUN which incorporates the Morin and Cluff (1980) runoff model and PUTU crop growth model. The model also incorporates empirical rainfall-runoff models, as well as the area under the rainfall intensity curve to estimate runoff. In semi-arid zones in the surroundings of Bloemfontein (South Africa), PUTURUN was implemented to simulate rainfall-runoff-maize yield phenomena under the IRWH technique. The model entails a rainfall intensity generator, which uses the “Woolhiser and Osborn (1985)” model which considers total rainfall amount and duration. This rainfall intensity generator considers the total amount and duration of event rainfall, the fraction of the cumulative event duration from the starting time to the total event amount, as well as the fraction of the cumulative event duration from the starting time of the rain to the total event duration (Walker & Tsubo, 2003).

Similarly, Young *et al*. (2002) developed a model known as Parched-Thirst (P-T). This model incorporates the Green & Ampt (1911) infiltration model and USDA-SCS-CN (1972) runoff routing model to estimate runoff; and two crop models, Parch for simulation of sorghum, millet and maize and Thirst for the simulation of rainfed, lowland rice. Parch was developed specifically for semi-arid areas. Growth is limited by light, water or nutrients. Parch does not simulate crop emergence, rather 100% emergence is assumed. In many cases, the second sowings and gap filling practiced by farmers make this assumption valid. If the crop is stressed by limited resources, responses such as leaf rolling and increased partitioning to roots are simulated.

Both PUTURUN and the P-T models were developed for low rainfall semi-arid areas in order to evaluate the benefit of different RWH practices through crop performance (growth and yield). Both models consider the following aspects: (i) estimating runoff from runoff producing area (RPA); (ii) estimating soil water storage and use within runoff receiving area (RRA); and (iii) estimating crop yield.

The models are, moreover, equipped with long-term climate generators that help to generate long-term daily climate data. The models also have rainfall intensity disaggregators that enable them to have rainfall intensities of short durations from rainfall data depending on the need of the models. For instance, PUTURUN uses input of one minute rainfall intensity while P-T uses five minute rainfall intensity. Besides, both models' software is user-friendly and can be run on recent Windows operating systems.

Mathematical models generally vary from simple to complex. Nevertheless, all models contain degrees of simplification, both to reduce computational requirements and to accommodate only as detailed a representation of relevant processes as considered useful for the main applications of the model. As a result, all models have strengths and weaknesses.

2.6 Description and growth requirements of case study crops

Potatoes and Swiss chard, which are shallow-rooted crops, were evaluated in this dryland RWH study. Therefore, their background and specific production requirements are presented briefly in the following sections.

2.6.1 Potatoes

A. Origin and background

Potato (*Solanum tuberosum* L.), a crop of the *Solanaceae* family, is native to the Andean highlands of Peru and Bolivia (South America), where the Incas cultivated it mainly for food (Brown, 1993; Rolot & Seutin, 1999). The potato crop belongs to the pre-Columbian era and was already cultivated there some 8000 years ago (Steyn, 2003). It was brought by Spanish explorers to Europe in about 1540 and was a major source of food in Ireland from 1600 to 1845 (Splittstoesser, 1977). Since then, many places across the world in turn became conquered by this 'hidden treasure' (http://www.fao.org/potato-2008/en/potato/index.html).

Of about 2000 *Solanum* species known, only about 180 bear tubers. Eight of these are used for food production, and only *S. tuberosum* is cultivated worldwide (Steyn, 2003). *S. andigena*, the sibling of the latter, is adapted to short day conditions and is mainly grown in the Andes. The potato is the only vegetable among the five principal world food crops (Splittstoesser, 1977). It rates fourth among the world's various agricultural products in production volume, after wheat, rice and maize (Fabeiro *et al*., 2001). Among root crops, potato comes first in terms of volume produced and consumed, followed by cassava, sweet potato, and yam (FAO, 2004). As learnt from FAO (2004), potato production occupies a respectable place in agriculture, with a production potential of about 347 x 10^6 t harvested annually on 18.9 x 10^6 ha planted.

B. Production factors

Potato is a temperate crop, which thrives well in cool and humid climates or seasons, even though it is cultivated in climatic regions from the tropics to the sub-polar region (Shalhevet *et al*., 1983). A number of environmental factors such as temperature, water, fertility, light intensity and duration, and carbon dioxide concentration affect the growth, development and yield of potatoes. Among these factors, the single most important uncontrollable factor is temperature. In many areas, poor tuber yield and quality are the result of the prevalence of high temperatures experienced during the growing season (Smith, 1968). High temperatures and long days favour the growth of the haulm, while low temperatures and short days encourage that of tubers (Sale, 1973; van der Zaag, 1992). Potato top growth is stimulated by day temperatures of more than 27°C and by night temperatures higher than 23°C. Low night temperatures of around 16°C and high day temperatures less than 30°C are ideal for tuber formation (Struik *et al*., 1997). Moreover, soil temperatures are also important for potato growth, development and yield. Furthermore, for optimal growth and high yield and quality, the potato crop needs ideal light intensity (Gardner *et al*., 1985) and photoperiod, as well as the interaction between these factors (van der Zaag, 1992).

Soil water is a principal limiting environmental factor in the production and quality of potato. Compared to other crops potato is relatively sensitive to water stress (Epstein & Grant, 1973; Shalhevet *et al*., 1983; Hang & Miller, 1986; Shock *et al*., 1998; Opena & Porter, 1999; Porter *et al*., 1999; Fabeiro *et al*., 2001). This is mostly attributed to its sparse and shallow root system since nearly 85% of the root length is concentrated in the upper 0.3 m soil layer

(Opena & Porter, 1999). Drought stress affects the development and growth of potato shoots, roots and tubers. Moreover, soil water stress leads to reduced leaf area and lower stem height and ground cover (Ojala *et al*., 1990). In the end, water stress induces reduced yields by decreasing growth of crop canopy and biomass.

Water is essential for plant growth as several physiological processes depend on it. It is a major constituent of living plant tissues, which consist of about 90% water. However, only a very small part (about 1%) of the water needed by a plant is used in metabolic processes; the rest is used for transpiration. Water stress may constrain or even completely stop one or more physiological processes such as transpiration, photosynthesis, cell enlargement, and enzymatic activities. According to various reports, stomatal resistance is a suitable indicator of plant water status (Rutherfoord & De Jager, 1975; Dwelle *et al*., 1981; Dwelle, 1985; Bansal & Nagarajan, 1986, Oosterhuis & Walker, 1987; Vos & Groenwold, 1989). Stomatal closure affects transpiration and photosynthetic rates, which may lead to decreased tuber yields.

According to Jefferies (1995), the effects of water stress on a plant depends on the timing, duration and severity of the stress. The susceptibility of potato to water stress depends mostly on the phenological (growth stage) factor, and to some extent on the genotypic and seasonal factors. During tuber initiation, water stress is known to reduce the number of tubers produced per plant. As confirmed by Cavagnaro *et al*. (1971), drought stress at the beginning of the tuberization stage induced a longer period of tuber formation but decreased tuber number, growth and yield. However, water supply is considered to be closely related to tuber size and quality during tuber bulking. Mid-bulking period, which occurs three to six weeks after tuber initiation, is particularly crucial to the total yield of potato since the plants become most sensitive to water stress during this stage (SFC, 1992). In addition, water stress delays tuber growth and this growth cannot recover fully after water has been resupplied. In the end, these conditions entail a second tuberization and bulking around the top stem end, leaving the other parts of the tuber stunted. In some potato varieties, tubers develop constricted areas signalling the stage of tuber growth at the time of water stress. Growth cracks, knobbiness, tuber malformations as well as other deficiencies in quality have also been linked to water stress followed by periods of adequate or surplus soil water. Furthermore, water stress may have antagonistic impacts on tuber relative density and reducing sugar content, two quality characteristics commonly affected by water supply. It is worth noting that water stress is not necessarily the result of drought only, as excessive water supply is harmful to plant as well (Kuglerl, 2002).

2.6.2 Swiss chard

A. Origin and background

Swiss chard (*Beta vulgaris* L.) is a plant in the *Chenopodiaceae* family which is now included in the *Amaranthaceae* family. Swiss chard is also known by many other common names such as chard, silverbeet, perpetual spinach, spinach beet, crab beet, bright lights, seakale beet, and mangold (Don, 2003). It is a type of beet that was developed for its large crisp leaves. It has originated in southern Europe and was first reported in the Mediterranean region and Canary Islands. Swiss chard was popular as long ago as 350 B.C. The crop derived its name from the fact that it is a favourite of the people of Switzerland whose settlers introduced it into the United States in the beginning of the 19th century (Splittstoesser, 1990). Swiss chard and beets have evolved from the same wild European plant and, therefore, belong to a common plant ancestry. Swiss chard, however, develops without the thickened, fleshy roots characteristic of beets; although it compensates for this with long leaf age. All domesticated beet varieties fall into the subspecies *Beta vulgaris* subsp. *vulgaris*, while *Beta vulgaris* subsp. *maritima (*ancestor of subsp. *vulgaris)*, and *Beta vulgaris* subsp. *adanensis* remain undomesticated.

B. Production factors

Swiss chard is a leafy vegetable which is able to re-grow and therefore supply harvests over several months. Plants can regenerate leaves and/or shoots after harvest and thus numerous harvests can take place from one sowing time. In the case of leafy vegetables, plants can reproduce leaves when the cutting level is above the growing point. For shoot type vegetables, new shoots and leaves can re-grow from lateral growing points (Maruo *et al*., 2003; Takagaki *et al*., 2003). According to investigations, leafy vegetables (lettuce, chard) and shoot vegetables (vegetable jute) can be successfully produced using a reaping and re-growth technique (Maruo *et al*., 2003). Therefore, the reaping and re-growth method has the potential to provide higher yields on less area with earlier cropping of leafy vegetables (lettuce, Chinese cabbage).

Several environmental and management factors may affect crop re-growth. The environmental factors that impact on re-growth include temperature, radiation interception, water stress and nutrition (Fu, 2008). Management factors that influence re-growth include plant size/plant remainder and reaping intervals. The following paragraphs briefly present the influence of temperature, light and water on crop growth and re-growth.

A major factor that has a marked impact on plant growth and development is temperature, which is regulated by other factors including daylength and vernalization (Hodges, 1991). Temperature and thermal time affect crop growth and development. Crops can re-grow only when the temperature is above the base temperature, they cease growing at extreme temperatures, and grow fastest at optimum temperature (Ferraris & Norman, 1976). For example, as was reported by Tobisa *et al.* (2003), higher re-growth of forage legume phasey bean (*Macroptilium lathyroides* L. Urb) took place at 25 – 30 ºC than at 20 ºC.

According to studies, the dry matter yield of a crop greatly depends on the radiation absorbed by the leaf canopy, the mean efficiency of conversion of the absorbed radiation to dry matter, and the partitioning of this between the harvested organs and the rest of the plant (Hay & Walker, 1989). Moreover, net CO_2 assimilation is affected by irradiance. In the reaping and re-growth system, LAI is rapidly decreased with cutting and removal of the plant tops and leaves; consequently, light interception is reduced. As the plant foliage resumes growth, LAI recovers gradually, resulting in progressive increase in intercepted radiation and assimilate production.

Water is known to be the most important factor affecting plant growth and yield. Water stress is a condition experienced by plants exposed to water loss from their tissues (Ehlers & Goss, 2003). In the production of leafy vegetables, harvests usually take place during the vegetative phase. At this stage, water deficits experienced are considered to reduce plant height (Doss *et al*., 1974; Nielson & Nelson, 1998); this reduction is reflected in low dry matter yield (Doss *et al*., 1974). This decreased dry matter yield resulting from water stress is usually linked to low LAI and radiation interception.

The influence of water stress on crop growth and re-growth has been investigated extensively. Roy (1985) pointed out that drought at any phase of wheat development decreased the green surface area of main stems by 20 – 40%. The per capita net growth rate for stressed plants decreased by about 60 – 80% compared with non-stressed plants. Consequently, dry matter growth was lowered to 75% of the unstressed control. According to Kuglerl (2002), under mild water stress grass internodes are shorter than those of well-watered grass. As a result, a higher leaf-to-stem ratio with less fibre is experienced. Severe water stress is conducive to leaf loss and a reduction in quality. However, as reported from experiments dealing with water stress effects on the development of Rhodes grass (*Chloris gayana L.*) under controlled environments, short periods of water stress before cutting markedly increased the subsequent re-growth after cutting and rewatering (Slatyer, 1967) . Furthermore, it is not drought stress alone that poses problems for crop growth and development since excess in soil water amount leads to waterlogging and crop root system oxygen-deficiency. As was revealed, oversupply of water can lead up to conditions that affect plant yield and health even though its impact on yield quality remains unclear (Kuglerl, 2002). Although no literature on the effect of water stress on Swiss chard was found, its mechanism and the the crop response to it are similar to the examples that have been given above.

CHAPTER 3

RAINWATER HARVESTING EXPERIMENT WITH POTATOES (*SOLANUM TUBEROSUM*, CV. BP1)

3.1 Introduction

Rainwater harvesting (RWH) is a favourable potential solution to the challenge of extreme climatic conditions and high inter-annual/ seasonal variability of weather conditions which adversely affect productivity in arid and semi-arid areas (Li *et al*., 2006). In these areas, optimising water management through *in-situ* and micro-catchment rainwater harvesting (MC RWH) has been shown to contribute to improved small-scale rainfed agriculture. Furthermore, these systems are simple to implement. *In-situ* RWH or soil and water conservation refers to systems that increase the amount of water stored in the soil profile by trapping or holding the rain where it falls (Hatibu & Mahoo, 1999; Stott *et al*., 2001). Tied-ridges are an example of such a technique and are promoted to conserve rainwater in fields (Jones & Stewart, 1990; Wiyo *et al*., 2000). MCRWH techniques involve collecting surface runoff from small uncropped catchment areas with short slopes (runoff area) and storing it in the root zone of an adjacent cropped infiltration area (run-on area) (Haile & Merge, 2002; Senkondo *et al*., 2004).

Several MCRWH systems have been utilized to meet the requirements of local conditions (Kunze, 2000; Haile & Merge, 2002; Senkondo *et al*., 2004). In South Africa, a case of the MC RWH technique was introduced as in-field rainwater harvesting (IRWH) (Botha *et al*., 2003). This method involves a runoff producing area (RPA), and a runoff receiving area (RRA). The technique prevents any net runoff, maximizes infiltration and stores any collected water in the soil layers beyond the sensitive evaporation zone (Botha *et al*., 2003). The computation of the ratio between the RPA and the RRA varies depending on localities and seasons (Oweis *et al*., 1999; Prinz & Malik, 2002; Ibraimo, 2011). Factors, such as rainfall intensity and amount, ground slope, soil factors, crop factors and surface treatments on the catchment area are responsible for this variability (Oweis *et al*., 1999; Prinz & Malik, 2002; Ibraimo, 2011).

MCRWH methods are characterized by a distinct division of catchment area and cropping area. Runoff catchment area is the most important component of these water harvesting systems as it determines the amount and quality of water collected (Frasier, 1983). However, in most RWH systems, there is a mismatch between runoff area and storage structures (Ngigi, 1996; Kiggundu, 1998). Therefore, for MCRWH technologies, the selection of the best (optimal) design ratio (runoff area to cropped area) is key to a successful RWH agricultural production since too large runoff area will be wasteful (water, energy and land resources) while too small will be deficient (Critchley & Siegert, 1991).

The aim of this chapter is to determine the effects of the different RWH techniques on dryland potato crop growth, yields and water use efficiency (WUE) during the 2009/2010 growing season at the Hatfield Experimental Farm of the University of Pretoria.

3.2 Materials and methods

3.2.1 Site description

The field experiment was conducted during the rainy crop growing season of 2009/2010 at the Hatfield Experimental Farm of the University of Pretoria, South Africa (25°45’ South, 28°16’ East, 1327 m above sea level). The mean maximum and minimum air temperatures of this ecotope are 30 °C and 1.5 °C. The average annual rainfall is 670 mm. In line with rainfall and potential evapotranspiration (ET), the hydro-climate of the site is classified as subtropical and semi-arid, with dry, mild winters and hot, wet summers. Rainfall is erratic with intermittent dry spells, and the precipitation is mostly characterized by intense thunderstorms which generate substantial runoff (Rockström *et al.*, 2007). The soil chemical composition of the site is: phosphorus: 35.5 mg kg^{-1}; calcium: 348 mg kg^{-1}; potassium: 71 mg kg^{-1}; magnesium: 124 mg kg^{-1}; and sodium: 20 mg kg^{-1}. The slope of the area varies between 3 and 3.5%. Soil depth is generally greater than 1.2 m (Annandale *et al.*, 2002). The average soil pH (H_2O) is 5.4 and so is the average pH (KCl). The soil texture and organic matter content alongside the soil profile is depicted in Table 3.1.

Table 3.1: Soil texture and organic carbon content (%) for different layers of the soil at the study area (Hatfield Experimental Farm).

Soil depth (cm)	Soil texture	Organic carbon content (%)
0-20	Sandy clay loam (67 % sand; 9 % silt; 24 % clay)	0.65
20-40	Sandy clay loam (53 % sand; 16 % silt; 31 % clay)	0.58
40-60	Sandy clay loam (49 % sand; 16 % silt; 35 % clay)	0.55
60-80	Sandy clay loam (46 % sand; 17 % silt; 37 % clay)	0.50

3. 2.2 Experimental design

An IRWH field trial with potatoes was carried out during the rainy growing season of 2009/2010. The experiment was a randomized complete block design (RCBD) with eight treatments and three replications (Appendix A – Figure A1). The field was separated into three blocks according to slope which was 3.50, 3.45, and 3.10 %. Three different cropping systems as in Figure 3.1 were used: (1) conventional tillage (CT), (2) tied-ridges (TR), and (3) IRWH. Runoff areas were either bare (B) or plastic-covered (P) and this was combined with three different design ratios of RPA to RRA (Figure 3.1). Therefore, the IRWH system consisted of six treatments: 1:1B, 1:1P, 2:1B, 2:1P, 3:1B and 3:1P. TR and IRWH made up RWH techniques. In IRWH, results on a total area basis consider the total plot area, while results on a cropped area basis only take the net cropped area into consideration.

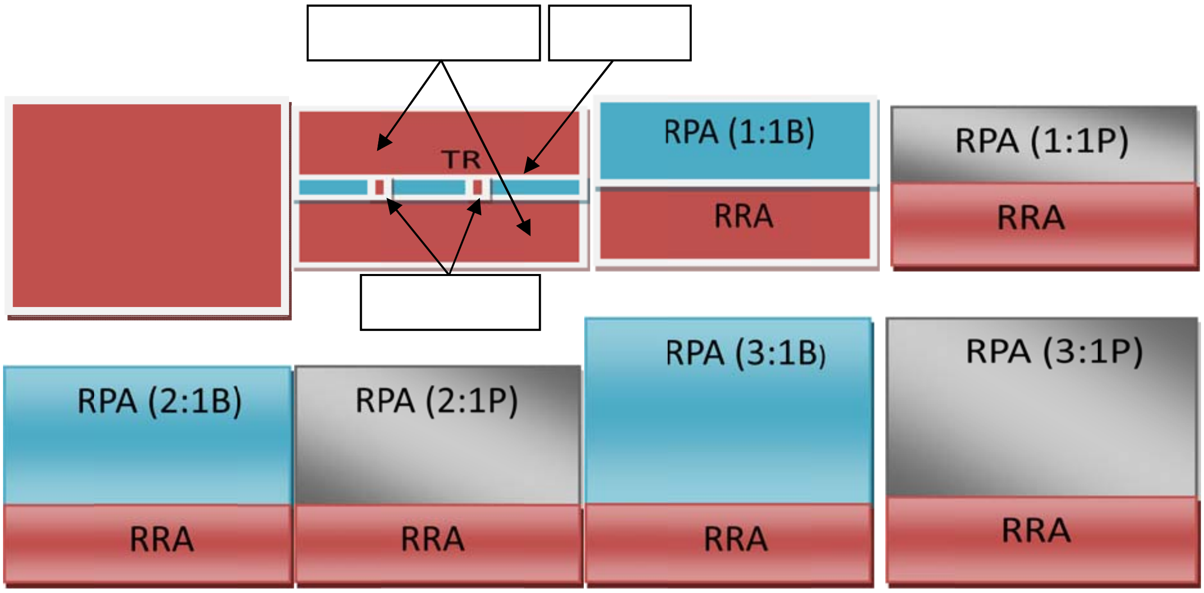


Figure 7: The different experimental treatments. CT = conventional tillage, TR = tied-ridges, RPA = runoff producing area, RRA = runoff receiving area, B = bare and P = plastic covered.

The size of the experimental units in the CT (Figure 3.2) and TR (Figure 3.3) plots was 5 m x 6 m (30 m^2) each. The TR plots had V-shaped furrows alternating with ridges (raised cropped areas). Each 84 cm long mini-furrow was separated from another by a 20 cm wide tie. There were in total, alongside each ridge, five mini-furrows and the same number of ties. The maximum depth for the mini-furrows was 20 cm, and so was the maximum height of the cross ties. Initially, the TR plots resembled those of the CT plots. To make the TR plots, mini-furrows were created using a hand hoe on both sides of the area for ridges by removing the soil from the furrow and using it to raise the ridge to 20 cm above the surface. The aim was to limit runoff so that water falling on the plot is totally retained thereby leading to slow and extended infiltration in the ridges (cropped area). In order to prevent this plot from overflowing, a drainage canal, deeper than and perpendicular to the mini-furrows was made. TRs were made before planting and reinforced whenever needed.

Figure 8: CT (in the front) during the 2009/2010 potato growing season.

Figure 9: TR with cross-tied furrows alternating with ridges, during the 2009/2010 potato growing season.

For the IRWH systems, all cropped areas were 1 m x 5 m and the runoff areas were 1 m x 5 m, 2 m x 5 m and 3 m x 5 m, for the design ratios of 1:1, 2:1, and 3:1, respectively. The size of the experimental units was 5 m x 6 m (30 m^2) for lower design ratios (1:1 and 2:1) and 5 m x 8 m (40 m^2) for the 3:1 design ratio. The catchment areas were made by demarcating the area and then evenly sloping it to adjust the slope to that of the corresponding block (or that of CT and TR in the corresponding block). The surface was then smoothed and compacted to induce runoff. Check borders (Figure 3.4a) of 20 cm height were raised around each catchment area to hold its runoff within the plot and to prevent outside runoff from entering the system. The soil removed from the catchment area/basin (Figure 3.4b) was used to create 100 cm wide and 30 cm high ridges (cropped areas) (Figure 3.4c) at the bottom of the corresponding catchment area. For the plastic-mulched plots, a polyvinyl plastic sheet was used to cover the runoff area. The purpose was to increase runoff generation by preventing soil surface initial abstraction and infiltration. For the plots with bare runoff areas, 20 cm wide ties (Figure 3.4d) were created to ensure even water distribution and infiltration along the cropped area. The ties were kept in good condition for the whole growing period. These ties were not the same as the cross ties in the TR plots although the size was the same.

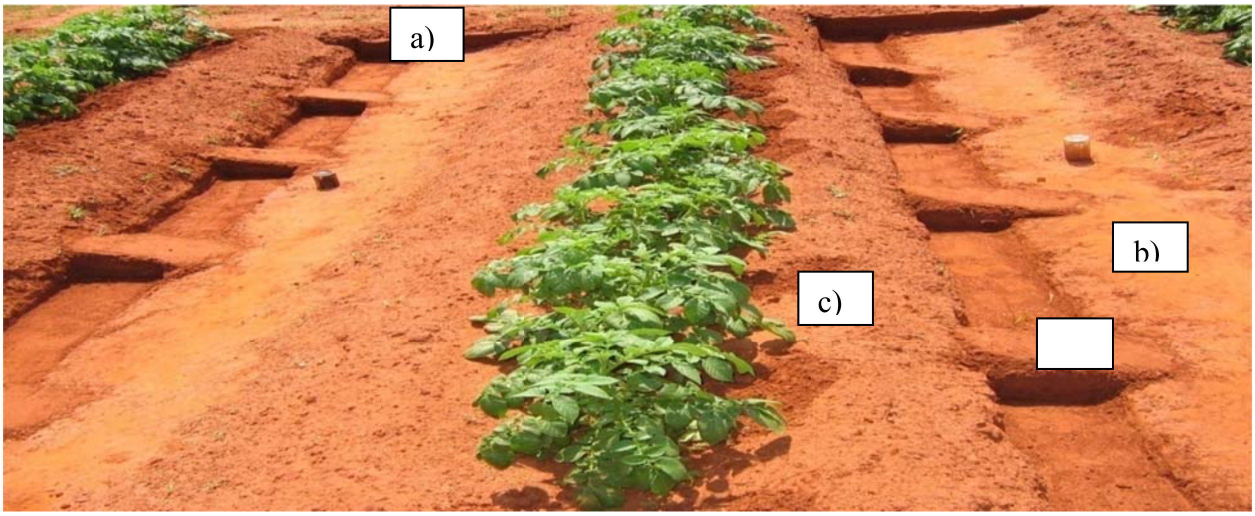


Figure 10: A 1:1B IRWH treatment plot with a) check borders, b) basins, c) cropping area and d) ties, during the 2009/2010 potato growing season.

3.2.3 Field preparation, equipment installation and soil sampling

The field preparation work started with clearing and preparing the field, building the RWH plots, and installing access tubes for the soil water content measurements (Figure 3.5 illustrates some of these activities). A range of tools, machines and instruments was utilized: spades, hoes, cut knives, rakes, hammers, pegs, rope, graders, pickaxes, sweepers, rotovator, theodolite, plastic sheet, etc. The soil was first cultivated once manually, then rotovated once before planting and once at planting when applying fertilizer. The rotovating was aimed to loosen the root zone and make it easily penetrable for water and the root system. The profile (up to 80 cm) soil samples were taken across the field and analyzed in the Soil Laboratory of the Department of Plant Production and Soil Science of the University of Pretoria. The results are presented in Section 3.2.1. The amount of fertilizers to apply before, at, and/or after planting was calculated according to the results of the soil analysis. These amounts of fertilizers are shown in the following section.

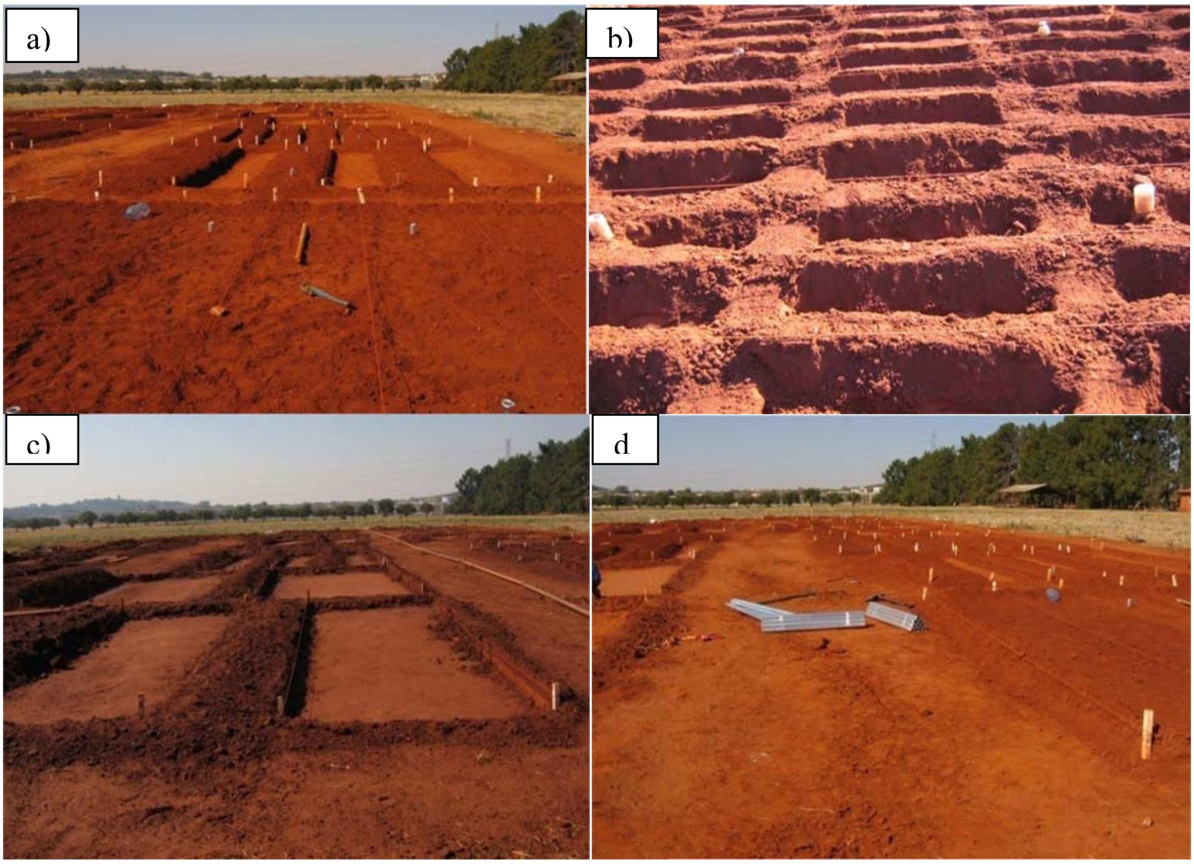


Figure 11: Field preparation: a) prepared plots with a CT in the front, b) a TR plot, c) a block with a 2:1 plot in the front and a 3:1 plot behind it, and d) access tubes on the ground and to be installed in well-prepared plots.

3.2.4 Field procedures, planting materials, agricultural practices and data collection

Sprouted tubers of potato (*Solanum tuberosum*, cv. BP1) were planted by hand at the beginning of October 2009, at 100 cm x 42 cm spacing, 13 cm deep. For CT (Figure 3.6) and TR, the plot plant population was 24,000 plants ha^{-1} (2.4 plants m^{-2}). For the IRWH treatments, the plot plant population was 12,000 plants ha^{-1} (1.2 plants m^{-2}), 8,000 plants ha^{-1} (0.8 plants m^{-2}) and 6,000 plants ha^{-1} (0.6 plants m^{-2}) for the design ratios of 1:1, 2:1 and 3:1.

Thus, the cropped area is 1 m wide. If the plot plant population is expressed on the net cropped areas, all treatments have the same plot plant population of 24,000 plants ha^{-1} (2.4 plants m^{-2}). Before planting, 1 t ha^{-1} of gypsum was applied to balance the soil calcium level with other cations in the soil. At planting, 3:1:5 (38) was utilized to supply 90 kg ha^{-1} N, 30 kg ha^{-1} P and 150 kg ha^{-1} K. The trial also needed 70 kg ha^{-1} N (LAN (28)) as top dressing four weeks after emergence.

Figure 12: CT plot with flowering potatoes during the 2009/2010 growing season.

Immediately after planting, the nematicide aldicarb (2 g plant^{-1}) and herbicide glyphosate (20 ml 10 L^{-1} of water) were applied in order to prevent nematodes and weeds. Thereafter, a light sprinkler irrigation (10 mm) was applied in order to trigger the growth of the sprouts and to ensure that the starter fertilizer was well incorporated into the soil. During the growing period, weeds in the cropping beds and runoff areas were controlled manually, while chemicals were sprayed on the remaining areas (inter-plots, inter-blocks and peripheries). Fungal diseases were controlled with dithane (20 ml 10 L^{-1} of water) and pests were controlled either manually or with methomex (20 ml 10 L^{-1} of water).

During the potato growing season, the following measurements were conducted:

Soil water content was measured on a weekly basis with a neutron probe (503DR CPN Hydroprobe (Campbell Pacific Nuclear, California, USA)) (Figure 3.7) through access tubes installed before planting. The readings were taken at 0 – 20, 20 – 40, 40 – 60, 60 – 80 and 80 – 100 cm soil depths. The device was calibrated for the specific soil before the trial commenced. Total evapotranspiration (ET) was calculated daily with the soil water balance equation (Eq. 3.1). The detail of how this equation was transformed according to the different treatments will be presented in Chapter 7 dealing with the SWB model, which was used to split ET into evaporation (E) and transpiration (T).

$$ET = R + I - Roff - D \pm \Delta S \qquad \text{(Eq. 3.1)}$$

where, ET = crop evapotranspiration (crop water use) (mm); R = precipitation (mm); I = irrigation (mm); Roff = surface runoff (mm), D = drainage (mm) and ΔS = change in soil water storage (mm).

Figure 13: Soil water content measurement with a neutron probe on the ridge of a 3:1P plot during the 2009/2010 potato growing season.

- Plant height was monitored fortnightly from the fourth week after emergence up to the beginning of the senescence stage, using a tape measure, by measuring the height of the plant from the ground level up to the tip of the fully straightened up main stem. In this regard, four plants per plot were randomly selected and labelled. These plants were also taken as being representative for the data collection of other parameters (presented below) during the growing season.
- Leaf area index (LAI) was measured on a fortnightly basis with an LAI-2000 Plant Canopy Analyzer (Li-Cor, Inc., Lincoln, Nebraska, USA). This device was preferred over the destructive method which required more plants to sample and is time consuming. In order to get better and more accurate results, the measurements were conducted either at dawn or dusk. The readings were taken across the rows comprising labelled plants, by placing the device above and below the canopy. The readings below the canopy were conducted by taking one measurement below a plant from one row, two readings across the inter-row and one measurement below the plant from the adjacent row.
- Leaf Soil Plant Analysis Development (SPAD) was measured with a Minolta SPAD-502 chlorophyll meter (Minolta Camera Co. Ltd, Japan) to estimate the N/chlorophyll status and to gauge chloroplast orientation (vertical or horizontal) in the leaves at the time of measurement. The readings were taken from three different trifoliates of the third leaf from the terminal bud of the labelled main stem. The average of these three readings was considered an integrated value for the plant. Readings were taken every two weeks.
- Leaf conductance was measured with a steady-state leaf porometer (Decagon Devices, Inc., Pullman, Washington, USA) in order to understand the extent of stomate opening which has an influence on transpiration and photosynthesis (or is a measure of plant stress). The readings were also taken on a fortnightly basis and from the same leaves as the SPAD measurements. It is a non-destructive method which is simple, accurate and time-saving.
- Photosynthetically active radiation (PAR) interception readings were taken with a ceptometer (Accupar model LP-80, Decagon Devices Inc., Pullman, Washington, USA) on a two-weekly basis by taking measurements above and below the canopy. PAR measurement helps in the calculation of the fractional radiation interception (FI_{PAR}) which is a function of the canopy LAI and the canopy structure (involving the radiation extinction coefficient for PAR – K_{PAR}) as shown in Equation 3.2. K_{PAR} was obtained by plotting measured FI_{PAR} against measured LAI values, using the CurveExpert software.

In order to have accurate readings, the measurements were carried out on clear days, between 12:00 and 14:00 when the sun was at maximum elevation angle.

$$FI_{PAR} = 1 - e^{-K_{PAR}LAI} \quad \text{(Eq. 3.2)}$$

- Photosynthesis measurement was carried out once during the growing season with an LI 6400 portable photosynthesis system (Li-Cor, Inc., Lincoln, Nebraska, USA), at the end of the tuber initiation stage. The aim was to explore the CO_2 assimilation rate of the different treatments. The readings were taken from the same stems and same leaf position as the chlorophyll measurements.

At one week before harvest, harvest and post-harvest the following activities were conducted:

- When most of tops turned yellow in February 2010, this was a sign that the plants had started senescing. Vines were killed manually one week before harvest date. The purpose of this was to ensure proper skin set and prevent bruising during tuber harvest and storing. Harvesting was conducted with a hand fork.
- Tubers were graded as large, medium and small according to their diameter (width, mm). They were classified as large when the diameter was greater than 75 mm, medium when it was between 55 and 75 mm, and small when less than 55 mm. For each category, fresh mass of tubers was determined.
- Six plants per plot were selected for the determination of the harvest index (HI). The HI is calculated from the total dry biomass and the dry mass of tuber yield at harvest; and is a measure of partitioning efficiency of dry matter to tubers. The HI is estimated using Equation 3.3 (Vos, 1997; Zvomuya *et al*., 2002; Araya & Stroosnijder, 2010):

$$HI = \frac{Dry\ tuber\ yield}{Total\ dry\ matter} X\ 100 \quad \text{(Eq.3.3)}$$

- Specific gravity (SG), which is an internal quality of tubers, was determined on samples selected randomly from each plot. To determine SG, tubers were weighed in air (Ma) and water (Mw); and the SG was calculated using Equation 3.4 (USDA, 1997):

$$\text{SG} = \frac{Ma}{(Ma - Mw)} \quad \text{(Eq. 3.4)}$$

- Chip colour was also determined as a measure of internal quality.
- Tubers were also analysed for visible external and internal qualities. The external qualities involved qualities affecting the external appearance of tubers as in Table 3.2; and the internal qualities involved those affecting the internal part of tubers as in Table 3.3.

Table 3.2: Scale used for external tuber quality characteristics (USDA, 1997).

Tuber characteristics	Score	Explanation
Secondary growth Growth cracks Mechanical damage Malformation	1 2 3 4 5	No tubers < 10 % tubers 10 – 30 % tubers 30 – 60 % tubers > 60 % tubers
Stolon indent Eye depth	1 2 3	Superficial Medium depth Deep
Skin colour	1 2 3 4 5	White Yellow White with markings Red Russet skin

Table 3.3: Scale used for internal tuber quality characteristics (USDA, 1997).

Tuber defects	**Score and explanation**	
Hollow heart Brown spot Vascular discolouration	% tubers with defects	
Tuber defects	**Score**	**Presence and % tuber surface area**
Dry rot	1	No tubers
	2	< 10 % tubers
	3	10 – 30 % tubers
	4	30 – 60 % tubers
	5	> 60 % tubers
Tuber defects	**Score**	**Presence and % of tuber surface area**
Common scab (area) Eelworm (root knot)	1	No tubers
	2	1 – 25%
	3	25 – 50%
	4	50 – 75%
	5	75 – 100%
Tuber characteristics	**Score**	**Explanation**
Flesh colour	1	White
	2	Cream
	3	Light yellow
	4	Intense yellow

3.2.5 Data processing

All data collected were statistically analyzed using ANOVA for SAS to test the effect of the different tillage systems (RWH treatments) on potato growth, biomass, yield, yield components, HI, WU and WUE. Whenever the F-test was significant (< 0.05), LSD values at that level was used to compare treatment means.

3.3 Results and discussion

3.3.1 Introduction

The first plants started to emerge nine days after planting and the emergence continued for nearly a week, to result in a 100% stand. Flowering took place about one month after planting, which probably coincided with tuber initiation phase (no destructive sampling was conducted). During the growing season, only a few incidences of pests were experienced since proactive measures were adopted in this regard. Moreover, the blossoming of the plants attracted several types of natural predators leading to excellent biological control. In November, the plants experienced severe lodging due to strong winds that accompanied a thunderstorm. In the beginning of December, the plants showed some yellowing and wilting which became severe by mid-December. On one hand, water stress conditions were suspected since there were several dry periods during December; and on the other hand, an incidence of a disease was suspected, probably an *Alternaria alternata* (brown spot) (according to the top symptoms), and this was confirmed by the Plant Pathology Department after the analysis of the yellowed samples. In a separate account, towards the end of the growing season, tubers were breaking the soil surface and were exposed to the sun. They were immediately covered with soil to protect them from rodents, greening, sunburn, and yield and quality loss. The following sections present the parameter data measured during the crop growing season, as well as yield, yield components, WU, WUE and tuber external and internal quality.

3.3.2 Soil profile water deficit

Figure 3.8 gives an illustration of soil profile water deficit (SWD) (up to a 100 cm soil depth), as well as rainfall during the crop growing season. The treatment values are different in the beginning mostly probably due to different soil profile water content during the fallow period. As it can be seen, the water deficit of all treatments varied according to the rainfall pattern. There were sharp decreases in soil water deficit values immediately after a spell of some rainfall events including at least one relatively high rainfall event. On the contrary, sharp increases in soil water deficit values occurred after a spell of dry days (rainless days or days with rainfalls of less than 1 mm). CT appeared to be the driest, followed by TR. 3:1P was the wettest as was expected; and was followed by 2:1P. In general, the soil water deficit for the treatments with plastic was lower than those with bare runoff areas, TR and CT.

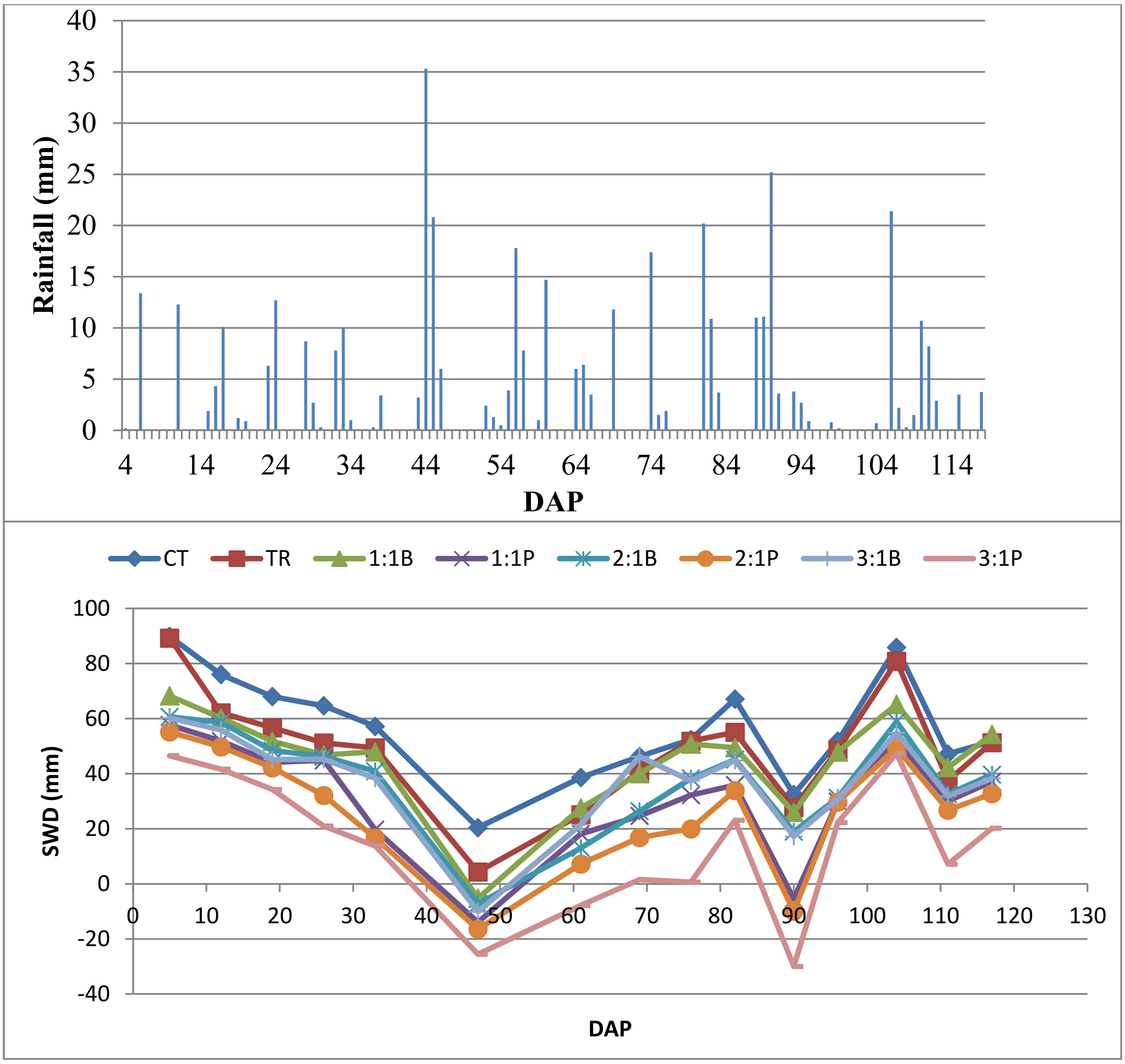


Figure 14: The profile soil water deficit (profile up to 100 cm depth, bottom) for the different treatments, as well as the rainfall pattern (top) during the 2009/2010 potato growing season.

3.3.3 Plant height

Figure 3.9 gives an illustration of main stem height (cm) and shows that the plant height increased rapidly in the beginning of the growing season and slowed down later. The figure also indicates that at the start of the growing season the heights of all RWH treatments were close to each other probably because the crop root system was not developed enough. Thereafter, the distinction among average plant heights was clear, especially for the 3:1P treatment plants which were the tallest; partly because differences existed between the root system development of the different treatments. There were no significant differences among treatment means at $P < 0.05$. IRWH (especially 3:1P) treatments made good use of stored water and thus outgrew the control treatment, CT. Finally, towards the end of November 2009, the crop suffered from lodging due to strong winds which is believed to have played a part in slowing down the crop elongation rate in general.

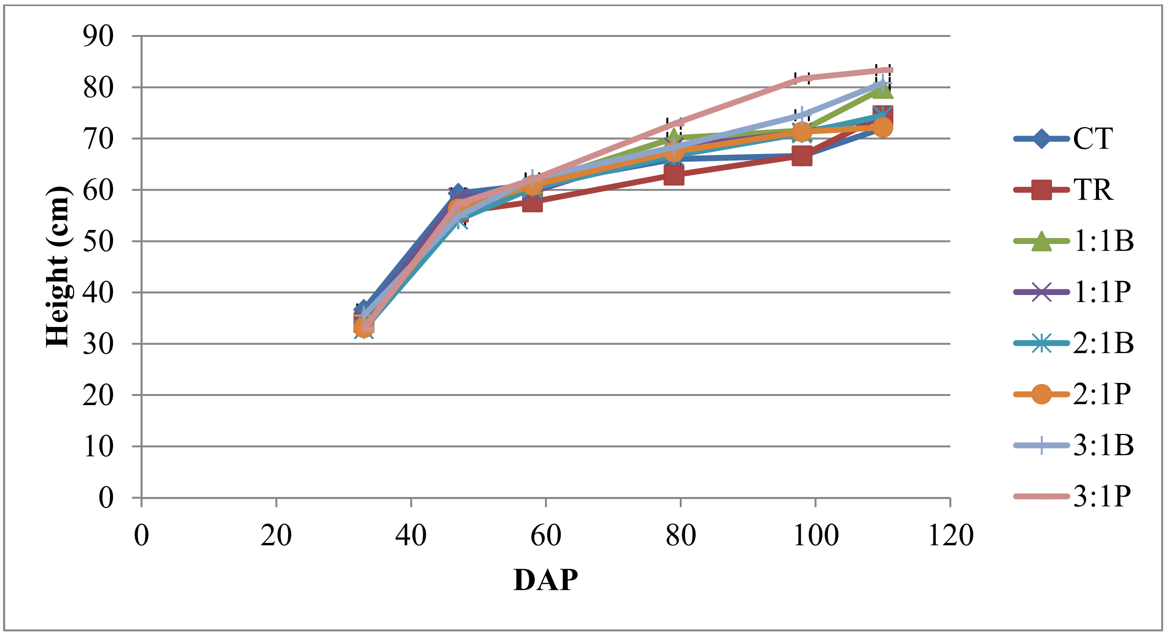


Figure 15: Plant height for the different treatments during the 2009/2010 growing season.

In the experiment conducted by Yuan *et al*. (2003), potato height responded positively and proportionally to the amount of water applied. An analysis of irrigation water on potato height by ANOVA at 0.05 level showed significant effects. Field trials on potato cultivars and three water supply treatments (droughted, rainfed and irrigated) carried out by Deblonde and Ledent (2001) resulted in a significant reduction in stem height of the droughted treatment compared with the irrigated treatment which was in general only slightly higher than the rainfed treatment. Meanwhile, the outcomes from Modisane (2007) disclosed that high temperatures stimulated stem elongation. These findings were in complete agreement with those published in the literature (Benoit *et al*., 1986; Manrique, 1990; van der Zaag, 1992). It is noteworthy to mention that, in the current case, the potato growing season was characterized by intermittent high temperatures which can to a certain extent explain the luxurious crop growth and tall plants.

3.3.4 Leaf chlorophyll content

Figure 3.10 presents leaf chlorophyll content with a SPAD chlorophyll meter. The figure shows that in general chlorophyll content decreased gradually from the beginning to the end of the growing season, except for TR and 2:1P for which the ultimate values were higher than the penultimate ones. It is not clear why these treatments deviated from the general trend. It is also evident that from the beginning until the middle of the growing season, SPAD values for all treatments were close to each other with no significant differences recorded. However, from the middle of the growing season, there was a difference of the SPAD treatment mean values and significant differences were shown on the last two data collections (Figure 3.10, Appendix B – Table B1 & B2). During this period, SPAD values for CT were declining rapidly and the gap between this treatment and other treatments were increasing, especially compared with 3:1P which had the highest SPAD values at the last two measurement events. The cause of the general decrease in SPAD values is probably the progressive depletion of nutrients by the crop in general, and of N in particular. It is not unusual for leaf N content to drop as the growing season progresses, as the literature imparts it below. The cause of the difference in the average SPAD of the different treatments should have arisen from their corresponding available soil water in the root system (Figure 3.8, soil water deficit).

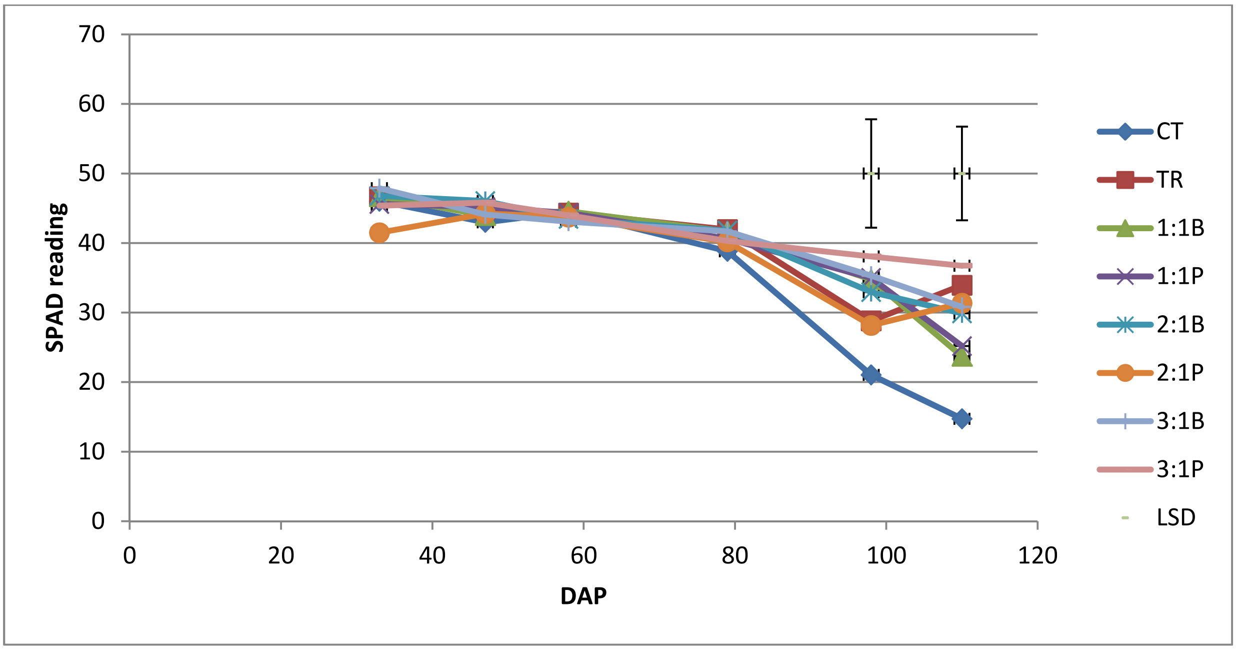


Figure 16: Potato SPAD measurement for the different treatments during the 2009/2010 growing season.

The trend of SPAD readings in the course of the potato growing season is in complete agreement with that obtained in the literature. Results of experiments on potato conducted by Gianquinto *et al*. (2004/2005) and which corroborated those of previous research (Vos & Marshall, 1994), displayed a significant linear relationship between SPAD readings and total N concentration in leaves. This is also in conformity with results found on cotton and maize crops (Schepers *et al*., 1992; Wood *et al*., 1993). Gianquinto *et al*. (2004/2005) established a rule of thumb stating that chlorophyll meter readings remain fairly constant, or sometimes increase up to 30 – 40 days after emergence, then decrease more or less rapidly depending on many factors, such as N supply, climatic conditions, cultural practices, cultivars, etc. It can be noted that during this study, the first SPAD measurement took place almost one month after planting. Therefore, according to the principle mentioned above, SPAD readings should have started to decrease when data collection started. Moreover, the separation of the treatment means that emerged towards the end of the growing season is probably attributable to the scarcity of rainfall at the end of the rainy season. Treatment CT showed the lowest SPAD readings than other treatments because it has equally exhibited the highest soil water deficit (Figure 3.8). This is in line with many reports which showed decreasing leaf chlorophyll under drought conditions (Ashraf *et al*., 1994). However, Gianquinto *et al*. (2004/5) maintained that the higher the soil water content, the lower the SPAD values and vice versa. This was corroborated by Danda and Behl (2004) who reported an increase in SPAD as relative water content decreased. Jagtap *et al*. (1998) indicated that one reason for these contrasting findings may be the difference in study conditions such as stress intensity and duration (water insufficiency or oversupply).

3.3.5 Leaf area index (LAI)

Figures 3.11 (total area) and 3.12 (cropped area) present the LAI values collected from the different treatments. The LAI values increased from the commencement of measurements until the start of the maturity stage, when LAI started to decline. According to Figure 3.11, CT had the highest LAI, followed by TR, in terms of values expressed on the whole plot area. As expected, the lowest LAI corresponded to 3:1B and 3:1P. In general, the treatments with plastic mulch displayed higher values than treatments with bare runoff areas. CT and TR overlapped nearly for the whole growing season, and so did the IRWH treatments with the same ratios. It is worthwhile to note that in terms of plot plant population, CT and TR had the highest value (the whole area was cropped), followed by 1:1B and 1:1P which had intermediate value, while 3:1B and 3:1P had the lowest value (with 2:1 in-between 1:1 and 3:1). The high LAI values for CT and TR were the results of the high plant population. Similarly, the LAI differences among the IRWH treatments were also the results of plant population (which was in inverse proportion with design ratio). As it can be seen from Figure 3.12, the plant population effect did not play a deciding role in terms of LAI values relative to the cropped areas. The order was reversed and the treatments with higher ratios (3:1 and 2:1) showed higher values (bigger plants), while TR and CT displayed lower values (smaller plant canopy).

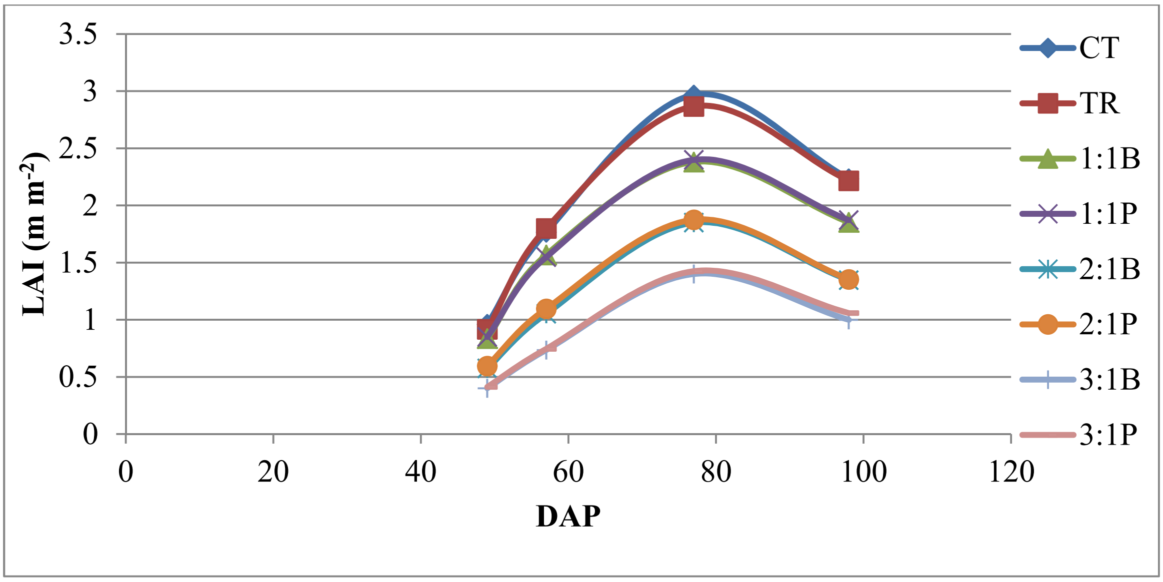


Figure 17: Potato LAI for the different treatments during the 2009/2010 growing season (expressed on the total plot area).

Dwelle, *et al*. (1981) reported a positive correlation between potato tuber yield and visual estimation of LAI. Variations in LAI, especially for short duration crops, can strongly influence crop growth rates and productivity. In a study of 14 potato clones, Moll (1983) concluded that both large leaf area and high photosynthetic rates are important for high yields. On their part, Khurana and McLaren (1982) found a linear relationship between potato tuber yields and interception of PAR, which is directly related to LAI. Several researchers agree that the maximum LAI achieved by a crop gives an indication of the total fraction of PAR interception, which determines photosynthetic production and tuber yield (Lahlou *et al*.., 2003; Anita & Giovanni, 2005; Bradley *et al*., 2005). For potatoes, a large photosynthetically active leaf surface is important to maintain tuber bulking rates for extended periods (Bradley *et al.*, 2005), which is required for high tuber yields. During the present investigation, as can be noted later, there was also a close relationship between LAI values and final total yields for results expressed on both the total plot area and the cropped area only.

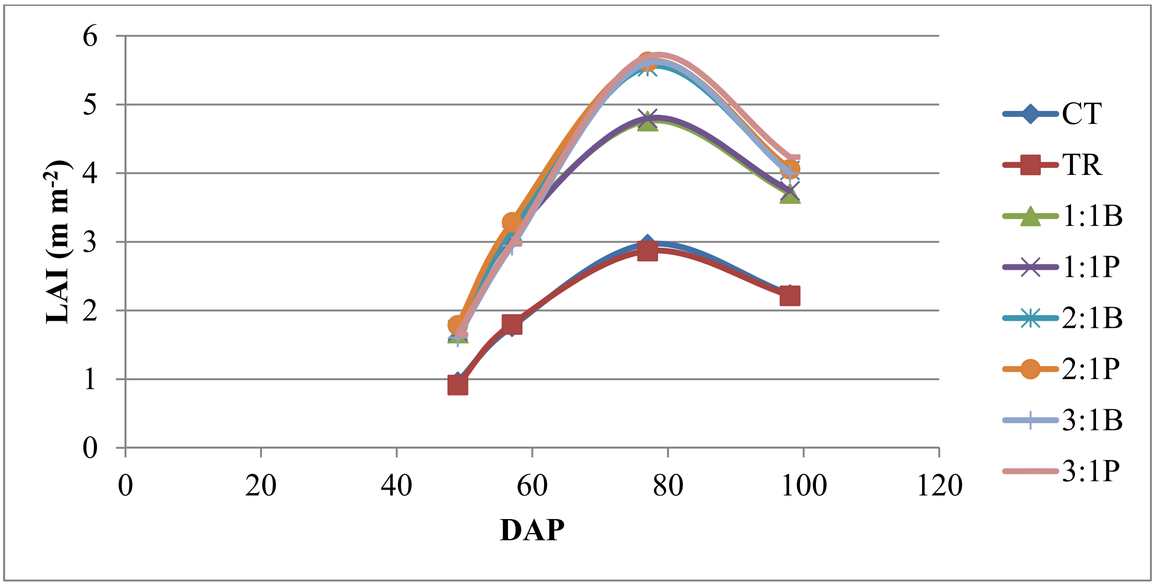


Figure 18: Potato LAI for the different treatments (expressed on the cropped area only) during the 2009/2010 growing season.

Significant genetic variation was observed among potato genotypes in LAI development in a warm climate (Bhagsari *et al.*, 1988; Sarekanno *et al.*, 2010). However, most of the genotypes, except for one cultivar (Pungo in 1984), failed to develop enough foliage to reach the LAI values of 4 to 5 m^2 m^{-2} which is common for potato in cool climates. Optimum LAIs for efficient photosynthesis of agricultural crops range from 4 to 5 m^2 m^{-2} (Scott & Wilcockson, 1978; Allen & Scott, 1980; Khurana & McLaren, 1982). In the current study, only one cultivar was used, therefore genotype was not a factor. LAI values hardly reached 3 m^2 m^{-2} for CT (end December), the treatment which showed the highest performance, in terms of the total plot LAI. This can partly be explained by recurrent high temperature dry spells. This agrees with the report found in the literature, stating that LAI values are below optimum in the dry season; and that higher temperatures enhance stem growth and development at the expense of the leaf area and tuberization (and yield) (Benoit *et al.*, 1983).

However, during the course of the present study, the range of maximum LAI values on the cropped areas varied between 3.0 and 5.7 m^2 m^{-2} (Figure 3.12).

3.3.6 PAR fractional interception (FI$_{PAR}$)

FI$_{PAR}$ values for the different treatments are shown in Figures 3.13, for the total plot area, and 3.14, for the cropped area only. According to the total plot area results, CT had the highest FI$_{PAR}$ followed by TR, with 1:1B and 1:1P having intermediate values, while the lowest FI$_{PAR}$ values were measured for 3:1B and 3:1P. As in the case of LAI values, the ranking was reversed if the results were expressed on the cropped areas only. The reasons behind the ranking of FI$_{PAR}$ values are those mentioned for LAI. These results can partly be supported by the explanations given to height, SPAD, stomatal conductance (below) and LAI which were affected by the soil water deficit levels.

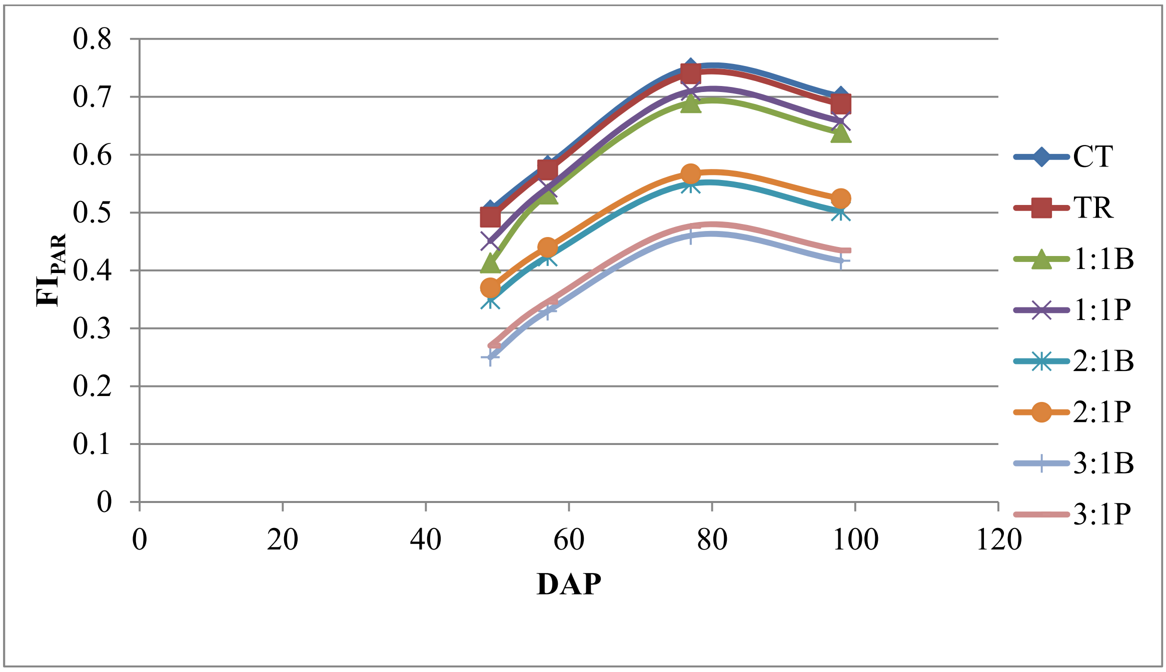


Figure 19: Potato FI$_{PAR}$ values for the different treatments (expressed on the total plot area) during the 2009/2010 growing season.

Fractional interception of PAR is an important indicator of biomass production and tuber yield (Williams *et al*., 1996; Lahlou *et al*., 2003). In accordance with the literature, the PAR interception of the plant canopy was measured in crop growth and haulm index studies (Allen & Scott, 1980; Burstall & Harris, 1983; Spitters, 1987), and combining the characteristics: plant height, stem number, and ground cover at tuberization has been proposed as a criterion to indirectly select for tuber yield (Moll & Klemke, 1990). Deblonde and Ledent (2001) reported that intercepted radiation was mostly influenced by the level of water application and to a lesser extent by other factors such as ambient conditions. In the current investigation, only rainwater was utilized as a means of water supply and, therefore, the RWH (IRWH and TR) treatments collected more water than CT, resulting in their higher FI values (intercepted radiation) (clearly with the FI_{PAR} values expressed on the plot cropped areas only – Figure 3.14).

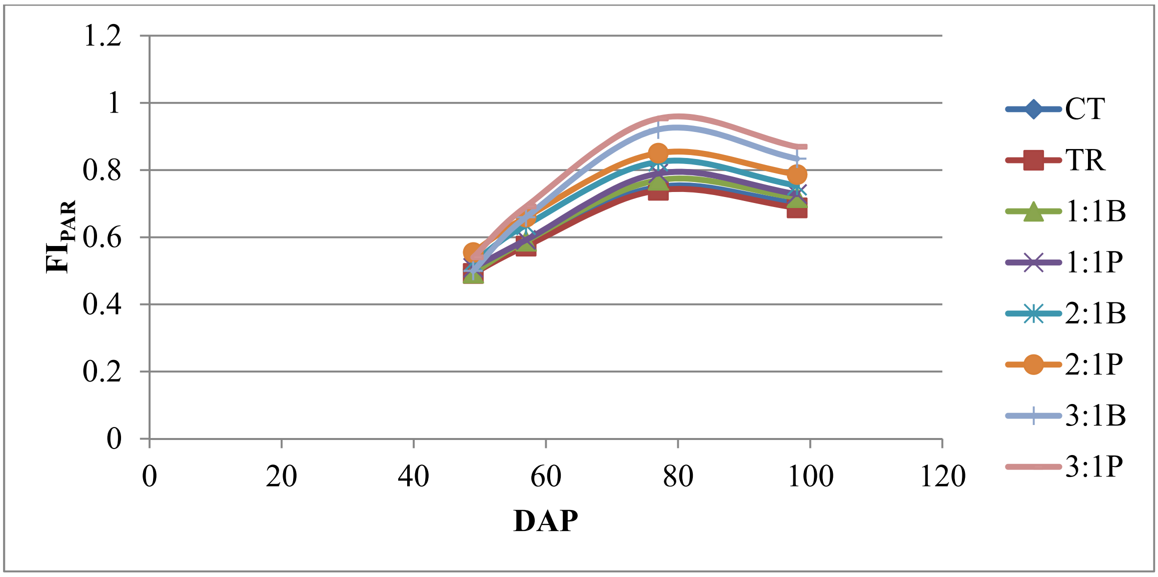


Figure 20: Potato FI_{PAR} for the different treatments (expressed on the cropped area only) during the 2009/2010 growing season.

3.3.7 Leaf stomatal conductance

Figure 3.15 shows that in general, the stomatal conductance for all treatments increased and decreased alternatively. These increases and decreases can partly be explained by the time when data collection took place during the crop growing period. Measurements taken soon after sufficient rainfall gave higher conductivities than those taken long after a rainfall event (for all treatments). The second increase did not reach the same level as the first increase, with the exception of 3:1P. The treatment 3:1P has collected more water than the rest at the times of data collection (Figure 3.15). This was in close relation with the amount of rainfall and therefore the soil water conditions during that interval. Moreover, when there was a short period without rainfall, all treatments shared similar stress symptoms. However, the decrease at the end of the growing season should partly be explained by the crop reaching maturity and senescence.

According to Campbell *et al*. (1976), research on leaf water potential in the potato has revealed that the control of stomata over transpiration is such that the plant has a low ability to maintain a wide difference between soil and leaf water potential. Transpiration in potato is restrained by stomatal closure at relatively high leaf water potentials (-0.4 MPa to -0.6 MPa) (Campbell *et al*., 1976) and water loss by transpiration is constrained by closing stomata. The closing of stomata widens the gap between canopy and air temperature; this gap may be used in the calculation of the crop water stress index (CWSI) (Idso *et al*., 1981; Jackson, 1982; Reginato, 1983). However, this has sparked controversy since it does not take into consideration the energy balance parameters involved (Hatfield, 1990). In the present investigation, although leaf water potentials of the different treatments were not recorded, information from soil water deficits (soil water contents), and the stomatal conductance results can reveal the sensitivity of potato to water stress (the treatment with the lowest soil water content exhibited the lowest stomatal conductance).

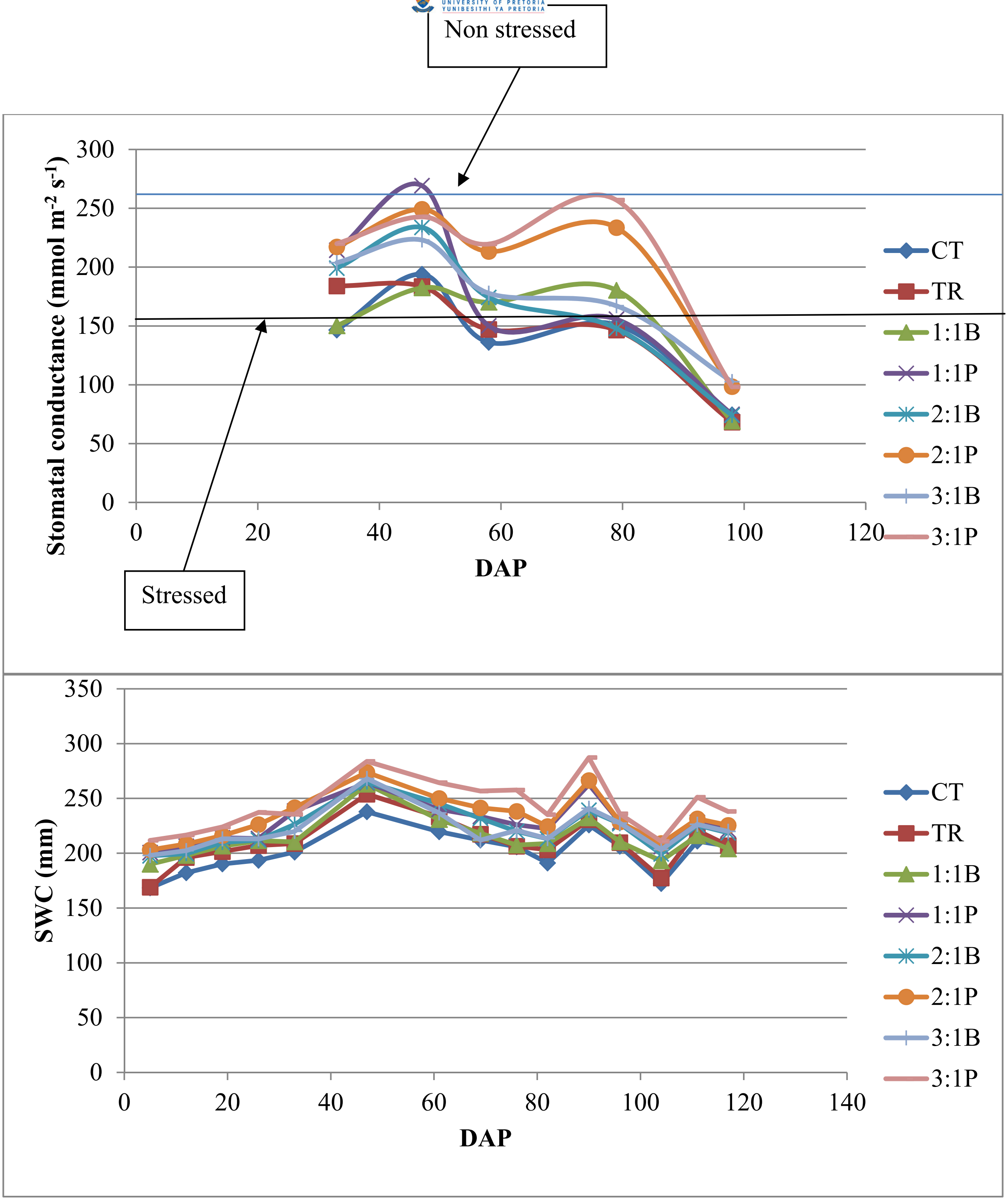


Figure 21: Potato stomatal conductance, as well as the profile soil water content (100 cm depth) for the different treatments during the 2009/2010 growing season.

3.3.8 Photosynthetic rate

Figure 3.16 illustrates photosynthetic rate values of the different treatments. The reading was taken once during the crop growing season (only in November when the device operator was available). The RWH treatments exhibited higher photosynthetic rates than CT. In addition, among the IRWH treatments, those with plastic mulch performed better than the treatments with bare surface runoff areas. This prevalence of the IRWH and TR treatments over CT in terms of photosynthetic rates was undoubtedly the result of water harvested and retained. The measurement was carried out 3 days after a series of 3 rain days (with 35.3, 20.8 and 6 mm, respectively).

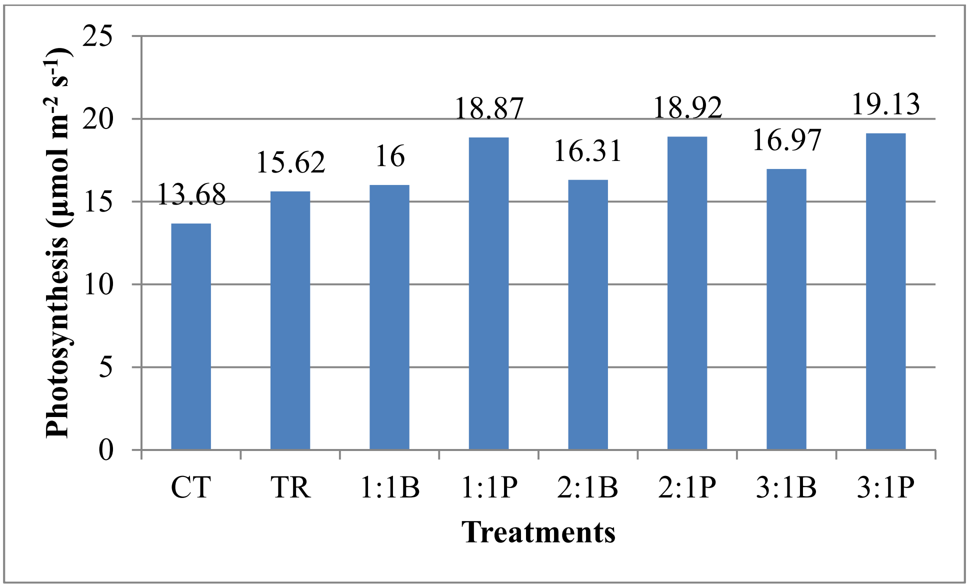


Figure 22: Potato photosynthetic rates during the 2009/2010 growing season for the different treatments (26/11/2009).

Many factors are known to affect photosynthetic capacity, including leaf age (Rawson *et al*., 1983), temperature (Ku *et al*., 1977), leaf water status (Moorby *et al*., 1975), transpiration rate (Sharkey, 1984), humidity (Bunce, 1984) and irradiance (Kremer & Kropff, 1999). According to Wong *et al*. (1979) and Schulze (1982), photosynthesis and stomatal conductance have often been found to change according to the response to variation in ambient conditions or leaf ages. These proportional changes result in a fairly stable internal CO_2 concentration. Studies on a number of species have proven that low radiation levels generally lead to decreased photosynthesis, biomass accumulation and yield, and may distort both total translocation of assimilates as well as assimilate partitioning patterns (Core, 1983; Craker *et al*., 1983; Dwelle, 1985; Gifford & Evans, 1981; Hang *et al*., 1984; Kemp & Whingwiri, 1980; Nayak & Murty, 1980; Wardlaw, 1970; Wardlaw, 1976). However, others (Inaba, 1984; Miura & Osada, 1981) have observed an increase in photosynthesis and biomass accumulation, e.g., *konjak* plants, grown under low irradiance. Low irradiance influences export of assimilates from photosynthetic organs in different ways. During the course of the day leaf water potential declines with increasing radiation load, and increases again when radiation declines in the afternoon. On bright days leaf water potential of well-watered potato plants can drop to from -0.8 to –1.0 MPa. On such days, conductance, transpiration, and photosynthesis of potato crops all increase with radiation up to their respective saturation points (Bodlaender *et al*., 1986; Vos, 1986). In the case of the current investigation, the RWH treatments showed higher photosynthetic rates than CT because their soil water contents were higher. The physiological processes should thus have augmented with radiation increase for these treatments.

3.3.9 Potato tuber yields and yield components

Tables 3.4 and 3.5 show the tuber yields from the different treatments. These tables indicate that for large and medium size tubers, there were no significant differences among treatment means expressed on either a total area or a cropped area basis. There were significant differences among treatment means for small size tuber yields, with CT having the highest mass, followed by TR and 1:1B. This can probably be attributed to intermittent short dry spells during the crop growing season. Treatment 3:1B had the lowest mass of small tubers followed by 3:1P. In terms of total yields (over total area), significant differences occurred and the order was as follows: CT > TR > 1:1P > 1:1B > 2:1P > 2:1B > 3:1P > 3:1B. The reason for the high yields achieved by CT and TR can exclusively be attributed to the highest number of plants per plot area. It was expected that TR would yield higher than CT, but this did not happen since this treatment was the most affected by disease incidence (*Alternalia alternata,* brown spot). If only the net cropped area is considered, values in all categories for CT and TR were unchanged (31.36 and 25.10 t ha^{-1}), while yields of the IRWH treatments doubled, tripled or quadrupled according to their net cropped areas. In the IRWH treatments, for example, the total area/cropped area yields of 3:1P, 2:1P and 1:1P were 11.26/45.04, 16.37/49.11 and 20.23/40.46 t ha^{-1}. According to the net cropped areas, the order of the total yields was: 2:1P > 3:1P > 2:1B > 3:1B > 1:1P > 1:1B > CT > TR. From Table 3.5 (cropped area yields) it is evident that no significant differences among treatment means occurred for the large- and medium-size tubers; only the small-size and total tuber yields showed significant differences. On this occasion, the treatments with ratios had higher yields than TR and CT. Moreover, as in the case of the results recorded according to the total plot areas, the treatments with plastic mulch yielded higher than those with bare runoff areas. This prevalence can partly be attributed to the relatively high values of photosynthesis and stomatal conductance which, in turn, resulted from relatively low soil water deficits for these treatments.

The effects of water stress on potato tuber yields are well documented (Haverkort, 1990; Steyn *et al*, 1998; Steyn *et al*., 2009). In general, yield and grade generally respond linearly to water used. However, in arid and semi-arid regions, it is a fact that irrigation plus rainfall is less than or equal to the potential evapotranspiration (Martin *et al*., 1992; Hegney & Hoffman, 1997). RWH can mitigate this situation by increasing the amount of water available to plants in the root zone. For example, tied-ridges can improve rainwater distribution for better utilization by crops (Hatibu, 2000; McHugh *et al*., 2007; Nuti *et al*., 2009; Temesgen *et al*., 2009) and increase the crop response to rainfall and nutrient availability (Jensen *et al*., 2003). In the course of the current study, however, this treatment was the most affected *Alternalia alternata*. As another example, MCRWH has the potential to increase crop yield in semi-arid areas (Yuan *et al*., 2003; Botha *et al*., 2007). This is in agreement with the results obtained in the current study if the yields are expressed relative to the cropped areas, while the yields expressed on the total area were influenced by the number of plants per plot of the different treatments. However, because potato is a shallow-rooted crop, this can be a handicap for the withdrawal of soil water stored in the deeper layers of the profile of the ridges after rainfall events.

Table 3.4: Fresh tuber yields (t ha^{-1}, total plot area).

Treatments	Large (t/ha)	Medium (t/ha)	Small (t/ha)	Total (t/ha)
CT	1.30a	9.00a	21.06a	31.36a
TR	1.02a	8.02a	16.06ab	25.10ab
1:1B	0.73a	6.40a	11.51bc	18.64bc
1:1P	1.46a	7.38a	11.39bc	20.23bc
2:1B	0.97a	5.06a	8.38cd	14.41bc
2:1P	1.24a	5.72a	9.41cd	16.37bc
3:1B	0.67a	4.07a	5.57d	10.31c
3:1P	0.78a	3.96a	6.52cd	11.26c
LSD (< 0.05)	NS	NS	16.03	11.71
CV (%)	45.80	34.39	5.09	22.43

Means followed by the same letter are not significantly different at P = 0.05.

Note: Small = tuber diameter < 55 mm, medium = tuber diameter varying from 55 to 75 mm and large = tuber diameter > 75 mm.

Since potatoes are very susceptible to water stress, high levels of available soil water are needed to achieve maximum yields (van Loon, 1981; Doorenbos & Kassam, 1986). Water stress negatively affects photosynthetic efficiency at all stages of growth, with drought during the periods of tuber initiation and bulking having the harshest effect on yield (MacKerron & Jefferies, 1986; Haverkort *et al*., 1990; Lynch *et al*., 1995; Yuan *et al*., 2003). Previous studies showed that limited soil water availability at different stages of growth results in earlier crop maturity (Karafyllidis *et al*., 1996), decreased plant growth, tuber yield, number of tubers per plant, and tuber size and quality (MacKerron & Jefferies, 1986; Ojala *et al*., 1990; Lynch *et al*., 1995; Karafyllidis *et al*., 1996; Dalla Costa *et al*., 1997; Yuan *et al*., 2003). However, while Karafyllidids *et al.* (1996) obtained the highest total yield with irrigation at 65% of soil water availability, Foti *et al*. (1995) found no significant differences in yield for the range of 66 to 100% of maximum available soil water. In the present investigation, only rainwater was utilized and no irrigation scheduling was practiced. However, CT, TR and the IRWH treatments with smaller design ratios (1:1) had high number of small size tubers, which can partly be attributed to several short intra-seasonal dry spells (Figure 3.8).

Table 3.5: Fresh tuber yields (t ha^{-1}, cropped area).

Treatments	**Large (t/ha)**	**Medium (t/ha)**	**Small (t/ha)**	**Total (t/ha)**
CT	1.35a	9.00a	21.06ab	31.36ab
TR	1.02a	8.02a	16.02b	25.10b
1:1B	1.46a	12.80a	23.02ab	37.28ab
1:1P	2.92a	14.76a	22.78ab	40.46ab
2:1B	2.91a	15.18a	25.14ab	43.23ab
2:1P	3.72a	17.17a	28.23a	49.11a
3:1B	2.68a	16.28a	22.28ab	41.26ab
3:1P	3.12a	15.83a	26.09ab	45.04ab
LSD (< 0.05)	NS	NS	11.34	21.48
CV (%)	40.85	30.51	17.06	19.06

Means followed by the same letter are not significantly different at P = 0.05.

Note: See the note for Table 3.4.

The yields obtained from the current experiment (expressed either on a total or cropped area basis) can be compared to those found in the literature for dryland potatoes (Tian *et al*., 2003; Wang *et al*., 2005). During the course of this investigation, according to the gross area, the highest total yield was 31.36 t ha^{-1} (CT), while the highest yield obtained according to the net cropped area was 49.11 t ha^{-1} (2:1P). In the experiment about the effect of irrigation systems and irrigation regimes on potato growth and yield reported by Erdem *et al*. (2006), the highest yield was 35.13 and 44.56 t ha^{-1} in 2003 and 2005, respectively. These results are in the range of the highest yields obtained in this study. However, the results (both total and cropped area) are relatively lower than those from Miller and Martin (1985) who, using sprinkler irrigation, obtained total yields ranging from 48.40 to 64.70 t ha^{-1}and 43.70 to 56.70 t ha^{-1} for 1982 and 1983, respectively. These high yields can be attributed to the fact that irrigation was used while in this case only rainwater was utilized. With regard to dryland potato production, Tian *et al.* (2003) carried out an experiment on the effect of RWH with ridge and furrow on potato yield in semi-arid areas. The highest yields obtained from the treatment with plastic-covered ridge (0.45 m wide) were 28.10 and 49.20 t ha^{-1}, expressed on the gross and the net cropped area, respectively. These results are in the range of those obtained in the present investigation. However, in another RWH potato production experiment reported by Wang *et al*. (2003), the highest yields (expressed on the gross area) from the treatment with plastic-covered ridge (0.45 m wide), were 3.60 and 2.10 t ha^{-1} in 2002 and 2003, respectively. Due to severe drought conditions, these results are obviously much lower than those obtained in the current study.

3.3.10 Water use (WU) and water use efficiency (WUE)

Table 3.6 gives an indication of rainfall (R, mm), irrigation depth (I, mm), change in soil water storage (ΔS, mm), T (mm), soil E (mm), total ET (mm), total yield (kg ha^{-1}) (total plot area), WUE (kg ha^{-1}mm^{-1}) (total plot area), total yield (kg ha^{-1}) (cropped area) and WUE (kg ha^{-1}mm^{-1}) (cropped area). ΔS is calculated from the soil water content measured during the crop growing season; E, T and ET are modelled. It is evident that ΔS, T, E and total ET varied with the different methods of RWH during the potato crop growing period. There were significant differences among treatment means of the average total ΔS of the different treatments. Negative ΔS means profile drier at the end than in the beginning. However, since the SWB model was used to split ET into E and T, no results on the statistical analysis of these three parameters are available although tangible differences were shown. Treatment 3:1P had the highest ET because it was expected to harvest the highest amount of runoff and subsequently to have a high transpiration rate (Table 3.6). Moreover, CT showed the lowest T and ET values and highest E value because it was flat and devoid of any runoff harvesting structure, thereby, runoff was lost and not retained in the field. In essence, the plants of the IRWH treatments with plastic mulch had higher T and ET than those with bare runoff areas which, in turn, presented higher T and ET values than TR and CT.

Table 3.6 also presents WUE of the different treatments, calculated depending on yields expressed on both the total plot and cropped area. It is obvious that the trends of WUE follow those of the different treatments in terms of yields. Water use efficiency (WUE) is the ratio between total harvestable yield or dry matter produced and the quantity of water consumed (Yuan *et al*., 2003; Onder *et al*., 2005; Erdem *et al*., 2006, Zhang *et al*., 2008), while rainwater (precipitation) use efficiency (RWUE or PUE) is calculated by dividing the total harvestable yield by the amount of rainfall received from planting to harvesting (Stroosnijder & Hoogmoed, 2004; Araya & Stroosnijder, 2010). However, in this study, since rainwater was the only means of water supply, WUE is almost equal to RWUE (PUE) (10 mm was sprinkled after planting). According to the total plot area results, the treatments with the high number of plants gave the highest yields and WUE values, while, in terms of the cropped area results, high yields and WUE values were associated with the IRWH treatments. For these latter treatments, in terms of yields and WUE values expressed on the basis of the total plot and cropped areas, the treatments with plastic mulch performed better than the treatments with bare runoff areas. Again, the case of TR with lower WUE values than CT should partly be explained by disease incidence. It is worth noting that the IRWH treatments did not present high yields and WUE values according to the gross areas because the effect of harvested runoff was not enough to compensate for the effect of lower rows of plants per plot. Potatoes are shallow-rooted crops and therefore experience difficulties in drawing the harvested runoff stored in deep layers.

Table 3.6: R, I, ΔS, T, E, ET (all in mm), yields (total plot and cropped areas, kg ha^{-1}) and WUEs (total plot and cropped areas, kg ha^{-1} mm$^{-1)}$ for the 2009/2010 growing season.

Treatments	**R (mm)**	**I (mm)**	**(ΔS) (mm)**	**T (mm)**	**E (mm)**	**Total ET (mm)**	**Yield (kg ha^{-1}) (total plot area)**	**WUE (kg ha^{-1} mm^{-1}) (total plot area)**	**Yield (kg ha^{-1}) (cropped area)**	**WUE (kg ha^{-1} mm^{-1}) (cropped area)**
CT	406.40	10.00	-32.91b	170.72	212.77	383.49	31360a	81.78a	31360ab	81.77ab
TR	406.40	10.00	-31.15b	179.12	206.13	385.25	25100ab	65.15ab	25100b	65.14b
11B	406.40	10.00	-29.81b	189.53	197.06	386.59	18640bc	48.23bcd	37280ab	96.43ab
11P	406.40	10.00	0.62ab	256.68	160.34	417.02	20230abc	48.51bcd	40460ab	97.02ab
21B	406.40	10.00	-10.92ab	247.79	157.69	405.48	14410bc	35.54cd	43230ab	106.61ab
21P	406.40	10.00	0.95ab	265.44	151.91	417.35	16370bc	39.22cd	49110a	117.67a
31B	406.40	10.00	-10.57ab	242.38	163.45	405.83	10310c	25.40d	41260ab	101.67ab
31P	406.40	10.00	10.73a	271.25	155.88	427.13	11260c	26.36d	45040ab	105.45ab
LSD (< 0.05)	—	—	34.54	—	—	—	11330	25.12	21477	48.49
CV (%)	—	—	-93.04	—	—	—	21.30	19.39	19.06	17.59

Means followed by the same letter are not significantly different at P = 0.05.

According to Anschütz *et al*. (2003), the crop water requirement implies T and E, usually referred to as ET, and it is the amount of water required by an individual crop for a full growing season. The plant daily or seasonal water requirement is characteristic for each type of crop. Moreover, within each crop type, there exist notable differences in water requirement. The crop water requirement is influenced by the climate in which the crop is grown, the length of the growing season, and the crop growth stages within this growing period. Following the investigation done by Zhao *et al*. (1997), it was revealed that there is a linear relationship between daily crop ET and soil water content. Furthermore, in conformity with the outcome from the experiment led by Li *et al*. (2006), soil water storage was higher in the MC treatments than in the control (flat plot). However, E was significantly higher for the RWH treatments than the control. In the course of their experiments (3 years), RWH treatments accounted for 35 – 533 mm increase in ET. In addition, since the large catchment captured more runoff than the small one, its ET increased accordingly. This confirms the tendency of the findings from the current study. The results of research works pointed out that the major advantages of RWH are that it is simple, cheap, efficient, replicable, adaptable and environment-friendly, and that RWH with ridges and basins can considerably improve soil water storage, prolong the period of water availability, and enhance growth and yield of agricultural crops (Boers *et al*., 1986; Ngigi, 2009). In the course of their study on the effects of rainwater systems on the soil water storage, Li *et al*. (2006) also declared that the soil water storage was higher for the MCs, in general. In the present case, however, the soil water storage in the IRWH treatments was not high enough to make a significant difference in yields and WUEs according to the total plot area because probably potato is a shallow-rooted crop.

According to Ritchie *et al*. (1983), the threshold LAI for most crops can vary from 3.00 to 3.50 m m^{-2}. Below this threshold LAI, ET and crop yield increase significantly with the increase in LAI, while in contrast, no significant increase in ET and crop yield occurs above it. Wang *et al*. (2005) respectively conducted experiments in 2001 at Gaolan County and in 2002 at Yuzhong County, China. The potato biomass and LAI in the plastic-mulched system increased more rapidly (up to around 2.80 and 2.40, respectively), with absorption of more soil water, due to the higher LAI and greater availabilities of soil water and nutrients. For Li *et al* (2006), crops also respond differently to water deficit in addition to their typical water requirements. According to their assertion, ‘When the crop water requirements are not met, crops with high drought sensitivity experience greater reductions in yield than crops with low sensitivity'. It is recommended that in the case of highly inaccurate and unpredictable runoff harvesting, crops with low sensitivity to drought are most suitable and therefore should take precedence. This calls for an unsuppressed necessity to breed and select deep-rooted potato crop in an effort to overcome the current high sensitivity to drought.

Optimising rainwater utilization is of paramount importance, and it necessitates the strict adoption of the principle of more crop per drop, as declared by the then UN General Secretary Kofi Annan (Welderufael *et al*., 2008). In scientific terms, this hints to improving RWUE which has also been redefined by Botha (2007) as the total long-term grain yield divided by the total long-term rainfall. The RWH technique can increase WUE through an improved water supply because of RWH and E reduction (Wang *et al*., 2008). In general, the trends for the WUE values related to the total amount of consumed water and the total fresh tuber yields for the various treatments showed that the lower the amount of water consumed, the higher the WUE (Fabeiro *et al*., 2001; Kashyap & Panda, 2003; Yuan *et al*., 2003; Onder *et al*., 2005). This can only materialize by increasing beneficial T while reducing wasteful E. As it was mentioned in this study, however, the higher RWUE values were not necessarily the result of low ET values, but rather higher yield.

3.3.11 Potato tuber internal and external characteristics and processing quality

A. Specific gravity

Table 3.7 shows the results of SG values obtained for the different treatments. SG gives an indication of crop maturity, harvest quality and storability of tubers. In other words, SG is a crucial quality parameter linked to the processing quality of tubers. Potatoes of high dry matter content, and therefore of high SG are important to the processing industry (Belanger *et al*., 2002). Potatoes of low SG do not process into good quality French fries and crisps (Sayre *et al*., 1975). In the present experiment, the range of SG values varied between 1.074 (CT) and 1.080 (TR, 2:1P & 3:1P) but differences were not significant. According to Mosley and Chase (1993), SG values between 1.060 and 1.069 are regarded as low, while values of 1.070 to 1.079 are medium and those of 1.080 to 1.089 are regarded as high. However, using potatoes with SG ranging up to 1.090, Iritani *et al.* (1971) showed the importance of processing high SG potatoes for chips to achieve low chip oil content and high chip yield. In a separate investigation, Tekalign and Hammes (2005) have reported SG values as high as 1.090 and 1.085 for non-flowering and flowering potato cultivars, respectively.

In conformity with Mosley and Chase (1993), most of the treatment means of the results obtained in the current study fell in the medium SG range. The medium SG values obtained can mostly be attributed to the cultivar used (cv. BP1), which is known to be medium-maturing and of a fair dry matter content and henceforth more suitable for cooking (boiling, baking, steaming). Moreover, these results can partly be explained by some wet spells and relatively high temperatures that now and then characterized the crop growing season (observation). Extremely high or low soil water content, typically when associated with high temperatures, can lead to unsatisfactory low SG values (Baritelle & Hyde, 2003; Stark *et al*., 2003).

Factors such as genotype and environment affect SG (Lana *et al*., 1970). The SG of early-maturing cultivars was reported to be typically lower than those of late-maturing cultivars (Belanger *et al*., 2002). Steyn *et al*. (2009) presented the SG values in increasing order of early-, intermediate- and late-maturing cultivars: 1.076, 1.078 – 1.082 and 1.080, respectively. Factors such as water application during the growing season can affect SG values. Potatoes are typically susceptible to drought stress during tuber setting and bulking (Steyn *et al*., 1992; Shock *et al*., 1998). According to the results from the study of the effect of deficit irrigation on potato SG, reduced values were obtained from the deficit irrigation treatment. The same reduced values were given by the well-irrigated treatment, which has been subjected to deficit irrigation after tuber initiation (Hang & Miller, 1986; Shock *et al.*, 1998). Throughout the experiment carried out by Waddell *et al*. (1999), it was confirmed that the SG of tubers from the dry treatments was significantly lower than that of tubers from the wet treatment under sprinkler irrigation. In this regard, Visser (2003) stated that the level of tuber quality undermining due to poor environmental and growing conditions is hugely determined by varietal characteristics. In addition, N fertilization can also affect potato tuber SG (Belanger, 2002). Long *et al*. (2004) reported a decrease in SG as N rates increased beyond the optimum rate for yield.

Table 3.7: Fresh tuber internal quality (SG).

Treatment	**SG**
CT	1.074a
TR	1.080a
1:1B	1.075a
1:1P	1.075a
2:1B	1.079a
2:1P	1.080a
3:1B	1.077a
3:1P	1.080a
LSD (< 0.05)	NS
CV (%)	0.45

Means followed by the same letter are not significantly different at $P = 0.05$.

In the course of the present study, the crop at times experienced some wet spells with several dry periods (Figure 3.8) associated with high temperatures, which can to some extent, explain the SG values obtained. It remains, however, unclear why the SG values from the different treatments did not show a general trend.

B. Chip colour

Table 3.8 presents chip colour results obtained from fresh tubers after harvest. According to this table, no significant differences among treatment means were shown. The highest value of chip colour was achieved for treatment 2:1P (51.2) followed by TR (50.1). The lowest chip colour value of 46.6 was obtained for treatment CT, followed by 1:1B (47.7). As it appears in the table, all chip colour values are higher than 45 which is a sign of good quality in terms of processing industry standards according to the literature (Modisane, 2007). Therefore, all treatments produced good chip quality, although Steyn (1997) mentioned that chip colour values equal to or higher than 50 indicate acceptable processing quality.

Table 3.8: Fresh tuber internal quality (chip colour).

Treatment	Chip colour
CT	46.6a
TR	50.1a
1:1B	47.7a
1:1P	48.2a
2:1B	49.4a
2:1P	51.2a
3:1B	49.2a
3:1P	49.8a
LSD (< 0.05)	NS
CV (%)	5.0

Means followed by the same letter are not significantly different at P = 0.05.

Kumar *et al*. (2004) revealed that potatoes destined for making chips/crisps, French fries and other fried products, need to have a low sugar (glucose and fructose) and high dry matter (starch) content to avoid browning of the end product. Cottrell *et al*. (1995) maintained that the standard limit for reducing sugars for tenable chipping quality is less than 0.2% on a fresh tuber mass basis. Many chemical constituents affect the colour of processed potato products, and sugars are broadly considered to depend on several factors such as genotype, temperature, water, cultural practices, length of growing season, and a number of pre-and post-harvest factors (Smith, 1987). However, Stevenson *et al*. (1964) found the genetic component to be a main factor for reducing sugar levels in a mature tuber and during storage. It was maintained that the temperature and length of growing season are the first runners-up to the genetic factor, given the key role played by temperature in many physiological processes of the plant (van Es & Hartmans, 1987; Pavlista & Ojala, 1997). During the course of the present study, no analysis of the tuber reducing sugar content occurred and only the tuber chip colour was determined. The results obtained on colour were acceptable, in general. According to Grassert *et al*. (1984), this can partly be attributed to some high levels of day temperatures and low levels of rainfall (that can affect soil temperatures) during the crop vegetative stage.

C. Other tuber internal and external characteristics

At harvest, 10 tubers from each treatment were randomly chosen for internal quality analysis. From Tables 3.9 and 3.10, it is clear that the colour and the internal appearance of all tubers were consistent (good) for all treatments. In terms of vascular discolouration, brown spot and hollow heart, which are other internal tuber flesh defects, the treatment means showed some differences, but no significant differences were present. For vascular discolouration, values varied between 2 and 3, which means that 3 – 4 of 10 tubers had this defect. Brown spot values for all treatments were mostly 5 and all the remaining were 4.7, close to 5. This means that almost no tubers suffered from brown spot incidence. Some differences can be seen with regard to tuber hollow heart defects. These values ranged from 3.7 – 4.7. This means that either no tuber was affected by this defect or only just one or two tubers were affected.

According to Pavlista (2002), inappropriate crop management during the growing period can result in vascular discolouration and brown spot. Low soil water content, especially when the crop is close to maturity or a rapid death of vines due to high temperature stress, can result in vascular discolouration. Growth disorders such as brown centre and hollow heart are mostly associated with abrupt changes in growing conditions during the season, for example rapid growth after a cool period or after mitigating water stress (Hochmuth *et al*., 2001). From Figure 3.8 (soil water deficit and rainfall), can be concluded that the growing period was marked by erratic rainfall events, with some water deficit and wet spells which should, to a certain extent, explain the occurrence of tuber internal defects. As it can be seen in Figure 3.8, the rainfall on the 20th and 21st of November 2009 was 35.3 and 20.8 mm, respectively. Prior to and after these rainfall events, the crop experienced low precipitation events, predominantly below 10 and 5 mm, respectively, which probably resulted in drought stress and therefore in tuber internal defects. During the course of December 2009 and January 2010, such steep fluctuations in precipitation continued to occur intermittently.

Table 3.9: Scale used for external tuber quality characteristics[1] (USDA, 1997).

Treatment	Internal appearance	Vascular discolouration	Brown spot	Hollow heart
CT	2	3.3a	4.7a	4.7a
TR	2	3.3a	4.7a	4.7a
1:1B	2	3.0a	5.0a	3.7a
1:1P	2	2.3a	5.0a	4.7a
2:1B	2	2.3a	5.0a	4.7a
2:1P	2	2.7a	5.0a	4.3a
3:1B	2	3.0a	4.7a	4.3a
3:1P	2	3.3a	5.0a	4.0a
LSD (< 0.05)		NS	NS	NS
CV (%)		29.6	7.3	15.5

[1] - Refer to Table 3.2 for explanations.

It can be noted that with regard to potato tuber external quality, cases of tuber secondary growth, cracking, common scab and rotten tubers were encountered. All these defects were highest in CT followed by TR, except for the rotten tubers where TR had more than CT. With regard to the IRWH treatments, those with plastic mulch had more defects than those with bare runoff. According to Selman *et al.* (2009), both tuber secondary growth and tuber cracking are physiological problems which are related to fluctuations in soil water and rapid, uneven uptake of water. Dry periods or periods of high temperature followed by rain can also cause growth malformations. As the current IRWH trial was carried out in the open field during summer, it is not unusual for huge fluctuations in environmental factors such as soil water and temperature. In addition, a warm and dry environment during tuber initiation has been reported as one of the factors that promote development of common scab (Gouws *et al.*, 2003). Likewise, hot, humid conditions are known to be optimal for infection of *Alternalia alternata* (brown spot), while rain, heavy dew and irrigation in dry areas are considered to promote its development on leaves. Moreover, the disease develops most rapidly during periods of alternating wet and dry weather, particularly on light soils. In the course of the present experiment, the fluctuations of environmental conditions have probably affected the internal characteristics of the different treatments.

Table 3.10: Scale used for internal tuber quality characteristics[1] (USDA, 1997).

Tuber defects	Score and explanation
Vascular discolouration Brown spot Hollow heart	5 = none 4 = 1 – 2 tubers bearers 3 = 3 tubers bearers (out of 10) 2 = 4 tubers bearers 1 = all tubers bearers
Flesh colour	4 = White 3 = Cream 2 = Pale yellow 1 = Dark yellow
Internal appearance	2 = Even colour (no glassiness between the inside and the outside of the flesh, vascular ring) 1 = Difference in colour (glassiness between the inside and the outside of the flesh, vascular ring)

[1] - Refer to Table 3.3 for explanations.

3.4 Conclusions and recommendations

On a total area basis, CT gave the highest potato yields and WUE, followed by TR. CT and TR had the highest number of plants per plot, followed by the IRWH treatments with smaller design ratios (1:1). In addition, the yield and WUE values for TR were lower than those for CT because of disease incidence (brown spot). It is not clear why this treatment was the most affected. For the IRWH, treatments with smaller design ratios (1:1) performed better than those with larger design ratios (2:1 & 3:1). The plastic-covered treatments also gave better results than the bare plots. However, if yields and WUE are expressed on a net cropped area basis, the treatments with larger design ratios, especially those with plastic mulch, showed the highest performance.

IRWH treatments had higher values of harvest index than CT and TR. CT also had the lowest values in terms of specific gravity and chip colour, while 2:1P, TR and 3:1P had the highest values. All treatments showed excellent results in terms of hollow heart and brown spot incidences. With regard to potato tuber external quality, cases of tuber secondary growth, cracking, common scab and rotten tubers were identified, particularly in CT.

The results expressed on both total area and net cropped area bases from the current study showed that normal rainfed agriculture was a good option for the ecotope. That is why the adoption of any RWH technique must be carried out according to local conditions. The part of the hypothesis 3 related to yield and WUE was rejected and the hypothesis 4 accepted. However, as has been recommended elsewhere in dryland regions, the RWH technique should be coupled with other new technologies such as those involving improved and resistant cultivars (deep-rooted and water and disease stress tolerant), soil fertility management, intensified weed and pest management, and increased use of crop-runoff integrated models for the prediction of potential growth and yields. Further research in RWH and IRWH, especially on a wide scale, must be undertaken in order to establish a reliable database in this regard. There is a necessity for more investigations on RWH with shallow-rooted crops like potatoes in different environments. Some good potato tuber yields have experimentally been produced with RWH and therefore more studies would reveal alternative strategies to overcome the constraints facing dryland potato production.

CHAPTER 4

RAINWATER HARVESTING EXPERIMENT (SWISS CHARD – *BETA VULGARIS*, CV. FORDHOOK GIANT)

4.1 Introduction

The introduction to this chapter on the effect of RWH treatments on crop growth and yield is mostly covered in Section 3.1 (introduction of the chapter on potato). The purpose of this chapter is to explore the effects of RWH techniques on Swiss chard growth, re-growth, yields and water use efficiency (WUE) during the 2010/2011 growing season at the Hatfield Experimental Farm of the University of Pretoria.

4.2 Materials and methods

4.2.1 Site description

The experiment was conducted at the Hatfield Experimental Farm of the University of Pretoria, South Africa. This section is nearly similar to Section 3.2.1 in Chapter 3. The only difference resides in soil chemical composition of the site which is: phosphorus: 29.5 mg kg^{-1}; calcium: 578 mg kg^{-1}; potassium: 35 mg kg^{-1}; magnesium: 153 mg kg^{-1}; sodium: 124 mg kg^{-1}; and the average organic carbon: 0.5%. The average soil pH (H_2O) is 5.7.

4.2.2 Experimental design

The field trial was a randomized complete block design (RCBD) with three replicates, and included three different tillage systems. The tillage systems provided eight treatments similar to those shown in Figure 3.1 in Chapter 3. A full account on the size, design and implementation of the plots can be found in Section 3.2.2, with the crop as the only difference.

4.2.3 Field preparation, equipment installation and soil sampling

These items have been extensively presented in Section 3.2.3. However, Figure 4.1a & b illustrates more field preparation work conducted prior to Swiss chard transplanting.

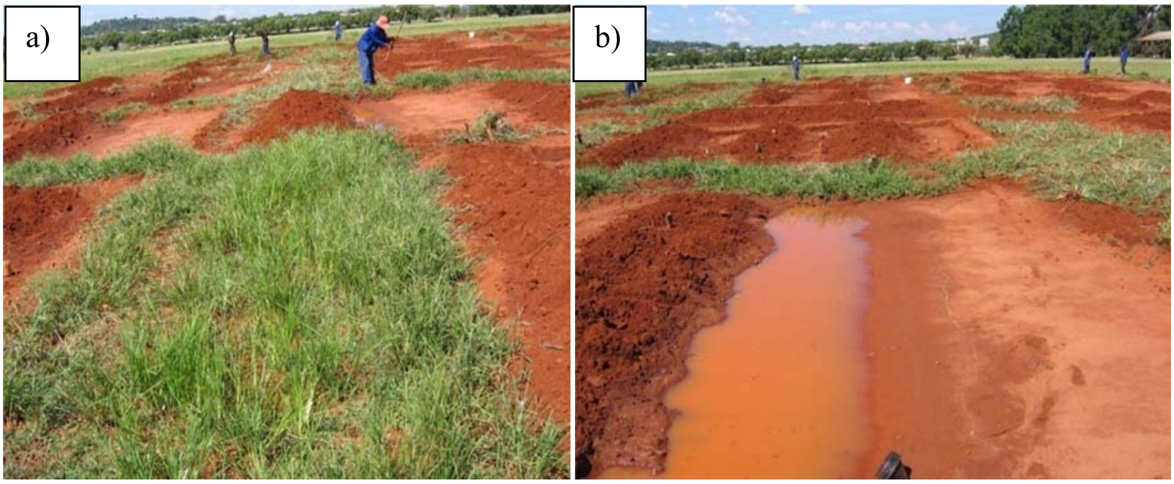


Figure 4.1: Field preparation for the 2010/2011 Swiss chard growing season: a) start of field clearing and, runoff producing area (RPA) and runoff receiving area (RRA) rehabilitation, and b) trapped runoff from the last rainfall event of the previous season.

4.2.4 Field procedures, planting materials, agricultural practices and data collection

Swiss chard seedlings were transplanted by hand on the 14th of May, 2010, at 45 cm x 25 cm spacing, 10 cm deep and one seedling station^{-1} (Figure 4.2a, b, c & d). For CT and TR, 13 rows were transplanted at twenty plants row^{-1}. The number of the plants for these plots was 86,667 plants ha^{-1} (8.67 plants m^{-2}). For the IRWH treatments, the spacing was similar to that of TR and CT but each ridge (cropped area) had two rows. Thus, the number of the plants for their respective plots was: 40,000 plants ha^{-1} (4 plants m^{-2}), 26,667 plants ha^{-1} (2.67 plants m^{-2}), and 20,000 plants ha^{-1} (2 plants m^{-2}) for design ratios 1: 1, 2:1 and 3:1. If the plants per plots were expressed relative to the net cropped areas, all IRWH plots would have the same number of the plants amounting to 80,000 plants ha^{-1} (8 plants m^{-2}). At transplanting, an NPK fertilizer (2:3:4 (30)) was applied at rates of 50 kg ha^{-1} N, 75 kg ha^{-1} P and 100 kg ha^{-1} K. The trial also required 70 kg ha^{-1} N (LAN (28)) as top dressings four weeks after transplanting.

Fertilizer application for the crop was conducted in accordance with soil analysis and guidelines for the crop.

Figure 4.2: Swiss chard transplanting in TR a), Swiss chard seedlings after transplanting in CT b), 1:1 c) and 2:1 d), respectively, during the 2010/2011 growing season.

Immediately after transplanting light sprinkler irrigation (10 mm) was applied to ensure good contact between the seedling root system and soil for good establishment. Sprinkling also permitted good incorporation of the starter fertilizer into the soil. This irrigation was delivered by twin nozzled Perrot sprinklers (PR 24-1) mounted on the top of 1.60-m risers. The diameter of the nozzles and risers was 3.97 mm. The sprinklers were discharging at a rate of 9 mm per hour. The day after Swiss chard transplanting, plastic sheeting was laid on the RPA of 1:1P, 2:1P and 3:1P treatments (Figure 4.3). During the Swiss chard growing season, sprinkler irrigation was applied to simulate rain since the trial was mainly conducted in autumn/winter. In the course of the growing season, appropriate field management practices were followed as stated in Section 3.2.4. The only exception was the height measurements which were conducted by straightening all leaves of the labeled plants and measuring the height from the soil surface to the tip of the tallest leaf. Another exception to the procedures in Section 3.2.4 is the calculation of specific gravity (applied to tuber crops) and harvest index (HI) (top biomass (harvestable yield) was also considered as the total biomass for Swiss chard).

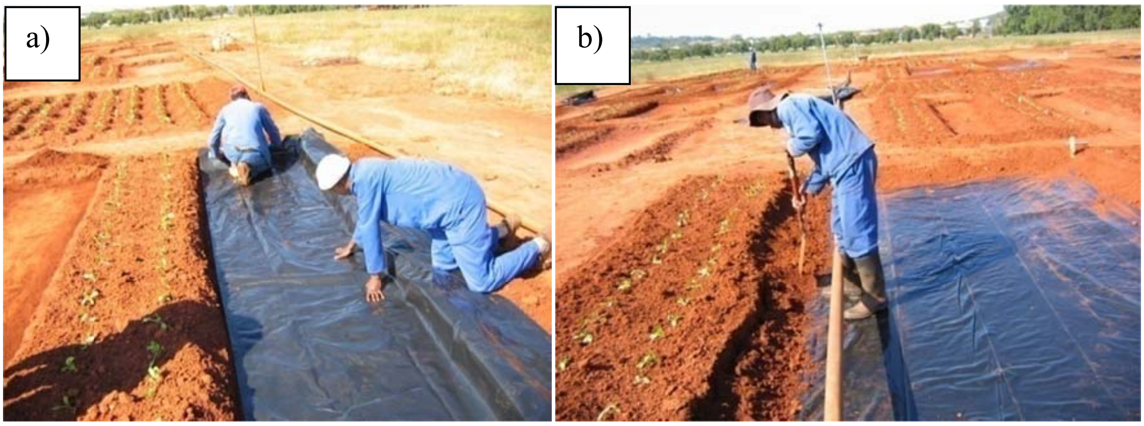


Figure 4.3: Plastic laying on the day after Swiss chard transplanting: a) in 1:1P and b) in 3:1P.

After transplanting, all seedlings vigorously established without delay as frequent sprinkler irrigation was applied (Figure 4.4). As reported earlier, the sprinkler irrigation was used to simulate rainfall during the off-season period. During the Swiss chard growing season, the application efficiency of this system was negatively affected by wind. This concern was more marked for the plots lying at the peripheries of the field. In an effort to overcome this problem, sprinkler irrigation was applied either in the morning or evening when the wind was relatively still. During the growing period, standard crop production practices were followed. No severe incidence of pests or disease was encountered during the growing season. Therefore, the Swiss chard leaves from all treatments were green and the ribs white for the entire growing season. The only incidence of *Cercospora* leaf spot occurred late in the season when the plants were growing old.

Seven Swiss chard harvests were carried out manually by carefully reaping the outer leaves and leaving the inner young leaves with the growing centre bud for the following harvest. Before harvesting, ten plants per plot were selected randomly for the sake of leaf area measurement and mineral content analysis. The selection was conducted on five opposite plants of the same ridge (cropped area). The leaves were then dried in an oven at 70°C for 48 hours after which they were weighed, and the dry mass determined. Thereafter, the dry samples were sent to the Soil and Plant Analysis Laboratory (Department of Plant Production and Soil Science, University of Pretoria) to be analyzed for mineral content.

Figure 4.4: Well established Swiss chard seedlings during the 2010/2011 growing season: a) CT plot in the foreground, b) TR plot, c) 1:1B plot and d) 2:1B plot in the foreground.

4.2.5 Data processing

All the data collected were statistically analyzed for randomized complete block design (RCBD) with three replicates using ANOVA for SAS to test the effect of the different tillage systems (RWH treatments) on Swiss chard growth, re-growth, biomass, yield, WU and WUE. Whenever the F-test was significant P (< 0.05), LSD values at that level was used to compare treatment means.

4.3 Results and discussion

4.3.1 Soil water deficit

Soil profile water deficits (SWDs) (up to a 100 cm soil depth) and the sprinkler irrigation/rainfall pattern during the crop growing season are illustrated in Figure 4.5. The increases and decreases in SWDs for the different treatments corresponded with sprinkler irrigation and/or rainfall events. CT showed the highest SWD values, followed by TR; while 3:1P had the lowest values, followed by 2:1P. In general, the situation of SWD values for all treatments is similar to the one that was mentioned in Section 3.3.1.

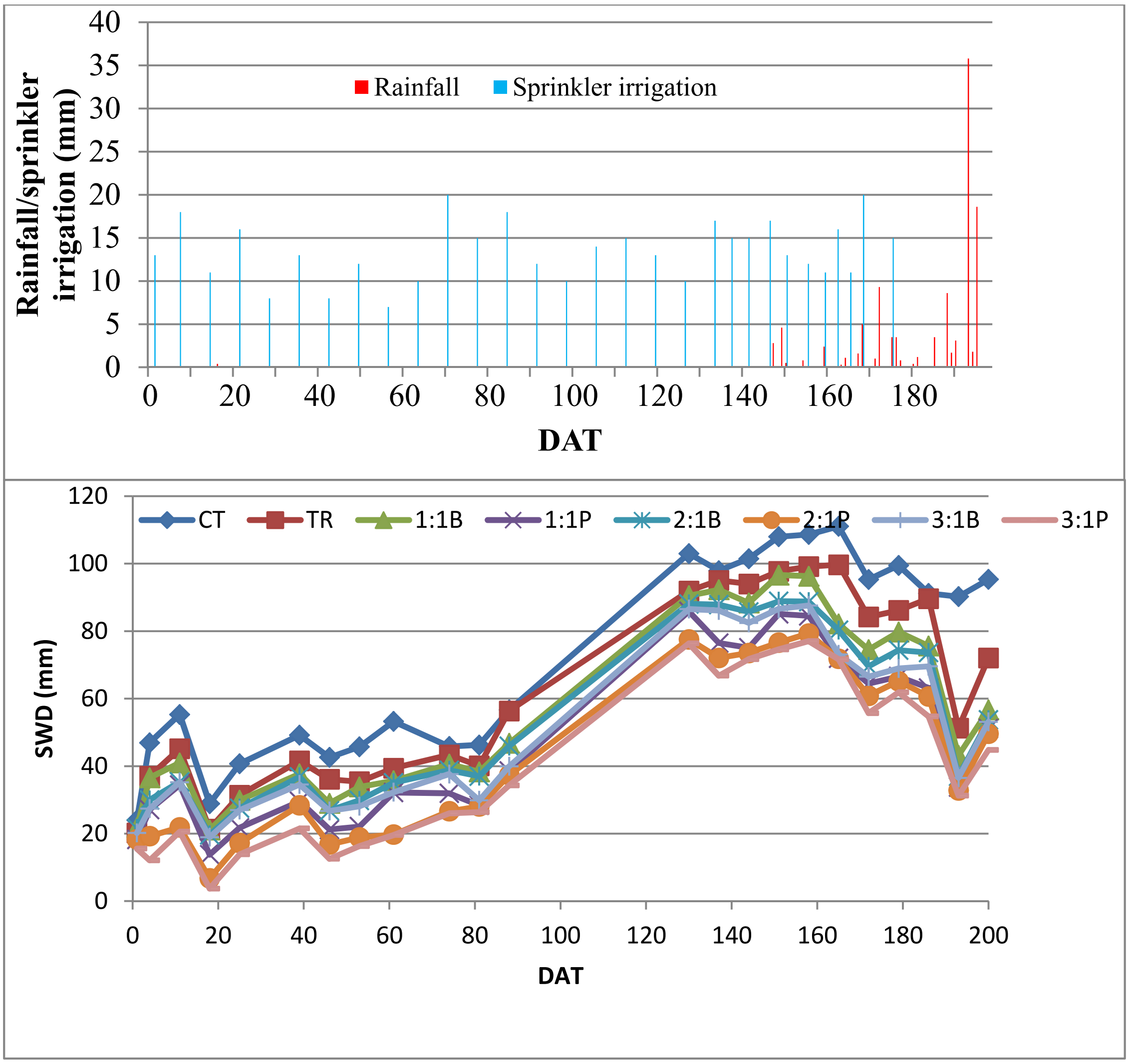


Figure 4.5: Soil water deficit (profile up to 100 cm, bottom)) for the different treatments, as well as the sprinkler irrigation and rainfall patterns (top) during the 2010/2011 Swiss chard growing season.

4.3.2 Plant height

The plant heights (cm) measured for the different treatments during the growing period are shown in Figure 4.6. The increases and decreases in the height values are the result of a growth/re-growth and harvesting system. Harvesting reduces dry matter of the plant while re-growth increases it systematically. In the beginning, all height values increased and followed the same increasing trend. This must have happened at the time the crop was sprinkled frequently (sprinkled after six days, despite low PET) to prevent it from wilting. Later in the season, when the crop was well established, the irrigation frequency was reduced (sprinkled after three days, despite high PET) to allow some stress and this resulted in separation of the treatment means. Figure 4.6 also indicates that from the middle of the growing season, values generally were higher than those from previous periods. This was the result of the fact that for the first harvest, the crop spent some time to establish; while for the following harvests, the crop grew from the crown of the well established plants. In addition, as it can be seen, there was a wide gap in change between consecutive height measurement values for the IRWH, especially from the middle up to the end of the growing season. This can partly be attributed to the trend in soil water deficit of the different treatments, especially under only rainfed conditions (Figure 4.5). In general, no significant difference among treatment means occurred, except for on one occasion in September, October and November (Figure 4.6, Appendix C – Table C1, C2 & C3). On these occasions as well as in the most cases of height measurements, the IRWH treatments showed higher values than TR and CT. It is evident that when the crop was sprinkled after an actually short interval (three days) or was subjected to rainwater only, the IRWH treatments benefited from the collected and stored runoff. Moreover, heights varied between 12 and 36 cm across the whole growing cycle. The lower limit was obtained in the beginning of the growing season, while the higher limit was obtained towards the end of the growing cycle.

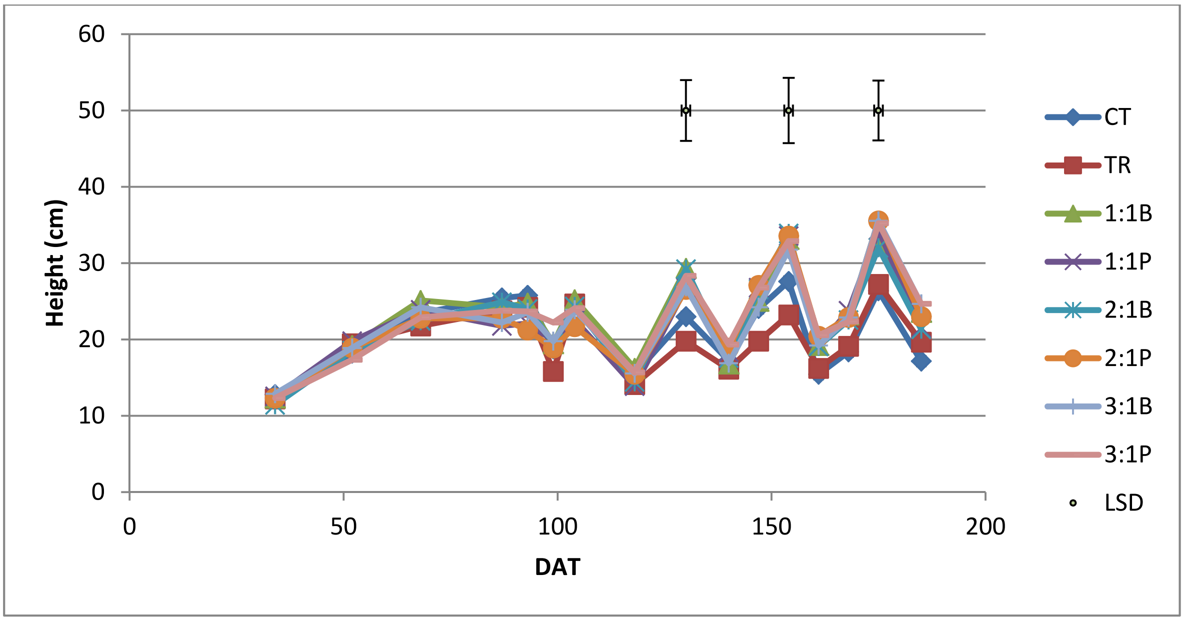


Figure 4.6: Swiss chard plant height for the different treatments during the 2010/2011 growing season. Vertical bars = LSD.

In general, water is the most important factor affecting plant growth and yield. Water stress is experienced by plants when there has been a loss of water from their tissues, a condition typical of periods of water shortage (Ehlers & Goss, 2003). Water stress can influence nearly all aspects of growth and development of plants (Roy, 1985). Water deficits experienced during the vegetative phase have been shown to reduce plant height (Doss *et al.*, 1974; Nielson & Nelson, 1998) and green leaf area (Ehlers & Goss, 2003), and this reduction has been related to dry matter yield (Doss *et al.*, 1974). Reduction in yield due to water stress is usually due to reduced LAI which causes reduced radiation interception. Rehman *et al.* (2009) also found that plant height was significantly affected by micro-watershed treatments. Micro-watersheds covered with plastic sheets produced maximum plant height, while minimum plant height was recorded in flat plots without micro-watersheds. This is in complete agreement with the height results observed during the present study. The increased plant height of maize under plastic covered ridges and furrow RWH systems was related to increased WUE, increased soil temperature (soil heat kept under the plastic sheet), more water and nutrients available for crop growth under these systems compared with bare fields (Li *et al.*, 2001). As revealed by Li *et al.* (2006), RWH treatments had a pronounced effect on the growth characteristics of *Caragana korshinskii*. The tree height, crown diameter, collar girth, above-ground biomass and WUE were significantly higher for the RWH treatments than the treatments with flat plots. The size of the MCs also had a considerable effect on growth parameter characteristics, yields and WUE of the tree. The better response of the growth of the tree to RWH treatments was largely due to improved soil water conditions through better utilization of runoff water. In RWH treatments, there was a deep penetration of water, such water would be available to the plant for a long time and would be less subjected to evaporation (Gupta, 1994), thus maintaining more favourable soil water conditions than the control.

4.3.3 Leaf chlorophyll content

Results for the SPAD values obtained during the Swiss chard growing season are presented in Figure 4.7. In the most cases, no significant differences among treatment means were obtained, except for on one occasion in October (Figure 4.7, Appendix C – Table C4). The data collected on the 1st October 2010 showed that there were significant differences among treatment means, with 2:1B, 3:1P and 3:1B having higher values (43, 41 and 41 SPAD, respectively), while CT had the lowest value (30 SPAD). In the early growing stages, all treatments showed an increasing trend in terms of SPAD values, which reflects the N and chlorophyll status of the crop for the different treatments. This was in conformity with the trend of the SWD (Figure 4.5). When the SWD was low, the crop was growing normally and this resulted in high SPAD values. This is a signal that the photosynthetic apparatus of the crop was functioning well. Later, during stress periods and when the age of the crop was advancing, SPAD values started to drop gradually. The most obvious decrease in SPAD values of the different treatments in Figure 4.7 was caused by the fact that the measurement was carried out when the crop was still very young and enough chlorophyll not yet accumulated.

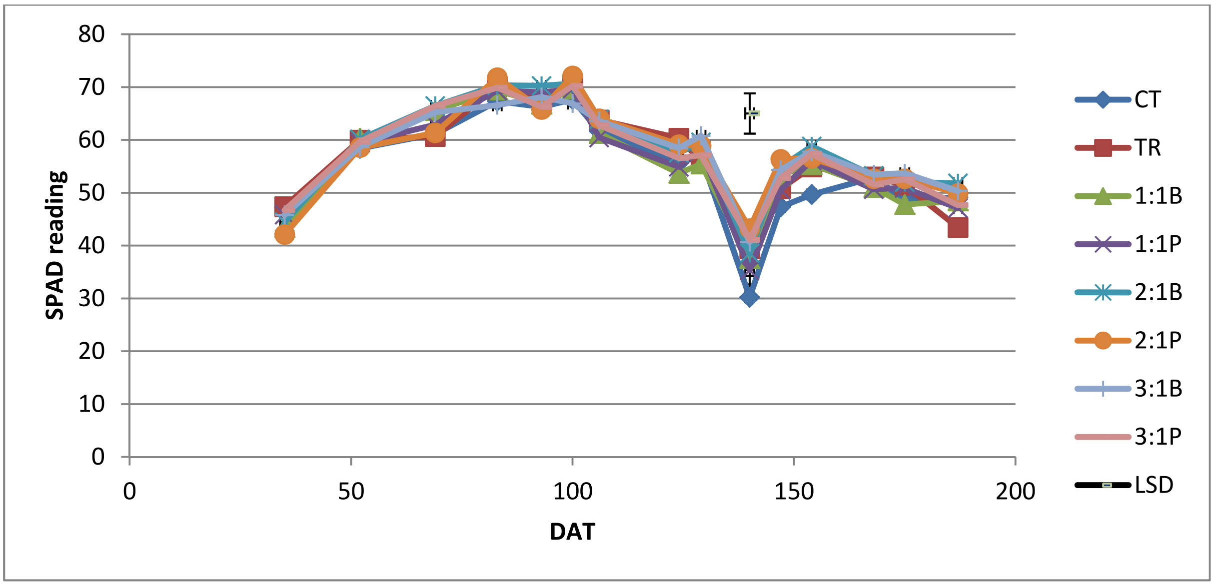


Figure 4.7: Swiss chard SPAD values for the different treatments during the 2010/2011 growing season. Vertical bars = LSD.

The correlation between SPAD readings and plant chlorophyll content has long been investigated. SHukla *et al.* (2004) and Spaner *et al.* (2005) have successfully used leaf chlorophyll concentrations estimated by SPAD meter for assessing the N status in wheat. According to the findings on peppermint (done in 1992 and 1993), leaf SPAD readings were correlated with stem nitrate levels at all sampling dates for both years of the study (Westcott & Wraith, 2003). It has also been established that nitrate concentration of petioles or stems has proven to be a reliable indicator of current N status in a wide variety of irrigated crops including potatoes (Williams & Meir, 1990; Westcott *et al.*, 1991), sugar beets (Ulrich &

Hills, 1990), vegetables (Geraldson & Tyler, 1990), and peppermint (Westcott *et al*., 1994). According to Gholizadeh *et al*., (2011), data collected at 55 and 80 days after transplanting (DAT) showed a range of 27 – 39 and 32 – 42 of SPAD readings, respectively. Higher SPAD readings at 80 compared to at 50 DAT were probably due to the effect of leaf thickness or specific leaf weight, accumulation of more N and chlorophyll within a fully expanded leaf. However, it was reported that the relationship between SPAD readings and N concentrations in maize leaves has been found to be dependent on hybrid, location, growth stage, and plant spacing (Schepers *et al*., 1992; Blackmer *et al*., 1993).

4.3.4 Leaf area index (LAI)

The LAI results provided by the plant canopy analyzer (LAI-2000 Licor) are illustrated in Figures 4.8 and 4.9. As in the case of height measurements, LAI values of the different treatments are characterized by increases and decreases, sometimes with a rapid change, especially in the beginning and the end of field measurements. It is evident that LAI decreased immediately after plant tops and leaves were cut and removed (Nassiri & Elgersma, 1998). In terms of the LAI values expressed on the total plot area, TR showed the highest results for the entire growing period; CT was always the runner-up. The results for the IRWH treatments showed that the ranking followed the same ascending order as the respective ratios. In other words, the lower the design ratio (example, 1:1), the higher the LAI value ranking. It can be noted that the number of plant population per plot played a prominent role in determining the LAI values. CT and TR had the highest plant population, followed by 1:1B and 1:1P which had intermediate values, while 3:1B and 3:1P had the lowest values. The high number of plants per plot in CT and TR resulted in high LAI values. Similarly, the LAI differences among the IRWH treatments were also the results of high number of rows of plants per plot (which was in inverse proportion with design ratio). However, the results in terms of LAI values expressed on the net area only showed that the IRWH treatments had higher results than TR and CT; and LAI values increased with increasing design ratios. The IRWH treatments with plastic mulch showed higher LAI values than those with uncovered runoff area. The ranking was as follows: 3:1 > 2:1 > 1:1 > TR/CT. This is because of the respective ranking in soil water deficit (runoff collected) for the different treatments (Figure 4.5).

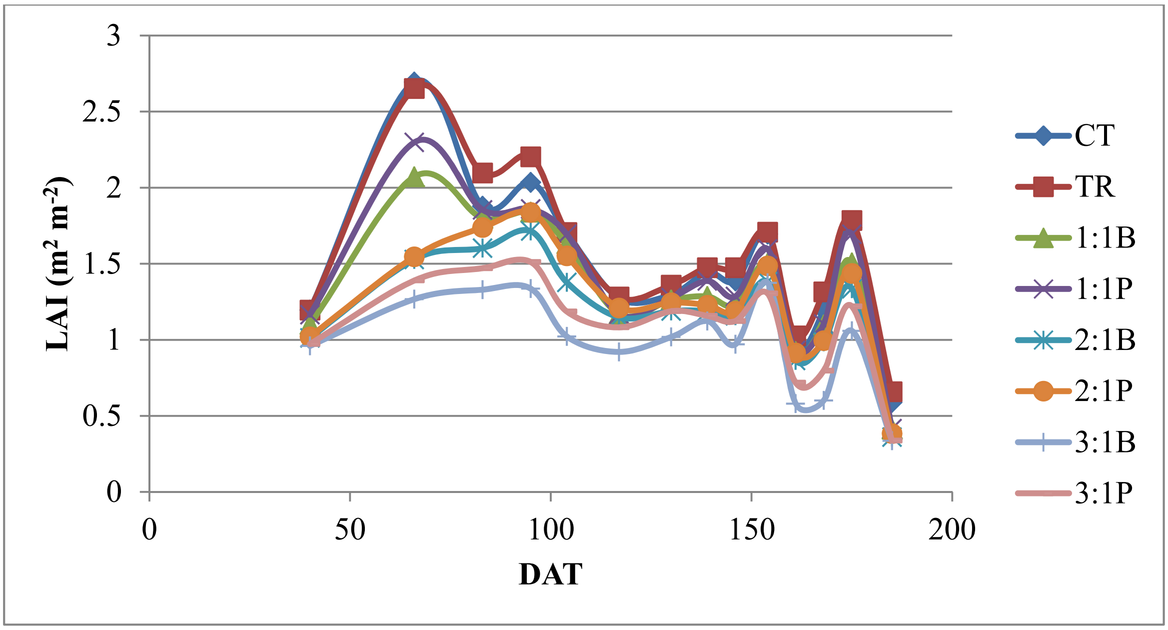


Figure 4.8: Swiss chard LAI for the different treatments (expressed on the total plot area) during the 2010/2011 growing season.

According to Khurana and McLaren (1982), the optimum LAIs for efficient photosynthesis of agricultural crops range from 4 to 5 m^2 m^{-2}. In reference with the work carried out on red beet (another crop of the Chenopodiaceae family) by Tei *et al.* (1996), a LAI value of 4.8 m^2 m^{-2} was found. In the course of the same investigation, the maximum LAI values for lettuce and onion were 12.7 and 3.2 m^2 m^{-2}, respectively. However, in this study, in terms of LAI expressed on the whole plot area, the highest LAI obtained was around 3 (TR and CT), which is much lower than all the figures afore-mentioned. The major reason for this discrepancy must be due to the method used to collect data. The plant canopy analyzer hardly gives values higher than 3 with vegetables. The relatively high LAI values were only obtained when only the results were expressed on a cropped area basis. In this regard, the highest LAI value for 3:1P was 6 m^2 m^{-2}. However, the LAI values obtained destructively ranged from 6 m^2 m^{-2} (3:1B) to 17 m^2 m^{-2} (TR) for results expressed relative to the total area, and 16 m^2 m^{-2} (CT) to 30 m^2 m^{-2} (3:1P) for results expressed on a net area basis (results not shown).

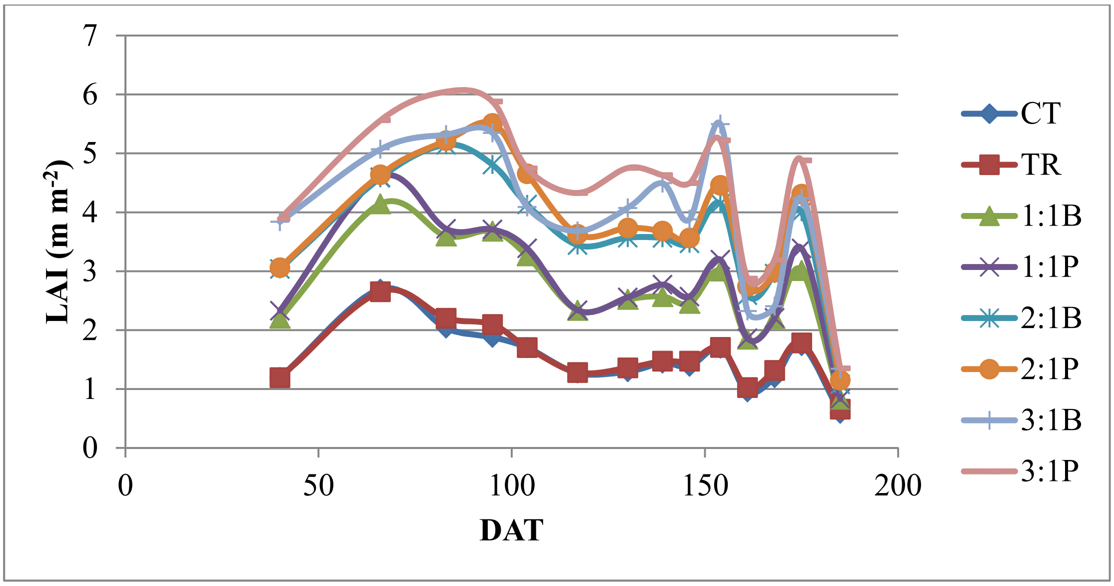


Figure 4.9: Swiss chard LAI for the different treatments (expressed on the cropped area only) during the 2010/2011 growing season.

4.3.5 PAR fractional interception (FI$_{PAR}$)

FI$_{PAR}$ values for the different treatments given by a ceptometer (Accupar model LP-80, Decagon Devices) are shown in Figure 4.10. The PAR measurements are used for the calculation of the fractional interception of solar radiation (FI$_{PAR}$). The order of FI$_{PAR}$ values is similar to that mentioned for LAI values. TR had the highest FI$_{PAR}$ followed by CT, while intermediate FI$_{PAR}$ values corresponded to 1:1B and 1:1P. The lowest FI$_{PAR}$ values were recorded for 3:1B and 3:1P. The reasons for this order of the FI$_{PAR}$ values are those mentioned for LAI. The number of rows (plants) per plot for CT and TR was the highest, followed by 1:1B and 1:1P, while 3:1B and 3:1P had the lowest plant population. However, the ranking was reversed if only the cropped area was taken into consideration, as shown in Figure 4.11. This was due to high runoff collected by the IRWH treatments, especially those with higher design ratios. It can also be noted that the exceptionally low FI$_{PAR}$ values were recorded when FI$_{PAR}$ measurements were conducted when the crop was still very young after the third and the fourth harvests, respectively. It was risky to take measurements on the windy or/and cloudy days. To compensate for this, measurements were conducted whenever the conditions allowed, including not long after harvest.

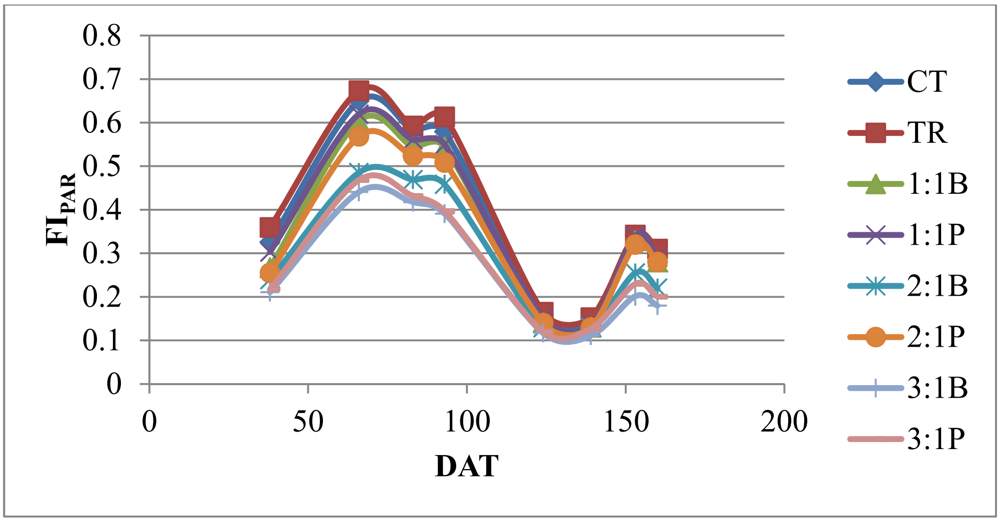


Figure 4.10: Swiss chard FI$_{PAR}$ for the different treatments (expressed on the total area) during the 2010/2011 growing season.

The fraction of radiation intercepted by a canopy is determined by canopy development and structure, and is mainly a function of LAI and extinction coefficient (Monteith, 1972). Canopy fractional skylight interception represents the fraction of direct and indirect solar radiation available to crops. In the case of horizontal planar interception encountered in agronomic crops, this can be quantified as the fraction of ground covered by the canopy (Annandale *et al*., 2004). The extent to which the crop canopy absorbs the available radiation depends not only upon the LAI but also upon the characteristics such as leaf angle and the canopy architecture (Russell *et al*., 1989; Guiducci *et al*., 1992). In addition, intercepted radiation is mostly influenced by the level of soil available water and to a lesser extent by other factors such as ambient conditions (Deblonde & Ledent, 2001). In this investigation, levels of water harvesting played a critical role in deciding the FI$_{PAR}$ values, especially with the results according to the net cropped area. The RWH treatments collected more water than CT, and this resulted in their higher FI$_{PAR}$ values as shown in Figure 4.11.

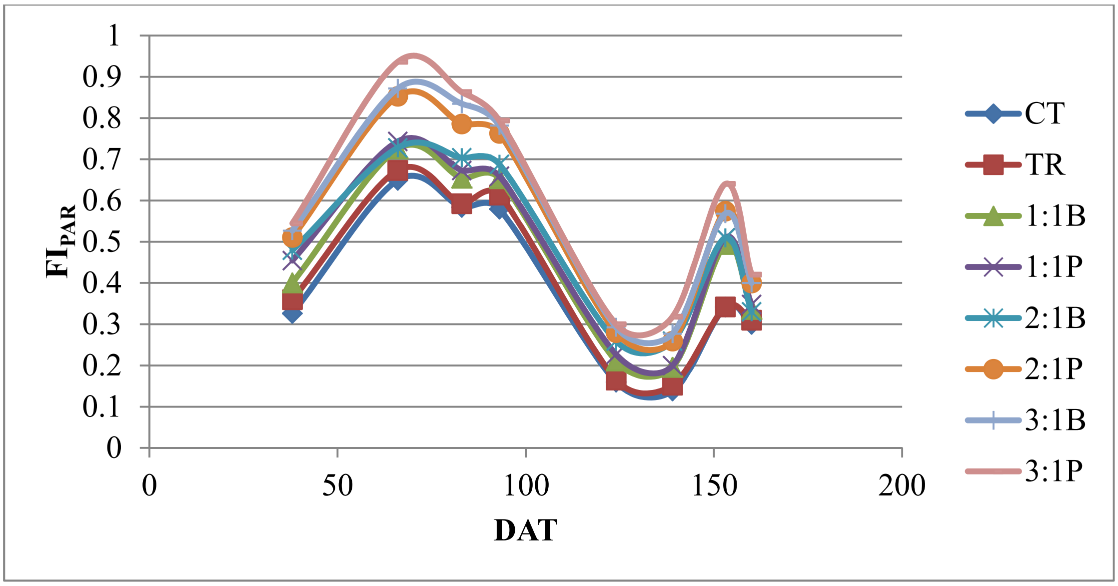


Figure 4.11: Swiss chard FI_{PAR} for the different treatments (expressed on the cropped area only) during the 2010/2011 growing season.

Studies have shown that there exists a linear relationship between dry matter and/or fresh leaf production and intercepted PAR in lettuce (Beccafichi *et al*., 2003; Tei *et al*., 2003; Caron *et al*. 2007). Thus, the dry matter yield of a crop, when other conditions are not limiting, is the product of the radiation absorbed by the leaf canopy, the mean radiation use efficiency (RUE), and the partitioning of this dry matter between the harvested parts and the rest of the plants (Charles-Edwards, 1982; Hay & Walker, 1989). Furthermore, the report of Wheeler *et al*. (1993) on lettuce and that of Kenter *et al*. (2006) on sugar beet confirmed that the total dry matter of these crops was nearly linearly related to the accumulated solar radiation and thermal time. For the present study, FI_{PAR} values, expressed on the total areas, varied between 0.12 and 0.69, the range with which the higher limit is close to the value of 0.68 found with red beet by Tei *et al*. (1996).

4.3.6 Leaf stomatal conductance and photosynthetic rate

Figure 4.12 illustrates the chard crop stomatal conductance results during the growing season. From the start to the middle of the growing period, the stomatal conductance results for the different treatments were close to each other and no significant differences occurred among treatment means. From the middle of the growing season on, however, differences became evident, with CT having the lowest values for the rest of the season. Moreover, CT showed the smallest gradient in fluctuations, compared to TR and the other treatments. This is also reflected in the fact that there were significant differences between CT and the other treatments (sometimes, differences between TR and IRWH was also significant) (Figure 4.12). As stated previously, in the beginning of the growing season, sprinkler irrigation was actually frequent in order to protect the young seedlings from cold stress. Moreover, PET was not high since it was in autumn. However, when the seedlings were completely established, the number of sprinkler irrigation actually decreased; and this resulted in noticeably lower stomatal conductance for CT compared to the other treatments. This can partly be attributed to the highest values in SWDs shown by this treatment during the growing season (Figure 4.5). It can be observed that TR showed highest values for the most of the growing season in the stark contrast with the soil water deficit situation. One reason for this seemingly paradoxical result is probably because soil water content readings and stomatal conductance data collection were not conducted the same day. Whenever data collection for stomatal conductance was taken not long after water application or rainfall, SWD for TR was low, as such, it is unquestionable that this treatment performed well in terms of stomatal conductance. Otherwise, TR SWD data should be controversial.

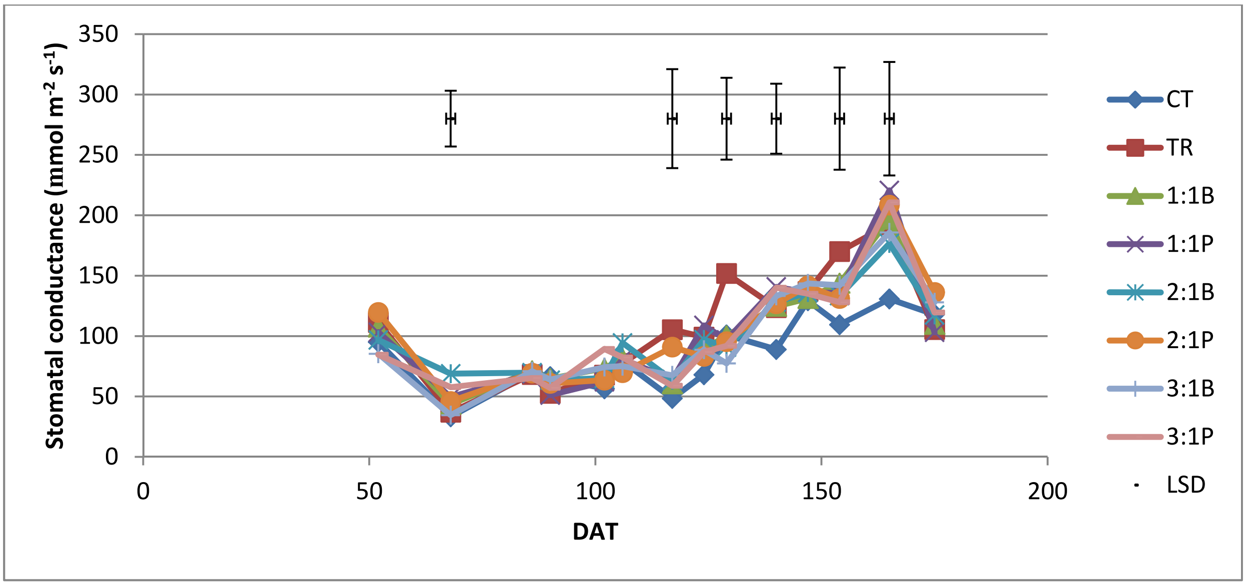


Figure 4.12: Swiss chard stomatal conductance for the different treatments during the 2010/2011 growing season.

Figure 4.13 displays the Swiss chard crop photosynthesis rate values for the different treatments in the middle of the growing period (15th July 2010). This data was collected when the crop was being watered very often, therefore, the values are close to each other. During this period of measurement, even the stomatal conductance results given by the porometer (Decagon Devices, Inc.) were very close to each other. It is also worthwhile to note that the data was collected only once during the crop cycle due to the unavailability of the operator of the LI 6400 photosynthesis device to take recurrent measurements. As can be observed in Figure 4.13, the photosynthetic rate of the treatment 3:1P was higher than the other treatments, followed by 2:1P and 1:1P. CT had the lowest value in terms of CO_2 assimilation, followed by TR and 1:1B. Thereby, although the photosynthesis measurement was taken only once (which is risky), the response was as expected – CT lowest (more stress – highest SWD) and 3:1P highest (less stress – lowest SWD) (Figure 4.5).

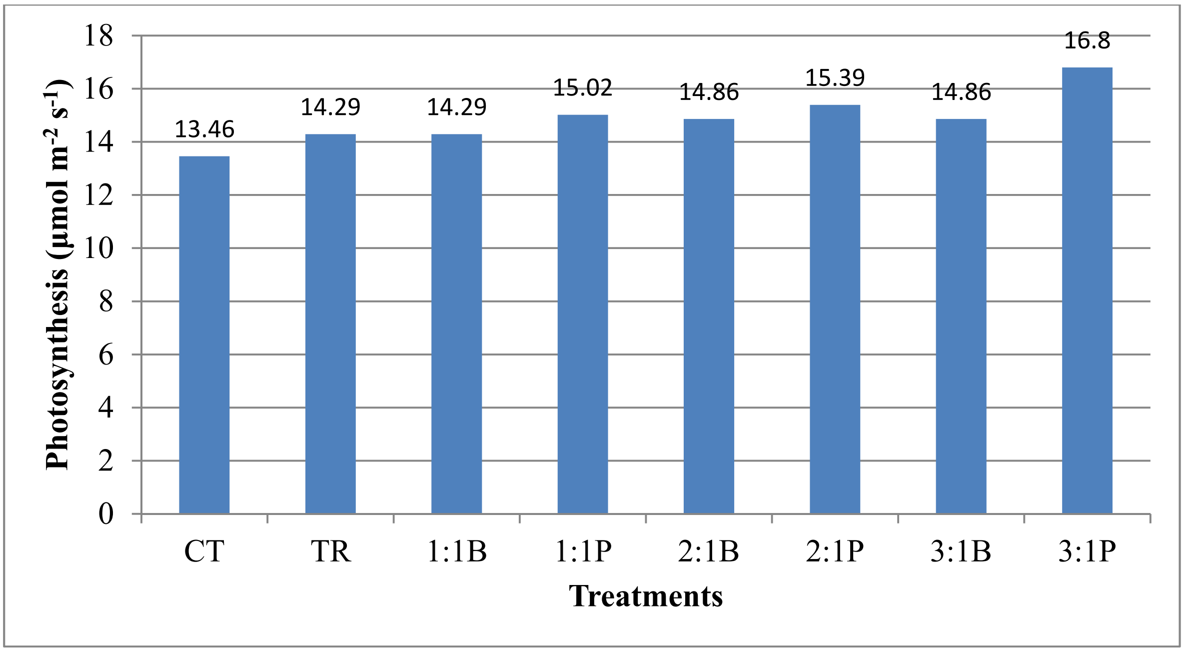


Figure 4.13: Swiss chard photosynthetic rates for the different treatments (15/07/2010).

Photosynthesis and stomatal conductance were often found to change proportionally to environmental factors and leaf age (Wong *et al.*, 1979; Schulze, 1986), and this is conducive to a fairly stable CO_2 concentration in the stomatal cavity (Wong *et al.*, 1979). There were some reviews showing variable effects of drought on the characteristics of gas exchange; and it was revealed that in some cases drought affects stomatal conductance and photosynthesis to a similar extent, while otherwise a larger relative effect on conductance and a decline in the internal CO_2 concentration were observed (Schulze & Hall, 1982; Schulze, 1986). However, Vos and Oyarzún (1987) have also observed a disproportional reduction in leaf photosynthesis and stomatal conductance during soil water depletion. It was reported that drought, in a short-term, effects on single leaf photosynthesis (stomata closure), while in a long-term, affects production (stomata closure, smaller LAI and faster senescence). The decline in photosynthesis resulting from water deficit can be due to a reduction in light interception as leaf expansion is reduced. It can also be attributed to a reduction in carbon fixation per unit leaf area as stomata close or as photo-oxidation damages the photosynthetic mechanism (Bruce *et al*., 2002). The results from an experiment carried out on different potato cultivars and irrigation regimes proved that a sizeable degree of variation in photosynthesis and stomatal conductance was obvious due to changing weather conditions and frequent irrigations (Steyn, 1997). During this experiment, in the dry treatments, the gradual fall and the rapid rise in photosynthesis due to frequent small irrigation amounts resulted in a great range of variation.

While the data on the drought sensitivity of gas exchange and photosynthesis for Swiss chard is lacking, there is evidence that as a vegetable crop, it is not an exception. For example, the results on red beet (Chenopodiaceae family) given by Tei *et al* (1996) substantiated this argument. They pointed out that drought stress significantly reduced taproot and leaf dry matter production of the red beet plant. The reduction in dry matter production was associated with changes in various parameters of photosynthesis, especially with the strong decline in gas exchange. The photosynthesis rates continuously decreased with increasing severity of stress. The reason for this downturn is the fact that drought persisted severely causing a decrease in stomatal conductance with reduced CO_2 diffusion into the leaf. However, Kirkham (1990) revealed that stomatal conductance reductions should not be taken as the main effect of severe water deficit on photosynthesis since non-stomatal factors also play a role. According to the literature, both stomatal and non-stomatal closure can take place only during severe and prolonged stress (Bloch *et al*., 2006). Lange *et al*. (1971) indicated that stomata might be sensitive to changes in environmental CO_2 concentration, and then appropriately open or close to balance internal CO_2 concentration. Other environmental and managerial factors are also able to make a substantial impact on photosynthesis (Aphalo & Jarvis, 1993). For example, each crop must be grown in its particular optimal cardinal temperatures, irradiance and nutrient levels and vapour deficits. High vapour pressure deficits tend to result in stomata closure (Lange *et al*., 1971).

4.3.7 Plant yields

Swiss chard is a biennial vegetable that can be harvested at staggered stages, with the first harvest taking place from 50 to 60 days after transplanting. However, this crop is mostly grown as an annual (the KwaZulu Natal Government, year unknown). In this study, Swiss chard seedlings were transplanted on the 14th May 2010 and the first harvest occurred on the 22nd July 2010 (Table 4.1 – 4.4), which is sixty nine days from the transplanting date. This delay can be partly explained by the cold harshness of the weather which made the growing conditions restrained. As a matter of fact, the crop was destined to grow in winter and so the transplanting was planned for autumn according to the South African calendar. Given the geographical position of the trial site (Hatfield, Pretoria), there is no rainfall during this period. In order to alleviate this lack of rain, rainfall was simulated with the help of a sprinkler irrigation system, but no rigorous irrigation scheduling management was exercised.

Total seven harvests were recorded for the entire Swiss chard growing season. The second harvest was conducted on the 16th August 2010, i.e. 23 days after the first harvest. The reason for this long period is still the cold weather. The third harvest took place on the 5th September 2010 (19 days after the second), and the fourth on the 27th September 2010 (20 days after the third). The fifth, sixth and seventh harvesting occurred on the 18th October 2010 (20 days after the fourth), 8th November 2010 (21 days after the fifth), and 29th November 2010 (21 days after the sixth), respectively. As can be seen from Table 4.1 – 4.4, the harvesting tempo stabilized at about three weeks after the third harvest.

Table 4.1: Swiss chard fresh mass yields (t ha^{-1}, total plot area).

Treatments	**22/7/10**	**16/8/10**	**5/9/10**	**27/9/10**	**18/10/10**	**8/11/10**	**29/11/10**	$\mathbf{Y_{T7}}$
	$\mathbf{Y_1}$	$\mathbf{Y_2}$	$\mathbf{Y_3}$	$\mathbf{Y_4}$	$\mathbf{Y_5}$	$\mathbf{Y_6}$	$\mathbf{Y_7}$	
CT	7.80a	7.80a	6.51a	5.65ab	7.54ab	6.14ab	5.52ab	46.96ab
TR	7.97a	8.26a	7.22a	7.09a	9.98a	8.55a	6.03a	55.10a
1:1B	4.32ab	3.92b	5.31a	5.01ab	5.96ab	5.85ab	5.52ab	35.89bc
1:1P	4.40ab	3.84b	5.55a	4.95ab	6.14ab	5.87ab	6.24a	36.99bc
2:1B	2.63b	2.54b	2.88b	3.30b	3.53b	4.32b	4.24ab	23.44cd
2:1P	3.27b	2.52b	2.87b	4.30ab	4.26b	3.80b	4.38ab	25.40cd
3:1B	1.99b	1.92b	2.65b	2.64b	2.78b	2.88b	3.31b	18.17e
3:1P	2.21b	1.97b	2.82b	2.97b	3.72b	3.27b	3.36b	20.32de
LSD (< 0.05)	4.16	2.03	2.06	3.33	4.96	3.88	2.37	15.93
CV (%)	33.38	17.17	16.00	25.75	31.34	26.51	17.06	16.87

Means followed by the same letter are not significantly different at P = 0.05. $Y_1 – Y_7$ = harvest 1 – harvest 7, and Y_{T7} = total (seasonal) yield.

Table 4.1 shows the fresh yields, expressed on the total area, achieved by the different Swiss chard harvests, as well as the dates on which they were carried out. From this table, it is evident that TR and CT produced more fresh yields than the other treatments throughout staggered harvests. This prevalence is more outstanding for harvests 1 and 2 when water was applied actually often to prevent the crop from wilting in winter. After seven harvests, aggregate yield for TR was 55.10 against 46.96 t ha^{-1} for CT (no significant difference was shown between the treatment means). Within the IRWH treatments, those with lower design ratios outperformed those with higher design ratios. There were significant differences between the treatment means, in terms of aggregate yields. Within the same design ratios, the treatments with plastic had higher yields than those with bare runoff areas. In most cases, no significant differences between the treatment means were showed. After harvest 7 accumulated yields were 35.89 and 36.99; 23.44 and 25.40; and 18.17 and 20.32 t ha^{-1} for 1:1B and 1:1P, 2:1B and 2:1P, and 3:1B and 3:1P, respectively. As was explained in Section 4.2.4, the plant population for CT and TR were the highest (more rows and therefore more plants per plot), followed by The IRWH treatments with smaller design ratios (1:1). For the IRWH treatments with higher design ratios (3:1), there were less rows and therefore less plants per plot. However, the plant population expressed relative to the net cropped area was almost the same for all treatments. In addition, in terms of dry mass amounts obtained for the different treatments (Table 4.2), the indication was that the trend was generally similar to that in Table 4.1.

Table 4.2: Swiss chard dry mass yields (t ha^{-1}, total plot area).

	22/7/10	**16/8/10**	**5/9/10**	**277/9/10**	**18/10/10**	**8/11/10**	**29/11/10**	
Treatments	**Y_1**	**Y_2**	**Y_3**	**Y_4**	**Y_5**	**Y_6**	**Y_7**	**Y_{T7}**
CT	1.01a	0.98a	0.54bc	0.64a	0.78ab	0.44bac	0.82a	5.21ab
TR	1.01a	0.92a	0.58ab	0.73a	1.13a	0.61bac	0.98a	5.96a
1:1B	0.51b	0.45b	0.68ab	0.65a	0.62b	0.67ab	0.62b	4.20bdc
1:1P	0.55b	0.42b	0.71a	0.74a	0.67ab	0.72a	0.74ab	4.55abc
2:1B	0.34b	0.30b	0.40cd	0.45a	0.45b	0.51bac	0.51b	2.96de
2:1P	0.40b	0.27b	0.42cd	0.54a	0.53b	0.47bac	0.52b	3.15de
3:1B	0.24b	0.23b	0.35d	0.42a	0.34b	0.34c	0.36b	2.28e
3:1P	0.27b	0.23b	0.35d	0.39a	0.43b	0.40bc	0.43b	2.50e
LSD (< 0.05)	0.45	0.23	0.16	0.37	0.47	0.32	0.53	1.37
CV (%)	28.58	17.12	10.82	22.62	25.95	21.30	16.06	14.72

Means followed by the same letter are not significantly different at P = 0.05. $Y_1 – Y_7$ = harvest1 – harvest 7, and Y_7 = total (seasonal) yield.

In terms of fresh yields expressed on the net cropped area only, the yields of CT and TR remained unchanged while the yields for the IRWH treatments were double for 1:1B and 1:1P, triple for 2:1B and 2:1P, and four-fold for 3:1B and 3:1P (Table 4.3). Significant differences among the treatment means were shown between CT and the other treatments. For this latter, another significant difference among the treatment means occurred between 3:1P and the other treatments. As stated previously, the IRWH treatments, especially those with higher design ratios, collected more water and subsequently gave higher yields per plant than CT(and slightly higher than TR). As a result, the yields relative to the net cropped area were higher for the IRWH treatments than CT and TR. In addition, the trend of the dry mass yields for the different treatments (Table 4.4) was similar to that of the fresh yields (Table 4.3).

Table 4.3: Swiss chard fresh mass yields (t ha^{-1}, cropped area).

Treatments	22/7/10	16/8/10	5/9/10	27/9/10	18/10/10	8/11/10	29/11/10	
	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7	Y_{T7}
CT	7.80a	7.80a	6.51b	5.65b	7.54b	6.14b	5.52c	46.96b
TR	7.97a	8.26a	7.22ab	7.09ab	9.98ab	8.55ab	6.04bc	55.10ab
1:1B	8.64a	7.84a	10.62ab	10.02ab	11.92ab	11.70a	11.04abc	71.78ab
1:1P	8.80a	7.68a	11.10a	9.90ab	12.28ab	11.74a	12.48ab	73.98ab
2:1B	7.89a	7.62a	8.64ab	9.90cb	10.59ab	12.96a	12.72a	70.32ab
2:1P	9.81a	7.56a	8.61ab	12.90a	12.78ab	11.40a	13.14a	76.20a
3:1B	7.96a	7.68a	10.60ab	10.56ab	11.12ab	11.52a	13.24a	72.68ab
3:1P	8.84a	7.88a	11.28a	11.88ab	14.88a	13.08a	13.44a	81.28a
LSD (< 0.05)	NS	NS	4.52	7.16	6.93	5.13	6.59	27.11
CV (%)	34.44	13.20	16.83	25.54	21.12	16.36	20.90	13.73

Means followed by the same letter are not significantly different at $P = 0.05$. $Y_1 – Y_7$ = harvest1 – harvest 7, and Y_7 = total (seasonal) yield.

According to the KwaZulu Natal Government (year unknown), the Swiss chard crop can be marketed from about 2 months, when the leaves have reached a full size; and the outer leaves are successfully harvested as soon as they are large enough. Yields of 40 t ha^{-1} or more are possible, but usually yields vary between 20 and 30 t ha^{-1}. In general, these amounts appear lower than the total yields harvested in the current study. The length of harvesting intervals and the total number of harvests might also have played a crucial role in determining the total tonnage harvested.

With regard to vegetable cultivation, Fu (2008) separated vegetables that are harvested as the whole plant from the ones for which outer leaves are harvested and the growing centre bud and surrounding young leaves are left to grow for the next harvest. For the first category, growers maintain a supply of vegetables by a repeat of sowing, growing and harvesting crops; while for the second group, plants are reaped above the growing point when they are ready to harvest. For this latter, new leaves emerge from the growing point in the next two or three days. Outer leaf reaping can be repeated when the leaves are ready, whilst the growing point is left to generate new leaves, and the cycles go on and on several times, given decent environmental conditions. According to the Department of Agriculture, Forestry and Fisheries (South Africa, year of publication not mentioned), the picking of Swiss chard leaves can carry on for several months until the leaf spot disease becomes severe or leaves turn tough and stringy. According to Myers (1991), the reaping can go up to one year. In the current study, the reaping and re-growth sustained over seven months and stopped when black spots started to appear. As was documented, this method of harvest and growing can be utilized to continuously produce leaves of lettuce and Chinese cabbage (Fogg, 1983; Takagaki *et al*., 2003). The reaping and re-growth method has the potential to provide higher yields on less area with earlier cropping of lettuce and Chinese cabbage. The method proved to save costs and labour; therefore, increasing benefits. This is also applicable to Swiss chard production since it has the potential for the reaping and re-growth production method.

Several environmental and management factors can affect plant re-growth. The influence on re-growth of temperature, radiation interception, water stress and nutrition falls in the environmental category of factors (Fu, 2008). The effects on re-growth of plant size/plant remainder and reaping intervals are classified under the management category of factors. In this investigation, however, given that all treatments were treated alike except for the levels of water harvested, the considerations were focused on the water effect on re-growth and yield. According to the literature, the yield components for leaf and shoot salad vegetables such as lettuce, Chinese cabbage, rocket, etc., are the green leaves and/or shoots. Any reduction in green leaves and/or shoots leads to less economic yield. In conformity with investigations on the effect of water stress on the yield of American lettuce led by Coelho *et al*. (2005), there was a correlation between water stress and reduction in crop marketable yields. It was reported that water stress seemed likely to affect the re-growth of salad vegetables and reduce the recovery of green leaves and/or shoots after cutting. Water stress has been shown to affect re-growth of plants. Many studies conducted on forage grasses have shown the re-growth reduction positively correlated with water stress or drought incidence (Sheaffer *et al*., 1992; Volaire, 1994). In this study, the IRWH treatments, notably those with plastic mulch, gave higher yield per plot due to more water collected (lower soil water deficit), but spacing was too wide (too few plants/area) to be compensated.

Table 4.4: Swiss chard dry mass yields (t ha^{-1}, cropped area).

Treatments	**22/7/10**	**16/8/10**	**5/9/10**	**27/9/10**	**18/10/10**	**8/11/10**	**29/11/10**	**Y_{T7}**
	Y_1	**Y_2**	**Y_3**	**Y_4**	**Y_5**	**Y_6**	**Y_7**	
CT	1.01a	0.98a	0.54b	0.64b	0.78b	0.44b	0.82b	5.21c
TR	1.01a	0.92a	0.58b	0.73ab	1.13b	0.61b	0.98ab	5.96bc
1:1B	1.02a	0.90a	1.36a	1.30ab	1.24ab	1.34a	1.24ab	8.40ab
1:1P	1.10a	0.84a	1.42a	1.48ab	1.34ab	1.44a	1.48ab	9.10ab
2:1B	1.02a	0.90a	1.20a	1.35ab	1.35ab	1.53a	1.53ab	8.88ab
2:1P	1.2a	0.81a	1.26a	1.62ab	1.59ab	1.41a	1.56ab	9.45ab
3:1B	0.96a	0.92a	1.40a	1.68a	1.36ab	1.36a	1.44ab	9.12ab
3:1P	1.08a	0.92a	1.40a	1.56ab	1.72a	1.60a	1.72a	10.00a
LSD (< 0.05)	NS	NS	0.37	1.01	0.97	0.40	1.44	2.44
CV (%)	29.86	12.26	11.17	27.28	24.37	11.25	17.70	12.12

Means followed by the same letter are not significantly different at P = 0.05. $Y_1 – Y_7$ = harvest1 – harvest 7, and Y_7 = total (seasonal) yield.

4.3.8 Plant water use (WU) and water use efficiency (WUE)

Table 4.5 shows rainfall (R, mm), irrigation depth (I, mm), change in soil water storage (ΔS, mm), T (mm), soil E (mm), total ET (mm), total yields (total plot area, kg ha^{-1}), WUE (total plot area, kg ha^{-1}mm^{-1}), total yields (cropped area, kg ha^{-1}) and WUE (cropped area, kg ha^{-1}mm^{-1}). As it can be seen, ΔS, T, E and total ET of Swiss chard varied with the different treatments. In terms of ΔS and T, CT showed the lowest values and was followed by TR and 1:1B. However, in respect of E, CT and TR had the highest values, followed by the IRWH treatments with higher design ratios (3:1); while 1:1P showed the lowest value. As it can be seen from Table 3.6, ETs for 3:1P, 3:1B, TR and CT were higher than the other treatments. For the former two, high ET resulted from relatively high T and E; while for the latter two, high ET was mostly given by high E. CT presented the lowest ΔS and T values and high E value because it was a conventional plot with no runoff harvesting structures. As the most of the growing season was in winter, CT and TR performed similarly in terms of E. Moreover, the IRWH treatments presented high values in terms of ΔS and T because they were able to collect and store more water than CT and TR. In contrast, the SWDs of the IRWH treatments were lower than the other treatments (Figure 4.5).

Table 4.5 also shows the WUE results of the different treatments expressed on both the total plot and cropped area, and which exactly followed the similar trend as in the case of yields. However, with regard to WUE expressed relative to the net cropped area only, no significant difference between treatment means was shown for all IRWH treatments. Water use efficiency (WUE) represents the relation between total harvestable yield or dry matter produced and the quantity of water consumed (Yuan *et al*., 2003; Onder *et al*., 2005; Erdem *et al*., 2006, Zhang *et al*., 2008). During this study, both sprinkler irrigation and rainwater were used as means of water source and, therefore, WUE include both parameters.

The crop water requirement stresses plant T and soil E usually collectively referred to as ET; and it is the amount of water to satisfy the water requirements of a specific crop for the whole growing season (Thornthwaite, 1948; Anschütz *et al*., 2003). De Wit (1958) maintained that only the T fraction of ET directly influences crop production. An individual agricultural crop is characterized by a specific daily or seasonal water ET, and for a given crop, WU is versatile mostly following climatic conditions, the length of the growing season and the crop growth stages (Anschütz *et al*., 2003). The relationship between crop production and irrigation also depends on the salinity of the soil and irrigation water, the uniformity of the irrigation applications, the spatial variability of the soil physical properties (e.g., weed and pest control, fertility, plant population, row spacing and planting date) (Hexem & Heady, 1978; Vaux & Puitt, 1983). In the current case, it was revealed that the higher the RWH potential of a MC (3:1), the higher the soil available water and thus the higher the ET. However, the treatments with lower design ratios (1:1 and 2:1) showed relatively low ET most probably due to their nature (small MC) and the winter (cold) growing season.

Water deficits at critical crop development stages have been reported to adversely affect crop yields (Hagan *et al*., 1959). The effects of water deficits and/or irrigation additions at specific crop growth stages were compiled by Salter and Goode (1967) for many types of crops. In general, crop water deficits during floral initiations or anthesis have been reported to the greatest effects on crop economic or grain yields through reductions in seed or grain numbers, while water deficits after anthesis through grain filling generally reduce seed or grain mass. Doorenbos and Kassam (1979) provided summary information regarding effects of critical periods of water deficits on crop production. In this regard, no critical stages were mentioned for sugar beet which is related to Swiss chard. It was only hinted that root production and flowering phases should be crucial.

Although no rainwater literature for Swiss chard was found, principles can be explained with examples of other crops. Welderufael *et al*. (2008) pointed out that the average maize yield at Melkassa for 16 years with the conventional tillage was 2 t ha^{-1}. The average water productivity for this yield, expressed in terms of water used for ET was estimated to be 6.5 kg ha^{-1} mm^{-1} (Weldelrufael, 2006). Using IRWH, since runoff is reduced to zero, an increased yield can be expected because more water is available for ET. This assertion was corroborated by Hensley *et al.* (2000) and Botha *et al.* (2007) for field experiments comparing the IRWH and the conventional production techniques with maize on the Glen Bonheim ecotope.

Table 4.5: R, I, ΔS, T, E, ET (all in mm), yields (total plot and cropped area, kg ha^{-1}) and WUEs (total plot and cropped areas, kg ha^{-1} mm^{-1}) for the 2010/2011 growing season.

Treatments	**R (mm)**	**I (mm)**	**(ΔS) (mm)**	**T (mm)**	**E (mm)**	**Total ET (mm)**	**Yield (kg ha^{-1}) (total plot area)**	**WUE (kg ha^{-1} mm^{-1}) (total plot area)**	**Yield (kg ha^{-1}) (cropped area)**	**WUE (kg ha^{-1} mm^{-1}) (cropped area)**
CT	485.00	119.10	13.37b	178.00	398.00	576.00	46960ab	81.53ab	46960b	81.53b
TR	485.00	119.10	23.88b	187.00	398.00	585.00	55100a	94.19a	55100ab	94.19ab
1:1B	485.00	119.10	24.93b	188.60	241.00	429.60	35890bc	83.54ab	71780ab	167.09a
1:1P	485.00	119.10	31.33b	201.78	237.69	439.47	36990bc	84.17ab	73980ab	168.34a
2:1B	485.00	119.10	28.05b	214.90	305.20	520.10	23440cd	45.07bc	70320ab	135.20a
2:1P	485.00	119.10	48.36b	232.70	280.80	513.50	25400cd	49.46bc	76200a	148.39a
3:1B	485.00	119.10	29.61b	248.04	341.64	589.68	18170e	30.81c	72680ab	123.25a
3:1P	485.00	119.10	89.76a	266.42	325.71	592.13	20320de	34.32c	81280a	137.27a
LSD (< 0.05)	—	—	42.64	—	—	—	15.93	26.42	27.11	45.03
CV (%)	—	—	40.92	—	—	—	16.87	17.99	13.73	14.50

Means followed by the same letter are not significantly different at P = 0.05.

According to Viets (1962), crop productivity is strongly influenced by nutrition and water availability. Viets (1962) investigated these interactions in terms of WUE for crops with unlimited water supplies. When water supply to a crop is fixed, any management factor that increases production, such as fertilizers, weed and disease control, planting density and geometry will increase WUE. According to the report of Omran & Wanas (2007) on the effect of the compost and its application position on spinach WUE, it was evident that the compost applied to the entire profile achieved the highest effect on increasing WUE followed by subsurface and surface applications, respectively, irrespective of the type of the compost involved. The decrease in ET, the increase in WUE, and about 13% water saving on average were associated with compost application regardless of the compost type or application position. According to Onder *et al*. (2005), the potato seasonal ET changed between 226 and 473 mm in 2000 and between 166 and 391 mm in 2002. The potato seasonal ET values increased with the climatic factors and the length of the growing period. However, lower ET values obtained in 2002 were possibly due to the lower temperature during the growing season. The mean IWUE varied between 102.5 and 309.0 for surface drip irrigation treatment, and between 99.1 and 265.7 kg ha^{-1} mm^{-1} for subsurface drip irrigation treatment; while the mean total WUE fluctuated between 66.6 and 106.4 for surface drip irrigation treatment, and between 65.7 and 114.3 kg ha^{-1} mm^{-1} for subsurface drip irrigation treatment. The authors concluded that although there were no significant difference between these two drip irrigation methods in terms of yield and WUE, the surface drip irrigation has more advantages over the subsurface drip irrigation because this latter involves both replacement difficulties and high system cost. In the course of this experiment, ET varied between 430 and 592 mm and WUE fluctuated in the range of 30.81 – 94.19 kg ha^{-1} mm^{-1} on the total plot area; and 81.53 – 168.34 kg ha^{-1} mm^{-1}, on the net cropped area. The length of the growing season and the number of harvests can partially explain the higher values in terms of ET and WUE obtained during our investigation.

Shangguan *et al*. (2002) investigated the effect of RWH on crop growth, yield and WUE. The experimental results of applying the harvested runoff to pepper crop grown in the plastic greenhouse showed that the pepper crop yield increased with irrigation amount. The linear regression model for the pepper yield and irrigation amount indicated that the pepper yield increased by 8.57 kg for each increase in water supply of 1 mm. Moreover, the stored rainwater harvested from the plastic greenhouse surfaces was used in the greenhouse in winter and spring, producing benefits of about $US5 per cubic meter of rainwater. WUE was higher in 2004 than in 2002 and 2003; and this may be due to less water collected by the pepper crop in the dry season of 2004. Zhao *et al*. (1997) reported that WUE of *Caragana korshinskii* decreased with the amount of water supply, and therefore that the linear relationship between WUE and the amount of water supplied was negative. Good growth of *Caragana korshinskii* was partly attributed to the late season runoff retention in 2003, and higher above-ground biomass for the large catchments was attributed to the higher soil water storage in the soil profile.

4.3.9 Plant mineral content

The crop samples were taken to the Laboratory of the Department of Plant Production and Soil Science of the University of Pretoria for analysis in order to determine the total nutrient content. Mineral concentration for each treatment for Block I is illustrated on Table 4.6 (the mineral analysis was only conducted on the samples from Block I, and therefore, no statistical tests were performed). In most cases, CT had the lowest nutrient concentration, except for K. 3:1P had the highest nutrient content for both N and P (3.85 and 0.56 %, respectively). The IRWH treatments took turn to give the highest nutrient content as: 1:1P for Ca, 3:1B for K and S, 1:1B for Mg, and 2:1B for Fe. An exception to this was 2:1P but its results were in the first three, in general. In essence, it can be noted that the IRWH treatments did well compared to TR which, in turn, was better than CT, in general. This denotes the crucial role played by the soil water content for each treatment. The investigation of Nishihara *et al*. (2001) on spinach (another vegetable belonging to the Chenopodiaceae family) monitored and controlled by the matric head (water content) span, revealed that the treatment with adequate water content range resulted in spinach leaves which improved quality and quantity and more commercially desirable and valuable product.

Table 4.6: Swiss chard mineral content for block I (BI).

Treatments	**Minerals**						
	(%)						**(mg 100 g^{-1})**
	N	**P**	**Ca**	**K**	**Mg**	**S**	**Fe**
CT	2.90	0.04	0.77	1.84	0.83	0.16	42
TR	2.94	0.38	1.12	1.79	1.77	0.40	265
1:1B	3.31	0.40	1.37	1.78	2.35	0.39	213
1:1P	3.33	0.37	1.58	2.01	2.02	0.39	190
2:1B	3.38	0.40	1.32	1.68	2.06	0.39	569
2:1P	3.16	0.44	1.44	1.96	1.99	0.50	351
3:1B	3.37	0.45	1.12	2.43	2.15	0.55	317
3:1P	3.85	0.56	1.43	1.50	2.30	0.50	244

4.4 Conclusions and recommendations

A reaping and re-growth system was applied to the Swiss chard crop, which resulted in seven harvests. The results expressed on the net cropped areas from the current trial undoubtedly showed that RWH has the potential to optimize rainwater utilization by increasing soil water availability, improving crop growth, yield and WUE. This shows that RWH technique has the potential to ensure food security in dryland areas if land is not limiting. Therefore, the part of the hypothesis 4 related to yield and WUE was accepted. However, the use of the technique should also consider the new technologies and recommendations as those mentioned in Section 3.4 of Chapter 3. Nevertheless, the outcomes expressed per total area basis showed that the CT, TR and 1:1 treatments performed better than 2:1 and 3:1. This means that for areas with long-term rainfall and limiting land resource, normal rainfed agriculture can be the best option. Therefore, the part of the hypothesis 3 related to yield and WUE was partly accepted and hypothesis 4 fully accepted.

The choice of an RWH or IRWH technique or design ratio must be dictated by local conditions. Where annual rainfall is fairly high and land is limiting, TR and the 1:1 design ratio are better considerations. On the other hand, where annual rainfall is low and land is not limiting, higher design ratios can be implemented. The status of the surface of a runoff producing area (RPA) must be adjusted according to financial affordability. Accordingly, where financial means are lacking, the RPA surface can be treated with cost effective manipulations (for example, compacting and smoothing); while in contrast, costlier surface treatments can be adopted (for example, plastic sheeting). However, the present study showed that plastic mulch is not recommended. Moreover, in an effort to conceive a judicious and accurate design ratio, more rainfall intensity data and a 2D SWB model are needed (the model accounts for wetting fronts in all directions; therefore, potential crop growth, FI_{PAR} and soil water use should be predicted with some more accuracy). These recommendations can be highly valuable tools in the conception and implementation of RWH projects, particularly in present-day periods where the world is confronted with the issues of global warming, water scarcity, an exploding population and food insecurity.

RWH is a multidisciplinary topic since it involves social, economic, political, scientific, financial and other arenas. Therefore, all these stakeholders must get included in deciding the suitability and feasibility of an RWH system. Moreover, water and land management as well as their ownership legislations are to be reconsidered so that all concerns and conflicts linked to RWH are addressed. In the educational sphere, an RWH discipline should be introduced in school programmes. Finally, in order to suit RWH technology to the framework of the United Nations (UN) millennium development goals (MDGs) of aiming to halve hunger by 2015, specific crops should be prioritized. Swiss chard is one of the vegetables that can be grown in battling malnourishment in developing countries. Therefore, associating the cultivation of this vegetable with RWH can greatly contribute to the UN aspirations.

CHAPTER 5

ANALYSIS OF LONG-TERM RAINFALL AND SEASONAL RAINFALL AND RUNOFF AT THE HATFIELD EXPERIMENTAL FARM

5.1 Introduction

Although arid and semi-arid environments of sub-Saharan Africa are characterized by poorly distributed rainfall, crop production is often not necessarily affected by absolute water scarcity, but by recurring dry spells. According to Aghajani (2007), drought mitigation can be planned by understanding seasonal rainfall behaviour. Dry spell analysis is important in estimating the probability of intra-seasonal drought upon which management practices can be adjusted accordingly (Tesfaye & Walker, 2004; Kumar & Rao, 2005). It is of prime importance to know how long a wet spell is likely to persist, and to learn about the probabilities of experiencing dry spells of various durations at critical times during the growing season (Dennet, 1987; Sivakumar, 1992). Furthermore, even during the course of high seasonal rainfall, if the interval between consecutive rain events is too long it may cause total pasture and crop failure (Tilahun, 2006; Araya, 2005).

In arid and semi-arid regions where severe crust formation and low infiltration typically occur, crop productivity remains low due to less than optimal rainfall characteristics, inadequate land conditions and lack of proper management of these resources (Mwenge-Kahinda *et al.*, 2005). Sustainable rainwater harvesting (RWH) based on the collection of rainfall runoff from a prepared catchment surface and the storage thereof in the adjacent crop area, was found to be successful for crop yield improvement and tree establishment in these areas (Bruins *et al.*, 1986; Reij *et al.*, 1988). Moreover, RWH systems, especially micro-catchment rainwater harvesting (MCRWH) are particularly useful in holding runoff and halting soil erosion where high rainfall intensity is pronounced. In order to increase runoff efficiency and decrease sediment loss, numerous RWH surface treatments (catchment ability) have been investigated in many arid and semi-arid areas of the world (Dutt *et al.*, 1981; Evett & Dutt, 1985). However, understanding the feasibility of a RWH system construction requires rainfall analysis and knowledge about prevailing rainfall patterns (Dennet, 1987; Rappold, 2005).

The purpose of this chapter was to study rainfall distribution and to investigate how factors such as runoff plot size, the status of runoff areas, as well as rainfall event characteristics can affect runoff, runoff efficiency and soil loss during the 2009/2010 and 2010/2011 growing seasons at the Hatfield Experimental Farm. The runoff information provided by this study was used to estimate runoff amounts with different runoff models in Chapter 6.

5.2 Materials and methods

5.2.1 Characterisation and analysis of the long-term (15 years) summer rainfall data (October – May) at the Hatfield Experimental Farm (1995/1996 – 2009/2010)

Long-term (15-year: 1995/1996 – 2009/2010) weather data during the rainy seasons were obtained from the Weather Stations at the Hatfield Experimental Farm and the National Weather Service. The former is an automatic station, while the latter consists of both automatic and manual weather stations. Daily data were used to calculate monthly and annual data.

A. Characterisation of the long-term growing period

In this study, the length of the growing period was defined according to FAO (1978), as the period of the year (in days) when rainfall (R) amounts exceed half the potential evapotranspiration (PET/2); and unusual onsets or cessations to the rainy season were ignored. As such, the entire October – May period was considered regardless of possible variability. A normal growing period is characterised by a dry period, a moist period (also called intermediate period) and a wet (or humid period). The growing period is computed on a simple water balance model basis, by comparing monthly water availability with monthly crop water demand (R with PET). However, due to the lack of crop factor estimates and thus PET calculation, crop reference evapotranspiration (ETo) was adopted during the course of this investigation. ETo was calculated using the weather data from the nearby Roodplaat Weather Station for a 30-year period (1961 – 1990). The long-term rainfall and ETo data were also used to calculate the aridity index (AI) of the ecotope. The long-term AI was calculated as the ratio of the mean monthly R and the mean monthly ETo , i.e. R/ ETo according to UNESCO (1979). It is noteworthy to mention that the AI indices for the

2009/2010 and 2010/2011 were computed using the monthly R and ETo data collected during these seasons.

Berger (1989) has also advanced another definition of the onset and cessation of the normal rainy season. In the current study, however, it was preferred not to make use of this definition because the rainfall onset and cessation windows were very erratic for the analyzed long-term rain data. Moreover, Inthavong *et al*. (2011) have defined the start of the growing period (SGP) as the time when the soil water content within the top layer is greater than field capacity for at least three weeks running. In this regard, the end to the growing period (EGP) is defined as the time when the top layer soil water content is lower than wilting point. The calculations are performed on a weekly basis, with the number of weeks showing stored water in the field being defined as the length of growing period. However, the concept was not considered for the current study either.

B. Probability of dry spells

During the course of the current study, a dry day was adopted as a day with rainfall of less than 1 mm; and a dry spell as a sequence of dry days bordered by wet days on both sides (Kumar & Rao, 2005). Frequency analysis of dry spells was adapted from Belachew (2002). According to this latter author, the number of times q that a dry spell of a given duration (in days) occurs was counted on a monthly basis for a Yr-year period. The dry spells (one day, two days, three days …) were obtained and processed from historical data. The probabilities of occurrence of dry spells were estimated by considering the total number of days in a given month n. The total possible number of days, N, for that month over the analysis period was calculated as follows:

$$N = n * Yr \qquad \text{(Eq. 5.1)}$$

Subsequently the percentage probability P of a d-day(s) dry spell was given by:

$$P\ (\%) = \frac{q}{N}\ (\%) \qquad \text{(Eq. 5.2)}$$

Percentage cumulative frequency of any dry spell was computed as the sum of percentage frequencies of that dry spell and lower dry spells.

C. Exceedance probability of receiving annual and monthly rainfall

Exceedance probability is the probability that a given amount of annual or monthly precipitation is exceeded. As in the case of Ibraimo (2011), the long-term annual and monthly rainfalls were arranged in an ascendant order and fit into a normal probability distribution function (Eq. 5.3) to provide the probability of exceedance of a certain rainfall level. For the long-term annual rainfalls, return periods of the probability of exceedance of certain rainfall levels were also calculated. According to Rappold (2005), information on exceedance probability is useful for the choice of crops or cultivars because each crop or cultivar has a specific water requirement at each stage of the growth cycle. In addition, this information is also helpful for designing appropriate water storage structures for IRWH or supplementary irrigation.

$$f(x;\mu,\sigma^2) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \qquad \text{(Eq. 5.3)}$$

D. Monthly probability of a rain day and monthly percentage cumulative frequency of a rain day

In this study, a rain day was adopted as a day with rainfall higher than 1 mm (Kumar & Rao, 2005). The method used for the rain day frequency analysis was the same as the one used for the dry spell analysis which was adapted from Belachew (2002). As such, the number of times b that a rain day with a rain depth of the range of (t_{-1} – t) mm occurs was counted on a monthly basis for a Yr-year period. The rain days with rain depths of the ranges of ((1 – 5 mm), (6 – 10 mm), (11 – 20 mm)...) were obtained and processed from historical data. The estimation of the probabilities of occurrence of rain days with different rain depth ranges was conducted by considering the total number of days in a given month n. The total possible number of days, N, for that month over the analysis period was calculated as in Eq. 5.1. Then the probability P that a rain day with a rain depth range may be equal to (t_{-1} – t) mm was computed as in Eq. 5.2. Monthly percentage cumulative frequency of any rain day with a certain rain depth range was calculated as the sum of percentage frequencies of that rain depth range and lower rain depth ranges.

5.2.2 Installation/rehabilitation of runoff measurement structures and devices

The runoff trial plots were previously described in detail by Ibraimo (2011). The runoff trial plots were located directly next to the RWH trials mentioned in Chapters 3 & 4. Each runoff plot consisted of a runoff area, a gutter to collect the runoff, a pipe to convey the water to the runoff measurement device, and a runoff collection drum, which was housed in a pit (20 m^3) (Figure 5.1). All runoff plots had the same width of 5 m, with runoff lengths of 3 m, 2 m or 1 m and had fascia board borders to contain the runoff water. The dimensions of the runoff plots were therefore: one plot of 3 m x 5 m, two plots of 2 m x 5 m and one plot of 1 m x 5 m, giving runoff areas of 15 m^2, 10 m^2 and 5 m^2 respectively. All plot surfaces were cleared from vegetation, smoothed and compacted, except for the second 2 m x 5 m runoff plot, which was covered with a sheet of black plastic (2 x 5P). The pit corresponding to this latter runoff plot housed a 200-L drum and its rainfall and runoff data were monitored manually. The pits corresponding to other runoff plots housed a 100-L drum and had an electronic tipping bucket device which was connected to a datalogger (the volumes per tip of the tipping buckets are shown in Appendix D, – Table D1). All pits housing the drums were covered with corrugated iron sheets to prevent evaporation (E), rainfall or runoff from outside the plots to interfere with runoff measurements. An automatic rain gauge was installed next to the runoff plots and was also connected to the datalogger. The intent was to automatically record rainfall amount, duration and intensity, as well as runoff volumes. However, problems were occasionally experienced with the tipping buckets, in which case we had to resort to manual measurements. For this purpose, the volumes of water collected by the drums were manually measured and rainfall was read from a standard rain gauge installed next to the field.

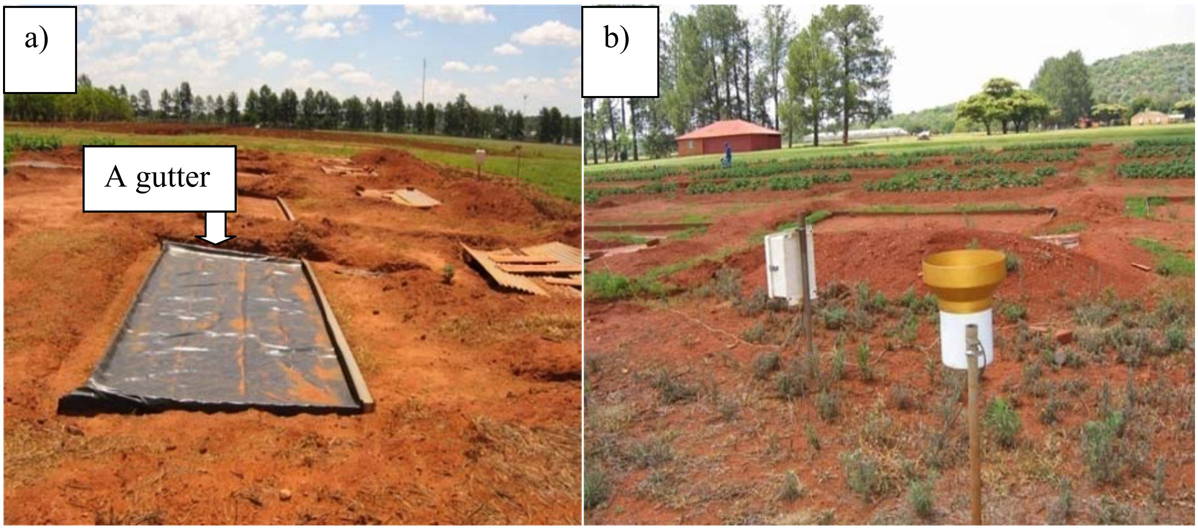


Figure 5.1: Rainfall and runoff harvesting and recording plot layout during the 2009/2010 and 2010/2011 growing seasons at the Hatfield Experimental Farm: a) runoff catchment area for the 2 x 5P runoff plot with a gutter and covered pit (to the right), and b) automatic rain gauge and datalogger.

5.2.3 Soil infiltration measurement

Infiltration rate is a measure of the tempo at which soil absorbs water (rainfall or irrigation) and cumulative infiltration is the total quantity of water that enters the soil in a given time (Horton, 1940; Morin & Cluff, 1980; Brady & Weil, 2002). Soil infiltration measurements were conducted on a windless day, by means of a sprinkler infiltrometer developed by the ARC Institute for Agricultural Engineering (ARC-IAE) in Pretoria, South Africa (Reinders & Louw, 1984). Knowledge of the field infiltration rate is useful in handling and predicting crust formation and runoff creation. Since crusting dictates the infiltration capacity, sprinkling was applied seven days ahead of the infiltrability measurement, with the aim of creating favourable conditions for the crust to form. To carry out this task, a pump unit delivering a minimum of 4.4 m^3 h^{-1} at 80 kPa pressure was used. Firstly, the sprinkler infiltrometer was positioned directly next to the test plots and then, rain gauge tops were placed on the soil surface at 0.5 m intervals, with the starting point at 1.5 m away from the infiltrometer and the furthest at 5.0 m from the infiltrometer. When the necessary connections (piping, rain gauge tops, sprinkler infiltrometer) were complete, the pump was run and the time recorded by a chronometer. A wetting front then appeared gradually around the first rain gauge top and expanded in the direction away from the instrument. Later, the front shifted from the first rain gauge top to the second one and the time elapsed was recorded (in minutes) while the first top was removed and its content measured with a rain gauge (in mm). The process was repeated (time and volume of water collected recorded) until the wetting front reached the last rain gauge top. According to Reinders and Louw (1984), at least three measuring points are necessary for a reliable test. Moreover, the duration of the test must be at least half an hour. The amount of water collected by each rain gauge top represents the cumulative infiltration (Ic) water before runoff initiation. The results obtained from the test were used to draw the cumulative infiltration and infiltration rate graphs of which the power functions are presented by Eqs. 5.4 and 5.5. The constants c and k in these equations were derived from the regression curves fitted to these graphs. For the current study, the infiltrability investigation was conducted on a flat surface (conventional), a runoff receiving area (RRA) (ridge or cropped area) and a runoff producing area (RPA) (runoff area). These three different test plots were randomly selected from the RWH experiment (potatoes) referred to in Section 3.2.2 of Chapter 3 (exactly the same plots involved in Chapter 4).

The cumulative infiltration (Ic) (mm) is computed as follows:

$$\boxed{Ic = ct^{k}} \qquad \text{(Eq.5.4)}$$

where c and k are constants (derived from the regression curve fitted to the Ic graph), and t the time (minutes) taken.

The infiltration rate (It) (mm hr^{-1}) is then calculated by using the following equation:

$$\boxed{It = kct^{k-1}} \qquad \text{(Eq. 5.5)}$$

where c, k and t are the same as in Eq. 5.4 and t^{k-1} shows that It is a derivative of ct^{k} (Ic) .

5.2.4 Runoff and sediment collection

The runoff and sediment collection (Figure 5.2) corresponded to each rainfall event or each harvestable aggregate rainfall event, except for some weekends and public holidays. Besides, some rainfall events were nocturnal, leaving little time span for runoff withdrawal. Morin and Cluff (1980) defined a rain-day as a period beginning at midnight, during which a rainfall event occurred. This definition is similar to the one provided by the World Meteorological Organization (WMO) of the United Nations, Geneva; but from 08:00 AM to 08:00 AM the following day due to the standard annual measurement method. This latter method was adopted in this study. The collection of runoff volume and sediment amount was conducted with the structures and devices described in Section 5.2.2. Sediment from the bottom of the drums as well as a sample of 500 ml of the suspension were taken (Figure 5.3), weighed and dried in an oven at 105°C for three days.

Figure 5.2: Runoff and sediment collection 1: a) adjusting the 200-L drum and b) collection of runoff and sediment from a 100-L drum under a tipping bucket.

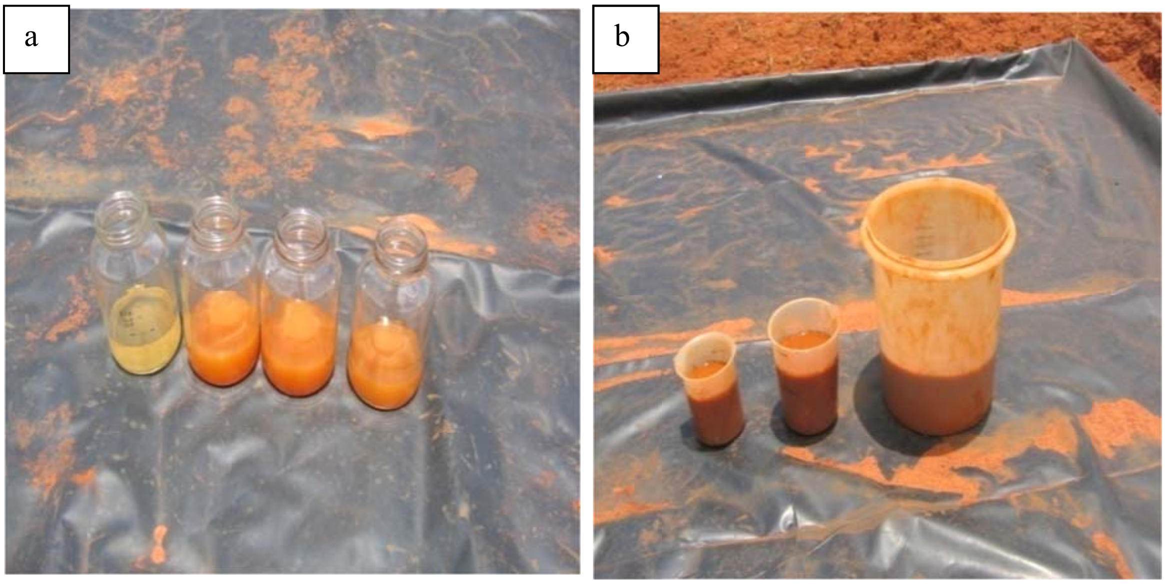


Figure 5.3: Runoff and sediment collection 2: a) suspension from 2 x 5P (clear), 1 m x 5 m, 2 m x 5 m and 3 m x 5 m plots and b) sediment and suspension from the drum bottoms of 1 m x 5 m, 2 m x 5 m and 3 m x 5 m, respectively.

5.3 Results and discussion

5.3.1 Characterisation and analysis of the long-term (15 years) summer rainfall data (October – May) at the Hatfield Experimental Farm (1995/1996 – 2009/2010)

This section presents the results from the characterisation and analysis of the long-term rainfall data during a normal rainy season at the Hatfield Experimental Farm. The rainfall data for the 2009/2010 (potato) and 2010/2011 (Swiss chard) growing seasons are presented in Sections 5.3.2A and 5.3.2B, respectively.

A. Characterisation of the long-term growing period

Figure 5.4 illustrates the long-term characteristics of the normal rainfall season, which presents R, ETo and ETo/2. From this figure, it is clear that the long-term R was above ETo/2 during the October – end-April period of the crop growing season; and below ETo/2 after April. The growing season length is helpful in determining crop growth cycle lengths and calendars under average conditions. Real years may sometimes divert significantly from the average.

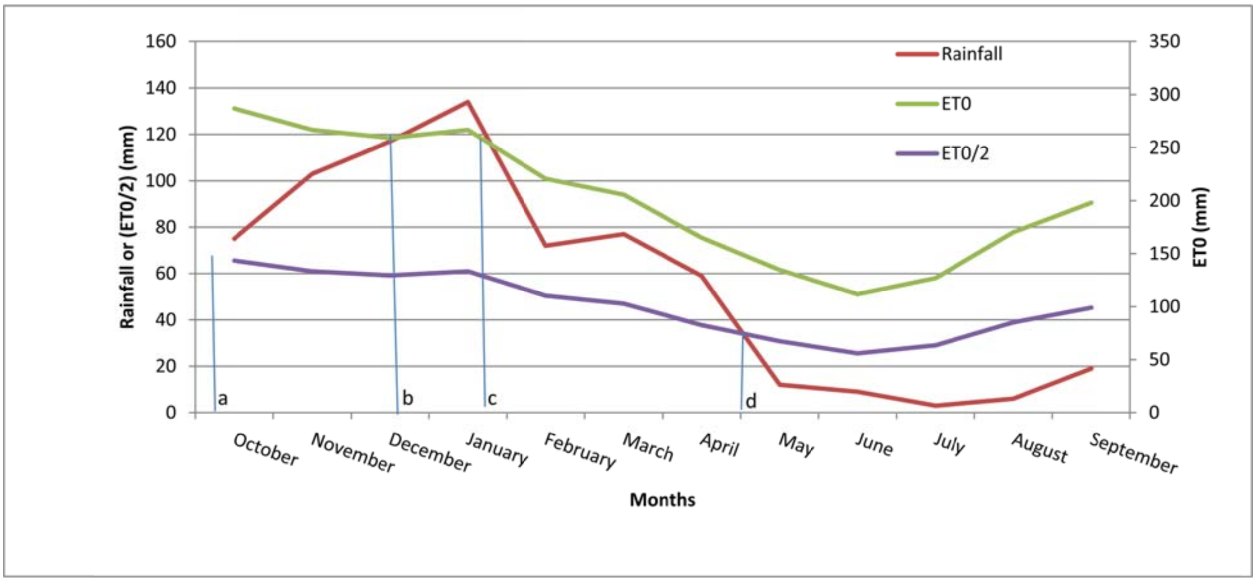


Figure 5.4: Long-term normal R season (mean monthly R, ETo and ETo/2 (all in mm)) at the Hatfield Experimental Farm.

A normal growing period is characterized by a dry period, a moist period (also called intermediate period) and a wet (or humid) period. A beginning period (a in Figure 5.4) occurs when R equals half ETo and marks the start to the normal rainy season. The beginning heralds the transition from the dry period to the intermediate period (from a to b in Figure 5.4) when ETo/2 < R < ETo. A wet (humid) period (from b to c in Figure 5.4) is the period during which R exceeds ETo. The end of the wet period (c in Figure 5.4) marks the transition from the wet period to another intermediate period (from c to d) when again ETo/2 < R < ETo. An end to the growing period (d in Figure 5.4) starts at the point where the R curve crosses the ETo/2 graph. According to the above criteria, the onset of the normal rainy season commenced in October, while a part of December and a part of January can be considered as wet period since the R amounts were higher than ETo values. Finally, April marked the end of the available growing season as after this month R was lower than ETo/2 values.

The results for the normal growing season for the 15-year period appear favourable to the potato trial (spring potato) since they show that April signals the end of the normal growing season, while the potato crop growth cycle started in the beginning of October (2009/2010) and ended at the end of January. Should the crop grow beyond April, unpredictable intra-seasonal dry spells (water stress) were imminent. This is important for plant breeders and farmers to select those cultivars the growth cycles of which do not exceed the period of the rainy season. However, the Swiss chard (a winter crop) growing season occurred from May until November (2010), just at the start of the normal rainy season. Therefore, RWH should be only beneficial to Swiss chard production in the areas with winter R.

B. Probability of dry spells

The occurrence of some threshold dry spells is summarized in Figure 5.5. The occurrence of dry spell incidents has peculiar relevance to rainfed agriculture, as rainfall is one of the key limiting factors for plant life in rainfed agriculture (Belachew, 2000; Röckstrom *et al*., 2002). As it can be seen from Figure 5.5, the probability of occurrence of dry spells varied from month to month. The shorter the dry spell interval, the higher the probability of occurrence. For the October – May period, the probability of occurrence of dry spells of 1 day and 2 days were 26 and 17%, respectively; while that of 14 and 21 days were 0.9 and 0.2%, respectively. As in the case of Mzezewa *et al*. (2010), the month of December experienced the highest probability of occurrence of dry spell periods of 1 and 2 days (results not shown)**.** Also Figure 5.5 presents cumulative frequency of dry spell durations. It can be seen that shorter dry spells formed an important percentage of the total dry spell periods. Figure 5.5 shows that dry spells equal or less than 10 days represent more than 90% of the total dry spells. It was reported that, in general, occurrence of dry spells of all durations decreased from October to March, the period that coincides with the summer rainy season in South Africa (Lynch *et al*., 2001; Kosgei, 2008). The probability of having a dry spell increases with shorter periods (i.e. more chance of having a 1-day or 5-day dry spell than a 10-day or 21-day dry spell).

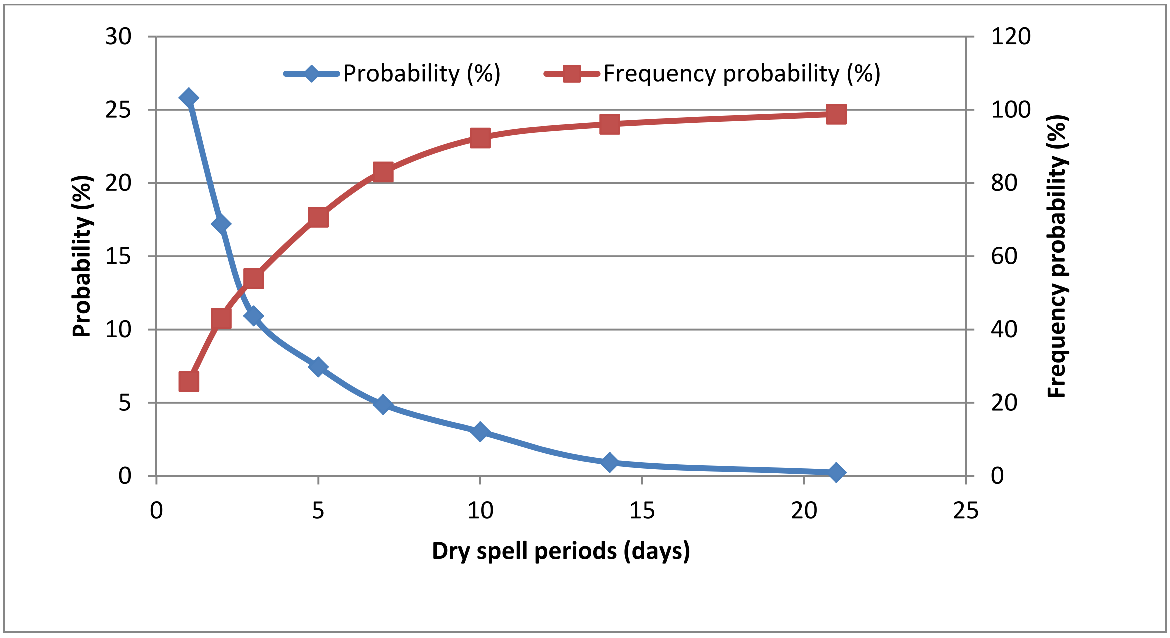


Figure 5.5: Probability and cumulative frequency of a d-day(s) dry spell, for d = 1, 2, 3, 5, 7, 10, 14 and 21, for 15-year rainy seasons.

C. Exceedance probability of receiving annual and monthly rainfall

Table 5.1 indicates the 15-year period probability of receiving yearly rainfall amounts greater than given minimum rainfall levels. From Table 5.1, it can be seen that the probability of exceeding various amounts of annual rainfall diminished as the threshold rainfall amount increased, while conversely, the return period increased. For instance, there was 90% chance of receiving rainfall greater than 450 mm (each year), whilst the chance of receiving 1200 mm was only 2% (once out of 50 years). There was a 64% probability of exceeding 650 mm of annual rainfall.

Table 5.2 gives the 15-year period probability of receiving monthly rainfall greater than certain threshold levels. Table 5.2 denotes that the probability of getting various amounts of monthly rainfall declined as the threshold rainfall amount increased. The probability of receiving rainfall amounts of 25 mm was the greatest, followed by the probability of receiving a monthly rainfall amount of > 50 mm. The probability of receiving a rainfall of 300 mm per month was close to zero. The probability of receiving high rainfall (> 100, 150, 200 and 250 mm) was greatest in January (70, 42, 29 and 11%, respectively) and lowest in May (close to zero). This indicates that January is the long-term wettest month at the Hatfield

Experimental Farm. In a semi-arid area in Limpopo, Mzezewa *et al*. (2010) found that the month of December was the wettest, with a 58% probability of receiving > 100 mm, followed closely by January, with the probability of 56%. In the present case, however, the probabilities of having a monthly rainfall > 25 and 50% were highest for the month of December. A 45% chance of receiving a rainfall amount equal to or greater than 100 mm was recorded in March, which confirms earlier reports that summer rainfall in South Africa occurs mainly between October and March (Landman & Klopper, 1998).

Table 5.1: Probability of receiving annual rainfall (October – May) greater than 450, 550, 650, 700, 800, 900 and 1200 mm and their respective return periods at the Hatfield Experimental Farm for 15 year rainy seasons (1995/1996 – 2009/2010).

Annual rainfall (mm)	Probability of exceedance (%)	Return period (years)
450	90	1.1
550	78	1.3
650	64	1.7
700	52	1.9
800	31	3.2
900	17	5.9
1200	2	50

Table 5.2: Probability of receiving monthly rainfall (October – May) greater than 25, 50, 100, 150, 200, 250 and 300 mm at the Hatfield Experimental Farm for 15 year rainy seasons (1995/1996 – 2009/2010).

Month	**Monthly rainfall (mm)**						
	25	**50**	**100**	**150**	**200**	**250**	**300**
	Probability of exceedance (%)						
October	60	48	15	3	0	0	0
November	95	87	47	12	0	0	0
December	100	98	61	22	0	0	0
January	95	90	70	42	29	11	0
February	90	87	61	40	17	7	0
March	80	70	45	20	15	9	2
April	55	35	10	0.3	0	0	0
May	45	20	0.1	0	0	0	0

D. Monthly probability of a rain day and monthly percentage cumulative frequency of a rain day

Figures 5.6 and 5.7 respectively offer the probability of having a rain day with a certain rain depth range and the percentage cumulative frequency thereof. As in the study conducted by Mzezewa *et al*. (2010), frequency distribution with storms equal or less than 5 mm accounted for the greatest proportion of rainy events. April showed the highest probability of a rain day ≤ 5 mm (53%), followed by October (44%). As the rainfall amount per rain day increased, the probability declined for all months, in general. From Figure 5.6 can be seen that December had high probabilities in the ranges of (11 – 20) and (21 – 30) (27 and 11%, respectively). Figure 5.6 also indicates that the probability of having a rain day of (91 – 100) mm is almost null. In general, however, the data which are not shown here indicated that the probability of having a rain day was highest in December and January, while the lowest belonged to May. The period of October – January (during which the potato trial occurred) had a long-term probability of a rain day of 63% (data not shown). It was also revealed that scarce heavy rainfalls made a considerable fraction of the total rainfall (results not shown). This is in accordance with the findings reported by Mzezewa *et al*. (2010), as well as other results reported on long-term rainy days in semi-arid regions (Harrison, 1983; Li & Gong, 2002).

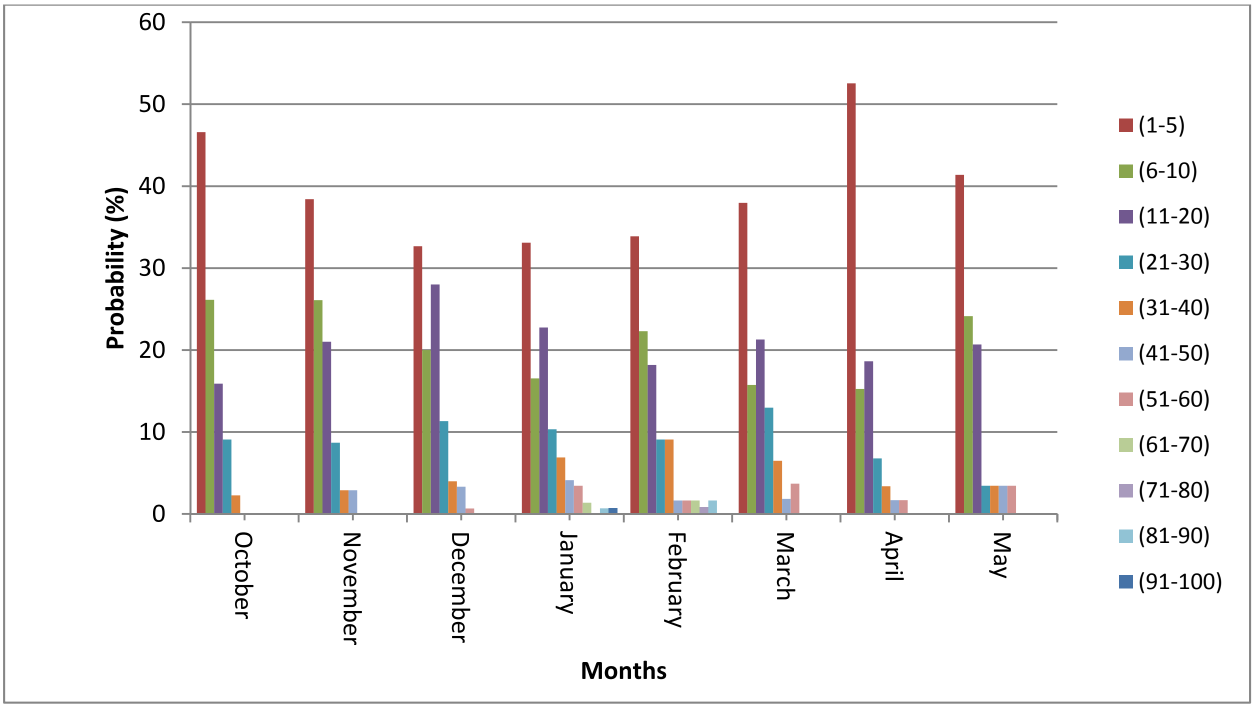


Figure 5.6: Monthly (October – May) probability of a rain day of a rain depth range of (1 – 5), (6 – 10), (11 – 20)...(91 – 100) mm for 15 year rainy seasons (1996 – 2010).

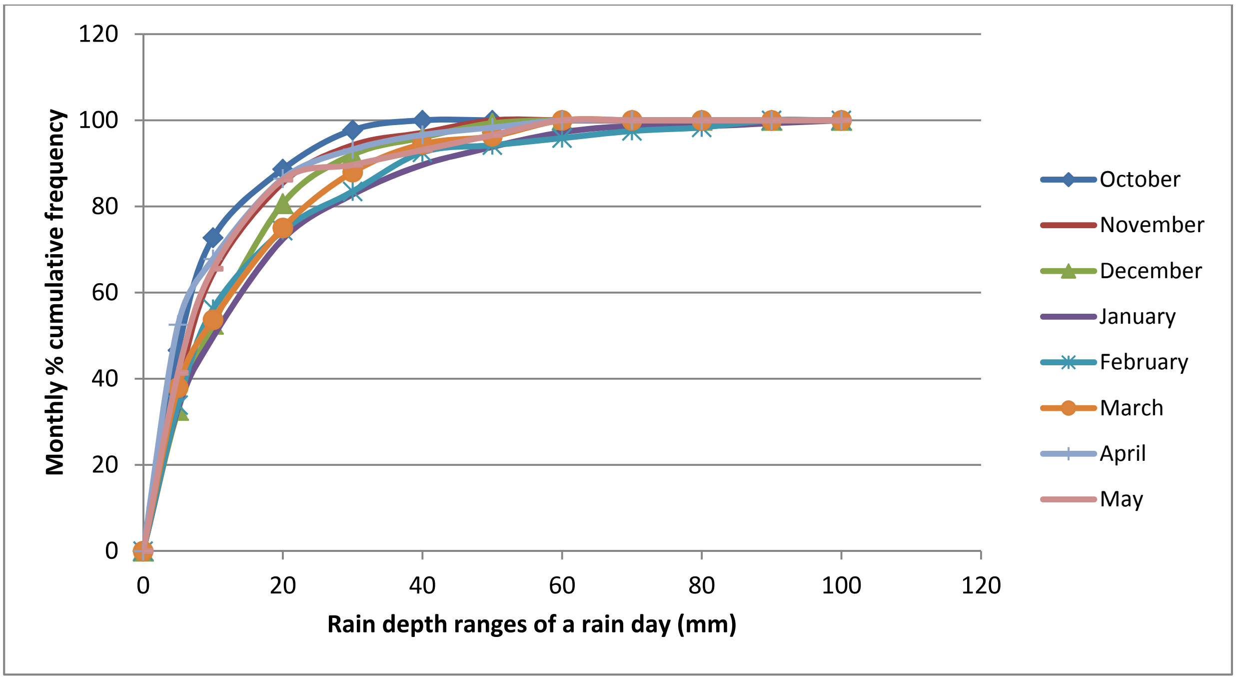


Figure 5.7: Monthly (October – May) percentage cumulative frequency of a rain day with a rain depth range of (1 – 5), (6 – 10), (11-20)...(91 – 100) mm for 15 year rainy seasons (1996 – 2010).

5.3.2 Weather data during the 2009/2010 and 2010/2011rainy seasons

A. Weather data during the 2009/2010 rainy season

The weather data during the 2009/2010 potato growing season at the Hatfield Experimental Farm are illustrated in Table 5.3. It is worth noting that the potato was planted on the 8th October 2009 and harvested on the 9th February 2010, with weather data collection stopping at the end of January 2010. From Table 5.3 it can be observed that ETo varied between 112 and 146 mm for October and December, respectively; while the total seasonal ETo amounted to 505 mm. Monthly water content fluctuated between 63 and 129 mm for October and December, respectively, while the total amounted to 407 mm. Minimum and maximum temperatures fluctuated in the range of 14.0 – 17.4°C, and 26.6 – 28.9°C, respectively. Table 5.3 also shows the values of the aridity index (AI) during the potato growing season. According to Tsiros *et al*. (2008), the AI represents climatic aridity and is used to determine the adequacy of rainfall in satisfying the water needs of the crop. In RWH terms, AI can be of paramount significance as it can help in determining rainfall/runoff amount to expect for a given period. From Table 5.3 can be seen that AI varied between 0.56 (October) and 0.90

(January), while the mean value in the course of the potato growing period was 0.80. In general, all these values are higher than the long-term AI for this area calculated using the 30-year data (1961 – 1990) which is 0.40 (October – January). However, in consistency with Table 5.3, the AI values calculated during the potato growing season fell under humid zones, except for October, which AI fell under dry sub-humid regions (according to the standard defined by UNEP, 1992).

Table 5.3: Monthly weather data during the 2009/2010 potato growing season at the Hatfield Experimental Farm.

Month	**R[1] (mm)**	**ETo[2] (mm)**	**Min. T (°C)**	**Max. T (°C)**	**AI[3]**
October	63	112	15.0	28.7	0.56
November	104	124	14.0	26.6	0.84
December	129	146	15.6	28.9	0.88
January	111	123	17.4	28.4	0.90
Seasonal total	407	505			
Average					0.80

[1] – Precipitation; [2] – crop reference evapotranspiration; [3] – AI: aridity index.

The daily rainfall pattern during the rainy season of the potato growing cycle is presented in Figure 5.8. The total rainfall at the research site during the 2009/2010 rainy season was 768 mm, mainly occurring between October and May. Given that the average annual seasonal rainfall of the study site is 670 mm, it is obvious that the 2009/2010 rainy season was depicted as wet season. This is in accordance with the AI values reported above. According to Figure 5.9, the 30-year (1970/1971 – 1999/2000) normal probability distribution curve for Hatfield (Pretoria), an annual rainfall of 768 mm has a probability of exceedance of approximately 33%. This means that it is expected that in only one out of 3 years the annual rainfall will be equal to or higher than 768 mm in Pretoria. Likewise, the probabilities of exceedance of 300 and 1000 mm are nearly 98% and 5%, respectively. This means that a rainfall event of 300 mm can be expected each year, while that of 1000 mm can be expected only after 19 years.

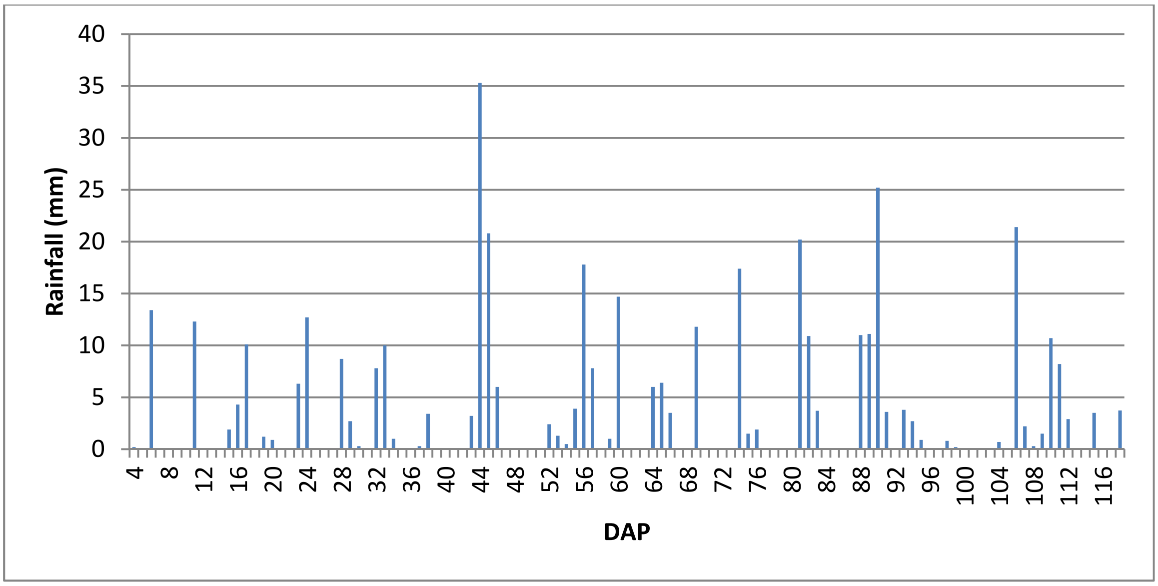


Figure 5.8: Rainfall during the 2009/2010 potato growing season at the Hatfield Experimental Farm.

For the whole 2009/2010 summer rainy season, there were 70 rainfall events with rainfall amounts ≥ 1 mm. As it can be seen from Table 5.3, the total rainfall amount during the potato growing season (from 8th October 2009 to 31st January 2010) was 407 mm. This amount was mostly made up of 54 rainfall events with amounts ≥ 1 mm. In the course of the growing season, rainfall ranged between 1 mm and 35 mm. The growing season was mainly characterized by small rainfall events, with only 18 rainfall events (33.3% of the total events) actually reaching an amount of 10 mm. The amount of rainfall was highest in December – 129 mm (31.6%) and lowest in October – 63 mm (15.5%). The onset and cessation of rainfall were normal and the rainfall events almost occurred at uniform frequencies. The highest rainfall (35 mm) occurred on the 20th November 2009. The frequency of rainfall in the course of the growing period was high, but characterized by recurrent small rainfall events. Actually, 26 (48%) of the total growing season rainfall events were linked to a depth of ≤ 5 mm per event and as a result, conditions of insufficient soil water content were now and then experienced and this may have constituted a cause of concern for the soil plant available water necessary for optimum crop growth.

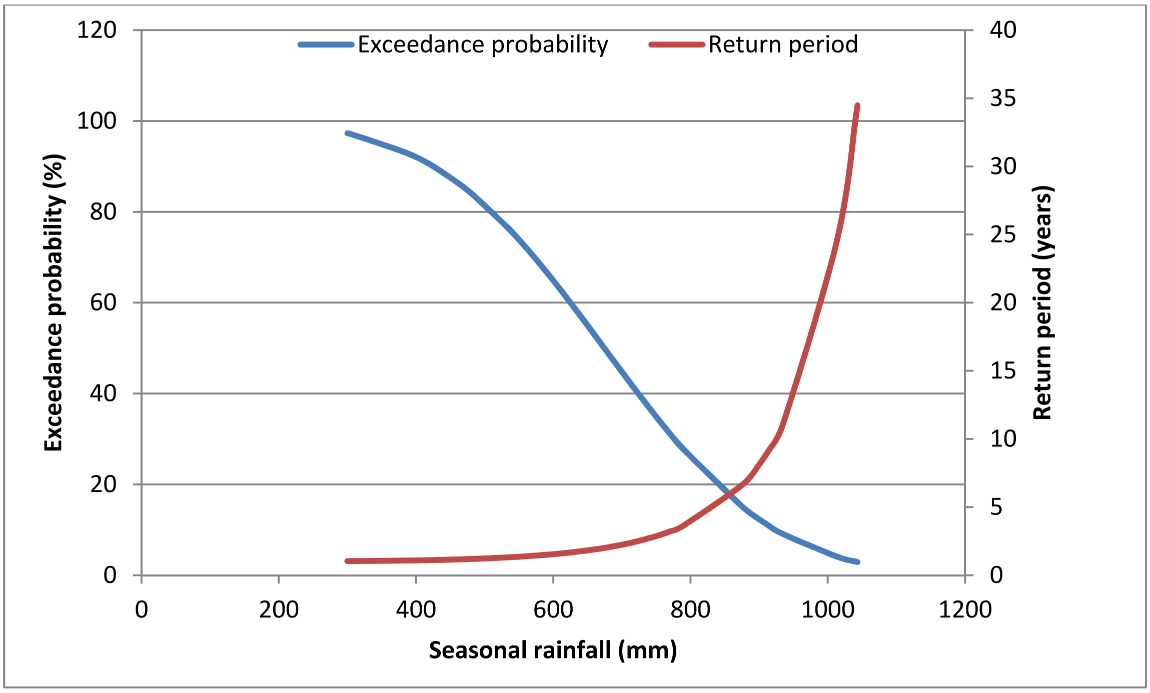


Figure 5.9: Probability of exceedance of various amount of long-term (1970/1971 – 1999/2000) seasonal rainfall.

B. Weather data during the 2010/2011 rainy season

Table 5.4 presents the weather data during the 2010/2011 Swiss chard growing season at the Hatfield Experimental Farm. Swiss chard was transplanted on the 14th May 2010 and the last harvest took place on the 29th November 2010. Table 5.4 shows that October and November had an ETo of 132 mm. Minimum and maximum temperatures fluctuated in the range of 14.7 – 15.3°C, and 28.8 – 30.3 °C, respectively. Table 5.4 also offers the values of the aridity index (AI) during the Swiss chard growing season. The calculations of these AI values were based on the UNESCO (1979) guideline as defined above. From Table 5.4, it can be observed that AI varied from 0.14 (October) to 0.76 (November), whilst the average value during the Swiss chard growing season was 0.45. This latter index as well as AI value for November (0.76) are higher than the long-term AI for this location, calculated with the 30-year data (19961 – 1990), which is 0.30 (October – November). However, AI for October (0.14) is lower than the typical value of the site during this period. This can partly be attributed to the delay of the rainy season for 2010/2011. According to UNEP (1997), the low AI for October defined the study area as an arid area, while the AI value for November characterized Hatfield (Pretoria) as a humid area. The average AI value during this period characterized the area as semi-arid. Therefore, the AI for November at Hatfield (Pretoria) can be considered as unusual.

Table 5.4: Monthly weather data during the 2010/2011 Swiss chard growing season at the Hatfield Experimental Farm.

Month	**R (mm)**	**ETo (mm)**	**Min. T (^{o}C)**	**Max. T (^{o}C)**	**AI**
October	19	132	14.7	30.3	0.14
November	100	132	15.3	28.8	0.76
2-month total	119	264			
Average					0.45

Figure 5.10 shows the rainfall pattern during the 2010/2011 rainy season which started towards the end of the Swiss chard growing period (sprinkler irrigation was used for the most of the growing season but neither irrigation scheduling nor runoff/soil collection was considered). The 2010/2011 rainy season on the study field displayed a total rainfall amount of 900 mm, mainly falling between October and May. Since the mean seasonal rainfall of the study site is 670 mm, the 2010/2011 rainy season proved to be a wet season, as rainfall was higher than the average. This is only partly in agreement with the AI value of the current study for November. In accordance with Figure 5.9, the 30-year normal probability distribution curve for Hatfield (Pretoria), an annual rainfall of 900 mm has a probability of occurrence of approximately 13%. This means that it is expected only one year out 8 years, to have annual rainfall equal to or more than 900 mm at Hatfield (Pretoria).

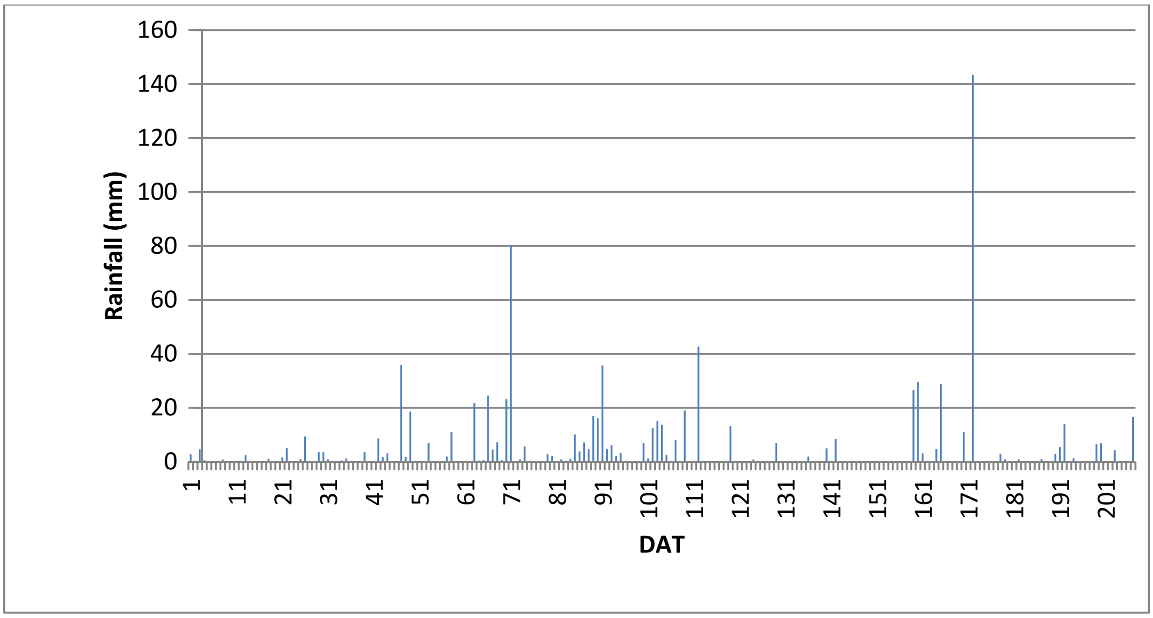


Figure 23.10: Rainfall during the Swiss chard growing season (2010/2011) at the Hatfield Experimental Farm. DAT = days after transplanting.

For the entire 2010/2011 Swiss chard growing rainy season, there were 73 rainfall events with rainfall amounts ≥ 1 mm. However, the crop growing season (from 14th May 2010 to 29th November 2010) only accounted for 19 rainfall events with the depth ≥ 1 mm, contributing 119 mm of total rainfall (Table 5.4). The range of rainfall during the crop growing season was 1 – 35 mm. The Swiss chard growing season was mainly characterized by small rainfall events, with only 6 rainfall events (31.6% of the total events) actually reaching the depth of 5 mm. The amount of rainfall was highest in November – 99.8 mm (84%) and lowest in October – 19.1 mm (16%). The rainfall started late and occurred at nearly regular frequencies. The highest single rainfall event (35 mm) occurred in November. The frequency of rainfall during the growing period was fairly high and as a result, the amount of rainfall per single event was clearly very small, with 68.4% of the total rainfall events with a depth of ≤ 5 mm per event. These rainfall events were too little to contribute adequately to the soil water for sustainable crop growth. Therefore, supplementary sprinkle irrigation (simulating rain) carried on until almost the end of the growing season, i.e. on the 21st November 2010, with the high rainfall starting on the 23rd of November 2010.

The results from the studies of the 2009/2010 and 2010/2011 rainy seasons were, in general, in agreement with the literature. For instance, according to research in semi-arid Kenya, the annual (seasonal) rainfall can be estimated by a normal distribution (Rowtree, 1989), while the return period for a certain annual (seasonal) rainfall amount (in years), can be defined as the inverse of its probability of exceedance (FAO, 2004). In addition, according to this latter organisation and Mzezewa *et al*. (2010), the probability of exceeding certain amounts of annual rainfall declined as the threshold rainfall amount increased. In addition, in agreement with the findings reported by Mzezewa *et al*. (2010) for a summer rainfall semi-arid area in Limpopo, frequency distribution with storms of equal or less than 5 mm accounted for the greatest proportion of rainy events. However, in general, the AI values for the study site during the crop growing seasons were unusual according to the literature. For example, it is known that the study ecotope is a semi-arid area (Rockström *et al*., 2007). Moreover, Bennie and Hensley (2001) reported that only a strip of the country, mainly the mountainous areas with natural and commercial forests, has a sub-humid climate.

In Sections 5.3.1 and 5.3.2, the long-term normal growing season was characterised and the long-term and seasonal rainfalls analysed. For a given ecotope, the long-term rainfall data (including dry spells) can help understanding the amount of seasonal or monthly rainfall and runoff to expect. This information is useful since knowledge of expected runoff and therefore the type of crop or cultivar to grow can help in designing the appropriate type and size of RWH structure to construct. However, the situation can be improved if the long-term rainfall data is used with the rainfall data forecast of actual rainy seasons. However, other factors, such as infiltration rate, affecting runoff must be considered in order to upgrade the efficiency of runoff and RWH systems. The following paragraphs deal with infiltration, runoff-related and soil loss data.

5.3.3 Soil infiltration

Figures 5.11 and 5.12 present the results for infiltration rate and cumulative infiltration obtained for the ridge (cropped area), conventional and runoff (catchment) area, respectively. As it can be observed through the superimposed graphs, in terms of both cumulative infiltration and infiltration rate, the value rankings were in order: ridge > conventional > runoff. This sequence was the result of the values given by both initial and final (steady-state) infiltration rates for the 3 different surfaces. These values were 25.7 and 2.8, 38.7 and 3.8 and, 53.1 and 4.9 mm hr^{-1}, for runoff, conventional and ridge, respectively. These differences can partly be attributed to the status of the respective soil surfaces, as all surfaces were exposed to the same field conditions before the measurement. The runoff area was a compacted surface, the conventional was a ploughed flat surface, while the ridge was a ploughed and raised bed.

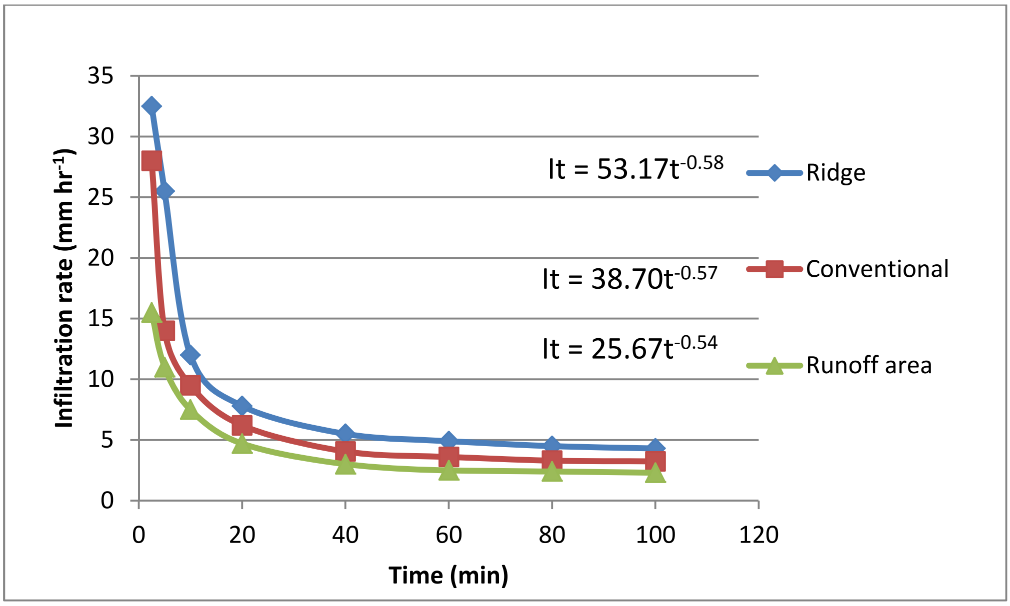


Figure 24.11: Infiltration rate (mm hr^{-1}) during the 2009/2010 growing season at the Hatfield Experimental Farm.

The current results are close to those reported by past investigators. For example, the findings of Ibraimo (2011), disclosed that infiltration rates on the cropped areas were higher than on the runoff areas. For the former areas, the soil texture and structure have been perturbed by the ploughing, which broke down the soil crust; while the latter areas were smooth and compacted. According to reports, infiltration rate values in the range of 6 – 7 mm hr^{-1} were found in the course of several studies, e.g., Hoogmoed and Stroosnijder (1984) in the Sahel (West Africa) and Hensley *et al*. (2000) at Glen (South Africa). For the former author, the soil was a loamy fine sand (5% clay and 20% silt) with wet crust, while for the latter one, the study area was a semi-arid ecotope with a clay soil. Moreover, Zere *et al*. (2005) predicted a final infiltration value of 5 mm hr^{-1} and 10 mm hr^{-1} on bare untilled and maize cropped treatments at the Glen ecotope, respectively. The nuance between the values found in the literature and the current test can be attributed to many factors. First, the soil at the Hatfield Experimental Farm is a sandy clay loam with clay content of around 30%. These characteristics and the surface status mentioned above can be specific causes for such differences. Secondly and in general, infiltration rate is influenced by factors such as soil surface and subsurface physico-chemical properties (texture, structure, organic matter, soil crusting, soil compaction, etc.); rainfall characteristics (intensity and amount); and surface features (slope, vegetation, surface storage and runoff) (Horton, 1940; Morin & Cluff, 1980). Different study ecotopes can, therefore, be expected to have different infiltration rates.

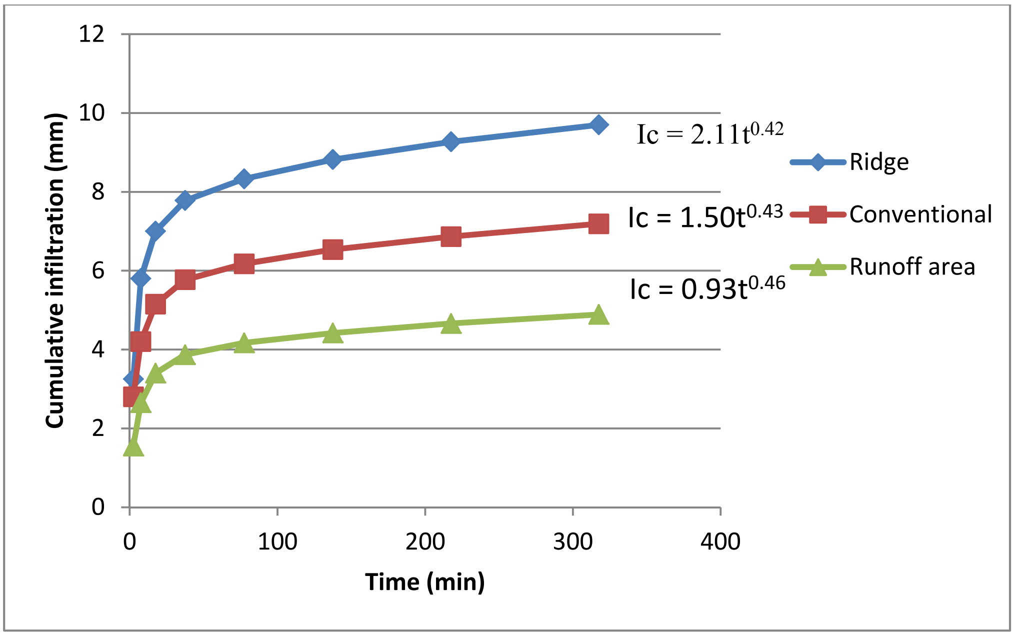


Figure 25.12: Cumulative infiltration (mm hr^{-1}) during the 2009/2010 growing season at the Hatfield Experimental Farm.

Over the years, investigations carried out in arid and semi-arid regions have shown that soil crusting is a major cause of low infiltration (Morin, 1967; Seginer & Morin, 1970). According to Tarchitzky *et al.* (1984), crust formation is an important process, usually observed on bare soil surfaces, because of its effects on infiltration, erosion and seedling emergence. The crust creation is possible because of the impact of drops of water from rain or sprinklers on the soil surface. It was proven that the IRWH technique is suitable for semi-arid areas with crusting soils that have a high water storage capacity (Botha *et al.*, 2003). According to Bennie and Hensley (2001), soil surfaces with a silt plus clay content of more than 20% are susceptible to crust formation. Moreover, it was disclosed that the degradation of the structure of the topsoil under rainfall, which leads to soil sealing and crusting, can cause an important decrease in the soil infiltration rate of agricultural soils, particularly under conventional tillage (Boiffin, 1984; Casenave, 1989). Taking 1 minute as the initial infiltration rate interval and 60 minutes as the final infiltration interval, the respective infiltration rates for the conventional during the current investigation were 38.7 and 3.8 mm hr^{-1}. As mentioned above, these values were higher than those of the runoff area, but lower than those of the ridge area. According to Slatyer (1967), final infiltration rates on cultivated sandy loam soils were within the interval 3.8 and 7.6 mm hr^{-1}. However, the soil at the Hatfield Experimental Farm is mainly a sandy clay loam and this can partly explain the difference between the results given by the present study and those given by Slatyer (1967). According to Morin and Benyamini (1977), soil crusting plays the major role in determining the final infiltration rate, rather than the antecedent soil water content. They proved that the effect of the latter in crusted soils was minimal. These findings were corroborated by the experiment conducted by Morin *et al*. (1983). All these investigations showed a higher value for final infiltration rate prior to the crust formation. Once the crust was created, the final infiltration rate value remained constant at different antecedent soil moisture conditions. This is favourable to runoff generation and, therefore, to the RWH agriculture.

As mentioned above, Figure 5.12 illustrates the cumulative infiltration curves obtained from the study. According to previous studies, in arid and semi-arid regions, where water scarcity is the main limiting factors for rainfed agriculture, soil infiltration rate plays a critical role in determining the cumulative infiltration amount to be available in the soil root zone during a particular rainfall event that can be used by crops. In accordance with the results from Ibraimo (2011), after 1 hr (60 min.) from the start of sprinkling, the cumulative infiltration on the ridge was nearly 8.2 mm, compared to 5.4 mm for the runoff area. The 60 minute interval has been selected in line with FAO (1991), which recommends that on cultivated soils, steady-state infiltration rates are believed to be in the range of 10 – 60 minutes from the onset of a rainfall event. These outcomes from Ibraimo (2011) were lower than those found during this investigation. The calculated 60-minute cumulative infiltrations for the ridge and runoff areas were 11.8 and 6.1 mm, respectively (the calculated 60-minute cumulative infiltration for the conventional was 8.7 mm). This discrepancy can result from many factors, including those mentioned above (on infiltration rates), as well as management practices.

5.3.4 Results and discussion on runoff from runoff plots during the 2009/2010 and 2010/2011 rainy seasons

A. Results and discussion on runoff from runoff plots during the 2009/2010 rainy season

Table 5.5 shows the different runoff amounts collected from the different plots during the 2009/2010 rainy season. However, owing to some technical incidents with the equipment, complete data sets could only be collected for 10 rainfall events for the season. With regard to the amount of runoff collected from the drums installed in the pits at the bottom of each runoff plot (totals not shown), 3 m x 5 m gave the highest runoff amount (2366 L equivalent to 1577 m^3 ha^{-1}), followed by 2 m x 5 m (2264 L equivalent to 2264 m^3 ha^{-1}) and 1 m x 5 m (1200 L equivalent to 2400 m^3 ha^{-1}). 2 x 5P gave more runoff than the others (5249 L equivalent to 5249 m^3 ha^{-1}, not shown) because the runoff plot is able to collect more water than the others since its surface was covered with plastic mulch, which as such, prevented any water from infiltrating into the soil. The runoff results given by the different drums showed that the bigger the runoff plot area the higher the volume of runoff water collected. However, in terms of runoff volume per hectare (unit), 1 m x 5 m had the highest value, because its runoff efficiency was equally the highest. This runoff plot was narrow, and therefore, only relatively low runoff loss was allowed throughout infiltration and E.

In terms of bare runoff plots, the amount of the runoff collected varied according to the size of the area, the soil characteristics, the surface status, slope, antecedent moisture conditions, as well as climatic conditions. These factors are important in determining rainfall threshold (the minimum rainfall required to generate runoff) and runoff efficiency (the proportion of total rainfall which becomes runoff). As has been observed during the current study, for normal conditions, at least 3 mm of total rainfall was required to satisfy the initial abstraction and generate runoff with 2 x 5P. However, this amount of total rainfall to produce runoff for 2 x 5P is much lower than what was needed to satisfy the conditions of the soil surface retention for the bare-surfaced runoff plots. For instance, on the 24th February 2010, even a total rainfall of 6.8 mm could not generate runoff for the bare-surfaced runoff plots, whereas 2 x 5P collected more than 60 L (observation). This implies that at least more than 6.8 mm of total rainfall was required for the bare-surfaced runoff plots to generate runoff. The threshold rainfall amounts for these bare-surface runoff plots are not clear, but according to the results from the current study, their threshold rainfall was close to each other. In addition, for 2 x 5P, in the case of extreme conditions, for example after a long dry spell , it needed more than 3 mm of total rainfall to be able to initiate runoff. The same applied to the others, of course in relation with their respective runoff thresholds. In any case, before runoff starts, some rainfall is required to saturate the soil surface and fill up surface depressions (Foster, 1949).

From Table 5.5, can be perceived that runoff efficiencies for 3 m x 5 m, 2 m x 5 m, 1 m x 5 m and 2 x 5P fluctuated within the range of 22.4 – 56.1, 24.2 – 57.7, 28.2 – 67.5, and 62.7 – 88.3, respectively. It is clear that, among the bare runoff plots, the smaller the catchment area size, the higher the runoff efficiency. This outcome can partly be assigned to the fact that the longer the runoff flow path, the wider the time interval for runoff loss through infiltration and evaporation. At the same time, Table 5.5 shows that on all occasions, among the bare-surface plots, 1 m x 5 m provided the highest results for runoff depth, followed by 2 m x 5 m, while 3 m x 5 m trailed them. In this context, 2 x 5P was plastic-mulched and therefore yielded the highest in every item for the already mentioned reasons. In addition, it is evident that for all runoff plots, the lowest runoff depth and runoff efficiency was recorded for the lightest rainfall event (7.8 mm), because a bigger proportion of the rainfall first infiltrated into the soil before the start of runoff. Moreover, it is logical that all runoff plots experienced a splashing phenomenon to/from outside of the fascia boards. This situation was particularly encountered with heavy rainfall events.

Table 5.5: Rainfall, runoff depth (RD) and runoff efficiency (RE) (the runoff volume in L is given in the parentheses) recorded for different rainfall events during the 2009/2010 rainy season.

Date	Rain (mm)	Runoff plots and their runoff-related data							
		1 m x 5 m		2 m x 5 m		3 m x 5 m		2 x 5P	
		RD (mm)	RE (%)	RD (mm)	RE (%)	RD (mm)	RE (%)	RD (mm)	RE (%)
13/10/09	13.4	6.3 (31.5)	47.0	5.6 (56.2)	42.0	4.3 (65.1)	32.4	10.9 (108.9)	81.3
18/10/09	12.3	6.1 (30.5)	49.6	4.6 (45.5)	37.0	4.1 (60.9)	33.0	10.5 (104.8)	85.2
24/10/09	10.1	4.3 (21.3)	42.1	3.5 (35.0)	34.7	2.9 (44.0)	29.0	8.0 (80.0)	79.2
31/10/09	12.7	5.0 (24.9)	39.2	4.5 (45.0)	35.4	4.2 (63.6)	33.4	10.0 (100.0)	78.8
4/11/09	8.7	3.1 (15.4)	35.3	2.5 (25.0)	28.7	2.4 (36.0)	27.6	6.0 (60.0)	69.0
8/11/09	7.8	2.2 (11.0)	28.2	1.9 (18.9)	24.2	1.8 (26.3)	22.4	4.9 (48.9)	62.7
2/12/09	22.2	15.0 (75.0)	67.5	12.8 (128.0)	57.7	12.4 (186.0)	55.9	19.6 (196.0)	88.3
8/12/09	23.5	14.8 (73.8)	62.8	13.0 (129.9)	55.3	12.8 (192.0)	54.5	20.2 (202.4)	86.1
22/12/09	20.8	12.2 (61.0)	58.7	11.8 (118.0)	56.7	11.7 (175.1)	56.1	17.0 (170.0)	81.7
7/1/10	35.3	21.3 (106.7)	60.5	19.2 (192.2)	54.5	18.7 (280.2)	52.9	30.3 (303.2)	85.9

B. Results and discussion on runoff from runoff plots during the 2010/2011 rainy season

Table 5.6 gives an illustration of the different amounts of runoff collected (with the rainfall volume in parentheses) and runoff efficiency for the different treatments. There were 26 rainfall events which generated runoff. In terms of the amount of volume of water collected from the drums in the pits at the bottom of runoff plots (totals not shown), 3 m x 5 m collected the highest volume (5348 L equivalent to 3565 m^3 ha^{-1}), followed by 2 m x 5 m (5102 L equivalent to 5102 m^3 ha^{-1}) and 1 m x 5 m (2736 L equivalent to 5473 m^3 ha^{-1}). It is worthwhile to notice that 2 x 5P collected more water than the rest (13080 L equivalent to 13080 m^3 ha^{-1}) for the reason mentioned above. The runoff volume gathered from the bottom of the drums showed that it widely depended on the size and the surface status of the contributing runoff areas. The amount of the water volume harvested from the bare runoff plots depended solely on the size of the area, the soil characteristics, the surface status, sloping gradient and length, antecedent soil water conditions, and climatic conditions. These factors are vital in defining to threshold (the minimum rainfall needed to initiate runoff) and runoff efficiency (the percentage of the total rainfall converted into runoff). As mentioned above, during the Swiss chard growing season, each rainfall event of about 3 mm and more could produce runoff on 2 x 5P (observation). In contrast, the runoff plots with bare surfaces required much higher threshold amounts to generate runoff. For example on the 22th December 2010, with a rainfall event of 6.5 mm, only 2 x 5P generated runoff while on the 24th February 2011, only 2 x 5P and 3 m x 5 m produced runoff with a rainfall event of 6.8 mm (observation). Therefore, 2 m x 5 m and 1 m x 5 m necessitated a minimum rainfall higher than 6.8 mm to trigger runoff. It must be noted that these respective threshold amounts could change (increase or decrease) due to several factors, mostly those affecting rainfall, catchment surface and soil characteristics.

In terms of runoff efficiency, it is evident from Table 5.6 that only the results for runoff harvested on 10 occasions are presented. As in the case of the 2009/2010 rainy season, failure of the automatic tipping buckets and datalogger imposed the manual handling of measurements which have sometimes led to uncontrollable overflowing problems. Table 5.6 shows that the range of runoff efficiencies were 28.7 – 68.2%, 30.9 – 69.5%, 31.4 – 71.7% and 69.7– 84.9% for 3 m x 5 m, 2 m x 5 m, 1 m x 5 m and 2 x 5P, respectively. It is obvious that the smaller the runoff area, the higher the runoff efficiency. These findings can partly be attributed to the fact that, on long non-mulched catchments, a massive runoff can be lost out of infiltration and E. It is also evident that the more impervious is the watershed, the higher the runoff efficiency. 2 x 5P was covered with plastic and therefore provided the highest results in terms of runoff volume, runoff depth and runoff efficiency.

Table 5.6: Rainfall, runoff depth (RD) and runoff efficiency (RE) (the runoff volume is given in the parentheses) recorded for different rainfall events during the 2010/2011 rainy season.

Date	**Rain (mm)**	**Runoff plots and their runoff-related data**							
		1 m x 5 m		**2 m x 5 m**		**3 m x 5 m**		**2 x 5P**	
		RD (mm)	**RE (%)**	**RD (mm)**	**RE (%)**	**RD (mm)**	**RE (%)**	**RD (mm)**	**RE (%)**
28/10/10	14.1	7.6 (38.2)	54.2	6.3 (63.0)	44.6	6.2 (92.6)	43.7	11.7 (116.8)	82.8
29/11/10	7.0	3.0 (15.2)	43.3	2.2 (21.6)	30.9	2.0 (30.2)	28.7	5.0 (49.5)	70.7
22/12/10	6.5	—	—	—	—	—	—	4.5 (45.3)	69.7
5/1/11	16.1	8.4 (42.0)	52.1	8.1 (81.0)	50.3	8.0 (120.3)	49.8	12.8 (128.0)	79.5
7/1/11	40.3	27.2 (133.3)	67.5	25.1 (251.0)	62.3	25.4 (380.6)	63.0	33.0 (329.6)	81.8
11/1/11	11.6	3.6 (18.2)	31.4	4.5 (45.3)	39.0	4.4 (65.6)	37.7	8.5 (85.0)	73.3
21/1/11	51.9	37.2 (186.0)	71.7	36.1 (360.9)	69.5	35.4 (530.9)	68.2	44.0 (439.9)	84.8
24/1/11	27.1	15.2 (75.8)	55.9	15.1 (151.0)	55.7	14.1 (211.4)	52.0	23.0 (230.0)	84.9
27/1/11	43.0	26.1 (130.6)	60.7	25.9 (259.1)	60.2	25.1 (376.7)	58.4	36.0 (360.0)	83.7
8/2/11	14.1	9.1 (50.7)	64.8	7.5 (75.3)	53.4	7.5 (112.5)	53.2	10.0 (100.0)	70.9

In terms of runoff efficiency, it is evident from Table 5.6 that only the results for runoff harvested on 10 occasions are presented. As in the case of the 2009/2010 rainy season, failure of the automatic tipping buckets and datalogger imposed the manual handling of measurements which have sometimes led to uncontrollable overflowing problems. Table 5.6

shows that the range of runoff efficiencies were 28.7 – 68.2%, 30.9 – 69.5%, 31.4 – 71.7% and 69.7– 84.9% for 3 m x 5 m, 2 m x 5 m, 1 m x 5 m and 2 x 5P, respectively. It is obvious that the smaller the runoff area, the higher the runoff efficiency. These findings can partly be attributed to the fact that, on long non-mulched catchments, a massive runoff can be lost out of infiltration and E. It is also evident that the more impervious is the watershed, the higher the runoff efficiency. 2 x 5P was covered with plastic and therefore provided the highest results in terms of runoff volume, runoff depth and runoff efficiency.

The current investigation results for both seasons can be substantiated by the literature. It was reported that the watershed-runoff relationship in arid and semi-arid areas has long been reported and it turns out that the volume of the harvested runoff is directly proportional to the size and length of the runoff harvesting structure (Li *et al.*, 2006, Ali *et al.*, 2010; Ibraimo, 2011). However, the unit runoff volume (runoff yield expressed on m^3 per ha basis) is inversely proportional to the catchment area (Ali *et al.*, 2010). These latter authors did research on the effect of the MCWH technique on a sandy-clay-loam soil of which, according to USDA soil classification guidelines, the soil near the surface varied from sandy-clay-loam to sandy-loam. This type of soil was considered vulnerable to crust formation and thereby tendentious to low infiltration rate and high runoff generation (Morgan, 1995). The results revealed that small MCs eventually generated 25% higher annual runoff yield than large MCs. Both per plot area and per ha runoff results of the current study perfectly agreed with these findings (Table 5.6). Furthermore, factors other than the catchment size and length also have the potential to interfere with runoff depth and volume. For example, Mishra & Singh (2003) maintained that several factors affect surface runoff; and these include among others, precipitation (amount, duration and intensity), soil type, initial soil water content, vegetation and topography (Mishra & Singh, 2003). According to Anschütz *et al.* (2003), factors impacting on infiltration and runoff are soil type, texture and structure, sealing and crusting, vegetation, slope length, and size and conditions of runoff producing areas.

5.3.5 Soil loss during the 2009/2010 and 2010/2011 rainy seasons

A. Soil loss during the 2009/2010 rainy season

Table 5.7 shows the different amount of soil in sediment and suspension, and the volume of runoff collected from the different drums. In terms of the amount of soil in sediment, 30.3, 29.3 and 14.7 kg were obtained for 3 m x 5 m, 2 m x 5 m and 1 m x 5 m, respectively. As regards the amount of soil in suspension, the order was similar to the one obtained with the soil in sediment, i.e., runoff plots 3 m x 5 m, 2 m x 5 m and 1 m x 5 m yielded 6.3, 6.0 and 3.0 kg of soil, respectively. From Table 5.7, it can be observed that both the quantity of soil in sediment and suspension amount to 36.6, 35.3 and 17.6 kg, respectively. These amounts, on a hectare basis, are equivalent to 24.4, 35.3 and 35.3 t for the different runoff plots, respectively. This means that the increase in soil loss is not directly proportional to the increase in runoff plot size, i.e. the relationship is not linear. However, the results for 2 m x 5 m and 1 m x 5 m are very close to each other. It is also worthwhile mentioning that the per m^2 outcomes were 2.4, 3.5 and 3.5 kg m^{-2} for 3 m x 5 m, 2 m x 5 m and 1 m x 5 m, respectively.

The findings of the current research showed that the amount of soil in the sediment and suspension are not necessarily proportional to the amount of runoff collected. This can be seen in Table 5.7 by comparing the sediment data for December with those for February. This situation also applied to suspension by analysing daily data (observation). Similarly, the size of the area does not always reflect the amount of soil loss (observation). From Table 5.8, the suspension concentration of the runoff plots varied in the range of 2.27 – 4.54, 2.27 – 4.45 and 1.80 – 3.67 g L^{-1} for 3 m x 5 m, 2 m x 5 m and 1 m x 5 m, respectively. The longer the runoff area the more loaded the runoff due to the distance covered.

Table 5.7: Amount of soil in sediment and suspension and the volume of runoff from the drums for the 2009/2010 rainy season.

Month	**Runoff plots**									**Total (sediment + suspension)**		
	1 m x 5 m			**2 m x 5 m**			**3 m x 5 m**					
	Sed[1]	**Sus[2]**	**Run[3]**	**Sed[1]**	**Sus[2]**	**Run[3]**	**Sed[1]**	**Sus[2]**	**Run[3]**	**1 m x 5 m**	**2 m x 5 m**	**3 x 5 m**
October	2.68	0.07	18.04	8.53	0.14	29.74	8.56	0.20	43.71	2.75	8.66	8.76
November	6.20	1.29	565.76	9.15	2.56	1010.65	9.23	2.63	1025.23	7.48	11.70	11.85
December	1.86	0.70	222.85	3.14	1.39	397.29	3.29	1.39	397.29	2.55	4.51	4.68
January	2.01	0.74	280.53	4.39	1.20	530.75	4.93	1.28	537.95	2.74	5.59	6.21
February	1.93	0.21	113.00	4.15	0.75	295.93	4.32	0.82	361.98	2.13	4.89	5.14
Total	14.68	2.98	1200.17	29.33	6.03	2264.34	30.32	6.30	2366.14	17.63	35.33	36.61

Sed[1]: soil amount in sediment (kg) runoff plot^{-1}; Sus[2]: soil amount in suspension (kg) runoff plot^{-1} and Run[3]: runoff volume collected from the drums (L) runoff plot^{-1}.

Table 5.8: Suspension concentration (g L^{-1}) for the 2009/2010 rainy season.

Month	**Runoff plots**								
	1 m x 5 m			**2 m x 5 m**			**3 m x 5 m**		
	Sus[1]	**Run[2]**	**Con[3]**	**Sus[1]**	**Run[2]**	**Con[3]**	**Sus[1]**	**Run[2]**	**Con[3]**
October	0.07	18.04	3.67	0.14	29.74	4.45	0.20	43.71	4.54
November	1.29	565.76	2.28	2.56	1010.65	2.54	2.63	1025.23	2.56
December	0.70	222.85	3.10	1.39	397.29	3.48	1.39	397.29	3.48
January	0.74	280.53	2.61	1.20	530.75	2.27	1.28	537.95	2.38
February	0.21	113.00	1.80	0.75	295.93	2.54	0.82	361.98	2.27

Sus[1]: suspension (g); Run[2]: runoff (L) and Con[3]: concentration (g L^{-1}).

B. Soil loss during the 2010/2011 rainy season

Table 5.9 shows the different amounts of the monthly soil sediment, suspension and the volume of runoff collected from the different drums. The results are presented on a monthly basis since the runoff data collection carried on to the end of the rainy season. With regard to the amount of soil in sediment, 3 m x 5 m, 2 m x 5 m and 1 m x 5 m received 40.7, 38.4 and

19.8 kg per plot, respectively. These amounts, on a hectare basis, amounted to 27.1, 38.4 and 39.7 t for the different runoff plots, respectively. In terms of the amount of soil in suspension, the order remained consistent with the one observed with the soil in sediment, i.e., 12.6, 11.4 and 5.8 kg for 3 m x 5 m, 2 m x 5 m and 1 m x 5 m, respectively. The conversion of these amounts into tonnes and their expression on a hectare basis resulted in 2.9, 3.8 and 6.8 t for 3 m x 5 m, 2 m x 5 m and 1 m x 5 m, respectively. Table 5.9 indicates that the total quantity of soil in sediment and suspension amounted to 53.3, 49.8 and 25.6 kg per runoff plot for 3 m x 5 m 2 m x 5 m and 1 m x 5 m, respectively. Converting these values into t ha^{-1}, the results became 35.5, 49.8 and 51.2 t ha^{-1}for the respective runoff plots. This shows that the relationship between soil loss and runoff plot size is not linear as noted previously. In addition, it is worthwhile to mention that the per m^2 results were 3.55, 4.98 and 5.12 kg m^{-2} for the above-mentioned runoff plots, respectively.

As in the case of the 2009/2010, the present study (Table 5.9) showed that the relationship between the amount of soil in the sediment (or in the suspension) and the amount of runoff collected (or the size of the runoff plots) is not linear. For instance, in May 2011, 2 m x 5 m collected a runoff of 133.3 L, resulting in sediment with 1.57 kg of soil and a suspension with 0.13 kg of soil (the total of 1.7 kg). But in April 2011, this runoff plot generated a runoff of 308.7 L, resulting in sediment with 1.39 kg of soil and a soil suspension with 0.07 kg of soil (a total of 1.46 kg). From Table 5.10, the suspension concentration of the individual runoff plots varied in the range of 1.36 – 4.54, 0.23 – 4.44 and 0.08 – 3.66 g L^{-1} for 3 m x 5 m, 2 m x 5 m and 1 m x 5 m, respectively. The reason behind this trend is the same as the one given in the previous section.

Table 5.9: Amount of soil in sediment and suspension and the volume of runoff from the drums for the 2010/2011 rainy season.

Month	**Runoff plots**									**Total (sediment + suspension)**		
	1 m x 5 m			**2 m x 5 m**			**3 m x 5 m**					
	Sed[1]	**Sus**[2]	**Run**[3]	**Sed**[1]	**Sus**[2]	**Run**[3]	**Sed**[1]	**Sus**[2]	**Run**[3]	**1 m x 5 m**	**2 m x 5 m**	**3 x 5 m**
October	0.81	0.02	5.46	2.58	0.04	9.00	2.59	0.06	13.23	0.83	2.62	2.65
November	5.96	1.24	543.95	8.79	2.46	971.70	8.87	2.52	985.72	7.19	11.24	11.39
December	2.88	1.07	345.46	4.86	2.14	615.87	5.10	2.14	615.87	3.94	6.99	7.24
January	4.48	1.63	625.70	9.77	2.68	1183.8	10.99	2.85	1199.86	6.11	12.45	13.83
February	2.19	0.23	128.27	4.70	0.85	335.92	4.90	0.93	410.89	2.41	5.55	5.83
March	2.46	1.45	864.83	4.77	3.02	1543.8	4.96	3.39	1585.73	3.91	7.78	8.35
April	0.48	0.13	173.03	1.39	0.07	308.65	1.50	0.42	308.62	0.61	1.45	1.91
May	0.61	0.04	49.76	1.57	0.13	133.25	1.79	0.33	241.43	0.65	1.70	2.12
Total	19.84	5.78	2736.43	38.40	11.36	5102.0	40.69	12.6	5348.11	25.62	49.75	53.29

Sed[1]: soil amount in sediment (kg) runoff plot^{-1}; Sus[2]: soil amount in suspension (kg) runoff plot^{-1} and Run[3]: runoff volume collected from the drums (L) runoff plot^{-1}.

For both rainy seasons, not all rainfall events were considered due to overflowing, therefore, it was not possible and appropriate to calculate the seasonal runoff, sediment loss or suspension. Moreover, the increase in soil loss was not directly proportional to the increase in plot size, i.e. the relationship is not linear. Furthermore, observation from both cases showed that the concentration was high at the beginning of the rainy season and then lowered later on. The outcomes from both rainy seasons can be explained by the literature. Ibraimo (2011) has carried out an IRWH trial on the same field with maize for the period 2007/2008. Only the mixed sediment was collected and the results were: 49.8 kg per plot (33.2 t ha^{-1}), 46.6 kg per plot (46.6 t ha^{-1}) and 27.2 kg per plot (54.4 t ha^{-1}) for 3 m x 5 m, 2 m x 5 m and 1 m x 5 m, respectively. The experiment was about IRWH with maize during the rainy season of 2007/2008 and only the mixed sediment was collected from the drums on each rainfall event. These values are in the range of those from the current investigation. The little disparity could have been caused by the amount, duration and intensity of rain storms of the different growing seasons and years. Also, differences in surface management could lead to discrepancies in the collected runoff and sediment due to topography and surface status. Another factor that could induce disparities is the operation errors and overflowing as the data collection in the current study was now and then conducted manually. In terms of per m^2 results, Botha *et al*. (2003) have reported a soil loss rate in the 2m-long cropping area of 3.70 kg m^{-2} season^{-1} on a Glen/Bonheim Ecotope (Bloemfontein), which is lower than the result we collected from the 2m-long microplot (4.98 kg m^{-2}). Factors such as number of runoff collected, topography, soil characteristics, field management are able to cause disparities between the two ecotopes.

Table 5.10: Suspension concentration (g L^{-1}) for the 2010/2011 rainy season.

Month	**Runoff plots**								
	1 m x 5 m			**2 m x 5 m**			**3 m x 5 m**		
	Sus^1	**Run^2**	**Con^3**	**Sus^1**	**Run^2**	**Con^3**	**Sus^1**	**Run^2**	**Con^3**
October	20.00	5.46	3.66	40.00	9.00	4.44	60.00	13.23	4.54
November	1240.00	543.95	2.26	2460.00	971.70	2.53	2520.00	985.72	2.56
December	1070.00	345.46	3.10	2140.00	615.87	3.47	2140.00	615.87	3.47
January	1630.00	625.70	2.61	2680.00	1183.80	2.26	2850.00	1199.86	2.38
February	230.00	128.27	1.79	850.00	335.92	2.53	930.00	410.89	2.26
March	1450.00	864.83	1.68	3020.00	1543.83	1.96	3390.00	1585.73	2.14
April	130.00	173.03	0.75	70.00	308.65	0.23	420.00	308.62	1.36
May	40.00	49.76	0.08	130.00	133.25	0.98	330.00	241.43	1.37

Sus^1: sediment (g); Run^2: runoff (L) and Con^3: concentration (g L^{-1}).

Very high soil losses on steep areas have been reported. For example, according to the main erosion results from the 250 runoff plots carried out in Rwanda and Burundi, the rainfall erosivity index (Wischmeier & Smith, 1960) varied from 250 to 700 in Rwanda (Ryumugabe & Berding, 1992) and attained 950 in Burundi (Duchaufour & Bizimana, 1992). At the same time, they reported that erosion on bare plots in these countries was very high (300 to 700 t ha^{-1} year^{-1}), while the risk of runoff was only within 40% of major storms. However, it is worth mentioning that the rainfall range in these countries is 1000 – 2000 mm per year and that the investigation was conducted on ultisols of very steep slopes, varying between 23 and 55% (Ndayizigiye, 1992; Köning, 1992; Duchaufour & Bizimana, 1992; Rishirumuhirwa, 1992). Similarly, high suspension concentrations have been also reported in the literature. Gebreegziabher *et al.* (2009) pointed out that the highest suspension concentration was linked to the onset of the rainy season for all treatments. In the first two rainfall events, the runoff from the traditional ploughing system yielded a suspension concentration of 166 g L^{-1}, while no sediment was collected from the permanent raised beds and the intermediate system. On the 4th July 2005, the suspension concentrations for the above-mentioned treatments were 199, 179 and 69 g L^{-1}, respectively. In a separate development, Shangguan *et al.* (2002) declared that in general, road produced relatively high sediment output from relatively large runoff volume. Instantaneous sediment concentrations from roads were initially constant at 100 g L^{-1} but fell over time as loose material was flushed from the surface. During the current investigation, the suspension concentrations were, in general, high in the beginning of the rainy season as was the case in the above-mentioned studies. Gebreegziabher *et al.* (2009) attributed this pattern to the impact of the direct rain splash on the bare surface of the top layer of loose soil, which detached and transported the soil aggregates in the beginning of the rainy period, but which was resisted by the relatively resilient soil surface later in the season. Owing to several factors, the total sediment loss and suspension concentrations provided by the present trial are by far lower than all the results from the steep areas reported in the literature.

5.4 Conclusions and recommendations

Arid and semi-arid environments of sub-Saharan Africa represent areas where rainfall is unpredictable and crop production is affected by both water stress and recurrent dry spells. In these regions, sustainable soil and water conservation as well as improved crop yield can be achieved by means of rainwater runoff harvesting. However, knowledge of rainfall probability and predictability during a crop growing season is primordial.

The long-term (15 year) data of the Hatfield Experimental Farm showed that the probability of getting or exceeding different amounts of monthly and annually rainfall shrank as the threshold rainfall amounts increased. The month of January was the wettest month in the long term. However, the data from the 2009/2010 rainy season revealed that the month of December was the wettest. The site is also characterized by high probability of light rainfalls (storms of equal or less than 5 mm) and short dry spells; with an AI of 0.40 (semi-arid), even though the potato growing season (2009/2010) had a mean AI of 0.80 (humid). The

2009/2010 rainy season at the Hatfield Experimental Farm had a total rainfall of 768 mm, which is higher than the average rainfall (670 mm); while ETo was relatively low. In the case of the 2010/2011 Swiss chard growing season, only a short period towards the end of the growing season received rainfall since it is a winter crop and the study site is in a summer rainfall area. The long-term AI for the period October – November was 0.32. During the 2010/2011 rainy season, November revealed as humid with an AI of 0.76 while the mean 2-month AI was 0.45. However, the entire 2010/2011 crop growing season showed a rainfall amount of 900 mm.

With respect to runoff volume collected from the drums installed in the pits at the southern end of each runoff plot, it was revealed that for the bare runoff plots, the longer the surface runoff area the higher the collected runoff, sediment and suspension. However, in general, the situation was reversed when the volumes were reported on a hectare basis. Actually, in terms of runoff depth, runoff efficiency, it turned out that the smaller the runoff plot the deeper the runoff depth, and the higher the runoff efficiency. In addition, the increase in soil loss is not directly proportional to the increase in runoff plot size. Since the runoff plot with plastic mulch was impervious to water, it collected more water and showed higher values in terms of runoff depth and runoff efficiency.

The definition of the growing season according to FAO (1978) can provide some guidance in the prediction of wet and dry spells, as well as in the planning of the seeding time or what cultivar to plant in rainfed (RWH) agriculture. However, in order to further elucidate the growing season understanding, it should be advisable to make use of a synergy between this concept and others, for example, Berger (1989) and Inthavong *et al*. (2011). This should call for a convergence of efforts from different scientific disciplines to come up with brilliant ideas and ingenious work in this regard. Furthermore, an automatic weather station (where not available), as well as devices for soil analysis and soil water content assessing should be available in order to provide sufficient climatic and soil water data in arid and semi-arid areas.

In the runoff recording and harvesting systems, failure and overflowing problems are common and therefore should be strenuously addressed. For the automatic system breaking down, extra caution must be exercised to ensure that the devices are in good working condition. For the overflowing concern, massive containers (for example, waterproof underground tanks) should be built next to the drum housing pits in order to collect all water from the runoff plots and prevent it from spilling over the drums and being lost. This water can be used in supplemental irrigation in the event of intra- or off-seasonal dry spells or simply when supplementary irrigation is applied to RWH plots. In this regard, a drip or micro-irrigation system should be installed and connected to the runoff collecting tanks and operated when needed. This can further be generalized that supplemental irrigation should always accompany RWH agriculture.

Among other issues pertaining to the runoff recording and harvesting systems, can be mentioned the problem rising from the amounts of runoff and sediment (in the case of the automatic equipment failure) which remain in the tipping buckets when a rainfall event has stopped, especially, in the event of heavy storms. As a matter of fact, the system is not to be tampered with when collecting runoff and sediment (and thus nutrients) from the drums, and these uncounted amounts lead to erroneous conclusions towards the exact extent to which these items have amounted. The calibration of the tipping bucket may only ambiguously address the runoff problem but can never solve the issue of sediment and nutrients. Therefore, there should always be inaccuracy between data from consecutive rainfall events. To mitigate this matter, devices to record the amount of sediment and nutrients in the collected runoff should be inevitable. Moreover, there is an emphasized necessity for the use of models on rain erosivity, soil erodability and nutrient loss from runoff. As an addendum to all these recommendations, increased field experiments on runoff management are crucial. Finally, the trials showed how effective is RWH in terms of combating soil erosion; therefore, the part of the hypothesis 3 related to soil erosion was accepted.

The 15-year weather data analysis showed that the onset of the normal growing season is in October while the cessation is in April. In RWH agriculture terms, this is propitious to the spring potato crop production at Hatfield (Pretoria) which is a summer rainfall region. During the course of the 2009/2010 RWH trial, the potato crop was planted in the beginning of October; it reached the maturity stage in the end of January and was harvested in the beginning of February. This shows that the crop harvest was conducted in the second intermediate period of the normal growing season, nearly three months before the end of the normal growing season. The total rainfall from the planting date until crop harvest was 407 mm; while ET for the different treatments mentioned in Chapter 3 (Section 3.3.10) varied from 383 mm to 427 mm for CT and 3:1P, respectively. Early research has also reported that seasonal potato ET ranged from 350 to 800 mm for different climatic conditions (Fabeiro *et al*., 2001; Panigrahi *et al*., 2001; Ferreira & Carr, 2002; Onder *et al*., 2005). However, it was reported that the ideal seasonal R for the potato crop to provide optimum yield should vary between 900 and 1400 mm (farmafripedia.ikmmergent.net/index.php/Irish_potatoes). However, the 30-year exceedance probability of this amount is low since for example, at Hatfield there is only 13% chance of exceeding 900 mm and null probability of exceeding 1400 mm. It is therefore evident that without the implementation of RWH technique it should be risky to carry out dryland potato production.

CHAPTER 6

PARAMETERIZATION OF RUNOFF PREDICTION MODELS

6.1 Introduction to rainfall-runoff models

In semi-arid climatic regions of the world, it is important to increase crop productivity with RWH because these areas face water scarcity and therefore food insecurity. Many types of RWH techniques have been reported (Boers & Ben-Asher, 1982; Frasier & Mayers, 1983; Carter & Miller, 1991; Hensley *et al*., 2000; Wiyo *et al*., 2000); however, field experiments for assessing these systems are very expensive and laborious. As a result, several models of RWH and comprehensive models of rainfall-runoff-yield systems have been developed (Gould & Nissen-Petersen, 1999; Young *et al*., 2002). A model is a simplified representation of a system where the system is a part of a reality that contains interrelated elements (De Wit, 1982; Haverkort & Kooman, 1996; Muleta & Nicklow, 2005). Simple linear (Hensley *et al*., 2000), curve number (CN) (USDA-SCS, 1985), Morin and Cluff (1980), as well as other models have been developed for the prediction of runoff in RWH crop production (Hensley *et al*., 2000).

Runoff models were developed in the late 1960’s and early 1970’s (Madsen *et al*., 2002). Most of these runoff models consist of two types: on one hand, infiltration models are used to disaggregate rainfall into runoff and infiltration, and on the other hand, runoff models are used to simulate runoff (Horton, 1940; Morin and Cluff, 1980; Morin *et al*., 1983; Madsen *et al*., 2002; Chahinian *et al*., 2005; Xuefeng & Marino, 2005). Recently, the runoff models have been combined with several physical and conceptual infiltration models developed in this regard. These models include among others: Green and Ampt (1911), Horton (1940), Philip (1957), Soil Conservation Service (SCS) – USDA (1972), Morel-Seytoux (1978) and Morin and Cluff (1980). Besides Philip (1957) and Morel-Seytoux (1978) which are physical models, the remaining are either conceptual or empirical models (Chahinian *et al*., 2005).

In the current study, three models were evaluated for their ability to simulate runoff resulting from rain falling on the runoff plots involved. These runoff plots are different from the experimental plots for the different treatments used in the RWH trials presented in Chapters 3 and 4. The models used are as follows: linear regression equations, CN (USDA-SCS-CN (1972)) model, and the Morin and Cluff (1980) model. Both the linear regression and CN models are considered as empirical models. Therefore, their inclusion in the runoff simulation can be explained by the fact that they follow simpler procedures, which do not need rainfall intensity data for runoff modelling. Rainfall intensity data is seldom available for most weather stations or water harvesting sites. The choice of the Morin and Cluff (1980) runoff model can be attributed to the fact that it follows a conceptual procedure of runoff estimation from bare runoff plots, involving the main factors interacting with surface runoff. As a result, the model becomes more accurate and spatially-temporally distributed.

The purpose of this chapter was to parameterize, calibrate and validate runoff prediction models using the runoff information (reported in Chapter 5) from the two growing seasons (2009/2010 & 2010/2011) at the Hatfield Experimental Farm. Moreover, the runoff data collected from the 2009/2010 growing season were used for model calibration while those from the 2010/2011 rainy season were utilised for model validation.

6.2 Calibration and validation of the linear regression model

Rainfall-runoff linear regression analysis is based on the data of runoff and rainfall events. For IRWH, the runoff volume for each runoff plot is to be plotted against the corresponding rainfall amount. Linear regression model equations must be parameterized for each runoff plot, based on daily rainfall and runoff amounts. However, due to the technical problems experienced with the equipment, complete data sets could only be collected for 10 rainfall events for the 2009/2010 rainy season and 10 rainfall events for the 2010/2011 rainy season at the Hatfield Experimental Farm. The linear equation is expressed as:

$$\mathrm{Roff} = \mathrm{RE}*(\mathrm{R} - \mathrm{R_o}) \qquad \text{(Eq. 6.1)}$$

subject to $\mathrm{R} > \mathrm{R_o}$, or Roff = 0 otherwise

where: Roff is runoff (mm); RE is runoff efficiency (from regression equation, %); R is precipitation (mm); and $\mathrm{R_o}$ is the threshold rainfall (from regression equation, mm).

The Roff volume was measured in litres (L) and therefore conversion was required to turn the data into amounts of mm for the sake of consistency. In this regard, for each runoff plot, the volume Roff obtained in L was divided by the corresponding surface area in m^2, and the outputs are presented in Section 6.2.1 for the respective growing seasons.

6.2.1 Results and discussion on the calibration and validation of the linear regression model

The data recorded during the 2009/2010 (potato) and 2010/2011 (Swiss chard) growing seasons were used to investigate the rainfall-runoff relationship for the study area. As mentioned above, the rainfall and runoff data records from the first growing season were utilised in the model calibration (Figure 6.1) whereas those from the second rainy season were used in the model validation (Figure 6.2). To carry out the calibration process, the daily runoff depth from each runoff plot was plotted against daily rainfall amount, as shown by Figure 6.1. In addition, as runoff efficiencies for the runoff plots with bare runoff areas were close to each other, their equations were combined into one equation.

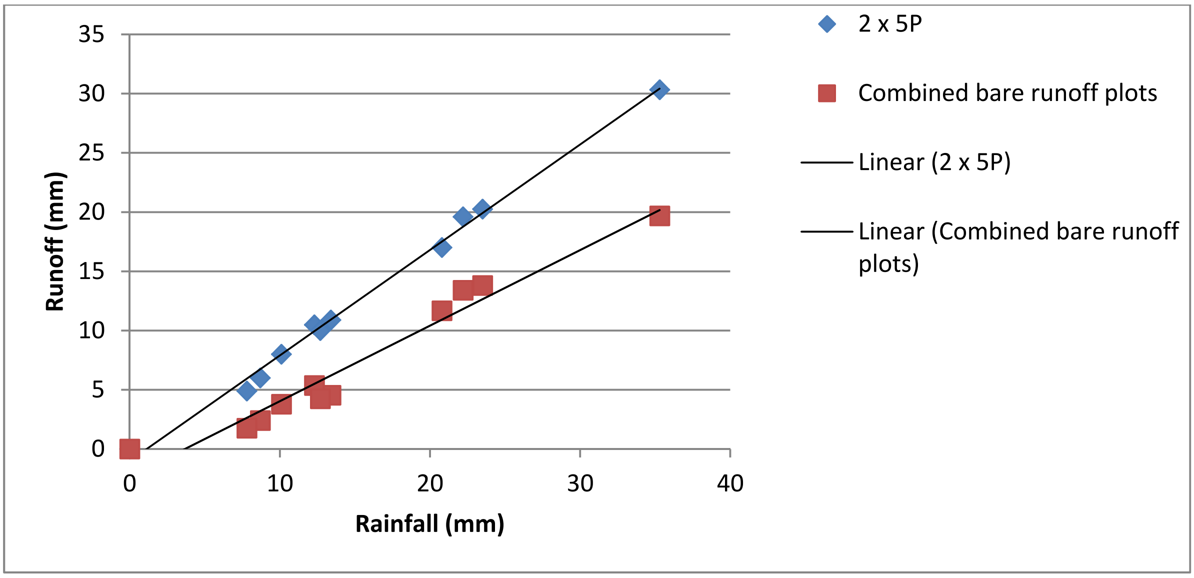


Figure.6.1: Linear regression model calibration for the plastic-covered runoff plot and the combined bare runoff plots for the 2009/2010 season.

From Figure 6.1 can be observed that the linear regression lines were fitted to the collected data to provide equations for estimating runoff produced rainfall events for each runoff plot.

The obtained equations for Figure 6.1 (2009/2010) are as follows:

Roff = 0.89 (R – 1.13) (with R > 1.13, otherwise Roff = 0) (R^2 = 0.99) (Plastic) (Eq. 6.2)

Roff = 0.64 (R – 3.68) (with R > 3.68), otherwise Roff = 0) (R^2 = 0.96) (Bare) (Eq. 6.3)

Eq. 6.2 represents runoff **(**mm) for the plastic-covered runoff plot (2 x 5P), for the 2009/2010 while Eq. 6.3 is a representation of the combined bare runoff plots for the rainy season. As shown by the equations, rainfall and runoff were in direct proportion and the measured runoff was perfectly predicted by the simulated runoff. This was confirmed by high coefficients of determination of 0.99 and 0.96 for the plastic-covered runoff plot and the combined bare runoff plots. The slopes of the equations are the runoff efficiencies, whilst the intercepts give an indication of rainfall thresholds before runoff occurrence. The runoff efficiency for the combined bare runoff plots was 64% while that for the plastic-covered runoff plot was 89%. The rainfall threshold of the combined bare runoff plots for both seasons was 3.68 while that of the runoff plot with plastic mulch was 1.13. These values seem to be lower than those measured, since the runoff thresholds of 2 x 5P and the combined bare runoff plots were 3 and more than 6.8 mm, respectively. However, the results given by the present study were in agreement with those reported in the literature, maintaining the existence of the direct correlation between runoff volume and rainfall amount. For example, Ibraimo (2011) found coefficients of determination of 0.9 for the bare runoff plots and 1.00 for the plastic-mulched runoff plot. In the study by Li *et al* (2004), positive coefficients of determination of 0.6 and 1.00 were reported for earthen and plastic-covered catchments, respectively. In addition, as shown in Figure 6.2, the model validation for the runoff plot with plastic and the combined runoff plots performed well, with coefficients of determination of 0.94 and 0.95, respectively.

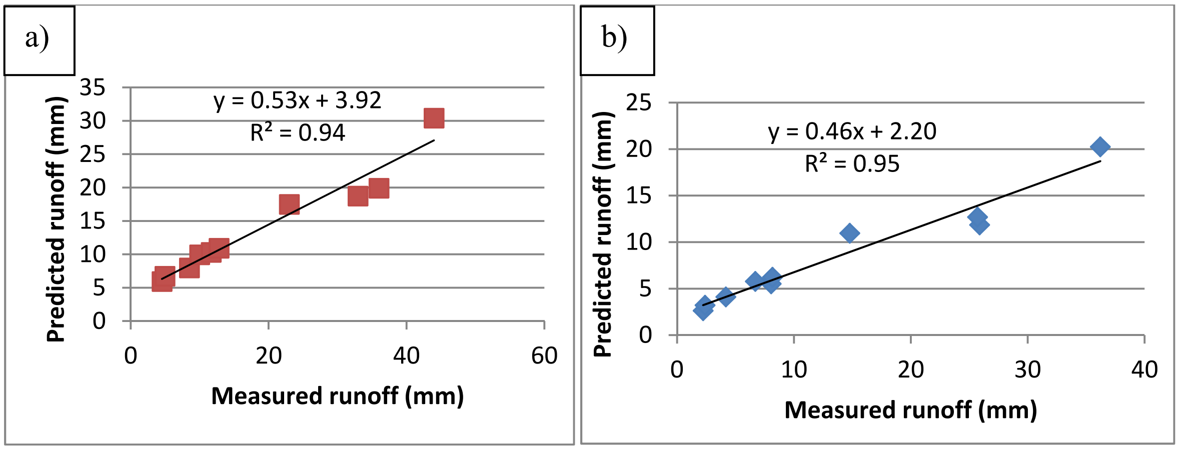


Figure 6.2: Linear regression model validation with predicted runoff (2009/2010) vs. measured runoff depth (2010/2011) for a) the plastic-covered runoff plot and b) the combined bare runoff plots.

6.3 Calibration and validation of the runoff curve number (CN) model

The SCS-CN (1972) indicates empirical relationships between the depth of direct runoff and the depth of precipitation after runoff commencement. This procedure can estimate runoff simply and straightaway. The equation of this method is as follows:

$\mathrm{Roff} = (R - 0.2*s)^2 / (R + 0.8*s)$ (subject to $R > 0.2*s$ or $\mathrm{Roff} = 0$ otherwise) (Eq. 6.4)

where: Roff is runoff (mm), R is precipitation (mm) and s initial abstraction (soil surface storage and retention) (mm).

This equation has been modified according to Woodward *et al.* (2003) to better simulate runoff from corresponding rainfall volumes. The modified model makes use of an initial abstraction ratio of 0.05 in lieu of 0.2. The initial abstraction value thus decreases, resulting in earlier runoff production for a given rain event. This earlier runoff generation is propitious for RWH in arid and semi-arid regions with high frequencies of small rainfall events. The modified equation is as follows:

$\mathrm{Roff} = (R - 0.05*s)^2 / (R + 0.95*s)$ (with $\mathrm{Roff} = 0$ for $R \leq 0.05$) (Eq. 6.5)

s is computed as:

$$s = (20000 / CN) - 200 \qquad \text{(Eq. 6.6)}$$

where: CN is the dimensionless curve number. CN is determined from antecedent soil water (moisture) content (AMC), which is an index of soil wetness for different hydrological soil groups in the USA. The CN could vary in the range of 0 – 100 (Mishra & Singh, 2003). A low CN gives the response expected from a field with good infiltration, while a high CN denotes the response from a field with a fairly uniform soil with a low infiltration capacity. Furthermore, 20000 and 200 are arbitrarily selected constants with the same units as s (in. or mm, 1 in. = 25.40 mm); and the conversion between $s_{0.05}$ and $s_{0.2}$ is:

$$\boxed{s_{0.05} = 1.33 * s_{0.2}^{1.15}} \qquad \text{(Eq. 6.7)}$$

As in the case of the linear regression model, the rainfall and runoff data recorded during the 2009/2010 rainy season were utilised for the calibration of the CN model while those for the 2010/2011 growing season were used for the model validation. The model calibration started by selecting a CN and therefore an s through trial and error, with a view to choose a CN which provides the best statistical parameter values to support the model performance. Then, predicted runoff was regressed against measured runoff from the 2009/2010 rainy season. The model validation was then carried out by plotting predicted runoff from the 2009/2010 rainy season against measured runoff from the 2010/2011 growing season. Moreover, the results of the calibration exercise were evaluated using the graphs of simulated and measured values, and statistical parameters such as the coefficient of determination (R^2), Willmott (1982) index of agreement (D), root mean square error (RMSE), and mean absolute error (MAE, %) (De Jager, 1994). To evaluate the model prediction relevance criteria, De Jager (1994) recommended that R^2 and D should be > 0.8, and MAE < 20%. According to Wikipedia (http: //en.wikipedia.org), Nash-Sutcliffe model efficiencies can range from -∞ to 1. An efficiency of 1 (Ef = 1) corresponds to a perfect match of simulated to the measured data. An efficiency of 0 (Ef = 0) indicates that the model predictions are as accurate as the mean of the measured data, while an efficiency below 0 (Ef < 0) occurs when the observed mean is a better predictor than the model. In essence, the closer the model efficiency is to 1, the more accurate the model is.

6.3.1 Results and discussion on the calibration and validation of the curve number (CN) model

Figure 6.3, the model calibration outcome, gives an illustration of the positive correlation between the predicted and observed runoff results for the 2009/2010 season. As presented in Table 6.1, the best soil and statistical results for 1 m x 5 m and 2 m x 5 m were obtained with a runoff CN of 96 and an s of 15.9 mm; whilst the best results of the predicted runoff for 3 m x 5 m were attained with a runoff CN of 95 and an s of 20.8 mm. The statistical parameters indicate that all runoff plots performed almost similarly with the CN model. The predicted runoff depth was positively correlated with the measured runoff. This was translated by high R^2 values. In addition, Table 6.1 shows that the runoff depth was well predicted with the CN model, which is reflected by high model efficiency (Ef) (or index of agreement – D, observation) values. Nevertheless, high MAE values linked with 1 m x 5 m show that there were variability among data. In addition, as shown in Figure 6.4, the model validation for the different bare runoff plots performed well, and this was reflected by high coefficients of determination.

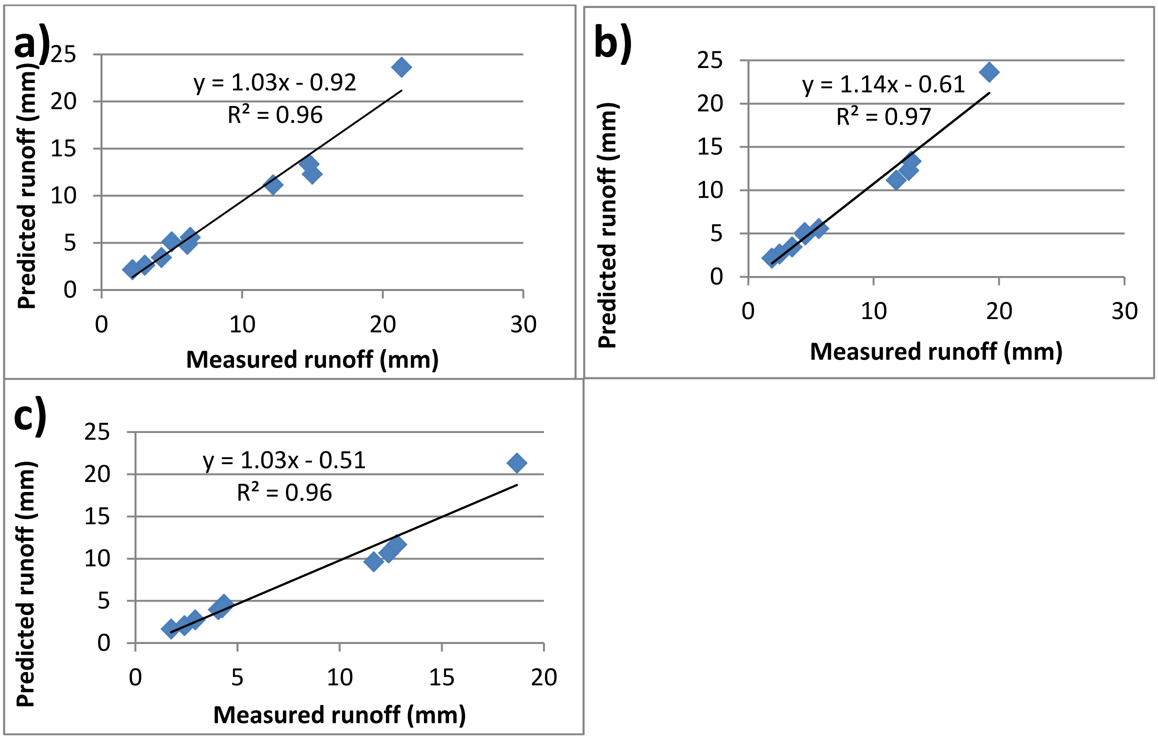


Figure 6.3: CN model calibration with predicted runoff vs. measured runoff depth for a) 1 m x 5 m, b) 2 m x 5 m and c) 3 m x 5 m runoff plots during the 2009/2010 season.

Table 6.1: Soil and statistical parameter characteristics of the CN model for the 2009/2010 rainy season.

Runoff plots	Soil parameters		Statistical parameters			
	CN	s (mm)	R^2	MAE (%)	RMSE	Ef
1 m x 5 m	96	15.90	0.98	39.40	1.48	0.97
2 m x 5 m	96	15.90	0.99	2.98	0.12	0.99
3 m x 5 m	95	20.80	0.99	16.67	0.63	0.98

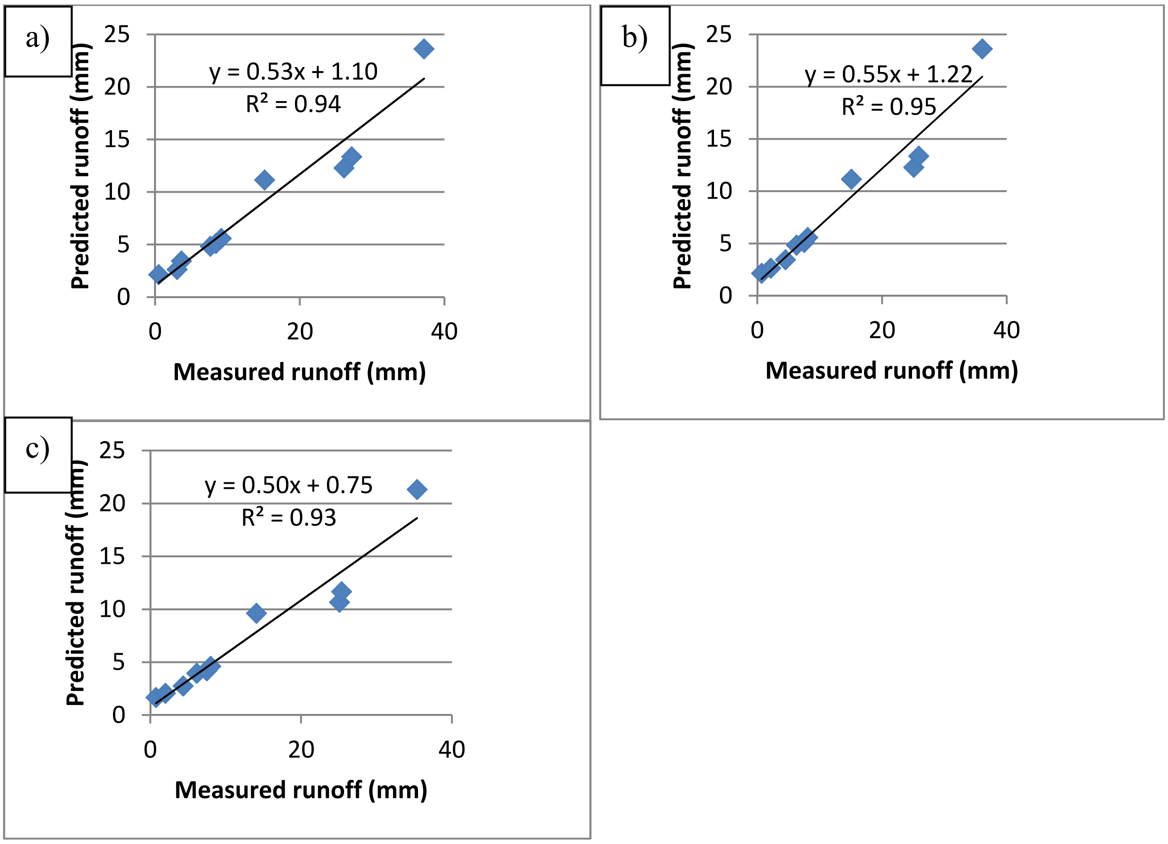


Figure 6.4: CN model validation with predicted runoff (2009/2010) vs. measured runoff depth (2010/2011) for a) 1 m x 5 m, b) 2 m x 5 m and c) 3 m x 5 m runoff plots.

The selection of the suitable CN value for the CN model becomes most critical. The higher the CN value, the closer the predicted runoff is to the observed runoff. As mentioned above (Mishra & Singh, 2003), a low CN shows a watershed in the field with high infiltration, whilst a high CN indicates the opposite tendency. In the current study, the CN which gave the best statistical parameters was 95 for 3 m x 5 m, and 96 for 1 m x 5 m and 2 m x 5 m. This discrepancy was probably due to the fact that CN strongly depends on antecedent soil water content which is characteristic for different hydrological soil groups in the USA.

6.4 Calibration and validation of the Morin & Cluff (1980) model

With the Morin & Benyamini's (1977) model, Morin & Cluff (1980) built a conceptual model which makes it possible to compute the runoff of any storm, segment by segment over the total storm duration. The model is as follows:

$$\sum Roff_i = \sum_{i=1}^{n} (I_i * \Delta t_i + s_{i-1} - Id_{\Delta ti} - s_m) \qquad \text{(Eq. 6.8)}$$

where Roff$_i$ is the surface runoff during segment i of the rainfall (mm); s_{i-1} is the surface storage and retention for the previous time segment t_{i-1} (mm); s_m is the maximum surface storage and retention (mm); I_i is the rainfall intensity (mm hr^{-1}); $Id_{\Delta ti}$ is the potential infiltration during any time segment Δt_i (mm); Δt_i is any time segment (hr); i is the number of the given periods per rainfall event (i = 1, 2, 3 . . .).

The integration of the Morin and Benyamini's (1977) equation over time provided $Id_{\Delta ti}$ (Morin & Cluff, 1980):

$$\boxed{Id_{\Delta ti} = I_{tf} * \Delta ti \frac{(I_{ti} - I_{tf})}{-\gamma * I_i} * [\exp(-\gamma * R_i) - \exp(-\gamma * R_{i-1})]} \qquad \text{(Eq. 6.9)}$$

$$\boxed{R_i = \sum I_i * \Delta ti} \qquad \text{(Eq. 6.10)}$$

where R_i is the cumulative rainfall over interval i (mm); R_{i-1} is the cumulative rainfall in the previous interval i-1 (mm); I_{ti} and I_{tf} are the soil initial and final infiltration rates (mm hr^{-1}), γ is the soil factor, which is an empirical soil parameter representing surface aggregate stability or resistance to reorientation (mm^{-1}).

The total amount of runoff per rainfall event (Roff) is the sum of runoff amounts over the whole period (all time intervals) is:

$$\boxed{Roff = \sum_{i=1}^{i=n} Roff_i} \qquad \text{(Eq.6.11)}$$

As in the cases of the linear regression and CN models, the rainfall and runoff data recorded during the 2009/2010 rainy season were used for the calibration of the Morin and Cluff (1980) model while those for the 2010/2011 growing season were used for the model validation. The model calibration commenced by choosing a surface retention (s) and soil stability factor (γ) via trial and error, with the aim to select the values which offer the best model performance. The processes of model calibration, evaluation and validation were performed as in Section 6.3.

6.4.1 Results and discussion on the calibration and validation of the Morin and Cluff (1980) model

Figure 6.5 shows the results of the calibration of the Morin and Cluff (1980) for the rainfall events of predicted vs. measured runoff using the Morin &Cluff (1980) model, for the 2009/2010 and 2010/2011 rainy seasons at the Hatfield Experimental Farm. As it can be observed from Table 6.2, the selected surface retention (s) and soil stability factor (γ) values were 2.49 mm and 0.69 mm^{-1}, respectively. Similarly to the CN model, the statistical parameters of the Morin & Cluff (1980) model predictions showed that all runoff plots performed very closely to each other. The predicted runoff was directly correlated with the observed runoff, and this was reflected by high R^2 values (0.97). Table 6.2 also denotes that runoff was well predicted with the Morin & Cluff (1980) model, which is explained by an Ef value of 1 (and high D, observation). However, MAE values indicated that there were variability among data, with all values > 20%. These results were evaluated according to De Jager (1994) as stated above. In addition, as shown in Figure 6.6, the model validation for the different bare runoff plots performed well, and this was indicated by high coefficients of determination.

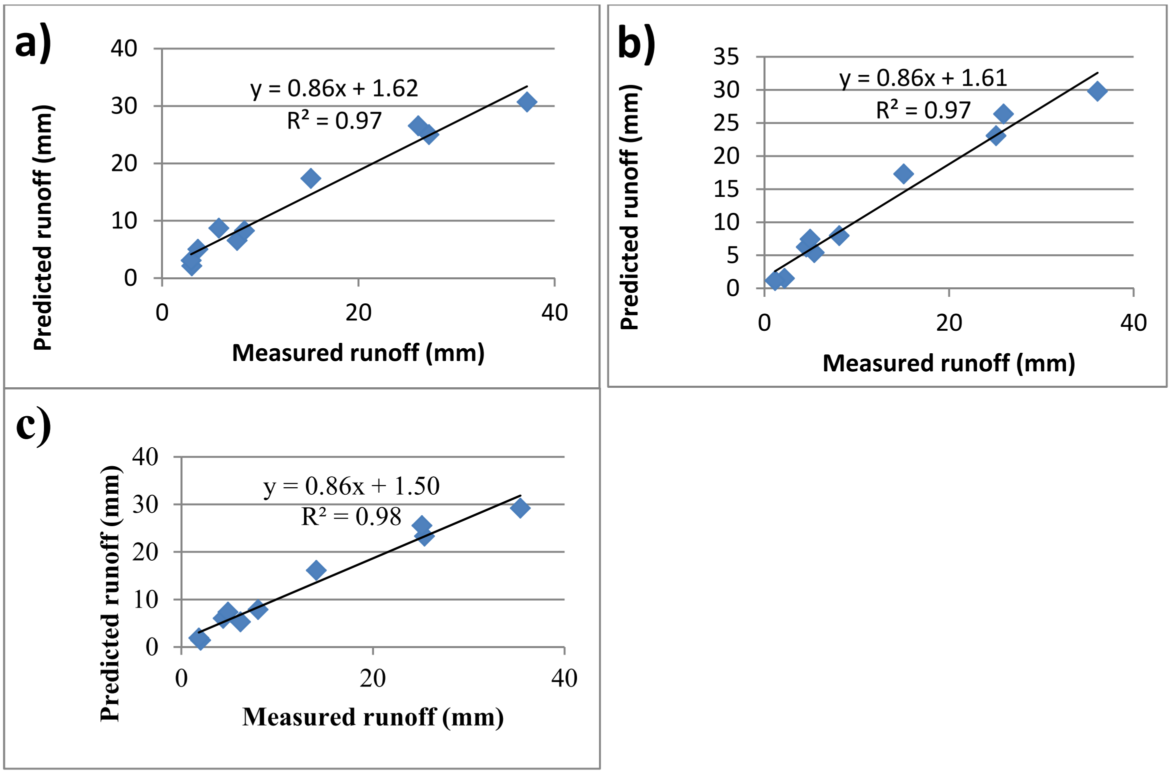


Figure 6.5: Morin & Cluff (1980) model calibration with predicted runoff vs. measured runoff depth for a) 1 m x 5 m, b) 2 m x 5 m and c) 3 m x 5 m runoff plots during the 2009/2010 season.

Table 6.2: Soil and statistical parameter characteristics of the Morin and Cluff (1980) model for the 2009/2010 rainy season.

Runoff plots	**Soil parameters**		**Statistical parameters**			
	s (mm)	**Γ(mm^{-1})**	**R^2**	**MAE (%)**	**RMSE**	**Ef**
1 m x 5 m	2.49	0.69	0.99	23.60	0.75	1.00
2 m x 5 m	2.49	0.69	0.99	19.40	0.61	1.00
3 m x 5 m	2.49	0.69	0.99	18.05	0.57	1.00

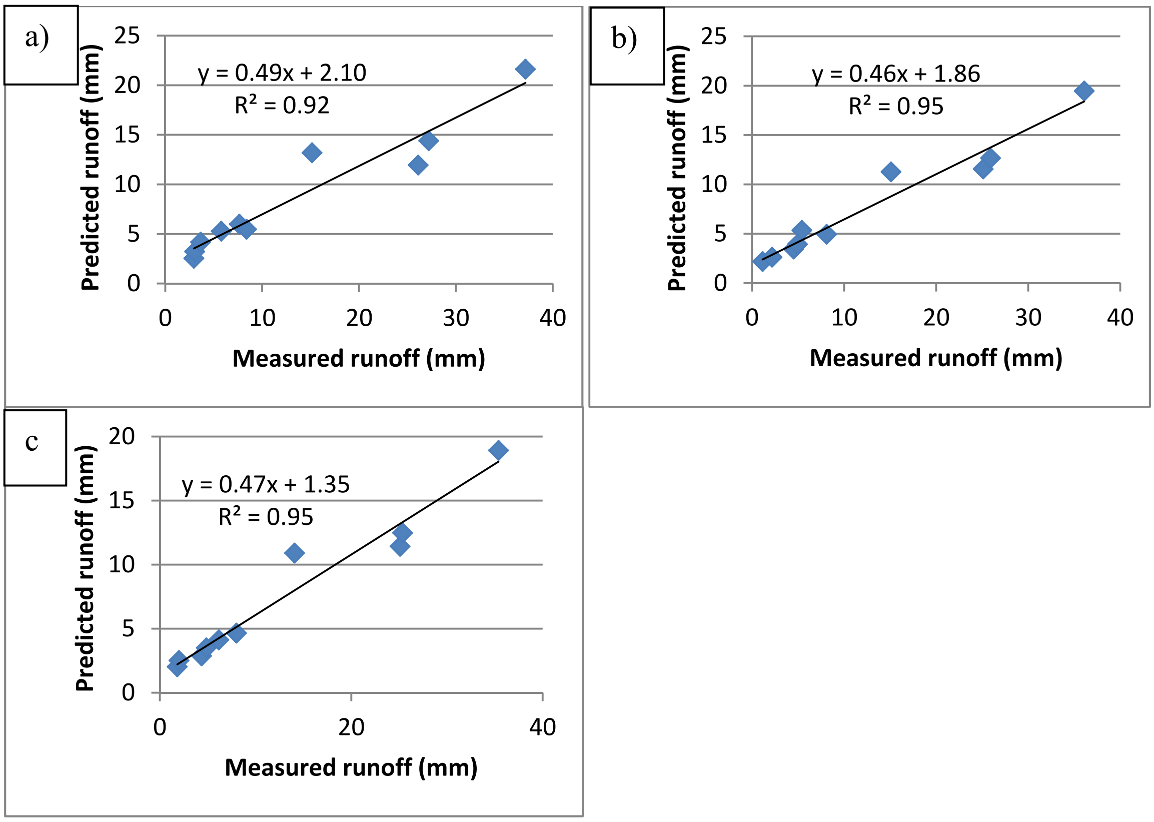


Figure 6.6: Morin and Cluff (1980) model validation with predicted runoff (2009/2010) vs. measured runoff depth (2010/2011) for a) 1 m x 5 m, b) 2 m x 5 m and c) 3 m x 5 m runoff plots.

Figure 6.7 indicates the cumulative (predicted) runoff versus the cumulative time for the respective bare runoff plots for the 7th January 2010 at the Hatfield Experimental Farm. The graphs are superimposed with a top-bottom order of 1 m x 5 m, 2 m x 5 m, 3 m x 5 m and predicted runoff. On the specific day the rainfall amounted to 35.3 mm. However, at the time that the automatic recording malfunctioned, the rainfall was 29.4 mm. The corresponding cumulative runoff amounts were 18.4, 17.8, and 17.7 mm for 1 m x 5 m, 2 m x 5 m and 3 m x 5 m, respectively; while the predicted runoff depth was 17.2 mm. The model predicted that runoff started after 1.58 hr, when the cumulative rainfall was 4.0 mm. However, according to the observed results, runoff inception for the different runoff plots started at different times. For both 1 m x 5 m and 2 m x 5 m, runoff began at nearly the same time after 1.25 hr when the cumulative rainfall was 3.1 mm. It was not until the 1.3 hr that 3 m x 5 m initiated runoff, when the cumulative rainfall was 3.4 mm. With regard to the rainfall end time, the model simulated that the rainfall ended after 9.6 hr, while field observations showed that it ended after 9.39, 10.01 and 10.12 hr for 1 m x 5 m, 2 m x 5 m and 3 m x 5 m, respectively.

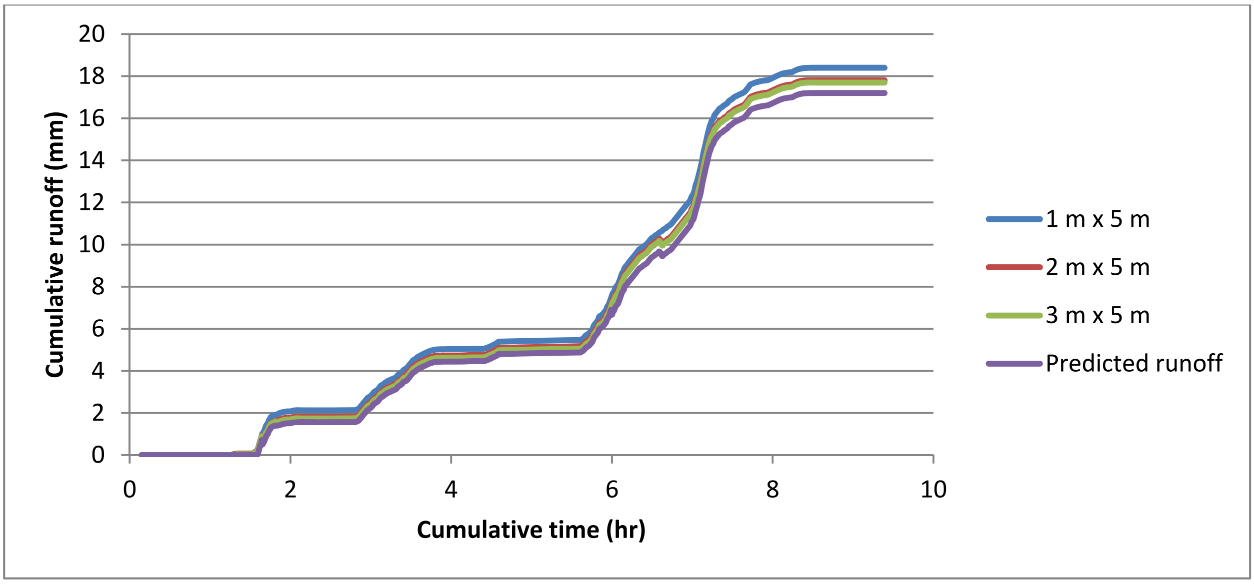


Figure 6.7: Morin & Cluff (1980) model predicted runoff vs. cumulative time for 1 m x 5 m, 2 m x 5 m and 3 m x 5 m for the rainfall event of 7th January 2010.

Figure 6.8 illustrates the cumulative (predicted) runoff versus cumulative time for the respective bare runoff plots for the 27th January 2011 at the Hatfield Experimental Farm. The curves are superimposed with a bottom-up order of 3 m x 5 m, 2 m x 5 m and 1 m x 5 m predicted runoff. On the 27th January 2011, the rainfall amounted to 43.0 mm. The observed cumulative runoffs were 26.6, 26.1, 25.9 mm for 1 m x 5 m, 2 m x 5 m and 3 m x 5 m, respectively, while the predicted runoff depth was 25.5 mm. The model predicted that runoff started after 1.62 hr, when the cumulative rainfall was 4.5 mm. Nevertheless, according to the recorded results, runoff onset for the runoff plots in the study occurred at the separate time. For both 1 m x 5 m and 2 m x 5 m, runoff started at nearly the same time after 1.28 hr when the cumulative rainfall was 3.0 mm. It was not until the 1.34 hr that 3 m x 5 m initiated runoff, when the cumulative rainfall was 3.20 mm. As regards the rainfall end time, the model predicted that the rainfall ended after 15.68 hr, while field observations show that it stopped after 15.89, 15.96 and 16.13 hr for 1 m x 5 m, 2 m x 5 m and 3 m x 5 m, respectively.

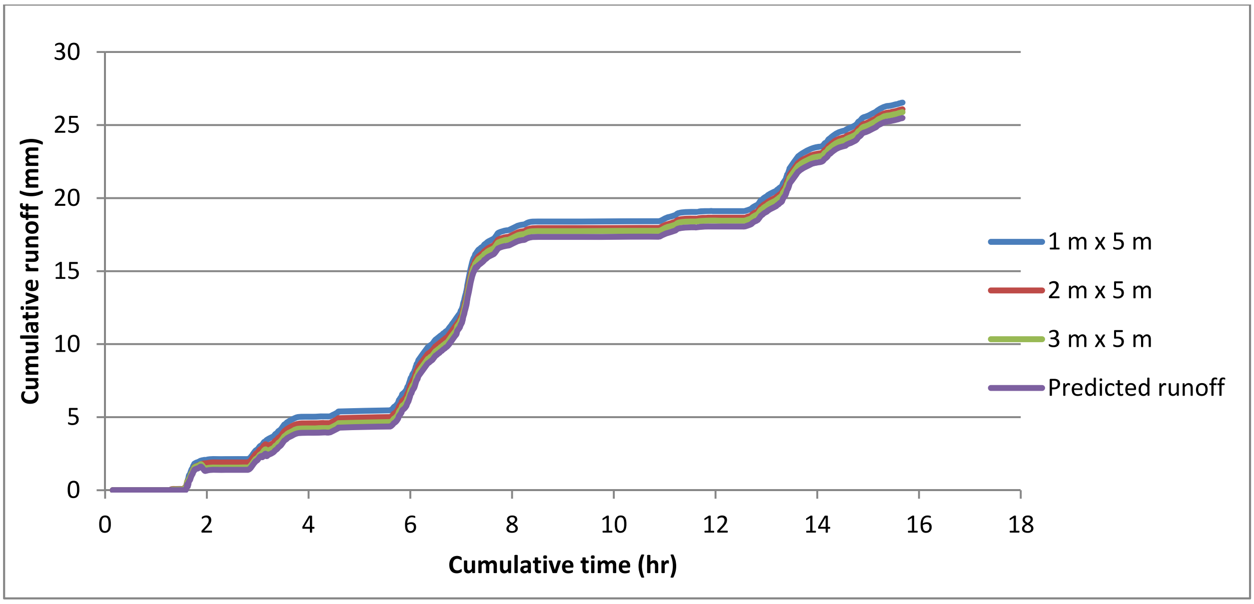


Figure 6.8: Morin & Cluff (1980) model predicted runoff vs. cumulative time for 1 m x 5 m, 2 m x 5 m and 3 m x 5 m for the rainfall event of 27th January 2011.

The Morin and Cluff (1980) runoff model was found to be very effective in estimating runoff in regions with high rainfall intensities and soils characterized by crust formation, like those of semi-arid areas (Welderufael, 2006); with infiltration rate more dependent on the soil crust physical morphology than the antecedent soil water. The model was tested and verified in the experiments conducted in the semi-arid areas of USA (Morin & Cluff, 1980) and Israel (Morin *et al.*, 1984) by comparing predicted results with observed experimental data. A rainfall intensity record arranged in a minute intensity base was used. The outcomes showed a coefficient of determination higher than 0.98 between the measured and model predicted runoff for both places.

6.5 Conclusions and recommendations

The linear regression equations, runoff CN (USDA-SCS-CN (1972)) model, and the Morin and Cluff (1980) runoff model were used to predict runoff generation during the 2009/2010 and 2010/2011 rainy seasons for the respective potato and Swiss chard growing seasons at the Hatfield Experimental Farm. Runoff data from the 2009/2010 growing season were used for model calibration while those from the 2010/2011 rainy season were utilised for model validation. The calibration results for the regression model revealed that runoff and rainfall were in direct proportion, which was indicated by high coefficients of determination, especially that of the runoff plot with plastic mulch which had an R^2 of 0.99 against 0.96 for the combined bare runoff plots. In the case of the CN method, CNs of 96 and 95, and s values of 15.90 and 20.80 mm (for the 2009/2010 growing season) were found to predict runoff well. The model calibration showed a positive correlation between the predicted and the observed runoff data. This was reflected by high coefficients of determination and high model efficiency (Ef) values. For the Morin and Cluff (1980) model, the best s and soil stability factor (γ) values selected for the 2009/2010 crop growing season were 2.49 mm and 0.69 mm^{-1}. As in the case of the CN model, the Morin and Cluff (1980) model calibration indicated a positive correlation between the predicted and the observed runoff data. The predicted runoff was directly correlated with the observed runoff, which was showed by high coefficients of determination values. The runoff was well predicted with the Morin and Cluff (1980) model, which is explained by an Ef = 1. Moreover, the validation of the three runoff models also performed well as it was indicated by the statistical parameters for model evaluation. Such calibrated models can be very useful to give guidance on the potential of RWH on specific ecotopes.

The results from the regression and CN models can be useful in arid and semi-arid areas, as these are empirical models which do not need rainfall intensity. However, empirical models are known to be site-related and can only be transferred with care. For instance, the CN model is highly sensitive to variables which are difficult to adjust, particularly the CN which is determined by the AMC, an index of wetness for different hydrological soil types of the USA. There is a need for a universal guideline in this regard. Before this issue can be addressed, unlimited runoff trials for each site and more scientific research are required in order to elucidate the ambiguity in respect of CN and s. In addition, the model must be tested for a wider range of watersheds. The Morin and Cluff (1980) model is believed to be very useful in the prediction of runoff in semi-arid areas which are characterized by severe soil crust formation and low infiltration rates. However, its high reliance on long-term rainfall intensity data makes it less useful to many potential users in dryland regions. More efforts in this regard must be conducted in order to install automatic weather stations to record data on shorter time step bases. Moreover, more models which account for rainfall time distribution should be involved in runoff prediction. Finally, rainfall-runoff relationships for the study ecotope were established satisfactorily with the rainfall and runoff data collected during the 2009/2010 rainy season. Furthermore, the Morin & Cluff (1980) model for the selected ecotope was perfectly parameterized and calibrated. This shows that the hypotheses 1 and 2 were accepted. The runoff models used in this study are highly recommended for the study ecotope.

CHAPTER 7

THE SOIL WATER BALANCE (SWB) MODEL PARAMETERIZATION AND CALIBRATION FOR POTATOES AND SWISS CHARD

7.1 Introduction

The Soil Water Balance (SWB) model is a generic crop, mechanistic, irrigation scheduling model (Campbell & Diaz, 1988; Annandale *et al*., 1999). SWB makes use of weather, soil and crop units to provide a detailed description of the soil-plant-atmosphere continuum (SPAC), and thus to calculate the soil water balance and crop growth. The Penman-Monteith reference crop evapotranspiration (ET) (Allen *et al*., 1998) coupled with a mechanistic crop growth model, which uses soil water and grows a realistic canopy and root system offer the best possible estimate of the soil water balance. The model has been packaged in a user-friendly format in an attempt to make it useful for real-time irrigation scheduling (Annandale *et al*., 1999).

According to Geremew (2008), SWB presents several advantages over the more empirical methods (Smith, 1992b). The description of crop development with the use of thermal time can be used instead of different crop factors for different planting dates and regions. Moreover, separating evaporation (E) from transpiration (T) resolves the issue of irrigation frequency, especially in the course of the crop's initial stage, when soil E is high as the crop canopy cover is still low (Villalobos & Fereres, 1990). When water is supply-limited, the model accurately describes deficit irrigation strategies (Annandale *et al*., 1999).

SWB's ability to merge crop water modelling and irrigation scheduling approaches enables it to become an invaluable tool which can assist farmers in decision-making. In this context, the model's accuracy in simulating potato crop growth and soil water balance components is expected to be high. Generic crop models incorporate a general principle implemented to all crops (including potato and Swiss chard), no matter how divergent they are in terms of physiological and ecological principle between crop classes, for example, cereals and root crops (Gayler *et al*., 2002). With regard to potatoes, Bennie *et al*. (1996) have grown spring potato (*Solanum tuberosum* cv. Buffelspoort BP13) at the experimental station of the

University of the Orange Free State. The model validation for the spring period was carried out with the available data from an autumn season (Steyn, 1997). According to this latter author, however, the model did not account for the impacts of photoperiod and high temperatures on phenology and photosynthate translocation, which resulted in inconsistent simulation results. Therefore, the incorporation of photoperiod in the model can improve the universal usefulness of the model in different growing seasons (spring and autumn).

Given that SWB uses a generic crop growth procedure, experiments have at first to be carried out in order to determine different crop specific parameters required to calibrate and run it. In this regard, the present investigations aimed at the generation of specific parameters for rainfed potatoes (*Solanum tuberosum*, cv. BP1) (2009/2010) and Swiss chard (*Beta vulgaris*, cv. Fordhook Giant) (2010/2011) grown at the Hatfield Experimental Farm of the University of Pretoria, South Africa. The obtained values were then to be incorporated in the SWB model database so that they become available for simulating potato and Swiss chard water use and growth.

7.2 Model description

SWB offers two types of model options: (i) the mechanistic crop growth model calculates crop growth and soil water balance components; and (ii) the FAO-type crop factor model computes the soil water balance without mechanistically simulating dry matter production and canopy development. During the current investigation, only the crop growth model was utilized and as such, the FAO model is not described in this chapter. In the crop growth model, SWB calculates water balance and crop growth using three units, i.e. soil, crop and weather. In the weather unit, the computation of the daily grass reference ET (ETo) is performed with the Penman-Monteith equation. The three sub-units of the SWB model are briefly described in the following paragraphs.

The soil unit simulates the dynamics of water movement in the soil profile in order to determine soil water availability to the crop. Water movement is simulated with a cascading model which divides the soil profile into a number of layers. Soil water movement which is computed in this unit involves the following procedures: (i) soil parameter initialization; (ii) soil day step calculation; (iii) soil water storage; and (iv) allowable depletion.

The soil day step procedure is conducted on a daily basis. It involves five more procedures which are performed in the following order: (i) amount of precipitation intercepted by the canopy (mm); (ii) runoff (mm); (iii) infiltration and redistribution (mm); (iv) E (mm); and (v) T (mm).

In case either sprinkler/flood or localized irrigations are performed, SWB provides options to determine the soil water balance. If sprinkler/flood irrigation is involved, the model also simulates the wetting of the soil surface. In the case of drip or micro-irrigators, SWB computes the soil water balance for both irrigated and non-irrigated surface layers. The irrigated fraction of the surface is selected in the input field table. SWB then simulates one-dimensional water movement in the soil for both sprinkler/flood and localized irrigation.

The aim of the crop unit is to simulate crop growth. Crop growth includes three procedures: (i) initialization; (ii) planting; and (iii) day step calculation. Crop initialization sets initial values of several crop parameters to zero. Crop height requires a starting value > 0 and this is set to 0.001 m. The procedure for crop planting is initiated once a valid planting date has been identified. Total dry matter (TDM) is set to TDM at emergence (crop specific parameter). For most crops, TDM at emergence is estimated to be equivalent to seed mass density. The crop day step procedure is performed on a daily basis. It includes the following computations: (i) growing day degrees (GDD); (ii) fractional interception of radiation (FI_{PAR}); (iii) crop height (Hc); (iv) dry matter production increment (DM_i); (v) harvestable dry matter increment (HDM_i); (vi) partitioning of DM_i into plant organs; (vii) partitioning of DM_i under conditions of water stress; (viii) leaf area index (LAI); and (ix) rooting depth (RD).

The canopy extinction coefficient for PAR (K_{PAR}) can be used to calculate photosynthesis as a function of intercepted PAR. The canopy extinction coefficient for total radiation (Ks) is required for predicting radiation-limited DM production (Monteith, 1977), for partitioning ET into E from the soil surface, and crop T (Ritchie, 1972). The procedure recommended by Campbell and van Evert (1994) was used to convert K_{PAR} into K_S:

$$K_S = K_{bd}{*}(a_s)^{1/2} \quad \text{(Eq. 7.1)}$$

$$K_{bd} = K_{PAR} /(a_p)^{1/2} \quad \text{(Eq. 7.2)}$$

$$a_s = (a_p{*}a_n)^{1/2} \quad \text{(Eq. 7.3)}$$

where, K_{bd} = canopy radiation extinction coefficient for black leaves with diffuse radiation; a_s = leaf absorptance of solar radiation; a_p = leaf absorptance of PAR; and a_n = leaf absorptance of near infrared radiation (NIR) (0.7 – 3 µm). The value of a_p was assumed to be 0.8, whilst a_n was assumed to be 0.2 (Goudriaan, 1977). a_s is the geometric mean of the absorptances in the PAR and NIR spectrum.

In the crop unit, SWB calculates crop DM accumulation in direct proportion to T corrected for vapour pressure deficit (VPD) (Tanner & Sinclair, 1983). It also calculates radiation-limited growth (Monteith, 1977) and takes the lower of the two. This DM is partitioned to roots, stems, leaves and grains or fruits. Partitioning depends on phenology calculated with thermal time and modified by water stress. The crop specific growth parameters required by SWB are generated from measured data to enable simulation of growth and water use of crops. According to Tanner & Sinclair (1983), the relationship between DM production and crop T needs to be corrected to account for atmospheric conditions, mainly for VPD. Hence, dry matter-water ratio (DWR) is calculated using Eq. 7.4 (Annandale *et al.* (1999):

$$DWR = (DM{*}VPD)/ET \quad \text{(Eq. 7.4)}$$

where, DM (kg m^{-2}) is measured at harvest; VPD = the seasonal average; and ET = the seasonal crop ET in mm, which is equivalent to kg m^{-2}. DWR and VPD are measured in Pa.

ET is obtained using Eq. 3.1 (given in Section 3.2.4 of Chapter 3) for daily interval.

Dry matter production can also be calculated from the radiation conversion efficiency (Ec), under conditions of radiation-limited growth, according to Monteith (1977):

$$DM = Ec^* \, FI_{PAR} \, ^*Rs \qquad \text{(Eq. 7.6)}$$

where, Rs = the solar radiation.

In SWB, the daily DM_i and its partitioning into different plant parts are calculated as either transpiration-limited (Eq. 7.4) or radiation-limited (Eq. 7.6). Hence, SWB calculates the leaf dry matter (LDM) and stem dry matter (SDM) as follows (Annandale *et al.*, 1999):

$$LDM = CDM/(1 + PART^*CDM) \qquad \text{(Eq. 7.7)}$$

$$SDM = CDM – LDM \qquad \text{(Eq. 7.8)}$$

where, CDM = canopy DM and PART = the leaf-stem partitioning factor (crop specific parameter).

Similarly, SWB uses the LDM to calculate the leaf area index (LAI) as:

$$LAI = SLA^*LDM \qquad \text{(Eq. 7.9)}$$

SLA represents the specific leaf area, which is calculated as the seasonal average of the ratio of LAI and LDM. Leaf-stem DM partitioning parameter (PART) is determined as a function of SLA, LAI and CDM, by combining Eqs. (7.7) and (7.9). Hence, the correlation between CDM and (SLA*CDM/LAI-1) and the regression line which is forced through the origin, represents PART in m^2 kg^{-1}. PART is described as:

$$PART = (SLA^*CDM/LAI-1)/CDM \qquad \text{(Eq. 7.10)}$$

The weather unit computes potential evapotranspiration (PET) from available meteorological input data (Smith *et al.*, 1996; Smith, 1992b). Daily ETo and PET are calculated in the weather unit and used in the soil unit to calculate T and E. The weather unit includes the procedure for initializing weather parameters, and five functions where the following parameters are calculated: (i) extraterrestrial radiation (R_a, MJ m^{-2} day^{-1}); (ii) VPD (kPa); (iii) net radiation (R_n, MJ m^{-2} day^{-1}); (iv) FAO ETo (mm day^{-1}); and (v) PET (mm day^{-1}). The weather input parameters required to enable these calculations are presented in Section 7.3.1.

PET is divided into potential evaporation (PE) and potential transpiration (PT) by calculating canopy radiation interception from simulated leaf area (Ritchie, 1972). Under conditions where T is less than PT, the crop has undergone stress that reduced leaf area development. This makes the crop growth model of SWB very suitable for predicting crop water requirements when deficit irrigation strategies are applied (Annandale *et al*., 1999). SWB calculates PET according to eq. 7.11:

$$PET = ETo * Kc_{max} \qquad \text{(Eq. 7.11)}$$

where Kc_{max} = the maximum value of the crop factor (Kc) following rain or irrigation (Allen *et al*., 1998).

T rate depends on the atmospheric evaporative demand, the soil-water potential and the FI_{PAR} of solar radiation by the crop canopy. FI is calculated from LAI as:

$$FI_{PAR} = 1\text{-}\exp(-K_{PAR} * LAI) \qquad \text{(Eq. 7.12)}$$

$$\text{Hence, } K_{PAR} = -\ln(1 - FI_{PAR}) / LAI \qquad \text{(Eq. 7.13)}$$

where, K_{PAR} represents the canopy extinction coefficient, it can be calculated using field measurements of LAI and FI_{PAR} K_{PAR} is calculated from FI_{PAR} measurements with the ceptometer, which measures photosynthetically active radiation.

7.3 Materials and methods

7.3.1 Materials

The RWH study with spring potato (*Solanum tuberosum* cv. BP1) and Swiss chard (*Beta vulgaris* cv. Fordhook Giant), which were respectively grown during the 2009/2010 and 2010/2011seasons at the Hatfield Experimental Farm, have been dealt with in detail in Chapters 3 and 4. In the present chapter, the crop specific growth parameters developed from the field experiments are presented and discussed. Moreover, the SWB model is parameterized and calibrated using the field measurements. However, no model validation was performed due to the fact that different crops were involved in the RWH-crop experiments. Since the model is fairly simple, the input data required to run it are limited and usually easily obtainable (Annandale *et al*., 1996a). The required management, weather, soil and crop data inputs are as follows:

Management inputs:

- Starting date of the simulation;
- Planting date;
- Irrigation timing options;
- Irrigation system; and
- Area of the field (ha).

Soil inputs:

- Soil layer thickness (m);
- Drainage factor;
- Maximum drainage rate (mm day^{-1});
- Volumetric water content at field capacity (mm m^{-1}) and permanent wilting point (mm m^{-1});
- Initial volumetric water content (mm m^{-1}); and
- Bulk density (Mg m^{-3}).

Weather inputs:

- Latitude (°North or °South) and altitude (m.a.s.l.);
- Maximum and minimum daily temperature (°C);
- Precipitation and irrigation (mm);
- Solar radiation (MJ m^{-2} d^{-1});
- Vapour pressure or minimum and maximum humidity (%) or wet and dry bulb temperatures (°C); and
- Wind speed (m s^{-1}) and measurement height (m).

Crop inputs:

- Cardinal temperatures (base and optimum temperatures for development (°C);
- Thermal time requirements for emergence, onset of the reproductive stage, transition period, crop maturity and leaf senescence (in day degrees, °Cd);
- VPD corrected DWR (kPa);
- Maximum RD (m);
- Canopy solar radiation extinction coefficient (Kc);
- Ec (kg MJ^{-1});
- PART (m^2 kg^{-1});
- Maximum Hc (m); and
- SLA (m^2 kg^{-1}).

7.3.2 Methods

Table 7.1 shows the different treatments and the corresponding soil water balance equations thereof. These different soil water balance models contributed to the estimation of the runoff area (R_{RA}); and were parameterized for the study area using different design ratios and different surface treatments. The SWB cascading and crop growth model type were used to respectively simulate the soil water balance and crop yield components measured under rainwater harvesting conditions (Annandale *et al*., 1999).

As can be seen from Table 7.1, runoff for CT (R0) has a minus sign to show that it is an output of the system, while Roff for the IRWH treatments has a plus sign to denote that it is an input of the system. In addition, no Roff is shown for TR to indicate that Roff is considered zero. This can be explained by the fact that no runoff whatsoever is generated in this treatment. Actually, the rainfall is retained where it falls by the tied ridges and as such it loses runoff generation potential. R0 is negative for CT because runoff is lost as soon as it is generated. For the IRWH treatments, R is positive because all water is held and no runoff is supposed to be lost from the system (except for surface E).

Table 7.1: RWH treatments and their soil water balance equations.

Treatments	Soil water balance	Notes
CT	$ET = R + I - R0 - D \pm \Delta S$	Eq. 7.14
TR	$ET = R + I - D \pm \Delta S$	Eq. 7.15
1:1B	$ET = R + I + Roff_{1b} - D \pm \Delta S$	Eq. 7.16
1:1P	$ET = R + I + Roff_{1p} - D \pm \Delta S$	Eq. 7.17
2:1B	$ET = R + I + Roff_{2b} - D \pm \Delta S$	Eq. 7.18
2:1P	$ET = R + I + Roff_{2p} - D \pm \Delta S$	Eq. 7.19
3:1B	$ET = R + I + Roff_{3b} - D \pm \Delta S$	Eq. 7.20
3:1P	$ET = R + I + Roff_{3p} - D \pm \Delta S$	Eq. 7.21

where ET, R, I, D and ΔS are the same as in Eq. 3.1; R0 = runoff for CT, while Roff with index values of 1, 2 and 3, stand for runoff for the different IRWH treatments according to their specific design ratios. The letters b and p reflect the status of the surface of the runoff areas (bare or plastic-mulched).

7.4 Model parameterization and calibration

To calibrate the SWB model, crop yield simulations were run using the data collected from the trials, for a sandy clay loam soil for all the water harvesting treatments tested in the study area. The SWB model calibration involved the adjustment of some soil parameters (drainage factor, drainage rate and runoff number) so that simulated results could match observed values for the CT, TR and IRWH techniques. In general, the parameters used in the SWB model calibration are presented in Table 7.2 and 7.3. Field data collected during the 2009/2010 and 2010/2011 growing seasons for potato and Swiss chard at the Hatfield Experimental Farm were used for comparison purposes (measured and simulated). These included LAI, crop yield, total dry matter yields and soil water deficits. Non-measured variables were either obtained from the literature or estimated (from calibration for CN). In addition, for potato, some field data such as LAI were sometimes transformed because of the model format, while for Swiss chard, the LAI values calculated from LA measured with a LA meter at each harvest were used.

The following statistical parameters were used to evaluate the performance of the model in simulating crop growth under RWH conditions: coefficient of determination (R^2), Willmott index of agreement (D) and mean absolute error (MAE) (De Jager, 1994). According to this latter, the model performance can be evaluated as in Table 7.4.

Table 7.2: Measured and input data sets of the soil and crop specific parameters involved in the SWB model calibration for the RWH-BP1 potato (2009/2010).

Soil and crop specific parameters	**Parameter value**	**Source**
Drainage factor	0.7	Estimated
Maximum drainage rate (mm d^{-1})	70	Estimated
Runoff curve number	70 (CT), 96 (1:1B, 2:1B & 3:1B), 100 (TR, 1:1P, 2:1P & 3:1P)	Estimated (CT, TR, 1:1P, 2:1P & 3:1P), CN calibration (1:1B, 2:1B & 3:1B)

Table 7.2: Measured and input data sets of the soil and crop specific parameters involved in the SWB model calibration for the RWH-BP1 potato (2009/2010) (continued).

Initial soil water content (mm m^{-1})	190	Measured
Canopy solar radiation extinction coefficient	0.54	Measured
Corrected dry matter-water ratio (Pa)	7.0	Measured
Radiation conversion efficiency (kg MJ^{-1})	0.00175	Measured
Base temperature (°C)	2.0	Annandale *et al*. (1999)
Temperature for optimum crop growth (°C)	22.0	Annandale *et al*. (1999)
Cutoff temperature (°C)	28.0	Annandale *et al*. (1999)
Emergence day degrees (d °C)	350	Measured
End of vegetative growth day degrees (d °C)	750	Measured
Day degrees for maturity (d °C)	2250	Measured
Transition period day degrees (d °C)	750	Measured
Day degrees for leaf senescence (d °C)	1400	Measured
Maximum crop height (m)	0.6	Measured
Maximum root depth (m)	1.0	Measured
Fraction of total dry matter translocated to heads/tubers	0.450	Estimated
Canopy storage (mm)	1.0	Estimated
Leaf water potential at maximum transpiration (kPa)	-550	Annandale *et al*. (1999)
Maximum transpiration (mm d^{-1})	7.0	Estimated
Specific leaf area (m^{2} kg^{-1})	22.0	Estimated

Table 7.2: Measured and input data sets of the soil and crop specific parameters involved in the SWB model calibration for the RWH-BP1 potato (2009/2010) (continued).

Leaf-stem partition parameter ($m^2\ kg^{-1}$)	2.0	Annandale *et al*. (1999)
Total dry matter at emergence ($kg\ m^{-2}$)	0.005	Annandale *et al*. (1999)
Fraction of total dry matter partitioned to roots	0.100	Estimated
Root growth rate ($m^2\ kg^{-0.5}$)	3.0	Estimated
Stress index	0.95	Estimated

Table 7.3: Measured and input data of the soil and crop specific parameters involved in the SWB model calibration for the RWH-Fordhook Giant Swiss chard (2010/2011).

Soil and crop specific parameters	**Parameter value**	**Source**
Drainage factor	0.7	Estimated
Maximum drainage rate ($mm\ d^{-1}$)	70	Estimated
Runoff curve number	70 (CT), 96 (1:1B, 2:1B & 3:1B), 100 (TR, 1:1P, 2:1P & 3:1P)	Estimated (CT, TR, 1:1P, 2:1P & 3:1P), CN calibration (1:1B, 2:1B & 3:1B)
Initial soil water content ($mm\ m^{-1}$)	210	Estimated
Canopy solar radiation extinction coefficient	0.30	Measured
Corrected dry matter-water ratio (Pa)	6.5	Measured
Radiation conversion efficiency ($kg\ MJ^{-1}$)	0.0030	Measured
Base temperature (^{o}C)	4.4	Annandale *et al*. (1999)
Temperature for optimum crop growth (^{o}C)	25.0	Estimated

Table 7.3: Measured and input data of the soil and crop specific parameters involved in the SWB model calibration for the RWH-Fordhook Giant Swiss chard (2010/2011) (continued).

Cutoff temperature (°C)	29.0	Estimated
Emergence day degrees (d °C)	1.0	Measured
End of vegetative growth day degrees (d °C)	2800	Measured
Day degrees for maturity (d °C)	2800	Measured
Transition period day degrees (d °C)	10.0	Measured
Day degrees for leaf senescence (d °C)	2800	Measured
Maximum crop height (m)	0.4	Measured
Maximum root depth (m)	0.8	Measured
Fraction of total dry matter translocated to heads/tubers	0.500	Estimated
Canopy storage (mm)	1.0	Estimated
Leaf water potential at maximum transpiration (kPa)	-1500	Annandale *et al*. (1999)
Maximum transpiration (mm d^{-1})	10.0	Estimated
Specific leaf area (m^2 kg^{-1})	6.0	Measured
Leaf-stem partition parameter (m^2 kg^{-1})	1.460	Annandale *et al*. (1999)
Total dry matter at emergence (kg m^{-2})	0.0300	Estimated
Fraction of total dry matter partitioned to roots	0.280	Estimated
Root growth rate (m^2 kg$^{-0.5}$)	3.50	Estimated
Stress index	0.85	Estimated

Table 7.4: Model evaluation parameters and their accuracy criteria levels (after de Jager, 1994).

Statistical parameters	Abbreviations	Reliability criteria
Number of measured values	N	-
Coefficient of determination	R^2	> 0.80
Willmott (1982) index of agreement	D	> 0.80
Root mean square error	RMSE	-
Mean absolute error expressed as a percentage of the mean of the measured values	MAE (%)	< 20

7.5 Model calibration results and discussion

7.5.1 Potatoes

Figures 7.1a – h, illustrate the outputs (according to the cropped plot area) for the model calibration of simulated (solid lines) and measured (symbols) values of root growth, LAI, TDM, HDM and soil water deficits (SWDs) for the different treatments. Moreover, statistical indicators are given in the top right corner of the graphs to show the status of model calibration. No measurements were carried out for the root growth and, thus, only the simulated output is featured. All statistics of TDM and HDM are 0 except for N (number of items) and MAE. N was 1 because TDM and HDM were only collected once at harvest, given the limited number of the plants available for destructive sampling. The calibration showed that the IRWH treatments had the highest simulation outputs, followed by TR and CT, respectively. This was an indication that the individual plants of the IRWH treatments did well because of the collected runoff. However, the total area results showed that TR had the highest simulation results, followed by CT and IRWH (TR and CT had more rows of plants per plot area than IRWH) (Figure 7.2 is an illustration of a comparison of the simulated total area and cropped area results). The model, in general, predicted the growth, yield and soil water deficit well. This can be explained by the values given by the statistical parameters which, in general, are in the range of those presented by De Jager (1994), except for SWDs of some IRWH treatments. Several factors could have influenced the agreement between the simulated and measured values of the SWDs of these treatments; for example, errors in the measured data or some SWB shortcomings as referred to in Section 7.7. The factors should have affected the agreement either individually or concurrently.

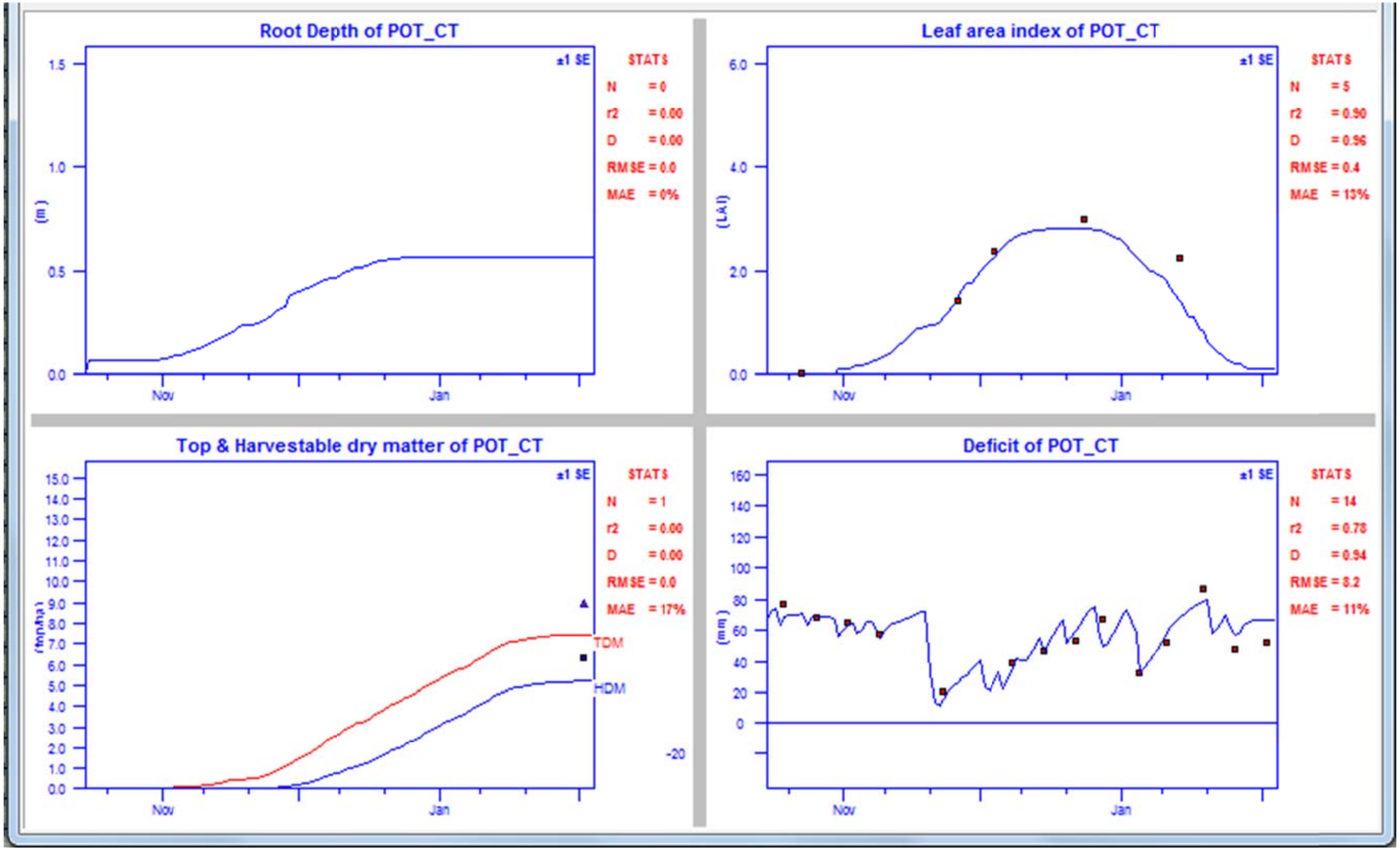


Figure 7.1: a) Simulated (solid lines) and measured values (symbols) for root depth (RD, m), leaf area index (LAI, m m^{-2}), total dry matter (TDM, t ha^{-1}) and harvestable dry matter (HDM, t ha^{-1}), and soil water deficit (mm) for CT for the 2009/2010 potato growing season.

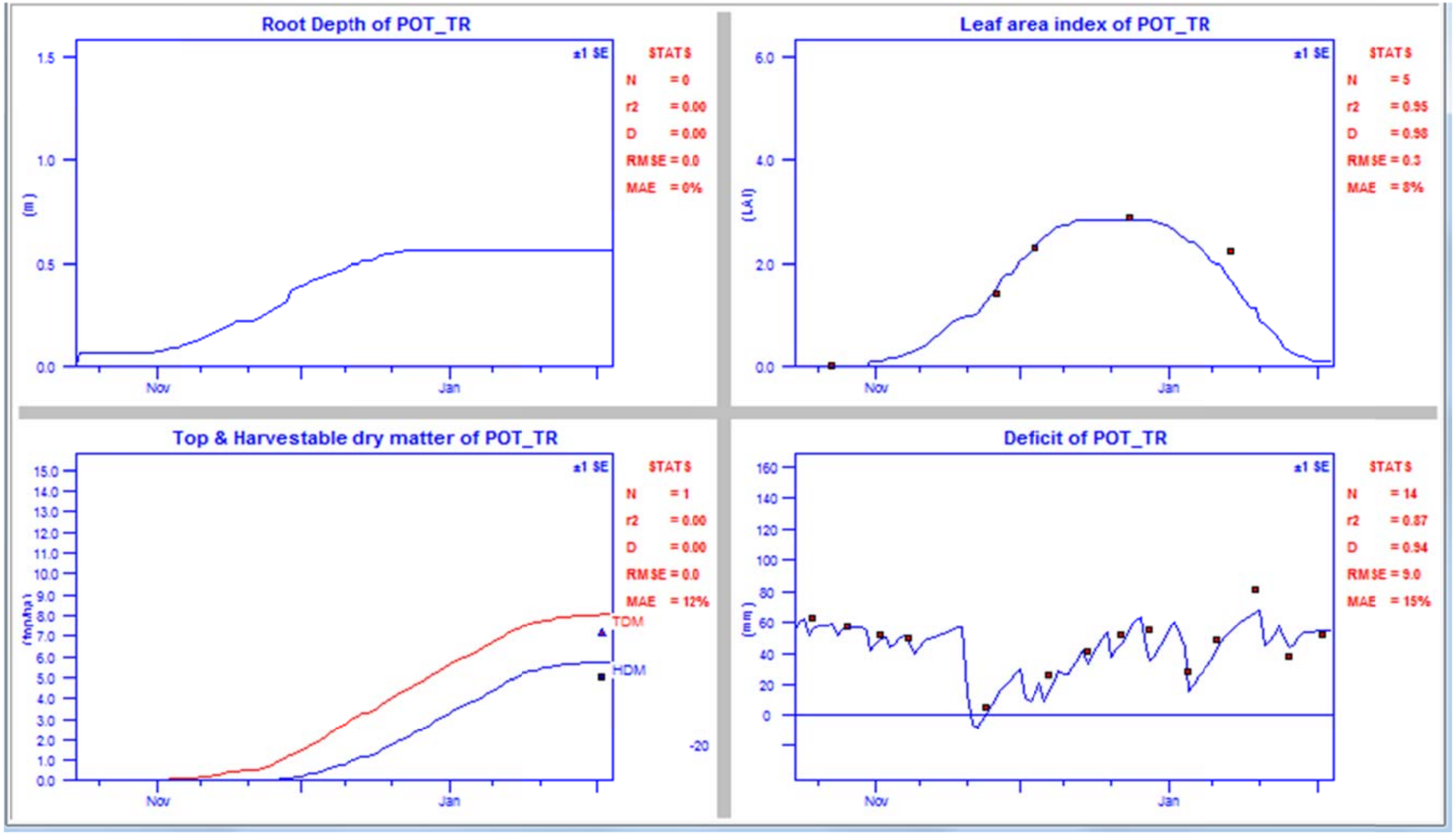


Figure 7.1: b) Simulated (solid lines) and measured values (symbols) for root depth (RD, m), leaf area index (LAI, m m^{-2}), total dry matter (TDM, t ha^{-1}) and harvestable dry matter (HDM, t ha^{-1}), and soil water deficit (mm) for TR for the 2009/2010 potato growing season.

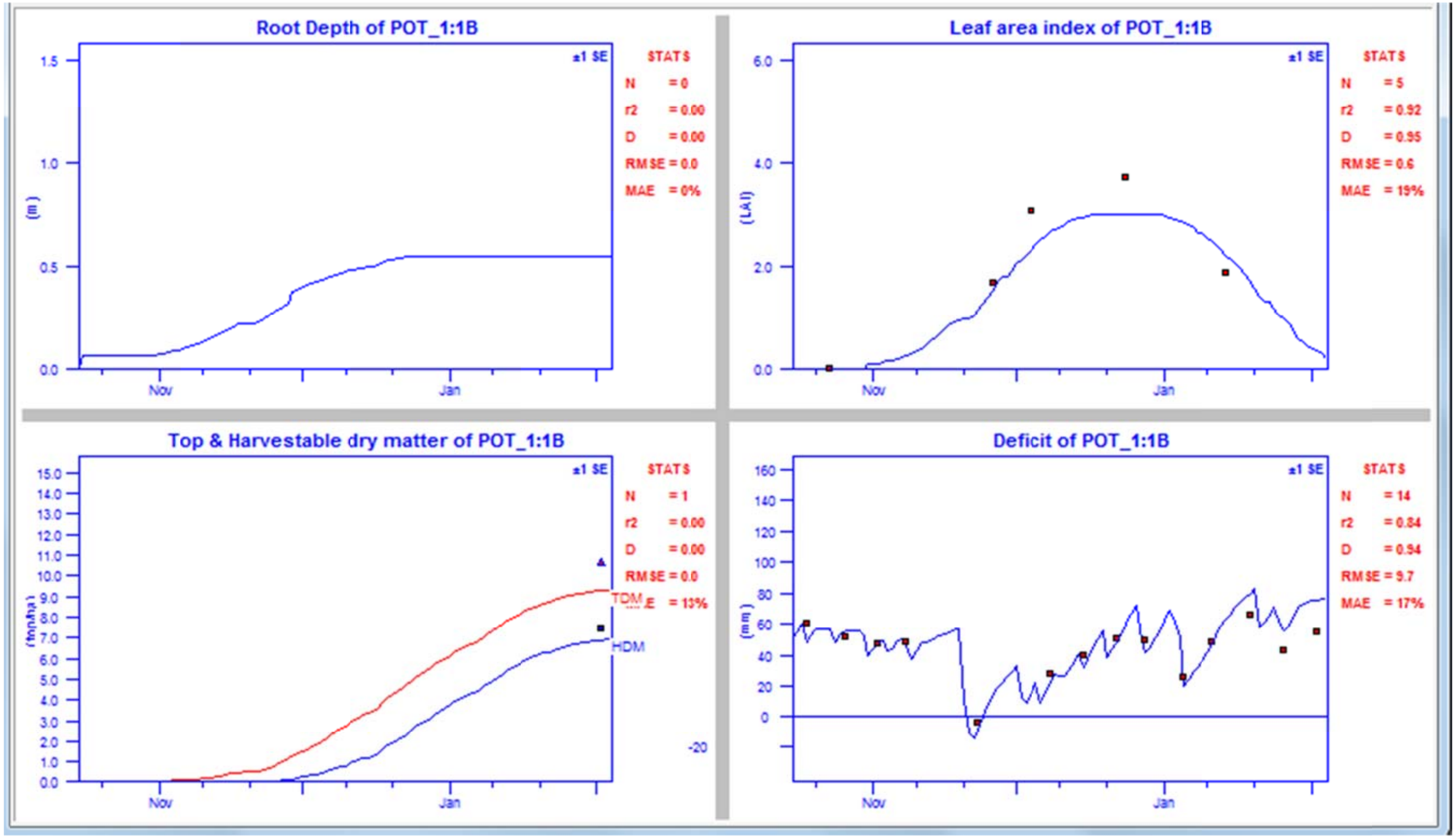


Figure 7.1: c) Simulated (solid lines) and measured values (symbols) for root depth (RD, m), leaf area index (LAI, m m^{-2}), total dry matter (TDM, t ha^{-1}) and harvestable dry matter (HDM, t ha^{-1}), and soil water deficit (mm) for 1:1B for the 2009/2010 potato growing season.

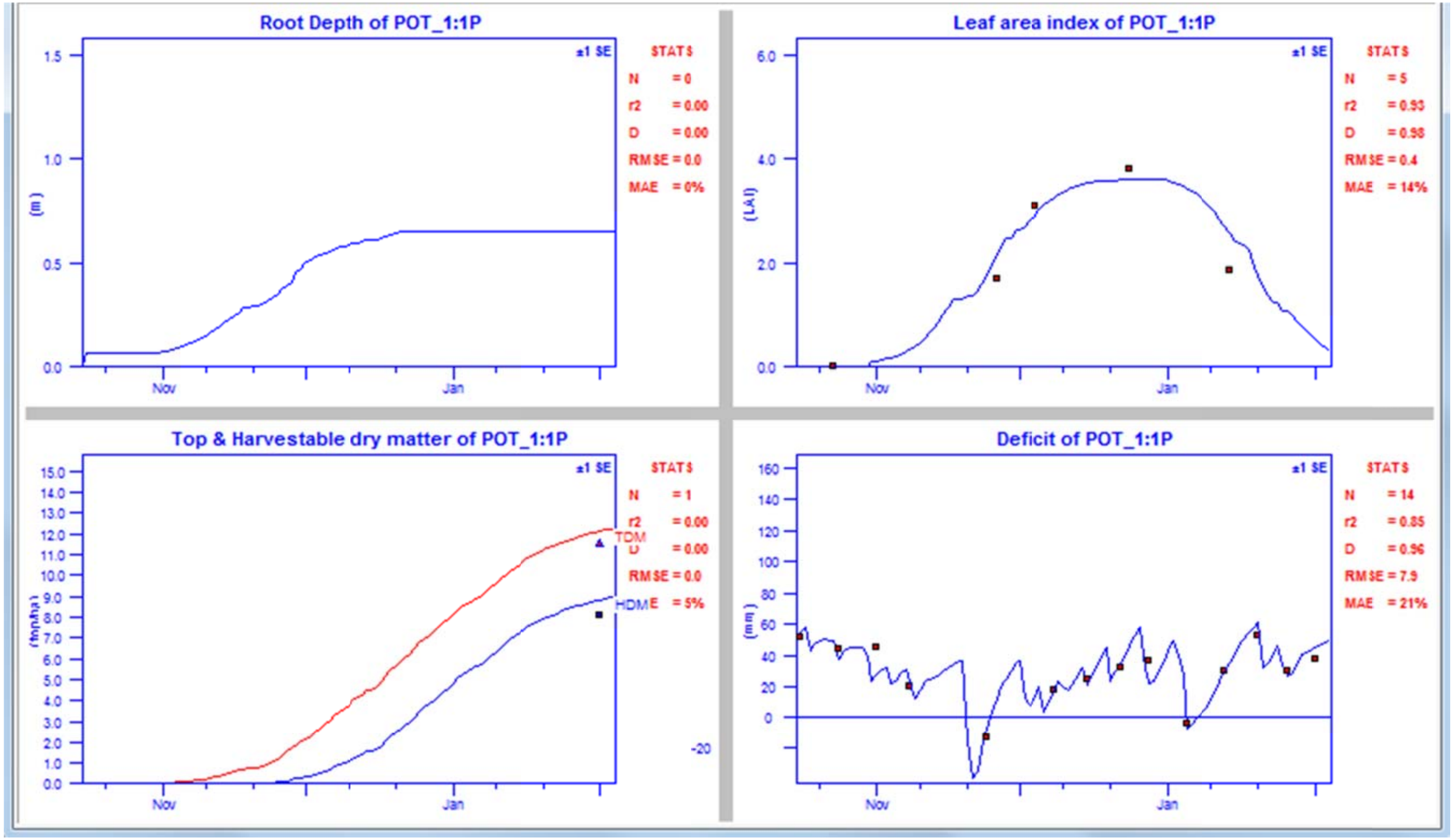


Figure 7.1: d) Simulated (solid lines) and measured values (symbols) for root depth (RD, m), leaf area index (LAI, m m^{-2}), total dry matter (TDM, t ha^{-1}) and harvestable dry matter (HDM, t ha^{-1}), and soil water deficit (mm) for 1:1P for the 2009/2010 potato growing season.

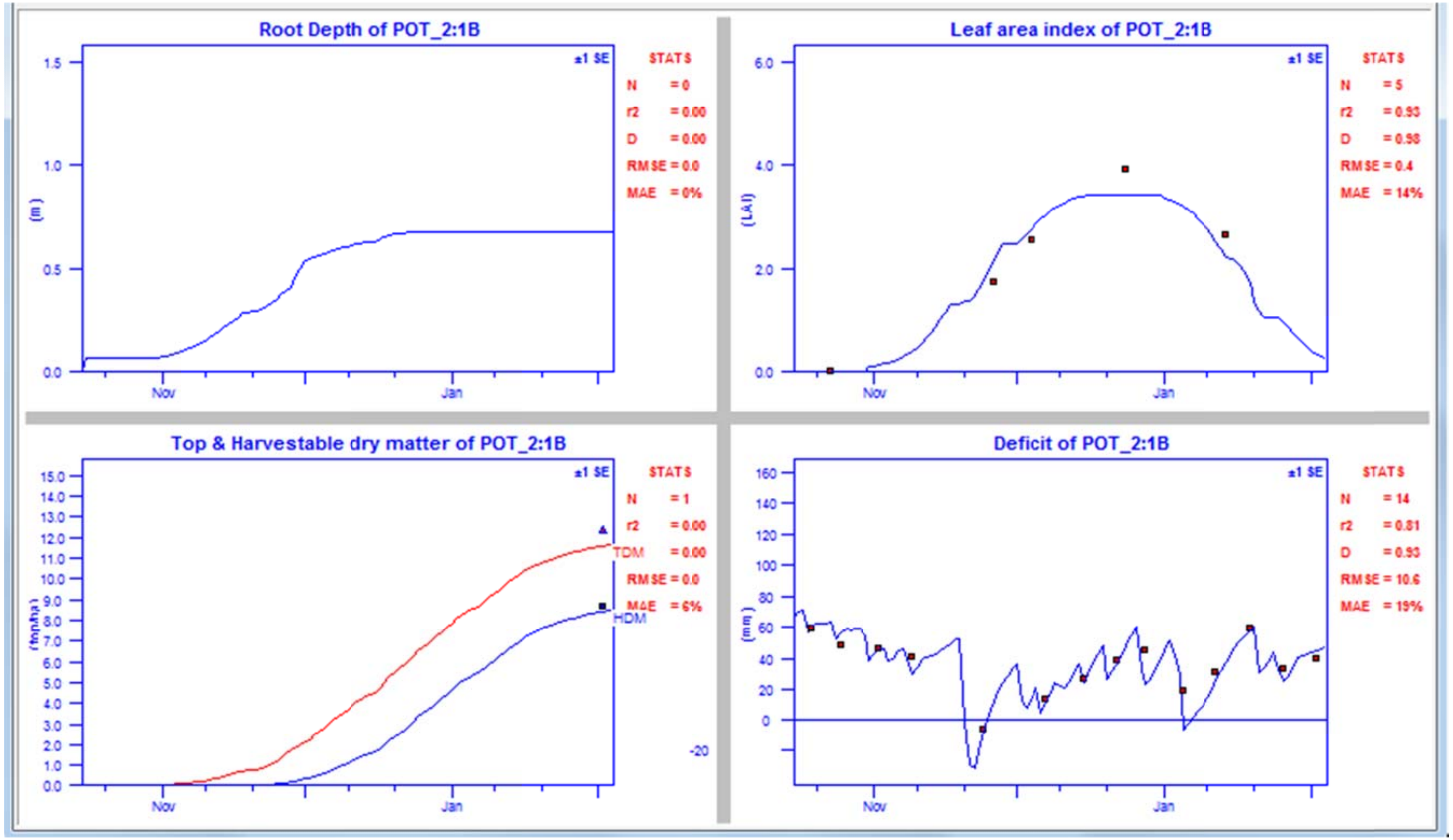


Figure 7.1: e) Simulated (solid lines) and measured values (symbols) for root depth (RD, m), leaf area index (LAI, m m^{-2}), total dry matter (TDM, t ha^{-1}) and harvestable dry matter (HDM, t ha^{-1}), and soil water deficit (mm) for 2:1B for the 2009/2010 potato growing season.

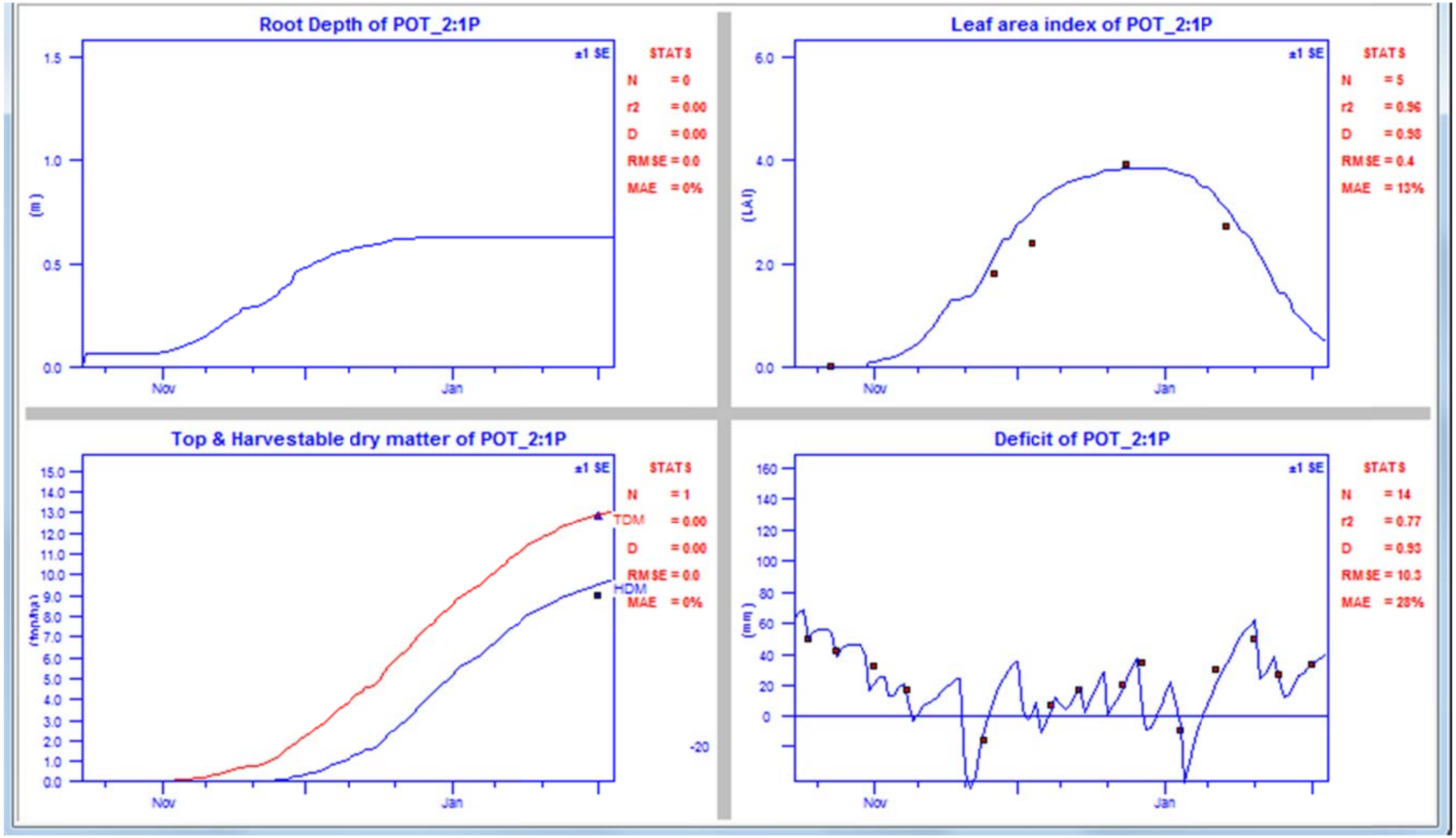


Figure 7.1: f) Simulated (solid lines) and measured values (symbols) for root depth (RD, m), leaf area index (LAI, m m^{-2}), total dry matter (TDM, t ha^{-1}) and harvestable dry matter (HDM, t ha^{-1}), and soil water deficit (mm) for 2:1P for the 2009/2010 potato growing season.

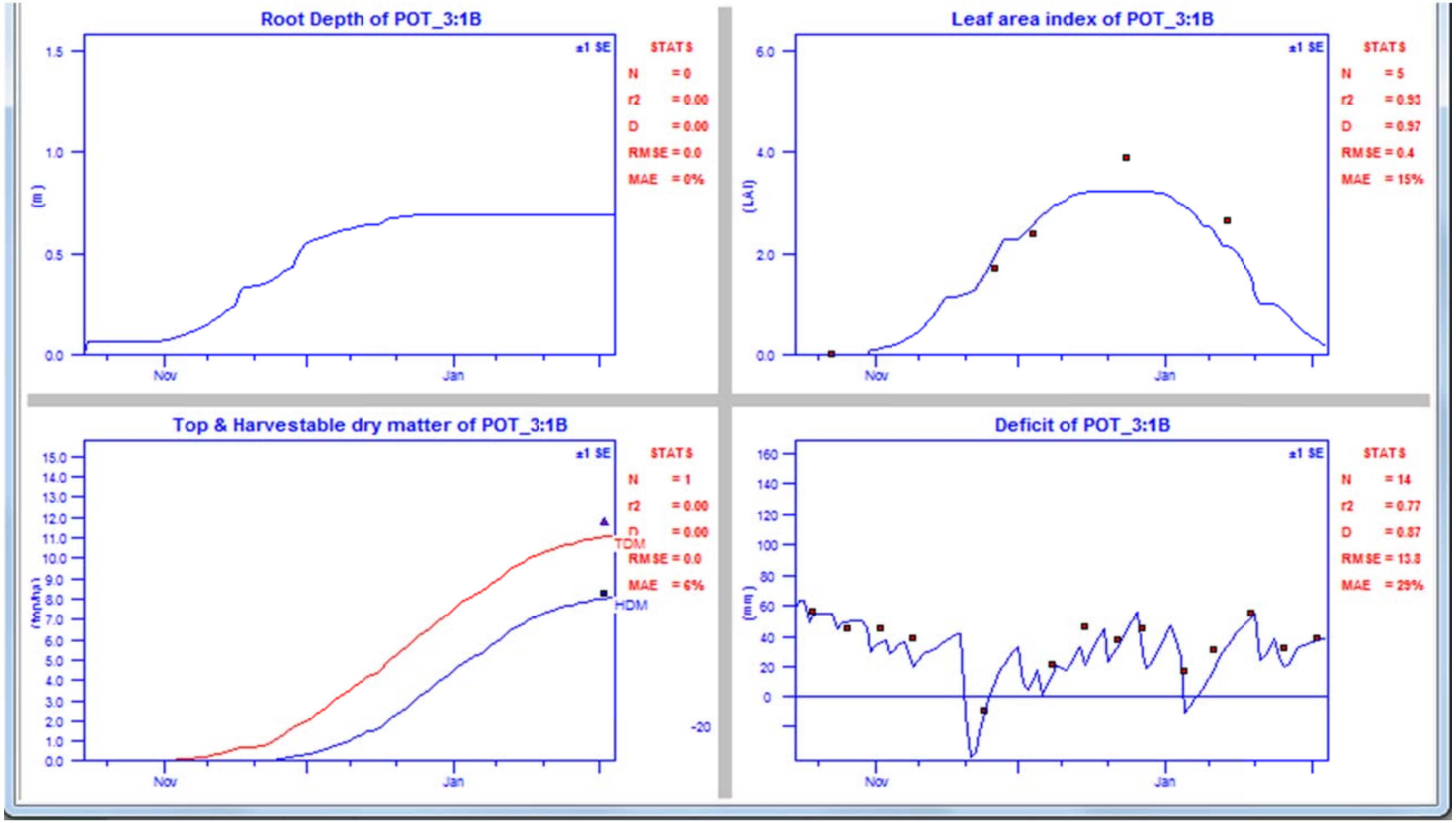


Figure 7.1: g) Simulated (solid lines) and measured values (symbols) for root depth (RD, m), leaf area index (LAI, m m^{-2}), total dry matter (TDM, t ha^{-1}) and harvestable dry matter (HDM, t ha^{-1}), and soil water deficit (mm) for 3:1B for the 2009/2010 potato growing season.

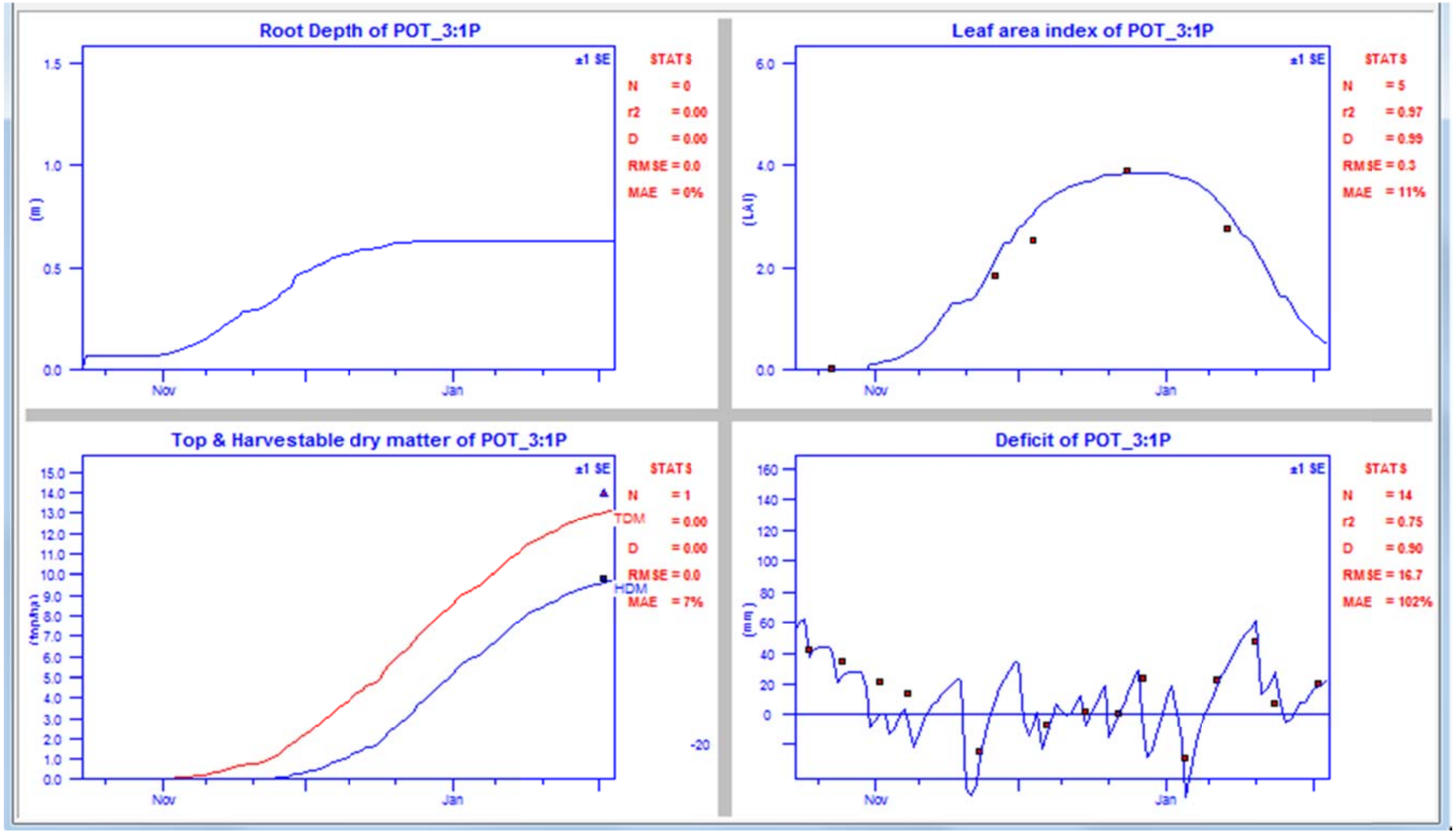


Figure 7.1: h) Simulated (solid lines) and measured values (symbols) for root depth (RD, m), leaf area index (LAI, m m^{-2}), total dry matter (TDM, t ha^{-1}) and harvestable dry matter (HDM, t ha^{-1}), and soil water deficit (mm) for 3:1P for the 2009/2010 potato growing season.

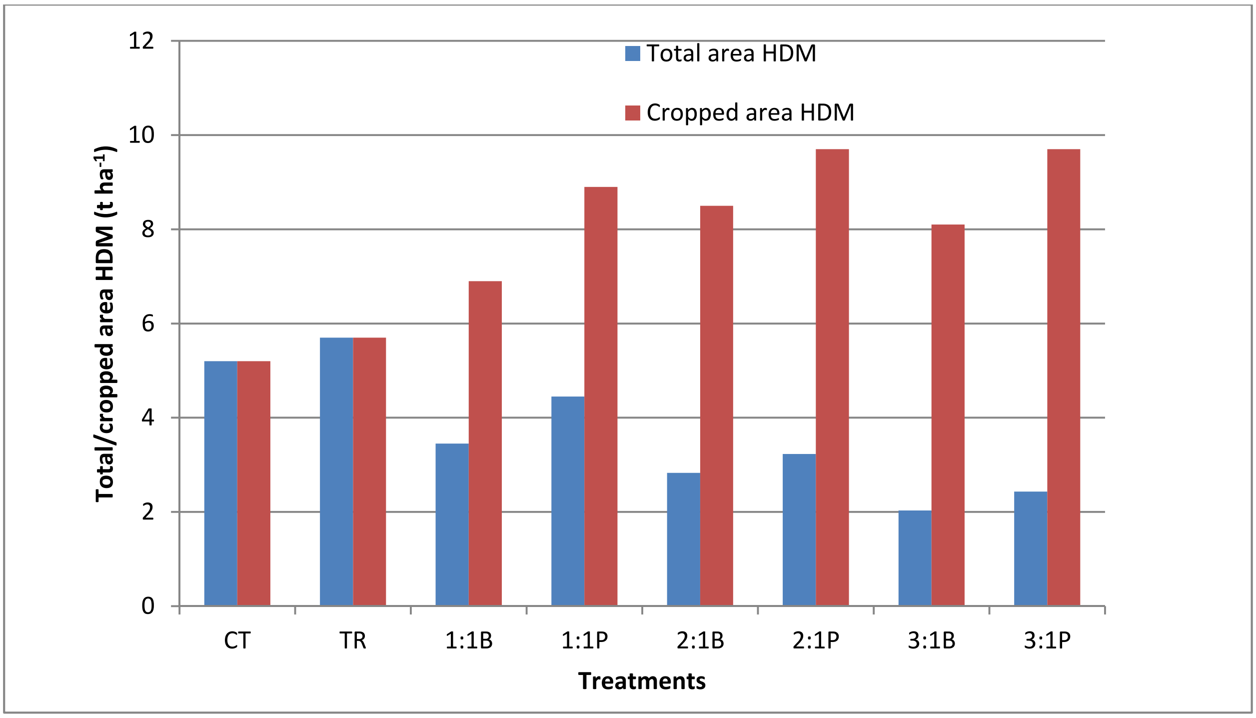


Figure 7.2: Total plot area and net cropped area simulation HDM (t ha^{-1}) for the 2009/2010 potato growing season.

7.5.2 Swiss chard

Figures 7.3a – h represent the outputs for the model calibration of simulated (solid lines) and measured (symbols) of root growth, LAI, TDM and SWDs for the different treatments (according to the cropped plot area). No HDM outputs are presented since this parameter was estimated to be equal to TDM for Swiss chard (all leaves can be harvested). In addition, statistical results are given in the top right corner of the graphs to denote how the model calibration performed. As explained previously, the root growth was not experimentally measured and, therefore, only the simulated results are presented and all statistics are 0. LAI and TDM outputs show alternating increases and decreases, illustrating that the crop was harvested several times during the growing season. As in the case of the potato crop, the results of the calibration indicated that the IRWH treatments had the highest simulation outputs, followed by TR and CT, respectively. This showed that the individual plants of the IRWH treatments performed well because of the collected runoff. However, on a total area basis, TR had the highest simulation results, followed by CT and the IRWH treatments (TR and CT had more plants per plot area than IRWH) (Table 7.5 gives a comparison of the simulated total area and cropped area outputs). In general, by observing the graphs, the TDM simulation results for the respective treatments show that there was an agreement between the measured and simulated values. However, the statistical parameters show the opposite; and this can partly be attributed to the harvesting and growing method (approach for pastures). LAI values were, in general, overestimated; and this occurred due to water stress experienced by the crop as no strict irrigation scheduling was applied. These water stress spells were also the cause of the blunt portions of the graphs (for example, on CT). The LAI simulations are low in the beginning because TDM at emergence was lower than TDM after harvests. The SWD results show that the measured values were predicted by the SWB model satisfactorily (according to De Jager (1994)), except for 3:1P. In general, there were underestimations in the beginning because the model assumed that the canopy was still small and so were the SWD values. Towards the end, however, there were overestimations for the treatments with bare runoff areas, and underestimations for the treatments with plastic-covered runoff areas. The model assumed stress spells for the former treatments and wet periods for the latter ones.

The disagreement between the simulated and measured TDM and LAI (and SWD for 3:1P) values should have been caused by a number of factors, for example, the growing and harvesting method (approach for pastures), crop water stress, human or device error in the measured data or some SWB drawbacks as mentioned in Section 7.7 below. These different factors should have affected the agreement either separately or concurrently.

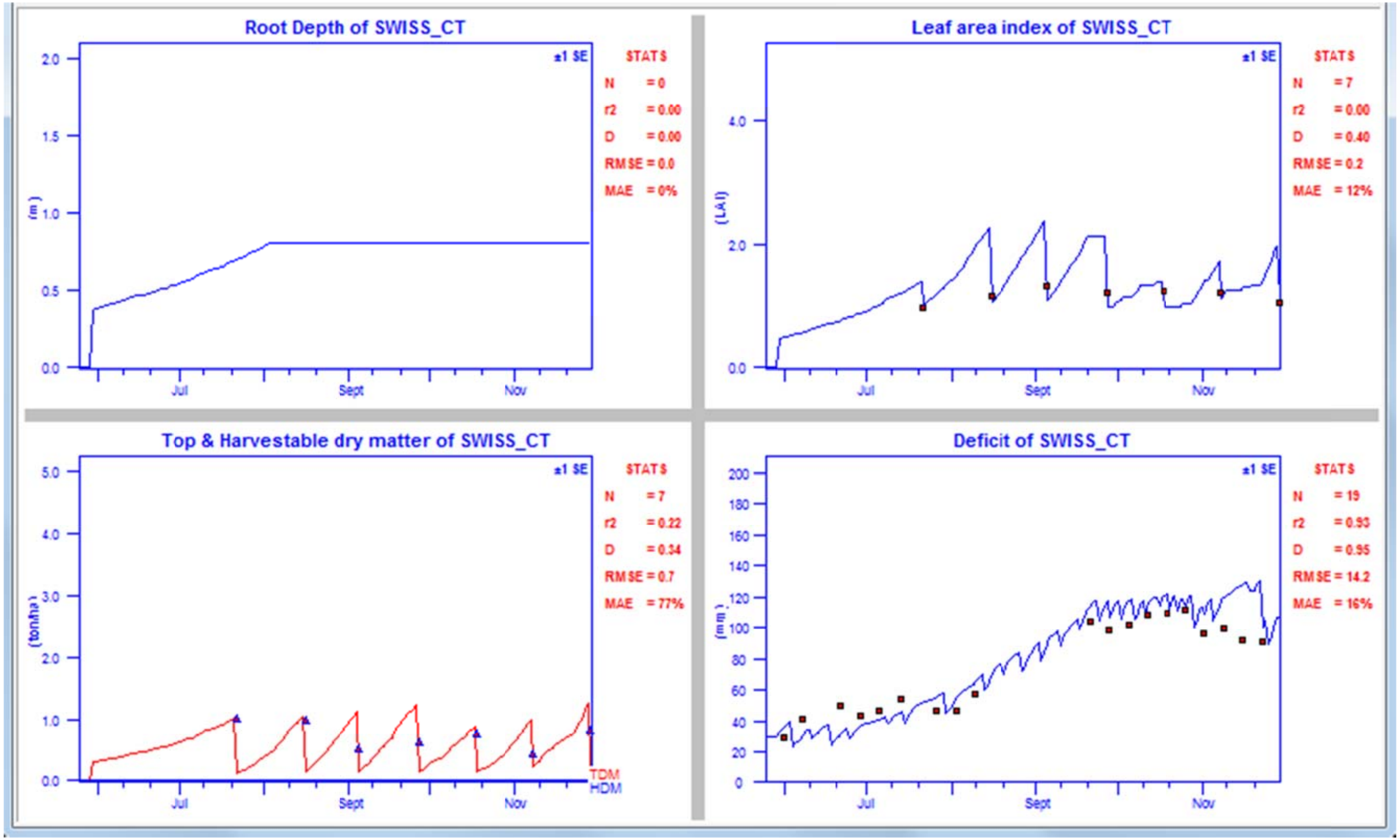


Figure 26: a) Simulated (solid lines) and measured values (symbols) for root depth (RD, m), leaf area index (LAI, m m^{-2}), total dry matter (TDM, t ha^{-1}) and soil water deficit (mm) for CT for the 2010/2011 Swiss chard growing season.

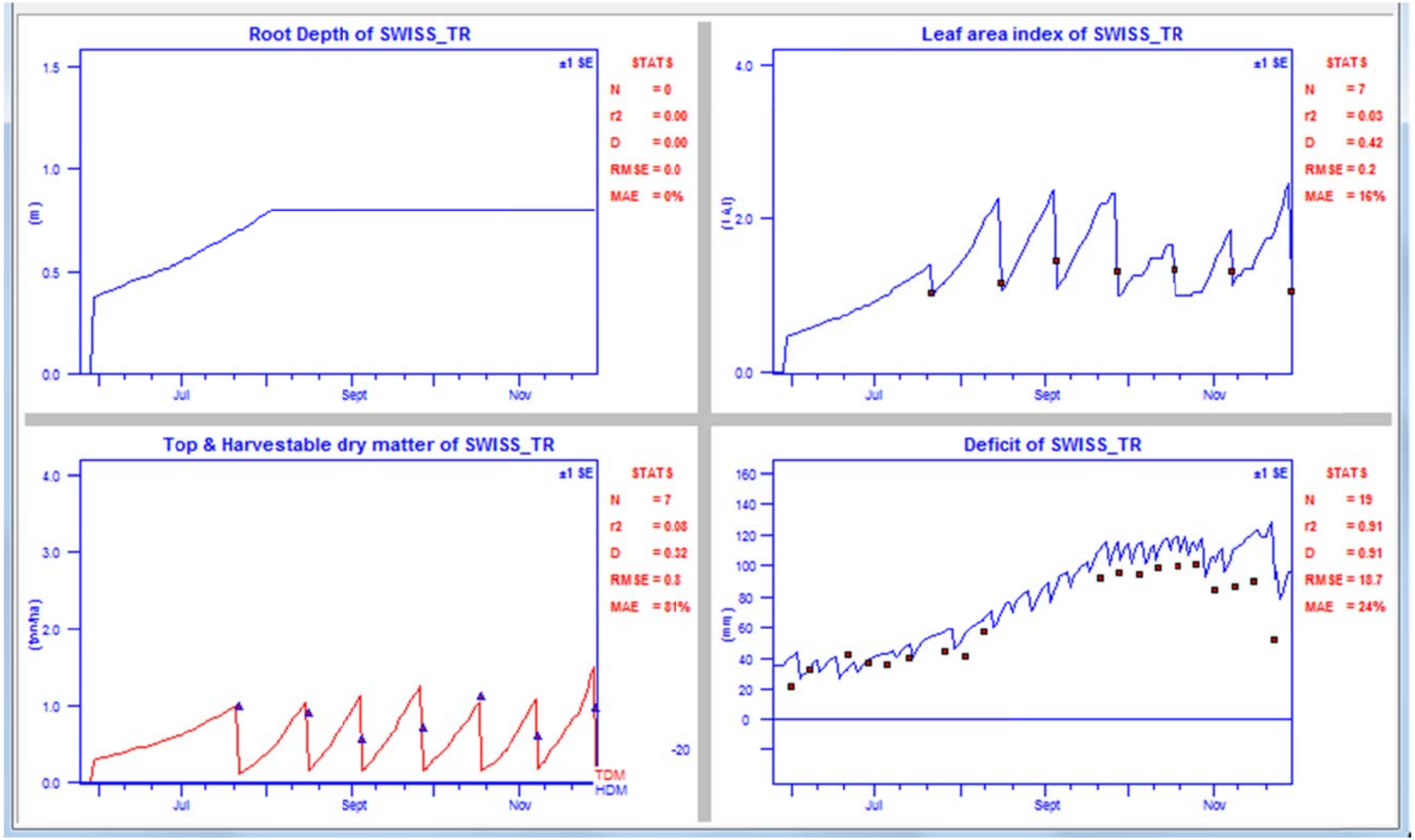


Figure 7.3: b) Simulated (solid lines) and measured values (symbols) for root depth (RD, m), leaf area index (LAI, m m^{-2}), total dry matter (TDM, t ha^{-1}) and soil water deficit (mm) for TR for the 2010/2011 Swiss chard growing season.

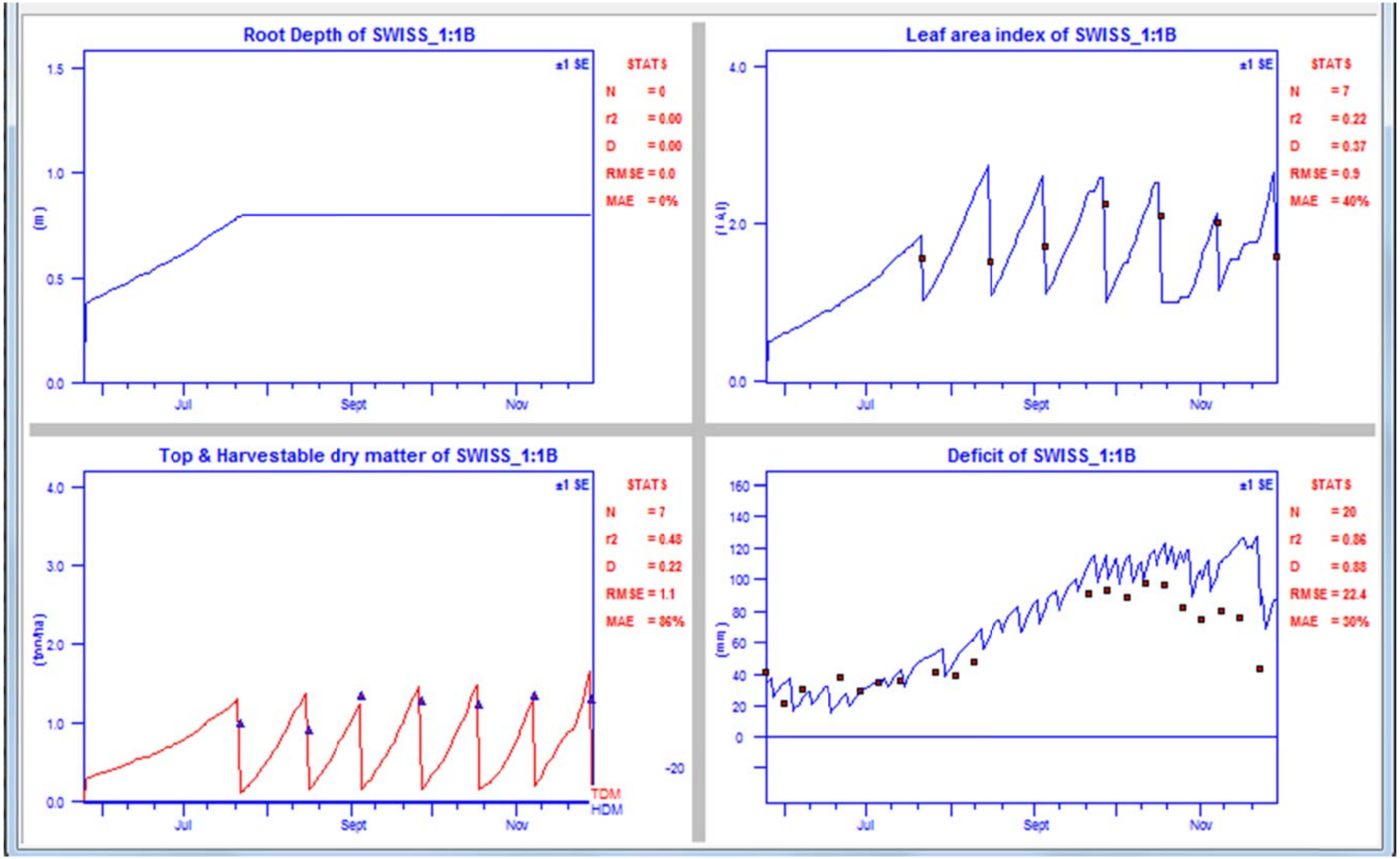


Figure 7.3: c) Simulated (solid lines) and measured values (symbols) for root depth (RD, m), leaf area index (LAI, m m^{-2}), total dry matter (TDM, t ha^{-1}) and soil water deficit (mm) for 1:1B for the 2010/2011 Swiss chard growing season.

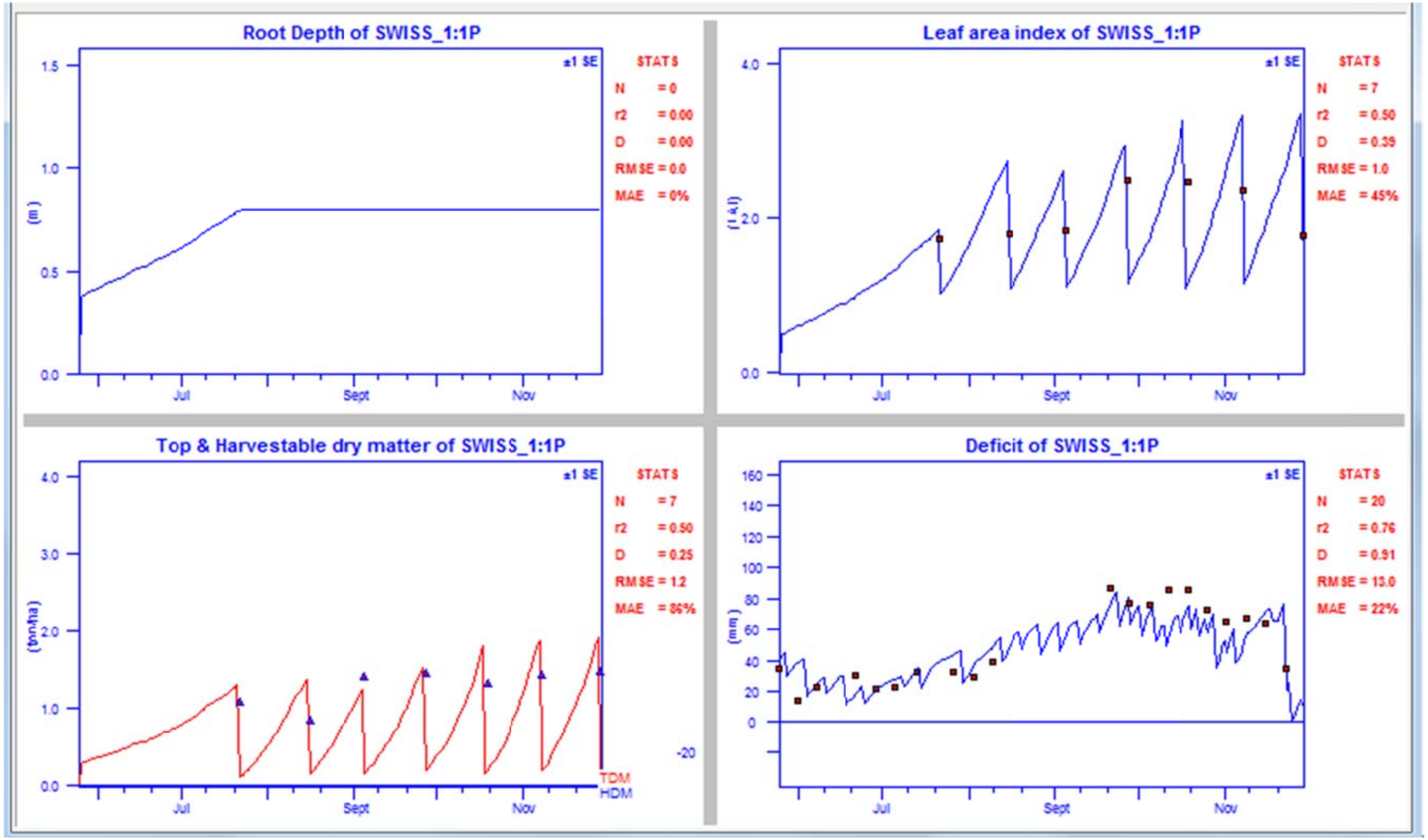


Figure 7.3: d) Simulated (solid lines) and measured values (symbols) for root depth (RD, m), leaf area index (LAI, m m^{-2}), total dry matter (TDM, t ha^{-1}) and soil water deficit (mm) for 1:1P for the 2010/2011 Swiss chard growing season.

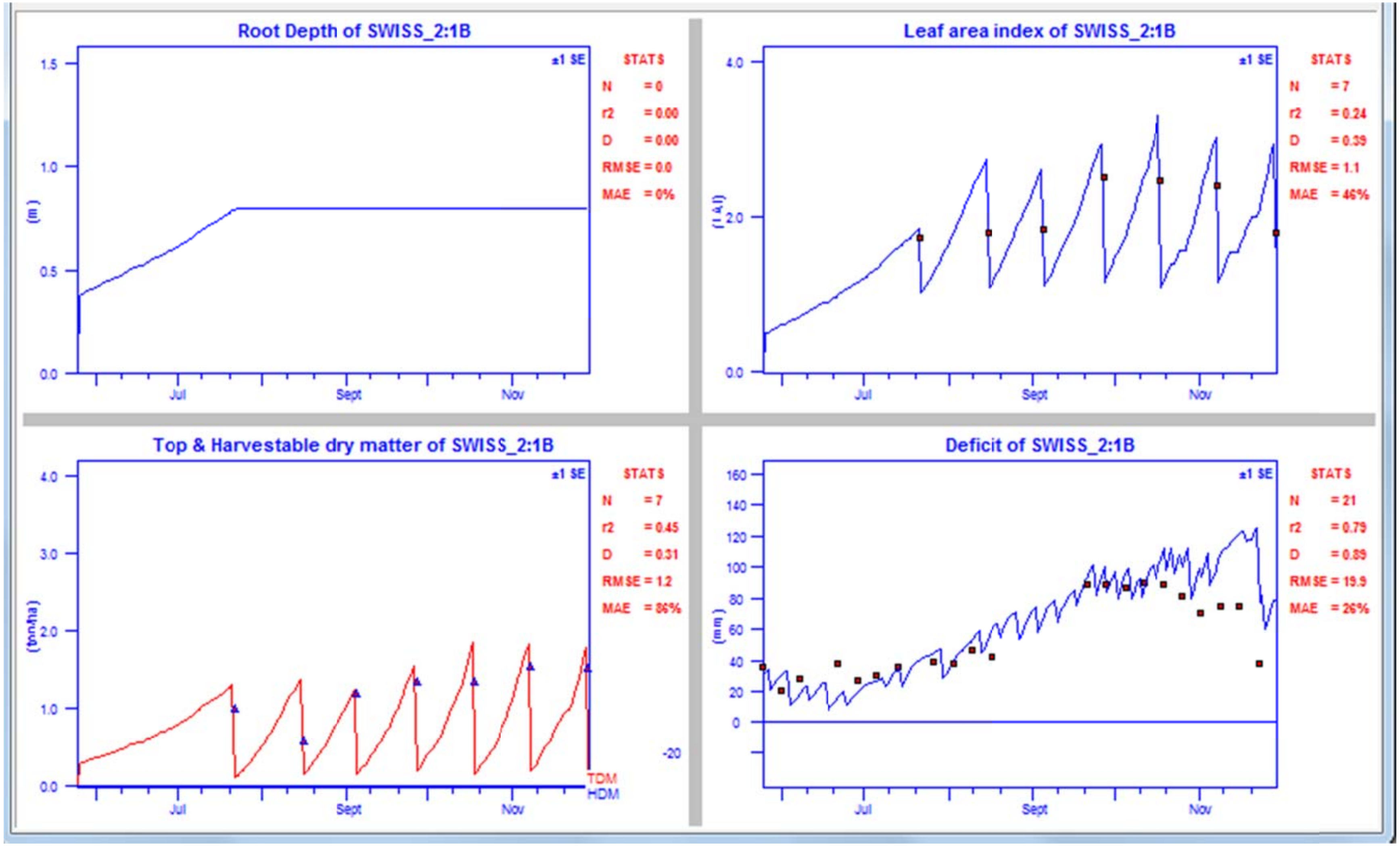


Figure 7.3: e) Simulated (solid lines) and measured values (symbols) for root depth (RD, m), leaf area index (LAI, m m^{-2}), total dry matter (TDM, t ha^{-1}) and soil water deficit (mm) for 2:1B for the 2010/2011 Swiss chard growing season.

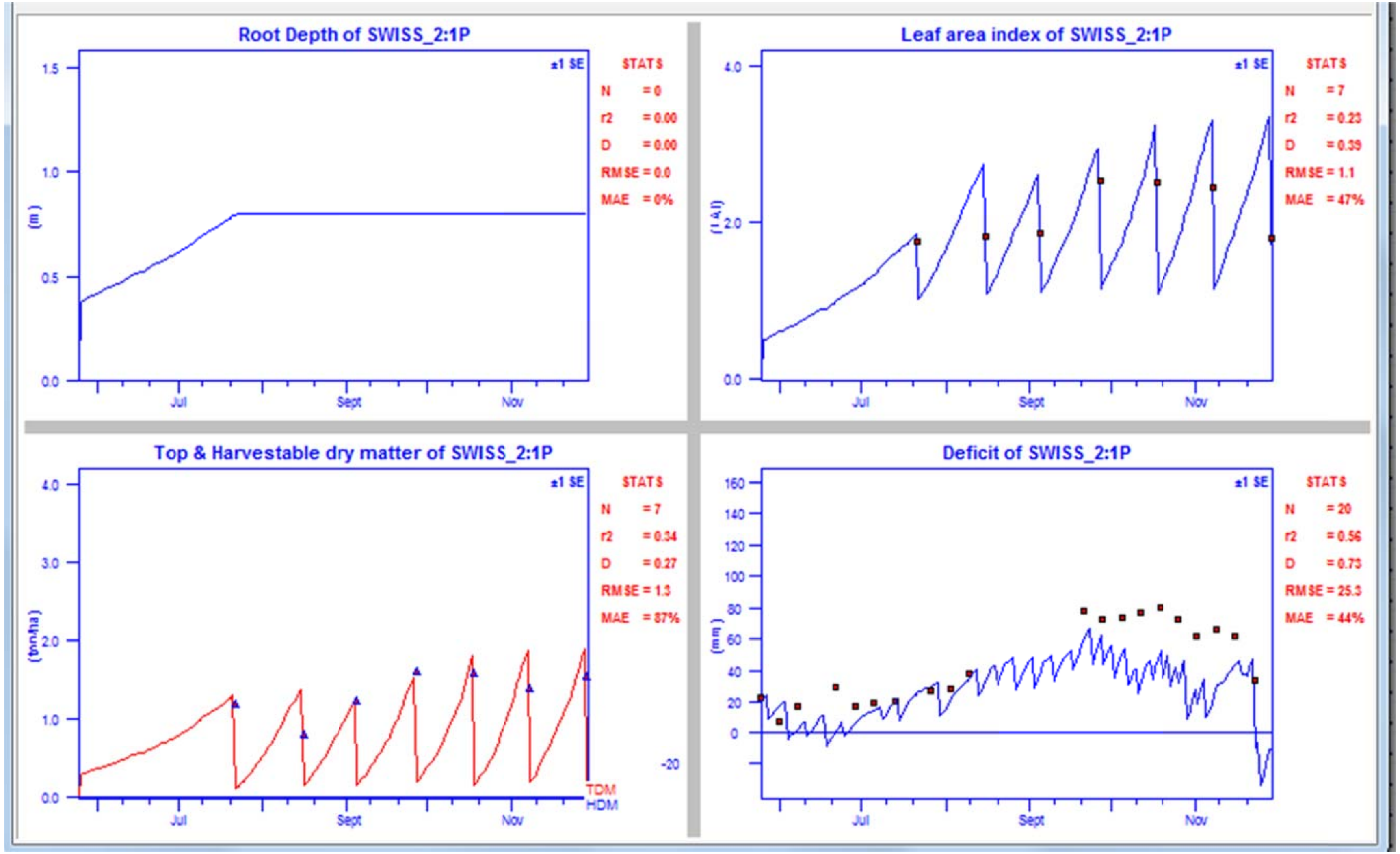


Figure 7.3: f) Simulated (solid lines) and measured values (symbols) for root depth (RD, m), leaf area index (LAI, m m^{-2}), total dry matter (TDM, t ha^{-1}) and soil water deficit (mm) for 2:1P for the 2010/2011 Swiss chard growing season.

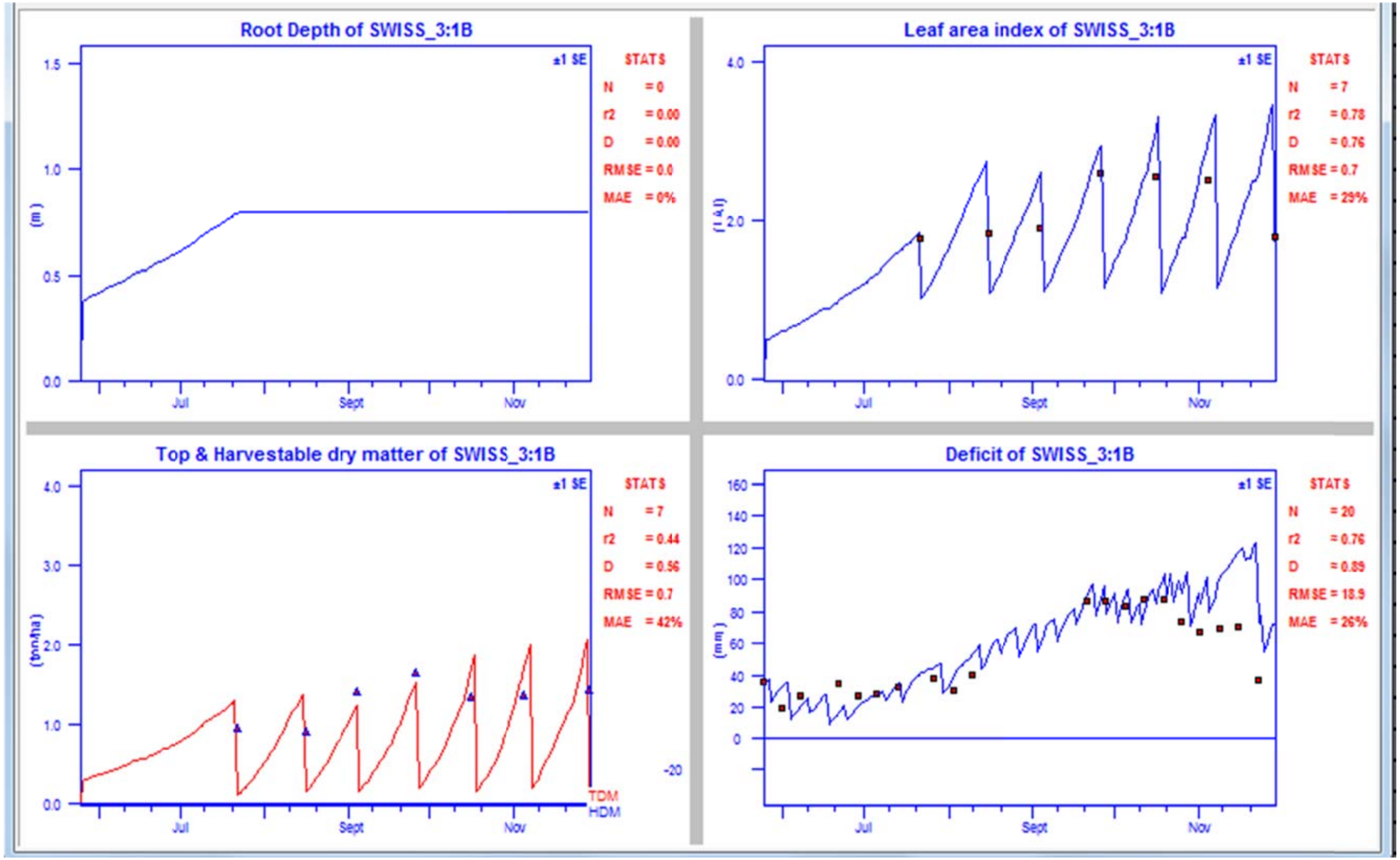


Figure 7.3: g) Simulated (solid lines) and measured values (symbols) for root depth (RD, m), leaf area index (LAI, m m^{-2}), total dry matter (TDM, t ha^{-1}) and soil water deficit (mm) for 3:1B for the 2010/2011 Swiss chard growing season.

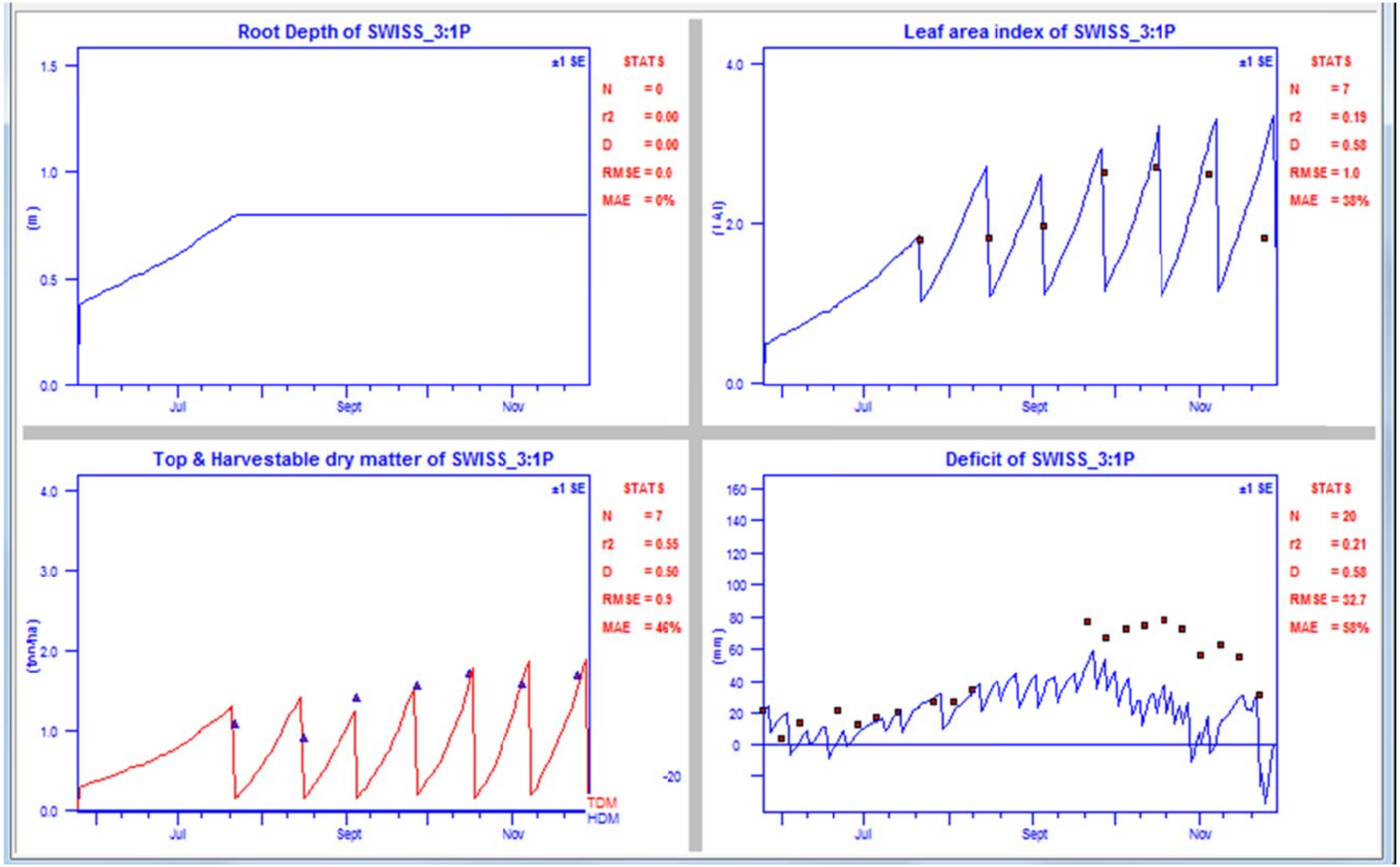


Figure 7.3: h) Simulated (solid lines) and measured values (symbols) for root depth (RD, m), leaf area index (LAI, m m^{-2}), total dry matter (TDM, t ha^{-1}) and soil water deficit (mm) for 3:1P for the 2010/2011 Swiss chard growing season.

Table 7.5: Total plot area and net cropped area simulation HDM (t ha^{-1}) for the 2010/2011 Swiss chard growing season (cropped area results in the parentheses).

Dates	**Treatments**							
	CT	**TR**	**1:1B**	**1:1P**	**2:1B**	**2:1P**	**3:1B**	**3:1P**
22/07/2010	1.0	1.0	0.65 (1.3)	0.65 (1.3)	0.43 (1.3)	0.43 (1.3)	0.33 (1.3)	0.33 (1.3)
16/08/2010	1.0	1.0	0.70 (1.4)	0.70 (1.4)	0.47 (1.4)	0.47 (1.4)	0.35 (1.4)	0.35 (1.4)
05/09/2010	1.1	1.1	0.65 (1.3)	0.65 (1.3)	0.43 (1.3)	0.43 (1.3)	0.33 (1.3)	0.33 (1.3)
27/09/2010	1.2	1.3	0.75 (1.5)	0.75 (1.5)	0.50 (1.5)	0.50 (1.5)	0.38 (1.5)	0.38 (1.5)
18/10/2010	0.9	1.1	0.75 (1.5)	0.90 (1.8)	0.63 (1.9)	0.60 (1.8)	0.48 (1.9)	0.45 (1.8)
08/11/2010	1.0	1.1	0.65 (1.3)	0.95 (1.9)	0.60 (1.8)	0.63 (1.9)	0.50 (2.0)	0.48 (1.9)
29/11/2010	1.3	1.5	0.85 (1.7)	0.95 (1.9)	0.60 (1.8)	0.63 (1.9)	0.53 (2.1)	0.48 (1.9)

7.6 Scenario simulations for potential potato planting dates

Throughout this dissertation, it was always mentioned that arid and semi-arid areas are characterised by erratic rainfall which is varying in both space and time. As such, in these regions, knowledge of the onset and cessation of rainfall, as well as information on wet and dry spells probability are beneficial in choosing the best planting dates and optimising crop growth and yields. During this study, long-term weather data (period of 30 years) of the study ecotope were used to classify rainy seasons in dry, normal and wet rain ranges as it is defined in FAO (1998). According to this organisation, wet, normal and dry years (seasons) in tropical areas, can be defined by exceedance probability ranges of 0 – 20, 20 – 80, and 80 – 100%, respectively. Once the classification was established, 2 wet, 2 normal and 2 dry rainy seasons were chosen to run the simulation model of CT, TR and 2:1B for the 4 different planting dates (8 October, 15 October, 29 October and 15 November), using the same crop parameter values and soil type as in the model calibration. The selection of the treatments was based on the goal to compare CT, TR and IRWH. Only potato scenario simulations are presented because Swiss chard growth mostly occurred in winter which is a dry season at the study location.

Scenario simulation outputs of potato TDM and HDM (according to the total area) of CT, TR and 2:1B for the selected rainy seasons are presented in Table 7.6 (Appendix E – Table E1 presents results according to the net cropped area). The simulation results for TR are the highest, followed by CT and 2:1B (the lowest). As explained earlier, the IRWH treatments had lower plants per plot area than CT and TR. The TDM and HDM values obtained by the scenario simulations are, in general, higher than the field results from the current study, except for the very dry season of 1978/1979. From Table 7.6 it can be seen that TDM and HDM varied from season to season, from treatment to treatment and from planting date to planting date. The seasonal variation can partly be attributed to the high inter- and intra-seasonal variability in rainfall distribution. As is shown, for each treatment, TDM and HDM values at the different planting dates varied according to the rain distribution of the different growing seasons. In general, TDM and HDM in the very dry season (1978/1979) increased with the delay of the planting dates. This should probably be attributed to the fact that rainfall is not enough in the first months of the rainy season, but it can increase progressively later on to the benefit of the crop. For the dry season (1991/1992), wet season (1995/1996) and normal season (1997/1998), however, TDM and HDM for the different treatments can increase or decrease with the delay of planting dates according to the rainfall distribution during the growing season. So-called normal or wet season can be characterised by a series of light rainfalls and dry spells, and few very heavy rainfalls which can result in high seasonal rainfall amount. This is why high seasonal rainfall amount does not always correspond to high plant growth and yield (e.g. normal seasons vs. wet seasons (in particular the 1999/2000 season) in Table 7.6); especially if the dry spell periods coincide with the crop growth sensitive stages. A long delay of planting, however, is always unbeneficial to crop growth and yield because the crop should experience dry spells as the rainy season should be heading to cessation.

Table 7.6 also gives an indication of how planting date decision in dryland potato production can affect biomass and yields, depending on both the average rainfall and the rainfall distribution during the growing season. For the dry season (1991/1992), the ideal planting date for all treatments was 15 October. This means that the earlier the crop planting, the higher the TDM and HDM. This can partly be explained by rainfall distribution during the crop growing season, and the fact that as the crop is planted earlier in the season, it is possible to avoid dry spells at the end of the growing season, when tuber yield (HDM) is most sensitive to water stress. For the normal seasons the results from all treatments show that any time in October is suitable, with 08 October being the most ideal planting date. For the wet seasons, 08 October 1995/1996 and 29 October 1999/2000 appear to be best ideal planting dates. All these results can be ascribed to the rainfall distribution during the crop growing season, the length of the crop growth cycle and the planting date (not too late).

Table 7.6: Simulated potato DM (t ha^{-1}) scenarios for CT, TR and 2:1B at the study ecotope for dry, normal and wet years (total area).

Sowing Date		**Yield (t ha^{-1})**											
		CT											
		08 October			**15 October**			**29 October**			**15 November**		
Year	Spell	Rainfall (mm)	TDM	HDM	Rainfall (mm)	TDM	HDM	Rainfall (mm)	TDM	HDM	Rainfall (mm)	TDM	HDM
1978/1979	Dry	154	2.6	1.2	150	2.8	1.3	128	3.0	1.5	115	3.4	1.2
1991/1992	Dry	293	8.6	6.2	280	9.7	6.8	249	9.4	5.4	230	6.9	2.9
1997/1998	Normal	382	16.6	12.5	365	15.7	11.8	359	15.1	10.4	295	10.9	6.3
1998/1999	Normal	343	14.1	10.4	311	12.7	9.1	305	11.6	7.2	290	9.1	4.5
1995/1996	Wet	668	16.7	12.6	786	15.7	11.5	736	14.8	9.8	691	9.5	5.1
1999/2000	Wet	459	6.5	5.2	459	11.0	8.9	447	13.9	10.0	434	11.0	6.0
Sowing Date		**TR**											
		08 October			**15 October**			**29 October**			**15 November**		
Year	Spell	Rainfall (mm)	TDM	HDM	Rainfall (mm)	TDM	HDM	Rainfall (mm)	TDM	HDM	Rainfall (mm)	TDM	HDM
1978/1979	Dry	154	3.4	1.5	150	3.8	1.8	128	3.8	1.9	115	4.2	1.6
1991/1992	Dry	293	10.3	7.7	280	11.1	7.9	249	10.7	6.3	230	7.0	3.0
1997/1998	Normal	382	17.1	12.8	365	16.2	12.1	359	15.3	10.6	295	11.0	6.4

Table 7.6: Simulated potato DM (t ha^{-1}) scenarios for CT, TR and 2:1B at the study ecotope for dry, normal and wet years (total area) (continued).

1998/1999	Normal	343	14.7	11.0	311	13.7	9.8	305	12.1	7.7	290	9.3	4.6
1995/1996	Wet	668	16.9	12.7	786	15.9	11.7	736	14.9	9.9	691	9.5	5.1
1999/2000	Wet	459	8.0	6.2	459	12.6	9.9	447	15.2	10.6	434	11.0	6.0
Sowing Date		**2:1B**											
		08 October			**15 October**			**29 October**			**15 November**		
Year	Spell	Rainfall (mm)	TDM	HDM	Rainfall (mm)	TDM	HDM	Rainfall (mm)	TDM	HDM	Rainfall (mm)	TDM	HDM
1978/1979	Dry	154	1.3	0.6	150	1.6	0.8	128	1.5	0.7	115	1.7	0.7
1991/1992	Dry	293	3.8	2.8	280	4.7	3.4	249	4.6	4.1	230	3.2	1.3
1997/1998	Normal	382	6.7	5.0	365	6.3	4.7	359	6.1	4.1	295	4.3	2.4
1998/1999	Normal	343	6.4	4.8	311	5.9	4.3	305	5.4	3.4	290	3.9	1.9
1995/1996	Wet	668	6.8	5.1	786	6.5	4.7	736	5.9	3.8	691	4.0	2.1
1999/2000	Wet	459	3.3	2.5	459	4.8	3.7	447	5.9	4.0	434	4.4	2.3

7.7 Conclusions and recommendations

During the current study, the SWB model was used to respectively predict the growth, development and yields of potato and Swiss chard crops at the Hatfield Experimental Farm. Data collected from the field during the 2009/2010 and 2010/2011 growing seasons were used to calibrate the model for these crops. The same parameter data used in the calibration of the SWB model for potato were also used in the SWB scenarios for the crop. No SWB scenarios were performed for Swiss chard because this crop grows in winter while the rainy season of the study site is in summer. The results of the calibration are shown in Figures 7.1a – h and 7.3a – h for potato and Swiss chard, respectively. The results of the scenario simulations are presented in Table 7. 5. In general, the SWB model predicted growth, water use and yields of the potato crop well, according to De Jager (1994) (except for some IRWH SWD results). For Swiss chard, however, only SWDs were well simulated (except for 3:1P); the TDM graph showed an agreement between the measured and simulated values (by observation), while the statistical parameters indicated a disagreement. This disagreement was partly attributed to the harvesting and growing method used (approach for pastures). The LAI graph showed overestimation because the canopy could not develop fully due to drought spells. However, by observing the TDM simulation and SWD results, an improvement should be possible if the simulation of the growing and harvesting method is well understood. Finally, the model was, in general, well calibrated for the potato cultivar and poorly calibrated for the Swiss chard cultivar. Therefore, the hypothesis 5 can only be partly accepted.

Scenario simulation results showed that TDM and HDM varied from season to season, from treatment to treatment and from planting date to planting date. On a total area basis, TR had the highest outputs, followed by CT while 2:1B had the lowest results. In general, the scenario simulations for all treatments showed higher TDM and HDM than the field results from the present investigation, except for the very dry season of 1978/1979. In terms of planting dates, the treatment TDM and HDM varied according to the rain distribution of the different growing seasons. In the very dry season (1978/1979), the treatment TDM and HDM increased with the delay of the planting dates. However, for the dry season (1991/1992), wet season (1995/1996) and normal season (1997/1998), the treatment TDM and HDM varied depending on planting dates and rainfall distribution during the growing season. The ideal planting dates for the dry season (1991/1992) were 15 and 29 October. October appeared to be the ideal planting month for the normal seasons, but 08 October was the most ideal planting date. The best planting dates for the wet seasons were 08 October (for 1995/1996) and 29 October (for 1999/2000).

The SWB model can mechanistically predict the growth, phenology, yields and water use of many plants. Nevertheless, the SWB model simulation is not consistent since it does not consider the effects of photoperiod and high temperatures (varying with seasons) on phenology and assimilate translocation (Steyn, 1997). As such, the incorporation of photoperiod in the model and taking the effect of high temperatures into consideration will improve its range of usefulness for different cultivars and growing conditions. At the same time, including the effect of photoperiod will improve the simulation of crops like potato for which tuber initiation is very sensitive to both photoperiod and temperatures. In addition, the model does not account for the soil waterlogging stress problem which cannot only lead to error in outputs but also to water drainage and nutrient leaching beyond the rootzone, resulting in water loss, environmental pollution and soil salinisation. In this regard, the model must incorporate a waterlogging aspect to better predict soil water stress (excessive soil water, in the case of occurrence of heavy rainfalls which are the causes of overflowing and underground drainage), nutrient leaching and soil salinisation processes. Moreover, the model should simulate the soil water movement vertically and laterally (2D SWB model although it usually requires more soil physical parameters, such as hydraulic conductivity, which are not readily available), instead of the current vertical prediction only. Furthermore, even though the model is simple, it needs to be made simpler to facilitate its operation. Basic computer operations such as copy or cut and paste are not always possible. Finally, it should be suggested that the refinement of the crop growth parameters for the crops used in this study carry on.

From the tendency of the results given by the scenarios (observation of the entire results), the ideal RWH technique, design ratio or planting date can be selected according to local conditions (weather, land, etc.). Results on cropped areas showed that IRWH can be recommended for the study field, especially and logically in the cases of low rainfalls. If land is limiting, 1:1B should be a better option; while if land is not limiting, 2:1 and 3:1 are better options. However, results per total area basis revealed that if land is limiting at the study ecotope, CT, and especially TR are the best options. This is especially true in the case of normal or wet seasons with evenly distributed rainfall. In terms of planting dates, for the very dry season, the scenario outputs showed that the later the planting, the higher the crop growth and yield. For dry, normal and wet seasons, the scenarios indicated that yields varied according to the rain distribution during the season, but October was the ideal planting month. This shows that the selection of the ideal RWH technique and the optimal design ratio for the study ecotope is governed by the expected rainfall amount for the specific season. Therefore, the hypothesis 6 was accepted. However, the selection of the ideal planting date for RWH yield optimisation should depend on the real situation of the seasonal rainfall distribution. Finally, the potato scenarios gave an indication that although the SWB model needs to be improved, it can still be a useful tool in selecting the ideal RWH technique, design ratio or planting date for ultimate prediction of optimum growth and yield for the cultivar involved. Therefore, at the time the SWB model is not yet fully evolved to the 2 SWD model, its use for crop growth, yield and soil water balance is highly recommended.

CHAPTER 8

GENERAL CONCLUSIONS AND RECOMMENDATIONS

8.1 General conclusions

According to Botha *et al.* (2003), in-field rainwater harvesting (IRWH) technology is specifically designed to trap rainfall within the field for plant benefits. Hence, the aim of the study was to investigate whether RWH can achieve the full potential of dryland crop production to ensure food security and improve the livelihoods of the people of drought/hunger-stricken areas through higher yields and improved WUEs. In this regard, two RWH field experiments with potatoes (2009/2010) and Swiss chard (2010/2011) were carried out in the semi-arid area of the Hatfield Experimental Farm, University of Pretoria. Three cropping systems were used: (1) conventional tillage (CT), (2) tied-ridges (TR), and (3) In-field Rainwater Harvesting (IRWH).

For the 2009/2010 growing season, the total area yields and WUE of TR and CT were in general higher than those of the IRWH treatments. This is because TR and CT had more plants per plot than the IRWH treatments. Although the IRWH treatments harvested more runoff than CT and TR, this could not compensate for their relatively fewer plants per plot. During the course of the 2009/2010 potato growing season, the yields and WUE of TR were lower than those of CT because of disease incidence. However, for the 2010/2011 Swiss chard growing season, TR performed better than CT, as was expected. In terms of yields and WUEs expressed on the net cropping area, the IRWH treatments had higher yields and WUE than TR, which, in turn, performed better than CT. For the 2009/2010 growing season, in terms of potato tuber internal quality such as harvest index, specific gravity and chip colour, the IRWH treatments generally performed better than TR and CT. However, with regard to hollow heart and brown spot incidences, all treatments had excellent results**.** In respect of potato tuber external quality, cases of tuber secondary growth, cracking, common scab and rotten tubers were recorded, and CT was the most affected. For the 2010/2011 Swiss chard growing season, in terms of plant mineral content, CT had the lowest nutrient concentration, in general.

In terms of the long-term (15 years) rainfall data at the Hatfield Experimental Farm, it was revealed that the probability of having or exceeding different monthly and annually rainfall declined as threshold rainfall increased. January was the long-term wettest month, although the data from the 2009/2010 rainy season showed that December was the wettest month. The ecotope is also characterised by a high probability of light rains and short dry spells. The long-term AI of the site is 0.40 (semi-arid) notwithstanding the 2009/2010 potato growing season with a mean AI of 0.80 (humid) since the total rainfall was higher than the habitual average. During this season, the runoff volume collected from the drums disclosed that for the bare runoff plots, the wider the runoff area, the higher the collected runoff, sediment and suspension. However, in terms of runoff depth and runoff efficiency, the smaller the catchment area the deeper the runoff depth and the higher the runoff efficiency. Moreover, the increase in soil loss and the increase in runoff plot size are not in direct proportional relationship. It is worthwhile to note that the runoff plot with plastic had the highest values in all these items, except for soil sediment and suspension (not applicable). This account on the long-term and seasonal rainfall, as well as on runoff on the study site is also applicable to the outcomes from the 2010/2011 Swiss chard growing season, with the exception that the rainfall onset delayed so that rainfall started in November.

During the 2009/2010 potato and 2010/2011 Swiss chard growing seasons at the Hatfield Experimental Farm, results from calibration of the linear regression model showed that runoff and rainfall were directly proportional. This was reflected by elevated coefficients of determination, particularly that of the plastic-covered runoff plot which had a coefficient of determination of 0.99. During the 2009/2010 rainy season, the curve number (USDA-SCS-CN (1972)) model analysis had a CN of 96 and an initial abstraction value (s) of 15.90 mm for 1 m x 5 m and 2 m x 5 m. This method showed a CN and an s of 95 and 20.80 mm for 3 m x 5 m. The CN model calibration results showed an agreement and positive correlation between the predicted and the observed runoff data, translated by high coefficients of determination and model efficiencies. The Morin & Cluff (1980) model calibration analysis resulted in the best surface retention and soil stability factor of 2.49 mm and 0.69 mm^{-1}, respectively. Both predicted and observed runoffs were in agreement and directly proportional, which was showed by high coefficients of determination and model efficiencies. In addition the validation of the different runoff models involved in the study was good as it was indicated by high coefficients of determination.

The SWB model is a real-time crop growth irrigation scheduling model which uses the SPAC to calculate crop growth and the soil water balance. During the present investigation, the SWB model was used to respectively predict the growth, development and yields of potato and Swiss chard crops at the Hatfield Experimental Farm. The calibration of the model for these crops was carried out using data collected from the field during the 2009/2010 (potato) and 2010/2011 (Swiss chard) growing seasons. In addition, the data used to calibrate the SWB model for potato were also used in this crop SWB scenarios conducted in order to select the ideal RWH technique, design ratio or planting date. However, Swiss chard is a winter crop which was grown (mostly by sprinkler irrigation) in a summer rainfall area and, therefore, no SWB scenarios were performed for it (no long-term rainfall data for its growing season at the study site). The calibration showed that for both crops, the total area simulation results for TR were the highest, followed by CT and 2:1B (an IRWH treatment), respectively (TR and CT had more plants per plot area than 2:1B). However, the net cropped area outcomes indicated that 2:1B was the best performer, followed by TR and CT, respectively (the individual plants of 2:1B performed well because of the collected runoff). In general, there was an agreement between SWB model simulations and the data collected during the 2009/2010 potato growing season, according to De Jager (1994). With regard to Swiss chard, however, there was, in general, a disagreement between the simulated and observed results, except for the SWDs. This disagreement was partly explained by the harvesting and growing method used, as for example, by observing the TDM results, an agreement was obvious while the statistical parameters showed otherwise. However, in general (for both crops), any disagreement which occurred should have resulted from factors such as errors in the measured data or some SWB shortcomings.

Scenario simulation results showed that TDM and HDM varied from season to season, from treatment to treatment and from planting date to planting date. As in the case of the calibration results, the simulation results expressed per total area basis showed that, TR had the highest outputs, followed by CT and 2:1B, respectively (TR and CT had higher number of plants per plot than 2:1B). The results on a net area basis are presented in Appendix E (Table E1). In general, the scenario simulations for all treatments showed higher TDM and HDM than the field results from the present investigation, except for the very dry season of 1978/1979. During the very dry season, the later the planting dates the higher the treatment TDM and HDM. In the dry season (1991/1992), the ideal planting dates were 15 and 29

October. For normal and wet seasons, for example 1995/1996 (wet) and 1997/1998 (normal), the long-term TDM and HDM for all treatments varied according to the rain distribution during the growing season (whether or not evenly distributed across the season). A so-called wet season can be a result of a combination of many light rainfalls and few very heavy rainstorms. During normal seasons, for example 1997/1998, the treatment long-term results revealed that planting can be conducted across the entire month of October, with 08 October being the most ideal planting date. During wet seasons, 08 October 1995/1996 and 29 October 1999/2000 appear to be the best ideal planting dates.

8.2 General recommendations

RWH technique has the potential to contribute to maximizing rainwater utilization and increasing green economic benefits in arid and semi-arid regions of the world. Nevertheless, in order to make the technique more efficient, there is a need for concordance of forces between the technique and various state-of-the-art technologies. For example, nutrient loss analysis technologies should be applied to RWH trials. Numerous small- and large-scale experiments should be carried out in order to institute a reliable database and to identify which best design ratio or RPA surface treatment for a given site. However, this should be dictated by financial and agrarian affordability. Moreover, RWH is a multidisciplinary issue and therefore, all the stakeholders involved must be drawn in the decision-making of RWH projects.

The description of the growing season according to FAO (1978) is a good guidance in determining the planting period or the type of cultivar in rainfed agriculture. However, for a more exhaustive analysis and understanding of the growing season, the methods advanced by Berger (1989) and Inthavong *et al.* (2011) should also be taken into consideration. Moreover, sound structures should be installed in order to provide sufficient climatic and soil water data in arid and semi-arid areas. The technical problems in runoff harvesting systems should be overcome by exercising extra caution with the systems, and by building appropriate tankers to collect water from drum overflowing. The tankers should be connected to a micro-irrigation system which should be operated in case of necessity. The issue of the tipping bucket residual runoff, sediment and nutrients should be addressed by conceiving new devices (or upgrading the tipping buckets) to record all items of data involved in rainfall falling on runoff plots. However, runoff management trials and the involved runoff, sediment and nutrient loss are to be emphasized. In addition, there is a need for a renewed interest in the use of models in terms of rain erosivity, soil erodability and nutrient loss via runoff.

The regression models and CN methods are site-related and thus multiple site experiments must be carried out in order to get more accurate runoff prediction results. Since CN greatly relies on AMC, an index of wetness characterizing different hydrological American soil types, an evolutionary improvement of the method is imperative to make it more spatially distributed. Moreover, the method must be tested for wide catchment purposes. As the Morin and Cluff (1980) model highly depends on the long-term rainfall intensity data, automatic weather stations should be installed to satisfy this need. Furthermore, the use of models which take rainfall time distribution into consideration should be emphasized during runoff prediction.

SWB is a generic mechanistic model that can simulate the growth, development, yields and water balance of many plants. However, some shortcomings linked to this model have aroused an immediate urgency for a much needed improvement. For example, the model disregards the effects of photoperiod and high temperatures on phenology and photosynthate translocation (Steyn, 1997). The model will be improved largely if these factors are considered. A particular improvement in crop simulations of crops such as potato is expected if photoperiod is a consideration, since tuber initiation hugely depends on this factor. Another striking example of the model shortcoming is the lack of the soil waterlogging problem provision; for example, in the case of heavy rainfalls which are the cause of overflowing and underground drainage. If this factor is considered, the model improvement will enable the display of the effect of waterlogging stress on outputs. Moreover, the waterlogging involvement will provide useful information on the water drainage and nutrient leaching situation which are the sources of water and nutrient loss, environmental pollution and soil salinisation. Furthermore, as the model just simulates the vertical soil water movement and discounts the horizontal soil water movement implication, a paradigm shift to a 2D SWB model should improve the crop growth and soil water use predictions. Finally, the management of the model should further refine its operations; and a further refinement of the crop growth parameters used in the current study should carry on.

The long-term potato simulations showed that the SWB model can be helpful in selecting the ideal RWH technique, design ratio or planting date. Although there is an area for improvement, the scenarios revealed that the model have the potential to predict optimum growth and yield for the cultivar involved, therefore, its use is highly recommended if 2D SWB is not available.

LIST OF REFERENCES

AGHAJANI, G.H., 2007. Agronomical Analysis of the characteristics of the precipitation (Case study: Sazevar, Iran). *Pakistan J. Biol. Sci*. 10(8), 1353-1358.

ALDON, E.F. & SPRINGFIELD, H.W., 1975. The Negev, the challenge of a desert. Havard university Press. Cambridge, Mass., USA.

ALI, G.A., ROY, A.G., LEGENDRE, P., 2010. Spatial relationships between soil moisture patterns and topographic variables at multiple scales in a humid temperate forested catchment. *Water Resour. Res*. 46(10), W10526, doi, 10.1029/2009wr008804.

ALLEN, E.J. & SCOTT, R.K., 1980. An analysis of growth of the potato crop. *J. Agric. Sci. Camb*. 94, 583-606.

ALLEN, R., PERREIRA, L.S., RAES, D. & SMITH, M., 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage, Paper No. 56, Rome, Italy. p.300.

AMERMAN, C.R. & MCGUINESS, J.L., 1968. Plot and small watershed runoff: Its relation to larger areas. *Trans. ASAE* 10(4), 464-466.

ANAYA, M.G. & TOVAR, J.S., 1975. Different soil treatments for harvesting water for radish production in the Mexico valley. *Proc. Water Harvesting Syrup*, Phoenix, AZ, ARSW-22. USDA, p.315-320.

ANITA, I & GIOVANNI, M., 2005. Physiological and growth response to moderate water deficit of off-season potatoes in Mediterrean environment. *Agric. Water Manage*. 82, 193-209.

ANNANDALE, J.G., van der WESTHUIZEN, A.J. & OLIVIER, F.C., 1996a. Die fasilitering van tegnologie oordrag deur verbeterde besproeiingsriglyne vir groente en'n meganistiese gewasmodeleringsbenadering. WNK Verslag No 476/1/96. Pretoria.

ANNANDALE, J.G., BENADÉ, N., JOVANOVIC, N.Z., STEYN, J.M. & DU SAUTOY, N., 1999. Facilitating irrigation scheduling by means of the soil water balance model. *Water Res. Comm. Rep. No.* 753/1/1999, Pretoria, South Africa.

ANNANDALE, J.G., JOVANOVIC, N.Z., MPANDELI, N.S., LOBIT, P. & du SAUTOY, N., 2002. Two dimensional energy interception and water balance model for hedge grow tree crops. WRC Report No. 945/1/02.

ANNANDALE, J.G., JOVANOVIC, N.Z., CAMPBELL, G.S., DU SAUTOY, N. & LOBIT, P., 2004. Two-dimensional solar radiation interception model for hedgerow fruit trees. *Agric. Forest Meteorol*. 121(2004), 207-225.

APHALO, P.J. & JARVIS, P.G., 1993. The boundary layer and the apparent responses of stomatal conductance to wind speed and to the mole fractions of CO_2 and water vapour in the air. *Plant Cell Environ*. 16, 771-783.

ANSCHÜTZ, A., KOME, A., NEDERLOF, M., de NEEF, R. & van de VEN, T., 2003. Water harvesting and soil moisture retention. Agrodok 13, Agromisa Foundation, Wageningen, 2003, the Netherlands.

ARAYA, A., 2005. An Agro-climatic characterization towards improving barley production in the Giba catchment, Northern Ethiopia. MSc. Dissertation, MAGM program. University of Zimbabwe, Harare, Zimbabwe.

ARAYA, A. & STROOSNIDJER, L., 2010. Assessing drought risk and irrigation need in Northern Ethiopia, URL:http:www.sciencedirect.com/science (Accessed 23/06/2011).

ASANTE, Y.O. & STEPHENSON, D., 2006. Estimation of storm runoff loads based on rainfall related variables and power low models – Case study in Alexandra. *Water SA*. 32(2), 137-143.

ASHRAF, M.Y., AMZI, A.R., KHAN, A.H. & ALA, S.A., 1994. Effect of water stress on total phenol, peroxidase activity and chlorophyll content in wheat. *Acta Physiol. Plant*. 16, 185-191.

BANSAL, K.C. & NAGARAJAN, S., 1986. Leaf water content, stomatal conductance and proline accumulation in leaves of potato (*Solanum tuberosum* L.) in response to water stress. *Ind. J. Plant Physiol.* 29(29), 397-404.

BARITELLE, A.L. & HYDE, G.M, 2003. Specific gravity and cultivar effects on potato tuber impact sensitivity. *Postharvest Biol. Technol.* 29, 279-286.

BECCAFICHI, C., BENINCASA, P., GUIDUCCI, M. & TEI, F. 2003. Effect of crop density on growth and light interception in greenhouse lettuce. *Acta Hort*. 614, 507-513.

BEGG, J.E. & TURNER, N.C., 1976. Crop water deficits. *Adv. Agron*. 28, 161-217.

BELACHEW, A., 2000. Dry-spell analysis for studying the sustainability of rain-fed agriculture in Ethiopia: The case of Arbaminch area. *Proc. 8th. Nile 2002 Conf.* 22 June 2002, Addis Ababa, Ethiopia. International Commission on Irrigation and Drainage (ICDID).

BELANGER, G., WALSH, J.R., RICHADS, J.E., MILBURN, P.H. & ZIADI, N., 2002. Nitrogen fertilization and irrigation affects tuber characteristics of two potato cultivars. *Am. J. Potato Res.* 79(4), 269-279.

BENNIE, A.T.P., van RENSBURG, L.D., STRYDOM, M.G. & du PREEZ, C.C., 1996. Die effek van voorafgeprogrammeerde tekortbesproeiing op plantreaksie.
Waternavorsingskommissie Verslag, Pretoria, South Africa (Accessed 30/10/2009).

BENNIE, A.T.P. & HENSLEY, M., 2001. Maximizing precipitation utilization in dryland agriculture in South Africa – a review. *J. Hydrol*. 241(2001), 124-139.

BENOIT, G.R., STANLEY, C.D., GRANT, W.J. & TORREY, D.B., 1983. Potato top growth as influenced by temperatures. *Am. Potato J*. 60, 489-501.

BENOIT, G.R., GRANT, W.J., & DEVINE, O.J., 1986. Potato top growth as influenced by day-night temperature differences. *Agron. J*. 78, 264-269.

BERGER, P., 1989. Rainfall and agro-climatology of the Laikipia Plateau, Kenya. Africa Studies Series A7, Institute of Geography, University of Berne, Switzerland.

BHAGSARI, A.S., WEBB, R.E., PHATAK, S.C. & CASIMIR, A.J., 1988. Canopy photosynthesis, stomatal conductance and yield of *Solanum tuberosum* grown in a warm climate. *J. Am. Soc. Hort. Sci*. 65, 393-406.

BLACKMER, T.M., SCHEPERS, J.S. & VIGIL, M.F., 1993. Chlorophyll meter readings in corn as affected by plant spacing. *Commun. Soil Sci. Plant Anal*., 24 2507-2516.

BLOCH, D., HOFFMANN, C.M., MARLANDER, B., 2006. Impact of water supply on photosynthesis, water use and carbon isotope discrimination of sugar beet genotypes. *Eur. J. Agron*. 24, 218-225.

BODLAENDER, K.B.A., VAN DE WART, M. & MARINUS, J., 1986. Effects of drought on water use, photosynthesis and transpiration of potatoes. 2. Drought, photosynthesis and transpiration. p.44-54. *In*: A.G.B. Beekman (*ed*.). *Potato Res. of Tomorrow*. Pudoc, Wageningen.

BOERS, Th. M. & BEN-ASHER, J., 1982. . A review of rainwater harvesting. *Agric. Water Manage.* 5, 145-158.

BOERS, Th. M., ZONDERVAN, K., BEN-ASHER, J., 1986. Micro-catchment-water-harvesting (MCWH) for arid zone development. *Agric. Water Manage*. 12, 21-39.

BOERS, T.M., 1997. Rainwater harvesting in arid and semi-arid zones. International Institute for Land Reclamation and Improvement. Publication 55. Wageningen, The Netherlands. www.alterra.wur.nl/Internet/webdocs/ilri-publicaties/Pub55/Pub55.pdf (Accessed 06/04/2009).

BOIFFIN, J., 1984. *La dégradation structurale des couches superficielles du sol sous l'action des pluies.* PhD. Thesis, *Institut National Agronomique Paris* – Grignon, Paris, p. 320.

BOTHA, J.J., van RENSBURG, L.D., ANDERSON, J.J., HENSLEY, M., MACHELI, M.S., van STADEN, P.P., KUNDHLANDE, G., GROENEWALD, D.G. & BAIPHETHI, M.N., 2003. Water conservation techniques on small plots in semi-arid areas to enhance rainfall use efficiency, food security, and sustainable food production. WRC. Report No. 1176/1/03. Water Research Commission, Pretoria, South Africa.

BOTHA, J.J, ANDERSON, J.J, GROENEWALD, D.C., van RENSBURG, L.D. & HENSLEY, M., 2007. Application of the In-field rainwater harvesting technique in rural communities in South Africa to fight poverty and food insecurity. Institute for Soil Climate and Water.

BRADLEY, A, JEFFREY, K. & STARK, C., 2005. Potato irrigation management. University of Idaho, Cooperative extension system, *Bul.* 789, 1-15.

BRADY, N.C. & WEIL, R.R., 2002. The nature and properties of soils. 13th ed., Pearson Education Inc., New Jersey, p 200.

BROWN, C.R., 1993. Origin and history of potato. *Am. Potato J.* 70, 363-373.

BRUCE, W.B., EDMEADES, G.O. & BARKER, T.C., 2002. Molecular and physiological approaches to maize improvement for drought tolerance. *J. Exp. Bot*. 53(366), 13-25.

BRUGGEMAN, A. & OWEIS, T., 1998. Runoff modeling of micro-catchment water harvesting.
www.icarda.org/Publications/Program Reports/ (Accessed 14/08/2009).

BRUINS, H. J., EVENARI, M. & NESSLER, U., 1986. Rainwater–harvesting agriculture for food production in arid zones: the challenge of the African famine. *Appl. geogr*. 6,13-32.

BUDYKO, M.I., 1974. Climate and Life. Academic Press, Orlando, FL, p.508.

BUNCE, J.A., 1984. Effects of humidity on photosynthesis. *J. Exp. Bot*. 35, 1245-1257.

BURSTALL, L. & HARRIS, P.M., 1983. The estimation of percentage light interception from leaf area index and percentage ground cover in potatoes. *J. Agric. Sci*. (Cambridge), 100(1983), 241-244.

CAMPBELL, G.S. & DIAZ, R., 1988. Simplified soil water balance model to predict crop transpiration. *In*: F.R. Bidinger & C. Johanson (eds.). Drought research priorities.

CAMPBELL, G.S. & van EVERT, F.K., 1994. Light interception by plant canopies: efficiency and architecture. *In*: J.L. Monteith., R.K. Scott & M.H. Unsworth (eds.). Resource capture by crops. Nottingham Univ. Press. 35-52.

CAMPBELL, M.D., CAMPBELL, G.S., KUNKEL, R. & PAPENDICK, R.I., 1976. A model describing soil-plant-water relations for potatoes. *Am. Potato* J. 53, 431-441.

CARON, B.D., MANFRON, P.A., LUCIO, A.D., SCHMIDT, D., MEDEIROS, S.L.P., BONNECARRERE, R.A.G. & DOURADO-NETO, D., 2007. Equations to estimate shoot phytomass of lettuce. *Ciencia Rural*. 37(5), 1248-1254.

CASENAVE, A. & VALENTIN, C., 1989. *Les Etats de surface de la zone Sahélienne. Influence sur l'infiltration*. OSTROM, Paris, France, p. 230.

CAVAGNARO, J. B., DELIS, B.R. & TIZIO, R.M., 1971. Drought hardening of the potato plant as an after-effect of soil drought conditions at planting. *Pot. Res*. 14: 181-192.

CHAHINIAN, N., MOUSSA, R., ANDRIEUX, P. & VOLTZ, M., 2005. Comparison of infiltration models to simulate flood events at the field scale. *J. Hydrol*. 306, 191-214.

CHARLES-EDWARDS, D.A., 1982. Physiological determinants of crop growth. London. Academic Press.

COELHO, A.F.S., GOMES, E.P., SOUSA, A.P. & GLORIA, M.B.A., 2005. Effect of irrigation level on yield and bioactive amine content of American lettuce. *J. Sci. Food Agric*. 85, 1026-1032.

COLES, N.A., CATTLIN, J.J., FARMER, D. & STANTON, D., 2004. Water management: what's in a name? Paper presented at the 13th International Soil Conservation Organisation Conference (Conserving Soil and Water for Society: Sharing Solutions, ISCO 2004), ASSSI, Brisbane, Australia, July 4-8.

CONNOLLY, R.D., 1998. Modelling effects of soil structure on the water balance of soil-crop systems: a review. *Soil & Tillage Res*. 48(1998), 1-19.

CONWAY, G., 1997. The Doubly Green Revolution: food for all in the 21st century. New York (USA): Penguin Books. p.335. www.bioinformatics.vg/Books/th/The_Doubly_Green_Revolution_Food_for_All_in_the_Twenty-First_Century_0801486106.html (Accessed 24/12/2009).

CORE, W.J., 1983. Growth and morphogenesis of sun and shade plants. I. The influence of light intensity. *Acta Bot. Neerl.* 32(1/2), 49-62.

COTTRELL, J.E., DUFFUS, C.M., PATERSON, L. & MACKEY, G.R., 1995. Properties of potato starch: Effects of genotype and growing conditions. *Phytochemistry*. 40, 1057-1064.

CRAKER, L.E., SEIBERT, M. & CLIFFORD, J.T., 1983. Growth and development of radish (*Raphanus sativus*, L.) under selected light environments. *Ann. Bot*. 51, 59-764.

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

DALLA COSTA, L., VEDOVE, G.D., GIANQUINTO, G., PERESSOTTI, A., 1997. Yield, water used efficiency and nitrogen uptake in potato: Influence of drought stress. *Potato Res.* 40, 19-34.

DANDA, G.S. & BEHL, R.K., 2004. Indices of drought tolerance in wheat genotypes at early stages of plant growth. *J. Agron. Crop Sci.* 190, 1-6.

DEBLONDE, P.M.K. & LEDENT, J.F., 2001. Effects of moderate drought conditions on green leaf number, stem height, leaf length and tuber yield of potato cultivars. *Europ. J. Agron*. 14(2001), 31-41.

de JAGER, J.M., 1994. Accuracy of vegetation evaporation ratio formulae for estimating final wheat yield. *Water SA*. 20(4), 307-314.

DENNETT, M.D., 1987. Variation of rainfall - the background to soil and water management in dryland regions. *Soil Use Manage.* 3 (2), 47-51.

De WIT, C.T., 1958. Transpiration and crop yields. Instituut Voor Biologisch en Scheikundig Onderzoek van Landbouwgewassen, Veersl. Landbouskd. Onderz. 64. 6, Wageningen, Netherlands.

De WIT, C.T., 1965. Photosynthesis of leaf canopies. *Agric. Res. Reports*. 66.3, Pudoc, Wageningen, p.57.

De WIT, C.T., 1982. Simulation of living systems. *In*: Eds. F.W.T. Penning de Vries & H.H. van Laar, Simulation Monographs, Pudoc, Wgeningen, The Netherlands, p.3-8.

DON, M., 2003. Eat with the beet. *The Guardian*. www.en.wikipedia.org/wiki/Chard (Accessed 28/04/2011).

DOORENBOS, J. & KASSAM, A.H., 1986. Yield response to water. FAO irrigation and drainage paper No.33, FAO, Rome, Italy.

DOSS, B. D., PEARSON, R. W., & ROGER, H. T., 1974. Effect of soil water stress at various growth stages on soybean yield. *Agron. J.* 66, 297-299.

DUCHAUFOUR, H. & BIZIMANA, M., 1992. Restauration de la fertilitė et conservation des sols au Rwanda. *Bull. Rėseau Erosion*. 12, 161-178.

DUTT, G.R., HUTCHINSON, C.F. & GARDUNO, M.A., 1981. Rainfall collection for agriculture in arid and semi-arid regions. Commonwealth Agricultural Bureaux. Farnham House, Farnham Royal, Slough, United Kingdom.

DWELLE, R.B., 1985. Photosynthesis and photoassimilate partitioning. p.35-58. *In*: P.H Li. (ed.). Potato physiology. Academic Press, Orlando, Florida.

DWELLE, R.B., KLEINKOPF, G.E. & PAVEK, J.J., 1981. Stomatal conductance and gross photosynthesis of potato (*Solanum tuberosum* L.). *Potato Res*. 24, 49-59.

EHLERS, W. & GOSS, M., 2003. *Water Dynamics in plant production*. UK: CAB.

EL-AMAMI, S., 1977. Traditional technologies and development of the African environments, utilization of runoff waters: the 'Meskats' and other techniques in Tunisia. African Environments 3 (3/4), 107-120.

EL-SWAIFY, S.A., PATHAK, P., REGO, T.J., SINGTH, S., 1985. Soil management for optimized productivity under rainfed conditions in the semiarid tropics. *Adv. Soil Sci*. 1, 1-64.

EPSTEIN, E. & GRANT, W., 1973. Water stress relations of the potato plant under field conditions. *Agron. J*. 65, 400-404.

ERDEM, T., ERDEM, Y., ORTA, H., & OKURSOY, H., 2006. Water-yield relationships of potato under different irrigation methods and regimes. *Sci. Agric*. (*Piracicaba, Braz*.), 63, 226-231.

EVENARI, M., SHANAN, L. & TADMOR, N.H., 1968. Runoff farming in desert: Part 1: Experimental layout. *Agron. J*. 60, 29–38.

EVENARI, M., SHANAN, L. & TADMOR, N.H., 1982. The Negev, the challenge of a desert.
Havard University press, Cambridge, Mass., USA. p.345.

EVETT, S.R. & DUTT, G.R., 1985. Effect of slope and rainfall intensity on erosion from sodium dispersed, compacted earth micro-catchments. *Soil Sci. Soc. Am. J*. 49, 202-206.

FABEIRO, C., DE SANTA OLALLA, F.M. & DE JUAN, J.A., 2001. Yield size of deficit irrigated potatoes. *Agric. Water Manage*. 48, 255-266.

FALKENMARK, M., ROCKSTRÖM, J., 2004. Balancing water for humans and nature. The new approach in ecohydrology. Earthscan, London, p 247.

FAO, 1978. Report on the agro-ecological zones project: methodology and results for Africa. World Soil Resources Report 48/1. FAO, Rome, p.158 and 8 tables.

FAO, 1991. A manual for the design and construction of water harvesting schemes for plant production. Food Agriculture Organization (FAO) of the United Nations. Rome. FAO Soils Bulletin 17.

FAO, 1998. FAOMET version 2.0 user's manual. Food and Agriculture Organization (FAO) of the United Nations. Rome.

FAO, 2002. Crops and Drops. Making the best use of water for agriculture. FAO, Rome, Italy.

FAO, 2004. The State of Food Insecurity in the World. Food and Agricultural Organization of the United Nations, Rome, Italy, p.41.

FAO, 2008. International Year of the Potato. Hidden Treasure. http://www.fao.org/potato-2008/en/potato/index.html (Accessed 25/04/2009).

FAO, 2009. Water harvesting. p.1-9. *In*: FAO Corporate Document Repository.

FAO, FAOSTAT. 2004. Food and Agriculture Organisation of the United Nations, Statistical Databases. http://faostat.fao.org (Accessed 24/06/2009).

FERRARIS, R. & NORMAN, M. J. T., 1976. Factors affecting the regrowth of *Pennisetem americanum* under frequent defoliation. *Austr. J. Agric. Res.* 27, 365-371.

FINK, D.H., FRASIER, G.W. & MYERS, L.E., 1979. Water harvesting treatment evaluation at Granite Reef. *Water Res. Bull.* 15, 861-873.

FINNIGAN, J.J., 1985. Turbulent transport in flexible plant canopies. *In*: The Forest-Atmosphere Interaction. p.443-480. B.A. Hutchison & B.B. Hicks, (ed.). Dordrecht. The Netherlands,Reidel.

FISHER, M., RAO, I.M., AYARZA, M.A., LASCANO, C.E. & SANZ, J.I., 1995. Carbon Storage by introduced deep-rooted grasses in the South American Savannas. Science September 15.

FOGG, H.G.W., 1983. Salad crops all year round. UK: Newton Abbot.

FOSTER, E.E., 1949. Rainfall and runoff. The Macmillan Company. New York.

FOTI, S., MAUROMICLE, G., & IERNA, A., 1995. Influence of irrigation levels on growth and yield of potato cv. Spunta. *Potato Res.* 38, 307-318.

FOX, D.M., Le Bissonnais, Y. & QUETIN, P., 1998. The implications of spatial variability in surface seal hydraulic resistance for infiltration in a mound and depression micro-topography. *Catena* 32, 101-114.

FRASIER, G.B., 1980. Harvesting water for agricultural, wildlife, and domestic uses. *J. Soil Water Conserv*. 35, 125–128.

FRASIER, G.W., MAYERS, L.E., 1983. Water Harvesting Handbook. *USDA-Agric. Res. Srvc*., Agriculture Handbook No. 600. US Govt. Printing Office, p.45.

FU, J., 2008. Effects of different harvest start times on leafy vegetables (lettuce, pak choi and rocket) in a reaping and re-growth system. A thesis submitted in partial fulfillment of the requirements of the Degree of Master of Agriculture Science. Lincoln University.

GARDNER, H.R., 1975. Different soil treatments for harvesting water for radish production in the Mexico valley. p.315-320. *In*: *Proc. Water Harvesting Symp*., Phoenix, AZ, ARS W-22. USDA.

GARDNER, F.P., PEARCE, R.B. & MITCHELL, R.L., 1985. Physiology of crop plants. Iowa State University Press, Ames, IA, USA, p. 186-208.

GAYLER, S., WANG, E., PRIESACK, E., SCHAAF, T. & MAIDI, F.X., 2002. Modelling biomass growth, N-uptake and phonological development of potato crop. *Geoderma*. 105, 367-383.

GEBREEGZIABHER, T., NYSSEN, J., GOVAERTS, B., GETNET, F., BEHAILU, M., HAILE, M. & DECKERS, J., 2009. Contour furrows for in situ soil and water conservation, Tigray, Northern Ethiopia. *Soil & Tillage Res*. 103(2009), 257-264.

GERALDSON, C.M. & TYLER, K.B., 1990. Plant analysis as an aid in fertilizing vegetable crops. p.549-562. *In*: R.L. Westerman, (ed.). Soil Testing and Plant Analysis. 3rd ed. SSSA Book Ser. 3 SSSA, Madison, WI.

GEREMEW, E.B., 2008. Modelling the soil water balance to improve irrigation management of traditional irrigation schemes in Ethiopia. PHD Thesis. Department of Plant Production and Soil Science. Faculty of Natural and Agricultural Sciences. University of Pretoria.

GHOLIZADEH, A., AMIN, M.SM., ANUAR, A.R., AIMRUN, W. & SABERIOON, M.M., 2011. Temporal variability of SPAD chlorophyll meter readings and its relationship to total nitrogen in leaves within a Malayasian paddy field. *Austr. J. Basic Appl. Sci.*5(5), 236-245.

GIANQUINTO, G., GOFFART, J.P., OLIVIER, M.M., GUARDA, G., COLAUZZI, M., DALLA CORTA, L., DELLE VEDOVE, G., VOS, J. & MACKERRON, D.K.L., 2004/2005. The use of hand-held chlorophyll meters as a tool to assess the nitrogen status and to guide nitrogen fertilization of potato crop. *Potato Res*. 47, 35-80.

GIFFORD, R.M. & EVANS, L.T., 1981. Photosynthesis, carbon partitioning and yield. *Ann. Rev. Plant Physiol.* 32, 485-509.

GOUDRIAAN, J., 1977. Crop meteorology: a simulation study. Pudoc, Wageningen.

GOULD, J., NISSEN-PETERSEN, E., 1999. Rainwater catchment systems for domestic supply: design, construction and implementation. Intermediate Technology, London.

GOUWS, R., 2003. The battle against *Erwinia*. *Chips*. 3, 32-35.

GRASSERT, V., VOGEL, J. & BARTEL, W., 1984. Effect of cultivar and some environmental factors on the tendency of potato tubers to form sugars during several months storage at 4 °C. *Potato Res.* 27, 365-372.

GREEN, W.H. & AMPT, G.A., 1911. Studies on soil physics: 1. The flow of air and water through soils. *J. Agric. Sci*. 4, 1-24.

GUIDUCCI, M, ANTOGONI, A. & BENINCASA, P., 1992. Effect of water availability on leaf movement, light interception and light utilization efficiency in several field crops. *Rivista di Agronomia*. 27(4), 392-397.

GUPTA, G.N., 1994. Influence of rainwater harvesting and conservation practices on growth and biomass production of *Azadirachta indica* in Indian desert. *Forest Ecol. Manage*. 70, 329-339.

HAGAN, R.M., 1959. Interpretation of plant responses to soil moisture regimes. *Adv. Agron.* 11, 77-98.

HAILE, M. & MERGA, S.N., 2002. Workshop on the experience of water harvesting in the dry lands of Ethiopia: Principles and practices. Dry lands Coordination Group. Report No 19.

www.drylands-group.org (Accessed 12/09/2009).

HANG, A.N., MCCLOUD, D.E., BOOK, K.J. & DUNCAN, W.G., 1984. Shade effects on growth, partitioning and yield components of peanuts. *Crop Sci.* 24:109-115.

HANG, A.N. & MILLER, D.E., 1986. Yield and physiological responses of potatoes to deficit, high frequency sprinkler irrigation. *Agron. J.* 78(1986), 436-440.

HARRISON, M.S.J., 1983. Rain-day frequency and mean daily rainfall intensity as determinants of total rainfall over the Eastern Orange Free State. *J. Clim*. 3, 35-45.

HATFIELD, J.L. 1990. Measuring plant water stress with an infrared thermometer. *Hort. Sci.* 25, 1535-1538.

HATIBU, N. & MAHOO, H., 1999. Rainwater harvesting technologies for agricultural production: a case for Dodoma, Tanzania. Sokoine University of agriculture, Department of Agricultural Engineering and Land Planning.

HATIBU, N., 2000. Introduction. *In*: Rainwater Harvesting for Natural Resource Management: A Planning Guide for Tanzania. p.1-5. *In*: N.Hatibu & F.Mahoo (eds.). Technical Handbook no. 22. RELMA, Nairobi.

HATIBU, N., YOUNG, M.D.B., GOWING, J.W., MAHOO, H.F., MZIRAI, O.B., 2003. Development improved dryland cropping systems for maize in semi-arid Tanzania. Part 1: Experimental evidence for the benefits of rainwater harvesting. *Expl Agric*. 39(2003), 279-292.

HATIBU, N. & MAHOO, H., 2009. Rainwater harvesting technologies for agricultural production: A case for Dodoma, Tanzania. Sokoine University of Agriculture & Department of Agricultural Engineering and Land Planning, Mororgoro, Tanzania.

HAVERKORT, A.J., 1990. Ecology of potato cropping systems in relation to latitude and altitude. *Agr. Syst*., 32, 251-272.

HAVERKORT, A.J. & KOOMAN, P.L., 1996. The use of systems analysis and modeling of growth and development in potato ideotyping under conditions affecting yields. *Biomed. Life Sci. EUPHYTICA.*

HAY, R. K. M. & WALKER, A. J., 1989. An introduction to the physiology of crop yield. Harlow, Essex, England : Longman Scientific & Technical.p.292.

HEGNEY, M.A. & HOFFMAN, H.P., 1997. *Potato irrigation - development of irrigation scheduling guidelines*. Horticulture Research and Development Corporation Project NP 6. Western Australia, Australia, Department of Agriculture of Western Australia.

HENSLEY, M., BOTHA, J.J., ANDERSON, J.J., van STADEN, P.P. & DU TOIT, A., 2000. Optimizing rainfall use efficiency for developing farmers with limited access to irrigation water. Water Research Commission, Report No. 878/1/00, Pretoria, SA.

HEXEM, R.W. & HEADY, E.O., 1978. Water production functions and irrigated agriculture. Iowa State Univ. Press, Ames.

HOCHMUTH, G.J., HUTCHINSON, C.M., MAYNARD, D.N., STALL, W.M., KUCHAREK, T.A., WEBB, S.E., TAYLOR, T.G., SMITH, S.A. & SIMMONE, E.H., 2001. Potato production in Florida. *In*: D.N. Maynard & S.M. Olson (eds.). Vegetable production guide for Florida. Vance Publishing, New York.

HODGES, T., 1991. *Predicting Crop Phenology*. Boston, USA: CRC Press.

HODGES, T., 1992. A modular structure for crop simulation models: Implemented in the SIMPOTATO model. *Agron. J.* 84, 911–915.

HOOGMOED, W.B. & STROOSNIJDER, L., 1984. Crust formation on sandy soils in the Sahel. I. Rainfall and infiltration. *Soil & Tillage Res*. 4, 5-23.

HORTON, R.E., 1940. An approach toward a physical interpretation of infiltration capacity. *Soil Sci. Soc. Am. Proc*. 5, 399-417.

IBRAIMO, N.A., 2011. Rainwater harvesting: Management strategies in semi-arid areas. MSc. Dissertation. The Department of Plant Production and Soil Science, University of Pretoria, South Africa.

IDIKE, F.I., 2002. Experimental evaluation of infiltration equations for Nsukka soil. *J.Agric. Engin. Technol.*, 10, 28-34.

IDSO, S.B., JACKSON, R.D., PINTER, JR.P.J., REGINATO, R.J., & HATFIELD, J.L., 1981. Normalising the stress-degree-day parameter for environmental variability. *Agric. Meteorol*. 24(1), 45-55.

INABA, K., 1984. Effect of shading on leaf anatomy in *konjak* plant (*Amorphophallus konjak* K. Koch). *Japan J. Crop Sci*. 53(3), 243-248.

INTHAVONG, T., TSUBO, M. & FUKAI, S., 2011. A water balance model for characterization of length of growing period and water stress development for rainfed lowland rice. *Field Crops Res.* 121(2011), 291—301.

Irish potatoes. farmafripedia.ikmmergent.net/index.php/Irish_potatoes (Accessed 24/03/2011).

IRITANI, W.M., TODD, E.G. & WELLER, L., 1971. Shear press determinations of the raw product as a possible tool for quality measurement of potatoes. *Am. Potato J*. 48, 359-365.

JACKSON, R.J., 1982. Canopy temperature and crop water stress. *In*: Hillel (ed.). Advances in irrigation. Academic Press, New York, 1, 43-85.

JAGTAP, W.S. & JONES, J.W., 1989. Stability of crop coefficients under different climate and irrigation management practices. *Irrig. Sci*. 10, 231-244.

JEFFERIES, R.A., 1995. Physiology of crop response to drought. p.61-74. *In*: A.J. HAVERKORT & D.K.L MACKERRON (eds.). Potato ecology and modelling of crops under conditions limiting growth. Kluwer Academic Publishers, The Netherlands.

JENSEN, J.R., BERHARD, R.H., McDONAGH, J., MOBERG, J.P., NIELSEN, N.E. & NORDBO, E., 2003. Productivity in maize based cropping systems under various soil-water management strategies in a semi-arid, alfisol environment in East Africa. *Agric. Water Manage*. 59, 217-237.

JONES, O.R., STEWART, B.A., 1990. Basin tillage. *Soil Tillage Res*. 18, 249-265.

KAFLE, H.K. & BRUINS, H.J., 2009. Climatic trends in Israel 1970-2002: Warmer and increasing aridityinland. *Climatic Change*. 96, 63-77.

KARAFYLLIDIS, D.I., STAVROPOULOS, N. & GEORGAKIS, D., 1996. The effect of water stress on the yielding capacity of potato crops and subsequent performance of seed tubers. *Potato Res*. 39, 153-163.

KARNIELI, A., 1988. Storm runoff forecasting model incorporating spatial data. PhD. Thesis, University of Arizona, Tucson, p.249.

KASHYAP, P.S. & PANDA, R.K., 2003. Effect of irrigation scheduling on potato crop parameters under water stressed conditions. *Agric. Water Manage*. 59, 49-66.

KEATING, B.A. & CARBERRY, 1993. Resource capture and use in intercropping: solar radiation. *Field crop Res*. 34, 273-306.

KEMP, D.R. & WHINGWIRI, E.E., 1980. Effect of tiller removal and shading on spikelet development and yield components of the main shoots and on the sugar concentration of the ear and flag leaf. *Austr. J. Plant Physiol*. 7, 501-510.

KENTER, C., HOFFMANN, C.M., & MARLANDER, B., 2006. Effects of weather variables on sugar beet yield development. *Eur. J. Agron*. 24, 62-69.

KEYANTASH, J. & DRACUP, J. A., 2002. The quantification of drought: An evaluation of drought indices. *Bull. Amer. Meteor. Soc.*, **83,** 1167–1180.

KHURANA, S.C. & MC LAREN, J.S., 1982. The influence of leaf area, light interception and season on potato growth and yield. *Potato Res*. 25, 329-342.

KIGGUNDU, N., 2002. Evaluation of rainwater harvesting systems in Rakai and Mbarara Districts, Uganda. GHARP case study report. Greater Horn of Africa Rainwater Partnership (GHARP), Kenya Rainwater Association, Nairobi, Kenya.

KIJNE, J.W., BARKER, R. & MOLDEN, D., 2003. Water Productivity in Agriculture: Limits and opportunities for improvement. CAB International, Wallingford, UK.

KIRKHAM, M.B., 1990. Plant responses to water deficits. *In*: Irrigation of Agricultural Crops. *Agronomy Monograph*, 30. Madison, USA.

KÖNING, D., 1992. L’agriculture ècologique forestière. Une stratègie intègrèe de conservation des sols au Rwanda. *Bull. Rèseau Erosion*. 12, 130-139.

KOOMAN, P.L. & HAVERKORT, A.J., 1995. Modelling development and growth of the potato crop influenced by temperature and day length: LINTUL-POTATO. p.41-60. *In*: A.J. Haverkort & D.K.L. Mackerron (eds.). Potato ecology and modelling of crops under conditions limiting growth. Kluwer Academic Publishers, The Netherlands.

KOSGEI, J.R., 2008. Rainwater Harvesting Systems and their Influences on Field Scale Soil Hydraulic Properties, Water Fluxes and Crop Production. PhD. Thesis. University of Kwazulu-Natal, Pietermaritzburg, South Africa.

KREMER, E. & KROPFF, M.J., 1999. Comparative growth of triazine-susceptible and -resistant biotypes of *Solanum nigrum* at different light levels. *Ann. Bot*. 83, 637-644.

KU, S.B., EDWARDS, G.E. & TANNER, C.B., 1977. Effects of light, carbon dioxide and temperature on photosynthesis, oxygen inhibition of photosynthesis, and transpiration in *Solanum tuberosum. Plant Physiol.* 59, 868-872.

KUGLERL, J., 2002. Producing high quality orchardgrass and Timothy hay. Washington State University. Grant Adams Area County Extension, 35 C Street NW, Ephrata, WA 98823, kugler@wsu.edu.

KUMAR, D., SINGH, B.P. & KUMAR, P., 2004. An overview of the factors affecting sugar content of potatoes. *Ann. Appl. Biol*. 145(2004), 247-256.

KUMAR, K.K. & RAO, T.V.R., 2005. Dry and wet spells at Campina Grande-PB. *Rev. Brasil. Meteorol.* 20(1), 71-74.

KUMAR, R. & CHATUREVDI, S., 2009. Crop modelling: A tool for agricultural research. agropedia.iitk.ac.in./1772/revisions/2025/view (Accessed 22/02/2011).

KUNZE, D., 2000. Economic assessment of water harvesting techniques: A demonstration of various methods. *Q. J. Int. Agr*., 39(1), 69-91.

LAHLOU, O., OUATTAR, S. & LEDENT, J.F., 2003. The effect of drought and cultivar on growth parameters, yield and yield components of potato. INRA EDP science. *Agronomie,* 23, 257-268.

LANA, E.R., JOHANSEN, R.H. & NELSON, D.C., 1970. Variation in specific gravity of potato tubers. *Am. Potato J*. 47, 9-12.

LANDMAN, W.A. & KLOPPER, E., 1998. 15-year simulation of the December to March rainfall season of the 1980s and 1990s using canonical correlation analysis (CCA). *Water SA*. 24(4), 281-286.

LANGE, O.L., LOSCH, R., SCHULZE, E-D. & KAPPEN, L., 1971. Responses of stomata to changes in humidity. *Planta*. 100, 76-86.

LAW, B.E., CESCATTI, A. & BALDOCCHI, D., 2001. Leaf area distribution and radiative transfer in open-canopy forests: implications for mass and energy exchange. *Tree Phys*. 21, 777-787.

LE BISSONAIS, Y. & SINGER, M. J., 1992. 'Crusting, runoff and erosion response to soil water content and successive rainfalls'. *Soil Sci. Soc. Am. J. 56,* 1898-1903.

LE HOUÉROU, H.N., 1996. Climate change, drought and desertification – review. *J. Arid Environ.* (1996) 34, 133-185. Academic Press Limited.

LEISA, 1998. Challenging water scarcity (Editorial). ILEIA Newslett. *Low Ext. Input Sustain. Agri*. 14(1).

LI, X. Y., GONG, J.D., GAO, Q. & LI, F., 2001. Incorporation of ridge and furrow method of rainfall harvesting with mulching for crop production under semi-arid conditions. *J. Agr. Water Manage*. 50, 173-183.

LI, X. Y. & GONG, J.D., 2002. Compacted micro-catchments with local earth materials for rainwater harvesting in the semi-arid regions of China. *J. Hydrol*. 257(1-4), 134-144.

LI, X.Y. & XIE, Z.K., 2004. Runoff characteristics of artificial catchment materials for rainwater harvesting in the semi-arid regions of China. *Agric. Water Manage*. 65, 211-224.

LI, X.Y., SHI, P.J., SUN, Y.L., TANG, J. & YANG, Z.P., 2006. Influence of various *in-situ* rainwater harvesting methods on soil moisture of China. *Forest Ecol. Manage*. 223 (1), 143-148.

Loch, R.J., 1994. Structure breakdown on wetting. *Austr. Soc. Soil Sci*. p.113–132. *In*: H.B. So, G.D. Smith, S.R. Raine, B.M. Schafer & R.J. Loch (eds.). Sealing, crusting and hardsetting soils, productivity and conservation. Brisbane.

LONG, C.M., SNAPP, S.S, DOUCHES, D.S. & CHASE, R.W., 2004. Tuber yield, storability, and quality of Michigan cultivars in response to nitrogen management and seedpiece spacing. *Am. Potato J. Res.* 81, 347-357.

LYNCH, D.R., FOROUD, N., KOZUB, G.C. & FARRIES, B.C., 1995. The effect of moisture stress at three growth stages on the yield, components of yield and processing quality of eight potato varieties. *Am. Potato J.* 72, 375-386.

LYNCH, S.D., ZULU, J.T., KING, K.N. & KNOESEN, D.M., 2001. The analysis of 74 years of rainfall recorded by the Irwins on two farms south of Potchefstroom. *Water SA*. 27(4), 559-564.

MACKERRON, D.K.L. & JEFFERIES, R.A., 1986. The influence of early soil moisture stress on tuber numbers in potato. *Potato Res*. 29, 299-312.

MADSEN, H., WILSON, G. & AMMENTORP, H.C., 2002. Comparison of different automated strategies for calibration of rainfall-runoff models. *J. Hydrol.* 261(1-4), 48-59.

MANRIQUE, L.A., 1990. Growth analysis and yield of potato grown in the glasshouse during summer and winter in Hawaii. *Commun. in Soil Sci. Plantarum* 21, 237-249.

MARTIN, R.J., JAMIESON, P.D., WILSON, D.R. & FRANCIS, G.S., 1992. Effects of soil moisture deficits on the yield and quality of Russet Burbank potatoes. New Zealand Journal of Crop and Horticultural Science. 20, 1-9.

MARUO, T., AKIMOTO, S., WADA, N., TTO, M. TAKAGAKI, M. & SHINAHARA, Y., 2003. New leaf vegetable production system using automatic reaping harvester and rail system. *Acta Horticulturae*, 620, 63-70.

McHUGH, O.V., STEENHUIS, T.S., ABEBE, B. & FERNÁNDEZ, E.C.M., 2007. Performance of in situ rainwater conservation tillage techniques on dry spell mitigation and erosion control in the drought-prone North Wello zone of the Ethiopian highlands. *Soil and Tillage Res*. 97, 19-36.

MCINTYRE, D.C., 1958a. Permeability measurements of soil crusts formed by raindrop impact. *Soil Sci*. 85, 185-189.

MCINTYRE, D.C., 1958b. Soil splash and the formation of surface crusts by raindrop impact. *Soil Sci*. 85, 261-266.

MCNAUGHTON, K.G. & JARVIS, P.G., 1983. Predicting effects of vegetation changes on transpiration and evaporation. p.1-47. *In*: T.T. Kozlowski (ed.). Water deficits and plant growth. Vol.7. Academic Press, Orlando.

MEERTENS, H, NDEGE, L., & LUPEJA, P., 1999. The cultivation of rainfed lowland rice in Sukumaland, Tanzania. *Agric., Ecosyst. Environ*. 76, 31-45.

MISHRA, S. K. & SINGH, V. P., 2003. Soil conservation Service Curve Number (SCS–CN) Methodology. Volume 42 of Water Science and Technology Library, Kluwer Academic Publishers, Dordrecht, Netherlands.

MIURA, K. & OSADA, A., 1981. Effect of shading on photosynthesis, respiration, leaf area and corn weight in *konjak* plants (*Amorphophallus konjak* K. Koch). *Japan J. Crop Sci*. 50(4), 553-559.

MODISANE, P.C., 2007. Yield and quality of potatoes as affected by calcium nutrition, temperature and humidity. MSc. Dissertation. University of Pretoria.

MOLDEN, D., FRENKEN, K., BARKER, R., DE FRAITURE, C., MATI, B., SVENDSEN, M., SADOFF, C. & FINLAYSON, M.C., 2007. Trends in water and agricultural development. p.57–89. *In*: D. Molden (ed.) Water for food, water for life: A Comprehensive assessment of water management in agriculture. International Water Management Institute (IWMI), Colombo, Sri Lanka.

MOLL, A., 1983. Photosynthetic rate and yield of potato clones. *Potato Res*. 26: 191-202.

MOLL, A. & KLEMKE, T., 1990. A simple model for the evaluation of haulm characters in potato breeding. *Arch. Züchtungsforsch*, 20(1990), 151-158.

Monte Carlo Simulation: What It and How Does It Work? – Palissade http://www.palisade.com (Accessed 15/09/2009).

MONTEITH, J.L., 1972. Solar radiation and productivity in tropical ecosystems. *J. Appl. Ecology*. 9, 447-466.

MONTEITH, J.L., 1977. Climate and efficiency of crop production in Britain. *Phil. Trans. Roy. Soc. London*, 281(B), 277-294.

MOORBY, J., MUNNS, R. & WALCOTT, J., 1975. Effects of water deficits on photosynthesis and tuber metabolism in potatoes. *Austr. J. Plant Physiol*. 2, 323-333.

MOREL-SEYTOUX, 1978. Derivation of equations for variable rainfall infiltration. *Water Resour. Res*. 14(4), 561-568.

MORGAN, R.P.C., 1995. Soil erosion and conservation. Second edition. Longman, Harlow, UK.

MORIN, J., 1967. The kinetic of raindrop impact and its influence on infiltration capacity and erosion of soils. PhD. Thesis, Hebrew University, Jerusalem.

MORIN, J. & BENYAMINI, Y., 1977. Rainfall infiltration into bare soils. *Water Resour. Res*. 3, 813-817.

MORIN, J. & CLUFF, C.B., 1980. Runoff calculation on semi-arid watersheds using a Rotadisk Rainulator. *Water Resour. Res*. 16, University of Arizona, Tucson, Arizona 85721.

MORIN, J., RAWITZ, E., HOOGMOED, W.B. & BENYAMINI, Y., 1983. Tillage practice for soil and water conservation in the semi-arid zone. III. Runoff modeling as a tool for conservation tillage design. *Soil Till. Res*. 4, 215-224.

MORIN, J., RAWITZ, E., HOOGMOED, W.B., BENYAMINI, Y., 1984. Tillage practices for soil and water conservation in the semi-arid zone. III: Runoff modeling as a tool for conservation tillage design. *Soil Tillage Res*. 4, 215-224.

MOSLEY, A.R. & CHASE, R.W., 1993. Selecting cultivars and obtaining healthy seed lots. p.19-27. *In*: R.C. Rowe (ed.). Potato health management, APS Press, Minnesota, USA.

MULETA, M.K. & NICKLOW, J.W., 2005. Sensitivity analysis coupled with automated calibration for a distributed watershed model. *J. Hydrol*. 306, 127-145.

MWENGE-KAHINDA, J.-M., BOROTO, J.R. & TAIGBENU, A.E., 2005. Developing and integrating water resources management and rainwater harvesting systems in South Africa. *In*:
Proceedings of the 12th SANCIAHS Symposium, Johannesburg, South Africa.

MYERS, L.E., 1974. Water harvesting and management for food and fiber production in the semi-arid tropics. p.157-163. *In*: International Workshop on Farming Systems, ICRISTAT, Hyderabad, India, MYERS, C., 1991. Speciality and minor crops handbook. 1st ed. The Small Farmer Centre. University of California. Publication 33460.

MZEZEWA, J., MISI, T. & RENSBURG, L.D. van, 2010. Characterization of rainfall at a semi-arid ecotope in the Limpopo Province (South Africa) and its implications for sustainable crop production. ISSN 0378-4738 (Print) = Water SA Vol. 36 No. 1 January 2010. http://www.wrc.org.za (Accessed 14/02/2011).

MZIRAI, O.B., BWANA, T., TUMBA, S.D., RWEHUMBIZA, F.B. & MAHOO, H.F., 2002. PARCHED THIRST MODEL for Rainwater Harvesting. PT-MODEL Hand Book No. 01.

NAEF, F., 1981. Can we model the rainfall runoff process today? Hydrological Sciences. Bulletin 26 (3), 281-289.

NASSIRI, M. & ELGERSMA, A., 1998. Competition in perennial ryegrass-white clover mixtures under cutting 2 leaf characteristics, light interception and dry matter production during regrrowth. *Grass Forage Sci*. 53, 367-379.

NAYAK, S.K. & MURTY, K.S., 1980. Effect of varying light intensities on yield and growth parameters in rice. *Indian J. Plant Physiol*. 23(3), 304-317.

NDAYIZIGIYE, Fr., 1992. Valorisation des haies arbustives dans la lutte antièrosive en zone de montagne (Rwanda). *Bull. Rèseau Erosion*. 11, 120-139.

NEPAD. 2003. Action Plan for the Environment Initiative. New Partnership for Africa's Development, Midrand, South Africa.

NGIGI, S. N., 1996. Design parameters for RWCS in arid and semi-arid lands of Kenya. Unpublished. MSc. Thesis, University of Nairobi, Kenya.

NGIGI, S.N., 2003. What is the limit of up-scaling rainwater harvesting in a river basin? *Phys. Chem. Earth* 28(2003), 943-956.

NGIGI, S. N., SAVENIJE, H.G. & GICHUKI, F. N., 2005. Land use changes and hydrological impacts related to up-scaling of rainwater harvesting and management in upper Ewaso Ng'iro river basin, Kenya. Land Use Policy x, xx-xx.

NGIGI, S. N., 2009. Climate change adaptation strategies: water resources management options for smallholder farming systems in sub-Saharan Africa. Published by The MDG Centre for East and Southern Africa of the Earth Institute of Columbia University, New York with financial support from the Rockefeller Foundation.

NIELSEN, D. C. & NELSON, N. O., 1998. Black bean sensitivity to water stress at various growth stages. *Crop Sci.* 38(2), 422-427.

NISHIHARA, E., INOUE, M., KONDO, K., TAKAHASHI, K. & NAKATA, N., 2001. Spinach yield and nutritional quality affected by controlled soil water matric head. *Agric. Water Manage*. 51, 217-229.

NORMAN, J.M., 1980. Interfacing leaf and canopy light interception models: *In*: J.D. Hesketh & J.W. Jones (eds.). Predicting photosynthesis for ecosystem models, CRC Press, Boca Raton, FL, USA.

NORMAN, J.M. & CAMPBELL, G., 1983. Application of a plant-environment model to problems in irrigation. p.155-188. *In*: D. Hille, (ed.). Advances in Irrigation. Academic Press Inc, New York.

NUTI, R.C., LAMB, M.C., SORENSEN, R.B. & TURMAN, C.C., 2009. Agronomic and Economic response to furrow diking tillage in irrigated and non-irrigated cotton (*Gossypium hirsutum* L.). *Agric. Water Manage*. 96, 1078-1084.

OJALA, J.C., STARK, J.C. & KLEINKOPF, G.E., 1990. Influence of irrigation and nitrogen management on potato yield and quality. *Am. Potato J.* 67, 29-43.

OJSAVI, P.R., GOYAL, R.K., GUPTA, J.P., 1999. The micro-catchment water harvesting technique for the plantation of jujube (*Zizyphus mauritiana*) in an agroforestry system under arid conditions. *Agric. Water Manage.* 41, 139-147.

OMRAN, W.M. & WANAS, SH.A., 2007. Advantages of applying various compost types to different layers of sandy soil: 2-evaporation, evapotranspiration and water use efficiency. *J. appl. Sci. Res*. 3(12): 2100-2107.

ONDER, S., CALISKAN, M.E., ONDER, D. & CALISKAN, S., 2005. Different irrigation methods and water stress effects on potato yield and yield components. *Agric. Water Manage.* 73, 73-86.

OOSTERHUYS, D.M. & WALKER, S., 1987. Stomatal resistance measurement as an indicator of water deficit stress in wheat and soybeans. *S. Afr. J. Plant Soil*. 4(3), 113-120.

OPENA, G.B. & PORTER, G.A., 1999. Soil management and supplemental irrigation effects on potato. II. Root growth. *Agron. J.* 91, 426–431.

OWEIS, T., HACHUM, A., KIJNE, J., 1999. Water harvesting and supplemental irrigation for improved water use efficiency in dry areas. System-wide Initiative on Water Management. SWIM Paper No. 7.

OYONARTE, N.A., MATEOS, L. & PALOMO, M.J., 2002. Infiltration variability in furrow irrigation. *J. Irrig. Drain. Eng*. ASCE 128, 26-33.

PACEY, A. & CULLIS, A., 1986. Rainwater harvesting: the collection of rainfall and runoff in rural areas. London: Intermediate Technology Publications.

PANDY, D. N., GUPTA, A. K. & DAVID, M. A., 2003. Rainwater harvesting as an adaptation to climate change, Review Article, Current Science, Vol. 85, No.1, 10 July 2003.

PAVLISTA, A.D., & OJALA, J.C., 1997. Potatoes: chip and French fries processing. p.237-284. D.S. Smith, J.N. Cash, W.K. Nip, Y.H. HUI *(*eds.). Processing vegetables: Science and technologyTechnomic Publishing Company, USA.

PAVLISTA, A., 2002. Skin set of tubers, an indication of maturity is a major reason for desiccating potato vines. *Am. J. Potato Res.* 79, 301-307.

PHILIP, J.R., 1957. Theory of infiltration: 1. The infiltration equation and its solution. *J. Soil Sci.* 83, 345-357.

PILGRIM, D.H. & CORDERY, I., 1993. Flood runoff. *In*: D.R. Maidment (Editor), Handbook of Hydrology. McGraw-Hill, New York, Chapter 9.

PIMENTEL, D., BERGER, B., FILIBERTO, D., NEWTON, M., WOLFE, B., KARABINAKIS E., CLARK, S., POON, E., ABBETT, E. & NANDAOPAL S., 2004.Water Resources, Agriculture, and the Environment. Ithaca (NY): New York State College of Agriculture and Life Sciences,Cornell University. Environmental Biology Report 04-1.

PONCE, V. M. & HAWKINS, R. H., 1996. Runoff curve number: Has it reached maturity? *J. Hydrolog. Eng.* 1, 11–19.

PORTER, G.A., OPENA, G.B., BRADBURY, W.B., MCBURNIE, J.C. & SISSON, J.A., 1999. Soil management and supplemental irrigation effects on potato. I. Soil properties, tuber yield and quality. *Agron. J.* 91, 416–425.

PRINZ, D.& MALIK, A. H., 2002. Runoff farming. Institute of Water Resources Management, Hydraulic and Rural Engineering, Department of Rural Engineering, University of Karlsruhe, Germany. http://www.wca-infonet.org (Accessed 04/03/2010).

RAPPOLD, J. H., 2005. Precipitation analysis and agricultural water availability in the Southern Highlands of Yeme. *Hydrol. Proc*. 19(2), 2437-2449.

RAWSON, H.M., HINDMARSH, J.H., FISCHER, R.A. & STOCKMAN, Y.M., 1983. Change in leaf photosynthesis with plant ontogeny and relationships with yield per year in wheat cultivars and 120 progeny. *Austr. Plant Physiol*. 10, 503-514.

REGINATO, R.J., 1983. Field quantification of crop water stress. *Transactions of* ASAE 26, 772-775.

REHMAN, S., SHAD, K.K., AMANULLAH, A.R., KHAN, A.Z. & SHAH, N.H., 2009. Micro-watershed enhances rainwater use efficiency, phenology and productivity of wheat under rainfed condition. *Soil Til. Res*., 104, 82-87.

REIJ, C.; MULDER, P. & BEGEMANN, L., 1988. Water harvesting for plant production. Technical Paper No. 91. World Bank, Washington, DC, USA.

REIJ, C., 1991. Indigenous soil and water conservation in Africa. Gatekeeper Series, International Institute for Environment and Development, London, No.27.

REIJ, C., SCOONES, I., TOULIN, C., 1996. Sustaining the soil: Indigenous soil and water conservation in Africa. EarthScan, London, UK, p. 228.

REINDERS, F.B. & LOUW, A.A., 1984. Infiltration: measurement and use. ARC, Division of Agricultural Engineering. South Africa.

RENSBURG van, L.D., BOTHA, J.J. & ANDERSON, J.J., 2003. The nature and function of the in-field rainwater harvesting systems to improve agronomic sustainability. www.fao.org/ag/agl/aglw/wh/docs/vanresburg.doc (Accessed 12/03/2009).

RISHIRUMUHIRWA, Th., 1992. Ruissellement et ėrosion sous bananiers au Burundi. *Bull. Rėseau Erosion*. 12, 83-93.

RITCHIE, J.T., 1972. Model for predicting evaporation from a row crop with incomplete cover. *Water Resour. Res.* 8, 1204-1213.

RITCHIE, J.T., 1983. Efficient water use in crop production: discussion on the generality of relations between biomass production and evapotranspiration. p.29-44. *In*: H.M.Taylor (ed.). Limitations to efficient water use in crop production. Madison, USA: ASA-CSSA-SSSA.

RITCHIE, J.T., GRIFFIN, T.S. & JOHNSON, B.S., 1995. SUBTOR: functional model of growth, development and yield. p401-405. *In*: P. KABAT, B. MARSHALL, B.J. van den BROEK, J. Vos & H. van KEULEN (eds.). Modelling and parameterisation of the soil-plant-atmosphere system. A comparison of potato growth models. Wageningen Pers, The Netherlands.

ROCKSTRÖM, J., 2000. Water resources management in smallholder farms in eastern and southern Africa: An overview. *Phys. Chem. Earth* (B). 25(3), 275-283.

ROCKSTRÖM, J., JENNIE, B. & FOX, P., 2002. Rainwater management for increased productivity among small-holder farmers in drought prone environments. *Phys. Chem. Earth*, Parts A/B/C, 27(11-22), 949-959.

ROCKSTRÖM, J., FALKENMARK, M., 2000. Semi-arid crop production from a hydrological perspective gap between potential and actual yields. *Critical Rev. Plant Sci*. 19(4), 319-346.

ROCKSTRÖM, J., HATIBU, N., OWEIS, T., WANI, S., BARRON, J., BRUGGEMAN, A., QIANG, Z., FARAHANI, J. & KARLBERG, L. 2007. Managing water in rainfed agriculture. *In*: D. Molden (ed.). Water for food, water for life. A comprehensive assessment of water management in agriculture. International Water Management Institute. Earthscan, London, UK

ROLOT, J.L. & SEUTIN, H., 1999. Production of potato minitubers using a hydroponic technique. http://www.pubs.caes.uga.edu (Accessed 19/12/2009).

ROSEGRANT, M., CAI, X., CLINE, S., NAKAGAWA, N., 2002. The role of rainfed agriculture in the future of the global food production. Environment and Production

Technology Division, International Food Police Research Institute. Washington. www.unmillenniumproject.org/documents/tf02apr18.pdf (Accessed 16/05/2009).

ROSS, J., 1981. The radiation regime and architecture of plant stands. Dr. W. Junk Publishers, The Hague.

ROWTREE, K.M., 1989. Rainfall characteristics, rainfall reliability and the definition of drought: Baringo District. Kenya. *S. Afr. Geogr. J.* 71(2), 74-80.

ROY, S. K., 1985. *Environmental control of tillering and yield of wheat*. PhD thesis, Lincoln College, University of Canterbury, New Zealand.

RUSSELL, G., JARVIS, P.G. & MONTEITH, J.L., 1989. Absorption of radiation by canopies and stand growth. In: G. Russell, B. Marshall & P.G. Jarvis (eds.). Plant Canopies. Society for Experimental Biology Seminar Series. No.31.

RUTHERFOORD, R.J. & de JAGER, J.M., 1975. Water status and stomatal behavior of BP1 potatoes (Solanum tuberosum L.) and their effect upon yield. *Crop Production*. 4, 125-128.

RYUMUGABE, J.B. & BERDING, F.R., 1992. Variabilitė de l'indice d'agressivitė des pluies au Rwanda. *Bull. Rėseau Erosion*. 12, 113-119.

SALE, P.J.M., 1973. Productivity of vegetable crops in a region of high solar input. I. Growth and development of the potato. *Austr. J. Agric. Res*. 24, 733-749.

SALTER, P.J. & GOODE, J.E., 1967. Crop responses to water at different stages of growth. *Res. Rev. Commonw. Bur. Hort. East Malling*. 2, 93-100.

SAYRE, R.N., NONAKA, M. & WEAVER, M.L., 1975. French fry quality related to specific gravity and solids content variation among potato strips within the same tubers. *Am. Potato J.*, 52, 73-82.

SCHEPERS, J.S., FRANCIS, D.D., VIGIL, M., & BLOW, F.E., 1992. Comparison of maize leaf nitrogen concentration and chlorophyll meter readings. *Soil Sci. and Plant Anal.*, 23, 2173-2187.

SCHULZE, E.D, 1986. Carbon dioxide and water vapour exchange in response to drought in the atmosphere and in the soil. *Ann. Rev. Plant Physiol*. 37, 247-274.

SCHULZE, E.D. & HALL, A.E., 1982. Stomatal responses, water loss and CO_2 assimilation rates of plants in contrasting environments. *In*: p.181-230. O.L Lange, P.S Nobel, C.B. Osmond & H. Ziegler (*eds.*). Physiological plant ecology. II. Encyclopedia of Plant Physiology, 12B (New series), Berlin: Springer-Verlag.

SCOTT, R.K. & WILCOCKSON, S.J., 1978. Application of physiological and agronomic principles to the development of the potato industry. p 678-704. *In*: P.M. Harris (eds.). The potato crop. Chapman and Hall, London.

SEGINER, I. & MORIN, J., 1970. A model of surface crusting and infiltration of bare soils. *Water Resour. Res*. 6, 629.

SELMAN, L., ANDREWS, N., STONE, A. & MOSLEY, A., 2009. What's wrong with my potato tubers? www.extension.oregonstate.edu/catalog/pdf/em/em8948-e.pdf (Accessed 20/09/2010).

SENKONDO, E. M.M., MSANGI, A.S.K., XAVERY, P., LAZARO, E.A. & HATIBU, N., 2004. Profitability of rainwater harvesting for agricultural production in selected semi-arid areas of Tanzania. *J. Appl. Irrig. Sci*., 39(1), 65-81.

SFC (Small Farm Centre), 1992. United Department of Agriculture, Cooperative State Research Service. htt://www.sfc.ucdavis.edu (Accessed 16/12/2009))

SHALHEVET, J., SHIMSHI, D. & MEIR, T., 1983. Potato irrigation requirements in a hot climate using sprinkler and drip methods. *Agron. J*., 75, 13-16.

SHANGGUAN, Z.P., SHAO, M.A., LEI, T.W. & FAN, T.L., 2002. Runoff water management technologies for dryland agriculture on the Loess. *Int. J. Sustain. Dev. & World Ecol*. 9(2002), 341-350.

SHANAN, L. & TADMOR, N.H., 1976. Micro-Catchment Systems for Arid Zone Development. Hebrew University of Jerusalem, Center for International Agricultural Cooperation, Min. Agric., Rehovot, Israel, p.128.

SHARKEY, T.D., 1984. Transpiration-induced changes in the photosynthetic capacity of leaves. *Planta* 160, 143-150.

SHARMA, K.D., PAREEK, O.P. & SINGH, H.P., 1986. Micro-catchment water harvesting for raising Jujube orchards in an arid climate. *Trans. ASAE* 29(1), 112-118.

SHARMA, B., RAO, K., VITTAL, K., RAMAKRISHNA, Y. & AMARASINGHE, U., 2010. Estimating the potential of rainfed agriculture in India: Prospects for water productivity improvements. *Agri. Wat. Manage*. 97, 23–30.

SHEAFFER, C.C., PETERSON, P.R., HALL, M.H. & STORDANL, J.B., 1992. Drought effects on yield and quality of perennial grasses in the north central United States. *J. Prod. Agric*. 5(4), 556-561.

SHOCK, C.C., FEIBERT, E.B. & SAUNDERS, L.D., 1998. Potato yield and quality response to deficit irrigation. *Hort. Sci.* 33, 655-659.

SHUKLA, A.K., LADHA, J.K., SINGH, V.K., DWIVEDI, B.S., BALASUBRAMANIAN, V., GUPTA, R.K., SHAMA, S.K., SINGH, Y., PATHAK, H., PANDEY, P.S., PADRE, A.T. & YADAV, R.L., 2004. Calibrating the leaf colour chart for nitrogen management in different genotypes of rice and wheat in a system perspective. *Agron. J.* 96, 1606-1621.

SINCLAIR, T.R. 1984. Water-use efficiency in crop production. *Bio. Science.* 34, 36–40.

SIVAKUMAR, M.V.K., 1992. Empirical analysis of dry spells for agricultural applications in West Africa. *J. Clim.* 5**,** 532-539.

SJOKA, R.E., WESTERMANN, D.T., BROWN, M.J., KINCAID, D.C., MEEK, B.D., McCANN, I., HALDERSON, J. & THORNTON, M., 1991. Deep tillage effects on potato yield and quality. Proceedings of the 30th Annual Washington State Potato Conference and Trade Fair, 5-7 February 1991, Moses Lake, WA, Washington State Potato Commission, Moses Lake, WA, (1991), p.129-140.

SLATYER, R.O., 1967. Crop responses to water at different stages of growth. *Res. Rev. Commonw. Bur. Hort. East Malling*. 2, 93-100.

SMITH, O., 1968. Potatoes: Production, Storing and Processing. The Avi Publishing Company. Inc. New York.

SMITH, O., 1987. Effect of cultural and environmental conditions on potato processing. *In*: Potato Processing, p. 73-74. *In*: W.F. Talburt & O. Smith (eds.). New York: van Nostrand Reinhold Company.

SMITH, M., 1992b. Expert consultation on revision of FAO methodologies for crop water requirements. FAO – Food and Agriculture Organization of the United States, 28-31 May 1990. Rome, Italy.

SMITH, M., ALLEN, R.G. & PEREIRA, L.S., 1996. Revised FAO methodology for crop water requirements. Proc. Of the Int. Conf. on Evapotranspiration and Irrigation scheduling, San Antonio, Texas, USA. p.133-140.

SPANER, D., TODD, A.G., NAVABI, A., MCKENZIE, D.B. & GOONEWARDENE, L.A., 2005. Can leaf chlorophyll measures at differing growth stages be used as an indicator of winter wheat and spring barley nitrogen requirements in Eastern Canada? *J. Agron. Crop Sci*. 191, 393-399.

SPITTERS, C.J.T., 1987. An analysis of variation in yield among potato cultivars in term of light absorption, light utilization and dry matter partitioning. *Acta Hort*., 214(1987), 71-84.

SPLITTSTOESSER, W.E., 1977. Protein quality and quantity of tropical roots and tubers. *Hort. Sci*. 12, 294-298.

SPLITTSTOESSER, W.E., 1990. Vegetables growing handbook: organic and traditional methods. AVI Published by van Nostrand Reinhold, New York.

STARK, J.C., OLSEN, N., KLEINKOPF, G.E. & STEPHEN, L., 2003. Tuber quality in potato production systems. http://us.f356/ym/ShowLetter?Msgld. (Accessed 03/08/2009).

STEVENSON, F.J., AKELEY, R.V. & CUNNINGHAM, F.C., 1964. The potato – its genetic and environmental variability. *Am. Potato J*. 41, 46-53.

STEYN, J.M., 1997. Response of potato genotypes to different water regimes. PhD. Thesis, University of Pretoria, South Africa.

STEYN, P.J., 2003. The origin and growth stages of the potato plant. p.7-12. *In*: J.G. NIEDERWIESER (ed.). Guide to potato production in South Africa.

STEYN, J.M., DU PLESSIS, H.F. & NORTJE, P.F., 1992. Die invloed van verskillende waterregimes op up-to-date aartappels. I. Vegetatiewe ontwikkeling, fotosintese tempo en stomatadiffusie-weerstand. (In Afrikaans with English abstract). *S. Afr. J. Plant Soil*. 9, 113-117.

STEYN, J.M., DU PLESSIS, H.F., FOURIE, P., & HAMMES, P.S., 1998. Yield response of potato genotypes to different soil water regimes in contrasting seasons of a subtropical climate. *Potato Res*. 41(1998), 239-254.

STEYN, J.M., GEREMEW, E.B., ANNANDALE, J.G. & STEYN, P.J., 2009. Frodo and Darius: South African potato cultivars with good processing quality. *S. Afr. J. Plant Soil.* 26(1), 24-30.

STOCKLE, C.O. & NELSON, R., 1994. Cropping Systems Simulation Model Users' Manual. (version 1.01.00) Biological Systems Engineering Dept. Washington State University. p.167.

STOTT, D.E., MOHTAR, R.H., STEINHARDT, G.C., 2001. Water conservation, harvesting and management(WCHM) – Kenyan experience.

STROOSNIJDER, L. & HOOGMOED, W.B., 2004. Contribution of soil & water conservation to carbon sequestration in semi-arid Africa. *Bulletin du Réseau Erosion*. 23, 528-539.

STROOSNIJDER, L. & HOOGMOED, W.B., 1984. Crust formation on sandy soils in the Sahel. II. Tillage and its effect on the water balance. *Soil & Tillage Res*. 4, 321-337.

STROOSNIJDER, L. & SLEGERS, M., 2008. Soil Degradation and Droughts in Sub-Saharan Africa. p. 413-425. *In*: C. Dazzi & E. Costantini (eds.). The soils of tomorrow: Soils changing in a changing world. Advances in GeoEcology No. 39, Catena Verlag.

STRUIK, P.C., ASKEN, M.F., SONNINO, A., MACKERRON, D.K.L., BANG, U., RITTER, E., STATHAM, O.J.H., KIRKMAN, M.A. & UMAERUS, V., 1997. Forty years of potato research: Highlights, achievements, and prospects. *Potato Res*. 40: 5-81.

SULEMAN, S., WOOD, M.K., SHAH, B.H., MURRAY, L., 1995. Development of a rainwater harvesting system for increasing soil moisture in arid rangelands of Pakistan. *J. Arid Environ*. 31, 471-481.

SOIL AND WATER CONSERVATION BRANCH (SWCB), 1997a. Soil and water conservation manual for Kenya. Soil and water conservation branch. Ministry of agriculture, Nairobi. Edited by D.B. Thomas.

TADMOR, N. H., & SHANAN, L., 1969. Runoff inducement in an arid region by removal of vegetation. *Proc. Soil Sci. Soc. Am.* 33(5), 790–793.

TAKAGAKI, T., AMUKA, S., MARUO, T., SUKPRAKAN, S. & SHINOHARA, Y., 2003. Application of reaping method for harvesting leafy vegetables grown in capillary Hydroponic system. *Acta Horticulturae*, 620, 71-76.

TANNER, C.B. & SINCLAIR, T.R., 1983. Efficient water use in crop production: research or re-search? p.1-27. *In*: H.M. Taylor, W.A. Jordan & T.R. Sinclair (eds.). Limitations to efficient water use in crop production. ASA, Madison, Wisconsin.

TARCHITZKY, J., BANIN, A., MORIN, J. & CHEN, Y., 1984. Nature, formation and effects of soil crusts formed by water drop impact. *Geoderma* 33, 135-155.

TEI, F., SCAIFE, A. & AIKMAN, D.P., 1996. Growth of lettuce, onion and red beet. I. Growth analysis, light interception and radiation use efficiency. *Ann. Bot.*, 78(1996), 633-643.

TEI, F, BENINCASA, P. & GUIDUCCI, M., 2003. Critical nitrogen concentration in lettuce. *Acta Hort*. 627, 187-194.

TEKALIGN, T. & HAMMES, P.S., 2005. Growth and productivity of potato as influenced by cultivar and reproductive growth. II. Growth analysis, tuber yield and quality. *Sci. Hortic*., 105, 29-44.

TEMESGEN, M., HOOGMOED, W.B., ROCKSTRÖM, J. & SAVENIJE, H.H.G., 2009. Conservation tillage implements and systems for smallholder farmers in semi-arid Ethiopia. *Soil and Tillage Res.* 104(1), 185-191.

TESFAYE, K. & WALKER, S., 2004. Matching of crop and environment for optimal use: the case of Ethiopia. *Phys. Chem. Earth Parts A/B/C.* 29(15-18), 1061-1067.

THORNTHWAITE, C.W., 1948. An approach towards a rational classification of climate. *Geogr. Rev*. 38, 55-94.

TIAN, Y., SU, D.R., LI, F.M.& LI, X.L., 2003. Effect of rainwater harvesting with ridge and furrow on yield of potato in semi-arid areas. *Field Crops Res*. 84, 385-391.

Tied ridges better farmer yields.

(http://www.africanexecutive.com/modules/magazine/articles.php?) (Accessed 23/02/2010).

Tied ridges for water conservation. (http://www.infonet-biovision.org/default/ct/254/soilFertilityManagement) (Accessed 23/02/2010).

Graded contour ridges with cross ties lower than the main ridges to retain water between the cross ties, but allow excess rainwater to flow between the ridges rather than spill over or break the main ridges. (http:www.fao.org/docrep/006/y4690e/y4690e09.htm) (Accessed 23/02/2010).

TILAHUN, K., 2006. The characterization of rainfall in the arid and semi-arid regions of Ethiopia. *Water SA*. 32, 429-436.

TOBISA, M., TAJIRI, K., MURAKAMI, K., SHIMOJO, M. & MASUDA, Y., 2003. Effects of growth temperature and cutting height on re-growth of tropical forage legume phasey bean (*Macroptilium lathyroides* L. Urb). *Grassland Sci.* 49(2), 149-157.

TSIROS, E., KANELLOU, E., DOMENIKIOTIS, C. & DALEZIOS, N.R., 2008. The role of satellite derived vegetation health index and aridity index in agro-climatic zoning. *Geographical Research Astracts, 10. EGU2008-A-07223, 2008 SRef-ID: 1607-7962/gra/EGU2008-A-07223* General Assembly.

ULRICH, A. & HILLS, F.J., 1990. Plant analysis as an aid in fertilizing sugar beet. p.429-448. *In*: R.L. Westernman (ed.). Soil Testing and Plant Analysis. 3rd. ed. SSSA Book Ser. 3 SSSA, Madison, WI.

UNCCD, 1994. United Nations Convention to combat desertification in countries experiencing serious drought and/or desertification, particularly in Africa. Permanent Secretariat UNCCD, Bonn. Website: http://www.unccd.int/ (Accessed 30/11/2009).

UNEP, 1992. World Atlas of Desertification, 1st ed. Middleton N (coordinating ed.) Edward Arnold, Nairobi.

UNEP, 1997. World Atlas of Desertification, 2nd ed. Middleton N, Thomas D (coordinating eds.) Edward Arnold, London.

UNEP, 2003. Source book of alternative technologies for fresh water Augmentation in Africa. Technical publication series 8.

http://www.unep.or.jp/ietc/publications/techpublications/techpub-8a/zay.asp (Accessed 10/04/2010).

UNESCO, 1977. *World Map of Desertification.* United Nations Conference on Desertification Report 74/2. United Nations, New York.

UNESCO, 1979. Map of the world distribution of arid regions. Man and the Biosphere (MAB) Technical notes 7, UNESCO, Paris. United Nations Population Reference Bureau. 2004 United Nations Population Reference Bureau, World Population Data Sheet: Demographic Data and Estimates for the Countries and Regions of the World, The United Nations, USA (2004).

UN MILLENIUM PROJECT, 2005. Investing in development: A practical plan to achieve the millennium development goals. New York: Earthscan.

USDA, 1997. United States Standards for Grades of Potatoes for Chipping. Agricultural marketing of fruits and vegetables as a fresh product. USDA. http://www.ams.usda.gov/standards/fzpo (Accessed 20/03/2010).

USDA-SCS, 1972. National Engineering Handbook. Hydrology Section 4. Chapters 4-10. Washington D.C.: USDA-SCS.

USDA-SCS, 1985. National Engineering Handbook, Section 4 – Hydrology. Washington, D.C.: USDA – SCS.

USDA, 1975. Proceedings of the water harvesting symposium. Phoenix, AZ, 26-28 March. USDA, ARS. ARS W-22.

VALENZUELA, J.L., SANCHEZ, A. & ROMERO, L., 1994. Influence of nitrogen, phosphorus, and potassium fertilizations on foliar pigments in muskmelon leaves. *Commun. Soil Sci. Plant Anal.* 25, 1595-1604.

van der Zaag, D.E. (1992): Potatoes and their cultivations in the Netherlands. NIVAA, p.1-47.

van DIJK, J. & AHMED, M.H., 1993. Opportunities for expanding water harvesting in sub-Saharan Africa: the case of the teras of Kassala. Gatekeeper Series, *International Institute for Environment and Development, London, No. SA40.*

van ES, A. & HARTMANS, K.J., 1987. Sugars and starch during tuberization, storage and sprouting. *In*: Storage of Potatoes, p.79-113. Eds. A. Rastovski and A. van Es. Pudoc, Wageningen.

van Loon, C.D., 1981. The effect of water stress on potato growth, development, and yield. Ame*rican Potato Journa*l 58: 51-69.

van RENSBURG, L.D., BOTHA, J.J. & ANDERSON, J.J., 2003. The nature and function of the in-field rainwater harvesting systems to improve agronomic sustainability. www.fao.org/ag/agl/aglw/wh/docs/vanrensburg.doc (Accessed 14/05/2009).

VAUX, H.J. & PRUITT, W.O., 1983. Crop-water production functions. p.61-97. *In*: D. Hillel (ed.) Advances in irrigation. Vol. 2. Academic Press, New York.

VIETS, F.G., 1962. Fertilizers and the efficient use of water . *Adv. Agron*. 14, 223-264.

VILLALOBOS, F.J. & FERERES, E., 1990. Evaporation measurements beneath corn, cotton and sunflower canopies. *Agron. J.* 82, 1153-1159.

VISSER, A.F., 2003. Selecting a suitable potato cultivar. *In*: J.G. Niederwieser (ed.). Guide to potato production in South Africa. ARC-Roodeplaat Vegetable and Ornemental Plant Institute, CPD Printers, Pretoria.

VOLLAIRE, F., 1994. Effects of summer drought and spring defoliation on carbohydrate reserves, persistence and recovery of two populations of cocksfoot (*Dactylis glomerata*) in mediterrean environment. *J. Agric. Sci*. 122(2), 207-215.

VOS, J. & GROENWOLD, J., 1989. Genetic differences in water-use efficiency, stomatal conductance and carbon isotope fractionation in potato. *Potato Res*. 32, 113-121.

VOS, J. & MARSHALL, B., 1994. Nitrogen and potato production: strategies to reduce nitrate leaching. Proceedings of the 12th Triennial Conference of the European Association for Potato Research. INRA, France, p.101-110.

VOS, J. & OYARZÚN, P.J., 1987. Photosynthesis and stomatal conductance of potato leaves – effects of leaf age, irradiance, and leaf water potential. *Photo. Res.* 11: 253-264.

VOS, J., 1986. . Research on water relations and stomatal conductance in potatoes. 2. A comparison of three varieties differing in drought tolerance. *In*: A.G.B. Beekman (*ed*.). *Potato Res. of Tomorrow*. p.29-35. Pudoc, Wageningen.

WADDELL, J.T., GUPTA, S.C., MONCRIEF, J.F., ROSEN, C.J. & STEELE, D.D., 1999. Irrigation and nitrogen management effects on potato yield, tuber quality, and nitrogen uptake. *Agron. J.* 91 (1999), 991-997.

WALKER, S. & TSUBO, M., 2003. A simulator for rainfall-runoff-yield processes with in-field water harvesting. WRC Report No. KV 142/03.

WALKER. S., TSUBO, M. & HENSLEY, M., 2005. Quantifying risk for water harvesting under semi-arid conditions. Part II. Crop yield simulation. *Agric. Water Manage. 76, 94-107.* www.sciencedirect.com (Accessed 12/04/2009).

WALLEN, C.C., 1967. Aridity definitions and their applicability. *Geografiska Annaler*. 49a, 367-384.

WANG, J., MENDELSOHN, R., DINAR, A., HUANG, J., ROZELLE, S. & ZHANG, L., 2008. Can China continue feeding itself? - The impact of climate change on agriculture', World Bank Policy Research Working Paper 4470, Washington DC, USA: World Bank.

WANG, L., de KROON, H., BOGEMANN, G.M. & SMITS, A.J.M., 2005. Partial root drying effects on biomass production in *Brassica napus* and the significance of root responses. *Plant and Soil*. 276, 313-326.

WANG, Y., XIE, Z., MALHI, S.S., VERA, C.L., ZHANG, Y. & WANG, J., 2009. Effects of rainfall harvesting and mulching technologies on water use efficiency and crop yeld in the semi-arid Loess Plateau, China. *Agric. Water Manage*. 96(3), 374-382.

WARDLAW, I.F., 1970. The early stages of grain development in wheat: response to light and temperature in a single variety. *Austr. J. Biol. Sci.* 23, 765-774.

WARDLAW, I.F., 1976. Assimilate movement in lolium and sorghum leaves. I. Irradiance effects on photosynthesis, export and the distribution of assimilates. *Austr. J. Plant Physiol.* 3, 377-387.

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

WELDERUFAEL, W.A, Le ROUX, P.A. & HENSLEY, M., 2008. Quantifying rainfall-runoff relationships on the Dera Calcic Fluvic Regosol ecotope in Ethiopia. *Agric. Water Manage*. 95, 1223-1232.

WELKIE, G.W., 1996. Iron-deficiency stress responses of a chlorosis-susceptible and a chlorosis-resistant cultivar of muskmelon as related to root riboflavin excretion. *J. Plant Nutr*. 19, 1157-1169.

WESTCOTT, M.P., STEWART, V.R. & LAND, R.E., 1991. Critical petiole nitrate levels in potato. *Agron. J*. 83, 844-850.

WESTCOTT, M.P., KNOX, M.L. & WRAITH, J.M., 1994. Kinetics of soil-plant nitrate relations in potato and peppermint: A model for derivative diagnosis. *Commun. Soil Sci. Plant Anal.* 25(5-6), 469-478.

WESTCOTT, M.P. & WRAITH, J.M., 2003 Correlation leaf chorophyll readings and stem nitrate concentrations in peppermint. Western Nutrient Management Conference, Salt Lake City, UT.

WHEELER, T.R., HADLEY, P., MORISON, J.I.L. & ELLIS, R.H., 1993. Effects of temperature on the growth of lettuce (*Lactuca sativa* L.) and the implications for assessing impacts of potential climate change. *Eur. J. Agron*. 2, 305-311.

WILCOX, B.P., NEWMAN, B.D., BRANDES, D., DAVENPORT, D.W. & REID, K., 1997. Runoff from a semi-arid ponderosa pine hillslope in New Mexico. *Water Resour. Res.* 33, 2301-2314.

WILLIAMS, C.M.J. & MEIR, N.A., 1990. Determination of the nitrogen status of irrigated potato crops. I. Critical nutrient ranges for nitrate-nitrogen in petioles. *J. Plant Nutr*. 13, 971-984.

WILLIAMS, J.H., NAGESWARA ROA, R.C., DONGBEDJI, F. & TALWAR, H.S., 1996. Radiation interception and modeling as an alternative to destructive samplings in crop growth measurements. *Ann. Appl. Biol*. 129, 151-160.

WISCHMEIER, W.H. & SMITH, D.D., 1960. A universal soil-loss estimation equation to guide conservation farm planning, 7th Congr., ISSS. 1, 418-425.

WIYO, K.A., KASOMEKERA, Z.M.& FEYEN, J., 2000. Effect of tied-ridging on soil water status of a maize crop under Malawi conditions. *Agric. Water Manage*. 45, 101-125.

WONG, S.C., COWAN, I.R. & FARQUHAR, G.D., 1979. Stomatal conductance correlates with photosynthetic capacity. *Nature* 282, 424-426.

WOOD, C.W., REEVES, D.W., & HIMELRICK, D.G., 1993. Relationships between chlorophyll meter readings and leaf chlorophyll concentration, N status, and crop yield: *a review. Proceed. Agron. Soc. of New Zeal.* 23, 1-9.

WOODWARD, D.E., HAWKINS, R.H., JIANG, R., HJELMELT, A.T., van MULLEM, J.A. & QUAN, Q.D., 2003. Runoff curve number method: Examination of the initial abstraction ratio. World Water Congress No. 118. www.pubs.asce.org (Accessed 15/09/2009).

WOOLHISER, D.A. & OSBORN, H.B., 1985. A stochastic model of dimensionless thunderstorm rainfall. *Water Resour. Res*. 21(4), 511-522.

XUEFENG, C. & MARIŇO, M.A., 2005. Determination of ponding condition and infiltration into layered soils under unsteady rainfall. *J. Hydrol*. 313(3-4), 195-207.

YAIR, A. & RAZ-YASSIF, N., 2004. Hydrological processes in a small arid catchment: scale effects of rainfall and slope length. *Geomorphology*. 61, 55-169.

YOUNG, M.D.B., GOWING, J.W., WYSEURE, G.C.L.& HATIBU, N., 2002. Parched-Thirst: development and validation of a process-based model of rainwater harvesting. *Agric. Water Manage*. 55, 121-140.

YUAN, B.Z., NISHIYAMA, S. & KANG, Y., 2003. Effects of different irrigation regimes on the growth and yield of drip-irrigated potato. *Agric. Water Manage*. 63, 153-167.

ZERE, T.B., van HUYSSTEEN, C.W. & HENSLEY, M., 2005. Estimation of runoff at Glen in the Free State Province of South Africa. *Water SA*. 31, 17-21.

ZERIHUN, D., FEYEN, J., REDDY, J.M., 1996. Sensitivity analysis of furrow-irrigation performance parameters. *J. Irrig. Drain. Eng*. ASCE 122, 49-57.

ZHANG, L., DAWES, W.R., WALKER, G.R., 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resour. Res*. 37 (3), 701–708.

ZHANG, X.Y., CHEN, S.Y. & SUN, H.Y., 2008. Dry matter, harvest index, grain yield and water use efficiency as affected by water supply in winter wheat. *Irrig. Sci.* (2008) 27, 1-10.

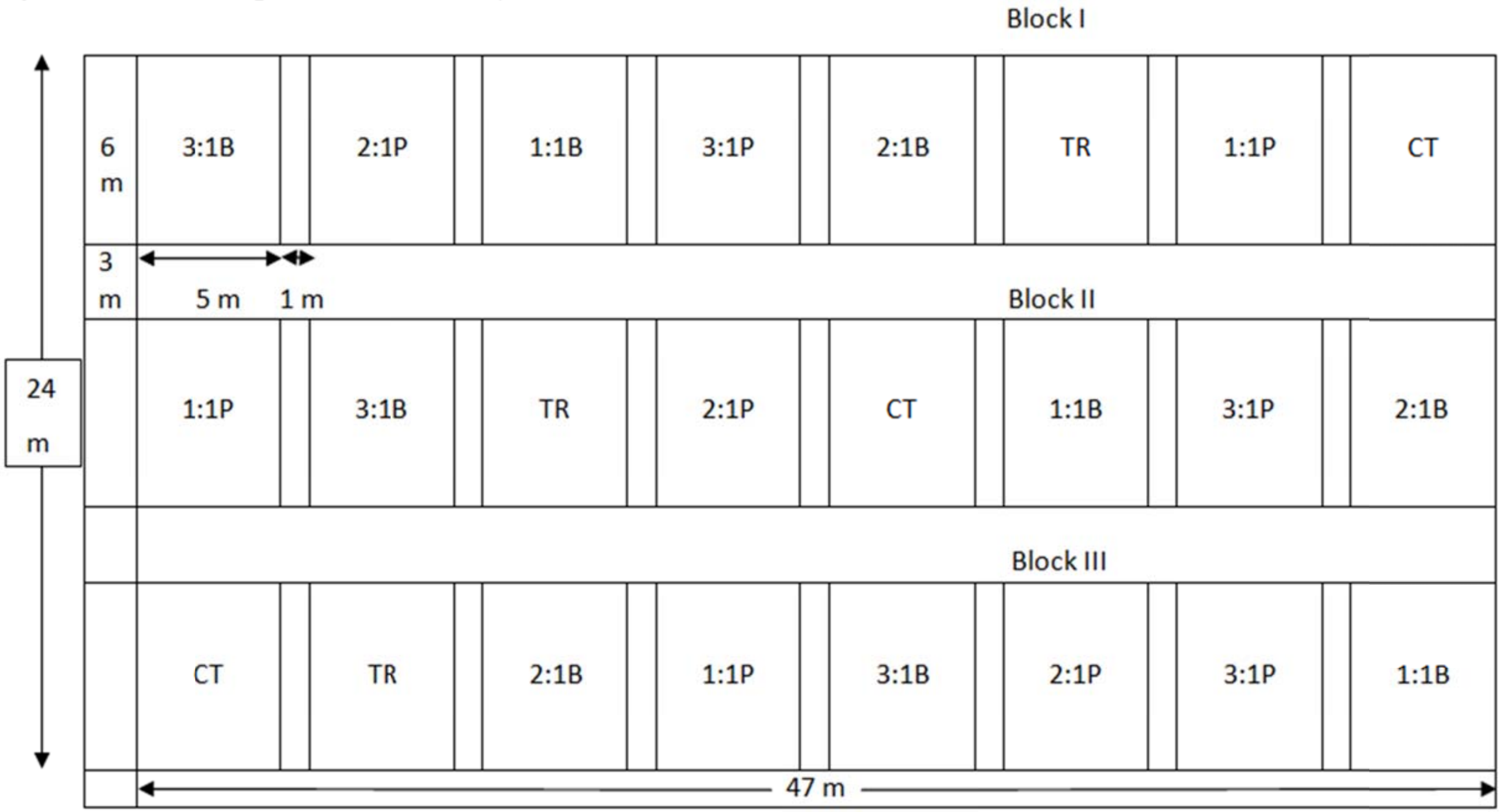
ZHAO, M., GUO, Z.Z., LI, A.D., WANG, Y.L. & ZHANG, D.K., 1997. A study of evapotranspiration of *Haloxylon ammodendron* and *Caragana korshinskii* by drainage water lysimeters. *Acta Bot. Boreal.-Occident. Sin.* 17 (3), 305-314 (in Chinese with English Abstract).

ZVOMUYA, F., ROSEN, C.J. & MILLER, J.C. Jr., 2002. Response of Russet Norkotah clonal selections to nitrogen fertilization. *Am. J. Potato Res*. 79(2002), 231-239.

LIST OF APPENDICES

Appendix A: RWH experimental field layout

Figure A1: RWH experimental field layout



Appendix B: Potato SPAD statistical analysis

Table B1: Potato SPAD statistical analysis results (14/01/2010)

Analysis of variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F value**	**Pr > F**
Treatments	7	629.29610	89.89944	3.01	0.0378
Replications	2	0.14475	0.07237	0.00	0.9976
Error	14	418.53899	29.90252		
Total	23	1047.97984	119.87433		
	R^2 = 60%; CV = 17.22; P = 0.05				
Least significant difference					
Tukey Grouping	**Mean**	**N**	**Treatment**		
A	38.067	3	3:1P		
B A	35.294	3	3:1B		
B A	34.978	3	1:1P		
B A	34.756	3	1:1B		
B A	32.939	3	2:1B		
B A	28.806	3	TR		
B A	28.156	3	2:1P		
B	21.033	3	CT		
	LSD ($P < 0.05$) = 15.76				

Means followed by the same letter are not significantly different at P = 0.05.

Table B2: Potato SPAD statistical analysis results (26/01/2010)

Analysis of variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F value**	**Pr > F**
Treatments	7	1070.94569	152.99224	6.99	0.0011
Replications	2	16.12923	8.06461	0.37	0.6982
Error	14	301.71739	21.87582		
Total	23	1388.79231	182.93267		
	R^2 = 78%; CV = 16.28; P = 0.05				
Least significant difference					
Tukey Grouping	**Mean**	**N**	**Treatment**		
A	36.733	3	3:1P		
A	33.925	3	TR		
A	33.322	3	2:1B		
A	31.350	3	2:1P		
A	30.817	3	3:1B		
B A	25.178	3	1:1P		
B A	23.722	3	1:1B		
B	14.732	3	CV		
	LSD (P < 0.05) = 13.48				

Means followed by the same letter are not significantly different at P = 0.05.

Appendix C: Swiss chard plant height and SPAD statistical analysis

Table C1: Swiss chard plant height statistical analysis results (21/09/2010)

Analysis of variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F value**	**Pr > F**
Treatments	7	227.73611	32.53373	4.27	0.0101
Replications	2	4.48148	2.24074	0.29	0.7499
Error	14	104.71711	7.62698		
Total	23	336.93470	42.40145		
	$R^2 = 68\%$; CV = 10.53; $P < 0.05$				
Least significant difference					
Tukey Grouping	**Mean**	**N**	**Treatment**		
A	29.333	3	1:1B		
A	29.222	3	2:1B		
A	28.333	3	3:1P		
B A	26.889	3	3:1B		
B A	26.778	3	1:1P		
B A	26.556	3	2:1P		
B A	23.000	3	TR		
B	19.778	3	CT		
	LSD ($P < 0.05$) = 7.96				

Means followed by the same letter are not significantly different at $P = 0.05$.

Table C2: Swiss chard plant height statistical analysis results (15/10/2010)

Analysis of variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F value**	**Pr > F**
Treatments	7	305.07292	43.58185	4.94	0.0054
Replications	2	1.98843	0.99421	0.11	0.8942
Error	14	122.63816	8.81696		
Total	23	429.69951	53.39302		
	R^2 = 71%; CV = 9.52; P = 0.05				
Least significant difference					
Tukey Grouping	**Mean**	**N**	**Treatment**		
A	33.889	3	2:1B		
A	33.556	3	1:1P		
A	33.556	3	2:1P		
A	33.111	3	1:1B		
A	32.889	3	3:1P		
B A	31.778	3	3:1B		
B A	27.611	3	TR		
B	23.222	3	CT		
	LSD (P < 0.05) = 8.56				

Means followed by the same letter are not significantly different at P = 0.05.

Table C3: Swiss chard plant height statistical analysis results (05/11/2010)

Analysis of variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F value**	**Pr > F**
Treatments	7	298.66551	42.66650	5.75	0.0027
Replications	2	15.36343	7.68171	1.04	0.3805
Error	14	98.72481	7.41452		
Total	23	412.75375	57.76273		
	R^2 = 75%; CV = 8.49; P = 0.05				
Least significant difference					
Tukey Grouping	**Mean**	**N**	**Treatment**		
A	35.556	3	3:1B		
A	35.556	3	2:1P		
A	35.222	3	3:1P		
B A	34.333	3	1:1P		
B A C	32.444	3	1:1B		
B A C	30.000	3	2:1B		
C	27.222	3	TR		
C	26.389	3	CT		
	LSD (P < 0.05) = 7.85				

Means followed by the same letter are not significantly different at P = 0.05.

Table C4: Swiss chard SPAD statistical analysis results (01/10/2010)

Analysis of variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F value**	**Pr > F**
Treatments	7	196.29167	28.04167	3.98	0.0133
Replications	2	13.39815	6.69907	0.95	0.4096
Error	14	98.52778	7.03770		
Total	23	308.21760	41.77844		
	R^2 = 68%; CV = 6.85; P = 0.05				
Least significant difference					
Tukey Grouping	**Mean**	**N**	**Treatment**		
A	43.222	3	2:1P		
B A	41.111	3	3:1P		
B A	40.667	3	3:1B		
B A	39.444	3	TR		
B A	38.556	3	2:1B		
B A	37.556	3	1:1B		
B	35.333	3	1:1P		
B	34.000	3	CT		
	LSD (P < 0.05) = 7.64				

Means followed by the same letter are not significantly different at P = 0.05.

Appendix D: Runoff volume per tip (L) for the different tipping buckets used in the RWH trial

Table D1: Runoff volume per tip (L) for the different tipping buckets used in the RWH trial

Tipping bucket	Volume of runoff per tip (L)
1	2.9
2	2.015
3	2.01

Appendix E: Simulated potato TDM and HDM (t ha^{-1}) scenarios for CT, TR and 2:1B at the study ecotope for dry, normal and wet years (2009/2010) (cropped area)

Table E1: Simulated potato TDM and HDM (t ha^{-1}) scenarios for CT, TR and 2:1B at the study ecotope for dry, normal and wet years (2009/2010) (cropped area)

Sowing Date		**Yield (t ha^{-1})**											
		CT											
		08 October			**15 October**			**29 October**			**15 November**		
Year	**Spell**	**Rainfall (mm)**	**TDM**	**HDM**	**Rainfall (mm)**	**TDM**	**HDM**	**Rainfall (mm)**	**TDM**	**HDM**	**Rainfall (mm)**	**TDM**	**HDM**
1978/1979	Dry	154	2.6	1.2	150	2.8	1.3	128	3.0	1.5	115	3.4	1.2
1991/1992	Dry	293	8.6	6.2	280	9.7	6.8	249	9.4	5.4	230	6.9	2.9
1997/1998	Normal	382	16.6	12.5	365	15.7	11.8	359	15.1	10.4	295	10.9	6.3
1998/1999	Normal	343	14.1	10.4	311	12.7	9.1	305	11.6	7.2	290	9.1	4.5
1995/1996	Wet	668	16.7	12.6	786	15.7	11.5	736	14.8	9.8	691	9.5	5.1
1999/2000	Wet	459	6.5	5.2	459	11.0	8.9	447	13.9	10.0	434	11.0	6.0
Sowing Date		**TR**											
		08 October			**15 October**			**29 October**			**15 November**		
Year	**Spell**	**Rainfall (mm)**	**TDM**	**HDM**	**Rainfall (mm)**	**TDM**	**HDM**	**Rainfall (mm)**	**TDM**	**HDM**	**Rainfall (mm)**	**TDM**	**HDM**

Table E1: Simulated potato TDM and HDM (t ha^{-1}) scenarios for CT, TR and 2:1B at the study ecotope for dry, normal and wet years (2009/2010) (cropped area) (continued)

1978/1979	Dry	154	3.4	1.5	150	3.8	1.8	128	3.8	1.9	115	4.2	1.6
1991/1992	Dry	293	10.3	7.7	280	11.1	7.9	249	10.7	6.3	230	7.0	3.0
1997/1998	Normal	382	17.1	12.8	365	16.2	12.1	359	15.3	10.6	295	11.0	6.4
1998/1999	Normal	343	14.7	11.0	311	13.7	9.8	305	12.1	7.7	290	9.3	4.6
1995/1996	Wet	668	16.9	12.7	786	15.9	11.7	736	14.9	9.9	691	9.5	5.1
1999/2000	Wet	459	8.0	6.2	459	12.6	9.9	447	15.2	10.6	434	11.0	6.0
Sowing Date		**2:1B**											
		08 October			**15 October**			**29 October**			**15 November**		
Year	**Spell**	**Rainfall (mm)**	**TDM**	**HDM**	**Rainfall (mm)**	**TDM**	**HDM**	**Rainfall (mm)**	**TDM**	**HDM**	**Rainfall (mm)**	**TDM**	**HDM**
1978/1979	Dry	154	3.9	1.7	150	4.8	2.3	128	4.6	2.1	115	5.2	2.0
1991/1992	Dry	293	11.3	8.3	280	14.0	10.2	249	13.8	12.2	230	9.7	4.3
1997/1998	Normal	382	20.2	14.9	365	19.0	14.0	359	18.3	12.2	295	13.0	7.3
1998/1999	Normal	343	19.2	14.3	311	17.8	13.0	305	16.1	10.3	290	11.8	5.8
1995/1996	Wet	668	20.4	15.2	786	19.5	14.1	736	17.8	11.5	691	12.1	6.2
1999/2000	Wet	459	9.9	7.4	459	14.4	11.2	447	17.8	12.0	434	13.1	6.8