Rainwater harvesting: management strategies in semi-arid areas

by

Nádia Alcina Ibraimo

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In the Faculty of Natural and Agricultural Sciences
University of Pretoria
Pretoria

Supervisor: Prof. J.M. Steyn
Co-Supervisor: Prof. J.G. Annandale

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UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

DECLARATION

I, Nadia Alcina Ibraimo declare that the dissertation, which I hereby submit for the degree MSc (Agric) Agronomy at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

SIGNATURE: --
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LIST OF SYMBOLS AND ABBREVIATIONS

A	Runoff plot area (m^2)
Brm	Crop rotation beans after maize
C	Runoff efficiency
Ce	Weight of an empty container (kg)
CN	Curve number
Cr	Runoff volume from the valve of a drum (ℓ)
Cs	Soil dry weight plus weight of an empty container (kg)
CT	Conventional tillage
D	Drainage (mm)
DM	Total top dry matter (kg m^2)
DWR	Vapour pressure-corrected dry matter/water ratio (Pa)
E	Evaporation (mm)
Ec	Radiation conversion efficiency (kg MJ^{-1})
E_f	Model efficiency
ET	Crop evapotranspiration
FC	Soil water content at field capacity (mm)
H_2O	Water
I	Rainfall intensity (mm hr^{-1})
Ia	Initial abstraction (mm)
Ic	Cumulative infiltration (mm)
Id	Actual soil infiltration (mm)
IRWH	In-field rainwater harvesting
It	Soil infiltration rate (mm hr^{-1})
K	Canopy extinction coefficient
Kc	Crop coefficient
KCl	Potassium chloride
LAI	Leaf area index
LSD	Least significant difference
LSE	Least squares error

M	Maize
Mrb	Crop rotation maize after beans
Nh	High rate of nitrogen (kg ha^{-1})
Nrec	Recommended rate of nitrogen (kg ha^{-1})
ObBr	Organic mulch in the basin, bare runoff area
ObOr	Organic mulch in the basin, organic mulch in the runoff area
ObSr	Organic mulch in the basin, stones in the runoff area
P	Rainfall depth (mm)
PAR	Photosynthetic active radiation
PAW	Plant available water (mm)
PC	Plastic cover
Po	Rainfall threshold (mm)
$\overline{PO}$	Average of the total observed storm events (mm)
Pr	Rainfall amount that produced runoff (mm)
PTr	Total amount of rainfall that produced runoff (mm)
ΔQ	Changes in soil water storage in the root zone (mm)
r	Correlation coefficient
R	Runoff depth (mm)
r^2	Coefficient of determination
RO	Observed runoff depth (mm)
RP	Predicted runoff depth (mm)
S	Surface retention (mm)
SAS	Statistical analysis system
SbOr	Stones in the basin, organic mulch in the runoff area
SbSr	Stones in the basin, stones in the runoff area
STy	Total amount of soil washed out with runoff in a certain period of time (kg)
Su	Sunflower
sx	Amount of soil washed out with 500 ml of runoff (kg)
$\overline{sx}$	Average amount of soil washed out with 500 ml of runoff (kg)
sy	Soil dry weight (kg)
t	Time (hr)

T	Transpiration (mm)
TR	Tied ridges
V	Volumetric water content (m^3 m^{-3})
VPD	Vapour pressure deficit (Pa)
WP	Soil water content at permanent wilting point (mm)
Z	Probe count rate ratios
γ	Soil factor (mm^{-1})
2mP	2 m runoff area long covered with plastic
1mB	1 m long bare runoff area
2mB	2 m long bare runoff area
3mB	3 m long bare runoff area
1:1B	Design ratio 1:1 of the in-field rainwater harvesting with a bare runoff area
1:2B	Design ratio 1:2 of the in-field rainwater harvesting with a bare runoff area
1:3B	Design ratio 1:3of the in-field rainwater harvesting with a bare runoff area
1:1P	Design ratio 1:1 of the in-field rainwater harvesting with a plastic covered runoff area
1:2P	Design ratio 1:2 of the in-field rainwater harvesting with a plastic covered runoff area
1:3P	Design ratio 1:3 of the in-field rainwater harvesting with a plastic covered runoff area

ABSTRACT

Rainfall in semi-arid areas is generally insufficient to meet crop water requirements, and above all erratic in distribution. This leads to crop yield fluctuation, which drastically affects food security. Rainwater harvesting technologies have been implemented in these areas in order to mitigate the effect of perennial droughts. The successful adoption of these technologies can contribute to poverty alleviation, and therefore improve the livelihood of resource-poor subsistence farmers. Field trials for testing different rainwater harvesting scenarios are expensive, time consuming and laborious. As a result, crop models must be used to help study these systems, and thereby make prudent water harvesting design choices for specific situations. For this purpose, a simple, one-dimensional soil water balance model (Soil Water Balance-SWB) was modified by incorporating linear runoff estimation models in order to predict the soil water balance and crop yield under different rainwater harvesting design scenarios and to select the design most likely to succeed in a particular locality. Field data collected during the 2007/2008 maize growing season, on sandy clay loam soils, at the Hatfield Experimental Farm of the University of Pretoria, was used to parameterize the different runoff models and to calibrate the SWB crop model. Various rainwater harvesting design scenarios were run for two different semi-arid areas, on different soil types to illustrate the application of the SWB model as a tool to help design the most appropriate rainwater harvesting strategy, taking into account whether arable land is limiting or not limiting for crop production. The SWB model was successfully calibrated. Simulation results reveal that in drier years bigger design ratios (cropping area: runoff area) of the in-field rainwater harvesting technique (IRWH) are most likely to be successful, while in wetter years smaller design ratios of the IRWH technique or even simpler rainwater harvesting strategies such as the tied ridge and the conventional tillage techniques can harvest sufficient rainfall for maximum crop production. Results from field trials conducted in Pretoria, on sandy clay loam soils, confirmed that, in a wet season, maize yield is maximized by a smaller IRWH design (1:1B). The SWB model can be used as a tool to help selecting the most appropriate rainwater harvesting strategy under specific conditions with minimum input requirements.

CHAPTER 1

GENERAL INTRODUCTION

Hudson (1987) defines semi-arid areas as regions where the rainfall is a problem because of amount, distribution, or unpredictability. According to Oweis *et al*. (1999), these areas are characterized by erratic and low rainfall varying from 350 to 700 mm per annum, periodic droughts and different associations of vegetative cover and soils.

The majority of the population in semi-arid areas depend on agriculture and pastoralism for subsistence. These activities face many constraints due to predominance of erratic rainfall patterns, torrential rainfall which is mostly lost to surface run-off, a high rate of evaporation which reduces yields, weeds growing more vigorously than cultivated crops and competition for scarce soil water reserves, low organic matter levels and high variability in response to fertilizers (Hatibu, 2000).

There is a need to optimize rainfall for crop production purposes in semi-arid areas. An optimisation of the rainfall management, through rainwater harvesting in sustainable and integrated production systems can contribute for improving the small-scale farmers' livelihood by upgrading the rainfed agriculture production. Rainwater harvesting categories, considered as appropriated for small-scale rainfed agriculture due to their relative simplicity in the implementation, are micro-catchment rainwater harvesting and in-situ rainwater harvesting. Micro-catchment rainwater harvesting systems consist of collecting surface runoff from small catchment areas with short slopes (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 rainwater harvesting, also called soil and water conservation, involves the use of methods 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).

Several micro-catchment rainwater harvesting techniques are used to satisfy the local conditions of water harvesting projects (Kunze, D., 2000; Haile & Merga, 2002; Senkondo *et al*., 2004). One of the most important on-farm types is the In-field rainwater harvesting technique, which has been implemented in dry areas around Bloemfontein, South Africa (Hensley *et al*., 2000). The technique consists of the following characteristics: a runoff area, which produces in-field run-off and a cropping basin, which allows the stoppage of runoff completely, maximizes infiltration and stores the collected water in the soil layers beneath the sensitive evaporation zone (Rensburg van *et al*., 2003). The design of such structures, which involves the calculation 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 catchment area (Oweis *et al*., 1999; Prinz & Malik, 2002). Thus, it varies between seasons and from one region to another. One of the advantages of selecting the best design of micro-catchment structures 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 the crop yield (Critchley & Siegert, 1991). In addition, it helps the farmers to maximize the use of arable land for crop production, since the catchment area uses potential arable land.

Many models of rainfall-runoff-yield systems have been developed to assess the implications of implementing rainwater harvesting systems under different scenarios using long-term climatic data. These models vary in complexity and accuracy. Where the basic long term climatic data is available, conceptual models have been developed for a better estimation of runoff; otherwise empirical models have been playing important rules on the management of these systems (Mzirai *et al*., 2002; Young *et al*., 2002). These models can then be useful to improve the understanding of field observations and to allow the transfer of experimental results to areas without monitoring systems.

In general, the main objective of this dissertation is to improve the dry land crop water productivity by using a soil water balance model as a tool to manage the soil water balance components under different rainwater harvesting conditions.

CHAPTER 2

LITERATURE REVIEW

2.1 RAINWATER HARVESTING TECHNOLOGIES

Rainwater harvesting is broadly defined as the collection and concentration of runoff for productive purposes such as crop, fodder, pasture or trees production, livestock and domestic water supply in arid and semi-arid regions (Gould, 1999; Stott, 2001; Fentaw *et al.*, 2002). For agriculture purposes, it is recognized as a method for inducing, collecting, storing and conserving local surface runoff in arid and semi-arid regions, in order to mitigate the effects of temporal shortages of rain (Oweis *et al.*, 1999; Prienz & Singh, 2001). It is an ancient practice and still forms an integral part of many farming systems worldwide. The first use of such systems is believed to have originated in Iraq over 5000 years ago, in the Fertile Crescent, where agriculture once started some 8000BC (Hardan, 1975).

Rainwater harvesting technologies can considerably improve the productivity of rainfed agriculture in semi-arid areas where the rainfall is usually insufficient to meet crop water requirements throughout the growing season. As reported by FAO (2000), 60% of the world's food is supplied by rainfed agriculture. The traditional practice of cultivating the land under dryland conditions, generally called conventional tillage, involves the use of plowing and several disk operations to prepare the soil for planting. Farmers normally implement these mechanical operations with the aim of increasing the soil water holding capacity through increased porosity, which enhances infiltration rates, and therefore reduces surface runoff, allowing the crop to have increased soil water availability. However, crop yields using conventional tillage are often very low, especially in semi-arid areas. One of the major reasons for this is the fact that large amounts of water are still lost through runoff, which increases water scarcity for crop production, as well as nutrient deficiency. Therefore, an optimization of rainfall utilization through the practice of rainwater harvesting techniques in dry areas would reduce the risk of crop failure due to improved water availability to plants.

Rainwater harvesting technologies have the following characteristics. Firstly, it is practised in arid and semi-arid regions, where surface runoff often has an intermittent character. Secondly, it is based on the utilization of runoff and requires a runoff producing area and a runoff receiving area. Finally, due to the intermittent nature of runoff events, water storage is an integral part of the system and it can be done directly in the soil profile or in small reservoirs, tanks and aquifers (Oweis *et al.*, 1999).

In crop production systems, rainwater harvesting is composed of a runoff producing area, normally called catchment area, and a runoff utilization area usually called cropping area. Its major categories are classified according to the distance between the catchment area and the cropping area as follows: External (Macro) catchment rainwater harvesting, In-situ rainwater harvesting and Internal (Micro) catchment rainwater harvesting (Hatibu & Mahoo, 1999).

2.1.1 Macro-catchment rainwater harvesting

Macro-catchment rainwater harvesting technology is referred to as rainwater harvesting from long slope external catchment areas (Prinz & Malik, 2002). In this application, the catchment area is usually as big as 1000 m^2 to 200 ha. The ratio between the catchment area and the cropping area ranges from 10:1 to 100:1, with the catchment area being located outside the arable areas. The catchment area may have an inclination of 5 to 50%; the cropping area is either terraced or located in flat terrain. There are two different types of systems within this technology: (1) Runoff farming, where the runoff collected from the catchment area is directly diverted to the cropping area, through a variety of bunds, ridges and furrows, as shown in Figure 2.1; and (2) Supplemental irrigation, where the runoff collected from the catchment area is stored in tanks or earth dams to supplement a crop with water during stress periods, as illustrated in Figure 2.2. These water storage systems require relatively high capital and labour investments (often too high for individual households) and are relatively complicated systems to design.

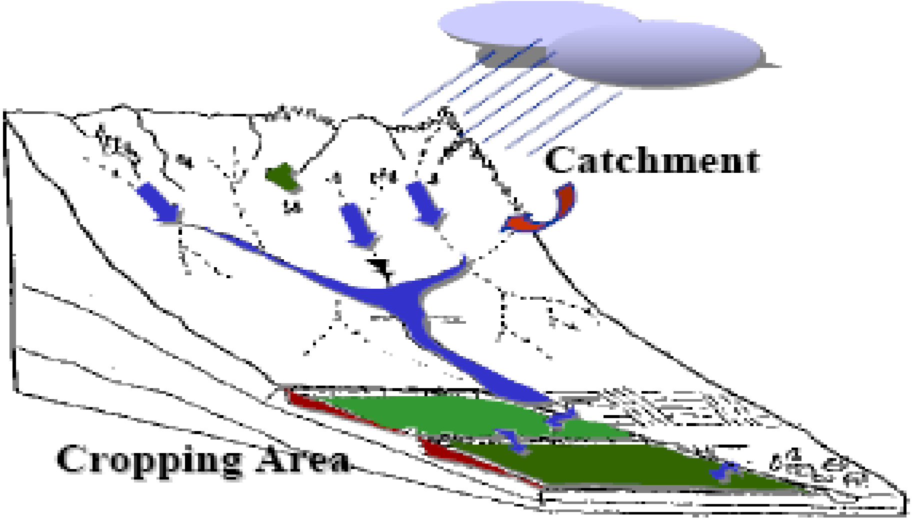


FIG. 2.1: Runoff farming system using high slopes catchment areas and terrain cropping areas (Prinz & Malik, 2002)

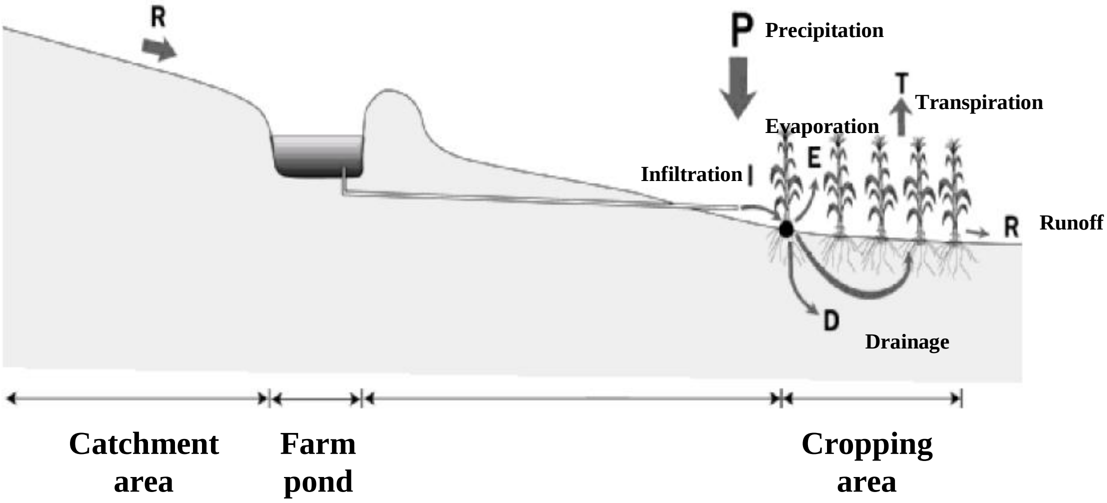


FIG. 2.2: Supplemental irrigation system for dry spell mitigation of maize through gravity-fed (SIWI, 2001)

2.1.2 In-situ rain water harvesting

In-situ rain water harvesting, often referred to as soil-water conservation, involves the use of methods 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; SIWI, 2001). In this application there is no separation between the runoff collection area and its storage area; the water is collected and stored where it is going to be utilized (UNEP, 1997). It performs well where the main constraints are soil related, but rainfall is adequate. Soil constraints may be related to low infiltration rates, caused by surfacing crusting, or to low percolation rates caused by restrictive layers in the soil profile (Mzirai *et al.*, 2002). This technology has the following advantages: it is less labor consuming and it can be implemented on a flat area or areas with very short slopes (less than 2%). One of the main systems within this category is conservation tillage (FAO, 1993).

Several authors define conservation tillage as any tillage or planting system in which at least 30% of the soil surface is covered by plant residue after planting to reduce water and wind erosion (FAO, 1993; Nyagumbo, 1999; Evans *et al.*, 2000; Carthy, 2001; Veenstra *et al.*, 2006). Reduction of soil erosion by water can also be achieved by the use of physical control measures, which provide surface protection by holding water to give it time to suck through the surface. These physical measures involve land shaping, construction of contour bunds, terraces and ridges (FAO, 1993). One of the most implemented techniques within this system is called tied ridges. It consists of alternate ridges and furrows following the contours. Small cross-ties of 15 to 20 cm high and 50-75 cm long are provided above furrows every 6 metres intervals to ensure an even storage of runoff, as illustrated in Figure 2.3 (Critchley & Siegert, 1991; Haile & Merga, 2002). Ridge spacing varies among crops. Mati (2005) reports the use of 80 cm ridge spacing for beans and 75 cm for sorghum and maize. This technique is especially effective on heavy soils, once constructed the ridges are not destroyed for a period of six seasons depending on the crop rotations practised by farmers. Planting is either done on the top or on both sides of the ridge (Nyagumbo, 1997; Mati, 2005). In some areas, pits of about 20 to 30 cm in diameter and 10 to 20 cm in depth are made along furrows instead of small ties (Mati, 2005).

One particular advantage of conservation tillage combined with ridges is the fact that by ridging, any organic matter or fertilizer which is present at or near the soil surface, will be concentrated in the ridge and will thus be of greater benefit to the crop. The following are usually the main disadvantages pointed by farmers: (1) weed control requires the application of herbicides; (2) germination of a crop planted on the top of the ridge is quite often observed to be slower than a crop planted on a flat land because ridges dry faster and will take longer to wet after a dry spell; and (3) when the crop is planted on the furrows, it is subjected to water logging problems, especially in higher rainfall areas with poor drained soils (Meijer, 1992).

FIG. 2.3: Tied Ridges for rainwater harvesting and conservation on maize in semi arid areas of Zimbabwe (Mutekwa & Kusangaya, 2006)

Tied ridges have been found to be very efficient in storing the rain water, which has resulted in substantial grain yield increase in some of the major dryland crops sorghum, maize, wheat, and beans in semi-arid regions of Ethiopia. Table 2.1 illustrates the average grain yield increase under tied ridges compared with the traditional practice of cultivation.

Table 2.1: Effect of tillage methods on grain yield of sorghum, mung bean and maize in semi-arid regions of Ethiopia (Mati, 2005)

Soil Conservation Method	**Grain yield (ton ha-^{1})**		
	Kobbo	Melkassa	Mean
Sorghum			
Flat planting (farmers practice)	1.6	0.8	1.2
Tied ridges planting in furrow	2.9	3	2.95
Mung bean			
Flat planting (farmers practice)	0.4	-	0.4
Tied ridges planting in furrow	0.7	-	0.7
Maize			
Flat planting (farmers practice)	1.2	-	1.2
Tied ridges planting in furrow	2.7	-	2.7

From Table 2.1 it can be seen that the average grain yield increase under tied ridges range from 50 to over 100 percent when compared to the traditional practice of flat cultivation. This increase varies from one region to another according to the soil type, slope and rainfall pattern (Mati, 2005).

2.1.3 Micro-catchment rainwater harvesting

Micro-catchment rainwater harvesting technology consists of collecting runoff from a runoff producing area over a flow distance of less than 30 m and storing it for consumptive use in the root zone of an adjacent cropping area. Rainfed farmers have been using these systems to minimize the effect of low and erratic rainfall in arid and semi-arid areas (Critchley & Siegert 1991; Tsakiris, 1991). The systems have been constructed in many different ways, such as small circular or square planting basins (example *Zai* and *Chololo* systems), earth basins surrounded by earthen bunds with an infiltration pit inside (example *Negarim* and Semi-circular bunds systems), alternate strips of catchment area and cropping area with and without ridges below it (example Strip tillage system), alternate strips of ridges and furrows (example Ridging system), and a field division into two distinct parts: a runoff producing area and a runoff receiving area (example Meskat-type system) (Critchley & Siegert, 1991; Hatibu & Mahoo, 1999; Prinz & Malik, 2002; Mati, 2005). The following are the main characteristics of these systems: (1) runoff harvested from short catchment length, usually less than 30 m; (2) runoff is stored in the soil profile of an adjacent cropping area; and (3) the ratio catchment: cropping area usually varies from 1:1 to 3:1 (Critchley & Siegert, 1991).

Micro-catchment rainwater harvesting 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 are effective on increasing productivity of flat rainfed land because of increased water availability (Prinz & Malik, 2002). This fact can help reduce the incentives that farmers have to cultivate steeps slopes, which are susceptible to soil erosion, as an insurance strategy against crop failure (Li *et al*., 2000). In addition, their implementation has created labour groups formation among farmers, which allow them to share tools, labour and ideas (Rosegrant *et al*., 2002). Furthermore, it is also found to be a very effective way of improving crop yield in arid and semi-arid areas (Haile & Merga, 2002; Mutekwa & Kusangaya, 2006).

However, there are also disadvantages associated with the implementation of micro-catchment rainwater harvesting systems:

1) High demand for labour. Construction and maintenance of the systems are normally labour intensive (Haile & Merga, 2002; Rosegrant *et al*., 2002; Senkondo *et al*., 2004). The catchment area has to be maintained in order to be free of vegetation (Prinz & Malik, 2002). Systems involving earth embankments need to be repaired after a heavy storm. Table 2.2 shows the volume of

earthwork and the labour involved in construction of some of the microcatchment systems;

2) Waterlogging problems during the high rainfall periods, which may cause irrevocable damage to the structures (Prinz & Malik, 2002; UNEP, 2003; Mutekwa & Kusangaya, 2006);
3) High costs of initial investment and system operation. These cover costs of tools, labour and training associated with investment and operating the technologies (Kunze, 2000; Rosegrant *et al*., 2002);
4) The catchment area uses potential arable land (Prinz & Malik, 2002);
5) Low crop density compared to in-situ rainwater harvesting systems (Prinz & Malik, 2002);

Table 2.2: Volume of earthwork and labour involved in construction of different micro-catchment rainwater harvesting systems (adapted from Critchley & Siegert, 1991)

	Micro-catchment rainwater harvesting systems					
Slope (%)	**Negarim**		**Semi-circular bunds**		**Contour ridges**	
	Earthwork (m^{3}ha^{-1})	Labour (Person day^{-1}ha^{-1})	Earthwork (m^{3}ha^{-1})	Labour (Person day^{-1}ha^{-1})	Earthwork (m^{3}ha^{-1})	Labour (Person Day^{-1}ha^{-1})
0.5	500	500	105	105	480	480
1	500	500	105	105	480	480
1.5	500	500	105	105	480	480
2	500	500	210	210	480	480
5	835	835	210	210	480	480

One of the clear examples of micro-catchment rainwater harvesting systems is the In-field rainwater harvesting. This system has been largely implemented in the semi-arid areas around Bloemfontein, South Africa, on clay soils. The system combines the advantages of water harvesting, no-till and basin tillage to collect as much runoff as possible (Hensley *et al*., 2000). Figure 2.4 illustrates the field layout of the system.

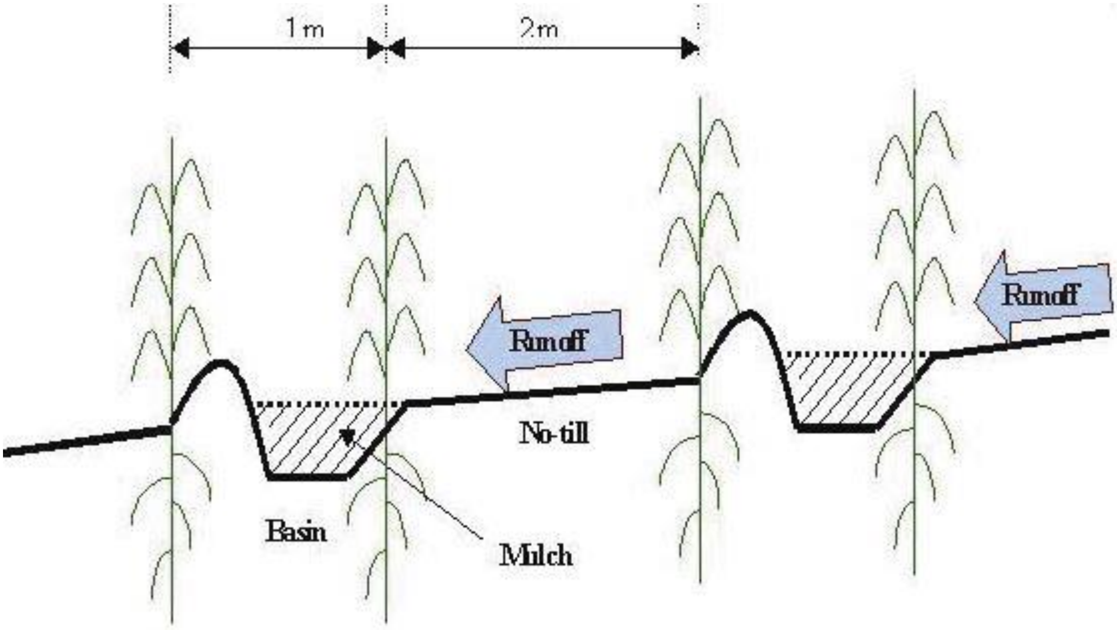


FIG. 2.4: In-field rainwater harvesting on maize production in semi-arid areas around Bloemfontein (adapted after Botha *et al*., 2005)

The system consists of a catchment area, which promotes in-field run-off and a cropping area, which allows the stoppage of ex-field runoff, maximizes infiltration and stores the collected water in the soil layers below the evaporation sensitive zone. Ridges are made directly below each cropping area to allow a better conservation of water in the soil profile. Mulch is 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). Herbicides are used to control weeds in the catchment area.

Another planting configuration in the in-field rain water harvesting technique is also found in certain regions of West Africa, where the main crop (usually a cereal) is seeded into the upslope side of the ridge between the top of the ridge and the furrow.

An intercrop, usually a legume, can be planted in front of the furrow, as demonstrated in Figure 2.5.

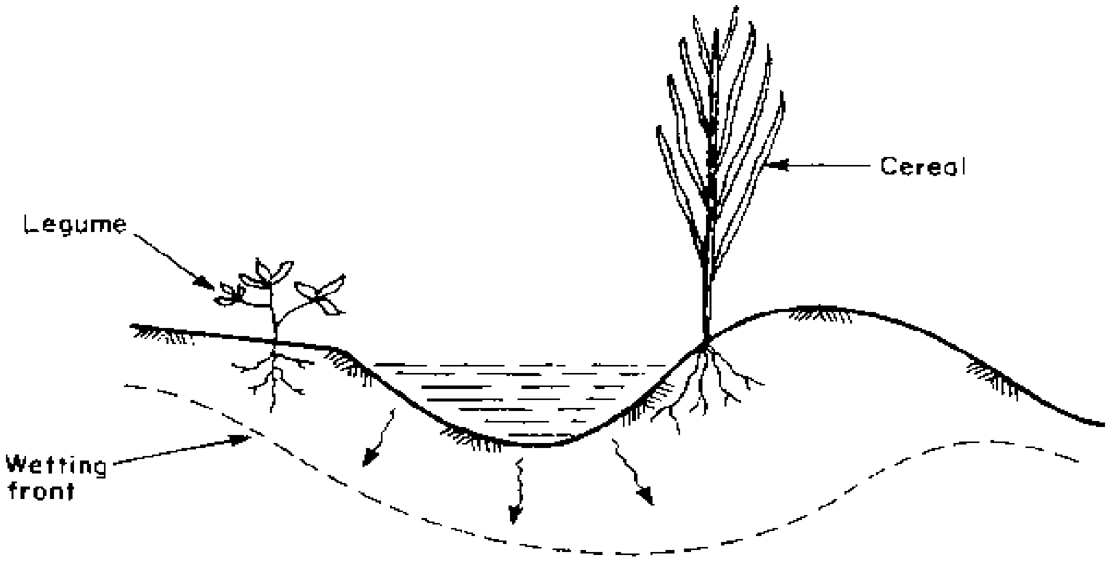


FIG. 2.5: Another planting configuration in the in-field rainwater harvesting system used in West-Africa (Critchley & Siegert 1991)

In this planting configuration, it is recommended that the use of approximately 65% of the plant population of rainfed cultivation, so that the plants can have more water available in years of low rainfall. Weeding must be carried out regularly around the plants and within the catchment area (Critchley & Siegert, 1991).

Botha *et al.* (2003) describe on-station field experiments conducted in semi-arid areas around Bloemfontein, South Africa, under In-field rainwater harvesting. These experiments were carried out in Glen/Bonheim ecotope, on clay soils with 1% slope. The average annual rainfall is 543 mm. One of the main objectives of on-station experiments was to evaluate the effect of four different water conservation crop production techniques combined with two different levels of fertilizer on maize and sunflower yield growing in rotation during three consecutive rainy seasons (Block A: sunflower/ maize/ sunflower; Block B: maize/ sunflower/ maize. The treatments were as follows: (1) organic mulch in the basin, bare runoff area (*ObBr*), with low level of fertilizer – 15 kg/ha of nitrogen, 5 kg/ha of phosphorus (*Lo*); (2) organic mulch in the basins, stones on the runoff area (*ObSr*), with low level of fertilizer (*Lo*); (3) organic mulch in the basins, organic mulch on the runoff area (*ObOr*), with low level of fertilizer (*Lo*); (4) stones in the basins, organic mulch on the runoff area (*SbOr*), with low level of fertilizer (*Lo*); (5) *ObBr*, with high level of fertilizer – 90 kg/ha of nitrogen, 20 kg/ha of phosphorus (*Hi*); (6) *ObSr*, with high level of fertilizer (*Hi*); (7) *ObOr*, with high level of fertilizer (*Hi*); and (8) *ObOr*, with high level of fertilizer (*Hi*). Planting densities of 22 000 plants/ha and 33 333 plants/ha (including the runoff areas) were used. Results concerning the nitrogen fertilizer effect on maize and sunflower yield are presented in Table 2.3. The values are mean for the four water conservation treatments.

Table 2.3: Maize and sunflower yield response to two different levels of nitrogen when cultivated in rotation under In-field rainwater harvesting (Botha *et al.*, 2003)

Parameter	Rotation	Block A		Rotation	Block B	
		Nitrogen levels			Nitrogen levels	
		Nrec	**Nh**		**Nrec**	**Nh**
Seed (kg/ha)	99/00 (Su)	2250^a	2083^b	99/00 (M)	3607^a	3612^a
	00/01 (M)	2848^a	2792^a	00/01 (S)	1921^a	1932^a
	01/02 (Su)	2473^a	2619^b	01/02 (M)	3330^a	3421^a
Precipitation (mm)	99/00 (Su)	228		99/00 (M)	228	
	00/01 (M)	280		00/01 (S)	280	
	01/02 (Su)	248		01/02 (M)	248	
Plant available water at planting (mm)	99/00 (Su)	145	148	99/00 (M)	148	148
	00/01 (M)	215	210	00/01 (S)	149	148
	01/02 (Su)	220	224	01/02 (M)	167	166

(Su) = sunflower, (M) = maize

Nrec = recommended level of nitrogen, Nh = high level of nitrogen

Values with similar letters are not statistically different at P = 0.05

From Table 2.3 it can be seen that the high nitrogen application within the sunflower/ maize/ sunflower rotation-experiment (Block A) significantly influences seed yield response. Maize that followed sunflower responded negatively, while sunflower responded positively when it followed maize. This can be explained by the fact that sunflower has the ability to extract more water from the potential root zone than maize. From block A, it can also be seen that under water limiting conditions (rainy season 1999/2000), the high nitrogen application led to sunflower yield losses. This fact occurred due to water stress. It is proved that high nitrogen application induces over-stimulation of vegetative growth, which increases the transpiration rate. This can deplete the stored water in the profile to a level that creates plant water stress during critical growing stages. Results from the maize/ sunflower/ maize rotation-experiment (Block B) showed no significant response to the high nitrogen application level for both crops. However, there was a maize yield increment from 2 612 kg/ha with no nitrogen application to 3 330 kg/ha and 3 607 kg/ha when 15 kg/ha of nitrogen was applied. This can lead to the conclusion that the 15 kg/ha of nitrogen application represents the optimum nitrogen level for the Glen/Bonheim ecotope when the available water (precipitation plus plant available water) fluctuates between 370 and 420 mm. Results of seed yield and harvest index for maize and sunflower as affected by water conservation techniques during the three seasons are presented in Table 2.4.

Table 2.4: Seed yield and harvest index for maize and sunflower as affected by water conservation treatments during three growing seasons (Botha *et al.*, 2003)

Crop	**Parameter**	**Season**	**Treatment**			
			ObBr	***ObOr***	***ObSr***	***SbOr***
Maize	**Seed (kg/ha)**	99/00	3455^b	3519^b	3962^a	3500^b
		00/01	2543^a	2908^b	3098^b	2731^a
		01/02	3281^a	3325^a	3607^a	3288^a
		Mean	**3093**	**3251**	**3556**	**3173**
	Harvest Index	99/00	0.46^a	0.48^a	0.50^a	0.49^a
		00/01	0.39^a	0.38^a	0.38^a	0.37^a
		01/02	0.45^a	0.42^a	0.46^a	0.44^a
		Mean	**0.43**	**0.43**	**0.45**	**0.43**
Sunflower	**Seed (kg/ha)**	99/00	1879^a	2190^a	2346^b	2251^a
		00/01	1716^a	1971^b	2138^c	1882^b
		01/02	2340^a	2519^b	2704^c	2622^b
		Mean	**1978**	**2227**	**2396**	**2252**
	Harvest Index	99/00	0.31^a	0.31^a	0.33^a	0.30^a
		00/01	0.37^a	0.42^a	0.43^a	0.36^a
		01/02	0.46^a	0.45^a	0.48^a	0.48^a
		Mean	**0.38**	**0.39**	**0.41**	**0.38**

From Table 2.4 it can be seen that on both maize and sunflower crops, the water conservation technique *ObSr* was in two of the three years significantly higher than *ObBr*. Organic (*ObOr*) mulch on the runoff area increased the yield by 5 and 13% on maize and sunflower, respectively, in comparison with the bare surface (*ObBr*). On maize, the harvest index varied between 0.37 and 0.50 during the three seasons, which can be considered good for dryland maize. These values indicate that water supply in the vegetative period was sufficient to meet the crop water demand; hence no severe water stress occurred. On sunflower, the harvest index varied between 0.3 and 0.48 over the three seasons. The lower harvest index is probably due to the replanting of the crop a bit later in the season, which probably restricted the reproductive growth period.

An additional objective of on-station experiments was to demonstrate the advantages of the In-field rainwater harvesting (IRWH) compared to conventional tillage (CT). A moderate level of nitrogen fertilizer (40 kg/ha) was applied at planting at all treatments. Planting densities of 22 000 and 133 333 plants/ha were used on maize and beans, respectively. The treatments were as follows: (1) organic mulch in the basin, bare runoff area, maize and dry beans planted annually in rotation; (2) stones in the basin and stones on the runoff area, maize and dry beans planted annually in rotation; (3) normal conventional tillage, maize and dry beans planted annually in rotation; (4) normal conventional tillage, maize planted annually; and (5) normal conventional tillage, beans planted annually. Results from this experiment are presented in Table 2.5.

Table 2.5: A comparison effect between conventional tillage and different water conservation techniques on seed yield and harvest index of maize and beans cultivated in rotation (Botha *et al.*, 2003)

Parameter	**Year**	**Treatments**					
		Crop rotation (beans and maize)					
		Brm			Mrb		
		CT	*ObBr*	*SbSr*	*CT*	*ObBr*	*SbSr*
Seed (kg/ha)	00/01	542	953	1136	1489	2693	3570
	01/02	381	931	1021	1521	3396	3940
	Mean	**462**	**942**	**1079**	**1505**	**3045**	**3755**
Harvest index	00/01	0.39	0.38	0.40	0.35	0.38	0.43
	01/02	0.30	0.48	0.41	0.36	0.49	0.47
	Mean	**0.35**	**0.43**	**0.40**	**0.35**	**0.44**	**0.45**
Precipitation for the season (mm)	00/01	280	280	280	280	280	280
	01/02	248	248	248	248	248	248
	Mean	265	265	265	265	265	265
Plant available water at planting (mm)	00/01	71	142	144	143	118	138
	01/02	47	165	179	68	130	233
	Mean	**59**	**154**	**162**	**106**	**124**	**189**

Brm = beans after maize

Mrb = maize after beans

From Table 2.5 it can be seen that the plant available water at planting of the two In-field rainwater harvesting treatments (*ObBr* and *SbSr*) was higher than the conventional tillage for both, beans and maize. This water advantage helped the crops to reach better seed yield and harvest index under these treatments compared to the conventional tillage. The highest seed yield for both crops was reached under the treatment stones in the basin, stones in the runoff area (*SbSr*), followed by the treatment organic mulch in the basin, bare runoff area (*ObBr*) and conventional tillage (*CT*) as the lowest. In-field rainwater harvesting system has the ability of capturing, storing and supplying more rain water than the conventional tillage system.

2.2 RAINWATER MICRO-CATCHMENT SURFACES

Micro-catchment rainwater harvesting systems are composed by two important parts: a runoff receiving area (also called cropping area) and a runoff collection area (also called rainwater micro-catchment surface). To design efficient micro-catchment water harvesting systems, the optimum ratio between catchment and cultivated area needs to be established. This ratio, for a particular crop, varies in space and time, depending on the climatic characteristics and soil factors (Bruggeman & Oweis, 1998). On one hand, if the design ratio is below the optimum ratio, crops will experience water stress. On the other hand, if it exceeds the optimum ratio, there will be surplus runoff, which may damage the water harvesting structure, cause crop yield reduction and increase production costs to the farmer (Critchley & Siegert, 1991). One of the main inputs of the design ratio equation is runoff, which is calculated over the cropping area where it is collected. The collected amount of runoff depends on how well managed the main components of the water balance of a micro-catchment surface are. Thus, this section aims to describe the main components of the water balance of a rainwater micro-catchment surface, its management as well as the models that have been used to estimate the collected amount of runoff.

2.2.1 Description of the water balance components

Young *et al*. (2002) have identified the main components involved in the water balance of a treated micro-catchment surface (also called treated runoff area) as follows: infiltration, rainfall and runoff, as evident in Figure 2.6. However, Foster (1949) and Kamphorst *et al.* (2000) state that, apart from these components, another very important factor is also involved, namely surface retention. According to FAO (1993a), in a treated runoff area, since it involves vegetation removing, the water balance does not include evaporation and transpiration. This is because these factors mainly occur due to interception of rainfall on the sparse vegetation.

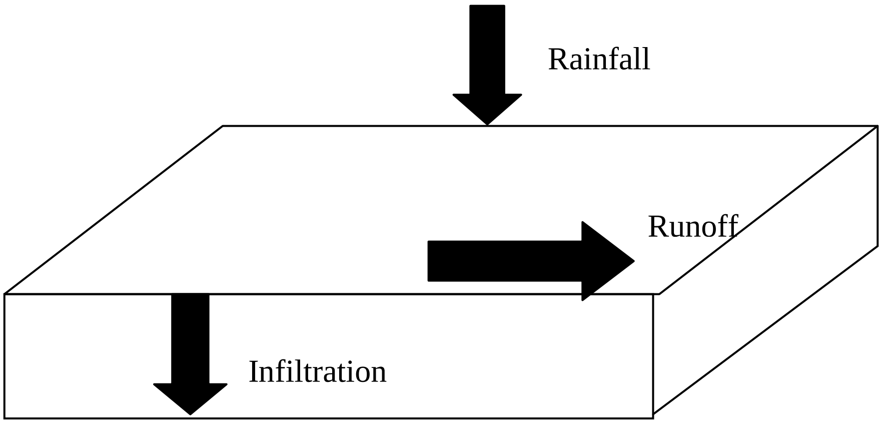


FIG. 2.6: Water balance components of a micro-catchment surface (adapted from Young *et al*., 2002)

Rainfall is the primary source of water for agricultural production, mainly in arid and semi-arid areas around the world. It is characterized by its amount, intensity and distribution in time. Rainfall in arid and semi-arid zones results largely from convective cloud mechanisms, producing storms typically of short duration and relatively high intensity (FAO, 1985). As stated by FAO (1993a), a rainstorm is a period of rain, in which the interval between rainfall segments does not exceed 24 hours.

According to Mena *et al.* (1998), the main rainfall characteristic affecting the runoff response of soils of low infiltrability is rainfall intensity. This is defined as the ratio of the total amount of rain (rainfall depth) falling during a given period to the duration of the period. It is expressed in depth units per unit time, usually as millimetres per hour (FAO, 1985; FAO, 1991). The high intensity rainfall usually has big drops that fall with more force on the soil surface. In fine textured soils, the soil aggregates breakdown rapidly into fine particles that seal the soil surface (FAO, 1993a). In addition, due to the presence of high clay content, these types of soil have a higher potential for swelling upon wetting. When rain comes and the soil surface becomes moist, the soil swells and the fine cracks and pores close and, as a result soil infiltration is reduced and more runoff is generated. Low intensity rainfall has finer drops. The soil surface is not sealed, rainwater infiltrates more easily and thus, surface runoff is reduced (FAO, 1985). Figure 2.7 shows the effect of high rainfall intensity sealing the soil surface.

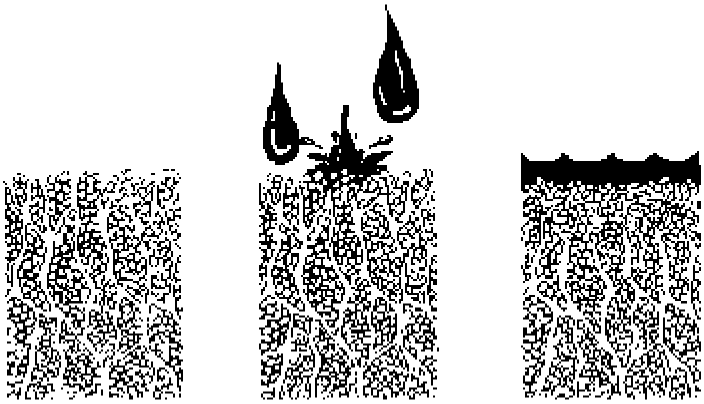


FIG. 2.7: Sealing of the soil surface by raindrops caused by high rainfall intensities (FAO, 1985)

Conversely, on coarser textured soils with higher infiltrabilities, the runoff generation is more governed by rainfall amount rather than rainfall intensity. In this type of soil, the amount of runoff is mostly generated by the saturation of a thin top soil layer (Mena *et al.*, 1998).

The soil infiltration occurrence on the runoff area from micro-catchment rainwater harvesting systems is seen as a factor that reduces the amount of water available for surface runoff (Boers, 1997; Li *et al.*, 2000b). The term “infiltration” means absorption of water into the soil from rainfall (Philips, 1956). Infiltration is of great importance to engineers and hydrologists because of its effect on reducing flood flows and surface runoff, which would otherwise be available for water supply and other utilization (FAO, 1991). It is also becoming an increasing, important issue to agronomists with regards to micro-catchment rainwater harvesting systems. In these systems, the aim of agronomists is to minimize infiltration on the runoff area in order to get as much runoff as possible to the cropping area, and to maximize infiltration on the cropping area so that the available water for crops will be taken full advantage of (Li & Gong, 2002a). Infiltration capacity has been defined by Slatyer (1967) as the maximum rate at which the soil, in a given condition, can absorb falling rain. Foster (1949) states that it is desirable in most cases to speak of the actual infiltration rate rather than infiltration capacity because the absorptive capacity of the soil varies greatly. In addition, there may not always be sufficient rain to supply the maximum rate.

Soil infiltration has been measured in a number of ways, either in laboratory or under field conditions. Measurements of infiltration under field conditions are more reliable than laboratory measurements. Because the “edge” effect from lateral water movement increases as the area of wetting decreases and the area or perimeter ratios decline, large ponding measurements are frequently the most accurate, which require spraying equipment. However, the area or water supply may be limited and a variety of alternative devices have been developed (Foster, 1949). One of the most commonly used methods is the ring infiltrometer (double or single ring infiltrometer). Double ring infiltrometers are more accurate than single ring infiltrometers. By using an outer ring, the three dimensional single ringed system is virtually turned into a one dimensional model by allowing water in the centre ring to flow almost exclusively straight down. This allows much easier calculation by taking out the need to account for lateral flow (Heffernan, 1998; Mckenzie *et al.*, 2002). Mckenzie *et al.* (2002), Lei *et al.* (2006) and Léonard *et al.* (2006) mention a number of problems associated with the use of this method. These include: (1) requirement of a flat undisturbed surface which sometimes is not available; (2) on crusted soil surfaces, the crust is usually broken by the ring insertion into the ground, which strongly affects infiltration rates; and (3) it cannot take into account the impact of rain drop splash and its effect on crusting and sealing the soil surface. To solve most of the problems encountered with the use of ring infiltrometers, sprinkler infiltrometers have been developed to determine the actual rates of soil infiltration in-situ (Reinders & Louw, 1984; van Es & Schindelbeck, 1998). The following are the advantages of using this type of infiltrometer: (1) it wets the soil in a more natural manner and eliminates soil slaking as a result of instantaneous ponding; (2) it reduces unnaturally high macropore flow under ponded conditions; (3) it provides a realistic surface boundary condition, including the effects of soil surface roughness which can greatly influence infiltration behavior; and (4) it is conservative with water (Ogden, 1997; van Es & Schindelbeck, 1998).

Many factors contribute to the variations in the infiltration rates (Foster, 1949; Slatyer, 1967; FAO, 1991; Miyazaki, 1993):

- The most important is porosity of the soil itself. Sandy soils have higher infiltration rates than clayey soils;
- Initial soil water content. The infiltration rate within the same soil type is lower when the soil is initially wet than when it is dry.
- The state of cultivation is also of certain importance but the effect is transitory; infiltration is high at the beginning of a rainstorm but diminishes rapidly, apparently because the pores on the surface quickly become clogged;
- Similarly, turbid water reduces infiltration;
- Organic matter on the soil surface and growing vegetation promote infiltration;
- Temperature of the soil also has an effect on the infiltration rate because of a variation in viscosity of water with temperature;
- Zones of low permeability always exert profound effects on infiltration rates. These zones can develop as surface crusts, as a clay pan, cultivator pan or hardpan zones. Dispersed clay structure under alkali conditions, compaction due to farm implements and other conditions are normally the factors causing zones of low permeability.

Slatyer (1967) proposed that four main groups of soils could be distinguished in terms of their expected minimum infiltration rates. These groups are presented in Table 2.6.

Table 2.6: Minimum infiltration rate of various groups of soils (Slatyer, 1967)

Soil groups	Minimum infiltration rate ($mm\ hr^{-1}$)
Deep sands, deep loess, aggregated silts	11.4 – 7.6
Shallow loess, sandy loams	7.6 – 3.8
Many clay loams, shallow sandy loams, soils low in organic matter, soils of high clay content	3.8 – 1.3
Soils of high swelling capacity, sodic soils	< 1.3

Surface retention has been termed as a surface layer of water, which is caused by the initial action of rainfall in saturating the soil surface, by filling the depressions of the surface with water in excess of the current infiltration rate. According to FAO (1993a), surface retention is a dynamic parameter, which allows maximum infiltration for low intensity rain segments, at the same time renewing the storage capacity free volume. Kamphorst (2000) states that surface retention depends on surface micro-topography, which is subject to spatial and temporal changes. Bissonnais *et al.*, (2005) mention other factors affecting surface retention such as roughness which is determined by the level of soil aggregate stability, presence of macropores, presence of rock fragments and soil compaction. Due to all these factors affecting the changes in surface retention, it is very difficult to monitor over time (Kamphorst, 2000). As indicated by FAO (1991), the depths of surface retention are not great in normal storms, but range from approximately 0.25 to 2.54 mm. However, during intense storms which cause disastrous floods the depths would be much greater. Reinders & Louw (1984) point another important factor affecting the depths of surface retention – land slope. Table 2.7 show the suggested depths of surface retention versus slope for typical conventional tillage practices under irrigation.

Table 2.7: Surface retention capacities versus slope for typical conventional tillage practices under irrigation (adapted from Reinders & Louw, 1984)

Land slope (%)	Allowable retention capacity (mm)
0 – 1	12.5
1 – 3	7.5
3 – 5	2.5

On a bare runoff area of a micro-catchment rainwater harvesting system, runoff constitutes the amount of water remaining from rainfall after the losses by filling up the surface retention and infiltration into the soil profile (Foster, 1949; Li *et al.*, 2000a). Because of the small runoff areas involved on micro-catchment rainwater harvesting systems, there is no base flow or groundwater outflow (Foster, 1949). Figure 2.8 shows the accumulated rain and discharge plotted against time for a small catchment area.

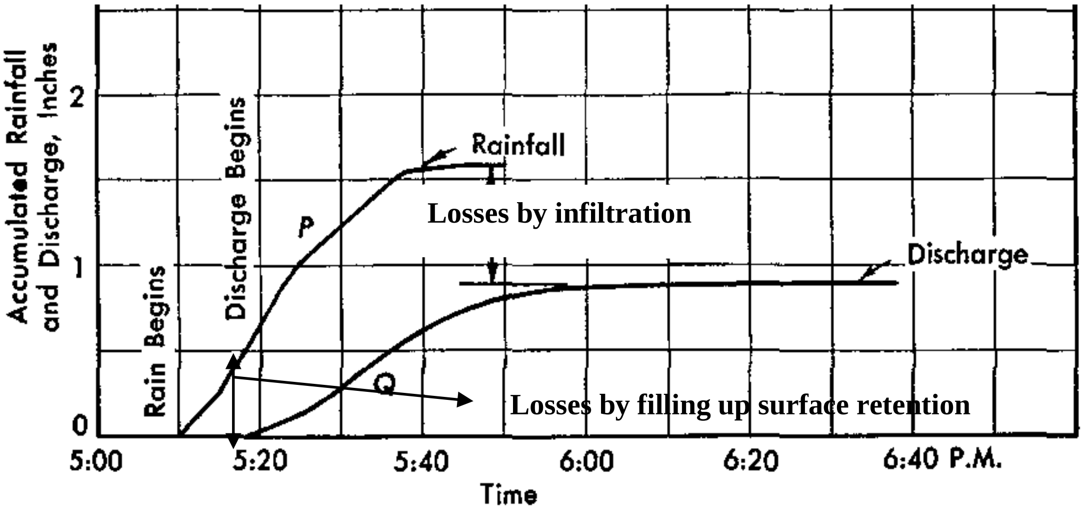


FIG. 2.8: Relationship between cumulative rainfall and discharge plotted against time as well as water losses involved in the process of runoff collection from a bare micro-catchment surface, storm of August 1, 1932 – Hays region (adapted from Foster, 1949)

The graph shows the difference between the total rain and runoff (discharge), which difference constitutes the losses due to filling up surface retention and infiltration on a bare runoff area. It can be seen that there is a lag of time between the inception of the rain and the beginning of the runoff. This is caused by the necessity of saturating the soil surface and filling surface depressions before runoff can begin (Foster, 1949).

Measurements of runoff from micro-plots can either be done under laboratory or field conditions. Laboratory measurements of runoff are not as accurate as those done under field conditions. This is due to the fact that under laboratory conditions, the plots are usually small, which lead to misleading results. In addition, soil sampling disturbs the normal physical characteristics of the site. Furthermore, the measured runoff does not take into consideration the effect of climatic variables of the place where the water harvesting will be implemented (Pan & Shangguan, 2006). One of the most used methods for micro-plots runoff measurement is the collection tank. Its use is cheaper than the other methods, it is simple in design and operation, while data processing is relatively simple and it can measure both, runoff and soil loss. But unfortunately, its use is limited to the determination of total runoff volume and soil loss only, so it is little used in research where detailed information is required on variations with time and soil loss such as pick runoff rate, runoff duration, and sediment concentration (Pathak, 2007). In addition, the accuracy of this technique is low and prone to human error (Bruggeman & Oweis, 1998). Another very popular device for micro-plots runoff measurement is the tipping bucket flow meter. This device has the advantages of measuring both, runoff amount and intensity. However, it is not practical for soil loss measurements (Reinster & Yonge, 2005).

2.2.2 Management of the micro-catchment surface

In the micro-catchment rainwater harvesting systems, runoff area is one of the most important components, since it determines the quantity and quality of water from runoff collection. Many runoff surface treatments have been proposed and tested in arid and semi-arid regions around the world. These surface treatments have different runoff responses on the micro-catchment surface, which consequently affect the required sizes of both, the runoff area and cropping area. These treatments can be grouped as follows: earthen runoff surface treatments, which allow water losses by filling up surface retention and infiltration and artificial runoff surface treatments with opposite effects. Earthen runoff surface treatments include vegetation removal (by hand or herbicide application), mechanical treatments (smoothing and compacting), colloidal dispersion methods (slaking) and hydrophobic applications (water repellents). Artificial runoff surface treatments embrace surface binding materials (cementing and sealing) as well as surface covering (asphalt, rubber and plastic) (Boers, 1997; Bruggeman & Oweis, 1998; Li & Gong, 2002a; Li *et al*., 2004). However, Li *et al*. (2004) state that there is no surface treatment that is suitable for all applications. It depends on local rainfall characteristics (amount, intensity and distribution), construction materials, site conditions, installations methods, and labour costs. Among these treatments, probably only cheaper treatments involving clearing, smoothing and compacting, are economically viable for crop production (Li & Gong, 2002). Besides surface treatments, the management of the micro-catchment surface involves the manipulation of other factors such as: micro-catchment size, ground slope and soil surface depth (Boers, 1997). In the next paragraphs a brief discussion about how to manage these factors in order to get as much runoff as possible, follows. Botha *et al*. (2003) state that soil erosion is not an issue in the In-field rainwater harvesting technique, which is one of the micro-catchment rainwater harvesting systems, because the soil that is washed out with runoff is totally concentrated in the cropping area.

Bruggeman & Oweis (1998) tested the effect of three different surface treatments (compaction – 5 kg/cm^2, sodium chloride – 1.25 kg/m^2 and a simple vegetation removal "natural" as control treatment) on the runoff potential of clay soils in an arid area of northern Syria. Table 2.8 shows the results of average runoff coefficients over five seasons for 4 m wide plots with different lengths, surface treatments, slopes and soil depths. The plots were weeded regularly with herbicides. The same soil type was used for this study. However, for the shallow soil treatment the top soil layer was removed to simulate the proprieties of an eroded soil. The runoff coefficient, also called runoff efficiency, is the ratio of runoff collected from the micro-catchment area to the precipitation falling in the same area.

Table 2.8: Average runoff coefficients of the micro-catchment surfaces with different lengths, runoff surface treatments, slopes and soil depths (Bruggeman & Oweis, 1998)

Soil depth	Slope	Natural			Compacted			Salt		
	%	4*	8	12	4	8	12	4	8	12
Shallow	5	0.11	0.04	0.04	0.17	0.09	0.05	0.34	0.24	0.13
Shallow	10	0.08	0.05	0.02	0.11	0.1	0.03	0.24	0.21	0.15
Deep	5	0.09	0.04	0.02	0.07	0.03	0.02	0.11	0.08	0.06
Deep	10	0.06	0.05	0.02	0.06	0.04	0.02	0.12	0.09	0.06

* Plot length (m)

From Table 2.8, it is obvious that the highest runoff efficiencies were obtained at the salt treated plots on the shallow soil. These runoff efficiencies decreased with an increase on the plots length and slope. The applied sodium chloride caused soil dispersion, resulting in the plugging and sealing of the surface pores by the finer soil particles, which is similar to the effect caused by irrigation with sodic water (Boers, 1997). However, Slatyer (1967) states that sodium chloride has an adverse effect on the quality of water for plant production. Salt causes a reduction in the rate and amount of water that the plant roots can take up from the soil and some of them are even toxic to plants when present in high concentration (FAO, 1985). Although most of the applied salts will stay in the surface layer of the micro-catchment area, some f them will dissolve and pollute the harvested water. The potential storage of the surface layer on shallow soils is lower compared to the deep soils. As a result the runoff efficiencies for the shallow soils are much higher. The runoff coefficients consistently decreased with an increase on the micro-catchment length due to the spatial variability in infiltration rate of the soil and micro-topography. Thus, the longer the plot the more chance the surface runoff has to infiltrate on its way down. Although the smaller catchments are more efficient, they may not yield sufficient amount of runoff needed for agricultural production. Thus, the longer the plots, the higher the probability of getting runoff volumes that meet the crop water requirements. Theorically, an increase in slope decreases the surface storage while increasing the water flow speed and thus reducing the potential for the runoff water to infiltrate (Boers, 1997). However, field experiments that tested runoff efficiencies with varying slopes show that this trend is only evident on slopes up to 5% due to a more even distribution of runoff on the micro-catchment area. On slopes above 5%, the water flow velocity is too high, which breaks the crust formation and, thus allows water to infiltrate. Results from Table 2.8 on shallow soils show that, in general, runoff efficiencies were higher on the 5% slope compared to the 10% slope. The difference was most pronounced for the 4 m long plots (Bruggeman & Oweis, 1998).

From Table 2.8, it is also evident that there was not big difference between the natural and compacted surface treatments in terms of runoff efficiencies. Boers (1997) states that, the main effect of compacted surface treatments is the soil surface retention reduction and the runoff efficiency obtained by using this type of surface treatment is difficult to generalize. It depends on factors such as antecedent soil water content, storm intensity, storm duration, micro-catchment size, and the number of years after treatment. Li & Gong (2002a) found that compaction also plays an important role on the crust formation and, thus causes a reduction in soil infiltration. However, where the soil type is naturally susceptible to crust formation, soil compaction does not make a significant difference in terms of runoff quantities (Barnes, 1971).

Li *et al.* (2004) evaluated six different surface treatments on plots with a 3.3 m width and 6 m length. The study was conducted in an arid area of China, on shallow sandy loam soils. The treatments were as follow: concrete, plastic film, gravel covered plastic film, asphalt fibre glass, cleared loess slope, and a natural loess slope. The layout consisted of three replications for each treatment arranged in a randomized block design. Plastic film treatments were established by covering the compacted soil surface with a 0.08 mm thick plastic film. Compaction was achieved with a roller, by reaching a topsoil bulk density of 1.6 g/cm^3. For gravel covered plastic film surface treatment, the plastic was covered by a layer of pebbles to reduce the light radiation in order to extend the life pan of the plastic film. The natural loess slope treatments were the originally undisturbed loess surfaces characterized by micro-biotic crust and sparse vegetation. The cleared loess slope consisted of removing all plant materials and debris from the soil surface, by hand. Table 2.9 shows the results in terms of monthly and annual runoff for different surface treatments.

Table 2.9: Monthly and annual runoff amounts (mm) and their respective runoff efficiencies (%) (Li *et al.*, 2004)

Treatment	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Annual**
Natural loess	8	2	5	11	0.2	1	28
slope	(15)	(10)	(10)	(11)	(1)	(9)	(11)
Cleared loess	9	2	6	13	0.5	2	33
slope	(17)	(10)	(11)	(14)	(3)	(15)	(13)
Concrete	28	10	23	44	4	8	116
	(51)	(46)	(40)	(48)	(31)	(57)	(46)
Plastic film	46	18	49	28	0.9	0.6	144
	(86)	(82)	(87)	(31)	(7)	(4)	(57)
Gravel-covered			44	50	8	8	111
plastic film	-	-	(79)	(55)	(57)	(60)	(56)
Asphalt fibreglass	43	17	49	55	11	12	188
	(81)	(81)	(88)	(60)	(77)	(85)	(74)

The values in parentheses are the runoff efficiencies calculated as percentage of rainfall

From Table 2.9, it can be seen that runoff was generally higher for all the treatments in the months between May and August, compared to September and October, which is in accordance with rainfall distribution in the study area. Monthly and annual runoff efficiencies for concrete, plastic film, gravel-covered plastic film and asphalt fibreglass surface treatments were higher than for natural loess slope and cleared loess slope surface treatments. This can be explained by the fact that these surface treatments do not allow water infiltration through the soil, which otherwise would considerably reduce the amount of runoff (Foster, 1949). Monthly and annual runoff efficiencies for cleared loess slope surface treatment were higher than for natural loess slope treatment. This is due to vegetation removal from the soil surface in this treatment, which otherwise would increase the water losses by vegetation interception and evaporation as well as the contribution to improved soil infiltration (Slatyer, 1967; Boers, 1997; Li *et al.*, 2000a). From Table 2.9, it is clear that the annual runoff for plastic film was slightly higher than for gravel covered plastic film, which can be explained by the fact that a layer of pebbles on the runoff surface reduces the availability of runoff by trapping and holding water (Li *et al.*, 2000b). However, the monthly runoff efficiencies showed an opposite trend. The runoff efficiencies for plastic film are in general lower than for gravel covered plastic film, and they decrease over time. This can be explained by the fact that plastic film deteriorates by weathering over time, while the gravel cover on the plastic film extends its longevity (Li *et al.*, 2001; Li *et al.*, 2004).

2.2.3 Runoff estimation

This section aims to describe simple empirical models, namely linear regression and runoff curve number, as well as a few parameters conceptual model “the Morin & Cluff’s (1980) runoff model” to study the relationship between rainfall and runoff on micro-plots.

The linear regression model is, in general, expressed as follows (Boers, 1997; Bruggeman & Oweis, 1998):

$$R = 0 \qquad \text{for } P \leq Po$$

Equation 2.1

$$R = c(P - P_o) \qquad \text{for } P > Po$$

Where: R is daily runoff (mm), P is daily rainfall (mm), and c and Po are constants. The constant Po is the rainfall threshold above which runoff occurs (mm), and c is the runoff efficiency after the rainfall threshold has been exceeded.

Daily observed runoff is regressed against daily rainfall to obtain the constants c and P (Asante & Stephenson, 2006). Least squares error (LSE), model efficiency (E_f) and coefficient of determination (R^2) are used to evaluate the agreement between observed and predicted runoff. Least square error and model efficiency are expressed by the following equations (Woodward *et al*., 2003)

$$LSE = \min \sum_{i=1}^{n} (RO_i - RP_i)^2 \qquad \text{Equation 2.2}$$

$$E_f = 1 - \frac{\sum_{i=1}^{n} (RO_i - RP_i)^2}{\sum_{i=1}^{n} \left(RO_i - P\overline{O}\right)^2} \qquad \text{Equation 2.3}$$

Where: RO_i (mm) and RP_i (mm) are respectively the observed and predicted runoff depths for the storm event i, n is the total number of storm events, and $P\overline{O}$ is the average of the total observed storm events.

Li *et al.* (2004) studied the performance of the linear regression model on runoff estimation from a micro-catchment surface, under different runoff surface treatments on shallow sandy loam soils. Runoff amount was linearly correlated to rainfall amount, rainfall intensity and both rainfall amount and intensity. Table 2.10 shows the results of this study.

Table 2.10: Linear regression equations and correlation coefficients between daily runoff amount (mm), rainfall amount (mm) and rainfall intensity (mm/hr), produced under different runoff surface treatments on a micro-catchment surface (Li *et al.*, 2004)

Treatment	Relationship	Equation	r
Natural loess slope	**runoff (R)/ rainfall amount (P)**	R = -0.27 + 0.14 P	0.57
Cleared loess slope		R = -0.43+ 0.19 P	0.6
Concrete		R = -0.46 + 0.60 P	0.83
Plastic film		R = -0.0050 + 0.88 P	0.99
Gravel-covered plastic film		R = -0.30 + 0.66 P	0.81
Asphalt fibreglass		R = -0.28 + 0.85 P	0.99
Natural loess slope	**runoff (R)/ rainfall intensity (I)**	R = -0.43+ 0.12 I	0.91
Cleared loess slope		R = -0.60 + 0.19 I	0.92
Concrete		R = 1.34 + 0.28 I	0.58
Plastic film		R = 4.15 + 0.36 I	0.46
Gravel-covered plastic film		R = 1.33 + 0.36 I	0.61
Asphalt fibreglass		R = 2.57 + 0.29 I	0.57
Natural loess slope	**runoff (R)/ rainfall amount (P)/ rainfall intensity (I)**	R = -0.62 + 0.046 P + 0.12 I	0.93
Cleared loess slope		R = -0.87 +0.068 P + 0.17 I	0.94
Concrete		R = -0.77 + 0.52 P + 0.0072 I	0.86
Plastic film		R = -0.093 + 0.87 P + 0.0094 I	0.99
Gravel-covered plastic film		R = -0.54 + 0.55 P + 0.071 I	0.84
Asphalt fibreglass		R = -0.33 + 0.82 P + 0.0027 I	0.99

From Table 2.10, it can be seen that the correlation coefficient between runoff and rainfall amount for earthen runoff surface treatments was much lower than the correlation coefficient between runoff and rainfall intensity. According to Slatyer (1967), shallow sandy loam soils have a low final infiltration rate, of about 3.8 to 1.27 mm/hr. In this case, the collected amount of runoff is more determined by rainfall intensity rather than rainfall amount, as explained in section 2.1. For artificial runoff surface treatments, where there is no water loss due to infiltration into the soil profile, the correlation coefficient between runoff and rainfall amounts was found to be much higher than between runoff and rainfall intensity. In general, only slight improvements are observed when the runoff is correlated against both, rainfall amount and intensity either for earthen or artificial runoff surface treatments.

Linear models are simple. They are used to estimate runoff from rainfall amounts or rainfall intensities only. However, their applicability is more trustworthy when they are used to estimate runoff from the site where they were parameterized or other sites with similar soil characteristics. The rainfall threshold and runoff coefficient for earthen runoff surface treatments greatly vary in space. This is due to high variability of infiltration rates and surface retention behavior from one place to another.

Bruggeman & Oweis (1998) report on a different approach to estimate runoff from daily rainfall. This method is called runoff curve number and was developed by the United State Soil Conservation Service. The runoff proprieties of the catchment area are represented by the curve number, which is selected from a table, based on land use, soil type, soil moisture, and hydrologic condition of the micro-catchment area. Similar to the linear model, runoff starts after some rainfall has been accumulated. This runoff threshold, referred to as the initial abstractions, which include water losses by plant interception, infiltration, and surface storage, was empirically estimated as 20% of the potential maximum retention (Walker *et al*., 2000).

The original runoff curve number method is given by the following equation (Bruggeman & Oweis, 1998; Huang *et al*., 2006):

$$R = \frac{(P - Ia)^2}{P - Ia + S} \qquad \text{for P> Ia}$$

Equation 2.4

$$R = 0 \qquad \text{for P} \leq \text{Ia}$$

Where: R is the surface runoff (mm); P is the rainfall (mm), S is the potential maximum retention or the maximum possible difference between P and R (mm), and Ia is an initial abstraction or event rainfall required for the initial of runoff (mm).

The relationship between Ia and S was empirically fixed at Ia = 0.2*S. Inserting this value into equation 2.5 gives (Bruggeman & Oweis, 1998; Yulianti & Barbara, 1999):

$$R = \frac{(P - 0.2 * S)^2}{P + 0.8 * S} \qquad \text{for P > 0.2*S}$$

$$R = 0 \qquad \text{for P} \leq 0.2\text{*S}$$

Equation 2.5

The potential maximum retention S in inches is given by the following equation (Bruggeman & Oweis, 1998):

$$S = \frac{1000}{CN} - 10$$

Equation 2.6

Where: CN is the dimensionless curve number, which ranges from zero to 100. The CN value is determined from land cover and management and from the hydrological soil group using a table from the SCN handbook.

The original curve number procedure has the following advantages: (1) it estimates direct runoff depth based on storm rainfall depth, supported by empirical data; (2) it relies on only one parameter, the runoff curve number CN; (3) it is well established method, having been widely accepted for the use in the United States and other countries. However, the following disadvantages have been found: (1) the method was originally developed using regional data, mostly from the Midwestern United States, and has been extended all over the world; (2) For lower rainfall depths, the method may be very sensitive to curve number and antecedent condition; (3) the model was designed for small watersheds of less than 227 ha; (4) the method fixes the initial abstraction ratio at 0.2 (Ponce & Hawkins, 1996). Due to all these disadvantages, this method has been criticized. It has been investigated to establish a logically consistent, experimentally verifiable system. Several traditional aspects of the system are explored. These include conflicting definitions of the antecedent moisture condition and physical significance of the maximum potential retention (Allen & Hjelmfelt., 1991).

Woodward *et al*., (2003) conducted a study to examine the initial abstraction ratio referred to as 0.2 on the original development of the curve number method. In this study, rainfall-runoff data from 307 watersheds or plots were used, covering 23 states, mainly in the East, Midwest, and South of the United State. Two different techniques, namely Event Analysis and Model Fitting, were used to determine the initial abstraction ratio from field data sets. Results from this study indicate that an initial abstraction ratio value of 0.05 gives a better fit to the data and would be more appropriate for use in runoff estimation. Using this ratio the runoff equation becomes:

$$R = \frac{(P - 0.05 * S)^2}{P + 0.95 * S} \qquad \text{for P > 0.05*S}$$

Equation 2.7

$$R = 0 \qquad \text{for P} \leq \text{0.05*S}$$

Using Equation 2.7, the S value is not the same as previously used assuming Ia/S = 0.2. The relationship between the value of $S_{0.05}$ and $S_{0.2}$ is as follows:

$$S_{0.05} = 1.33 * S^{1.15}{}_{0.2}$$

Equation 2.8

Where: $S_{0.05}$ and $S_{0.2}$ are in inches. The value of S in inches should be converted to mm to be used in Equation 3.7. The following conversion can be used: 1 in = 25.4 mm.

The advantage of using an initial abstraction ratio value of 0.05 is the fact that, it allows the calculation of a smaller Ia, giving direct runoff earlier in the event. This is appropriated for areas were the storm rainfall amounts are in general low (Woodward *et al*., 2003).

In the usual procedure, the CN value for each plot runoff event is a function of 5-day antecedent moisture condition II, in addition to fixed catchment characteristics such as land use and soils. However, Allen & Hjelmfelt (1991) as well as Kottegoda *et al.* (2000) point out that the definition of antecedent moisture condition II is not well defined. According to Allen & Hjelmfelt (1991), the Soil Conservation Service gives three definitions for this parameter: (1) antecedent moisture condition II as the average condition of the watershed wetness, while it is not clear if this is to be a quantitative or qualitative definition; (2) antecedent moisture condition II as a median curve number where no association with precipitation is expressed, and; (3) antecedent moisture condition II, which is based on 5-day antecedent rainfall. The same authors state that these three definitions are seldom compatible to each other. Kottegoda *et al.* (2000) suggest that the choice of CN value based on 5-day antecedent moisture condition II is not well defined probably due to diverse storm factors as well as geophysical and changing hydrological conditions, in addition to the varying lengths between rainfall events. These authors state that a better relationship is obtained between CN and the total rainfall of the actual event.

Welderufael (2006) suggests the use of the Morin & Cluff's (1980) runoff model to simulate runoff from micro-catchment surfaces. The Morin & Cluff's (1980) Runoff model is a conceptual model that integrates the Morin & Benyamini's (1977) infiltration equation. The model is given by the Equation 2.9 (Morin & Cluff, 1980):

$$\sum R_i = \sum_{i=1}^{n} \left(I_i * \Delta t_i + S_{i-1} - Id_{\Delta ti} - S_m \right) \qquad \text{Equation 2.9}$$

Where: R_i is the surface runoff during the event i of the rainfall (mm); S_{i-1} is the storage and retention of soil surface water in the previous time event Δt_{i-1} (mm); S_m is the maximum storage and retention of soil surface water (mm); I_i is the rainfall intensity (mm/hr); $Id_{\Delta ti}$ is the total amount of infiltration of rain water into the soil during any time event Δti (mm); Δti is any time event (hr); i is the number of the given periods per rainfall event (i= 1, 2, 3…).

$Id_{\Delta ti}$ is calculated by integrating the infiltration equation "Morin & Benyamini 1977" with time as follows (Morin & Cluff, 1980):

$$Id_{\Delta ti} = I_{tf} * \Delta ti + \frac{(I_{ti} - I_{tf})}{-\gamma * I_i} * [\exp(-\gamma * P_i) - \exp(-\gamma * P_{i-1})] \qquad \text{Equation 2.10}$$

$$P_i = \sum I_i * \Delta ti \qquad \text{Equation 2.11}$$

Where: P_i is the cumulative rainfall over event i (mm); P_{i-1} is the cumulative rainfall in the previous event i-1; It_f and It_i are the final and initial infiltration rates of the soil (mm/hr); γ is the soil factor (mm^{-1}), which is determined by the stability of the soil surface aggregates to the reorientation of soil particles, by the impact of the raindrops to form a crust.

The following parameters can be measured or determined in the field: rainfall intensity, initial and final infiltration rates, rainfall amount and changes in the surface storage and retention. The remaining parameter γ is then fixed by calibration. The values of γ are changed from 0 to 0.9 mm^{-1}. These values are tested in the runoff model and the simulated data is plotted against the measured data. The relationship between measured and predicted runoff data is evaluated using statistical functions to choose the best value of γ (Welderufael, 2006). Walker & Tsubo (2003) state that when some parameters of the Morin & Cluff's (1980) runoff model are not calibrated, they may be assumed by a mere experience of the operator. For example, these authors used the model to estimate runoff from a bare micro-catchment surface at Glen/Bonheim ecotope and assumed an initial infiltration rate of 25 mm/hr, a final infiltration rate of 6 mm/hr, a soil factor of 0.2 mm^{-1} and a maximum surface storage and retention of 0.025 mm. Zere *et al.* (2005) used the same model to estimate runoff from a bare micro-catchment surface at Glen/Tukulu ecotope. These authors explain that the model calibration was carried out repeatedly by changing the model parameters required by equations 3.9 and 3.10. The following initial values were chosen based on the previous experience of runoff measurements at Glen: It_i = 25 mm/hr, It_f = 10 mm/hr, γ = 0.2 mm^{-1} and S_{max}= 10 mm. The model was then run a number of times, each time changing one of the above parameters while keeping the rest constant. The best values were chosen with the aid of statistical functions.

The "Morin and Cluff's 1980" runoff model was found to be very effective in estimating runoff in regions with high rainfall intensities and soils characterized by crust formation (Welderufael, 2006).

2.3 MODELS FOR PREDICTING CROP YIELD AND EVALUATING MICRO-CATCHMENT RAINWATER HARVESTING SYSTEMS

In arid and semi-arid areas, the main constraint for crop production is the water scarcity. The atmospheric demand in these areas is usually lower than the crop water requirements, which results in a decline of crop yield. In order to reverse the situation, farmers have been using rainwater harvesting technologies. These technologies include water conservation methods, which increase the amount of water stored in the soil profile by reducing the proportion of rainfall that runs off the surface, and micro-catchment rainwater harvesting techniques, which increase plant available water by harvesting water from adjacent areas (Mzirai *et al.*, 2002).

Crop models have been developed to assess the benefits of implementing rainwater harvesting technologies, by simulating crop yield under different rainfall patterns and soil conditions. By using these simulation models, constraints related to limited resources to conduct field experiments in different rainy seasons and soil types, are eliminated (Walker & Tsubo, 2003).

2.3.1 PARCHED-THIRST model

PARCHED-THIRST model is a distributed model, which simulates the rainfall-runoff process, soil moisture movement and the growth of sorghum, rice, maize and millet in response to daily climate data. The model includes a climate generator, which can generate longer series of data and fill gaps of missing data using statistical proprieties of other data at the same site or from other climatically similar sites (Mzirai *et al.*, 2002; Young *et al*., 2002).

The runoff component is estimated by inputting rainfall intensity data at intervals of less than one day (typically 5 minutes), rainfall amount and duration on a daily basis. The model includes a rainfall desagregator, which generates 5-min rainfall intensity data by using distribution functions and regression equations (Young *et al*., 2002). Runoff and infiltration are calculated using the “Green and Ampt 1911” infiltration equation. This takes into account the depression storage and the effect of surface sealing. Depression storage is calculated from random roughness, which is modeled over time as a function of cumulative rainfall. Surface sealing is taken into account based on a crust factor, above which the development of a crust with time is ignored (it is usually after 0.5 cm of rain) (Mzirai *et al.*, 2002).

PARCHED-THIRST model incorporates two crop models: PARCH, for the simulation of sorghum, millet and maize, and ORYZA-W, for the simulation of rainfed, lowland rice. The PARCH model simulates crop growth in response to the capture of light, water and nutrients on a daily basis. This model was specifically developed for semi-arid areas. Young *et al*. (2002) and Gowing *et al*. (2003) report on several successful model simulations in semi-arid areas of Tanzania on maize. ORYZA-W model simulates water-limited growth and development of rice (Mzirai *et al.*, 2002).

PARCHED-THIRST model has been seen as a very important planning, research and teaching tool. As a planning tool, it can test various rainwater harvesting and rainfed scenarios and assess the benefits of each of them, and therefore be able to identify the best rainwater harvesting option at any particular place and rainy season. It can also predict crop yield in future years using the climatic generator component. As a research tool, it can test different treatments proposed in a field experiment in order to predict their response to the inputs. In addition, it can extrapolate the results of one or two years field experiments to different weather and soil conditions, different planting densities, as well as different soil-water management practices. As a teaching tool, it can help on rainfall-runoff relationship studies. It can also allow students to play with the program by simulating field experiment scenarios, and take them as real field experiments (Mzirai *et al.*, 2002).

2.3.2 PUTURUN model

PUTURUN model is a simulator for rainfall-runoff-maize yield processes under In-field rainwater harvesting technique, which has been implemented in semi-arid areas around Bloemfontein, South Africa. The model includes a rainfall intensity generator, which uses the “Woolhiser and Osborn 1985” type model. This rainfall intensity generator takes into account the total amount and duration of event rainfall, the fraction of the cumulative event amount at a given time from the starting time of rain 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).

The runoff component of the PUTURUN model is deterministically estimated using the “Morin and Cluff 1980” model, already describe in the subsection 2.2.3 (Morin & Cluff, 1980; Walker & Tsubo, 2003). The model also incorporates empirical rainfall-runoff models, as well as the area under the rainfall intensity curve model to estimate runoff.

PUTURUN model includes the PUTU Crop Growth model to predict yield of different maize cultivars. The model was developed under South African semi-arid conditions and proved to be efficient in simulating crop yields (Walker & Tsubo, 2003).

CHAPTER 3

RAINWATER HARVESTING TRIAL

3.1 OBJECTIVES AND HYPOTHESIS

A field trial was carried out during the crop growing season 2007/2008 at the Hatfield Experimental Farm of the University of Pretoria on sandy clay loam soils with the following objectives:

- To study the effect of different rainwater harvesting techniques namely, conventional tillage, tied ridge and in-field rainwater harvesting on growth and yield components of maize;
- To test the impact of using increased design ratios (cropping area: runoff area) of the in-field rainwater harvesting technique (IRWH) combined with different surface runoff area treatments (bare and plastic cover) on growth and yield components of maize;
- To determine maize specific growth parameters in order to calibrate the Soil Water Balance model (SWB).

The following hypothesis was formulated with the intension of being tested by field observations on the rainwater harvesting trial:

- If it is a dry season, crop yield will be maximized with the use of bigger design ratios of the IRWH technique with a plastic cover runoff area, while if it is a wet season smaller design ratios of the IRWH or even simpler rainwater harvesting strategies such as the tied ridge and the conventional tillage techniques can harvest sufficient rainfall for maximum crop production.

3.2 MATERIALS AND METHODS

3.2.1 Description of the study site

The study was conducted during the 2007/2008 rainy season at the Hatfield Experimental Farm of the University of Pretoria, South Africa, located at latitude of 25°45' S and longitude of 28°16' E. The climate of the region is semi-arid, with an average rainfall of 670 mm, falling mainly between October and March (Annandale *et al.*, 1999). The rainfall occurs as high intensity, short duration events, with sunny periods between rains. Mean maximum and minimum temperatures are 30 (January) and 1.5 °C (July), respectively. The soil macronutrient levels were as follows: 25 mg/kg phosphorus, 350 mg/kg calcium, 20 mg/kg potassium and 65 mg/kg magnesium. The slope of the area varies between 0.5 and 2%. Soil depth is generally more than 1.2 m (Annandale *et al.*, 2002). The soil pH in H_2O and in KCl is on average 6.1 and 5.8, respectively. The soil has a sandy clay loam texture. Table 3.1 gives details of the soil texture and organic matter content of the soil profile.

Table 3.1: Soil texture and carbon content along 1 m deep soil profile at the study area, Hatfield Experimental Farm

Soil depth (cm)	Soil physical characteristics classified as a Hulton form			Carbon content (%)
	Sand (%)	Silt (%)	Clay (%)	
0-10	67	9	24	0.65
10-20	67	9	24	0.65
20-40	53	16	31	0.58
40-60	51	15	35	0.55
60-80	46	17	37	0.60
80-100	62	17	20	0.35

Soil texture and pH, as well as carbon content of the study area were determined by the Soil Laboratory in the Department of Plant Production and Soil Science (University of Pretoria).

3.2.2 System construction

Three techniques were considered: conventional tillage (CT, treatment control), tied ridges (TR) and in-field rainwater harvesting (IRWH). For the IRWH technique, three design ratios (cropping area: runoff area) combined with two runoff surface treatments were tested. The selected design ratios were as follows: 1:1, 1:2, and 1:3. Runoff surface treatments were plastic cover and vegetation removal (bare runoff area). Rainwater harvesting system construction and treatments assignment followed the subsequent steps:

1) The field was divided into three strips across the land slope. These strips corresponded to blocks 1, 2 and 3 in the completely randomized block design. For this purpose as well as for land leveling, the same grader that was previously used to level the land for runoff plot construction was employed. Each strip of land was six metres in width and 50 m in length. A space of three metres was left between the strips to facilitate cultural operations. The grader leveled the first, second and third strip into slopes of 3, 2 and 1%, respectively.
2) Further, each strip of land was divided into eight plots along the slope. Plots were five metres long and one metre apart from each other. Borders were constructed around the plots.
3) The soil was cultivated twice, using a moldboard plough and disk. Cultivation depth was approximately 20 to 30 cm.
4) The soil was then rotovated, using a tractor mounted rotovator.
5) Two ton/ha of lime was manually applied and incorporated into the soil.
6) The rotovator was once again used to ensure better incorporation of the lime into the soil.

7) The IRWH system was constructed. The runoff areas for all IRWH treatments were created manually by increasing the land slope up to 6%. This was done to ensure that all runoff areas had homogeneous land slope and runoff surface characteristics. The slope of the cropping areas of the IRWH treatments remained constant at 3, 2 and 1% for blocks 1, 2 and 3, respectively. These slopes of the cropping areas of the IRWH treatments were the same as the ones for the CT and TR techniques in the different blocks. A thick black plastic sheet was used to cover the runoff areas of the plastic runoff surface treatment plots. The excavated soil from the runoff areas was moved downwards and concentrated just below the runoff areas, forming a ridge of about 30 cm in height. These ridges formed the cropping areas. On both sides of the ridge, earthen borders were constructed to avoid water losses by runoff. In front of the ridge, small cross-ridges were made to ensure better distribution of runoff along the cropping area. Each design ratio of the IRWH system was replicated in order to make a field border, as well as to fill the plot area. Figure 3.1 illustrates the design of the IRWH technique. All treatments of the IRWH technique had the same size of cropping area (five metres wide and one metre long). The runoff areas for the different IRWH treatments were also five metres wide, but had different lengths (1, 2 and 3 m) and surface treatments (vegetation removed, “bare surface”, or plastic cover). Therefore, the design ratios (cropping area: runoff area) were as follows: 1:1, 1:2 and 1:3.

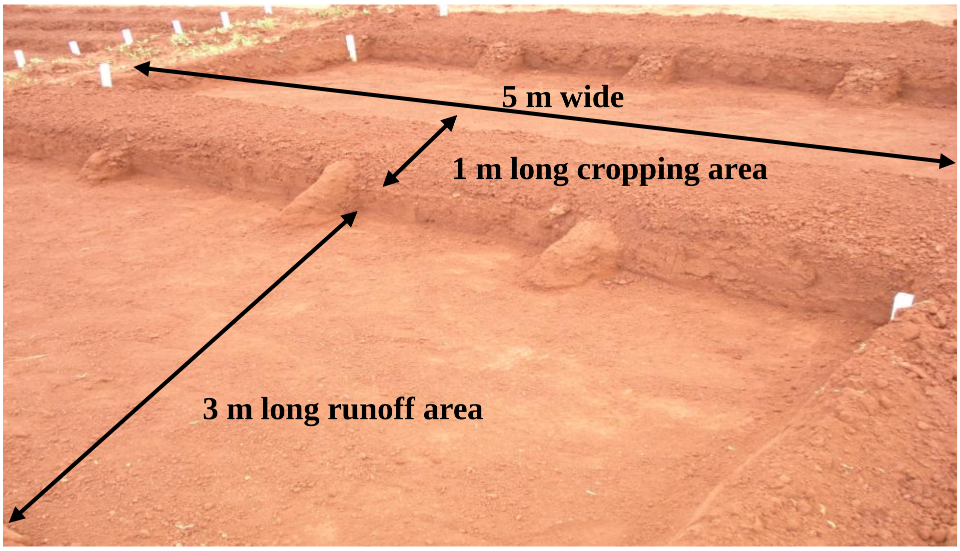


FIG. 3.1: Field layout of the 1:3 design ratio of the IRWH technique with a bare runoff area, Hatfield Experimental Farm

8) The tied ridge system was constructed by alternating ridges and furrows across the land slope. Ridges were constructed at about 50 cm apart from each other, with 15 cm in height. Small earthen ties were made along furrows at about one metre apart from each other to ensure even storage of runoff water. Planting was done on the top of the ridges to minimize water-logging problems in the case of being a wet rainfall season. Figure 3.2 illustrates a plot of this system.

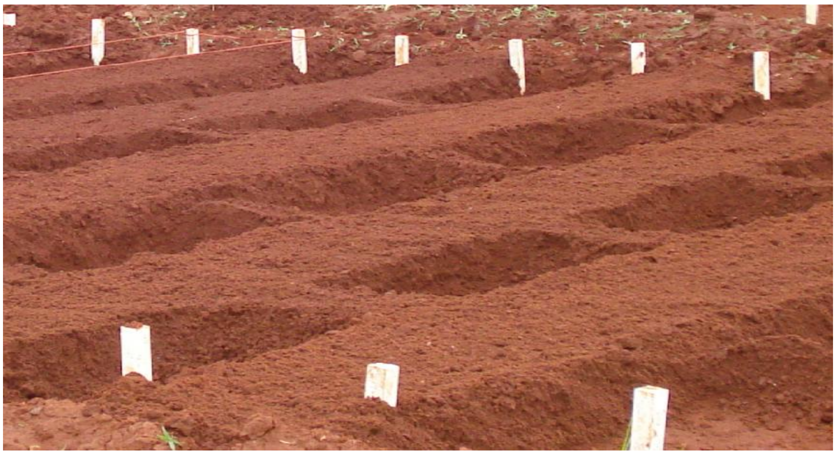


FIG. 3.2: Field layout of the tied ridges technique, Hatfield Experimental Farm

9) The conventional tillage technique (treatment control) simply involved the use of plowing and several diskings to prepare the soil for planting. Figure 3.3 illustrates a plot of the conventional tillage technique.

FIG. 3.3: Conventional tillage technique, Hatfield Experimental Farm

The general layout of the experiment was a randomized block design with eight treatments and three replications. The treatments were as follows:

(1) Conventional tillage (CT, treatment control);
(2) Tied ridges (TR);
(3) A design ratio of 1:1 (**1 m x 5 m cropping area: 1 m x 5 m runoff area**) of the infield rainwater harvesting technique, with a bare runoff area (1:1B);
(4) A design ratio of 1:2 (**1 m x 5 m cropping area: 2 m x 5 m runoff area**) of the infield rainwater harvesting technique, with a bare runoff area (1:2B);
(5) A design ratio of 1:3 (**1 m x 5 m cropping area: 3 m x 5 m runoff area**) of the infield rainwater harvesting technique, with a bare runoff area (1:3B);
(6) A design ratio of 1:1 (**1 m x 5 m cropping area: 1 m x 5 m runoff area**) of the infield rainwater harvesting technique, with a plastic covered runoff area (1:1P);
(7) A design ratio of 1:2 (**1 m x 5 m cropping area: 2 m x 5 m runoff area**) of the infield rainwater harvesting technique, with a plastic covered runoff area (1:2P);

(8) A design ratio of 1:3 (**1 m x 5 m cropping area: 3 m x 5 m runoff area**) in the infield rainwater harvesting technique, with a plastic covered runoff area (1:3P).

All experimental plots had a size of 5 m x 6 m. In the in-field rainwater harvesting technique, the choice of the cropping area size was considered to be arbitrary, since the crop canopy and root system might have expanded beyond the actual cropping area to intercept solar radiation, extract water and nutrients from the surrounding area. Based on that, the cropping area size of the in-field rainwater harvesting technique was assumed to be 1.4 m long (since there were two rows of crop and the spacing between them was 0.7 m) and five metres wide. Although the size of the cropping area was assumed to be bigger than its actual size, it does not reduce the size of the runoff area because it still collects the same amount of runoff as determined by its actual size. The trial experimental layout can be seen in Appendix 3.1.

3.2.3 Routine agronomic practices

The cropping areas of the IRWH treatments were five metres wide and one metre long. Within this cropping area of 5 m^2 two rows of crops were planted at a spacing of 70 cm between rows and 25 cm between plants. In the CT and TR techniques, within the same area of 5 m^2, only one crop row was planted at a spacing of 25 cm between plants. Crop rows were 100 cm apart for the CT and TR techniques. Therefore, plant population on a total area basis (including the space occupied by the runoff area in the IRWH technique) was 40 000 plants per hectare for the CT, TR and 1:1 design ratio of the IRWH technique. For the 1:2 and 1:3 design ratios of the IRWH technique, plant population on a total area basis was lower (26 667 and 20 000 plants per hectare, respectively) due to the bigger runoff area sizes (10 and 15 m^2, respectively). However, plant population on a cropping area basis (excluding the space occupied by the runoff areas) was the same for all IRWH treatments (57 143 plants per hectare). Figure 3.4 illustrates plant arrangement configuration in the different techniques tested at the study site.

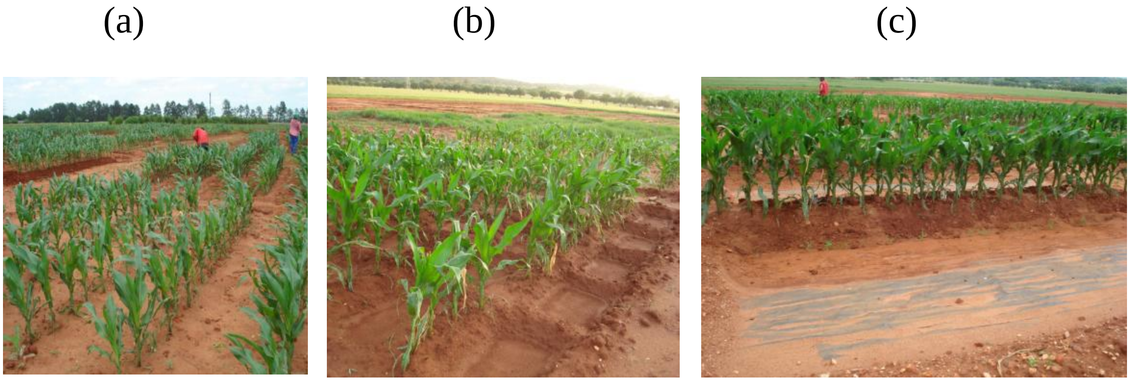


FIG. 3.4: Maize, six weeks after planting, under conventional tillage system (a), tied ridges system (b), and a 1:3 design ratio of the in-field rainwater harvesting system, with a plastic cover runoff area (c), Hatfield Experimental Farm

A Pioneer maize hybrid variety (Phb 3442) was planted on the 3rd November 2007. Planting was done with a manual planter at a depth of around 10 cm, placing two seeds per hole. Before planting, a 2:3:4 fertilizer (6.7% N: 10% P: 13.3% K, respectively) was applied in the cropping areas at a rate of 7.5 g per plant for all the different treatments. This is equivalent to 20 of kg ha^{-1} of N, 30 kg ha^{-1} P and 40 kg ha^{-1} K for the CT and TR treatments. Although the IRWH treatments received proportionally less fertilizer per hectare, depending on the runoff area size, it should be emphasized that every plant received the same amount of fertilizer in order to ensure that nutrients were not limiting for any treatment. The fertilizer was incorporated into the soil using a tractor mounted rotovator in the TR and CT techniques and a hand controlled rotovator in the RWH plots.

The field was irrigated for one hour right after planting to ensure good germination and to incorporate the broadcast fertilizer. The application rate of the sprinkler system was on average eight millimeters per hour. A second sprinkler irrigation (of the same intensity and amount) was applied about one week later to ensure a good crop stand.

Immediately after planting, the plots were protected with bird netting until about three weeks after emergence. At the beginning of the trial weeds were controlled by the following herbicides: 2,4-D (2,4-Dichlorophenoxyacetic Acid), applied just before planting and Banweed applied one week after planting to control annual broad leaf weeds at a rate of 50 ml of active ingredient per five litres of water per 100 m^2 of land, in both cases**.** Later in the season, weeds were controlled by hand. In the cropping areas of the in-field rainwater harvesting and conventional tillage techniques, hand hoes were used. In the runoff areas of the in-field rainwater harvesting technique and cropping areas of the tied ridges technique, weeds were pulled out by hand to minimize soil disturbance. LAN (Lime-ammonium-nitrate) fertilizer (28% nitrogen) was applied twice after planting. The first application was done one week after planting at a rate of 3.75 g per plant (42 kg ha^{-1} for CT and TR) and the second application was conducted four weeks after planting at a rate of 5.5 g per plant (62 kg ha^{-1} for CT and TR).

The following pests and diseases were controlled using the subsequent pesticides and physical measures:

- Cut worms were controlled by spraying cypermethrin directly onto the soil surface at a rate of 0.175 ℓ of active ingredient per 500 ℓ of water per hectare. The first application was made one week after planting and the second application three weeks after planting.
- Aphids were controlled by one application of mercaptothion eight weeks after planting. It was applied at a dosage of 150 ml of active ingredient per 100 ℓ of water per hectare.
- Common rust was controlled by one application of Ammistar Top 12 weeks after planting. It was sprayed at a dosage of 500 ml of active ingredient per hectare in 10 ℓ of water.
- Cobs were protected from damage using nets from the 12th week after planting up to the end of the trial.

3.2.4 Data collection, analysis and interpretation

Soil water content readings of five different soil layers (0 to 20 cm, 20 to 40 cm, 40 to 60 cm, 60 to 80 cm and 80 to 100 cm) were taken at least three times a week during the trial season using a neutron probe. This device was calibrated at the trial site for each individual soil layer to convert the count rate ratios (the ratio between counts in soil and standard count) into volumetric soil water content. For this purpose, wet and dry site neutron probe readings were determined with their corresponding volumetric water contents so as to get the best fit regression equations for each soil layer. Calibration results are presented in Appendix 3.2. At the wet spot, neutron probe readings were taken at about 48 hours after saturation of the soil profile, which have been termed according to many authors as the soil water content at field capacity. In the conventional tillage and tied ridge techniques, one aluminum access tube was installed in the middle of each experimental plot. This was done by making a hole into the soil of which the diameter was slightly smaller than that of the tube, using an auger. For the in-field rainwater harvesting technique plots, three access tubes were installed per cropping area (top, middle and end of the ridge) and the reading was taken as the average of the three access tubes. This was done because the slope of the runoff area was not completely uniform due to the fact that they were made manually, which could result in uneven distribution of runoff in the cropping area (see Figure 3.5c). In the IRWH technique one access tube was also installed in the middle of the runoff areas of the neighboring design ratios to monitor the amount of water lost through infiltration in the first 10 cm top soil layer during a rainfall event. This was done to avoid soil disturbance (due to the presence of the access tube and walking) in the monitored runoff area. Figure 3.5 illustrates the position of the neutron probe access tubes in the cropping area of the different techniques.

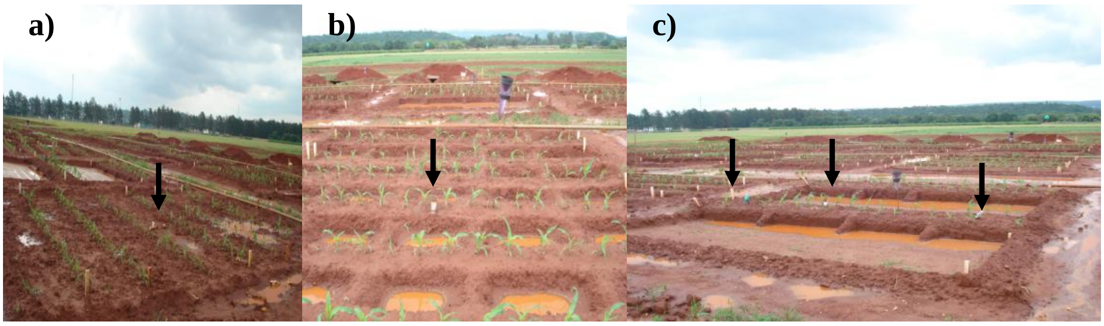


FIG. 3.5: Position of neutron probe access tubes installed in the cropping area of the CT plot (a), TR plot (b) and 1:2 design ratio of IRWH plot, with a bare runoff area (c), Hatfield Experimental Farm

Plant height was monitored from the fourth week after planting until the end of reproductive stage, using a measuring tape. For this purpose, six plants per experimental plot were randomly selected and marked with a rope. Plant height measurements were done using the same sample of plants per experimental plot. Plant height was considered as the height of the plant from the soil surface to the longest tip of a leaf when the plant is stretched up.

Leaf area index and interception of photosynthetic active radiation were measured in the three main crop growth stages, namely: vegetative, reproductive and ripening stages. The measurements were made using a light interception device (ceptometer, Decagon Devices Inc., model PAR-80), which is a non destructive method. Measurements were taken at a particular point (at the middle of the cropping area) by placing the probe above and below the canopy. Ten readings were taken in each position of the probe (above and below the canopy). After that this was averaged and taken as the final reading. Readings were taken at around midday or days when the sky was clear from clouds. Canopy extinction coefficients for photosynthetic active radiation (K_{PAR}) were then calculated using measured values of leaf area index (LAI) and fractional interception of photosynthetic active radiation (FI) for three different maize phenological stages under different rainwater harvesting treatments. K_{PAR} values were thereafter converted to canopy extinction coefficients for solar radiation (K_s). This calculation was done using the equations below (Annandale *et al.*, 1999 after Campbell and van Evert, 1994):

$$FI = 1 - e^{-K_{PAR}\,LAI} \qquad \text{Equation 3.1}$$

Which is equivalent to:

$$K_{PAR} = \frac{-\ln(1 - FI)}{LAI} \qquad \text{Equation 3.2}$$

$$K_s = K_{PAR}\sqrt[4]{a_n \frac{1}{a_p}} \qquad \text{Equation 3.3}$$

Leaf coefficients a_n and a_p were assumed to be 0.12 and 0.88, respectively.

Maize cobs were harvested manually between 26 and 28 March 2008, harvesting one block per day. The crop was harvested when the grain moisture content was 8%. Before harvest, a grain moisture test was conducted by randomly selecting two plants per block. The grain was weighed to determine the fresh weight and then dried in an oven at 65 ^{o}C for 72 hours. The grain was then re-weighed to determine the dry weight and the percentage of moisture in the grain. A sample of 10 plants per experimental plot was randomly chosen and harvested for final determination of crop yield and top dry matter. The number of plants per sample was limited by the number of plants per cropping area of the IRWH treatments (there were only 40 plants). Harvestable crop yield and total top dry matter were then measured per plant using a scale and averaged to get yield and total top dry matter per plant per experimental plot and per treatment. This was subsequently multiplied by the planting density to get the crop yield and total top dry matter per hectare. Harvest index was taken as the ratio between dry grain yield and total above ground dry matter yield per plant, and was expressed as a percentage. The number of seeds per cob per plant was determined using a seed counter. The number of rows per cob per plant was manually counted. The average mass per kernel per plant was taken as the ratio between the total grain mass per plant and the total number of seeds per plant. A 2.34 litre container was used to determine the hectolitre mass (the mass of a 100 litre container filled up with seeds) by conversion.

Different weather variables such as maximum and minimum temperatures, solar radiation, wind speed, relative humidity and rainfall were measured on an hourly and daily basis by an automatic weather station located approximately 20 m from the field trials site. Vapour pressure-corrected dry matter/water ratio (DWR) in Pa, which is a crop specific parameter determining water use efficiency, was then calculated for the pioneer maize hybrid variety (Phb 3442) following the subsequent equation (Annandale *et al*., 1999):

$$DWR = \frac{DM * VPD}{ET} \qquad \text{Equation 3.4}$$

Where: DM is total dry matter measured at harvest in kg/m^2; VPD represents seasonal average vapour pressure deficit in Pa and ET is seasonal crop evapotranspiration in mm which is equivalent to kg/m^2. In this study, DM was taken as an average of total top dry matter for the different rainwater harvesting treatments, excluding root dry matter because it was not measured. Therefore, the DWR value calculated with the Equation 3.4 should be seen as the lower limit. ET was calculated on a daily basis using Equation 3.5 and accumulated for the season.

$$ET = K_C * ETo \qquad \text{Equation 3.5}$$

Daily grass reference evapotranspiration (ETo) was calculated using the Penman Monteith method. Daily maize crop coefficient values (Kc) were calculated using the third order polynomial function (Equation 3.6) derived by Piccini *et al*. (2009) for the semi-arid region of Wintergarden Texas.

$$K_C = 0.36 - 8.89*10^{-3} DAP + 4.02*10^{-4} DAP^2 - 2.42*10^{-6} DAP^3 \qquad \text{Equation 3.6}$$

Where: DAP is the number of days after planting.

Radiation conversion efficiency (Ec), which is a crop specific parameter used to simulate dry matter production under conditions of radiation-limited growth was calculated for the pioneer maize hybrid variety (Phb 3442) based on observed values of fractional interception of photosynthetic active radiation (FI), total dry matter (DM) and solar radiation (Rs) for the crop growing season 2007/2008 as described by equation 3.7 (Annandale *et al*., 1999):

$$E_c = \frac{DM}{FI * R_s} \qquad \text{Equation 3.7}$$

The Ec value calculated with the Equation 3.7 was an average value for the conventional tillage and tied ridge technique, since for these techniques the same row spacing (100 cm) and planting densities on a total area basis (40 000 plants per hectare) were used. Equation 3.7, similarly to equation 3.4, it does not include root dry matter in the total dry matter. As a result, this calculated Ec value also represents a lower limit of radiation conversion efficiency.

Crop yield, yield components and growth analysis was done with the aid of SAS (Statistical Analysis System). Before statistical analysis, the data was submitted to normality tests to check weather the assumptions of analysis of variance were satisfied or not. In case of not being satisfied, the data was transformed to get normal data. LSD test (least significant difference test) for significant differences between treatments at the five percent significance level was used. Tables showing results of analysis of variance and significance testes are presented in Appendix 3.4.

3.3 RESULTS AND DISCUSSION

3.3.1 Soil water content of the root zone

Soil profile water contents were measured up to one metre depth during the maize growing season 2007/2008 for comparison of treatment effects on water use in the cropping area. The results are shown in Figure 3.6 for all the water harvesting treatments tested, namely conventional tillage (CT), tied ridge (TR), in-field rainwater harvesting with runoff areas covered with plastic (P) and in-field rainwater harvesting with bare runoff area (B), both cases with various design ratios cropping area: runoff area (1:1, 1:2 and 1:3).

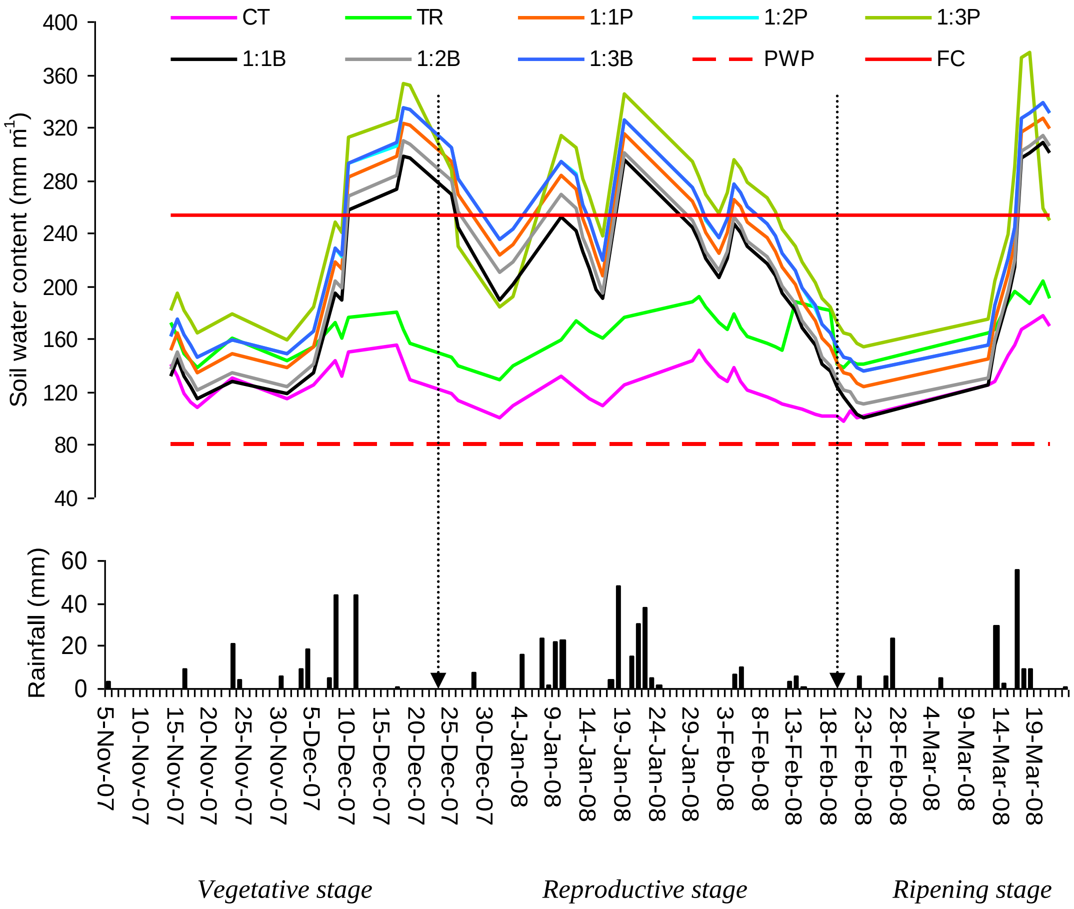


FIG. 3.6: Changes in the soil water content of the maize root zone during the rainy season 2007/2008 for different water harvesting treatments, Hatfield Experimental Farm

As can be observed from Figure 3.6, changes in soil water content during the maize growing season followed, in general, the same trend as the rainfall pattern. During wet periods (with consecutive rainfall events of bigger magnitude) it can be observed from Figure 3.6 an increase on the soil water content for all rainwater harvesting treatments. This increase on the soil water content is more pronounced for the in-field rainwater harvesting treatments. The reason for that is the fact that, in the in-field rainwater harvesting technique a part from the rain that falls in the cropping area, the system also collects runoff from the runoff areas, which is added to the cropping areas, contributing to an increase on the root zone plant available water. The sandy clay loam soils of the Hatfield Experimental Farm are characterized by high levels of surface crust, which considerably reduces soil infiltration and, thus increases runoff collection. In addition, the system is designed in such a way that no runoff losses or minimum runoff losses occur in the cropping area. It suggests that high percolation losses below the root zone accompanied with nutrient leaching might have occurred in the in-field rainwater harvesting treatments, especially during high rainfall periods. From Figure 3.6 it is evident that soil water content in the tied ridge technique is higher than the conventional tillage technique and lower than the in-field rainwater harvesting technique. The tied ridge technique is part of an *in-situ* rainwater harvesting technology, involves the use of methods 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; SIWI, 2001). In the case of the tied ridge technique, it consists of alternate ridges and furrows, with small cross-ties of 15 cm high and 50 cm long above furrows every 100 cm intervals to ensure full rainwater harvesting and even storage of runoff. Therefore, minimum or no runoff losses are expected to occur with the use of this technique. In the conventional tillage technique, part of the rainfall is harvested by conducting several mechanical operations to prepare the soil for planting, which reduces surface runoff by providing soil surface roughness. However, part of the rain that falls in the cropping area might be lost as runoff, contributing to a decrease on the soil water content levels, as illustrated in Figure 3.6. It can be seen from Figure 3.6 that, during reproductive stage (one of the most critical stages in terms of water needs on maize growth), the highest levels of soil water content were registered in the in-field rainwater technique. The lowest levels of soil water content were registered with the tied ridges, followed by the conventional tillage technique. This is one of the reasons why the lowest observed crop yield was obtained with the conventional tillage technique (7.7 ton/ha), which was not significantly lower than 9.4 ton/ha obtained with the tied ridge technique. The highest crop yields on a cropping area basis were obtained with the different in-field rainwater harvesting design rations (varying from 13.4 to 17 ton/ha), and they were significantly different from the crop yields obtained with the conventional tillage and tied ridge techniques as illustrated in Table 3.3.

3.3.2 Photosynthetic active radiation and leaf area index

Interception of photosynthetic active radiation (interception of PAR) and leaf area index (LAI) were measured once in the vegetative (six weeks after planting), reproductive (12 weeks after planting) and ripening (17 weeks after planting) for all the water harvesting treatments. Results of these measurements are illustrated in Figure 3.7 for all the water harvesting treatments.

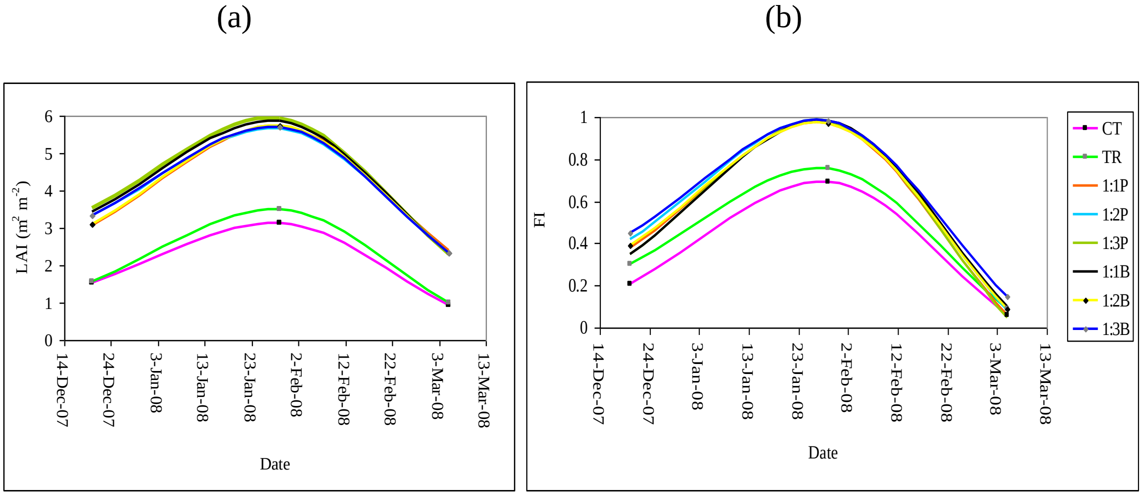


FIG. 3.7: Leaf area index (a) and fractional interception of photosynthetic active radiation (b) of maize during the growing season 2007/2008 for different water harvesting treatments, Hatfield Experimental Farm

Figure 3.7 shows changes on leaf area index and fractional interception of PAR on maize over time. The highest values of leaf area index and fractional interception of photosynthetic active radiation were obtained with the in-field rainwater harvesting technique, and the lowest with tied ridges and conventional tillage techniques. The difference might be attributed to the differences in spacing between two rows of crop. A row spacing of 70 cm was used in the in-field rainwater harvesting technique, while 100 cm row spacing was used for the conventional tillage and tied ridge techniques. In all the different techniques, the distance between plants was kept at 25 cm. Therefore, on a cropping area basis (excluding the space occupied by the runoff areas), a planting density of 40 000 plants per hectare was used for the conventional tillage and tied ridge techniques (4 plants per m^2), while for the in-field rainwater harvesting technique it was kept at 57 143 plants per hectare (6 plants per m^2). Sangoi & Salvador (1997) found out that increased planting densities results in an increase of leaf area index and consequently water consumption. As a result, increased planting densities should be accompanied with increased water supply in order to minimize crop water stress. From Figure 3.3, it can be seen that, soil water content for the different in-field rainwater harvesting designs is, in general, higher than for the tied ridge and conventional tillage techniques. As mentioned in Section 3.3.1, the amount of water supplied to the cropping area in the in-field rainwater harvesting technique (rainfall plus runoff from the runoff areas) is higher than the amount of water supplied to the cropping area of tied ridge and conventional tillage techniques (only rainfall). In addition, the in-field rainwater harvesting technique is designed in such a way that minimum or no runoff losses in the cropping area are expected, which contributes to increased plant available water in the root zone. So, the use of higher planting densities in the in-field rainwater harvesting technique was accompanied by the existence of higher levels of profile soil water content, which significantly increased final grain yield on a cropping area basis (see Table 3.3). Figure 3.8 illustrates statistical results of leaf area index at final reproductive stage for all the rainwater harvesting treatments considered in the present study.

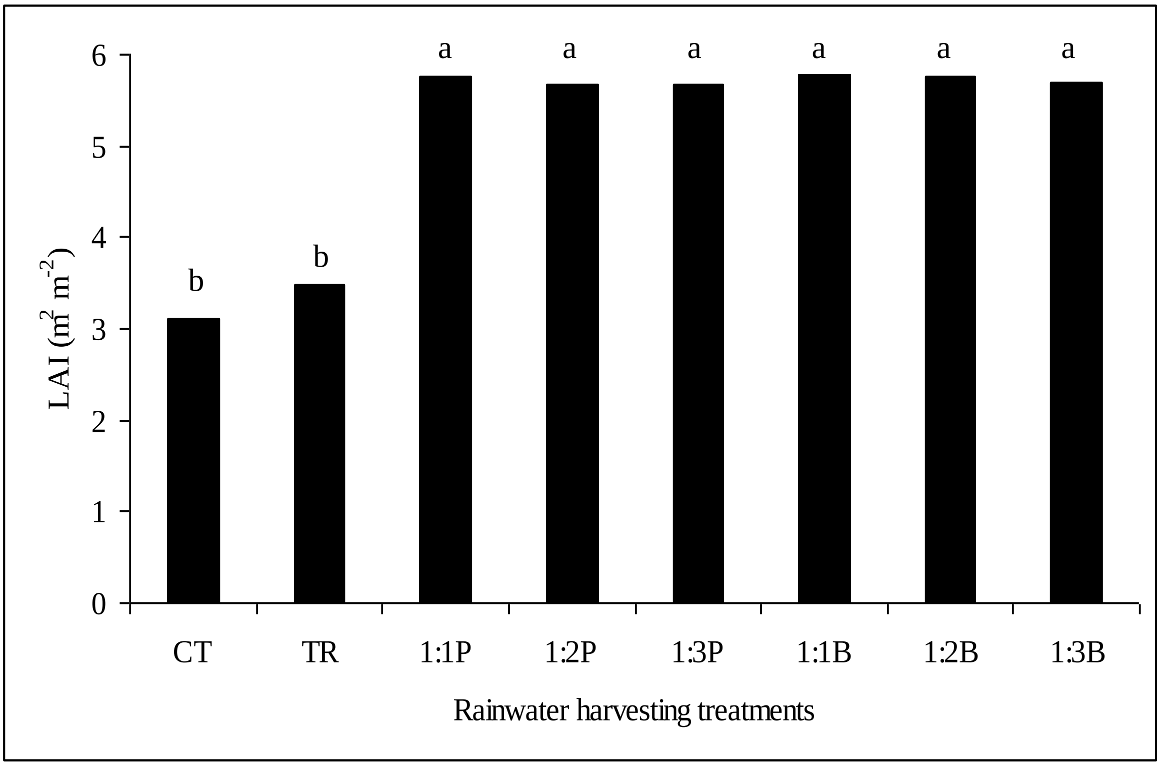


FIG. 3.8: Statistical results of leaf area index (LAI) over cropped area at final reproductive stage for different rainwater harvesting treatments (LSD at P=0.05, means with the same letter are not significantly different), Hatfield Experimental Farm

From Figure 3.8, it can be seen that, under in-field rainwater harvesting technique leaf area index values at final reproductive stage were significantly higher than leaf area index values under tied ridge and conventional tillage techniques. This is explained by the use of different planting densities and different amounts of water supplied to the cropping area as mentioned in Section 3.3.1. Bavec & Bavec (2002) also report on significant increase on leaf area index values at maize reproductive stage by increasing planting densities (leaf area index was on average 2.1 using a planting density of 4.5 plants per m^2, which was significantly lower than leaf area index of four using a planting density of nine plants per m^2). The same authors also report on significant increase on maize grain yield with increased leaf area index values at reproductive stage, which is in accordance with the findings from this study. On a cropping area basis, maize grain yield under in-field rain water harvesting technique was significantly higher than the grain yield under conventional tillage and tied ridge techniques.

Since the same row spacing (100 cm) was used for the conventional tillage and tied ridge techniques, leaf area index values observed during the growing season 2007/2008 with the use of these two techniques were plotted against their respective values of fractional interception of photosynthetic active radiation subtracted from one, and an exponential function was obtained from this relationship. In the in-field rainwater harvesting technique a row spacing of 70 cm was used in the different design ratios. Therefore, observed leaf area index values during the growing season 2007/2008 for the different design ratios of the in-field rainwater harvesting technique were regressed against their respective values of fractional interception of radiation subtracted from one, and an exponential function was also obtained. Figure 3.9 illustrates exponential regression functions for the conventional tillage, tied ridge as well as in-field rainwater harvesting techniques. The same figure presents canopy extinction coefficient for fractional interception of photosynthetic active radiation (K_{PAR}) and solar radiation (K_S) for the two different spacing of rows (70 and 100 cm) tested in the field trials.

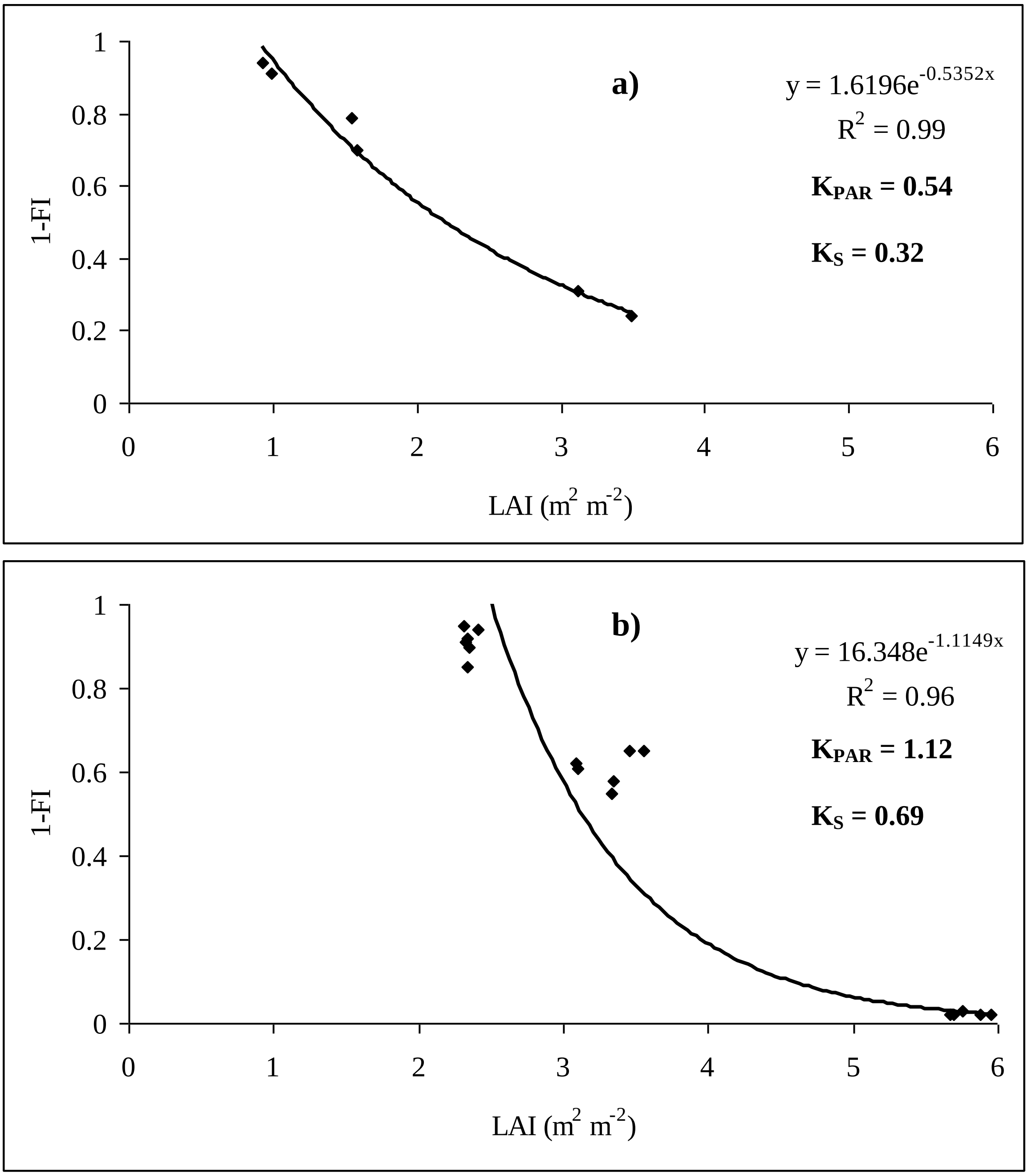


FIG. 3.9: Maize Canopy extinction coefficients for fractional interception of photosynthetic active radiation (K_{PAR}) and solar radiation (K_S) for conventional tillage and tied ridge techniques (a) and in-field rainwater harvesting (b), Hatfield Experimental Farm

As evident in Figure 3.9, maize canopy extinction coefficient for solar radiation under in-field rainwater harvesting technique with the use of 70 cm row spacing is higher than under conventional tillage and tied ridge techniques with the use of 100 cm row spacing (0.69 and 0.33, respectively). Riahinia & Dehdashti (2008) conducted a study to evaluate the effect of row spacing on maize canopy extinction coefficients. They observed a linear decrease of extinction coefficients as row spacing increases. For a row spacing of 65 cm, an extinction coefficient of about 0.45 was obtained, while for a row spacing of 100 cm, it was about 0.38. They concluded that, as row spacing decreases a greater light interception efficiency is verified. This could probably be the result of a more even distribution of plants and hence of the foliage. Drouet & Kiniry (2008) also conclude that narrow row spacing consistently had less transmitted light and greater values of extinction coefficient using the light model RIRI.

3.3.3 Vapour pressure-corrected dry matter/water ratio

Vapour pressure-corrected dry matter/water ratio (DWR), which is crop specific parameter determining water use efficiency was calculated as average for all rainwater harvesting treatments as presented in Table 3.2. In the same table are also illustrated average total top dry matter for all rainwater harvesting treatments (DM), as well as seasonal values of vapour pressure deficit (VPD) and crop evapotranspiration (ET) used for computing DWR.

Table 3.2: Calculated vapour pressure-corrected dry matter for the pioneer maize hybrid variety (Phb 3442) during the growing season 2007/2008 and the variables involved on its calculation

Variable	Variable value
DWR (Pa)	7.5
DM (kg/m^2)	2.4
VPD (Pa)	1321.9
ET (kg/m^2)	415.3

3.3.4 Radiation conversion efficiency

Figure 3.10 represents average total top dry matter of maize (DM) as a function of the daily cumulative product of fractional interception of photosynthetic active radiation (FI) and solar radiation (Rs). Radiation conversion efficiency (Ec) is the slope of the regression line forced through the origin. Ec value represents a lower limit, as root dry matter in not included in the total dry matter.

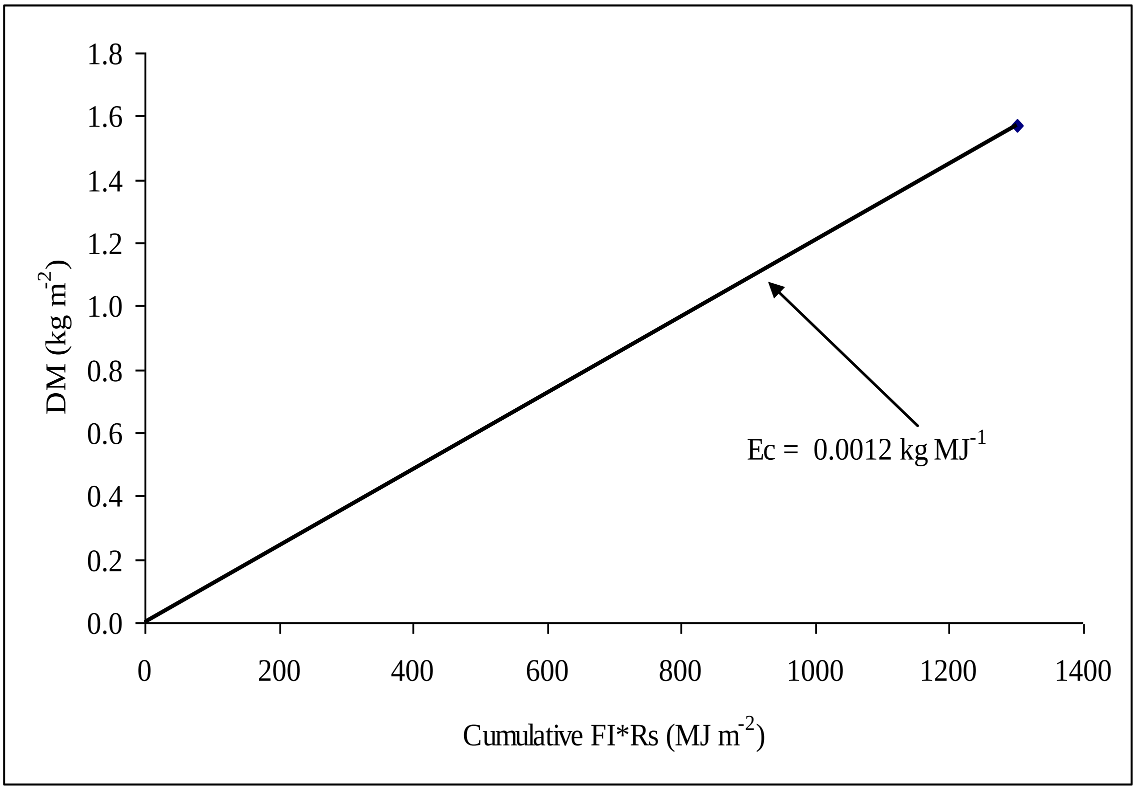


FIG. 3.10: Dry matter (DM) production of maize (pioneer hybrid variety -Phb 3442) as a function of the cumulative product of fractional interception and solar radiation (FI x Rs). Radiation conversion efficiency (Ec) is illustrated

3.3.5 Plant height

Plant height readings were taken on a weekly basis. Figure 3.11 shows how the crop performed during the growing season 2007/2008 under different rainwater harvesting treatments.

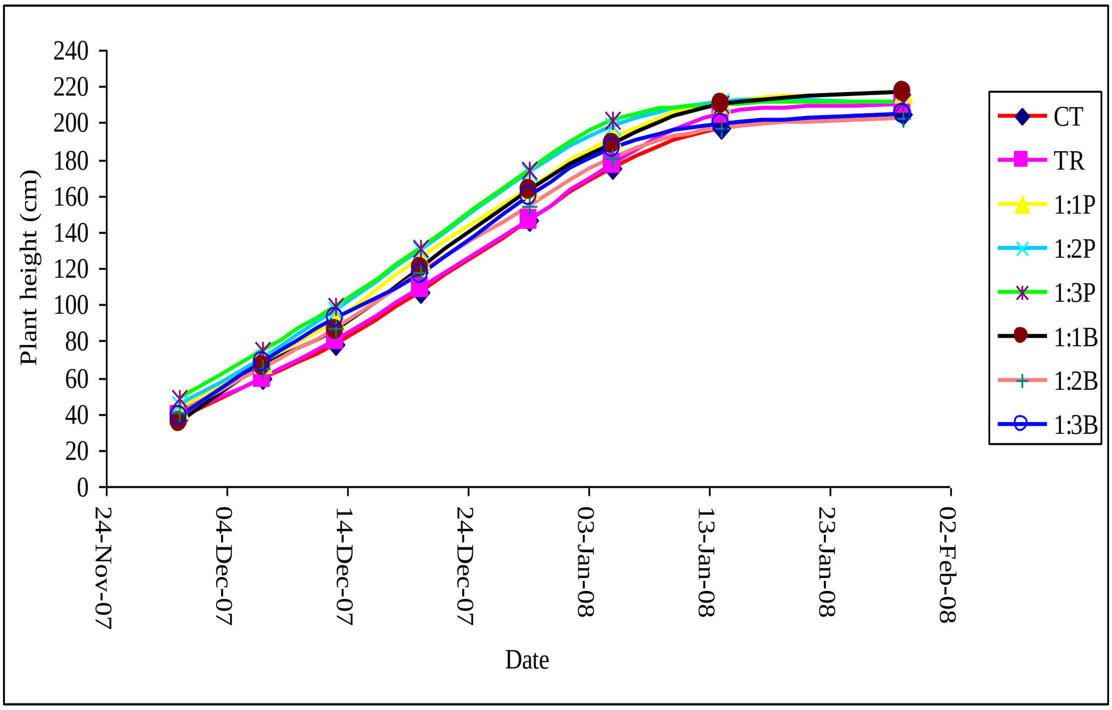


FIG. 3.11: Maize height during the growing season 2007/2008 under different rainwater harvesting treatments, Hatfield Experimental Farm

From Figure 3.11, it can be observed that maize plant height under conventional tillage and tied ridge techniques was slightly lower than under the different in-field rainwater harvesting treatments from early December until mid January 2008 (which coincides with maize mid reproductive stage). During this period, the crop experiences fast biomass accumulation, flowering and grain filling, which required a lot of water from the soil. However, during this time, as evident in Figure 3.6, soil water content levels were much lower under conventional tillage and tied ridge than under in-field rainwater harvesting. In addition, a lower planting density was used under conventional tillage and tied ridge when compared to in-field rainwater harvesting, which reduces the ability of the crop for competing for solar radiation interception, slowing plant height rate increment. This finding is in agreement with Sharifi *et al*. (2009), who observed an increase on maize plant height when planting densities were increased from 80 000 to 120 000 plants/ha, under rainfed conditions in a semi-arid area. From mid January 2008 to the end of the growing season, maize plant height under conventional tillage and tied ridge techniques was quite similar to plant heights of the different in-field rainwater harvesting designs. This can be explained by the fact that, during this period, all the different physiological processes occur in a much slower rate, and therefore, the crop did not require a lot of water.

3.3.6 Yield and yield components of maize

Maize grain yield, average mass per kernel, number of rows per cob, kernel number per cob, harvest index and hectolitre mass are summarized in Table 3.3 for all the rainwater harvesting treatments. Statistical analyses are presented in Appendix 3.3.

Table 3.3: Grain yield, average mass per kernel, rows and kernels number per cob, hectolitre mass and harvest index as affected by the different rainwater harvesting treatments on maize during the growing season 2007/2008, Hatfield Experimental Farm

Variable	Rainwater harvesting treatments							
	CT	**TR**	**1:1P**	**1:2P**	**1:3P**	**1:1B**	**1:2B**	**1:3B**
Grain yield per cropped area (ton/ha)	7.7 c	9.4 c	14.5 ba	13.8 b	17.0 a	14.9 ba	13.4 b	13.8 b
Grain yield per total area (ton/ha)	7.7 bc	9.4 ba	10.2 a	6.4 dc	5.9 dc	10.4 a	6.3 dc	4.8 d
Average mass per kernel (g)	0.25 c	0.31 ba	0.3 ba	0.28 bc	0.33 a	0.31 ba	0.31 ba	0.29 ba
Row number per cob	15 c	15 c	17 b	17 b	18 a	15 c	16 cb	16 cb
Kernel number per cob	779	771	849	853	929	838	772	851
	ANOVA results are not significant at P = 0.05							
Hectolitre mass (kg/hl)	77	79	79	78	78	78	78	78
	ANOVA results are not significant at P = 0.05							
Harvest index (%)	49	53	52	51	53	51	52	52
	ANOVA results are not significant at P = 0.05							

Means with the same letter are not significantly different

From Table 3.3 it can be seen that maize grain yield, when not considering the arable land reduced by the runoff areas (grain yield per cropped area), varied between 7.7 and 17.0 ton/ha. Crop yield under tied ridge and conventional tillage techniques was significantly lower than those obtained with the in-field rainwater harvesting technique. The highest grain yield was obtained with the 1:3P (17.0 ton/ha). However, it was not significantly higher than the one obtained with the 1:1B (14.9 ton/ha). The 1:1B strategy, on one hand, might be less expensive to be implemented than the 1:3P because it uses a bare runoff area instead of a plastic runoff area. On the other hand, it might involve more costs related to the amount of fertilizer , seeds and pesticides applied in the cropping area (because the extension of the cropped area with the 1:1 design ratio is bigger than the 1:3 design ratio). An economical feasibility study needs to be conducted to test cost and benefits of implementing these different rainwater harvesting scenarios. One more aspect that needs to be taken into consideration is the increased amount of drainage losses with an increase on the design ration, and from a bare runoff area to a plastic covered runoff area, especially in wetter seasons such as the 2007/2008 rainy season. Increased drainage losses are accompanied with increased nutrient leaching below the root zone, which can considerably reduce crop yield and cause environmental pollution. So, taking into account this factor, since there is no significant differences in crop yield between the 1:1B and the 1:3P, it is preferable to choose the 1:1B.

One possible explanation for the significant difference in terms of crop yield between the in-field rainwater harvesting and other techniques, on a cropped area basis, can be attributed to higher levels of fractional interception of photosynthetic active radiation with the in-field rainwater harvesting technique, since the spacing between two rows of crop was smaller (0.7 m) than in the conventional and tied ridges techniques (1 m). As mentioned by Sangoi (2001), narrow rows make more efficient use of available solar radiation and shade the soil surface more completely during the early part of the season, which results in less water being lost from the soil surface by evaporation. The maximization of light interception derived from early canopy closure also reduces light transmittance through the canopy. This results in small amount of sunlight reaching the ground, which decreases the potential for weed interference. According to the same author, optimum utilization of row spacing on maize ranges from 0.5 to 0.75 m under non limited conditions of water and nutrients. However, Fanadzo *et al*. (2007) state that there is increased risk of maize grain yield reduction due to soil moisture and nutrients scarcity when row spacing is reduced below 90 cm and planting density increased above 30 000 plants/ha under dryland conditions in general, in semi-arid areas. The 2007/2008 rainy season was exceptionally a wet season; that is why the use of high planting densities under in-field rainwater harvesting responded well. No water stress during the crop growing season was registered.

Although no significant differences were found in terms of crop yield on a cropped area basis between tied ridges and conventional tillage, it can be noticed from Table 3.3 that, crop yield is considerably higher under tied ridges (9.4 ton ha^{-1}) than under conventional tillage (7.7 ton/ha). It might be due to increased fertilizer use efficiency by the use of elevated ridges as cropping areas on the in-field rainwater harvesting and tied ridges techniques. It is well known that the practice of ridges improves infiltration; therefore, nitrogen can easily become available to the crop root system after a rainfall event. Hatfield *et al*. (1998) describes a number of advantages with the use of ridge tillage system. According to these authors, ridge tillage changes soil temperature and water patterns compared to conventional tillage. Warmer temperatures are attributed to a reduced water content related to high rates of gravitational drainage in the ridge and a lower specific heat in the ridged soil. These changes lead to an improved soil environment for crop emergence and early growth. The same authors also mention that ridge till system enhances rooting depth and improves pest management. In addition, soil water content under the tied ridge technique is higher than under the conventional tillage technique, because the system is designed in such a way that minimum or no runoff losses can occur. Moreover, as observed in Figure 3.6, soil water content levels were constantly below field capacity throughout the crop growing season 2007/2008 with the use of the tied ridge technique, so minimum waterlogging problems might have occurred, as well as drainage losses below the root zone.

As observed from Table 3.3, when taking into account the space occupied by the runoff areas (grain yield per total area), maize yield under the 1:1 design ratio (cropping area: runoff area) of the in-field rainwater harvesting either with a bare runoff area or with a plastic covered runoff area, was significantly higher than for other treatments with the exception of the tied ridge technique. However, crop yield under the tied ridge technique was not significantly higher than the one obtained under the conventional tillage technique during the crop growing season 2007/2008. The 2007/2008 crop growing season was a wet season (with 810 mm of total seasonal rainfall, distributed quite well throughout the crop growing season). Therefore, even the conventional tillage, tied ridge and the smallest design ratio of the in-field rainwater harvesting technique (1:1) could harvest enough rainfall to produce a good crop yield. The beneficial effect of the implementation of bigger design ratios of the in-field rainwater harvesting technique, such as 1:2 and 1:3 or even larger, is reduced in a wet season. The reason for that is the fact that it uses increased arable land to harvest runoff with less increment on the crop yield. From these specific field observations, it was noticed that grain yield does not increase in the same proportion as the supplied amount of runoff from the runoff areas in a wet season. For example, for the in-field rainwater harvesting treatment with a plastic covered runoff area, the total amount of runoff supplied to the cropping area over the whole growing season was 1 626, 4 336 and 7 046 litres for the 5, 10 and 15 m^2 runoff areas, respectively. However, the maize grain yield obtained was 14.5, 13.8 and 17.0 ton/ha for the design ratios 1:1, 1:2, and 1:3 (cropping area: runoff area), respectively. As a result, there is a decrease in grain yield with an increase of runoff area sizes on a total area basis (considering the space occupied by the runoff areas). Therefore, in the 2007/2008 wet season, field trials conducted at the Hatfield Experimental Farm of the University of Pretoria, revealed that the best rainwater harvesting strategy for maize production was the 1:1B, with the highest crop yield on a total area basis (10.4 ton/ha). That is why, if land is limiting for crop production as it is usually the case in most semi-arid areas, the fact that crop yield on a total area basis is reduced with an increase on the runoff area size should be considered. For instance, if there is only 1 ha available for crop production per household, the final maize crop yield obtained with the 1:3P will be 5.9 ton, while with the use of the 1:1B it will be 10.4 ton. In a dry season, an opposite trend could be expected. This increase in grain yield with an increment on the runoff collection could probably be significant, in such a way that, using bigger arable areas for runoff collection could still be advantageous for grain yield increment.

Average mass per kernel per treatment is related to the corresponding grain yield and kernel number per cob per treatment. Average mass per kernel under conventional tillage (CT) was significantly lower than for other treatments, with the exception of 1: 2 design ratio of the in-field rainwater harvesting with plastic covered runoff area (1:2P), which did not show significant differences. This is because the crop registered the lowest grain yield per plant with the conventional tillage technique. No significant differences were found between CT and 1:2P for the reason that under 1:2P, maize grain yield per plant was relatively low and kernel number per plant was quite high.

Row number per cob in the design ratio 1:3 of the in-field rainwater harvesting technique with a plastic cover runoff area (1:3P) was significantly higher than for other water harvesting treatments. It can be explained by the fact that this treatment harvests the highest amount of runoff to the cropping area. No significant differences of row number per cob were found between CT, TR, 1:1B, 1:2B, and 1:3B. Row number per plant from 1:1P and 1:2P was significantly higher than for the 1:1B, CT and TR treatments, but not significantly higher than for the 1:2B and 1:3B. This suggests that only runoff from the design ratio 1:3 with the runoff area covered with plastic significantly increased row number per cob. However, the grain mass and kernel number per cob were not significantly different from other in-field rainwater harvesting treatments.

Kernel number per cob did not show any significant difference between the water harvesting treatments, but in general, the values of kernel number per plant were higher under the in-field rainwater harvesting technique than under the conventional tillage and tied ridge techniques. However, a study conducted by Sharifi *et al*. (2009) on effect of plant population density on yield and yield attributes of maize hybrids under rain-fed agriculture, in a semi-arid area, revealed higher number of kernels with reduced planting density. According to these authors, an increase in grain cob^{-1} from lower planting densities might be due to the lower competition for radiation and nutrients, allowing the plants to accumulate more biomass with higher capacity to convert more photosynthesis into sink. The planting densities which were tested by them were 120 000, 100 000 and 80 000 plants/ha, corresponding to 354, 368 and 392 kernels/cob, respectively. In this study, planting density under in-field rainwater harvesting was 57 143 plants/ha, while under conventional tillage and tied ridge it was 40 000 plants/ha, and the corresponding number of kernels/cob was on average 850 and 775 kernels/cob, respectively. The reason why kernels number per cob was on average higher for the in-field rainwater harvesting technique, even though a higher planting density was used, is the fact that fertilizer were applied to the cropping areas at optimum rates to all treatments, and soil water content levels were, in general, higher for the in-field rainwater harvesting treatments throughout the growing season 2007/2008.

Hectolitre mass (which represents grain mass of a 100 litre galloon) is one of the maize quality parameters which are measured in order to reach at a particular grade of maize. Hectolitre mass of maze in this experiment was on average 78 kg/ha, and it can be classified as first grade in terms of this quality parameter (Hodges & Farrel, 2004). No significant differences were revealed in terms of hectolitre mass between the different treatments. Experimental research has shown that it is of more value to determine hectoliter mass for wheat than for maize, as there is a high correlation between hectoliter mass and flour yield of wheat as opposite to the low or zero correlation between hectoliter mass and maize grits. However, it has been proved that in order to guarantee a good milling quality in maize, it is desirable for maize cultivars to have high hectolitre mass values. Maize with low hectolitre mass values has a lower percentage of hard endosperm, and consequently, produces a lower yield of prime, large grits when milled. This is an indication that hectoliter mass can be used as a quality indicator of maize (Engelbrecht, 2008).

Harvest index statistical results did not show significant differences between diverse rainwater harvesting treatments. It might be attributed to the fact that 2007/2008 rainy season was a wet season, with about 605 mm of total rainfall falling during the crop growing season. As a result, harvest index values under conventional tillage and tied ridges techniques were relatively higher. Besides it, for these two techniques, a lower population density (40 000 plants/ha) was used, which reduces plant competition for water. De Lougherty & Crookston (1979) conducted a study to determine how the harvest index of maize was affected by changes in plant population under two different environments (drought vs. normal). They found out that increasing population densities resulted in significant decreases in harvest index in both environments.

3.4 CONCLUSIONS AND RECOMMENDATIONS

In the semi-arid area of Pretoria, on sandy clay loam soils, in a wet season, maize crop yield is maximized with the implementation of the 1:1 design ratio of the in-field rainwater harvesting with a bare runoff area, whether land is limiting or not limiting for crop production.

The in-field rainwater harvesting technique has the potential to harvest more rainfall than the tied ridge and conventional tillage techniques on sandy clay loam soils; as a result, it is the safest technique to be implemented in order to minimize crop risk failure in rain-fed agriculture.

In a wet season, if land is limiting for crop production, smaller design ratios of the in-field rainwater harvesting technique are more efficient in maximizing crop yield than bigger design rations, and there is no significant advantage of using a plastic covered runoff area rather than a bare runoff area.

Maize canopy extinction coefficient for solar radiation is increased by reducing row spacing and, therefore, increasing planting density.

Field trials testing the different rainwater harvesting design strategies studied should be repeated in different rainfall seasons to assess the effect of rainfall variability on the performance of these technologies. Trials should also be conducted in different soil types to identify potential conditions where a water harvesting project can be successful. An economical feasibility study must be carried out to assess the costs and benefits of implementing one of the studied rainwater harvesting strategies.

CHAPTER 4

RUNOFF TRIAL

4.1 OBJECTIVES AND HYPOTHESIS

A runoff trial was conducted next to the rainwater harvesting trial using 5 m wide runoff plots of differing lengths (1, 2 and 3 m) and different runoff surface treatments (bare and plastic cover). The size of these runoff areas (length and width), as well as runoff surface treatments were the same as the ones tested in the in-field rainwater harvesting technique. The trial had the following objectives:

- To quantify rainfall runoff relationships on runoff plots with differing lengths (1, 2 and 3 m) and surface treatments (bare and plastic cover) in the semi-arid area of Pretoria;
- To assess the amount of soil that is washed away with water on different runoff plot sizes;
- To determine soil specific parameters in order to parameterize different runoff estimation models which will be incorporated in the Soil Water Balance model in order to predict crop yield under different rainwater harvesting management scenarios.

The following hypotheses were formulated with the intension of being tested by field observations on the runoff trial:

- Runoff efficiency is reduced with an increase on the runoff plot length due to higher soil infiltrability;
- Runoff efficiencies of bare runoff plots on sandy clay loam soils are very low due to high infiltration rates;
- A plastic covered runoff plot harvests more rainfall than a bare runoff plot.

4.2 MATERIALS AND METHODS

4.2.1 Construction of runoff measurement system

Four different runoff measurement systems were constructed next to the rainwater harvesting trial (3 m away), following the slope direction. Each system consisted of a micro-plot, a gutter with a pipe and a collection hole in which the runoff measurement devices were located (Figure 4.1).

A grader was used to level the land to a uniform slope. A theodolite and a dumpy level were used to check the slope uniformity during this process. The grader could only increase the land slope up to a level of 1%.The slope of individual plots was afterwards increased by hand up to a level of 6% on average. This was done by using hoes, spades, rakes and pick axes. After getting the right slope, sweepers were used to smoother the soil surface.

Once preparing the soil surface, fascia board borders of 20 cm in height were inserted into the ground to a depth of 10 cm around each plot. A gutter was placed (at the lowest end of the plot) to divert the runoff water into a pipe which was connected to a measurement device.

Each collection hole was two metres deep, one metre long and five metre wide. The hole was constructed with steps to facilitate the runoff measurement operation. It was covered with metal sheets to screen off rain and wind. The runoff plots were five metres wide and one, two or three metres long. Two runoff surface treatments were tested: plastic cover and bare plots (vegetation removed).

FIG. 4.1: Runoff measurement system, Hatfield Experimental Farm

4.2.2 Rainfall and runoff measurement devices

From the beginning (03/11/2007) up to about half way through the experiment (12/02/2008), rainfall measurements were conducted using a manual rain gauge. It could only be used to monitor the total amount of rainfall per event. For this purpose, one rain gauge was placed close to each runoff plot. During the same period of time, runoff amount was monitored by collecting the runoff in drums of 200 litres in capacity. One drum was used per plot. To facilitate the runoff measurements, each drum was equipped with a valve at its bottom. A 10 litre container and a graduated cylinder were used to measure the collected amount of runoff precisely. The drums were covered with white plastic on the top to prevent water losses by evaporation. Figure 4.2 shows the drums that were used to measure runoff.

FIG. 4.2: Runoff measurement using collection tanks and small containers Hatfield Experimental Farm

Later in the season (due to lack of equipment at the beginning of the season), manual rain gauges and drums were replaced by an automatic rain gauge and tipping bucket runoff meters. This equipment allowed the collection of more detailed data on runoff and rainfall. Data related to the amount and duration of rainfall and runoff at intervals of less than 30 seconds per event rainfall was downloaded from the data logger on a weekly basis. Due to the limited number of tipping bucket runoff meters, these could only be connected to the bare surface runoff plots (plots were the runoff surface treatment consisted of a simple vegetation removal). The runoff plot covered with plastic was still being monitored by the manual collection tank. Data logger was fixed at a distance of 10 metres from the runoff plots and the automatic rain gauge was placed at 1.2 metres above ground level. Figure 4.3 shows the tipping bucket runoff meter attached to a micro-plot for runoff measurement, the data logger that was used to record the data automatically and the automatic rain gauge connected to the data logger.

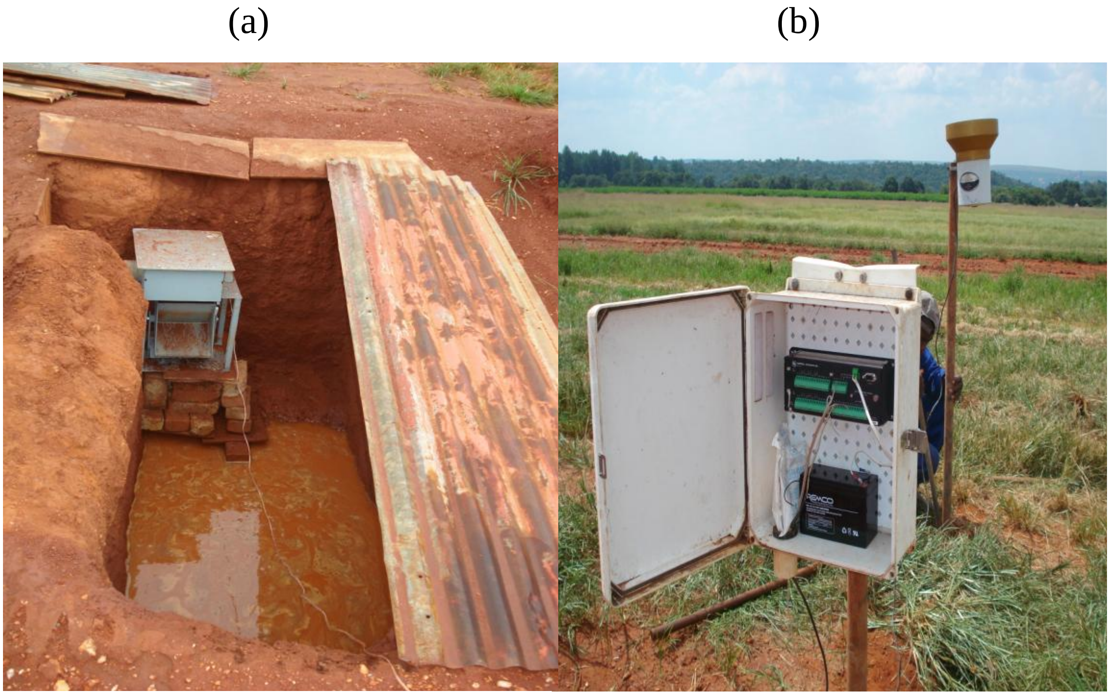


FIG. 4.3: A tipping bucket runoff meter for runoff measurement (a) and an automatic rain gauge attached to a data logger (b), Hatfield Experimental Farm

Tipping bucket runoff meters were calibrated under field conditions to determine the amount of runoff than each bucket holds per tip. Appendix 4.1 shows the calibration results for different tipping buckets used in the trial. In order to get the correct balance in terms of runoff collection between the two buckets, each tipping bucket needed to be adjusted. It was done by moving the screws up and down several times and applying water afterwards to check if both buckets gave equal amounts in terms of runoff collection per tip. To achieve this purpose, the following material was used: a ruler, a malleable container, a graduated cylinder and a spanner. Figure 4.4 illustrates the calibration of a tipping bucket under field conditions.

FIG. 4.4: Calibration of a tipping bucket runoff meter under field conditions, Hatfield Experimental Farm

4.2.3 Soil loss measurement

From the beginning (03/11/2007) until about half way through the experiment (12/02/2008), the amount of soil that was washed out with runoff was quantified using the same collection tanks that were used to catch runoff. It was monitored on a monthly basis. The amount of soil that settled in the bottom of the drums was collected in 5 ℓ containers. Different containers were used for different bare runoff plots. Previously, these containers were weighed using a scale, to know the weight of each of them when empty (Ce_y). Containers with soil were then dried in an oven at 105 °C for three days, whereafter, they were re-weighed to establish the soil dry mass plus the mass of the empty container (Cs_y). The soil dry mass (s_y) was obtained by subtracting the mass of the empty container from the mass of the container with dry soil, as shown in equation 4.1.

$$s_y = Cs_y - Ce_y \qquad \text{Equation 4.1}$$

Where: y = 1, 2 or 3 for the different runoff plots

Additionally, four samples of runoff water were collected from the valve of the collection tanks using 500 ml containers (Cr_x). These containers were firstly weighed to know the mass of each of them while empty (Ce_x). This was done with the aim of knowing how much soil is washed out with 500 ml runoff (s_x). For this purpose, these containers were dried at 105 ^oC for three days. Once dried, they were weighed to know the weight of each container with dry soil (Cs_x). Figure 4.5 shows the soil collection from the drums to determine the total amount of soil that is washed out with runoff during a certain period of time.

FIG. 4.5: Soil collection from the bottom of the drum (a), from the valve (b), 5 ℓ containers with soil from the bottom of the drum from different earthen runoff plots (c), and 500 ml containers with soil samples from the valve (d), Hatfield Experimental Farm

The amount of soil that was washed out with 500 ml runoff was then taken as average of the three containers (s$\bar{x}$), as illustrated in Equation 4.2.

$$\bar{s}_x = \frac{\sum_{i=1}^{n} Cs_x - Ce_x}{n} \qquad \text{Equation 4.2}$$

Where: i = number of 500 ml containers and n = total number of containers

The total amount of soil that was washed out with runoff (soil particles in suspension) in a certain period of time for each runoff plot (ST_y) was subsequently taken as a sum of the amount of soil that settled in the bottom of the drum (s_y) plus soil particles in suspension with runoff water during that period of time (sr_y). In order to quantify the amount of soil that was washed out with runoff within that period of time, the following procedure was used: firstly, rainfall events that produced runoff (Pr_{ir}) were selected; secondly, their respective amount of rainfall was summed (PTr); finally, this total amount of rainfall was multiplied by the runoff efficiency of each plot (c_y) to get the total amount of runoff in millimetres for that period of time (R_y). In order to get R_y in litres, R_y in mm was multiplied by the area of each plot (A_y). Equations 4.3 to 4.7 show how the total amount of soil particles in suspension with runoff, in a certain period of time, (ST_y) for each runoff plot, was obtained.

$$ST_y = s_y + sr_y$$ Equation 4.3

$$rt_y(mm) = PTr(mm) * c_y$$ Equation 4.4

$$PTr(mm) = \sum \Pr_{ir}(mm)$$ Equation 4.5

Where ir =1,2,3…rainfall events with runoff

$$R_y(L) = R_y(mm) * A_y(m^2)$$ Equation 4.6

$$sr_y = \frac{R_y(L)}{5*10^{-1}(L)} * \overline{s_x}$$ Equation 4.7

Later in the season, when the collection tanks were replaced by tipping bucket flow meters, soil loss from each runoff plot was monitored using the following procedure: a 100 litre drum was placed under one of the buckets of each tipping bucket runoff meter, as illustrated in Figure 4.6. This drum could only catch the amount of soil falling from one bucket. This amount of soil was subsequently multiplied by two to obtain the total soil loss for both buckets during a specific period of time. To obtain the total amount of soil that was washed out with runoff during this period of time, the same steps as described in the previous two paragraphs were followed. This procedure was only applied in two of the three bare runoff plots due to the limited availability of drums. In the third plot, the total soil loss during that period of time was estimated by taking into account the total amount of rainfall that produced runoff, its runoff efficiency, as well as a direct proportionality between the total amount of runoff and soil loss.

FIG. 4.6: A 100 ℓ drum, placed in one side of a tipping bucket runoff meter to catch soil losses due to runoff, Hatfield Experimental Farm

4.2.4 Soil surface retention measurements

Soil surface retention was monitored by measuring soil water content at first 10 and 20 cm soil depths. It was done on a daily basis, using a neutron probe. This device was calibrated at the trial's site to measure soil water content at first 10 and 20 cm soil depths. The following calibration equations were obtained:

At first 10 cm soil depth

$V = 0.14Z + 0.02$ Equation 4.8

At first 20 cm soil depth

$V = 0.19Z$ Equation 4.9

Where:

S = volumetric water content in m^3m^{-3}

Z = Probe count rate ratios

Volumetric water content obtained from the equations above was multiplied by the soil layer depth to get the corresponding soil water content in millimetres. Changes on the surface retention per rainfall event were taken as the difference between the soil water content of the actual day and the soil water content of the previous day for the first 10 and 20 cm soil depths. Surface retention variations per rainfall event were then correlated to the rainfall amount per event. This was done with the aim of finding a statistical function that could estimate soil surface retention from rainfall amount for any rainfall event.

Soil water content measurements were conducted in six runoff areas of the rainwater harvesting trial (three replications of the 1 m x 5 m runoff area and three replications of the 2 m x 5 m runoff area). These runoff areas had the same characteristics as the runoff plots and they were only used for the purpose of monitoring changes on the surface retention. One access tube was installed in the middle of each runoff area. The cropping areas receiving runoff from these runoff areas were not monitored during the trial period; they were only used as trial borders.

4.2.5 Soil infiltration measurements

Soil infiltration measurements were conducted using a sprinkler infiltrometer developed by the ARC Institute for Agricultural Engineering in Pretoria, South Africa (Reinders & Louw, 1984). Three test plots of three metres in width and four metres in length were prepared in the same site as the runoff trial plots. The preparation intended to provide to these plots the same soil surface characteristics as provided to the runoff trial plots. Since crust formation is one of the main factors dictating the soil infiltration capacity, it was previously created artificially. In order to achieve this objective, 200 litres of water were applied per plot, using a water sprayer attached to a hose pipe, which was connected into to a pump. The water sprayer was used to simulate the impact of rain drops on the soil surface. In order to ensure a good crust formation, the infiltration test was conducted at least seven days after wetting the plots.

The infiltration tests were carried out on a almost wind still day. The sprinkler infiltrometer was placed directly next to the test plot, with the shield opening facing the direction of the wind. At least three rain gauge tops were set out at 0.5 m distance intervals, with the starting point 1.5 m away from the infiltrometer. Before starting the test, the water container was filled with water. Figure 4.7 shows the sprinkler infiltrometer set up in one of the infiltration test plots.

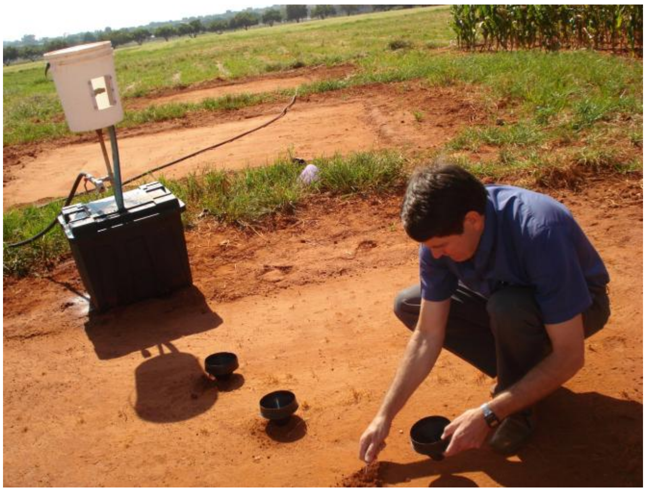


FIG. 4.7: Sprinkler infiltrometer set up for soil infiltration measurements, Hatfield Experimental Farm

After setting up the sprinkler infiltrometer, the infiltration test was ready to start. Firstly, the pump was started and the instrument was regulated at a water pressure of 85 kPa. As soon as the jets started rotating and spreading water, the time was noted using a chronometer. After a certain period of time, a wetting-front was formed around the first measuring point, and a layer of surface water was established behind this front. When this front moved from the first measuring point to the second, the time was noted and the first rain gauge top was removed. The accumulated water in this top was measured in mm using a rain gauge. The same procedure was repeated up to the last measuring point. The time for a wetting-front to move from one measuring point to the next was plotted against the corresponding amount of water in the bucket, and a cumulative infiltration equation, based on mathematical principles, was obtained, as showed in Equation 4.10.

$$Ic = ct^{k} \qquad \text{Equation 4.10}$$

Where:

Ic = cumulative infiltration; c and k = constants; t = time

The infiltration rate (It) was then calculated by using the following equation:

$$It = kct^{k-1}$$ Equation 4.11

Constants c and k, were derived from the Equation 4.10 and taken as an average from the three replications to get the final infiltration equations.

4.3 RESULTS AND DISCUSSION

4.3.1 Rainfall and runoff characteristics

Total rainfall at the study site during the rainy season 2007/2008 was 810 mm, falling between September and May. It was considered a wet season, since total rainfall was well above the average annual rainfall, of 670 mm. A Probability analysis curve of occurrence of seasonal rainfall in Pretoria is presented in Appendix 4.1. A data set of 42 annual rainfall totals from Pretoria was used to fit the curve. From this curve it can be seen that an annual rainfall of 810 mm has a probability of occurrence of approximately 4%. This means that it is expected only one year out of 25, to have annual rain equaled to 810 mm in Pretoria. During the crop growing season for 2007/2008 (from November to March), the total amount of rain was 605 mm. The rainfall distribution during this period is shown in Figure 4.8.

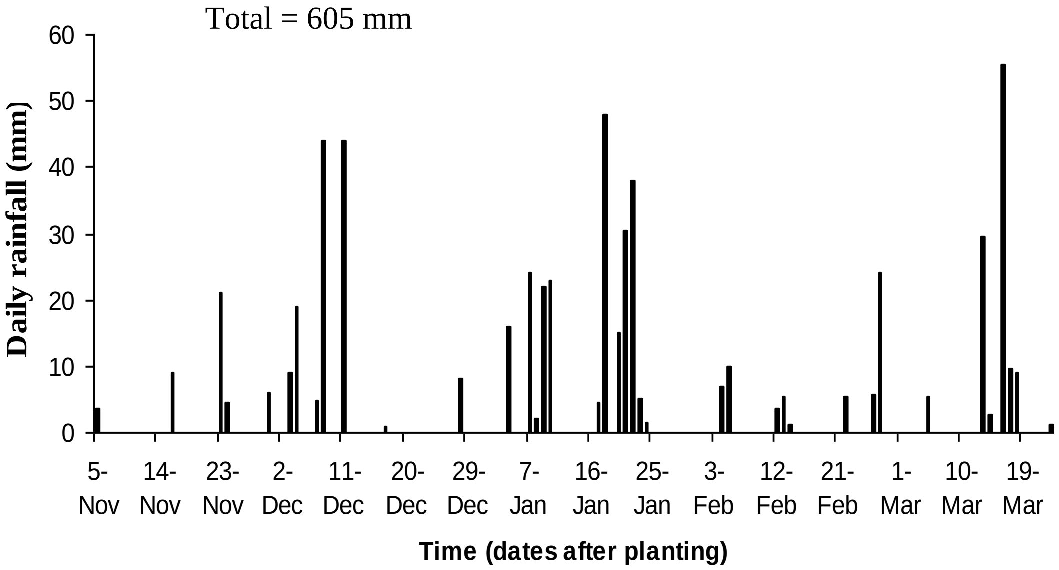


FIG. 4.8: Daily rainfall distribution during the maize growing season (2007/2008), Hatfield Experimental Farm

As can be seen from Figure 4.8, rainfall was erratic. The highest amount fell in January 2008 (38%), followed by December 2007 (26%) and March 2008 (19%). Little precipitation was registered in November (7%) and February (10%). During the maize growing season, 47 rainfall events occurred and about 54% of this number corresponded to events with 5 mm or more. From Figure 4.8, it can also be seen that rainfall events usually occur very close to each other, which indicates the presence of a strong effect of antecedent soil water content on the runoff process. Rainfall intensity was only monitored at a late stage of the maize growing season (from 4th to 23rd March 2008). During this period, rainfall intensity from seven rainfall events (six long duration events of more than 60 min and one short of less than 60 min) was recorded. It varied between 1 and 19 mm/hr. No linear correlation between rainfall amount and intensity from these rainfall events was found. This might be due to the fact that rainfall intensity was only recorded for a very small number of events and these included events of long duration. The higher the number of long duration rainfall events, the slighter the linear correlation between rain amount and rain intensity. Li & Gong (2002) recorded rainfall amount and intensity data from 70 events in the semi-arid region of China, for the rainy season 1998/1999. A slight correlation between rainfall amount and intensity was observed (r = 0.587). Walker & Tsubo (2002) analyzed relationships of peak rainfall intensity with event rainfall amount and duration at Glen (1992 to 2001; 401 data points), Bloemfontein (1962 to 992; 3128 data points) and Pretoria (1966 to 1996; 2676 data points). For all regions they found a slight correlation between rain amount and intensity, with r^2 varying from 0.2 for events of long duration to 0.7 for events of short duration. Runoff efficiencies per month and over the whole maize growing season (calculated as a percentage of the total amount of rainfall during that period of time) for different runoff treatments tested in the trial are presented in Table 4.1.The same table also shows runoff amount per month and over the whole maize growing season. Runoff treatments consisted of three different runoff plot lengths (1, 2 and 3 m) and two different surfaces (bare and plastic cover). All runoff plots were 5 m wide. It also presents the total runoff during the maize growing season. Table 4.1 does not present runoff characteristics for plastic covered runoff plots of 1 and 3 m length because runoff measurements were only conducted on a 2 m long plastic covered runoff plot. The reason for this is the fact that water losses from the plastic covered runoff plot are expected to be small since there are no losses due to infiltration or filling up of the surface retention. Some water losses from the plastic covered runoff plot are expected to occur due to deterioration of plastic over time. Therefore, only one plot length was considered to be sufficient for determining the runoff efficiency of plastic. Daily observed runoff from different runoff treatments tested in this present study is shown in Appendix 4.2.

Table 4.1: Monthly and seasonal runoff for different runoff surface treatments during the maize growing season 2007/2008, Hatfield Experimental Farm

Runoff treatment	Runoff variable	Nov	Dec	Jan	Feb	Mar	Seasonal
1 m Bare	Depth (mm)	14	100	127	25	57	323
	Volume (ℓ)	72	498	637	124	286	1615
	Efficiency (%)	35	68	60	47	56	53.4
2 m Bare	Depth (mm)	13	95	128	23.5	56	315
	Volume (ℓ)	129	950	1278	235	556	3148
	Efficiency (%)	34	65.8	62	45.9	53	52.1
3 m Bare	Depth (mm)	13	93.8	132	21.8	53.1	313
	Volume (ℓ)	188	1407	1973	327	797	4691
	Efficiency (%)	34	65.3	63	42.7	54	51.7
2 m Plastic cover	Depth (mm)	43	144	209	44.1	103	542
	Volume (ℓ)	426	1440	2087	441	1026	5420
	Efficiency (%)	96	91	91	75	91	89.2

As illustrated in Table 4.1, runoff volume from bare runoff plots increases with an increase in plot length, while runoff efficiencies show a general decline. These results were also confirmed by Bruggeman & Oweis (1998), who studied the effect of different bare plot lengths on runoff efficiencies. This can be due to the spatial variability in infiltrability of the soil and micro-topography. Thus, the longer the plot the more chance surface runoff has to infiltrate. However, from Table 4.1 it can be seen that runoff efficiencies in January did not follow the same trend as for other months. This can be explained by the occurrence of a greater number of events with large rainfall amounts during that period. In general, these rainfall events, as can be seen in Figure 4.8, happened consecutively on a daily basis. It resulted in a higher effect of antecedent soil water content. According to Slatyer (1967), the higher the antecedent soil water content the lower the infiltration rates, which increases runoff losses. Botha *et al.* (2003) report an average in-field runoff efficiency of 43% on a Glen/Bonheim ecotope in

Bloemfontein. This efficiency was measured from 2 m long runoff plots and 3 m wide, on clay soils with a 1% slope and a 0.2 mm^{-1} crust formation (Walker & Tsubo, 2002). At the Hatfield Experimental Farm, the same runoff plot length yielded a runoff efficiency of approximately 52%. Higher runoff efficiencies at Hatfield can be explained by the existence of a higher level of crust formation on the soil surface of 0.7 mm^{-1} and greater slope of 6%. From Table 4.1, it is evident that runoff efficiencies from the plastic covered runoff plot are much higher than from bare runoff plots. This can be attributed to the fact that with this type of surface treatment, there is no runoff loss by filling up surface retention and through infiltration into the soil profile. As mentioned by Li *et al.* (2004), small water losses from plastic surface treatment might be attributed to deterioration of plastic over time, as well as through the fact that plastic might not be tightly stretched over the ground, which does not allow free runoff movement over the surface, and as a result it is lost through evaporation.

The implication of the results illustrated in Table 4.1 is that with the in-field rainwater harvesting technique it was possible to harvest approximately 52% of the total amount of rainfall during the crop growing season with a bare runoff area and about 89% with a plastic covered runoff area. Most of this water will infiltrate below the evaporative zone, and thus become available for transpiration. Other part of it will be lost through evaporation and percolation.

4.3.2 Surface retention

Data for water losses through the filling up of the surface retention capacity during the runoff process is presented in Figure 4.9. These results correspond to changes in soil water content after a rainfall event at first 10 cm soil depth. Data related to surface retention monitored at first 20 cm soil depth did not show good results. At this soil depth, the obtained results are above what is expected for the variation of surface retention depths over time.

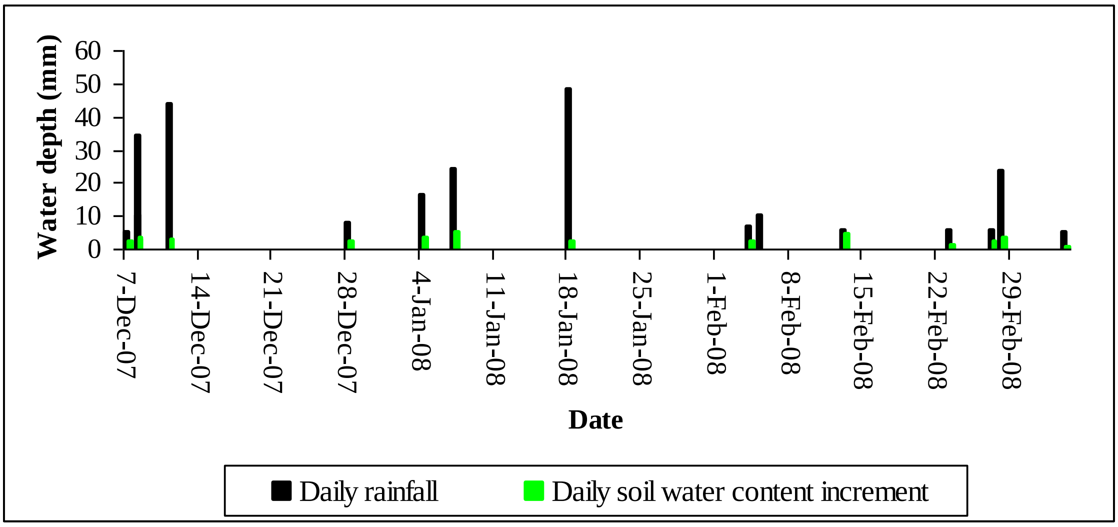


FIG. 4.9: Daily rainfall amount and corresponding water losses by filling up surface retention during the runoff process, Hatfield Experimental Farm

Data analysis reveals that there is no any linear correlation between daily rainfall amount and its correspondent water losses by filling up surface retention. As can be seen in Figure 4.9, large rainfall amounts can either produce smaller or bigger water losses by filling up surface retention. The same trend is considered for small rainfall events. According to the FAO (1993a), surface retention is a dynamic parameter, which allows maximum infiltration for low intensity rainfall events. Figure 4.9 shows that antecedent soil water content might also affect water losses by filling up surface retention. For instance, between 1st and 8th February 2008, two rainfall events occurred consecutively, and the event with the greater amount of rainfall had lower water losses by filling up surface retention. Unfortunately, rainfall intensity was not monitored during most of the trial period. Kamphorst (2000) emphasizes the fact that surface retention is a dynamic parameter, which is subject to spatial and temporal changes, depending on surface micro-topography. Reinders & Louw (1984) point out that land slope is another important factor affecting the depths of surface retention. According to these authors, the higher the land slope, the lower the water losses through the filling up of surface retention. From these authors observation, typical conventional tillage practices under irrigation have a value of 2.5 mm of surface retention in land slopes varying between 3 to 5%. As indicated by FAO (1991), the depth of surface retention is not great in normal storms, it range from approximately 0.25 to 2.54 mm. However, during intense storms, which cause disastrous floods, the depths would be much greater. In this study, an average value of 2.6 mm of surface retention was found for a land slope of 6% on average. As described in the materials and methods chapter, water losses by saturating the surface retention capacity were monitored by controlling changes in soil water content for each rainfall event, at first 10 cm soil depth using a neutron probe. This procedure assumes that surface retention occurs in the first 10 cm soil depth and does not take into account water losses by evaporation on the soil surface before and after a rainfall event. Neutron probes are also not so accurate to measure soil water content in the surface zone (at first 15 cm soil depth, due to the escape of fast neutrons through the surface).

As mentioned by Foster (1949), before runoff starts, some rainfall is needed to saturate the soil surface and fill surface depressions. Figure 4.10 shows this time lag between the inception of a rain event and the beginning of the runoff, which has been termed by surface retention.

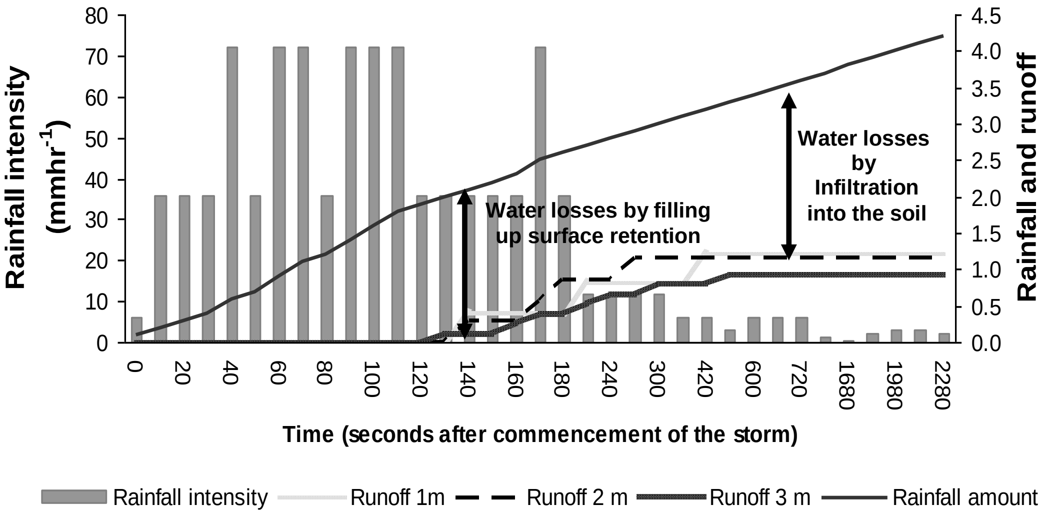


FIG. 4.10: Cumulative rainfall and runoff from bare runoff plots on the 13th April 2008, Hatfield Experimental Farm

As illustrated in Figure 4.10, runoff starts at about two minutes after the beginning of rainfall. A short period of time was necessary to saturate the soil surface and fill up surface depressions. It is explained by the fact that this rain storm started with high intensities, as evident in Figure 4.10. The depth of surface retention in this case was 1.9 mm. It is below the average depth of surface retention for this rainy season, which is 2.6 mm. Apart from being a rain storm with high rainfall intensities in the beginning, this small surface retention can also be explained by the effect of antecedent soil water content, which was high due to occurrence of three small rain events just before the incidence of this storm.

Figure 4.10 also shows a decrease of runoff efficiencies with an increase of length of runoff plots. The 1 m runoff plot produced the highest runoff (1.21 mm), followed by the 2 m runoff plot (1.15 mm), and, the 3 m long runoff plot had only 0.94 mm of runoff. Therefore, runoff efficiencies for the plots of 1, 2 and 3 m in length are 29, 27 and 22%, respectively. These runoff efficiencies are below the average for the rainfall events in this season. This might be explained by the fact that later in the event, rainfall intensities might have dropped below the final infiltration rate of the soil, which allowed much bigger water losses by infiltration into the soil profile.

4.3.3 Infiltration

Data obtained from field measurements using a sprinkler infiltrometer show high rates of absorption at the beginning of a rain event, and then a rapidly diminishing rate until a fairly constant ultimate value is obtained. Figure 4.11 shows curves of cumulative infiltration and infiltration rates for a sandy loam soil at the field trial site. These curves represent the characteristics of infiltration for the runoff areas.

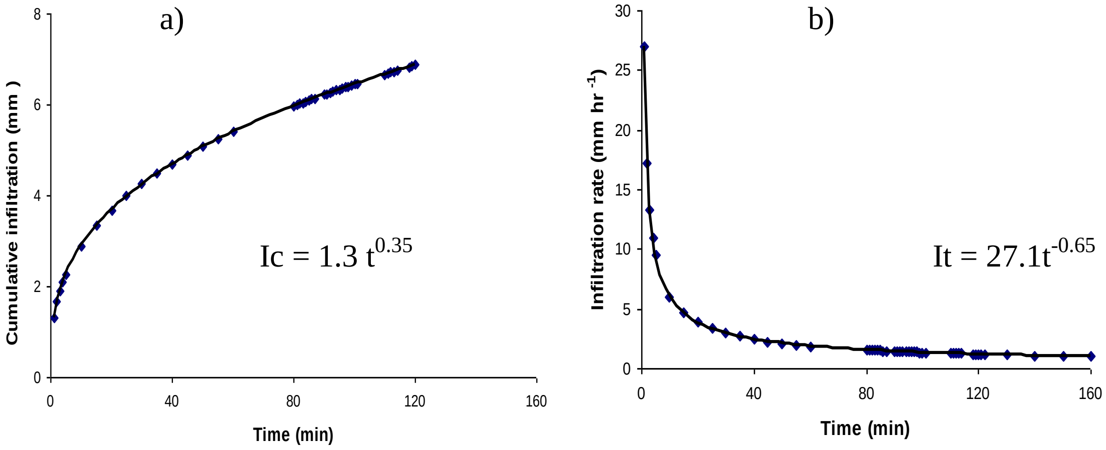


FIG. 4.11: Cumulative infiltration (a) and infiltration rate curve (b) on the runoff areas, sandy loam soil, Hatfield Experimental Farm

As illustrated in Figure 4.11b, infiltration rates tend to be constant after 120 minutes from the beginning of a rainfall event. Therefore, final infiltration rate at the trial site was taken at 120 minutes, and its respective value is 1.2 mm/hr. Initial infiltration rate was taken at one minute, and equals 27.1 mm/hr. Walker & Tsubo (2003) found a final infiltration rate of 6 mm/hr on a clay soil in Bloemfontein. This final infiltration rate was determined from runoff measurements, as the ratio between the amount of rainfall that is lost before runoff starts and its corresponding time. Another factor explaining the differences between these two values of final infiltration rate is the fact that the runoff areas in the Pretoria trial site develop a higher level of crust formation on the soil surface after a certain period of time. This will considerably reduce soil infiltration rate. Figure 4.12 shows cumulative infiltration and infiltration rates curve on the flat cropping areas at the study site.

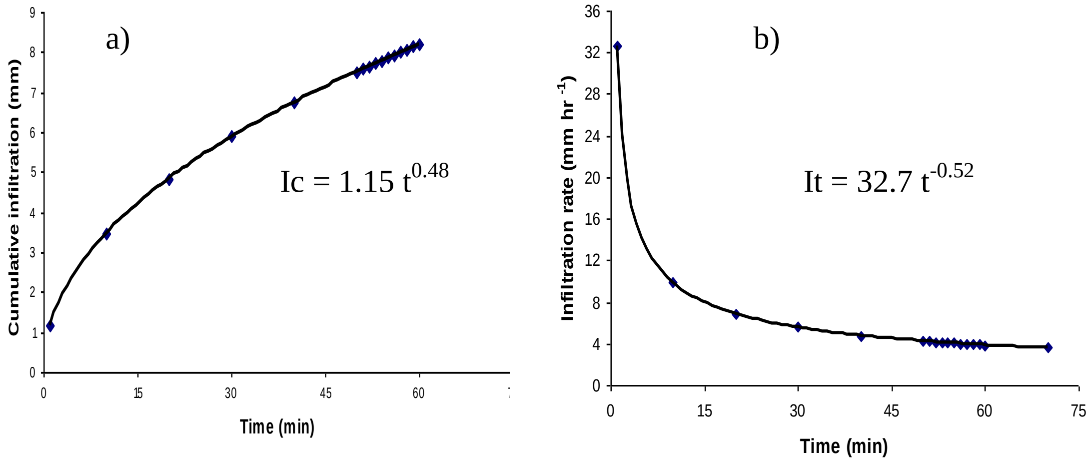


FIG. 4.12: Cumulative infiltration (a) and Infiltration rates curve (b) on the cropping areas, sandy loam soil, Hatfield Experimental Farm

The infiltration rates on the cropping areas are higher than on the runoff areas. This is due to the tillage practices on the cropping areas, which breaks the crust and consequently increases infiltration. After 60 minutes of a rainfall event, cumulative infiltration on the cropping area is about 8.2 mm, while in the runoff area it is about 5.4 mm. The initial and final infiltration rates on the flat cropping areas were determined for one minute and 60 minutes, respectively. The values for initial and final infiltration rates were 32.7 and 3.9 mm/hr. According to Slatyer (1967), final infiltration rates on cultivated sandy loam soils are within the interval 3.8 and 7.6 mm/hr. As stated by FAO (1991), final infiltration rates are usually found between 10 and 60 minutes after the beginning of a rainfall event on cultivated soils.

Data of soil infiltration measurements on the top of the ridges (cropping areas of the in-field rainwater harvesting technique) did not show good results. After 60 minutes from the beginning of a rainfall event, data analysis showed a cumulative infiltration of 7.2 mm and a final infiltration rate of 3.8 mm/hr. Soil infiltration on the ridges was expected to be higher than on the flat cropping areas for the reason that flat cropping areas were less compacted. Errors during soil infiltration readings while conducting the infiltration test might have occurred. This is because these ridges were very narrow (only 1 m wide), which makes the observation of the wetted-front movement from one measurement point to another difficult.

4.3.4 Sedimentation

In the in-field rainwater harvesting technique, soil movement occurs from the runoff areas to the cropping areas (upstream of ridges) due to the movement of water down-slope on the crusted soil surface. Therefore, there is no nutrients loss, since the amount of sediment that is carried out with water is concentrated on the upstream side of the cropping areas, allowing nutrients extraction by the crop root zone. However, the fact that there is sediment concentration increment upstream of the ridges overtime, the capability of runoff area in collecting runoff reduces. It results in lower sustainability of the rainwater harvesting system design. The amount of sediment concentrated in the cropping area from different runoff area lengths (1, 2 and 3 m in length) during the crop growing season 2007/2008 is presented in Table 4.2. All the runoff plots were 5 m wide.

Table 4.2: Amount of rainfall and corresponding runoff and sediment collected in the cropping area from different runoff area lengths during the crop growing season 2007/2008

Runoff area length (m)	**Variable (units)**	**3rd Nov to 11th Dec**	**12th Dec to 15th Jan**	**16th Jan to 29th Jan**	**30th Jan to 12th Feb**	**13th Feb to 23rd Mar**	**Seasonal**
1	Rain (mm)	155	136	142	17	155	605
	Runoff (ℓ)	392	294	519	34	376	1615
	Sediment amount (kg)	5.4	10.4	7.3	1.4	2.7	27.2
	Sediment rate (kg/m^2)	1.1	2.1	1.5	0.3	0.5	5.4
2	Rain (mm)	155	136	142	17	155	605
	Runoff (ℓ)	730	586	1042	66	725	3149
	Sediment amount (kg)	7.6	17.8	14.4	1.9	4.9	46.6
	Sediment rate (kg/m^2)	0.8	1.8	1.4	0.2	0.5	4.7
3	Rain (mm)	155	136	142	17	155	605
	Runoff (ℓ)	1084	874	1608	6.4	1027	4599
	Sediment amount (kg)	7.9	14.5	16.2	3.8	7.4	49.8
	Sediment rate (kg/m^2)	0.5	1	1.1	0.3	0.5	3.3

As can be seen from Table 4.2, the collected amount of sediment in the cropping area does not necessarily increases with an increase in the volume of runoff for each particular plot length. For example, from 12th December to 15th January, runoff was much less than for the rainfall periods 3rd November to 11th December, 16th to 29th January and 13th February to 23rd March, but the sediment collected was higher than for the other rainfall periods. It shows that rainfall intensity probably plays a more important role in the sediment collection than rainfall amount. This rainfall period probably had more rainfall events with higher intensities than other rainfall periods. Unfortunately, rain intensity was only monitored later in the season, from 4th to 23rd March. During this period, the average rainfall intensity was 6 mm hr^{-1}. Arnaez *et al*. (2007) report on a rate of sediment loss of 18.2 kg/m^2 with storms of 30 mm/hr, and 93.2 kg/m^2 with storms of 104 mm/hr on loamy soils in Spain. Table 4.2 also illustrates that the sediment collected increases disproportionably with an increase in the runoff length. The rate of sediment collection decreases with an increase of the runoff area size, which induces the conclusion that bigger runoff areas make an in-field rainwater harvesting system more sustainable than smaller runoff areas. Botha *et al*. (2003) report a rate of sediment collection in the cropping area of 3.7 kg/m^2/season for runoff areas of 2 m long. This study was done on a Glen/Bonheim Ecotope, Bloemfontein, which is a semi-arid area with predominance of clay soils with a level of crust formation of 0.3 mm^{-1}. The soils at Hatfield Experimental Farm are sandy clay loam, with a level of crust formation of 0.7 mm^{-1}. According to Bajracharya & Lal (1998), formation of a surface seal, which is a result of high rainfall intensities and subsequent crust, may greatly reduce infiltration and increase runoff and total soil loss. Besides that, weed control in the runoff areas was done by hand for most of the trial period, while at Glen it was controlled by herbicides with minimal soil surface disturbance. Moreover, the runoff areas at Glen had a land slope of 1%, while at Hatfield Experimental Farm slope was 6%. As mentioned by Kang *et al*. (2001) sediment losses per unit area increase with an increase of slope length. Therefore, these can be the reasons why the rate of sediment collection in the cropping area at Hatfield Experimental Farm, for the same runoff length, is 1 kg m^{-2} season $^{-1}$ higher than the rate in Bloemfontein.

4.4 CONCLUSIONS AND RECOMMMENDATIONS

Runoff efficiencies from bare micro-plots slightly decrease with an increase on the runoff plot length. The 1 m long runoff plot had an efficiency of 53.4%; the 2 m long runoff plot was 52.1% efficient, while the 3 m long runoff plot was 51.7% efficient. A plastic covered runoff plot has much higher runoff efficiency (89.2%) than a bare runoff plot (varying between 51 to 53%).

The amount of soil washed out with water increases with an increase on the runoff plot length. The amount of soil collected from the 1 m long plot during the crop growing season 2007/2008 was 27.2 kg, from the 2 m long plot it was 46.6 kg, while from the 3 m long plot it was 49.8 kg.

The sandy clay loam soil of the Hatfield Experimental Farm of the University of Pretoria proved to be appropriated for implementing in-field rainwater harvesting technique, being able to harvest about 50% of the rainfall with a bare runoff area. The most important factor contributing to increased runoff efficiency on this soil type is its high level of surface crust formation which considerably reduces infiltration rates, allowing more runoff to be collected.

Runoff measurement trial at the Hatfield Experimental Farm should be conducted in different rainy seasons to assess the effect of seasonal variability of rainfall characteristics (amount, intensity and frequency of rainfall events) on the occurrence of the runoff. The trial should be run in different soil types in order to identify potential soils for the implementation of the in-field rainwater harvesting technique.

CHAPTER 5

PARAMETERIZATION OF RUNOFF PREDICTION MODELS

5.1 INTRODUCTION

Many models have been used to simulate rainfall-runoff processes from micro-plots. These models include: (1) simple models such as unit hydrographs, linear regression and runoff curve number method; (2) mathematical models such as CLS; (3) Conceptual models such as the Morin and Cluff runoff model and; (4) physically-based models such as the Morel-Seytoux model (Naef, 1981; Chahinian, 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. However, it is almost impossible to use such models for practical purposes, because the necessary parameters cannot be evaluated in the required spatial and temporal resolution (Naef, 1981). Thus, the choice of one of these models depends on the objective of the study and the aspects that are considered to be of primary importance in the physical rainfall-runoff transformation process. In addition, the experience and computer size needed to calibrate the model, the availability of data and resources as well as the relation between the complexity of the model and the accuracy of the simulation influence the choice of a model (Naef, 1981; Tan *et al*., 2005).

In this study, runoff from rainwater micro-catchment surfaces was estimated using the following models: linear regression equations, runoff curve number method, and the “Morin and Cluff 1980” runoff model. Linear regression equations and runoff curve number method were included in the runoff estimation due to the fact that these are simpler procedures, which do not require rainfall intensity data for runoff modeling. In the majority of potential water-harvesting sites, rainfall intensity data is seldom available. The “Morin and Cluff 1980” runoff model was chosen for being a conceptual procedure of runoff estimation from bare runoff plots, which takes into account the main factors affecting surface runoff. This makes the model more accurate and transferable in space and time.

This chapter aims to parameterize the linear regression model, runoff curve number method, and the “Morin and Cluff 1980” runoff model using measured values of runoff, rainfall, soil infiltration and surface retention during the rainy season 2007/2008. The following hypothesis was formulated: The “Morin and Cluff 1980” runoff model will provide better estimations and more detailed understanding of the runoff process than the linear regression model and the runoff curve number method for being a conceptual procedure.

5.2 THE LINEAR MODEL

Linear regression equations were parameterized for each runoff plot, based on daily rainfall and runoff amounts. The model was expressed as follows:

$$\left.\begin{array}{ll} R = 0 & \text{for } P \leq Po \\ R = c(P - Po) & \text{for } P > Po \end{array}\right\} \qquad \text{Equation 5.1}$$

Where: R is daily runoff amount in mm; P is daily rainfall amount in mm; c is runoff efficiency; and Po is threshold rainfall in mm. R and P were measured at the runoff trial site on a daily basis. R was measured in litres and, therefore, needed to be converted to millimetres to be used in equation 5.2. In order to convert R in litres to R in millimeters, the following equation was used:

$$R(mm) = \frac{R(L)}{A(m^2)} \qquad \text{Equation 5.2}$$

Where: A is the area of each runoff plot.

Daily runoff amount from each runoff plot was plotted against daily rainfall amount. C and Po values were obtained from these regression equations for each runoff plot.

The linear model was parameterized using runoff data from 57 rainfall events measured during the rainy season 2007/2008 at the Hatfield Experimental Farm. Runoff amount (dependant variable) is plotted in Figure 5.1 against the corresponding rainfall amount (independent variable) for each particular runoff plot.

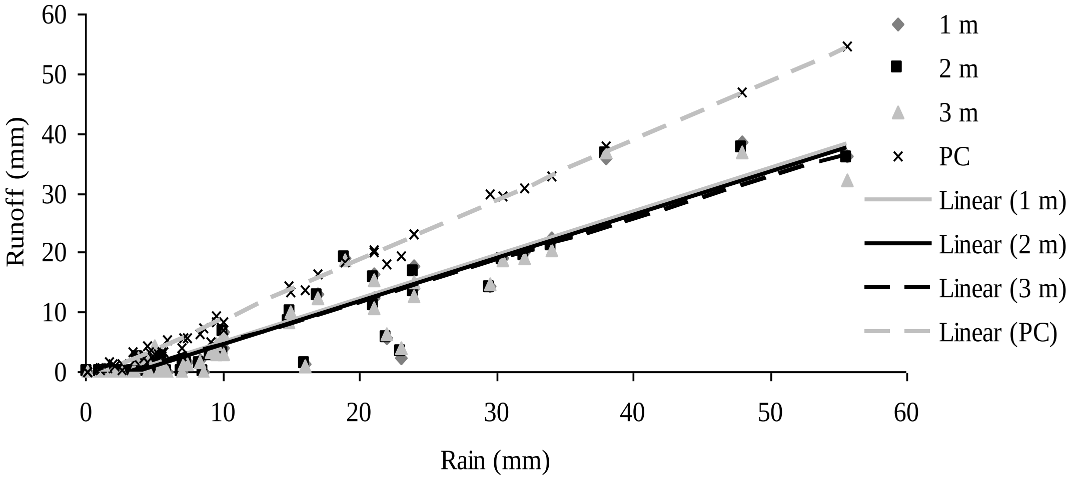


FIG. 5.1: Daily measured runoff data from four different treatments, namely, 1 m, 2 m, 3 m long runoff areas and Plastic Cover (PC) plotted against the corresponding rainfall (56 measurements), (Hatfield Experimental Farm)

A linear function was fitted through the data to obtain equations that estimate the amount of rainwater harvested from each rainfall event. The obtained equations follow:

$R_1 = 0.73 * (P - 3.5)$ for $P > 3.5$ ($r^2 = 0.88$) Equation 5.3

$R_1 = 0$ for $P <= 3.5$

$R_2 = 0.72 * (P - 3.6)$ for $P > 3.6$ ($r^2 = 0.88$) Equation 5.4

$R_2 = 0$ for $P <= 3.6$

$$R_3 = 0.70*(P-3.3) \qquad \text{for} \quad P > 3.3 \qquad (r^2 = 0.87) \qquad \text{Equation 5.5}$$

$$R_3 = 0 \qquad \text{for} \quad P <= 3.3$$

$$R_{PC} = P-1.4 \qquad \text{for} \quad P > 1.4 \qquad (r^2 = 0.99) \qquad \text{Equation 5.6}$$

$$R_{PC} = 0 \qquad \text{for} \quad P <= 1.4$$

Where: R_1, R_2, and R_3 are daily runoff amounts in mm for the 1, 2, and 3 m runoff lengths. R_{PC} is runoff in mm for the Plastic Covered plot. P is daily precipitation in mm.

As evident from equations 5.3 to 5.6, rainfall and runoff amount were positively correlated: the correlation coefficient was about 90% for the earthen runoff plots and 100% for the plastic covered runoff plot. Li *et al.*, 2004 also found a positive correlation between rain and runoff amount, of about 60% for the earthen runoff plots and 100% for the plastic covered runoff plot.

The linear model also shows a decrease in runoff efficiencies with an increase of runoff length as explained in Section 4.3.1. According to Bruggeman & Oweis (1998), the slope of the liner equation describes the efficiency of each particular runoff plot. In this case, the model estimates a runoff efficiency of 0.73 for the 1 m runoff plot, and a runoff efficiency of 0.70 for the 3 m runoff plot. For the plastic covered runoff plot, the model estimates a runoff efficiency of 1 after a 1.4 mm storage loss. However, different runoff efficiency values were obtained by dividing the total amount of measured runoff and the corresponding amount of rain falling in that particular plot. Taking into consideration this calculation procedure, the actual measured runoff efficiencies are as follows: 0.53 for the 1 m x 5 m plot, 0.52 for both, 2 m x 5 m plot and 3 m x 5 plot and 0.89 for the plastic covered plot. It can be seen from the equations above that, the rainfall threshold for the plastic covered runoff plot (Po = 1.4) is lower than for the earthen runoff plots (Po = 3.5 on average). This is due to the effect of plastic cover in avoiding water losses by filling up surface retention when the rainfall starts.

5.3 THE RUNOFF CURVE NUMBER METHOD

The Runoff curve number method modified by Woodward *et al*., (2003) was used in this study to estimate daily runoff amount from daily rainfall amount. This particular procedure was used due to the fact that it considers an initial abstraction ratio value of 0.05 instead of 0.2, which is used in the original Runoff curve number method (see section 2.2.3 for further details). The advantage of using an initial abstraction ratio value of 0.05 is the fact that it allows the calculation of a smaller initial abstraction value, giving direct runoff earlier in the rainfall event. This is appropriated for areas were the rainfall event amounts are in general small. Taking into account this alteration, the following runoff curve number equation was used:

$$\left.\begin{array}{ll} R = \dfrac{(P - 0.05 * S)^2}{P + 0.95 * S} & for\ P > 0.05 * S \\ R = 0 & for\ P \leq 0.05 * S \end{array}\right\} \qquad \text{Equation 5.7}$$

Where: S is the potential maximum retention or the maximum possible difference between P and R in mm. The potential maximum retention (S) in mm was calculated using Equation 5.8.

$$S = 1.33 * \left(\frac{25400}{CN} - 254 \right)^{1.15} \qquad \text{Equation 5.8}$$

Where: CN is the dimensionless curve number.

Runoff depths were estimated using Equation 5.11. For this purpose, a CN value equal to 96 was fixed by comparing predicted runoff values to the observed values, while doing an evaluation with the help of statistical parameters such as coefficient of determination (r^2) and model efficiency (E_f), since none of the land management practices, as well as the hydrological soil groups from the SCS curve number table could describe the conditions of the runoff areas from the present study sufficiently.

The best statistical results were found with the use of a runoff curve number of 96. The surface retention parameter was then calculated using Equation 5.8 and replaced in Equation 5.7 resulting Equation 5.9.

$$R = \frac{(P-1)^2}{(P+20)} \qquad for \quad P > 1 \qquad \text{Equation 5.9}$$

$$R = 0 \qquad for \quad P \leq 1$$

Where: R is estimated runoff depth in mm and P is the corresponding rainfall depth in mm.

Figure 5.2 shows a comparison between predicted and observed runoff for all the earthen runoff plots using a CN value of 96.

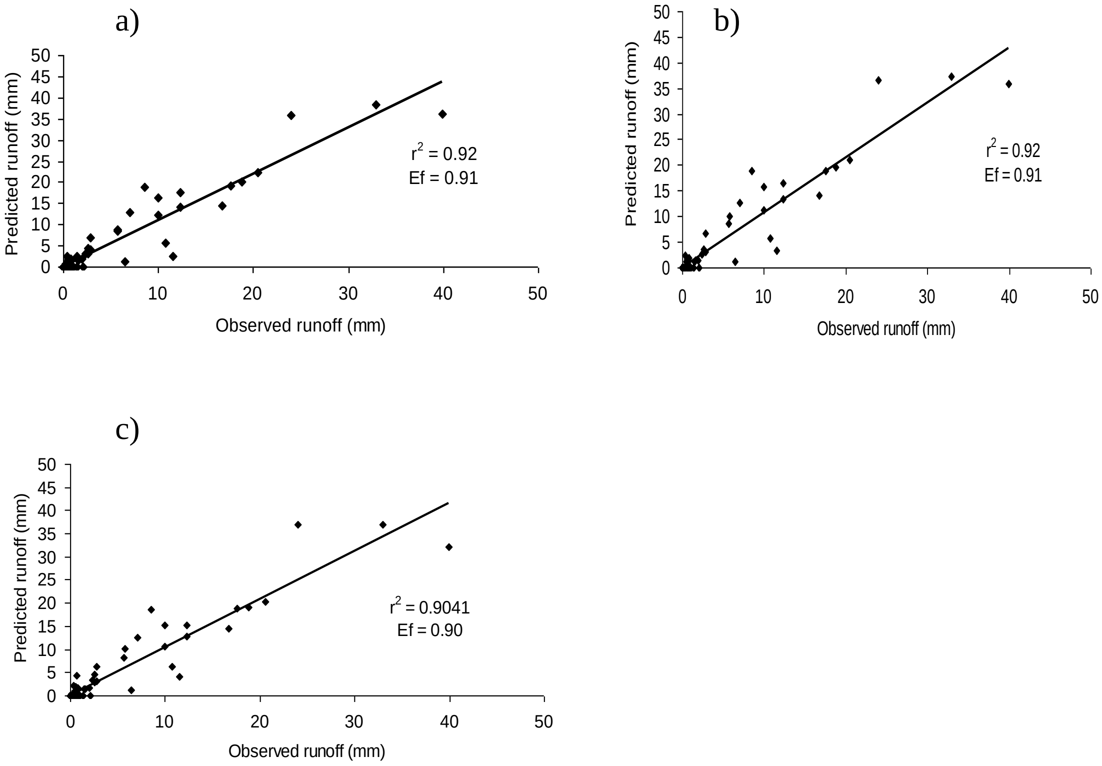


FIG. 5.2: Observed versus predicted runoff depth by the curve number model for the 1 m (a), 2m (b) and 3 m (c) plot lengths (from 5 November 2007 to 4 May 2008), Hatfield Experimental Farm

The most sensitive parameter in this model is the choice of the CN value. The higher the CN value the closer the predicted runoff is to the observed runoff. Statistical parameters r^2 and E_f show good correlation between predicted and observed runoff depths by fixing a CN value of 96 in the model. Huang *et al.* (2006) also identified the choice of the CN value from the SCS table as the most crucial factor affecting runoff prediction in the Loess Plateau of China. In their study, they concluded that another approach needed to be developed to adjust CN values for the conditions of that area. In addition, this model estimates only one value of runoff efficiency and rainfall threshold for every runoff plot length due to the fact that the choice of CN values from the SCS table does not take into account different plot lengths.

5.4 THE “MORIN and CLUFF 1980” RUNOFF MODEL

The “Morin and Cluff 1980” runoff model was used to estimate the amount of runoff per short segments of rain from a rainfall event, taking into account rainfall amount, duration and intensity, soil losses by infiltration and filling up surface retention, as well as a soil factor that describes the level of soil surface crust formation. The model is explained by the following equations:

$$\sum R_i = \sum_{i=1}^{n} \left(I_i * \Delta t_i + S_{i-1} - Id_{\Delta ti} - S_m \right) \qquad \text{Equation 5.10}$$

$$Id_{\Delta ti} = I_{tf} * \Delta ti + \frac{\left(I_{ti} - I_{tf} \right)}{-\gamma * I_i} * \left[\exp\left(-\gamma * P_i \right) - \exp\left(-\gamma * P_{i-1} \right) \right] \qquad \text{Equation 5.11}$$

Where: R_i is the amount of runoff in a time period Δt_i of a rainfall event in mm; I_i is the rainfall intensity during a time period Δt_i in $mmhr^{-1}$; Δt_i is the duration of a time period in hr; S_{i-1} is the storage and retention of soil surface water in the previous time period Δt_{i-1} in mm; S_m is the maximum storage and retention of soil surface water in mm; $Id_{\Delta ti}$ is the total amount of infiltration of rain water into the soil during any time period Δt_i in mm; i is the number of given time periods per rainfall event (i= 1, 2, 3…); P_i is the cumulative rainfall over a time period Δt_i in mm; P_{i-1} is the cumulative rainfall in the previous time period Δt_{i-1} in mm; It_f and It_i are the final and initial infiltration rates of the soil (mm/hr); γ is the soil factor (mm^{-1}), which is determined by the stability of the soil surface aggregates to the reorientation of soil particles, by the impact of the raindrops to form a crust.

Water loss by filling up surface retention (S) was taken as the average soil surface retention of the first 10 cm soil depth measured during the trial's rainy season. The initial and final soil infiltration rates were determined from the soil infiltration rate equation, which was parameterized using data from field measurements at the trial site (see Section 4.2.5). Periods of time of one minute and 100 minutes were used to determine initial and final infiltration rates, respectively. The soil factor was fixed by comparing simulated runoff values to the observed values, and using the help of statistical parameters such as r^2 and E_f for the evaluation. This was done by programming the "Morin and Cluff 1980" runoff model using Excel software, in which the values of soil factor were changed from 0 to 0.9 mm^{-1}. These values were tested in the runoff model and the simulated data was plotted against the measured data for the 1 m in length runoff plot. The performance of each value of soil factor was evaluated on the runoff simulation, using the following indices and objective functions:

- Slope of a least square regression between the predicted (dependent variable) and observed (independent variable);
- Coefficient of determination;
- Model efficiency.

The best soil factor value was considered the one which gave a coefficient of determination, model efficiency and a slop of the calibration equation close to one.

Rainfall amount and duration per time period within a rainfall event were taken from the data logger. It was programmed to give readings at one minute or shorter time periods. Rainfall intensity per each time period was calculated by dividing rainfall amount by its respective duration. Thus, runoff amount was estimated per time period, and thereafter was accumulated to get the total runoff amount within an event rainfall. The following parameters were obtained from field measurements and incorporated into the “Morin and Cluff 1980” runoff model: an initial soil infiltration rate of 27.1 mm/hr, a final soil infiltration rate of 1.21 mm/hr and an average surface retention depth of 2.6 mm. A soil factor of 0.7 mm^{-1} was selected. The best runoff prediction for different rainfall events is presented in Appendix 5.1. The model performance was evaluated using the following parameters: coefficient of determination (r^2), model efficiency (E_f) and slope of the linear regression equation. Figure 5.3 shows a comparison between predicted and observed runoff values using a soil factor of 0.7 mm^{-1}, which gave the best fitting to the data.

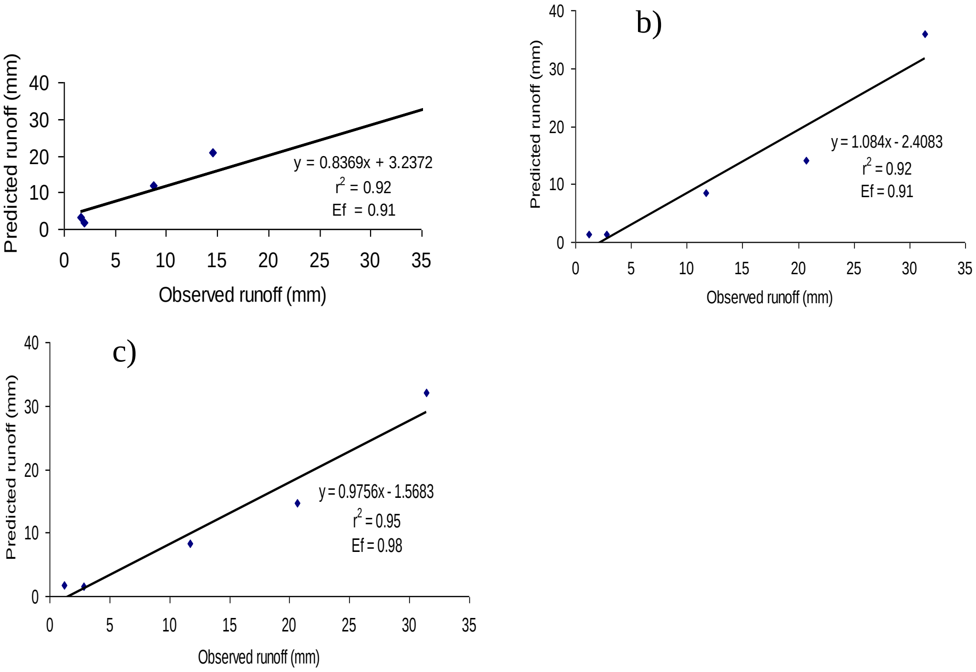


FIG. 5.3: Observed versus predicted runoff depth by the “Morin and Cluff 1980” runoff model for the 1 m (a), 2m (b) and 3 m (c) plot lengths (from five rainfall events), Hatfield Experimental Farm

As evident in Figure 5.3, the model shows good performance in terms of runoff prediction from bare runoff areas. For the same parameters, the longer the length of the runoff plot the better the runoff prediction by the Morin & Cluff (1980) model. It takes into account the most important factors affecting runoff generation from bare soil surfaces such as soil infiltration rates, water losses by filling up surface retention, level of crust formation on the soil surface and most importantly rainfall intensities. Welderufael (2006) used the same model to predict runoff from 2 m long bare micro-plots in a semi arid area of Ethiopia, on sandy loam soils with 1% slope. The model calibration was conducted using 12 rainfall events and the best model performance was found with a soil factor of 0.6 mm^{-1} and a surface retention depth of 0.4 mm. The model evaluation parameters show a r^2 and a linear equation slope of 0.94. One of the reasons that the model performance results obtained by Welderufael (2006) are better than the ones obtained in this present study for the same plot length might be the use of a bigger number of rainfall events for model calibration. Another reason might be the fact that not only soil factor was fixed by calibration, but the depth of surface retention as well. In addition, final infiltration rate also needed to be adjusted manually and expertly until the performance evaluation objective functions had reached their optimum level. Figure 5.4 shows predicted runoff by the Morin & Cluff (1980) model and observed runoff on bare runoff plots for the rainfall event of 16th March 2008.

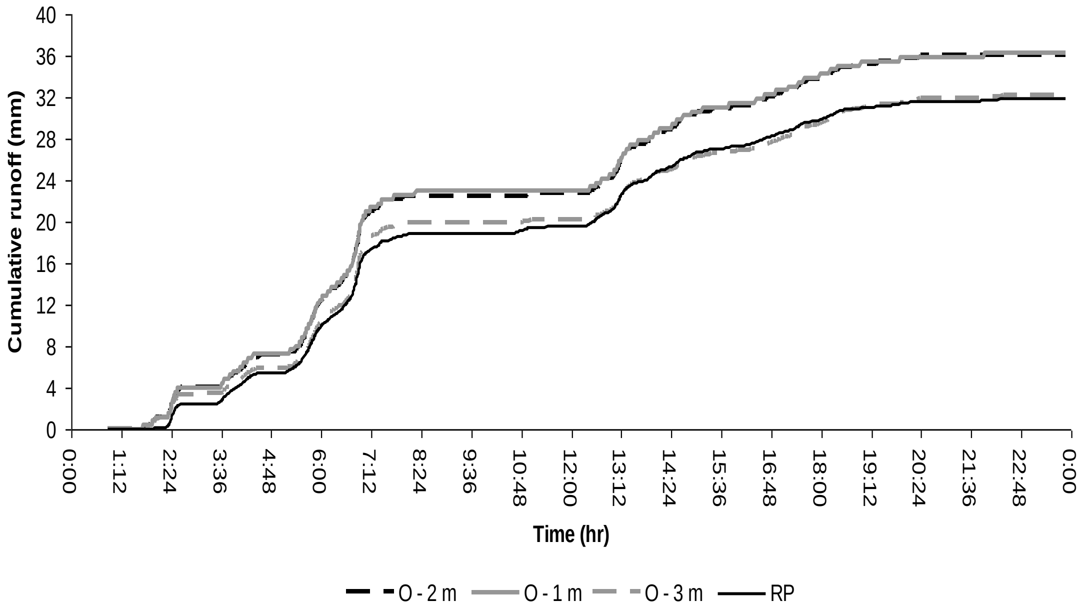


FIG. 5.4: Predicted runoff by "Morin and Cluff "model (RP) and observed runoff in the 1 m x 5 m plot (O-1 m), 2 m x 5 m plot (O-2 m) and 3 m x 5 m plot (O-3 m) for the rainfall event 16th March 2008 (from one o'clock AM on the 16th March to 12 o'clock AM on the 17th March), Hatfield Experimental Farm

rainfall event, the model predicts a total amount of 31.8 mm of runoff, which is close to the observed runoff on bare plots (36.27 mm for the 1 m long, 36 mm for the 2 m long and 32.16 for the 3 m long runoff plot). It means, for these specific runoff plots, the model gives a maximum error of 12% and a minimum of 1%. The model predicts that runoff starts after 2.6 mm of rainfall, while field observations indicate that the beginning of runoff varies from one plot length to another. It starts after 1.6, 1.4 and 1.1 mm of rainfall for the 1, 2, and 3 m runoff plot lengths, respectively. The model predicts that runoff ends at 22:23 hr, while field observations show that it ends at 22:03, 20:37 and 22:30 hr for the 1, 2, and 3 m runoff plot lengths, respectively.

5.5 CONCLUSIONS AND RECOMMENDATIONS

The “Morin and Cluff 1980” runoff model proved to be a very important tool to provide a better understanding of the runoff process in a semi-arid area. However, for its application, it requires long-term rainfall intensity data. Therefore, the installation of automatic weather stations to record climatic data at shorter time periods will be required in semi-arid areas.

Appropriated parameters for the linear regression model, as well as for the runoff curve number method were obtained. In the linear regression model, daily measured values of runoff were highly correlated to the corresponding rainfall amounts ($r^2 \approx 88\%$ for the earthen runoff plots and $r^2 \approx 99\%$ for the plastic covered runoff plots). Daily predicted runoff by the runoff curve number method was highly correlated to the equivalent observed runoff for the different earthen runoff plots ($r^2 \approx 91\%$). Therefore, these models can be used to predict runoff from micro-catchments in semi-arid areas with acceptable accuracy and minimum input requirements.

CHAPTER 6

A SOIL WATER BALANCE MODEL TO PREDICT MAIZE CROP YIELD UNDER DIFFERENT RAINWATER HARVESTING DESIGN SCENARIOS IN SEMI-ARID AREAS

6.1 INTRODUCTION

One of the major constraints affecting crop production in semi-arid areas is low and erratic rainfall. Therefore, water use through crop production needs to be optimized. In some semi-arid regions, this can be enhanced by using small scale rainwater harvesting technologies. Various water harvesting techniques have been adopted by farmers in semi-arid areas and they have generally showed good crop yield improvements. These techniques include tied ridges (which involve the use of small earthen ties across furrows in-between ridges to increase the amount of water stored in the soil profile by reducing surface runoff, trapping or holding water where it falls), and in-field rainwater harvesting (which involves the collection of surface runoff from micro catchment areas with short slopes and storage in the root zone of an adjacent run-on collection and infiltration area) (Kunze, 2000; Haile & Merga, 2002; Senkondo *et al*., 2004).

The success or failure of implementation of these systems depends on how well the system is designed, since the optimum design for a particular crop, varies from one season to another and from one place to another (depending on soil and seasonal weather conditions). As a result, crop models have been used as very important tools to help researchers and farmers study these systems, and thereby make prudent water harvesting design choices for specific situations. These models do not take into account all processes affecting soil-plant relationships; they only consider the most important factors (Mzirai *et al*., 2002; Young *et al*., 2002; Walker & Tsubo, 2003). Besides surface treatments, the management of the micro-catchment surface involves the manipulation of other factors such as: micro-catchment size, ground slope and soil surface depth (Boers, 1997). One of the largest factors having an impact on rainwater harvesting management strategies is the amount of water that is supplied to the crop during the growing season. The use of different surface treatments on the runoff area and different runoff area sizes can either increase or decrease the amount of water that is supplied to the cropping area.

Thus, this chapter aims to modify and calibrate a simple, one-dimensional soil water balance model (Soil Water Balance-SWB) by incorporating linear runoff estimation models in order to predict the soil water balance and crop yield under different rainwater harvesting design scenarios and to select the design most likely to succeed in a particular locality. It is expected, with the use of the modified SWB, to make reasonable estimates of crop yield and soil water balance components by predicting the amount of runoff collected in the runoff areas and add it to the amount of water supplied to the cropping area.

6.2 DESCRIPTION OF THE SOIL WATER BALANCE MODEL - SWB

SWB is a generic crop growth and irrigation scheduling model, which can be run using two types of model (Annandale *et al*. 1999):

a. The crop growth, mechanistic model calculates crop growth and soil water balance parameters.
b. The FAO-type crop factor model calculates the soil water balance without simulating dry-matter production mechanistically.

In this study, simulations were run using the crop growth model type. Therefore, only the crop growth type is described in this section. In the crop growth model type, SWB performs the calculation of the water balance and crop growth using three units, namely weather, soil and crop. In the weather unit, daily grass reference evapotranspiration is calculated using the Penman-Monteith equation.

In the soil unit of SWB, potential evapotranspiration is divided into potential evaporation and potential transpiration by calculating canopy radiant interception from simulated leaf area. This represents maximum limits of evaporation and transpiration, and these processes will only proceed at these rates if atmospheric demand is limiting. Water movement in the soil profile is simulated with a cascading model, which divides the soil profile into eleven different layers, each of them with its own physical proprieties. The soil day step procedure is performed on a daily basis following the subsequent order (Annandale *et al*. 1999):

a. Amount of precipitation intercepted by the canopy and or irrigation application;
b. Runoff from the cropping area;
c. Infiltration and redistribuition;
d. Evaporation; and
e. Transpiration

The two required inputs of SWB are rainfall and irrigation amounts. The amount of water intercepted by the canopy is assumed to be equal to the interception of radiation by the canopy. Runoff is calculated on days when rainfall and/or sprinkler/flood irrigation occur following the Runoff Curve Number method. Surface runoff is then subtracted from the rainfall and/or irrigation water allowing the remainder to infiltrate into the soil. Infiltration and redistribution of water in the soil profile are calculated on days when rainfall or drainage occurs. Water is distributed by filling soil layers to saturation, starting from the top of the profile and moving downwards. Water loss by evaporation is assumed to occur only from the top soil layer. Transpiration is calculated on days when root depth and fractional interception of radiation by photosynthetically active leaves are greater than zero using the “Campbell 1985” model (Annandale *et al*. 1999). Drainage is calculated when soil water content of a particular layer exceeds water content at field capacity taking into account a drainage factor, which is a specific soil input parameter.

In the crop unit, SWB calculates crop dry matter accumulation in direct proportion to transpiration corrected for vapour pressure deficit. It also calculates radiation-limited growth and takes the lower of the two. This dry matter is partitioned to roots, stems, leaves grain or fruits, depending on phenology calculated with thermal time and modified by water stress (Annandale *et al*. 1999).

6.3 METHODOLOGY

The soil water balance and crop yield components measured under rainwater harvesting conditions were simulated using the SWB cascading and crop growth model type, respectively (Annandale *et al*., 1999). For this purpose, the following soil water balance equations were applied to the virtual cropping area for the different rainwater harvesting designs:

<u>In-field rainwater harvesting technique</u>

$$T = P_{TCA} + R_{RA} - P_{ICA} - D - E \pm \Delta Q \qquad \text{(mm/day)} \qquad \text{Equation 6.1}$$

Where T is crop transpiration, which is directly related to crop growth, P_{TCA} is the total amount of precipitation incident on the cropped area, R_{RA} is runoff amount collected from the runoff area to the cropping area, P_{ICA} is the amount of precipitation intercepted by the canopy in the cropping area, ΔQ reflects changes in soil water storage in the root zone, D is the drainage loss and E is the surface soil evaporation.

Runoff collection from the runoff area (R_{RA}) was estimated with different runoff models, which were parameterized for the study area using different design ratios and different surface treatments. In SWB mode, only the linear model was used to predict R_{RA}. The “Morin and Cluff 1980” runoff model, despite being the best runoff predictor, was not incorporated in the SWB crop growth model due to the scarcity of long term rainfall intensity data.

The soil water balance equation for the cropped area of the in-field rainwater harvesting system (Equation 6.1) assumes that no water is lost by runoff from the cropped area. The systems were designed in such a way that no water losses through runoff did occur.

Tied ridges technique

$$T = P_{TCA} - P_{ICA} - D - E \pm \Delta Q \qquad \text{Equation 6.2}$$

In this system, the soil water balance equation did not include the contribution of runoff from the catchment area to the cropping area, since the rainwater is harvested, stored and used by the crop where it falls. The equation also did not include water losses by runoff in the cropping area, since the technique consisted of alternate ridges and furrows, with small ties across furrows to reduce the normal flow of surface runoff and store the harvested water for consumptive use by the crop.

Conventional tillage technique

$$T = P_{TCA} - P_{ICA} - D - E \pm \Delta Q - R_{CA} \qquad \text{Equation 6.3}$$

The soil water balance equation considered water losses by surface runoff in the cropping area (R_{CA}).

Crop growth and soil water balance components were calculated using the routines embedded in the SWB model as described in Section 6.2. Maize, cultivar PNR 6479, was chosen from the SWB model database to run the simulations. This cultivar is different from the Phb 3442 maize cultivar, which was used in the field trial. As a result, some of its specific growth parameters needed to be adjusted during the SWB model calibration in order to simulate observed soil water balance and yield components obtained in the field trial. The PNR 6479 maize cultivar specific growth parameters are presented in Appendix 6.1. The initial water content in the soil profile at was set at approximately 70% of plant available water. This value of initial soil water content was estimated based on the first readings of root zone soil water content during the crop growing season 2007/2008 at the Hatfield Experimental Farm of the University of Pretoria.

A flow diagram of the soil unit of SWB including the modifications made in order to predict crop yield under different rainwater harvesting management scenarios is, presented in Figure 6.1.

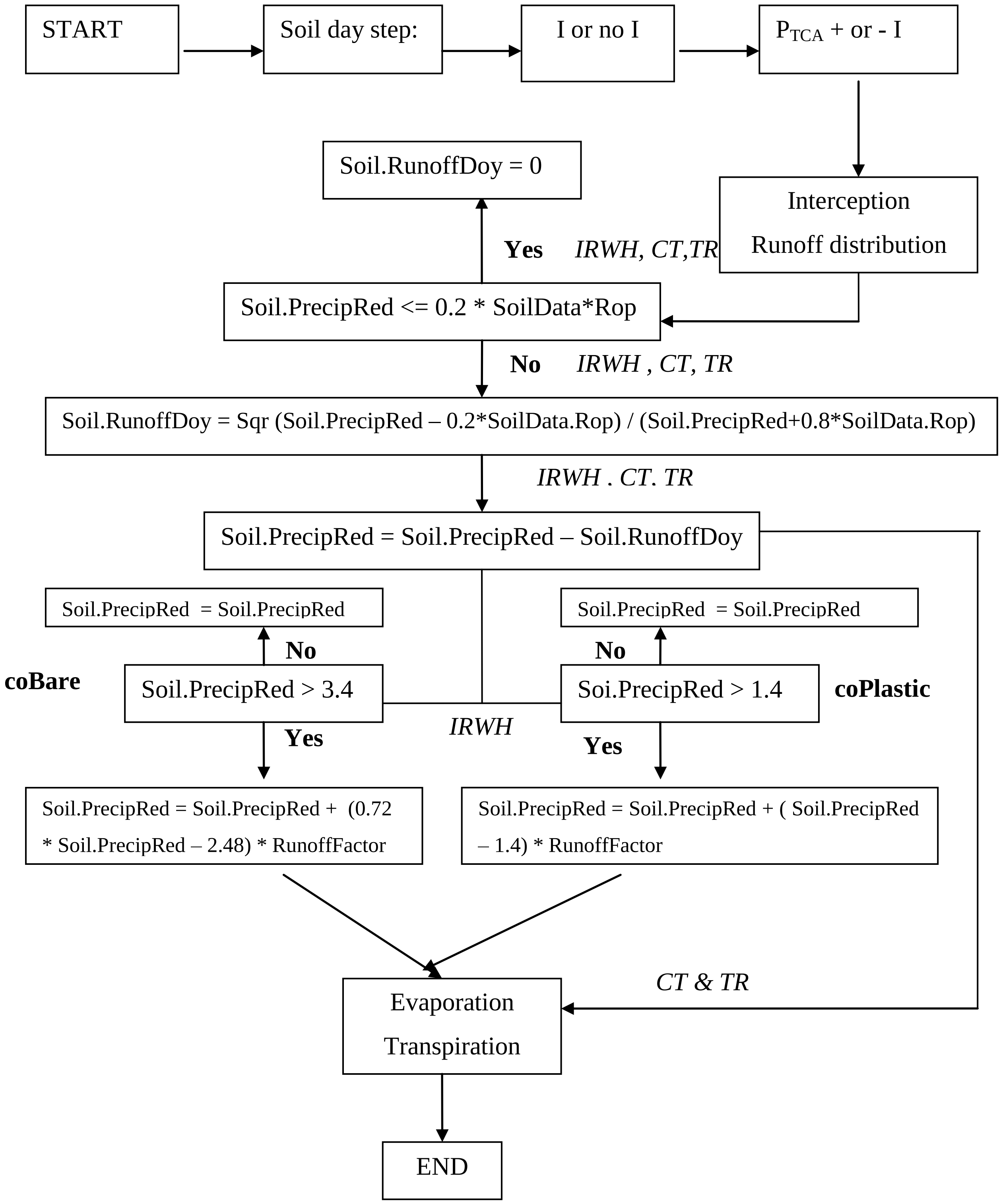
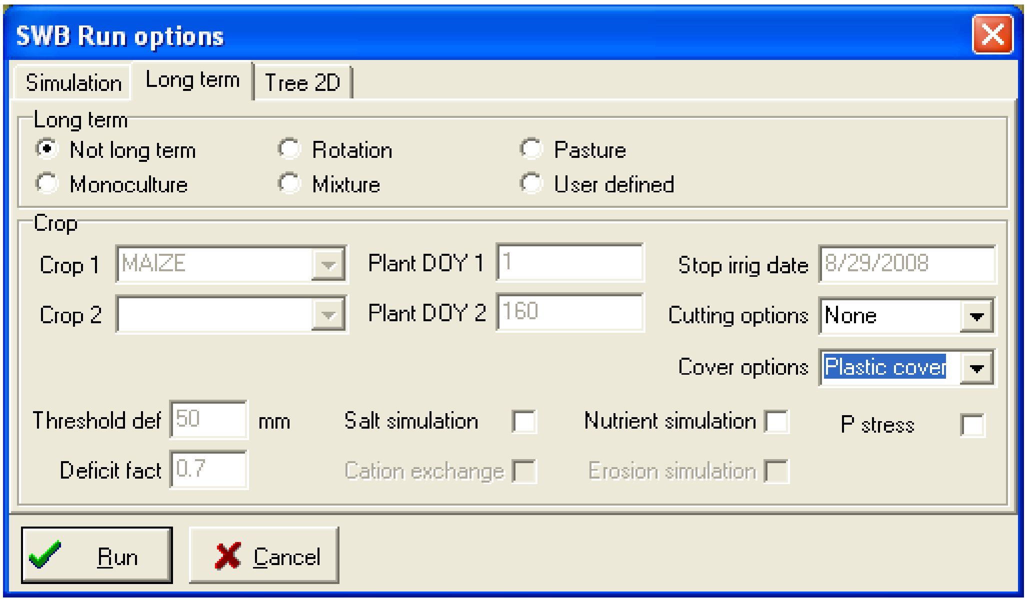


FIG. 6.1: A flow diagram illustrating the soil day step routine in the SWB, including modifications incorporated in the model in order to predict soil water balance under different rainwater harvesting designs

Where:

- **P_{TCA}** is the total rain that falls to the cropping area and **I** is the amount of sprinkler irrigation water in mm;
- **Soil.RunoffDoy** is the amount of runoff from the cropping area in mm;
- **Soil.PrecipRed** is the amount of water supplied to the cropping area through rainfall or sprinkler irrigation after crop interception in mm;
- **SoilData*Rop** is the runoff curve number in mm. It is an input parameter giving an indication of the storage of surface after the occurrence of an event of rain and or irrigation. For the in-field rainwater harvesting and tied ridge techniques, this runoff curve number is set at 10000 mm in order to simulate no runoff in the cropping area. For the conventional tillage technique the runoff curve number was fixed by calibration at 60 mm;
- **coBare** and **coPlastic** mean cover options bare and plastic, which are the two types of runoff surface treatment tested in the field trials;
- **RunoffFactor** is the design ratio (runoff area: cropping area);

In the SWB model Run Options screen, a window appears with different soil surface cover options. Figure 6.2 shows the cover options form as it appears on the screen. The user chooses cover option “None” to run simulations under the conventional tillage and tied ridge techniques. In the SWB model, simulations for conventional tillage technique differ from the ones for tied ridge technique by the choice of a different runoff number (for the conventional tillage this number is 60 mm, simulating a certain amount of runoff in the cropping area, while for the tied ridge technique a runoff number of 10 000 is used in order to simulate no runoff in the cropping area, as illustrated in Figure 6.3). The cover option “Bare runoff” is chosen to conduct simulations under the in-field rainwater harvesting technique with a bare runoff surface area, and “Plastic cover” for a plastic cover runoff surface area. The runoff models included in the SWB were parameterized at 6% slope, which was the same as that of the runoff areas in the field trials.

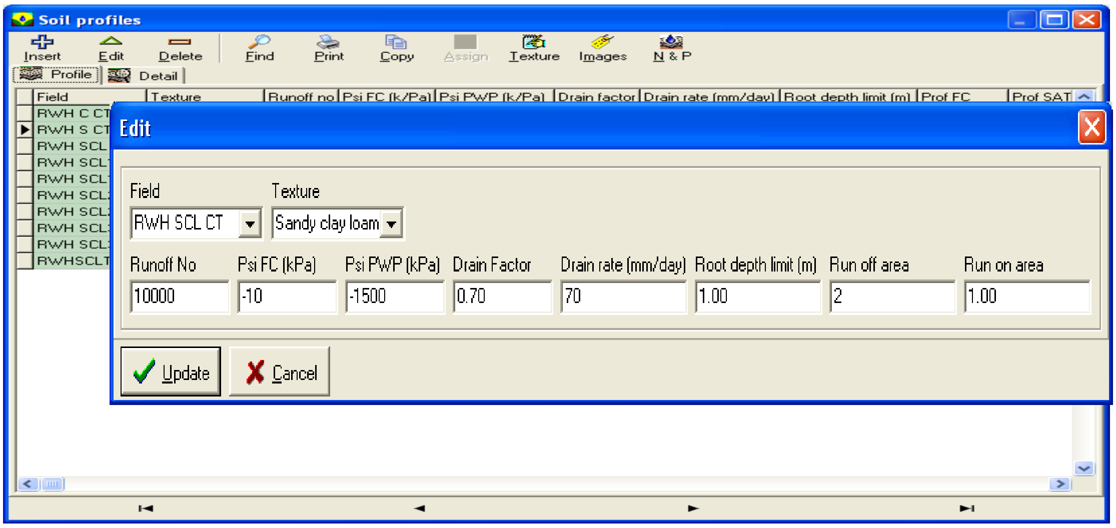


Long term
● Not long term ○ Rotation ○ Pasture
○ Monoculture ○ Mixture ○ User defined

Crop
Crop 1: MAIZE
Crop 2:
Plant DOY 1: 1
Plant DOY 2: 160
Stop irrig date: 8/29/2008
Cutting options: None
Cover options: Plastic cover
Threshold def: 50 mm
Deficit fact: 0.7
Salt simulation ☐
Cation exchange ☐
Nutrient simulation ☐
Erosion simulation ☐
P stress ☐

FIG. 6.2: SWB run options form for the different rainwater harvesting management scenarios as it appears on the screen

Figure 6.3 shows the SWB screen where the Runoff factor (which is the design ratio runoff area: cropping area) is changed based on the simulation that the user wants to run for the in-field rainwater harvesting technique. The same screen also shows where to change the runoff number, in order to predict water losses by runoff from the cropping area (for the conventional tillage technique) or to simulate no runoff (for the tied ridge and in-field rainwater harvesting techniques).



Field: RWH SCL CT
Texture: Sandy clay loam
Runoff No: 10000
Psi FC (kPa): -10
Psi PWP (kPa): -1500
Drain Factor: 0.70
Drain rate (mm/day): 70
Root depth limit (m): 1.00
Run off area: 2
Run on area: 1.00

FIG. 6.3: Soil profile form as it appears on the SWB screen illustrating where to include the magnitude of the runoff area compared to the run-on area to run simulations for a specific design ratio of the in-field rainwater harvesting system, as well as “Runoff No” which is changed in order to predict runoff in the cropping area (for the conventional tillage technique) or to simulate no runoff (for the tied ridge and in-field rainwater harvesting techniques)

SWB model calibration involved the adjustment of certain crop and soil parameters so that simulated results emulated observed values for the CT, TR and IRWH techniques. These parameters included the drainage factor, drainage rate, runoff number, dry matter water ratio, radiation conversion efficiency and specific leaf area. Field data collected during the 2007/2008 growing season at the Hatfield Experimental Farm, such as leaf area index, crop yield, total dry matter and deficit to field capacity, was used for comparison purposes. The following statistical parameters were used to evaluate the performance of the model in simulating crop growth under rainwater harvesting conditions: coefficient of determination (r^2), index of agreement (D) and mean absolute error (MAE) (De Jager, 1994).

After calibrating the SWB model, crop yield simulations were run using long-term weather data from Pretoria – Hatfield (from 1961 to 2000), for a sandy, sandy clay loam and clay soil for all the water harvesting treatments tested in the study area. Since the runoff models were only parameterized for a sandy clay loam soil (the study area soil type), the same runoff parameters were used for a sandy and a clay soil, assuming that they have the same level of crust formation and the same depth of surface retention. All other soil parameters were kept constant; expect plant available water in the root zone. Plant available water values of 72, 174 and 200 mm m^{-1} were used for sandy, sandy clay loam and clay soils, respectively (FAO, 2001). The initial soil water content in the beginning of a long-term simulation was assumed to be 70% of plant available water in all soil types.

These long-term crop yield simulations were arranged in an ascendant order and fit into a normal probability distribution function to illustrate the probability of excedence of a certain crop yield level under different rainwater harvesting conditions. This probability of excedence of a certain crop yield takes into account changes of rainfall amount and distribution from one crop growing season to another. The long-term rainfall record for Hatfield was also fit into the normal distribution function to obtain the probability of getting at least a certain amount of rainfall in a rainy season and its return period in years.

The normal probability distribution function is expressed in Equation 6.4 (Miller & Freund, 1977).

$$f\left(x;\mu,\sigma^2\right)=\frac{1}{\sqrt{2\pi\sigma}}e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \qquad \text{Equation 6.4}$$

Where: parameters μ and σ are the mean and standard deviation of a series of long-term simulated crop yield for each rainwater harvesting treatment (this long-term simulated crop yield for the semi-arid area of Pretoria goes from 1961 up to 2000); x is each of the simulated crop yield values from the long-term data series.

The return period of a certain seasonal rainfall amount, in years, is the inverse of its probability of excedence.

Simulations were also run for Chokwe, which is a semi-arid area located in the south of Mozambique. Soil and crop specific parameters were kept the same as the ones used for simulations in Pretoria. Crop yield and soil water balance component simulations were performed with only six consecutive years of weather data due to the limited availability of daily weather data for this locality.

6.4 RESULTS AND DISCUSSION

In order to calibrate SWB to predict crop yield under different rainwater harvesting techniques, certain parameters in the model were adjusted by making a comparison of observed to simulated root depths, leaf area index, crop yield and total dry matter, as well as deficit to field capacity values for the growing season 2007/2008 in Hatfield Experimental Farm of the University of Pretoria. These parameters with their respective values are included in Table 6.1.

Table 6.1: Soil and crop specific parameters used in the SWB model calibration for the different rainwater harvesting techniques on a sandy clay loam soil

Soil and crop specific parameters	**Parameter value**
Drainage factor*	0.7
Maximum drainage rate (mm/d)*	70
Runoff curve number (mm)*	60 (CT), 10 000 (TR & IRWH)
Initial soil water content (mm/m)*	110
Canopy extinction coefficient for solar radiation**	0.32 (CT & TR), 0.69 (IRWH)
Corrected dry matter-water ratio (Pa)*	9.5
Radiation conversion efficiency (kg/MJ)*	0.0016
Base temperature (C^o)***	10
Temperature for optimum crop growth (C^o)****	20
Cutoff temperature (C^o)****	30
Emergence day degrees (d C^o)**	60
Day degrees at end of vegetative growth (d C^o)**	820
Day degrees for maturity (d C^o)**	1650
Transition period day degrees (d C^o)**	12
Day degrees for leaf senescence (d C^o)**	900
Maximum crop height (m)**	2.2
Maximum root depth (m)**	1
Fraction of total dry matter translocated to heads*	0.05
Canopy storage (mm)*	0.3
Leaf water potential at maximum transpiration (kPa)*	-2000
Maximum transpiration (mm/d)*	9
Specific leaf area (m^2/kg)*	17
Leaf stem partition parameter (m^2/kg)*	1.8
Total dry matter at emergence (kg/m^2)*	0.003
Fraction of total dry matter partitioned to roots*	0.28
Root growth rate ($m^2/kg^{0.5}$)*	4
Stress index*	0.9

* Estimated by calibration against measurements of growth, phenology, yield and soil water content

** Observed in the field trials at the study site

*** Observed by Annandale *et al.*, 1999

**** Observed by Jovanovic & Annandale, 1999

As is evident from Table 6.1, a runoff curve number of 10 000 mm was used in the SWB for the simulations under tied ridge and in-field rainwater harvesting techniques. This number was chosen to eliminate estimation of any runoff from the cropping areas, since the design of these techniques assumes that there are no water losses by runoff in the cropping area. The runoff curve number of 60 used to simulate runoff losses in the cropping area of the conventional tillage technique was obtained by SWB model calibration (by comparing observed to simulated values of crop yield and soil water content in the root zone with the help of statistical parameters). The calculated value of canopy radiation extinction coefficient for the conventional tillage and tied ridge techniques was lower than the one for in-field rainwater harvesting (see Section 4.6). This was due to the use of a different row spacing (100 cm row spacing for the conventional tillage and tied ridge and 70 cm for the in-field rainwater harvesting technique). Minimum values of radiation conversion efficiency (a crop specific parameter used to calculate dry matter production under conditions of radiation-limited growth) and corrected dry matter-water ratio (a crop specific parameter determining water use efficiency) were calculated based on observed values of fractional interception of radiation, total dry matter and weather data during the crop growing season 2007/2008 (see Sections 4.7 and 4.8). A minimum radiation conversion efficiency value of 0.0012 kg/MJ was obtained by averaging fractional interception of radiation and total dry matter values from the conventional tillage and tied ridge treatments. A minimum dry matter-water ratio value of 7.5 Pa was calculated as an average for all the water harvesting treatments. These values needed to be increased based on SWB model calibration to give reliable simulations.

Soil water balance components and crop yields for the different rainwater harvesting treatments were simulated for the growing season 2007/2008 and compared to observed values. The 2007/2008 season had a total seasonal rainfall of 810 mm, which is above the average seasonal rainfall (670 mm) for Hatfield. Therefore, it can be classified as a wet season. As observed in the normal probability distribution curve for Hatfield – Pretoria, shown in Figure 6.4, the probability of exceding 810 mm of rain in a season is about 28%. This means, that on average, only 28% of the time (about one year out of 4) the total seasonal rainfall can be expected to exceed 810 mm.

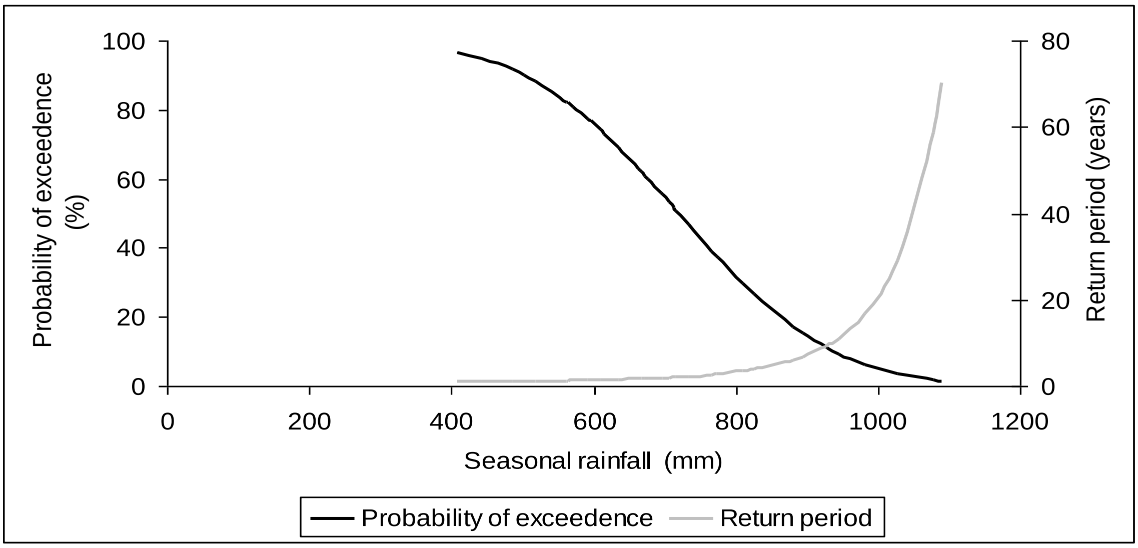


FIG. 6.4: Probability of exceedence of seasonal rainfall and the return period at Hatfield, Pretoria

The following rainfall intervals were established for a very dry, dry, wet and very wet rainfall seasons in the semi-arid area of Pretoria in accordance with Figure 6.4. The average seasonal rainfall in Pretoria is 670 mm. Table 6.2 shows rainfall intervals for the different rainy seasons.

Table 6.2: Rainfall intervals for a dry, very dry, wet and very wet season in Pretoria

	Total seasonal rainfall amount (mm)	
Season	Minimum	Maximum
Very dry	400	449
Dry	450	670
Wet	671	950
Very wet	950	1100

A comparison between simulated and observed crop yield in the 2007/2008 growing season, as well as simulated values of seasonal water balance components are presented in Table 6.3 to illustrate the performance of the SWB model calibration for Hatfield, Pretoria.

Table 6.3: A comparison between simulated and observed crop yield, as well as simulated seasonal soil water balance components in the cropping area, 2007/2008 wet season, Hatfield Experimental Farm, Pretoria

	Rainwater harvesting treatments							
Variable	**CT**	**TR**	**1:1P**	**1:2P**	**1:3P**	**1:1B**	**1:2B**	**1:3B**
Observed yield on the total area (ton/ha)	7.7	9.4	10.2	6.4	5.9	10.4	6.3	4.8
Simulated yield on the total area (ton/ha)	8.4	9.8	10.9	7.4	5.5	10.2	7.2	5.5
Observed rainfall (mm)	634	634	634	634	634	634	634	634
Observed runoff in the runoff area added to the cropping area (mm)	-	-	552	1105	1657	339	679	1017
Simulated transpiration (mm)	253	277	522	513	520	506	524	515
Simulated evaporation (mm)	285	283	136	146	144	139	134	137
Simulated drainage (mm)	0	15	404	956	1502	207	531	875
Simulated crop interception (mm)	7	7	13	13	13	12	13	13
Simulated runoff in the cropping area (mm)	76	0	0	0	0	0	0	0
Simulated changes in soil water storage (mm)	13	52	111	111	112	109	111	111
Mass balance error	0	0	0	0	0	0	0	0

Crop yield simulation results presented in Table 6.3, when taking into account the total area used for crop production (including the space occupied by the runoff areas in the in-field rainwater harvesting plots), show that the highest yield for the wet growing season 2007/2008 is obtained with the 1:1P, followed by the 1:1B. Crop yield simulations for in-field rainwater harvesting in a wet season, considering various runoff area lengths, indicate that the shorter the runoff area the higher the yield on a total area basis. Since it was a wet season, with 810 mm of total rainfall, the amplification of the runoff area in order to collect more runoff and increase plant available water in the cropping area, did not considerably increase the amount of water transpired by the crop. Apart from the rain that fell directly onto the cropping areas, large amounts of rainfall were harvested by the runoff areas and added to the cropping areas. For instance, for the design ratio 1:1B, 53.4% of the rainfall (339 mm) was harvested as runoff and added to the cropping area (see Table 4.1 in Section 4.3.1 for observed runoff efficiencies from different runoff area lengths). As a result, it is evident that, in a wet season, it is a waste of arable land attempting to enlarge the size of the runoff areas in order to increase the amount of water supplied to the cropping area for maximum crop production. It can also be observed that simulated drainage losses increased with an increase in the runoff area, and from a bare to a plastic covered runoff area. This is expected, since the collected amount of runoff from the runoff areas was double and three times more for the 1:2 and 1:3 IRWH design ratios, respectively, when compared to the design ratio 1:1. In addition, these large amounts of runoff added to the cropping area might have resulted in nutrient leaching (not simulated), and consequently in yield reduction. This is the reason why it is important to select the ideal design for the in-field rainwater harvesting on a total area basis, as land is usually limiting for crop production. Even if land was not limiting, it would be important to consider other factors associated with an increase of runoff area in a wet season. These include, besides massive drainage losses, which will lead to enormous nutrient leaching, water-logging problems, as well as a huge amount of labour involved in the construction and maintenance of the systems. The choice of the optimal in-field rainwater harvesting design, especially in wetter seasons, can maximize crop yield by considerably reducing drainage losses.

The third highest crop yield was obtained with the tied ridge technique, followed by the conventional tillage technique. Mzirai *et al.* (2002) state that the tied ridge technique performs well where the main constraints are soil related, but rainfall is adequate. Soil constraints may be related to low infiltration rates, caused by surface crusting. The 2007/2008 rainy season was quite wet, with a reasonably good rainfall distribution. The highest amount of rain fell in January 2008 (38%), followed by December 2007 (26%) and March 2008 (19%). Little precipitation was registered in November (7%) and February (10%). The crop was planted in November and harvested in March. Therefore, the low amount of rainfall registered in November might not have had a severe negative effect on the crop growth, since the root system and the canopy were still small. In addition, December and January were the wettest periods, which coincided with flowering and grain filling periods, were the crop needed a lot of water. As a result, it can be stated that, water was generally not limiting maize production during the growing season 2007/2008. Some yield reduction due to water-logging problems might have occurred because of the low infiltration rates in the cropping area (final infiltration rate of only 3.9 mm/hr), especially towards the end of the crop growing season. From Table 6.3, it can be observed that evaporation losses for the tied ridge and conventional tillage techniques are higher than for the in-field rainwater harvesting treatments. This might be attributed to the use of a wider row spacing (100 cm) in the conventional tillage and tied ridge techniques than in the in-field rainwater harvesting technique (70 cm). The SWB model was able to simulate these differences using different canopy extinction coefficients for different row spacings.

A comparison of simulated to measured values of root depth, leaf area index, total dry matter and harvestable dry matter, as well as deficit to field capacity are shown in Figures 6.5 to 6.12 for the different rainwater harvesting treatments. Statistical analyses are also included to illustrate the performance of the model after calibration.

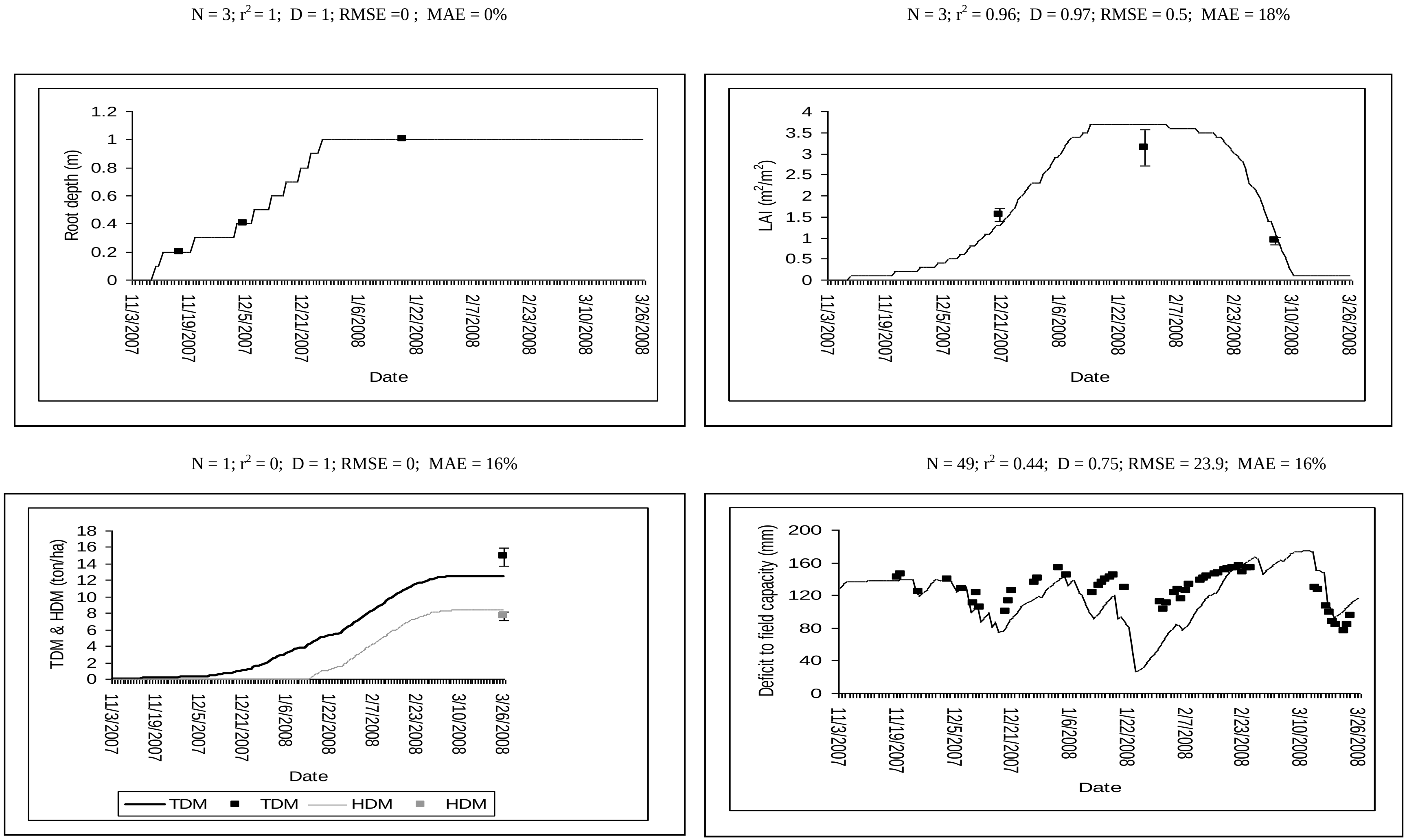
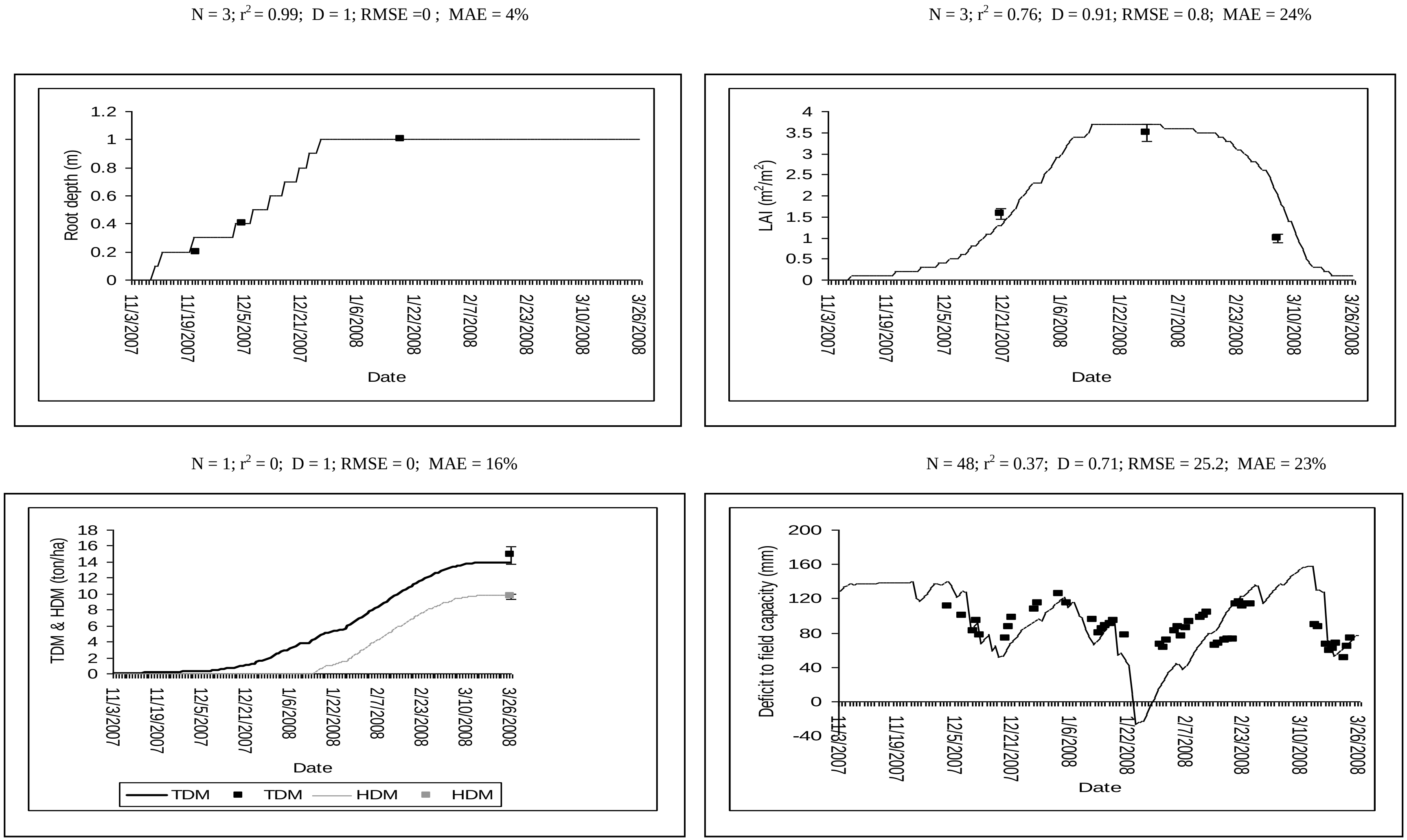


FIG. 6.5: Simulated (□) and measured values (■) root depth, leaf area index (LAI), top dry matter (TDM) and harvestable dry matter (HDM), as well as deficit to field capacity (2007/2008 wet season, treatment CT)



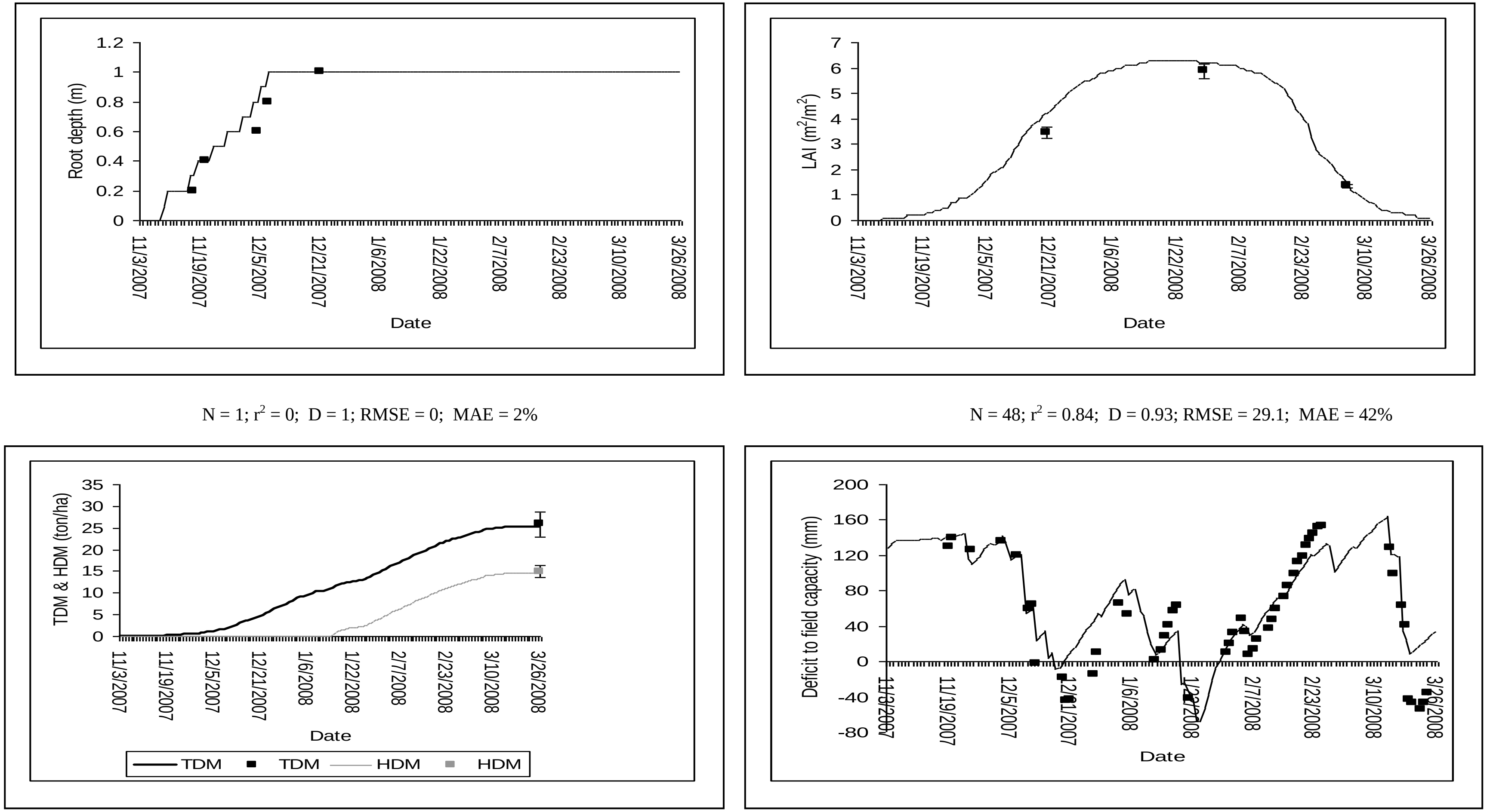
N = 3; r^2 = 0.99; D = 1; RMSE =0 ; MAE = 4%

N = 3; r^2 = 0.76; D = 0.91; RMSE = 0.8; MAE = 24%

N = 1; r^2 = 0; D = 1; RMSE = 0; MAE = 16%

N = 48; r^2 = 0.37; D = 0.71; RMSE = 25.2; MAE = 23%

FIG. 6.6: Simulated (□) and measured values (■) root depth, leaf area index (LAI), top dry matter (TDM) and harvestable dry matter (HDM), as well as deficit to field capacity (2007/2008 wet season, treatment TR)


N = 5; r^2 = 0.92; D = 0.95; RMSE =0.1 ; MAE = 17%

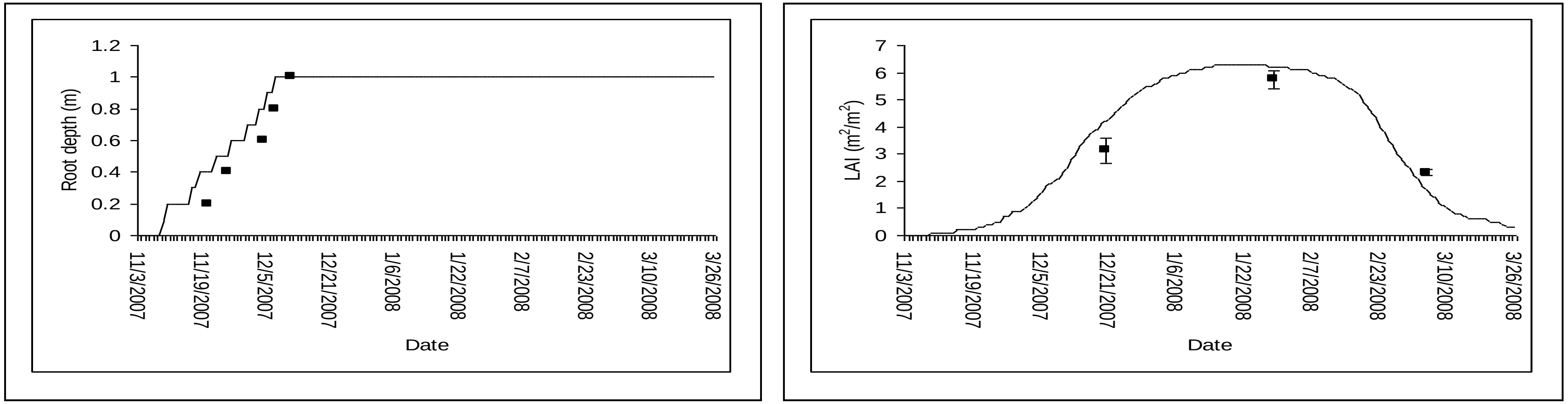
N = 3; r^2 = 0.98; D = 0.98; RMSE = 0.6; MAE = 12%

N = 1; r^2 = 0; D = 1; RMSE = 0; MAE = 2%

N = 48; r^2 = 0.84; D = 0.93; RMSE = 29.1; MAE = 42%

FIG. 6.7: Simulated (□) and measured values (■) root depth, leaf area index (LAI), top dry matter (TDM) and harvestable dry matter (HDM), as well as deficit to field capacity (2007/2008 wet season, treatment 1:1B)

N = 5; r^2 = 0.95; D = 0.92; RMSE =0.2 ; MAE = 22% N = 3; r^2 = 0.87; D = 0.94; RMSE = 1; MAE = 20%



N = 1; r^2 = 0; D = 1; RMSE = 0; MAE = 9% N = 51; r^2 = 0.78; D = 0.94; RMSE = 29.2; MAE = 52%

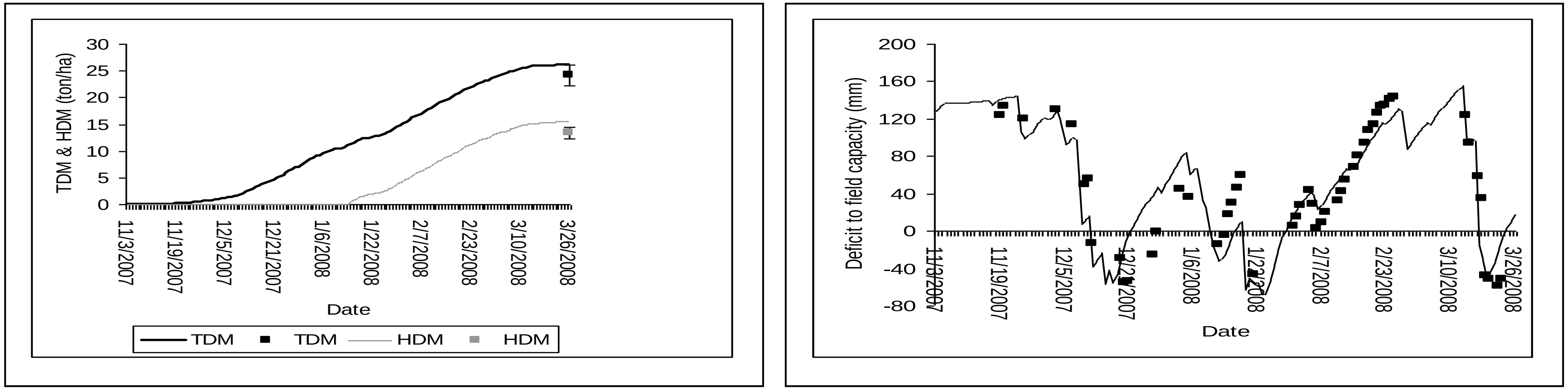
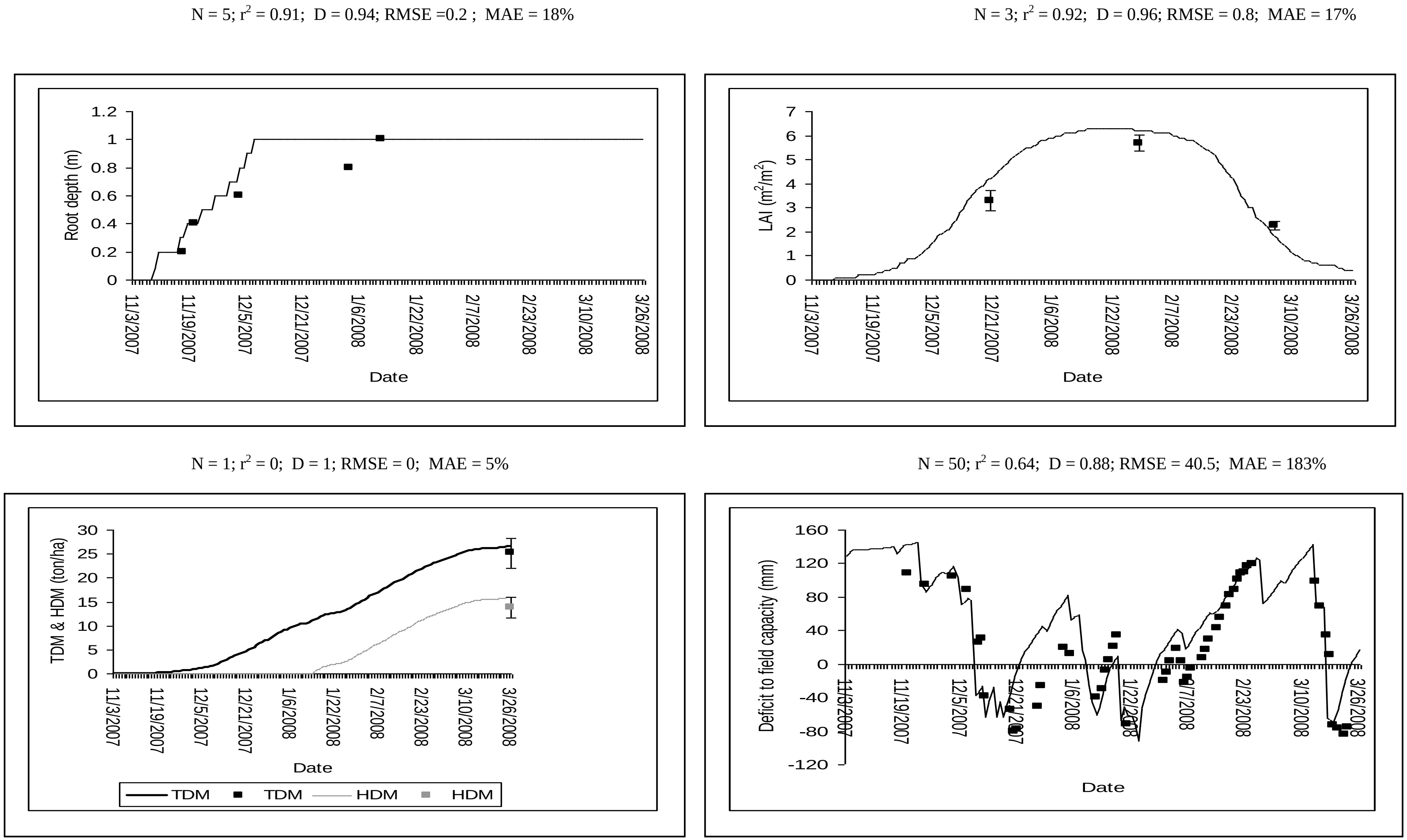


FIG. 6.8: Simulated (□) and measured values (■) root depth, leaf area index (LAI), top dry matter (TDM) and harvestable dry matter (HDM), as well as deficit to field capacity (2007/2008 wet season, treatment 1:2B)



N = 5; r^2 = 0.91; D = 0.94; RMSE =0.2 ; MAE = 18%

N = 3; r^2 = 0.92; D = 0.96; RMSE = 0.8; MAE = 17%

N = 1; r^2 = 0; D = 1; RMSE = 0; MAE = 5%

N = 50; r^2 = 0.64; D = 0.88; RMSE = 40.5; MAE = 183%

FIG. 6.9: Simulated (□) and measured values (■) root depth, leaf area index (LAI), top dry matter (TDM) and harvestable dry matter (HDM), as well as deficit to field capacity (2007/2008 wet season, treatment 1:3B)

N = 4; r^2 = 0.97; D = 0.94; RMSE =0.2 ; MAE = 21%

N = 3; r^2 = 0.85; D = 0.94; RMSE = 1; MAE = 21%

N = 1; r^2 = 0; D = 1; RMSE = 0; MAE = 1%

N = 51; r^2 = 0.81; D = 0.92; RMSE = 31.7; MAE = 86%

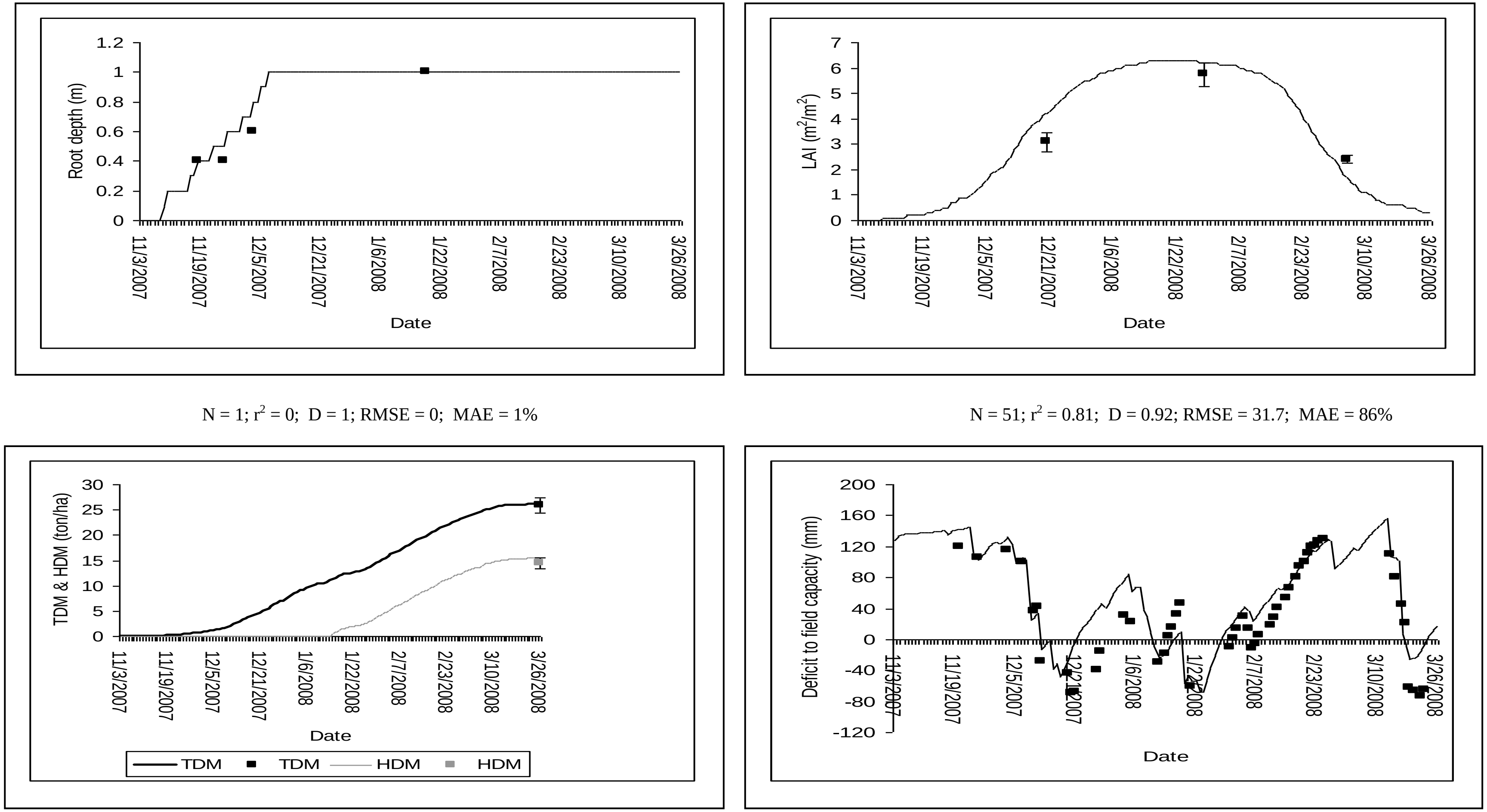
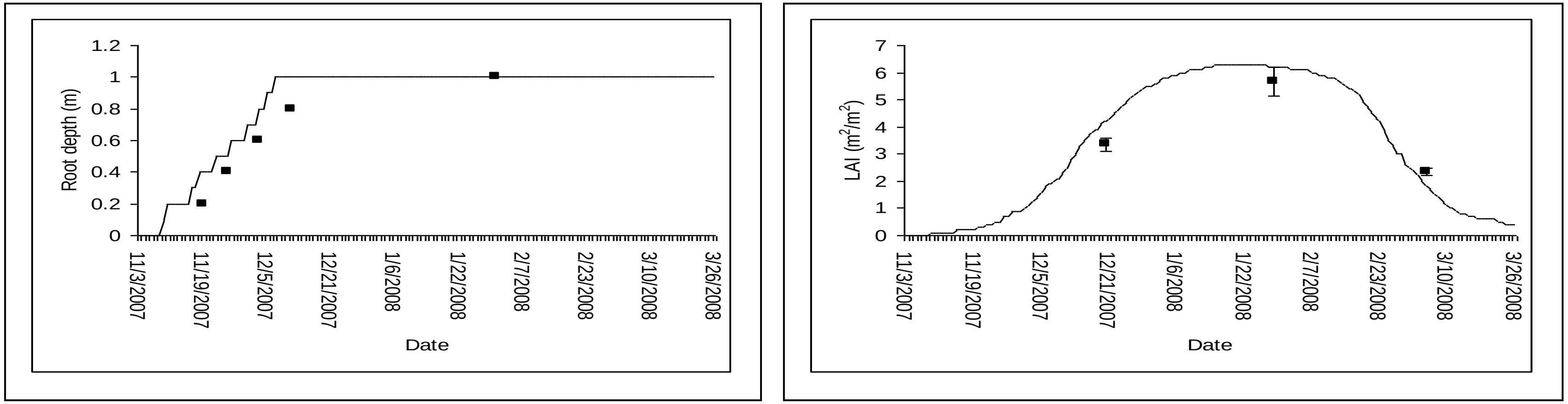


FIG. 6.10: Simulated (□) and measured values (■) root depth, leaf area index (LAI), top dry matter (TDM) and harvestable dry matter (HDM), as well as deficit to field capacity (2007/2008 wet season, treatment 1:1P)

N = 5; r^2 = 0.94; D = 0.92; RMSE =0.2 ; MAE = 23%

N = 3; r^2 = 0.93; D = 0.96; RMSE = 0.8; MAE = 17%



N = 1; r^2 = 0; D = 1; RMSE = 0; MAE = 4%

N = 51; r^2 = 0.62; D = 0.88; RMSE = 40.7; MAE = 166%

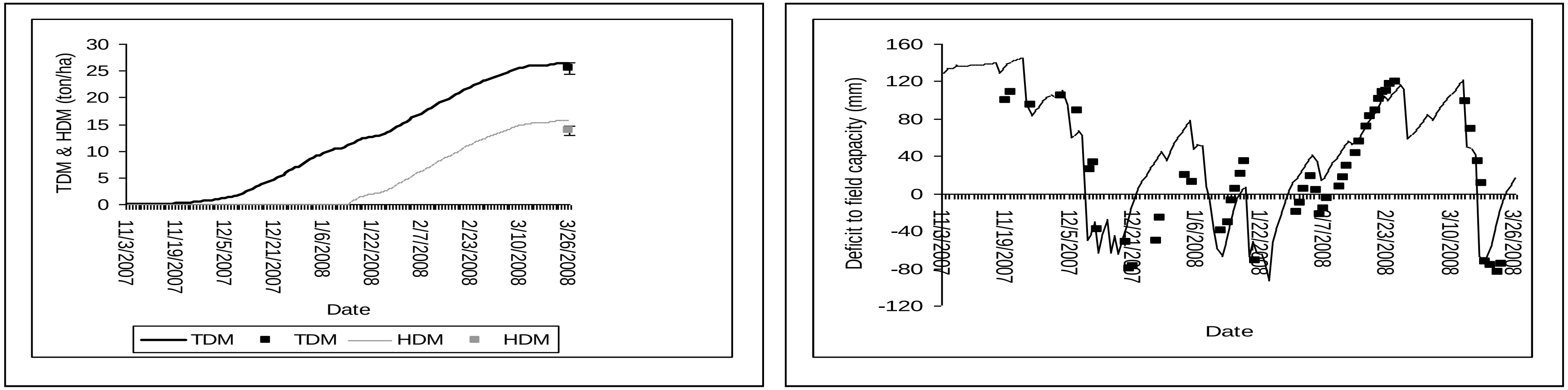
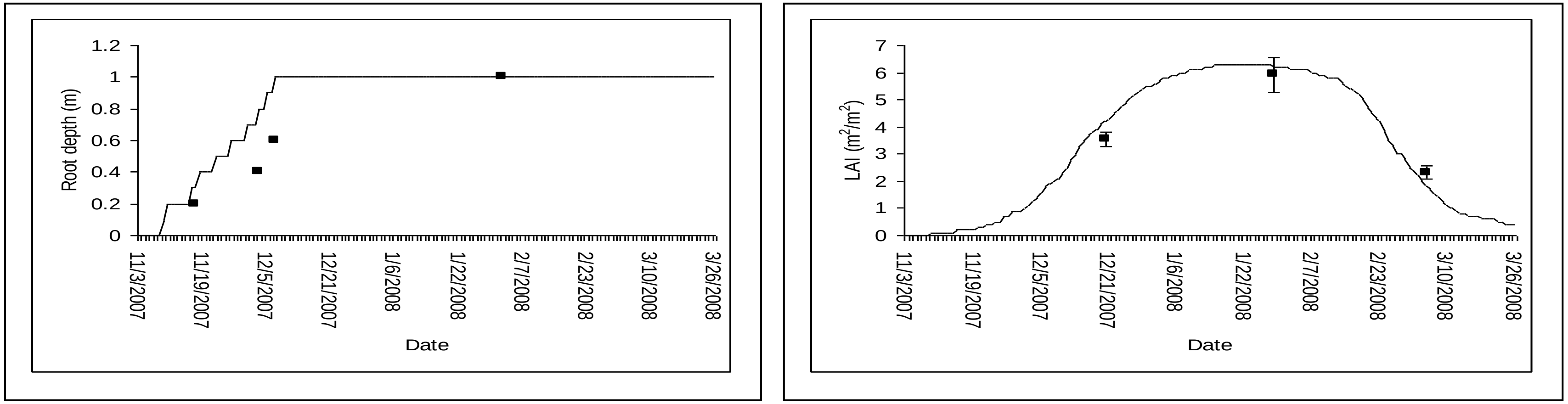


FIG. 6.11: Simulated (□) and measured values (■) root depth, leaf area index (LAI), top dry matter (TDM) and harvestable dry matter (HDM), as well as deficit to field capacity (2007/2008 wet season, treatment 1:2P)

N = 5; r^2 = 0.72; D = 0.80; RMSE =0.3 ; MAE = 40%

N = 3; r^2 = 0.95; D = 0.98; RMSE = 0.6; MAE = 12%



N = 1; r^2 = 0; D = 1; RMSE = 0; MAE = 11%

N = 50; r^2 = 0.5; D = 0.83; RMSE = 46.1; MAE = 594%

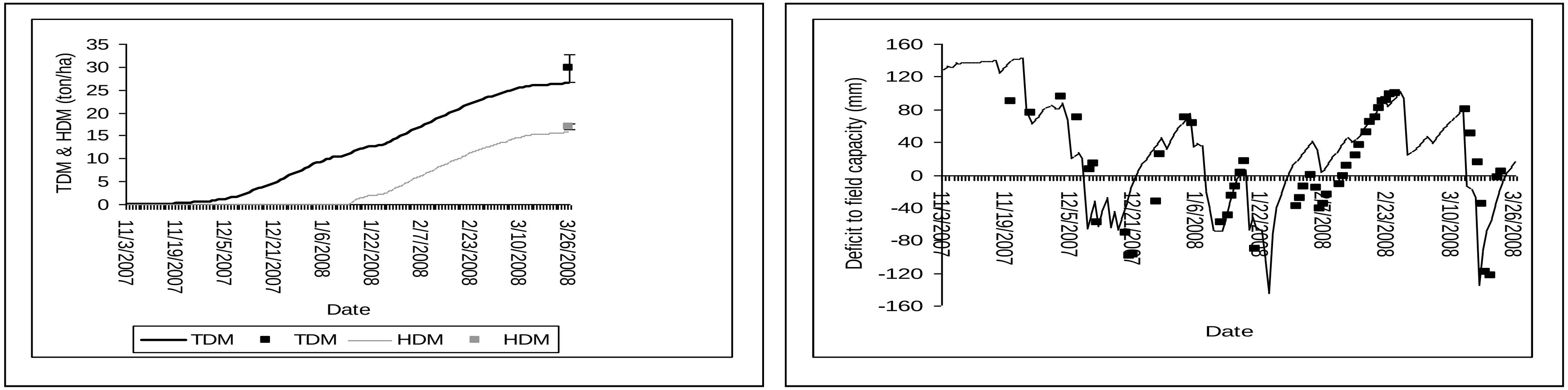


FIG. 6.12: Simulated (□) and measured values (■) root depth, leaf area index (LAI), top dry matter (TDM) and harvestable dry matter (HDM), as well as deficit to field capacity (2007/2008 wet season, treatment 1:3P)

According to De Jager (1994), the evaluation of the model is positive when the coefficient of determination (r^2) and Willmot (1982) index of agreement are greater that 0.8 and mean absolute error (MAE) is less than 20%. Taking into account the statistical parameters presented in Figures 6.5 to 6.12, the SWB model was calibrated with reasonable accuracy for all the rainwater harvesting treatments. It is important to highlight the fact that the SWB is a simple, one-dimensional model, which simulates crop dry matter accumulation in direct proportion to transpiration corrected for vapour pressure deficit. It also calculates radiation-limited growth, and takes the lower of the two. This dry matter is then partitioned to roots, stems, leaves and grain. Partitioning depends on phenology calculated with thermal time and modified by water stress (Annandale *et al.* 1999). SWB does not consider yield reduction due to water-logging or nutrient leaching. In addition, it does not take into account increased/or decreased evaporation losses by the implementation of ridges as cropping areas. Crop growth is better simulated by the SWB than soil water content. This might be related to possible errors while conducting soil water content measurements. Access tubes for measuring soil water content were installed in the middle of the cropping areas, and these cropping areas for the tied ridge and in-field rainwater harvesting were ridges. Therefore, the soil around the access tube was quite loose especially during wet periods, allowing it to move downwards and also creating air entry spaces around, which could have affected the soil water content readings. In addition, water losses by crop interception of rainfall, drainage and evaporation were estimated by the SWB model calibration, which might not reflect the actual losses occurring in the field at the study site.

6.5 CONCLUSIONS AND RECOMMENDATIONS

The Soil Water Balance model can be used to predict crop yield under rainwater harvesting conditions with reasonable accuracy. Scenarios can be run for different planting dates and initial soil water content levels. This makes the model a very useful tool to help planning the implementation of a rainwater harvesting project, especially in semi-arid areas, where rainfall is so erratic in amount and distribution throughout the season and from one season to another.

The Soil Water Balance model needs to be calibrated and validated for different soil types in order to predict crop yield for diverse places more precisely. It also needs to take into account yield reduction when the plant available water is above the optimum requirement for maximum crop growth. This can lead to water-logging problems and excessive drainage losses accompanied with nutrient leaching below the root zone. Thus, the nitrogen balance component should be incorporated in SWB crop yield simulations. The model needs to consider the effect of different planting densities on crop yield and soil water balance components. Consequently, a two dimensional modeling approach, which calculates crop dry matter accumulation in proportion to both, transpiration corrected for vapour pressure deficit and radiation-limited growth, would be more appropriated.

Analysis of long-term record of daily rainfall data is helpful to predict the probability of exceedence of certain seasonal rainfall amount and its return period in a semi-arid area. However, in order to infer the occurrence of certain type of rainy season more precisely, this type of study should be combined with medium term weather forecast studies. Based on that, the design of the in-field rainwater harvesting most likely to be successful in a particular season can be selected. This can maximize crop yield by mainly minimizing percolation losses in the crop root zone, which also protects the environment from pollution due to nutrient leaching.

CHAPTER 7

SELECTION OF THE IDEAL RAINWATER HARVESTING MANAGEMENT STRATEGY IN SEMI-ARID AREAS WITH THE HELP OF THE SOIL WATER BALANCE MODEL - SWB

7.1 OBJECTIVES AND HYPOTHESES

The main objective of this chapter is to select the ideal rainwater harvesting management strategy in two different semi-arid areas (Pretoria and Chokwe) with the help of the Soil Water Balance model. The following hypotheses were formulated with the intension of being tested by simulations:

a. The drier the climate, the bigger the runoff area: cropping area design ratio of the in-field rainwater harvesting technique needs to be;

b. The in-field rainwater harvesting technique will perform worse (per total surface area) than the tied ridge and the conventional tillage techniques under high rainfall amounts;

c. Under high rainfall amounts maize yield will be higher with the implementation of the tied ridges than with the conventional tillage technique;

d. The ideal rainwater harvesting management strategy for a particular place is mainly determined by the total annual rainfall amount;

e. The optimum in-field rainwater harvesting design is a function of a seasonal rainfall amount and soil surface characteristics;

f. The optimum in-field rainwater harvesting design system will maximize crop yield by minimizing wasteful water losses;

7.2 PRETORIA-SOUTH AFRICA

Crop yield simulations were run for long-term weather data from Pretoria – Hatfield, a semi-arid area, for sandy, sandy clay loam and clay soils using the SWB model. The long-term climatic data included 40 years of daily rainfall and maximum and minimum temperatures, which is the minimum weather data required for SWB simulations. These long-term crop yield simulations were fit into a normal probability distribution function to illustrate the probability of excedence of a certain crop yield level under different rainwater harvesting conditions in the semi-arid area of Pretoria. In terms of different soil types, the only change made in the SWB model was different values of field capacity and permanent wilting point, although it is known that different soil textures have different soil characteristics, such as drainage and evaporation rates, surface crusting, hydraulic conductivity, bulk density, porosity, organic matter content, soil temperature and others (Foster, 1949; Slatyer, 1967; FAO, 1991; Miyazaki, 1993). According to FAO (2001), typical values for plant available water vary from 50 to 110 mm/m on sandy soils, 120 to 175 mm/m on sandy clay loam soils and 120 to 200 mm/m on clay soils. Based on this, for sandy soils, soil water content at field capacity and permanent wilting point were assumed to be 116 mm/m and 44 mm/m, respectively. As a result, a plant available water of 72 mm/m was used. For sandy clay loam soils, at field capacity, a soil water content value of 254 mm/m was determined in the field, while permanent wilting point was assumed to be at 80 mm/m, giving a plant available water value of 174 mm/m. For clay soils, soil water content at field capacity and permanent wilting point were assumed to be at 300 mm/m and 100 mm/m, respectively. Therefore, a plant available water value of 200 mm/m was used in SWB. Other soil parameters for sandy and clay soils were kept the same as for sandy clay loam soils. The initial soil water content in the beginning of a long-term simulation was assumed to be 70% of plant available water in all soil types. Figure 7.1 illustrates the probability of exceedence of a certain level of crop yield on a total area basis (including the space occupied by the runoff areas in the IRWH technique), using different rainwater harvesting strategies in Pretoria for three different soil types.

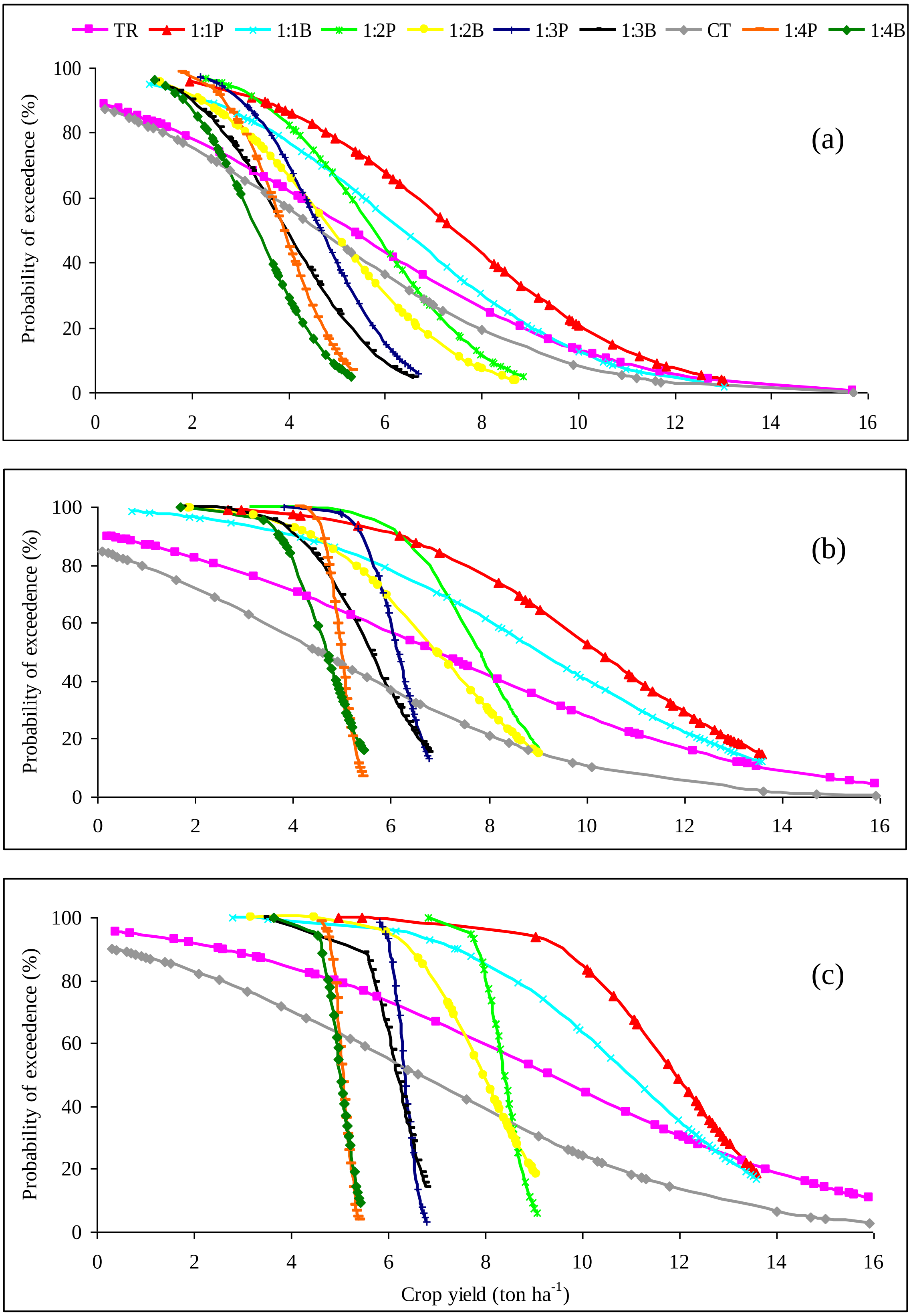


FIG. 7.1: Probability of exceedence of a certain level of crop yield on a **total area basis**, using different rainwater harvesting strategies on sandy soils (a), sandy clay loam (b) and clay soils (c) in the semi-arid area of Pretoria

An analysis of the probability of exceedence of a certain crop yield on a total area basis (considering all arable land used for crop production, including the space occupied by the runoff areas in the IRWH technique), as presented in Figure 7.1, is very important when arable land is limiting for crop production. The ideal rainwater harvesting strategy in this case will be the one giving higher crop yields with the use of less total arable land.

As observed in Figure 7.1, on sandy soils, the probability of exceeding a certain crop yield by using tied ridges instead of conventional tillage technique is almost the same. It means that, the advantage of implementing tied ridges by minimizing runoff losses in the cropping area is not pronounced. This is because on sandy soils the amount of plant available water that can be retained is much lower than on sandy clay loam and clay soils. Therefore the performance of tied ridges is constrained by the root zone water storage capacity of sandy soils. For this reason it can be stated that tied ridges is not a good strategy to be implemented on sandy soils. In addition, since sandy soils are light, they cannot sustain ridges for long periods. Moreover, runoff on sandy soils is expected to be very low due to high infiltration rates, which minimizes the difference in crop yield between the conventional tillage and the tied ridge techniques. Sandy clay loam or clay soils proved to be more appropriate for the implementation of tied ridges than sandy soils in the semi-arid area of Pretoria.

As illustrated in Figure 7.1, the 1:1 design ratio of the in-field rainwater harvesting technique with a plastic covered runoff area, followed by the same ratio with a bare runoff area is, in general, the ideal rainwater harvesting strategy for any seasonal rainfall amount below 950 mm on sandy, sandy clay loam and clay soils. In other words, the 1:1 design ratio of the in-field rainwater harvesting technique is, in most years, the ideal rainwater harvesting strategy in the semi-arid area of Pretoria. The probability of exceeding minimum expected maize yields is higher with the implementation of bigger design ratios of the in-field rainwater harvesting technique with a plastic covered runoff area. However, the difference is negligible when compared to 1:1 design ratio of the in-field rainwater harvesting system. In addition, there is an increased amount of drainage losses, and consequently nutrient leaching with an increase of the design ratios, which can lead to crop yield reduction (see Figure 7.2). Figure 7.2 illustrates simulated drainage losses for a dry and wet year on sandy, sandy clay loam and clay soils in the semi-arid area of Pretoria. A long-term simulation (from 1961 to 2000) was run for the different rainwater harvesting treatments, on different soil types, for Pretoria. For all the different simulations, planting date was set at 3rd November (the same as that one used in the field trial) and initial soil water content at the beginning of the long-term simulation was assumed to be 70% of plant available water for the different soil types. The 1992/1993 rainy season was randomly selected from the long-term simulation to illustrate drainage losses in a dry year for the different rainwater harvesting treatments. The total rainfall in the 1992/1993 season was 440 mm, with a probability of excedence of about 90%, and return period of approximately one year. During the crop growing season 1992/1993 (from November to March), the total amount of rainfall was 390 mm. The 1977/1978 rainy season was chosen to demonstrate drainage losses in a wet year. The total rainfall in this season was 950 mm, with a probability of exceedence of about 10%, and return period of 10 years, as presented in Figure 6.4. The total amount of rainfall during this crop growing season was 808 mm.

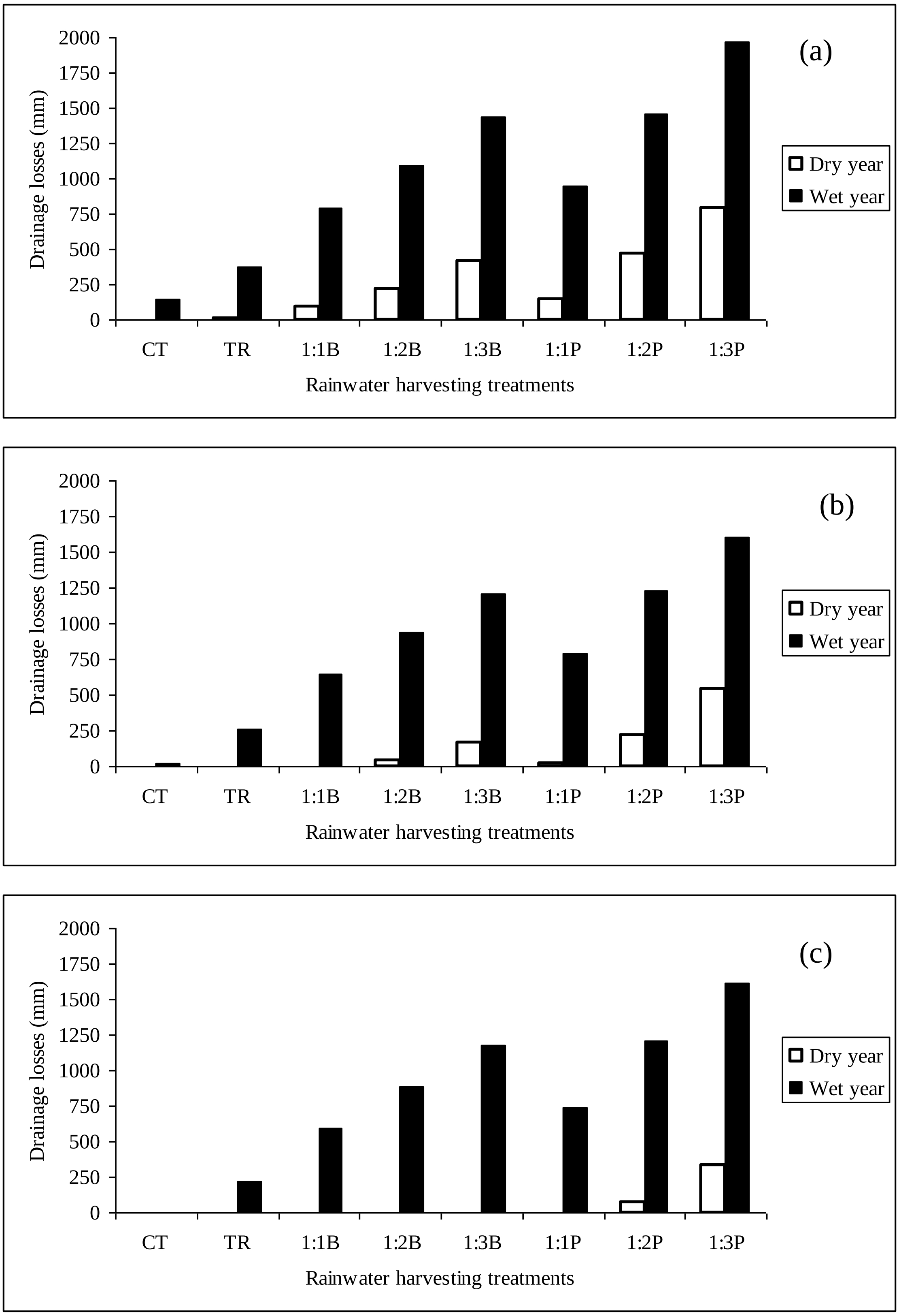


FIG. 7.2: Simulated drainage losses in the cropping area during a dry and a wet year on sandy soils (a), sandy clay loam (b) and clay soils (c) in the semi-arid area of Pretoria for different rainwater harvesting treatments

When comparing simulated values of drainage among the three soil types presented in Figure 7.2, it can be observed that the highest drainage losses are expected to occur on sandy soils, followed by sandy clay loam and clay soils. This is due to lower soil water storage capacity in the root zone from clay to sandy clay loam soils, and to sandy soils. In a wet year, drainage losses are expected to be much higher than in a dry year on all soil types. Simulated drainage losses presented in Figure 7.2 for sandy soils can be expected to be even higher if different soil parameters, such as higher drainage factor, drainage rate and soil infiltration rates, as well as lower soil water holding capacity than for sandy clay loam soils, would be used for the SWB simulations. On clay soils, lower drainage losses could be expected than those presented in Figure 7.2, due to lower drainage and infiltration rates and higher soil water holding capacity than for sandy clay loam soils.

Figure 7.1 illustrates that a 1:1 IRWH design ratio is the ideal rainwater harvesting strategy in the semi-arid area of Pretoria in most years, especially on sandy clay loam and clay soils. Figure 7.2, supports this statement, because in both soil types, sandy clay loam and clay soils, drainage losses for the 1:1 design ratio of the in-field rainwater harvesting method are expected to be negligible in drier years. This minimizes nutrient leaching below the root zone, and consequently maximizes crop yield.

As illustrated in Figure 7.1, on all soil types, there is more advantage to implement in-field rainwater harvesting than conventional tillage and tied ridges in very dry years (when the probability of exceedence of a certain amount of rainfall is above 90%). Based on Pretoria’s long-term rainfall data, this corresponds to rainfall amounts below 450 mm (see Figure 6.4). On sandy soils, the minimum expected crop yield by implementing the 1:1 IRWH design ratio is 1.3 and 1.9 ton/ha (for the bare and plastic covered runoff area, respectively), while by using tied ridges and conventional tillage it is only 0.2 ton/ha. On sandy clay loam soils, the minimum expected crop yield is 0.2 ton/ha for the use of conventional tillage, 0.3 ton/ha for the use of tied ridges, 0.7 ton/ha for the use of 1:1B and 2.9 ton/ha for the use of 1:1P. Minor improvements in the crop yield are observed by using bigger design ratios of IRWH for both sandy and sandy clay loam soils. On clay soils, the minimum expected crop yield for the use of 1:1 IRWH design ratio is 2.8 and 5 ton/ha (for the bare and plastic covered runoff area, respectively), while by using conventional tillage and tied ridges it is about 0.4 ton/ha. In other words, the risk of crop failure is minimized by the use of in-field rainwater harvesting instead of conventional tillage and tied ridges in a very dry year. It shows that in very dry years there is not much advantage in implementing tied ridges instead of conventional tillage on sandy soils because very little runoff is expected. These results are clearly illustrated in Figure 7.3, where predicted maize crop yield for a very dry year in Pretoria (for any seasonal rainfall amount below 450 mm and probabilities of exceedence above 90%) is plotted for different rainwater harvesting design strategies. The in-field rainwater harvesting technique becomes inefficient with an increase in the design ratios more rapidly on clay soils than on sandy and sandy clay loam soils. This is due to the fact that soil water storage capacity on clay soils is much higher than on sandy and sandy clay loam soils, which reduces the beneficial effect of increasing the size of arable land for runoff collection. There is no benefit in making runoff areas wider in a very dry year in the semi-arid area of Pretoria. This is probably due to erratic rainfall distribution during the crop growing season (long dry spells), which reduces the increment on the crop yield caused by an increase of water supply to the cropping area (rainfall plus runoff collected from the runoff areas).

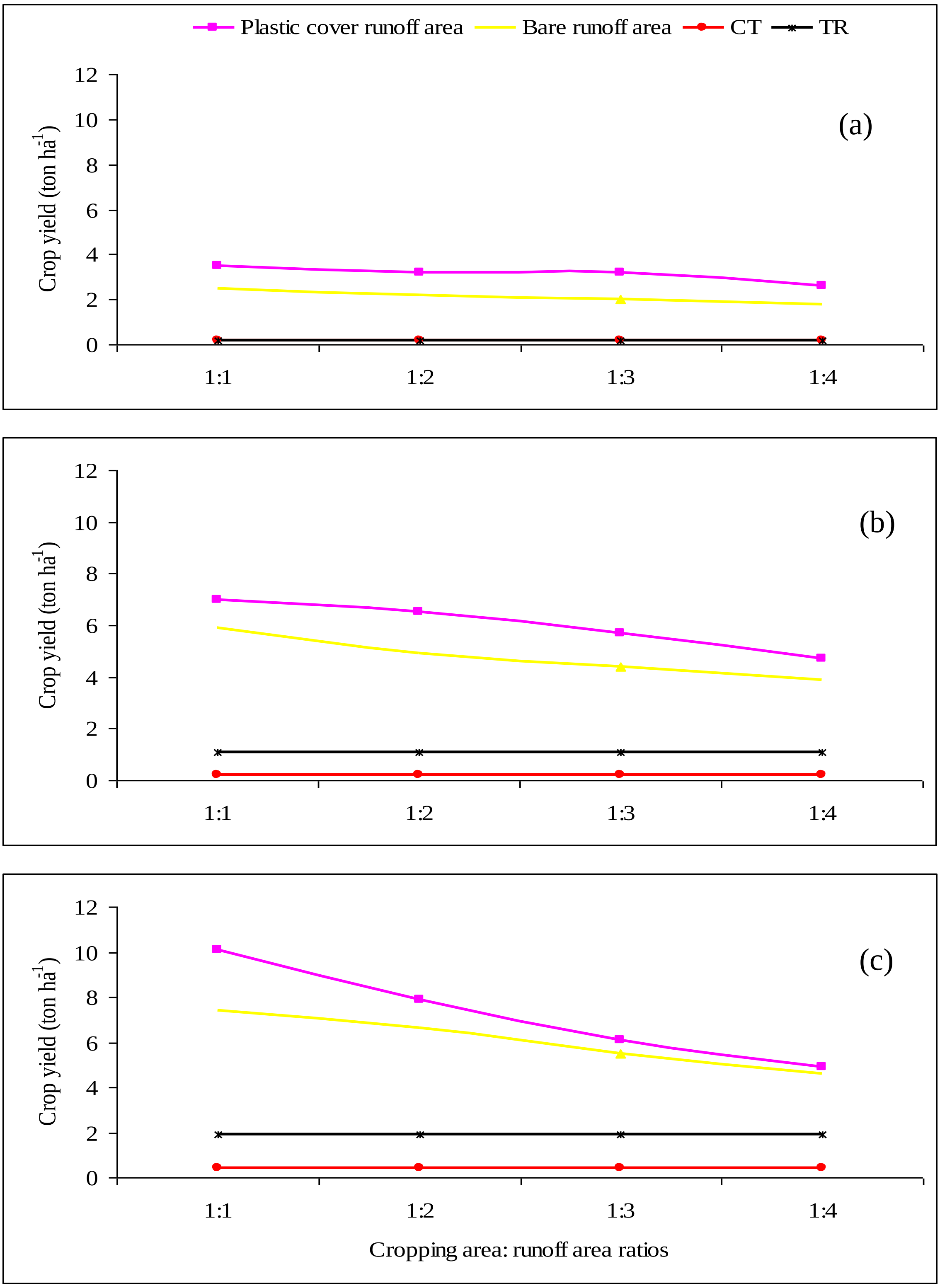


FIG. 7.3: Maize yield on a **total area basis** under different rainwater harvesting design strategies in a very dry year (for any seasonal rainfall amount below 450 mm, with a probability of exceedence above 90%) on sandy soils (a), sandy clay loam (b) and clay soils (c) in the semi-arid area of Pretoria

However, in a very wet year (when the probability of exceedence of a certain amount of rainfall is below 10%, which corresponds to rainfall amounts above 950 mm as evident in Figure 6.4), tied ridges proved to be more advantageous than the in-field rainwater harvesting technique on sandy clay loam and clay soils. The reason for this is that the rainfall is enough to supply the crop with an optimal amount of water during the growing season. In addition, when using tied ridges all arable land used for crop production is cropped, while with the use of the in-field rainwater harvesting technique part of it is used for runoff collection. Moreover, the amount of drainage losses is expected to be lower with the use of tied ridges than with the use of the in-field rainwater harvesting in a wet year (see Figure 7.2). Waterlogging can significantly mask the beneficial effect of using tied ridges in a wet year, but if planting is done on the top of the ridges (as it was tested in the field trials during the 2007/2008 maize growing season at the Hatfield Experimental Farm of the University of Pretoria) this problem can be minimized. The beneficial effect of implementing tied ridges rather than in-field rainwater harvesting in very wet years is evidently illustrated in Figure 7.4 for the semi-arid area of Pretoria. From Figure 7.4, it is obvious that, for the IRWH method, there is no advantage of using a plastic covered runoff area rather than a bare runoff area in very wet years (the crop yield line for the IRWH with a plastic covered runoff area overlaps with the crop yield line for the IRWH with a bare runoff area). On sandy soils, in a very wet year, any of three rainwater harvesting designs (either tied ridge, conventional tillage or the 1:1 IRWH design) can ideally maximize maize yield in the semi-arid area of Pretoria, but the probability of getting such high yields is almost zero, probably due to massive drainage losses occurring in the cropping area (see Figures 7.4, 7.1 and 7.2).

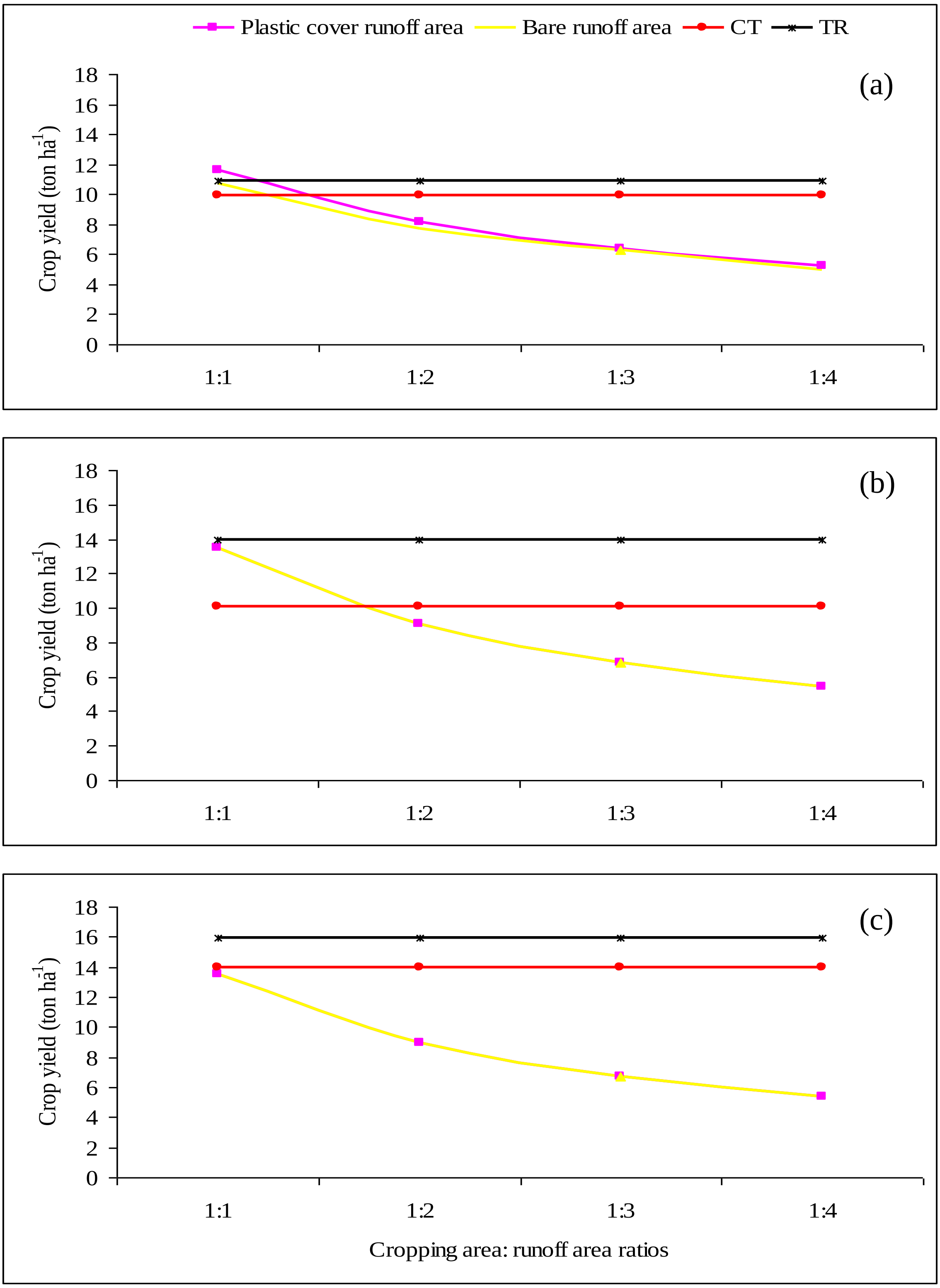


FIG. 7.4: Maize yield on a **total area basis** under different rainwater harvesting design strategies in a very wet year (for any seasonal rainfall amount above 950 mm, with a probability of exceedence below 10%) on sandy (a), sandy clay loam (b) and clay soils (c) in the semi-arid area of Pretoria

Figure 7.5 illustrates the probability of exceedence of a certain level of crop yield on a cropping area basis (excluding the space occupied by the runoff areas in the IRWH technique), using different rainwater harvesting strategies in Pretoria for three different soil types. An analysis of probability of exceedence of a certain crop yield on a cropping area basis (considering only the arable land occupied by the crop) is very important when arable land is not limiting for crop production. The ideal rainwater harvesting strategy in this case will be the one giving higher crop yields with the use of more arable land to collect runoff.

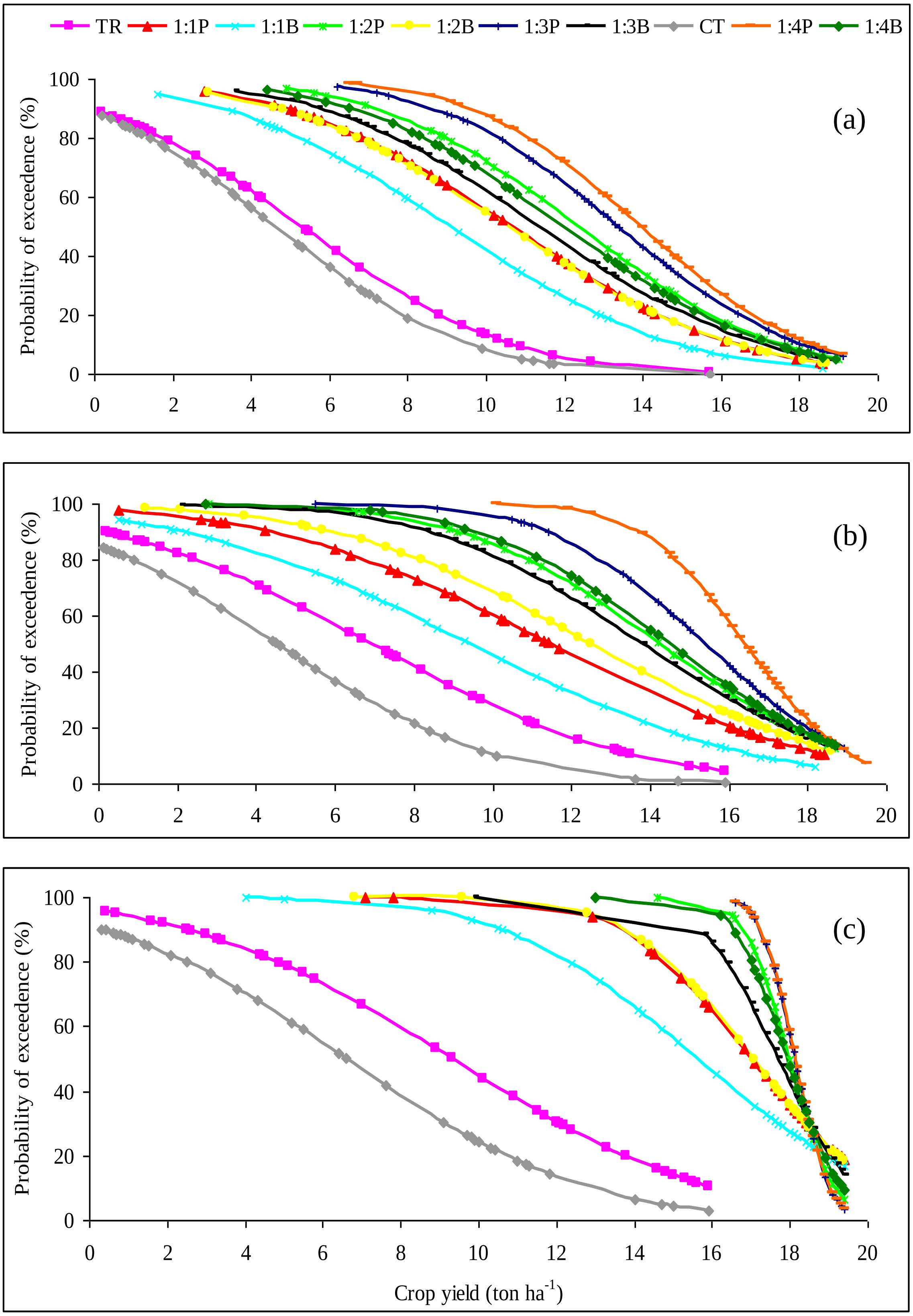


FIG. 7.5: Probability of exceedence of a certain level of crop yield on a **cropping area basis**, using different rainwater harvesting strategies on sandy soils (a), sandy clay loam (b) and clay soils (c) in the semi-arid area of Pretoria

As is evident in Figure 7.5, on sandy and sandy clay loam soils, in most of the years (for any total seasonal rainfall amount below 950 mm), the bigger the IRWH design ratio, the higher the probability of exceedence of a certain crop yield level in Pretoria. For instance for the driest rainy seasons (such as the season 1978/1979, with a total amount of rainfall of 370 mm), minimum expected crop yields increase with an increase in runoff area, and by using a plastic covered runoff area instead of a bare runoff area. On sandy soils, there is almost 100% probability of exceeding about 0.2 ton/ha when using conventional tillage or tied ridge, while with the use of the IRWH, it varies from 2 ton/ha with 1:1B to 6.5 ton/ha with 1:4P. On sandy clay loam soils, in a very dry season, there is complete certainty of exceeding 0.2 ton/ha using conventional tillage or tied ridge, while with the implementation of the IRWH, it ranges from 0.5 ton/ha with the 1:1B to about 10 ton/ha with the 1:4P. The 1:4 ratio uses four times the runoff area (to collect more runoff) than the 1:1 ratio for the same cropping area size. However, for very wet rainfall seasons, as evident in Figure 7.5, there is not much advantage in increasing the runoff area because there will be sufficient water for maximum crop production, even with smaller ratios of the IRWH systems.

On clay soils, since the soil water storage capacity in the root zone is bigger than for sandy and sandy clay loam soils, in most years (for total rainfall below 950 mm), higher crop yields can be obtained with relatively smaller IRWH design ratios. For instance, based on Figure 7.5, the probability of exceeding a certain crop yield in any rainy season, on clay soils, is exactly the same when comparing the 1:3P and 1:4P ratios. However, considering increased drainage losses, and consequent nutrient leaching below the root zone, as well as a high risk of water-logging, with an increase on the design ratio of the IRWH, it is preferable to choose 1:3P rather than 1:4P. There are other costs involved when using bigger design ratios of the IRWH, such as the use of bigger sizes of plastic on the runoff area, construction and maintenance of the system. In wetter rainy seasons (when the total rainfall is equal or above 950 mm), crop production is maximized by either the 1:1P or 1:2B. As illustrated in Figure 7.2, for clay soils, drainage losses in the 1:2B are higher than for 1:1P in a wet season. Therefore, the choice of any of these two techniques needs to take into account the drainage losses (which increases nutrient leaching), costs involved with the acquisition of plastic to cover the runoff area, labour for construction and maintenance of the systems and amounts of fertilizer and seeds.

From Figure 7.5, it was observed that on sandy soils, the probability of minimizing crop failure is slightly higher when using in-field rainwater harvesting than when using conventional tillage and tied ridge techniques. Instead of expecting to get 0.2 ton/ha of maize when using conventional tillage or tied ridge in a very dry year, the SWB simulations show that by implementing in-field rainwater harvesting, it is more likely to get higher crop yields, of around 1.3 ton/ha when using the 1:1 design ratio of the in-field rainwater harvesting with a bare runoff area, and 1.9 ton/ha for the same ratio but with a plastic cover runoff area. However, based on the minimum drainage losses presented in Figure 7.2 for sandy soils, the probabilities of exceeding minimum expected crop yields in a given dry year using the in-field rainwater harvesting technique would be much lower. This is because on sandy soils, higher drainage losses than those presented in Figure 7.2 can occur, if all soil parameters which characterize a sandy texture are included in SWB. The SWB model was only parameterized and calibrated for sandy clay loam soils, on which field trials were run during the growing season 2007/2008. Figure 7.2 also illustrates that, on sandy soils, drainage losses are expected to occur even for the 1:1 design ratio of the in-field rainwater harvesting technique, with either plastic or bare runoff area. This is evident in both seasons, dry and wet. As a result, it can be stated that, there is evidence that on sandy soils rainwater harvesting techniques might not perform well.

7.3 CHOKWE - MOZAMBIQUE

The district of Chokwe is located in Gaza Province, south of Mozambique. Its total area is about 1595 km^2, with over 200 000 habitants. It is delimited by the Limpopo and Mazimechopes Rivers, as well as by the Districts of Bilene, Chibuto, Guija, Mabalane and Massingir, in Gaza Province, and by the Magude District, in Maputo Province. The main socio-economic activity is crop production, followed by livestock farming. The biggest irrigation area in the country is located in this district, with about 26 000 hectares. Although 90% of the area is flood irrigated, the infrastructure is severely degraded, which considerably reduces the efficiency of the system for crop production. Therefore, the majority of the population relies on rainfed agriculture for subsistence. There are two different groups of small scale farmers practicing rainfed agriculture (FAEF, 2002):

- The first group involves those farmers who cannot afford to use fertilizers for crop production, the land cultivation is not mechanized (is done by hand) and the total arable land used for crop production is in general less than 2 ha per family;
- In the second group of farmers, the land cultivation is mechanized, with or without the use of fertilizers, and the total arable land used for crop production is generally less than 5 ha per family.

In general, the Chokwe District is characterized by a semi-arid climate, with very high rainfall variability throughout the year and from one year to another, which puts rainfed agriculture at a high risk of failure (FAEF, 2002). The average annual rainfall is about 620 mm, occurring mainly from October to March, and the average annual reference evapotranspiration is about 1500 mm. The probability of drought occurrence (deficit) in this area is above 30%, which results in about 50% probability of crop failure. Mean annual temperature is about 23.6 ^{o}C (FAEF, 2002). Monthly average temperatures through the year are presented in Table 7.1.

Table 7.1: Monthly average temperatures for Chokwe District (FAEF, 2002)

T (^{o}C)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Tmin	21	21.1	19.5	17.6	14.2	11.5	10.9	12.6	15.3	17.5	19.3	20.3	16.7
Tmax	33.7	33	32.1	30.7	28.6	26.2	26.1	27.9	30.2	31.8	32.6	33.3	30.5
Tmean	27.4	27.1	25.8	24.2	21.4	18.9	18.5	20.3	22.8	24.7	26	26.8	23.6

In terms of rainfall, the year is divided into two distinct periods: a rainy season (humid period), from October to March, when about 88% of the total rain falls, and a dry season, from April to September, when only 12% of the rain falls. Figure 7.6 shows the average distribution of rainfall throughout the year.

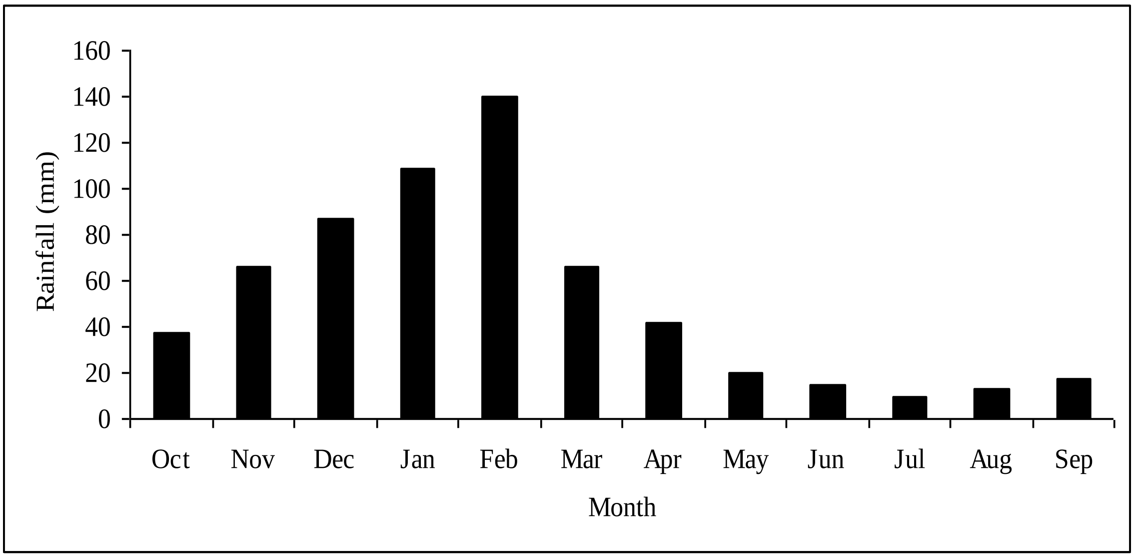


FIG. 7.6: Distribution of average monthly rainfall through the year at Chokwe (After FAEF, 2002)

The monthly water balance deficit, based on the Penman Monteith reference evapotranspiration and rainfall, through the year, is illustrated in Figure 7.7.

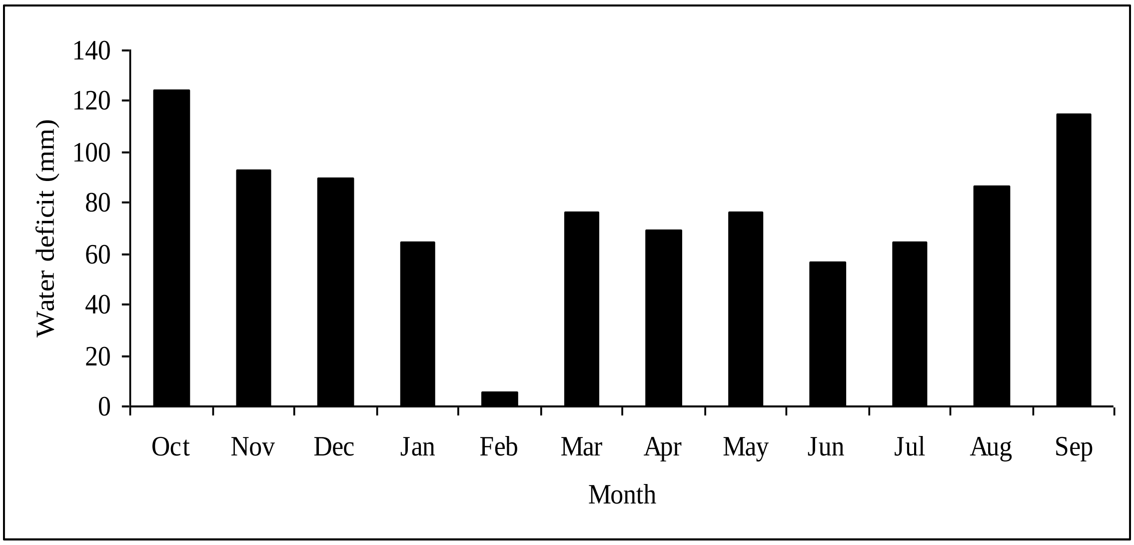


FIG. 7.7: Monthly water balance deficit for Chokwe (After FAEF, 2002)

From Figure 7.7, it is evident that there is water scarcity throughout the year at Chokwe. Therefore, an improvement in rainfed crop production through rainwater harvesting technologies should be beneficial.

In terms of soils, the Chokwe District is covered by a wide variety of soils. These include (FAEF, 2002):

- Sandy soils, with an excessive drainage rate, low natural fertility, low water retention capacity, non saline, non sodic and the water table is usually greater than 10 m deep;
- Sandy clay loam soils, with a sandy loam 40 cm top soil layer, and a 60 to 80 cm sandy clay loam subsoil. This subsoil is usually compacted with a high level of sodium;
- Clay soils, with low permeability.

Despite the wide variety of soils occurring at Chokwe District, the area is mainly covered by deep medium textured soils. Maize is among the main crops produced under rain-fed conditions. Other crops are cassava, beans and sweet potato. Soil fertility is usually improved by the use of crop residues. On average, maize yield under rainfed conditions is about 200 to 300 kg per hectare, being mainly dependent on the rainfall pattern during the crop growing season (FAEF, 2002).

A rainfall record of 33 years of seasonal rainfall totals was used in the Incomplete Gamma Distribution Function to establish rainfall intervals for wet, normal and dry seasons in Chokwe (Miller & Freund, 1977). Figure 7.8 illustrates the probability of exceedence of certain rainfall amounts and their return periods in the semi-arid area of Chokwe, in the south of Mozambique.

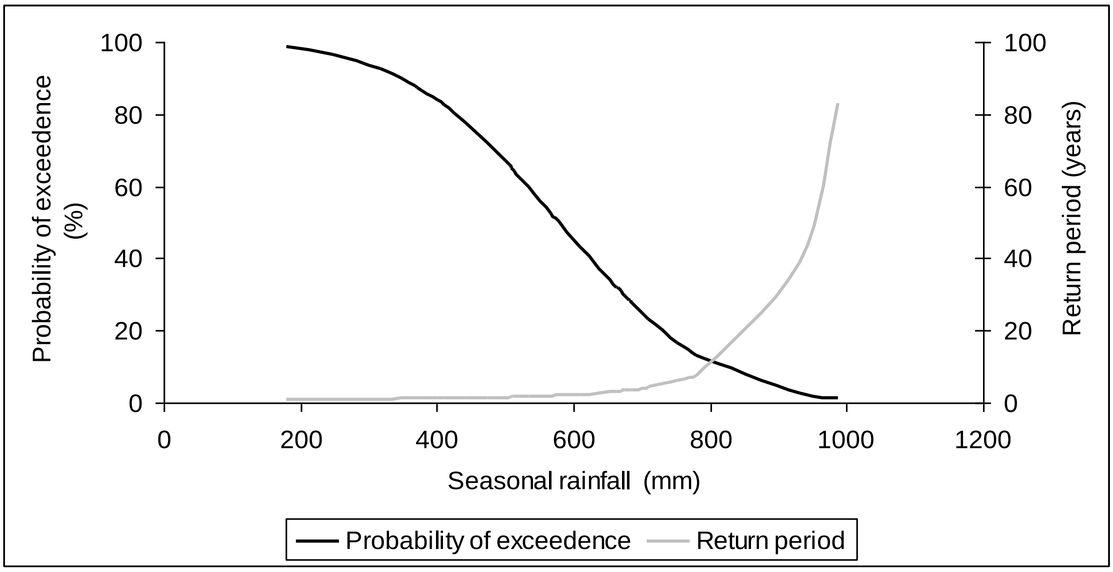


FIG. 7.8: Probability of exceedence of seasonal rainfall and return periods in the Chokwe semi-arid area, Mozambique

According to FAO (1998), probability ranges between 0 and 20 and between 80 and 100 are termed unusual, and values from 20 to 80 are considered normal in tropical regions. Based on this, any total annual rainfall amount between 0 and 20% probability of exceedence was considered to be a wet year, between 80 and 100% a dry year, and from 20 to 80% a normal year. Based on this FAO classification, rainfall intervals were established for a dry, normal and a wet season in the semi-arid area of Chokwe in accordance with Figure 7.8. Table 7.2 shows rainfall intervals for the different rainy seasons.

Table 7.2: Rainfall intervals for a dry, normal and a wet season in Chokwe

	Total seasonal rainfall amount (mm)	
Season	Minimum	Maximum
Dry	180	409
Normal	410	699
Wet	700	987

The ideal rainwater harvesting management strategy, in a wet, normal, and dry season, was selected for Chokwe district with the help of the SWB model for different soil types (sandy, sandy clay loam and clay soils). The same soil parameters as the ones used for the simulations in the semi-arid area of Pretoria were used for the simulations at Chokwe. There were only six years of data (from 2001 to 2007) with minimum required inputs (rainfall amount, maximum and minimum temperatures on a daily basis) available to run simulations with SWB. Before running simulations, various planting date strategies were tested for the different years of data. This was done because in a semi-arid area, the rainfall pattern (amount and distribution) is very erratic within a year and from one year to another. Therefore, a good choice of planting date can optimize seasonal rainfall, and consequently maximize crop yield by decreasing the risk of crop failure due to water deficit. The same maize variety as the one used for Pretoria (PNR 6479) was simulated. At Chokwe this maize variety exhibited a shorter growing cycle than at Pretoria. This is attributed to higher temperatures at Chokwe. Simulations were performed for conventional tillage. Different starting dates were set, between 15th September and 15th January, assuming that the initial water content in the soil profile was at 70% of plant available water at the beginning of the simulations (2001). This was done based on historical information for the period with the highest water balance deficit through the year at Chokwe. This period usually occurs from April to October (see Figure 7.7). Table 7.3 presents maize yield simulations for different planting dates in different years, at Chokwe on sandy clay loam soils.

Table 7.3: Maize yield simulations for different planting date strategies using conventional tillage technique in different rainy seasons, Chokwe – Mozambique

Maize growing cycle		2001/2002 Normal season		2002/2003 Normal season		2003/2004 Wet season	
Planting date	Harvest date	Crop yield (ton ha^{-1})	Rainfall (mm)	Crop yield (ton ha^{-1})	Rainfall (mm)	Crop yield (ton ha^{-1})	Rainfall (mm)
15-Sep	Early Jan	1.9	421	**5.6**	**229**	4.5	224
15-Oct	End Jan	**7.5**	**423**	0.3	184	4.5	436
3-Nov	Early Feb	5.3	455	0.2	108	4.8	332
15-Nov	End Feb	3.8	399	0.2	173	8.3	342
30-Nov	Early Mar	4.0	378	0.2	112	9.9	584
15-Dec	End Mar	2.1	252	0.5	99	**9.9**	**620**
30-Dec	Middle Apr	1.9	139	2.0	94	9.4	600
15-Jan	Early May	1	135	1.4	93	8.7	641
Maize growing cycle		2004/2005 Dry season		2005/2006 Wet season		2006/2007 Normal season	
Planting date	Harvest date	Crop yield (ton ha^{-1})	Rainfall (mm)	Crop yield (ton ha^{-1})	Rainfall (mm)	Crop yield (ton ha^{-1})	Rainfall (mm)
15-Sep	Early Jan	3.3	169	0.3	207	**5.7**	**302**
15-Oct	End Jan	4.0	230	0.9	319	4.4	293
3-Nov	Early Feb	4.2	201	0.9	324	3.9	284
15-Nov	End Feb	4.0	222	1.6	310	3.8	279
30-Nov	Early Mar	5.1	189	2.0	389	2.0	216
15-Dec	End Mar	**5.5**	**165**	0.5	457	1.8	204
30-Dec	Middle Apr	4.0	164	1.8	440	1.0	280
15-Jan	Early May	1.9	189	**5.4**	**331**	0.1	193

As observed in Table 7.3, the rainfall amount and distribution in the semi-arid area of Chokwe is quite variable throughout the year and from one year to another. Therefore, in order to choose a more representative planting date it would be necessary to have a longer record of climatic data. In this study only six years of weather data were used due to its limited availability. Based on Table 7.3, in two years out of six, the ideal planting date was found to be either in 15th September or 15th December. In other words, one of these two planting dates has the same probability of leading to the highest crop yield. If one chooses to plant on 15th September, the harvest will be expected in early January. Therefore, there will be higher chances of crop water stress during planting, and consequently increased risk of crop failure, because one of the highest water balance deficit periods occurs in September (see Figures 7.6 and 7.7). In addition, the highest rainfall periods are, in increasing order, December, January and February, which indicates that harvest (early January) will be during a very wet period, causing potential damage to the final maize crop yield. On the other hand, if one chooses to plant on 15th December, there will be enough water in the soil during planting (one of the critical periods for maize) and the expected harvest time is end of March, with much lower rainfall incidence. According to Reddy (1986), the best planting period at Chokwe is around January. Based on the crop yield simulations presented in Table 7.3, if one plants in mid January, the expected harvest will be in early May. As described previously, the rainy season at Chokwe (humid period) goes from October to March. Therefore, January seems to be a late period for planting since harvest will be expected in May.

Table 7.3 also illustrates that if maize is planted at an appropriate time, crop yields can be very low, even in a wet season, due to erratic rainfall distribution in that particular crop growing period. Therefore, the choice of planting date strategy can contribute to better rainfall optimization. It is proved that crop models are very important tools to study different rainwater harvesting management scenarios rapidly, and with low cost, but for their best performance they need reliable long-term climatic data as input. Hence, Mozambique needs to invest in a trustworthy automatic weather station network.

Crop yield simulations were run for a wet, normal and dry season, on sandy clay loam soils, with maize being planted on the 15th December. Simulations were also run for a wet season on clay soils and for a dry season on sandy soils. It was chosen this way based on the Limpopo River Basin main regions, in accordance with their rainfall characterization, as illustrated in Figure 7.9.

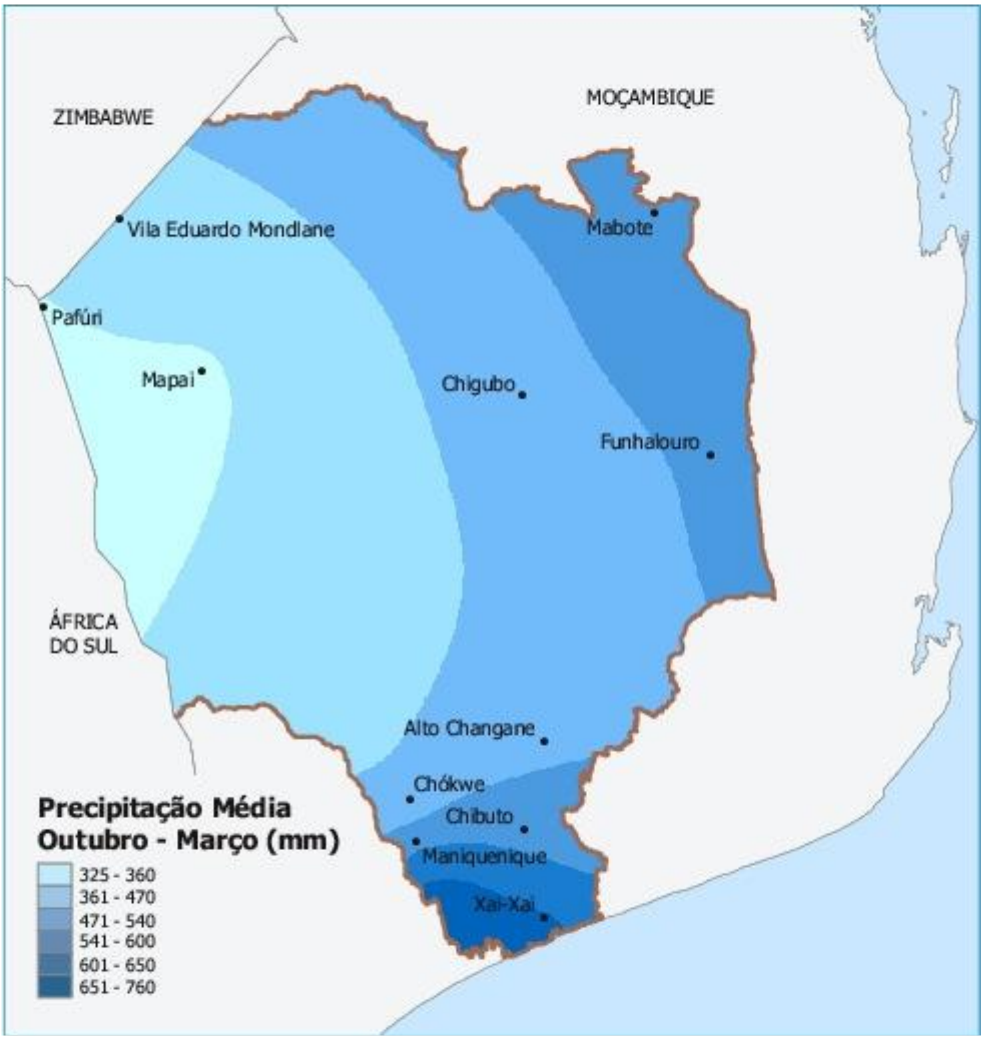


FIG. 7.9: Rainfall characterization in the Limpopo River Basin in Mozambique (INGC *et al*., 2003)

The Limpopo River Basin in Mozambique encompasses three main semi-arid regions, namely a Lower, Middle and Upper Region. The Upper Region is characterized by sandy soils and an average seasonal rainfall (from October to March) varying from 325 to 360 mm. In the Middle Region the soils are, in general, medium in texture and the average seasonal rainfall ranges from 361 to 600 mm. Chokwe is part of this region. The Lower Region is characterized by heavy soils of poor drainage and much higher rainfall than the Upper and Middle Limpopo Regions (average seasonal rainfall varying from 601 to 760 mm as illustrated in Figure 7.9).

The 2003/2004 rainy season, with a total seasonal rainfall of 952 mm, was chosen to run simulations for a wet year at Chokwe. The probability of occurrence of 957 mm of rain within a year in Chokwe is about 3% and its return period is 33 years. The 2006/2007 rainy season, with a total annual rainfall of 499 mm, was selected to run simulations for a normal year in Chokwe. Its probability of occurrence is about 72% and return period is 2 years. For a dry season, simulations were run for the 2004/2005 rainy season (with a total seasonal rainfall of 370 mm). The probability of occurrence of 370 mm of rain within a year in Chokwe is about 86% and its return period is one year. Figure 7.10 presents simulated crop yield on a total area basis for the wet, normal and dry seasons on sandy clay loam soils in Chokwe. The choice of the ideal rainwater harvesting design strategy on a total area basis is important at Chokwe, as land is usually limiting for crop production (each family cultivates, in general, less than 5 ha of arable land).

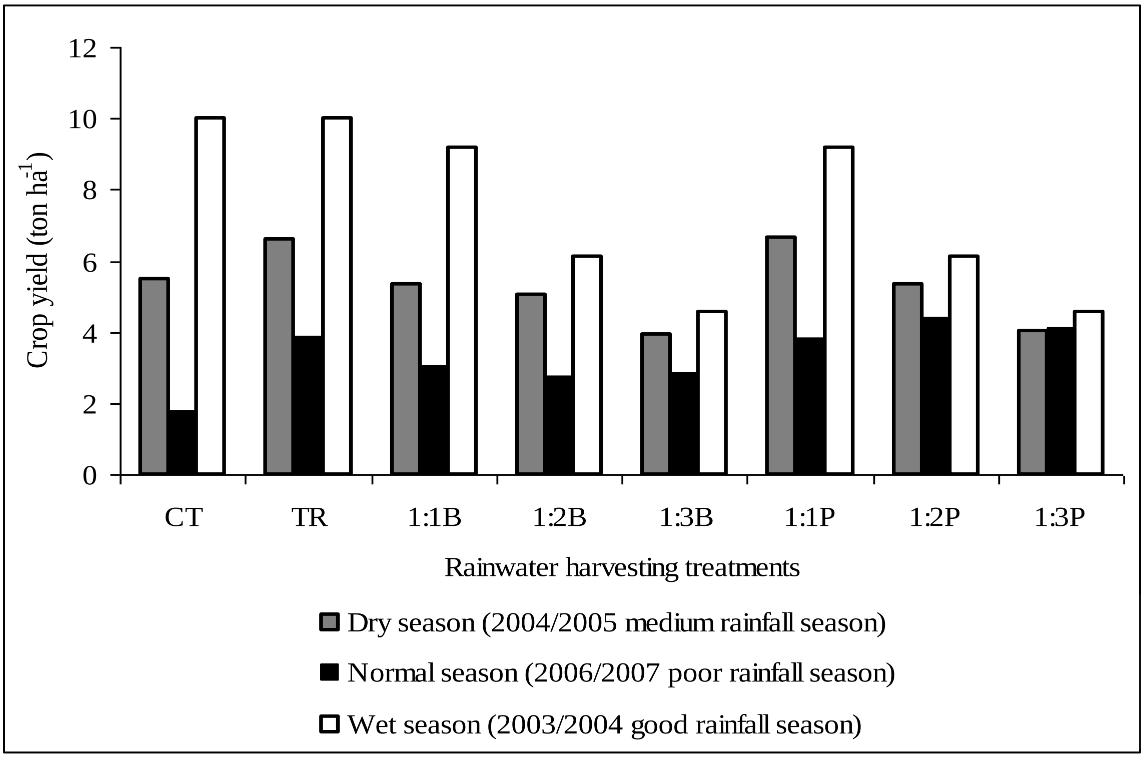


FIG. 7.10: Maize yield on a **total area basis** using different rainwater harvesting scenarios in a medium, poor and good rainfall season, on sandy clay loam soils in the semi-arid area of Chokwe

As observed in Figure 7.10, the highest maize yield on a total area basis was obtained in the wet season (with a high rainfall amount and well distributed “good season”), followed by the dry season (with a low rainfall amount, but well distributed “medium season”) and the normal season (with medium rainfall amount but poorly distributed “poor season”). This shows that rainfall distribution plays a very important role in determining final crop yield and is probably more influential than the rainfall amount in semi-arid areas. Therefore, in order to select the ideal rainwater harvesting scenario for a particular season with some certainty, it would be necessary to have a more representative long-term weather data record (at least 15 consecutive years of data). This would also give more reliable indication of the type of season forecasted by the weather meteorological services.

Based on the results illustrated in Figure 7.10, the highest crop yield in a good season at Chokwe is expected to be achieved with the implementation of either the tied ridge or conventional tillage techniques. With the implementation of the tied ridges, 186 mm of water is expected to be lost through drainage, as observed in Figure 7.11, but no runoff losses are expected to occur in the cropping area. These drainage losses are accompanied by nutrient leaching below the root zone. On the other hand, with the use of the conventional tillage technique, model simulations indicate that 184 mm of water is expected to run off, but no drainage losses are expected to take place in the cropping area as observed in Figure 7.11. These runoff losses contribute to top soil erosion, which also washes the nutrients away. Nutrient losses by either runoff or drainage can considerably reduce crop yield, contribute to environmental degradation, pollution of surface waters, and possible human health risks. The conventional tillage technique is less time consuming and labourious than the tied ridges. These reasons put the conventional tillage in advantage when compared to the tied ridges in a wet year.

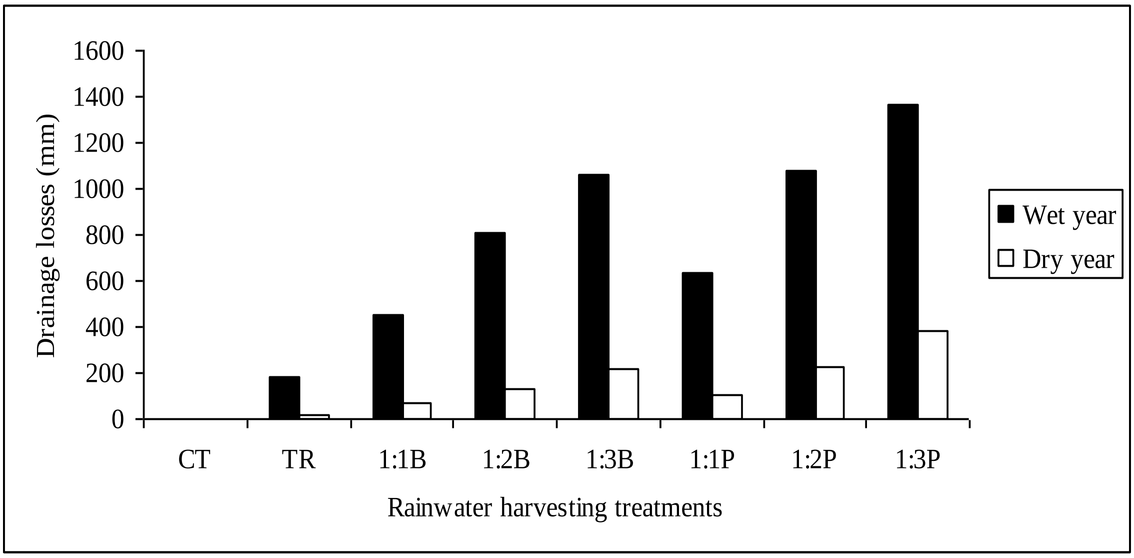


FIG. 7.11: Simulated drainage losses in the cropping area during a dry and a wet year on sandy clay loam soils in the semi-arid area of Chokwe for different rainwater harvesting treatments

Mzirai *et al.* (2002) state that tied ridge performs well under high rainfall amounts. However, in order to achieve best performance, the soil should be heavy, characterized by low infiltration rates caused by surfacing crusting, or by low percolation rates caused by hardpan zones in the soil profile. Therefore, field trials should be conducted at Chokwe to test these simulation results. These simulations were run for a sandy clay loam soil. The tied ridge technique was tested on maize at the Hatfield Experimental Farm, in semi-arid Pretoria, on sandy clay loam soils, in a wet season (with 605 mm of rainfall during the crop growing season). Field observations showed good crop yield, not significantly different from the highest yields obtained with the in-field rainwater harvesting technique. The tied ridge technique is less labour intensive than the in-field rainwater harvesting technique and it can be implemented on a flat area or areas with very gentle slopes (less than 2%), which is, in general, the case at Chokwe.

Crop yield simulation results presented in Figure 7.10 illustrate that, ideally, in a poor season, the best crop yield results, on a total area basis, are achieved with the 1:2P water harvesting scenario (4.4 ton/ha). However, the difference is not big, when compared to the crop yield using tied ridge technique (3.9 ton/ha). In this case, it is also preferable to use tied ridges rather than the 1:2 design ratio of in-field rainwater harvesting with the runoff area covered with plastic (1:2P). With the use of tied ridges, there will be less nutrient leaching and lower production costs because it does not involve the use of plastic. As observed from Figure 7.10, in a poor season such as the 2006/2007, if there is optimum nutrient supply and pests and diseases properly controlled, lowest expected maize yield simulated by the SWB is around 1.8 ton/ha, with the use of the conventional tillage technique. However, as reported by FAEF (2002), small scale farmers practicing rainfed agriculture get, on average, 200 kg/ha of maize at Chokwe. Other factors, rather than low and erratic rainfall, might be contributing to maize yield reduction at Chokwe semi-arid area. These factors could be low soil fertility, incidence of pests and diseases, bad seed quality, wrong choice of planting dates, lack of machinery and labour to operate the field in time in order to optimize the rainfall during the crop growing season.

Based on Figure 7.10, crop yields, in a medium rainfall season such as the 2004/2005, are slightly higher with the implementation of tied ridges than for the 1:1P system. This is most likely because rainfall during this season was much better distributed throughout the growing season than during the poor season (2006/2007), assuming that the crop was planted on the 15th December. In this case, it is also important to consider antecedent soil water content. The 2004/2005 medium season followed a wet season (2003/2004) with a total annual rainfall of 952 mm. Therefore, since simulations from 2001 to 2007 were run in the long-term (sequentially), the initial water content in the soil profile at planting during this medium season was almost at field capacity (about 93% of plant available water). The poor season (2006/2007) also followed a wet season (2005/2006), but with a lower total annual rainfall (721 mm). Therefore, initial soil water content at the beginning of the 2006/2007 crop growing season was much lower (about 55% of plant available water). In addition, rainfall was poorly distributed just before the flowering stage (the most critical stage for optimum maize growth). Figure 7.12 illustrates the impact of rainfall distribution and soil water deficit on crop yield during the medium season (2004/2005) and poor season (2006/2007) using the conventional tillage technique on sandy clay loam soils at Chokwe.

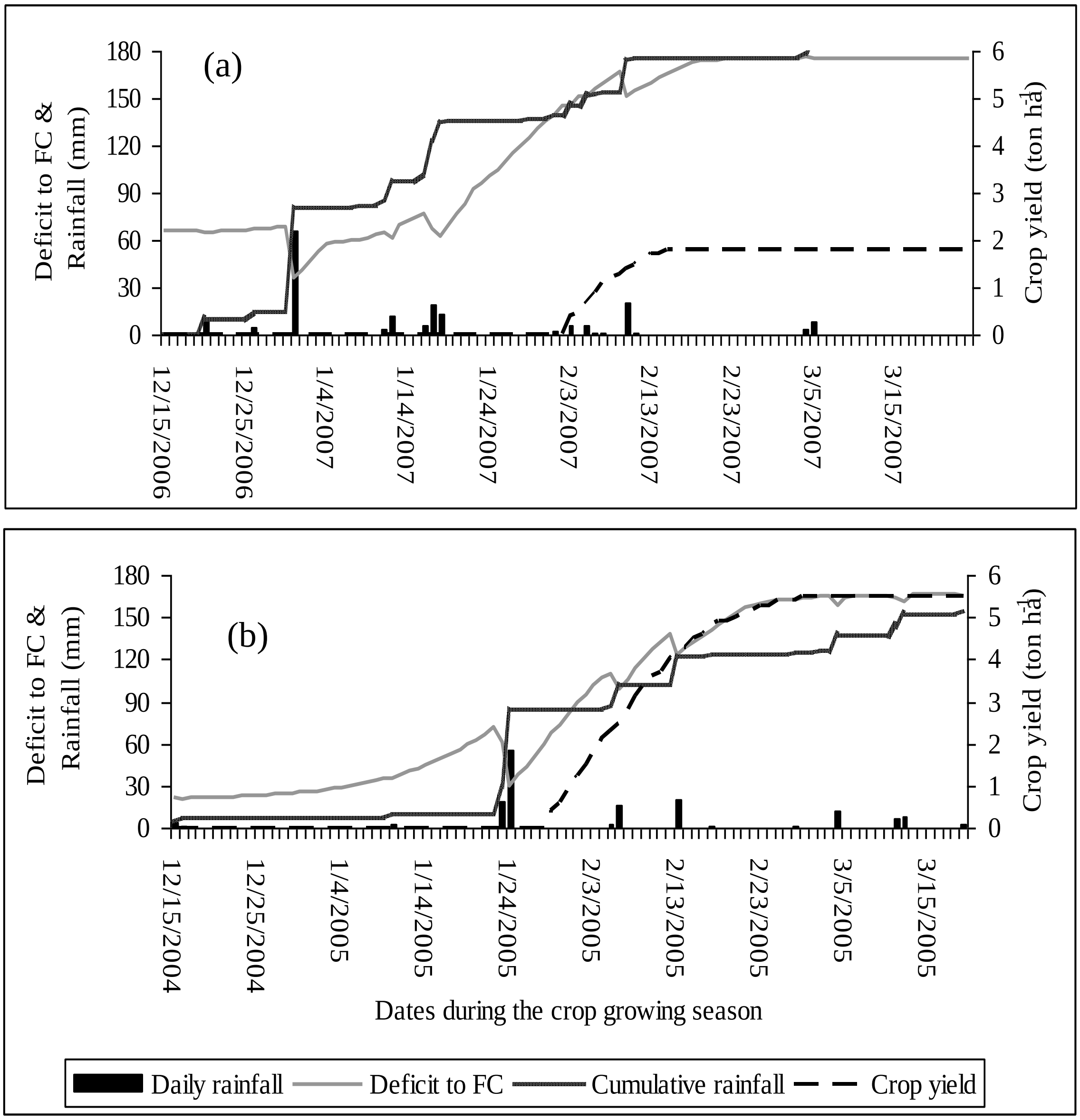


FIG. 7.12: The simulated effect of rainfall distribution and soil water deficit on the maize yield during a poor (a) and medium rainfall season (b) at Chokwe

SWB model simulations also showed higher evaporation losses during the 2006/2007 growing season (141 mm) when compared to the 2004/2005 season (100 mm). This might have contributed to the occurrence of higher soil water deficit during the 2006/2007 crop growing season. The difference in soil water deficit when comparing the two seasons, is more evident during vegetative stage. This is probably because crop canopy was smaller, allowing more exposure of the soil to solar radiation and therefore high soil evaporation when it rained frequently.

Figure 7.13 presents simulated crop yield on a cropping area basis for a good, medium and poor rainfall season (2003/2004, 2004/2005 and 2006/2007, respectively) on sandy clay loam soils at Chokwe.

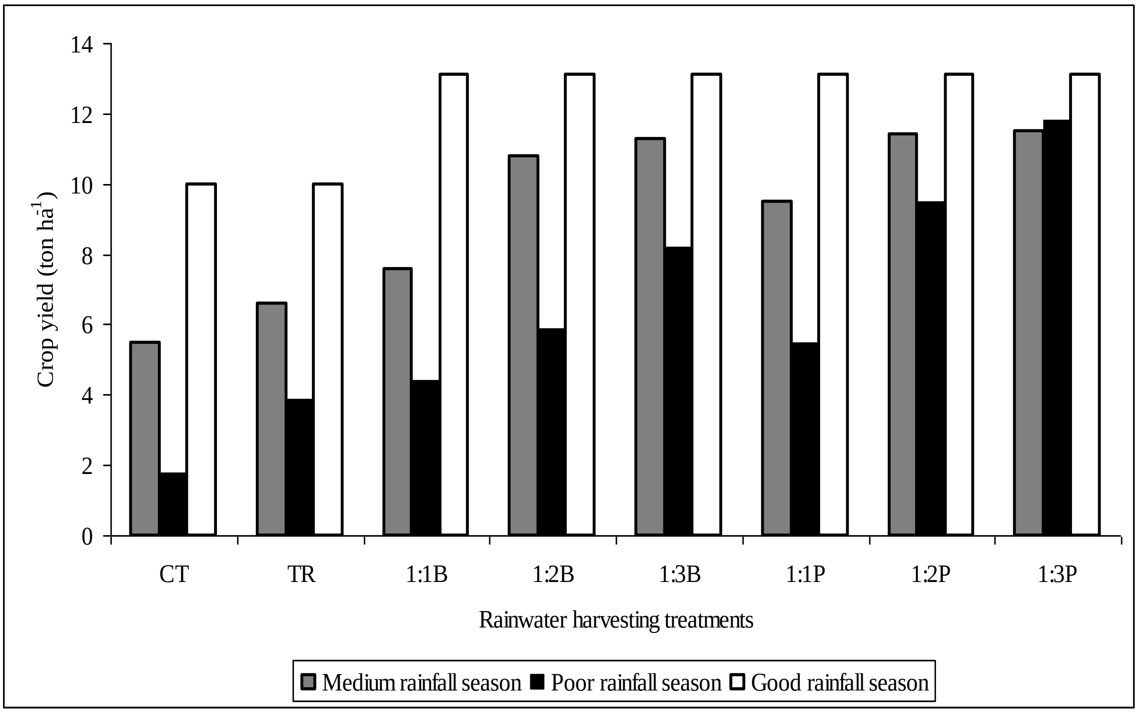


FIG. 7.13: Maize crop yield on a **cropping area basis** using different rainwater harvesting scenarios in a medium, poor and good rainfall season, on sandy clay loam soils in the semi-arid area of Chokwe

As is evident in Figure 7.13, when land is not limiting for crop production, in a medium rainfall season, the highest crop yield is obtained with the 1:3B rainwater harvesting strategy. In a poor rainfall season, the ideal rainwater harvesting design is the 1:3P or even a bigger design ratio. These results are based in weather data for only one dry season (medium rainfall season) and one normal season (poor rainfall season) at Chokwe due to limited availability of minimum required climatic data for SWB model simulations. In this particular dry season (medium season) used for simulations, the rainfall during the crop growing season was better distributed than the one falling during the normal season (poor rainfall season). In addition, initial water content at planting was higher for the medium rainfall season than for the poor rainfall season, as explained in Figure 7.12. Simulation results for the wet season "good rainfall season" reveal the 1:1B design as the ideal rainwater harvesting strategy. Since it is a wet season, it is expected that smaller design ratios of the IRWH to harvest sufficient rainwater for maximum crop production.

Figure 7.14 illustrates maze yield on both a total and cropping area basis, using different rainwater harvesting scenarios in the 2004/2005 dry season at Chokwe, on sandy soils. This is presented to illustrate expected crop yields in the Upper Limpopo River Basin Region of Mozambique, since this region is characterized by sandy soils and low rainfall amounts (between 325 and 360 mm on average within a season). The rainfall amount during the 2004/2005 crop growing season was 164 mm, well distributed throughout the season. Therefore, it was classified as a "medium rainfall season". There is no climatic data available to run appropriate simulations for this semi-arid region. As a result, weather data from a dry year at Chokwe, which is also a semi-arid region located within the Limpopo River Basin, was used to illustrate the ideal rainwater harvesting scenario in the Upper Limpopo River Basin Region.

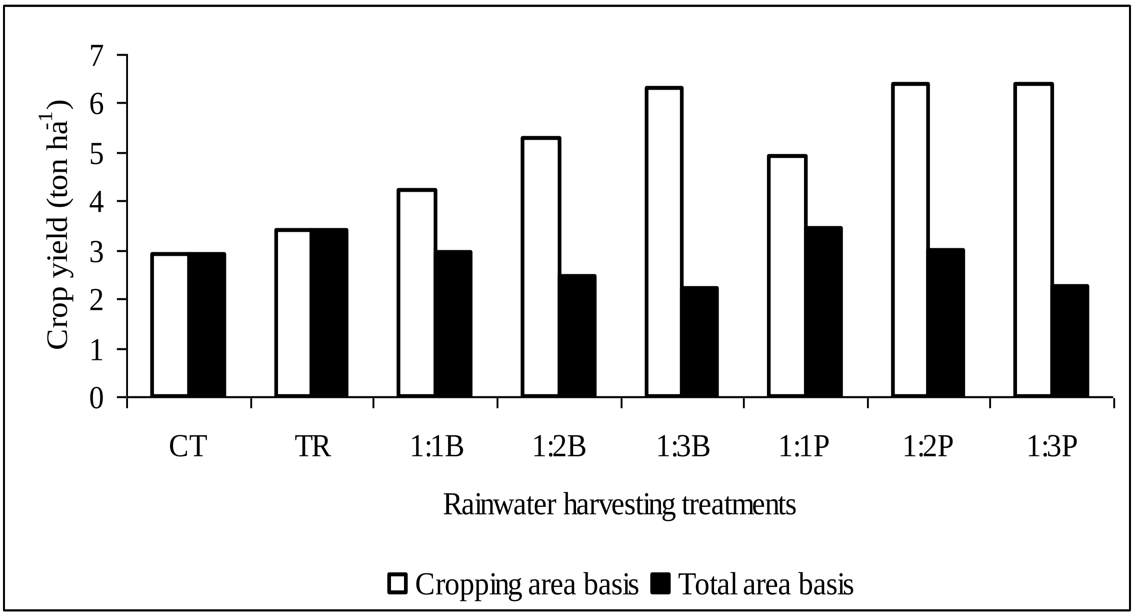


FIG. 7.14: Maize yield on both a **total area** and **cropping area basis** using different rainwater harvesting scenarios in a medium rainfall season in the Upper Limpopo River Region, on sandy soils

As illustrated in Figure 7.14, when land is not limiting for crop production, the ideal rainwater harvesting design is the 1:3B strategy in a medium rainfall season, in the Upper Limpopo River Region, on sandy soils. On the other hand, if land is limiting for crop production, the ideal rainwater harvesting strategy will be that of tied ridges. Based on drainage losses presented in Figure 7.15, on sandy soils in a medium rainfall season, very little drainage can be expected to occur with the use of tied ridge, which minimizes nutrient leaching below the root zone.

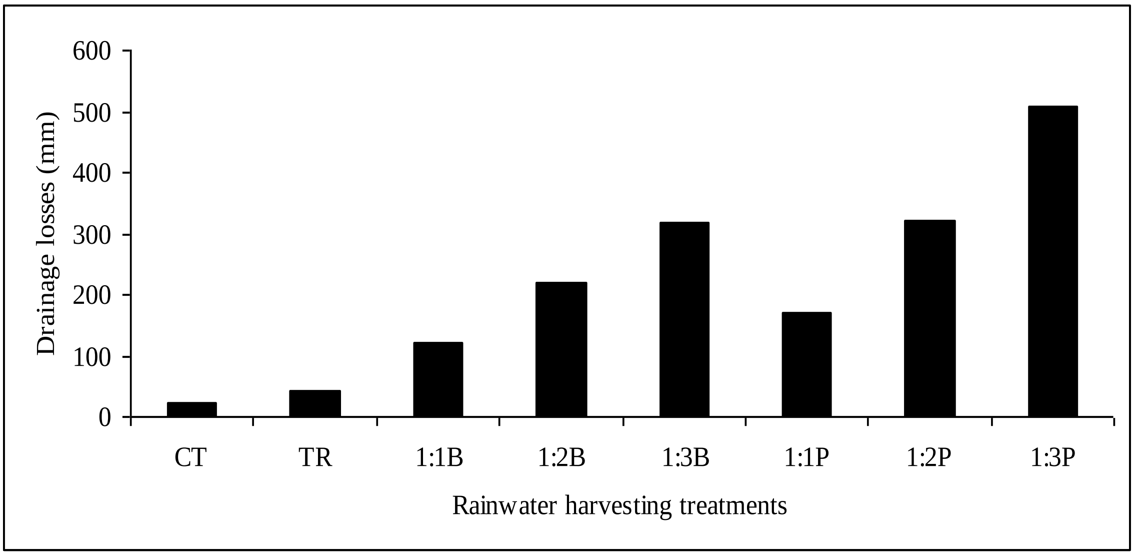


FIG. 7.15: Simulated drainage losses in the cropping area during a medium rainfall season on sandy soils in the semi-arid area of Chokwe for different rainwater harvesting treatments

The biggest advantage of tied ridges is that it captures all the rainfall by eliminating runoff losses. SWB simulations show that there is an improvement in crop yield (about 500 kg/ha more) using tied ridges rather than conventional tillage which does not eliminate runoff. Since sandy soils have light texture and poor structure, they are not good for mantaining ridges. Therefore, a similar technique as the tied ridges can be used. An example could be micro-basins. These consist of small circular pits dug to break the crusted soil surface, to store water and to build up soil fertility when combined with manure, crop residues or fertilizer. It works by combination of water harvesting and conservation of both water and fertility in the pit by preventing runoff losses. The holes are dug approximately 80 cm apart to a depth of 5 to 15 cm, with a diameter of between 15 to 50 cm. Crop residues are placed inside to improve infiltration capacity (UNEP, 2003). In general, the density is about 10 000 to 15 000 holes per hectare depending on the crop chosen (Cofie *et al*., 2004). Micro-basins have already been used in the Upper Limpopo River Basin region in Mozambique by small scale farmers to optimize rainfall. However, the yields are still very low. This might be due to other limiting factors such as fertilizers and pesticides.

Figure 7.16 illustrates maize yield on both a total and cropping area basis using different rainwater harvesting scenarios in the 2003/2004 wet season “good rainfall season” at Chokwe, on clay soils. This is presented to illustrate expected crop yields in the Lower Limpopo River Basin Region in Mozambique, which is characterized by heavy soils of poor drainage and high rainfall amounts. Similarly to the Upper Limpopo River Basin Region, in this region there is no climatic data available to run appropriate simulations.

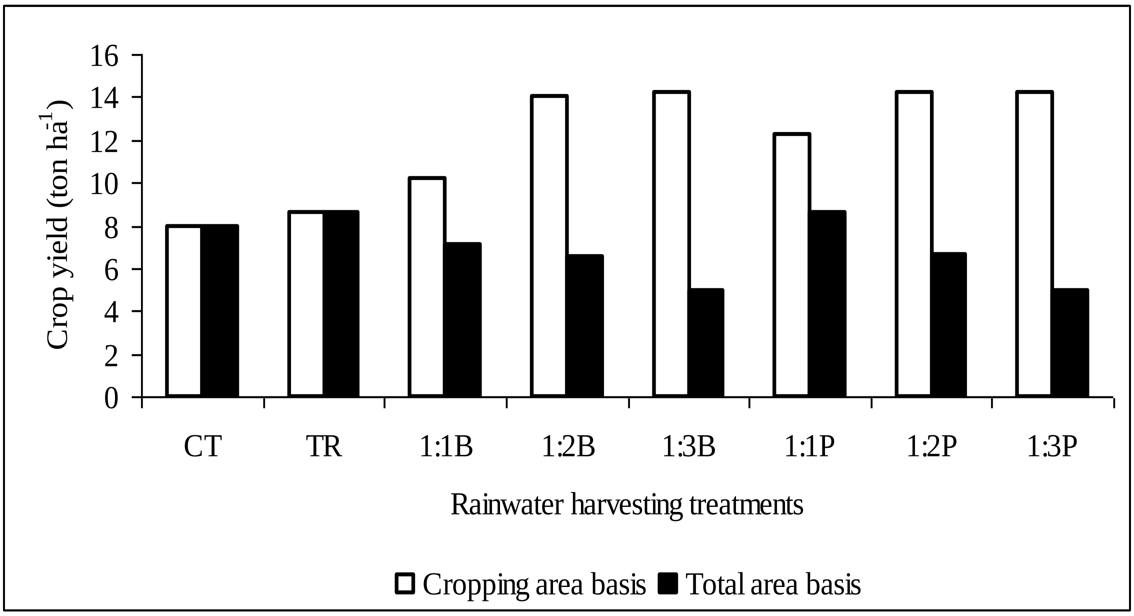


FIG. 7.16: Maize yield on both a **total area** and **cropping area basis** using different rainwater harvesting scenarios in a wet season in the Lower Limpopo River Basin Region, on clay soils

SWB simulations revealed the best crop yields when using tied ridges rather than any other rainwater harvesting scenario in a good rainfall season, on clay soils, if land is limiting for crop production in the Lower Limpopo River Basin Region. This is in accordance with Mzirai *et al.* (2002) statement that tied ridges perform well under high rainfall amounts, heavy soils and soil low percolation rates caused by hardpan zones in the soil profile. As a result, tied ridges can be a successful rainwater harvesting strategy in the Lower Limpopo River Region due to its appropriate soil and climatic characteristics. If land is not limiting for crop production, the ideal rainwater harvesting strategy is the 1:3B design. The 1:3B uses twice more arable land to produce 15 ton/ha than what the tied ridge uses to produce 9 ton/ha. Using the tied ridge technique 40 000 plants would occupy one hectare, whilst when using the 1:3B it would take two hectares of arable land, because part of it will be utilized for runoff collection (75% of arable land).

7.4 CONCLUSIONS AND RECOMMENDATIONS

Rainwater harvesting technologies performed well on sandy clay loam soils in both semi-arid areas, Pretoria and Chokwe. The most important soil characteristic contributing to the success of the rainwater harvesting technologies studied is the level of surface crust formation. The sandy clay loam soils of the Hatfield Experimental Farm of the University of Pretoria are characterized by high levels of surface crusting, which significantly reduces infiltration rates. For in-field rainwater harvesting this is an advantage, because it maximizes runoff collection, and for the tied ridge it allows water to infiltrate into the soil profile more slowly, which reduces drainage losses, and consequently, nutrient leaching. In Pretoria, if land is not limiting for crop production, the ideal rainwater harvesting strategy is the 1:4P or even bigger ratios in most years (when the total rainfall amount is below 950 mm). In very wet seasons (with a total seasonal rainfall above 950 mm), the ideal strategy (of those tested in the field trials or by SWB simulations) is 1:2B. On the other hand, if land is limiting for crop production, the ideal rainwater harvesting strategy in most years (for any total seasonal rainfall equals to or below 950 mm) is the 1:1 IRWH design ratio, with either bare (for wetter years) or plastic covered runoff area (for drier years). In very wet seasons (with a total rainfall above 950 mm), the ideal scenario is the tied ridge technique. At Chokwe, if land is limiting for crop production, the ideal rainwater harvesting strategy was found to be the tied ridge in a poor and medium rainfall season, while in a good rainfall season, simple conventional tillage can harvest sufficient rainfall for maximum crop production. If land is not limiting for crop production, the ideal rainwater harvesting strategy (of those tested) is the 1:3P in a poor rainfall season, the 1:3B in a medium rainfall season and the 1:1B in a good rainfall season. However, due to limited availability of weather data to run more realistic simulations, these results should be tested in the field. Minimum expected maize yield at Chokwe, simulated by SWB (without limitations of fertilizers and pests and diseases properly controlled), is approximately 1.8 ton/ha, in a poor rainfall season, using conventional tillage. This leads to the conclusion that current average maize yields at Chokwe (200 to 300 kg/ha), are well below attainable levels. Other factors such as fertility, pests and disease control, machinery and seeds are likely to play a more important role on crop production than water scarcity in this semi-arid region.

On sandy soils, in the semi-arid area of Pretoria, if land is limiting for crop production, the ideal rainwater harvesting strategy in most years (for any total seasonal rainfall equals to or below 950 mm) is the 1:1P design. In very wet years (for any total seasonal rainfall above 950 mm), maximum crop production is constrained by massive drainage losses expected to occur in the cropping area. If land is not limiting for crop production, in most of the years, the bigger the IRWH design ratio, the higher the probability of exceedence of a certain crop yield level. However, it is important to consider increasing drainage losses with an increase in the size of the runoff areas. As a result, crop yield simulations, under these different rainwater harvesting scenarios, should be run using a crop model that considers the effect of nutrient leaching on the crop yield. In the semi-arid area of Upper Limpopo River Basin, if land is not limiting for crop production, the ideal rainwater harvesting strategy is the 1:3B design (on sandy soils). On the other hand, if land is limiting for crop production, crop yield is maximized by the implementation of a similar technique as the tied ridge, such as micro-basins.

On clay soils, in the semi-arid area of Pretoria, if land is limiting for crop production, the ideal rainwater harvesting strategy in most of the years (for any total seasonal rainfall equal to or below 950 mm) is the 1:1P design. In wetter rainy seasons, crop production is maximized by the implementation of the tied ridge technique. If land is not limiting for crop production, the ideal rainwater harvesting strategy, in most of the years (for any total rainfall equals to or below 950 mm), is the 1:3P. In wetter rainy seasons, maximum crop production is obtained with either, the 1:1P or the 1:2B. Economical analysis should be conducted to evaluate the costs and benefits of implementing each of these techniques. In the semi-arid area of Lower Limpopo River Basin, if land is not limiting for crop production, the water harvesting design most likely to be successful is the 1:3B. Alternatively, if land is limiting for crop production, crop yield can be maximized by the use of the tied ridge technique.

The ideal rainwater harvesting management strategy for a particular semi-arid area is mainly determined by the rainfall distribution during the crop growing season. Therefore, optimum planting dates should be identified for a better rainfall optimization. Other factors playing an important role are rainfall amount during the crop growing season and initial soil water content in the profile.

GENERAL SUMMARY

Annual rainfall amount in semi-arid areas may appear to be enough to support crops but its distribution is usually so unevenly in space and time that conventional rainfed agriculture is hardly possible. Rain in these areas also tends to fall consecutively in a few hard showers, which is mostly lost by runoff. Rainwater harvesting has been playing a very important role as a method of inducing, collecting, storing and conserving local surface runoff in dry areas, in order to mitigate the effects of temporal shortages of rain.

Rainwater harvesting has been implemented in so many different ways around the world, starting from the simplest to the most complex technologies. The simplest technologies being used by small scale farmers are micro-catchment and in-situ rainwater harvesting. Micro-catchment rainwater harvesting consists of collecting runoff from a short slope runoff producing area over a flow distance of less than 30 m and storing it for consumptive use in the root zone of an adjacent cropping area. In this technology, apart from the rain, the crop benefits from an extra amount of water harvested from the runoff areas. In-situ rainwater harvesting involves the use of methods that increase the amount of water stored in the soil profile by trapping or holding the rain where it falls, which considerably reduces water losses by runoff.

Experimental evidences indicate that rainfed agriculture can significantly be upgraded trough the use of rainwater harvesting technologies in dry areas. However, a successful implementation of these technologies requires a number of field trials under different soil and climatic conditions, since the best option varies in space and time. The conduction of such field trials can be very expensive, time consuming and labourious. As a result, rainwater harvesting models have been very useful as an aid to researchers, planners and extensionists in interpreting experimental results and designing locally appropriate interventions.

The general objective of this study was to improve the dry land crop water productivity by using a soil water balance model as a tool to manage the soil water balance

components under rainwater harvesting conditions. In order to achieve this objective, the following specific objectives were established: a) To quantify rainfall-runoff relationships using conceptual and empirical procedures; b) To calibrate the soil water balance model under rainwater harvesting conditions; and c) To select the ideal strategy of rainwater harvesting management with the help of a soil water balance model.

Field trials were conducted on a sandy clay loam soil during the 2007/2008 rainy season at the Hatfield Experimental Farm of the University of Pretoria. One of the trials was carried out to test the response of different rainwater harvesting treatments on maize grain yield and yield components, as well as on soil water content changes in the root zone. The water harvesting treatments were as follows: conventional tillage (CT), tied ridges (TR), design ratio 1:1 of the in-field rainwater harvesting (IRWH) technique with a plastic cover runoff area (1:1P), design ratio 1:2 of the IRWH with a plastic cover runoff area (1:2P), design ratio 1:3 of the IRWH with a plastic cover runoff area (1:3P), design ratio 1:1 of the IRWH with a bare runoff area (1:1B), design ratio 1:2 of the IRWH with a bare runoff area (1:2B), and design ratio 1:3 of the IRWH with a bare runoff area (1:3B). Another trial was conducted to quantify rainfall-runoff relationships using empirical and conceptual runoff models. For this purpose the following measurements were done on 5 m wide bare runoff plots with differing lengths (1, 2 and 3 m): rainfall and runoff amount and intensity, soil infiltration and surface retention as well as sediment collection on the cropping area. On plastic covered runoff plots only rainfall and runoff amounts were monitored.

Results from the runoff trial show that runoff volume and sediment amount collected in the cropping area increase with an increase in the runoff plot length. On the other hand, runoff efficiencies and sediment collection rate decreased with an increase in the runoff plot length. No linear correlation was found between the depths of soil surface retention and the depths of rainfall. Other factors such as antecedent soil water content and rainfall intensity seem to have more impact on this process. A positive linear correlation was found between daily runoff from bare plots and rainfall depths (r^2 = 0.88 on average). Plastic covered runoff plot showed the best linear correlation with an r^2 of 0.99. Runoff curve number method showed good performance in terms of runoff prediction from bare runoff plots when the CN value is fixed by model calibration (r^2 = 0.91 on average). The best runoff prediction from bare plots was found with the conceptual model "Morin and Cluff 1980" model, showing an r^2 of 0.93 on average.

Rainfall analysis showed that the total amount of rain during the season 2007/2008 was about 810 mm, which is above the average annual rainfall for Pretoria. During the growing season the crop received approximately 605 mm of rain, with short dry spells. As a result, soil water content in the root zone did not drop below the permanent wilting point for all the rainwater harvesting treatments, which indicates that the crop did not experience any serious water stress during the growing season. High water losses by percolation might have occurred for the different IRWH designs. Crop yield statistical analysis did not show any significant difference among the different IRWH design treatments when not considering the space occupied by the runoff areas. However, grain yield from the IRWH treatments was significantly higher than for CT and TR techniques. No significant differences were found between CT and TR. When including the space occupied by the runoff areas (total area), grain yield from TR, 1:1B and 1:1P was significantly higher than from other water harvesting treatments. Conversely, no significant differences were found between TR and CT. The highest values of leaf area index at the reproductive stage were obtained with the IRWH technique and the lowest with the TR and CT techniques.

Crop yield simulations using the Soil Water Balance model showed that the ideal rainwater harvesting strategy varies from one season to another and from one region to another. In Pretoria, on sandy and sandy clay loam soils, if land is not limiting for crop production, the ideal rainwater harvesting strategy is the 1:4P or even bigger ratios in most years (when the total rainfall amount is below 950 mm), while on clay soils, it is the 1:3P design. However, if land is limiting for crop production, the ideal rainwater harvesting strategy in most years is the 1:1 IRWH design ratio, with either bare (for wetter years) or plastic covered runoff area (for drier years) on sandy, sandy clay loam and clay soils. At Chokwe, on sandy clay loam soils, if land is limiting for crop production, the ideal rainwater harvesting strategy was found to be the tied ridge in a poor and medium rainfall season, while in a good rainfall season, simple conventional tillage can harvest sufficient rainfall for maximum crop production. If land is not limiting for crop production, the ideal rainwater harvesting strategy (of those tested) is the 1:3P in a poor rainfall season, the 1:3B in a medium rainfall season and the 1:1B in a good rainfall season. The Soil Water Balance model can be used to predict crop yield under rainwater harvesting conditions with reasonable accuracy. Scenarios can be run for different planting dates and initial soil water content levels. This makes the model a very useful tool to help planning the implementation of a rainwater harvesting project, especially in semi-arid areas, where rainfall is so erratic in amount and distribution throughout the season and from one season to another. The model needs to be calibrated and validated for different soil types in order to predict crop yield for diverse places more precisely. It also needs to take into account yield reduction when the plant available water is above the optimum level for maximum crop growth, which leads to nutrient leaching due to drainage losses.

APPENDICES

Slope

Appendix 3.1: Rainwater harvesting Experimental trial layout

Block I

Conventional tillage (control)	Bare runoff area 1:1 Bare runoff area 1:1 Bare runoff area 1:1	Tied ridges	Plastic runoff area 2:1 Plastic runoff area 2:1	Bare runoff area 3:1 Bare runoff area	Plastic runoff area 1:1 Plastic 1:1 Plastic runoff area 1:1	Bare runoff area 2:1 Bare runoff area 2:1	Plastic runoff area 3:1 Plastic runoff area

Block II

Plastic runoff area 2:1 Plastic runoff area 2:1	Bare runoff area 3:1 Bare runoff area	Plastic runoff area 1:1 Plastic runoff area 1:1 Plastic runoff area 1:1	Bare runoff area 2:1 Bare runoff area 2:1	Conventional tillage (control)	Plastic runoff area 3:1 Plastic runoff area	Bare runoff area 1:1 Bare runoff area 1:1 Bare runoff area 1:1	Tied ridges

Block III

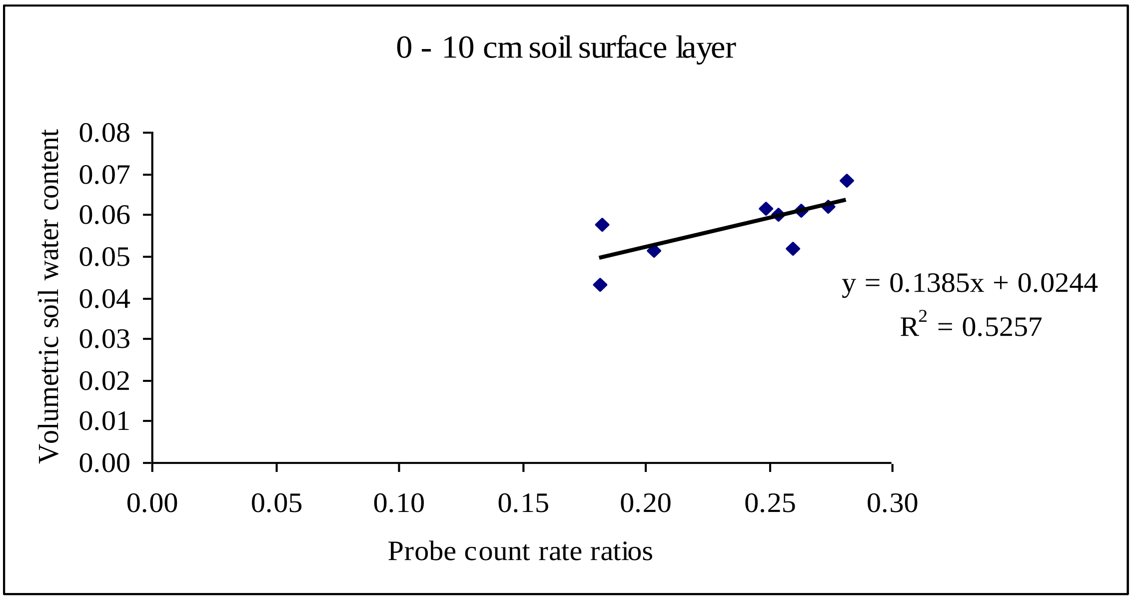
Bare runoff area 3:1 Bare runoff area	Plastic runoff area 2:1 Plastic runoff area 2:1	Bare runoff area 1:1 Bare runoff area 1:1 Bare runoff area 1:1	Plastic runoff area 3:1 Plastic runoff area	Tied ridges	Bare runoff area 2:1 Bare runoff area 2:1	Conventional tillage (control)	Plastic runoff area 1:1 Plastic runoff area 1:1 Plastic runoff area 1:1

Space between blocks: 3 m
Cropping area size in the IRWH technique: 1 m x 5 m

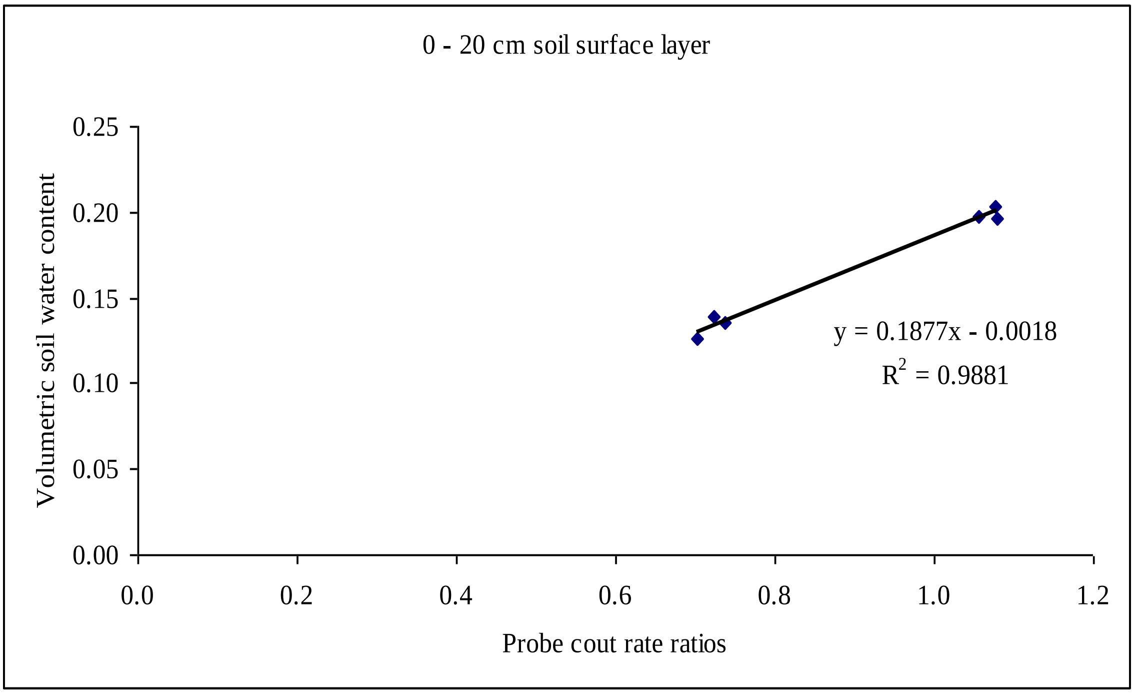
Space between treatments: 2 m
Conventional tillage plot: 6 m x 5 m

Total area : 25 m x 60 m
Tied ridges plot: 6 m x 5 m

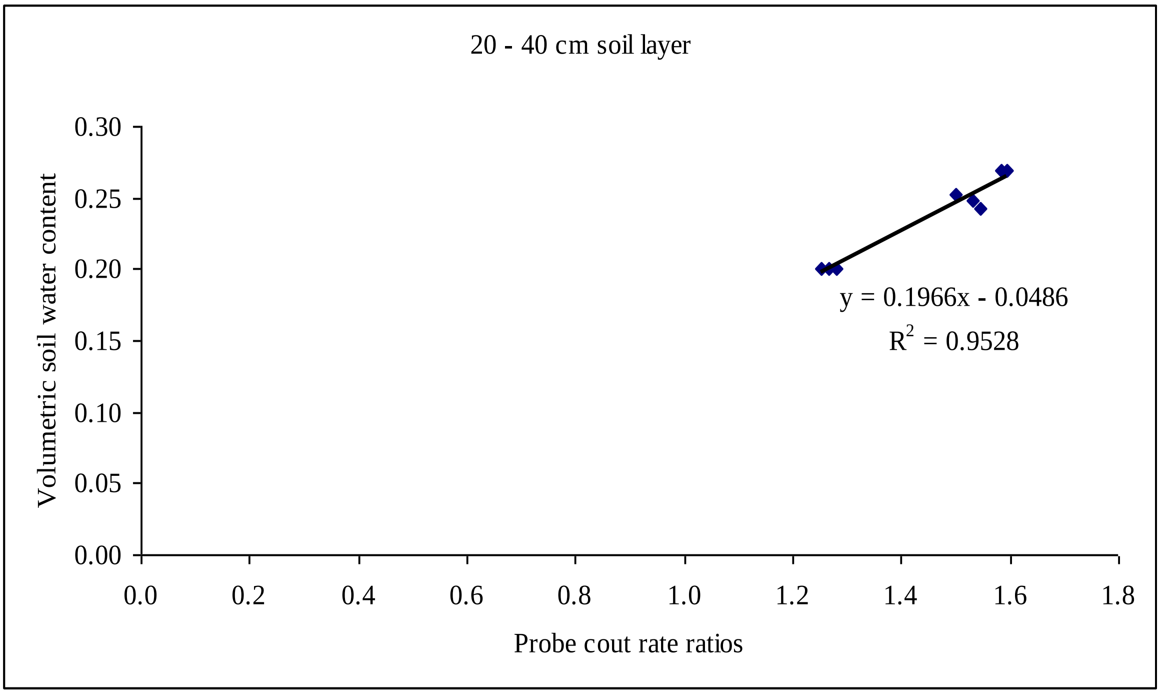
Appendix 3.2: Neutron probe calibration results at the study site



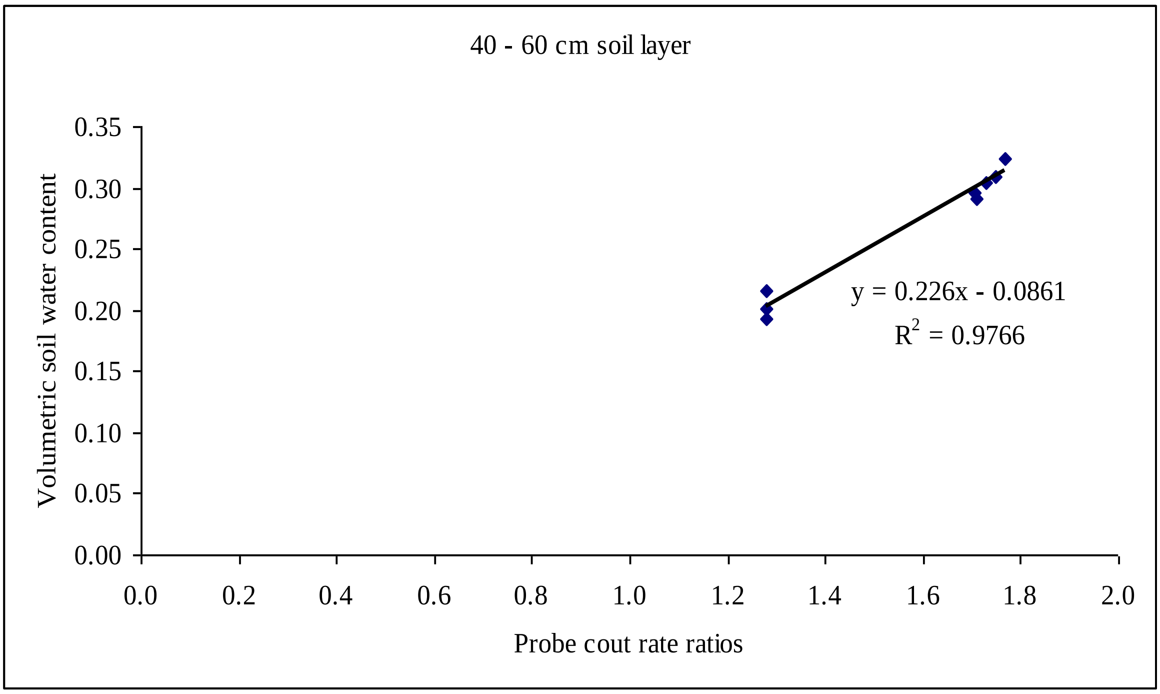
Average bulk density = 1.71 ton m^{-3}



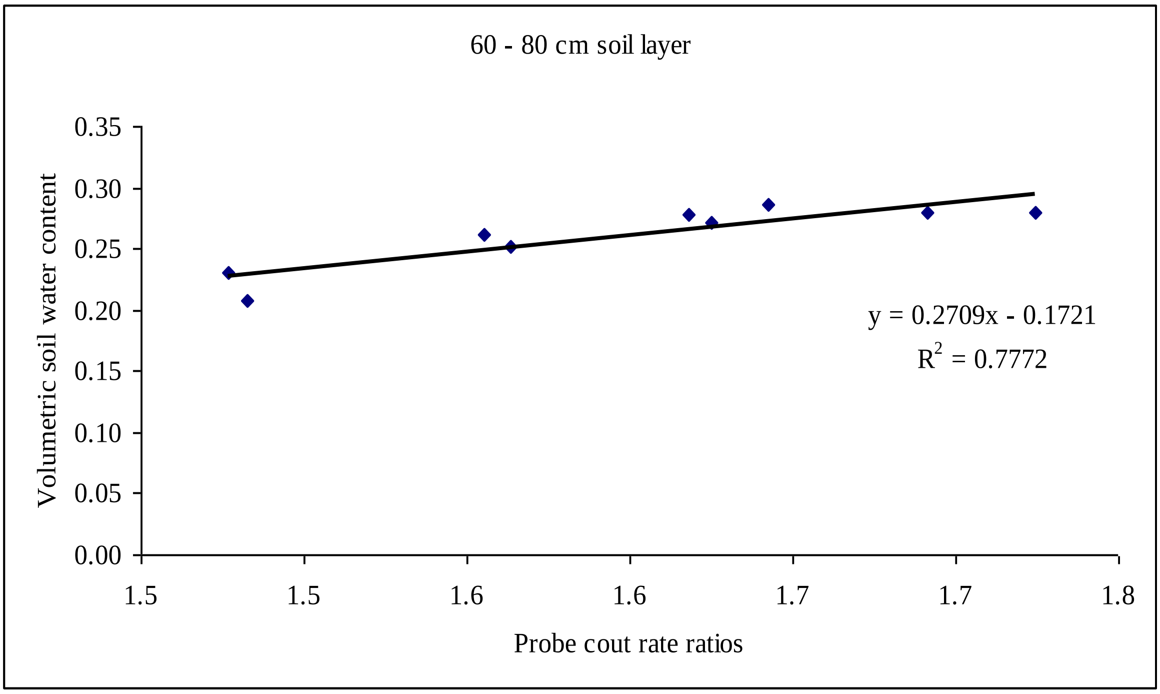
Average bulk density = 1.67 ton m^{-3}



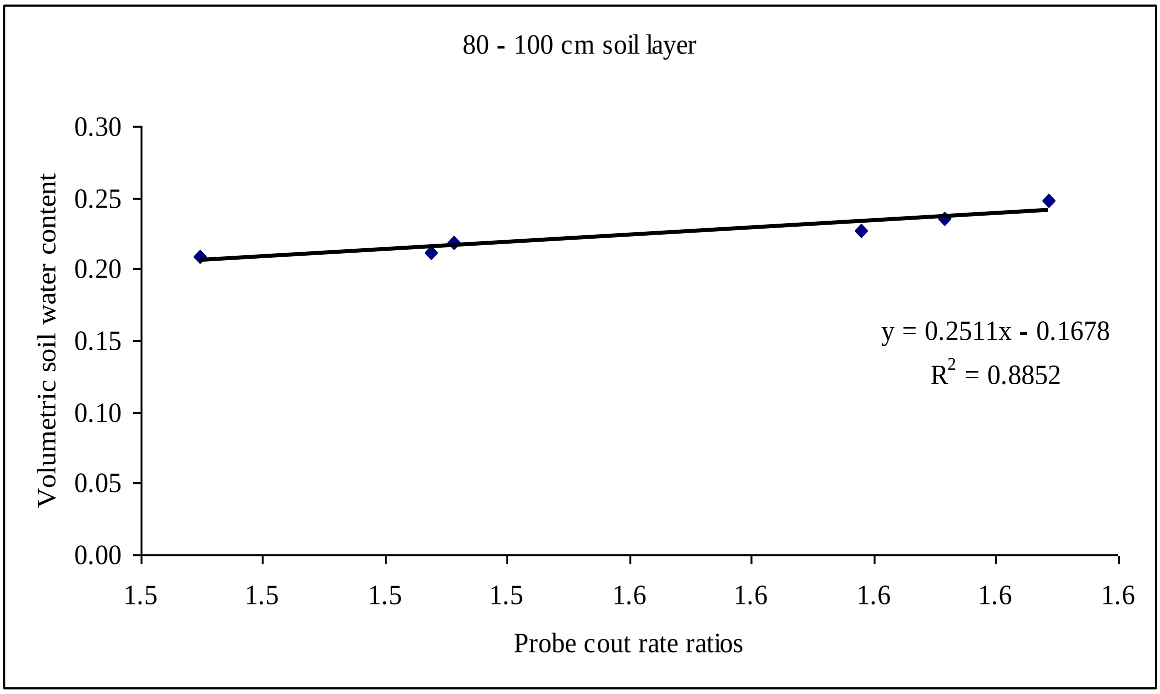
Average bulk density = 1.63 ton m^{-3}



Average bulk density = 1.51 ton m^{-3}



Average bulk density = 1.45 ton m^{-3}



Average bulk density = 1.50 ton m^{-3}

Appendix 3.3: Crop yield, yield components and growth statistical analysis results

Maize yield excluding the space occupied by the runoff areas (kg ha^{-1})

Analysis of variance

Source	DF	Type I SS	Mean Square	F value	Pr > F
Replications	2	21.68	10.84	2.05	0.1652
Treatments	7	680.17	97.17	18.41	<.0001

R^2 = 0.90 CV = 13.19 P = 0.05

Least significant difference

t Grouping		Mean	N	Treatment
	A	17	3	3mP
	A			
B	A	14.9	3	1mB
B	A			
B	A	14.5	3	1mP
B				
B		13.8	3	2 mP
B				
B		13.8	3	3mB
B				
B		13.4	3	2mB
	C	9.40	3	TR
	C			
	C	7.73	3	CT

LSD = 4.02 P = 0.05

Maize yield including the space occupied by the runoff areas (Kg ha^{-1})

Analysis of variance

Source	DF	Type I SS	Mean Square	F value	Pr > F
Replications	2	3.71	1.85	1.65	0.23
Treatments	7	94.40	13.49	12.03	<.0001

$R^2 = 0.86$ CV = 13.86   P = 0.05

Least significant difference

t Grouping		Mean	N	Treatment
	A	10.4	3	1mB
	A			
	A	10.2	3	1mP
	A			
B	A	9.4	3	TR
B				
B	C	7.7	3	CT
	C			
D	C	6.4	3	2mP
D	C			
D	C	6.3	3	2mB
D	C			
D	C	5.9	3	3mP
D				
D		4.8	3	3mB

LSD = 1.85   P = 0.05

Average mass per kernel (g plant^{-1})

Analysis of variance

Source	DF	Type I SS	Mean Square	F value	Pr > F
Replications	2	0.0023	0.0011	2.15	0.15
Treatments	7	0.012	0.0017	3.19	0.031

R^2 = 0.66   CV = 7.7   P = 0.05

Least significant difference

t Grouping		Mean	N	Treatment
	A	0.33	3	3mP
	A			
B	A	0.31	3	1mB
B	A			
B	A	0.31	3	2mB
B	A			
B	A	0.31	3	TR
B	A			
B	A	0.30	3	1mP
B	A			
B	A	0.29	3	3mB
B				
B	C	0.28	3	2mP
	C			
	C	0.25	3	CT

LSD = 0.040   P = 0.05

Rows number per plant

Analysis of variance

Source	DF	Type I SS	Mean Square	F value	Pr > F
Replications	2	0.014	0.0071	4.04	0.0413
Treatments	7	0.100	0.0144	8.15	0.0005

$R^2 = 0.82$ CV = 1.51 P = 0.05

Least significant difference (Data submitted to logarithmic transformation)

t Grouping		Mean	N	Treatment
	A	2.908	3	3mP
	B	2.833	3	2mP
	B			
	B	2.811	3	1mP
	B			
C	B	2.773	3	3mB
C	B			
C	B	2.771	3	2mB
C				
C		2.730	3	TR
C				
C		2.708	3	1mB
C				
C		2.707	3	CT

LSD = 0.0735 P = 0.05

Kernels number per plant

Analysis of variance

Source	DF	Type I SS	Mean Square	F value	Pr > F
Replications	2	12133.1	6066.5	1.79	0.2035
Treatments	7	62136.7	8876.7	2.62	0.0596

$R^2 = 0.61$ CV = 7.02 P = 0.05

Hectare litre mass (kg 100L^{-1})

Analysis of variance

Source	DF	Type I SS	Mean Square	F value	Pr > F
Replications	2	2.33	1.17	1.26	0.31
Treatments	7	8.63	1.23	1.33	0.31

$R^2 = 0.46$ CV = 1.23 P = 0.05

Harvest index

Analysis of variance

Source	DF	Type I SS	Mean Square	F value	Pr > F
Replications	2	3.08	1.54	0.28	0.76
Treatments	7	44.29	6.33	1.14	0.39

$R^2 = 0.38$ CV = 4.55 P = 0.05

Stover at harvest per plant (g plant^{-1})

Analysis of variance

Source	DF	Type I SS	Mean Square	F value	Pr > F
Replications	2	425.19	212.59	0.84	0.45
Treatments	7	5012.84	716.12	2.85	0.046

R^2 = 0.61 CV = 8.12 P = 0.05

Least significant difference

t Grouping		Mean	N	Treatment
	A	223.87	3	3mP
	A			
B	A	205.17	3	2mP
B	A			
B	A	200.87	3	1mP
B	A			
B	A	199.40	3	3mB
B				
B		193.13	3	1mB
B				
B		186.17	3	2mB
B				
B		177.83	3	CT
B				
B		177.50	3	TR

LSD = 27.78 P = 0.05

Appendix 4.1: Calibration results for different tipping bucket flow meters used in the trial

Tipping bucket	Volume of runoff per tip (L)
1	2.015
2	2.88
3	2.01

Appendix 4.2: Daily observed runoff depths for different runoff treatments during the rainy season 2007-2008 in Hatfield experimental farm

		Runoff (mm) from different plot lengths and surface treatments			
Date	Rainfall (mm)	1 m Bare	2 m Bare	3 m Bare	2 m Plastic covered
5-Nov-07	3.5	0.0	0.0	0.0	3.2
17-Nov-07	8.6	0.0	0.0	0.0	7.5
21-Nov-07	1.7	0.0	0.0	0.0	1.6
22-Nov-07	0.1	0.0	0.0	0.0	0.0
23-Nov-07	21.0	12.3	11.2	10.7	20.5
24-Nov-07	4.5	2.0	1.7	1.9	4.2
26-Nov-07	0.1	0.0	0.0	0.0	0.0
29-Nov-07	0.1	0.0	0.0	0.0	0.0
30-Nov-07	6.0	0.0	0.0	0.0	5.5
4-Dec-07	9.6	4.5	3.6	4.5	8.5
5-Dec-07	16.9	12.9	12.7	12.6	16.5
6-Dec-07	2.1	0.0	0.0	0.0	1.0
7-Dec-07	4.7	0.0	0.0	0.0	3.2

8-Dec-07	10.0	4.0	3.1	3.1	7.0
8-Dec-07	34.0	22.4	21.1	20.4	33.0
11-Dec-07	32.0	20.2	19.5	19.2	31.0
14-Dec-07	21.0	16.4	15.9	15.3	20.2
15-Dec-07	1.0	0.0	0.0	0.0	0.5
16-Dec-07	19.0	19.0	19.0	18.7	18.5
17-Dec-07	1.0	0.0	0.0	0.0	0.6
28-Dec-07	7.0	0.0	0.0	0.0	4.0
4-Jan-08	16.0	1.4	1.3	1.1	13.6
7-Jan-08	24.0	14.0	13.4	12.7	23.0
8-Jan-08	2.0	0.0	0.0	0.0	1.2
9-Jan-08	22.0	5.6	5.8	6.3	18.0
10-Jan-08	23.0	2.5	3.2	4.2	19.6
17-Jan-08	4.5	0.0	0.0	0.0	1.7
18-Jan-08	48.0	38.4	37.4	36.9	47.0
20-Jan-08	15.0	8.6	10.0	10.2	13.5
21-Jan-08	30.5	19.2	18.9	18.9	29.5
22-Jan-08	38.0	36.0	36.5	36.9	37.8
23-Jan-08	5.0	1.6	1.4	4.3	3.1
24-Jan-08	1.5	0.0	0.0	0.0	0.7
4-Feb-08	7.0	0.0	0.0	0.0	2.7
5-Feb-08	10.0	6.8	6.6	6.4	8.5
13-Feb-08	5.5	0.0	0.0	0.0	2.6
14-Feb-08	1.2	0.0	0.0	0.0	0.6
22-Feb-08	5.5	0.0	0.0	0.0	3.5
26-Feb-08	5.7	0.3	0.3	0.3	3.2
27-Feb-08	24.0	17.6	16.6	15.1	23.0
5-Mar-08	5.3	0.0	0.0	0.0	3.0
13-Mar-08	29.5	14.5	14.1	14.6	29.8
14-Mar-08	2.7	0.0	0.0	0.0	0.2
16-Mar-08	55.6	36.3	36.0	32.2	54.5

17-Mar-08	9.5	3.2	2.9	2.9	9.4
18-Mar-08	9.1	3.2	2.6	3.4	4.9
23-Mar-08	1.1	0.0	0.0	0.0	0.8
29-Mar-08	14.9	8.8	8.5	8.3	14.5
31-Mar-08	3.8	2.4	2.3	2.3	2.7
7-Apr-08	2.7	0.0	0.0	0.0	1.5
10-Apr-08	5.5	2.0	2.0	1.6	3.0
12-Apr-08	1.6	0.0	0.0	0.0	0.8
13-Apr-08	4.2	1.2	1.2	0.9	2.3
1-May-08	3.6	0.0	0.0	0.0	1.9
2-May-08	7.2	2.4	1.2	1.5	5.8
3-May-08	8.3	2.0	1.4	1.7	6.5
4-May-08	7.4	1.6	1.4	1.5	5.6

Runoff plot width = 5 m

Appendix 5.1: The best runoff prediction by the Morin and Cluff (1980) runoff model for different rainfall events during the rainy season 2007-2008 at Hatfield experimental farm

Rainstorm of May 3rd, 2008

i	Δt_i (hr)	$\sum \Delta t_i$ (hr)	P_i (mm)	$\sum P_i$ (mm)	I_i (mmhr^{-1})	$Id_{\Delta ti}$ (mm)	$\sum Id_{\Delta ti}$ (mm)	R_i (mm)	$\sum R_i$ (mm)
1423	0.15	0.15	0.10	0.10	0.67	0.18	0.18	0.00	0.00
1432	0.15	0.30	0.10	0.20	0.67	3.68	3.86	0.00	0.00
1441	0.15	0.45	0.10	0.30	0.67	3.44	7.30	0.00	0.00
1453	0.20	0.65	0.10	0.40	0.50	4.30	11.60	0.00	0.00
1458	0.08	0.73	0.10	0.50	1.20	1.68	13.27	0.00	0.00

1501	0.05	0.78	0.10	0.60	2.00	0.94	14.22	0.00	0.00
1504	0.05	0.83	0.10	0.70	2.00	0.88	15.10	0.00	0.00
1507	0.05	0.88	0.10	0.80	2.00	0.83	15.92	0.00	0.00
1512	0.08	0.97	0.10	0.90	1.20	1.29	17.21	0.00	0.00
1514	0.03	1.00	0.10	1.00	3.00	0.48	17.70	0.00	0.00
1516	0.03	1.03	0.10	1.10	3.00	0.45	18.15	0.00	0.00
1518	0.03	1.07	0.10	1.20	3.00	0.43	18.58	0.00	0.00
1520	0.03	1.10	0.10	1.30	3.00	0.40	18.98	0.00	0.00
1521	0.02	1.12	0.10	1.40	6.00	0.19	19.17	0.00	0.00
1523	0.03	1.15	0.10	1.50	3.00	0.35	19.52	0.00	0.00
1524	0.02	1.17	0.10	1.60	6.00	0.17	19.69	0.00	0.00
1527	0.05	1.22	0.10	1.70	2.00	0.47	20.16	0.00	0.00
1528	0.02	1.23	0.10	1.80	6.00	0.15	20.30	0.00	0.00
1531	0.05	1.28	0.10	1.90	2.00	0.42	20.72	0.00	0.00
1532	0.02	1.30	0.10	2.00	6.00	0.13	20.85	0.00	0.00
1535	0.05	1.35	0.10	2.10	2.00	0.37	21.22	0.00	0.00
1538	0.05	1.40	0.10	2.20	2.00	0.35	21.56	0.00	0.00
1541	0.05	1.45	0.10	2.30	2.00	0.33	21.89	0.00	0.00
1543	0.03	1.48	0.10	2.40	3.00	0.21	22.10	0.00	0.00
1545	0.03	1.52	0.10	2.50	3.00	0.20	22.30	0.00	0.00
1546	0.02	1.53	0.10	2.60	6.00	0.09	22.39	0.00	0.00
1549	0.05	1.58	0.10	2.70	2.00	0.26	22.65	0.00	0.00
1550	0.02	1.60	0.10	2.80	6.00	0.08	22.73	0.02	0.02
1552	0.03	1.63	0.10	2.90	3.00	0.16	22.89	0.00	0.02
1553	0.02	1.65	0.10	3.00	6.00	0.07	22.97	0.03	0.04
1555	0.03	1.68	0.10	3.10	3.00	0.14	23.11	0.00	0.04
1556	0.02	1.70	0.10	3.20	6.00	0.07	23.18	0.03	0.07
1558	0.03	1.73	0.10	3.30	3.00	0.13	23.31	0.00	0.07
1559	0.02	1.75	0.10	3.40	6.00	0.06	23.37	0.04	0.11
1601	0.03	1.78	0.10	3.50	3.00	0.12	23.49	0.00	0.11
1603	0.05	1.83	0.10	3.60	2.00	0.17	23.65	0.00	0.11

1605	0.05	1.88	0.10	3.70	2.00	0.16	23.81	0.00	0.11
1606	0.02	1.90	0.10	3.80	6.00	0.05	23.87	0.05	0.16
1608	0.03	1.93	0.10	3.90	3.00	0.10	23.96	0.00	0.16
1609	0.02	1.95	0.10	4.00	6.00	0.05	24.01	0.05	0.22
1612	0.05	2.00	0.10	4.10	2.00	0.14	24.15	0.00	0.22
1613	0.02	2.02	0.10	4.20	6.00	0.04	24.19	0.06	0.27
1615	0.03	2.05	0.10	4.30	3.00	0.08	24.28	0.02	0.29
1617	0.03	2.08	0.10	4.40	3.00	0.08	24.36	0.02	0.31
1623	0.10	2.18	0.10	4.50	1.00	0.24	24.59	0.00	0.31
1627	0.07	2.25	0.10	4.60	1.50	0.15	24.75	0.00	0.31
1635	0.13	2.38	0.10	4.70	0.75	0.29	25.04	0.00	0.31
1637	0.03	2.42	0.10	4.80	3.00	0.07	25.11	0.03	0.33
1642	0.08	2.50	0.10	4.90	1.20	0.17	25.29	0.00	0.33
1645	0.05	2.55	0.10	5.00	2.00	0.10	25.39	0.00	0.33
1650	0.08	2.63	0.10	5.10	1.20	0.16	25.55	0.00	0.33
1653	0.05	2.68	0.10	5.20	2.00	0.10	25.65	0.00	0.34
1657	0.07	2.75	0.10	5.30	1.50	0.12	25.77	0.00	0.34
1659	0.03	2.78	0.10	5.40	3.00	0.06	25.83	0.04	0.38
1704	0.08	2.87	0.10	5.50	1.20	0.15	25.98	0.00	0.38
1706	0.03	2.90	0.10	5.60	3.00	0.06	26.04	0.04	0.42
1710	0.07	2.97	0.10	5.70	1.50	0.11	26.15	0.00	0.42
1712	0.03	3.00	0.10	5.80	3.00	0.06	26.21	0.04	0.46
1716	0.07	3.07	0.10	5.90	1.50	0.11	26.32	0.00	0.46
1717	0.02	3.08	0.10	6.00	6.00	0.03	26.34	0.07	0.54
1720	0.02	3.10	0.10	6.10	6.00	0.03	26.37	0.07	0.61
1722	0.03	3.13	0.10	6.20	3.00	0.05	26.42	0.05	0.66
1727	0.05	3.18	0.10	6.30	2.00	0.08	26.50	0.02	0.68
1730	0.05	3.23	0.10	6.40	2.00	0.08	26.57	0.02	0.71
1738	0.13	3.37	0.10	6.50	0.75	0.20	26.77	0.00	0.71
1740	0.03	3.40	0.10	6.60	3.00	0.05	26.82	0.05	0.76
1744	0.07	3.47	0.10	6.70	1.50	0.10	26.92	0.00	0.76

1746	0.03	3.50	0.10	6.80	3.00	0.05	26.97	0.05	0.81
1749	0.05	3.55	0.10	6.90	2.00	0.07	27.04	0.03	0.84
1751	0.03	3.58	0.10	7.00	3.00	0.05	27.09	0.05	0.89
1754	0.05	3.63	0.10	7.10	2.00	0.07	27.16	0.03	0.92
1756	0.03	3.67	0.10	7.20	3.00	0.05	27.20	0.05	0.98
1759	0.05	3.72	0.10	7.30	2.00	0.07	27.27	0.03	1.01
1802	0.05	3.77	0.10	7.40	2.00	0.07	27.34	0.03	1.04
1806	0.07	3.83	0.10	7.50	1.50	0.09	27.43	0.01	1.05
1809	0.05	3.88	0.10	7.60	2.00	0.07	27.50	0.03	1.08
1813	0.07	3.95	0.10	7.70	1.50	0.09	27.58	0.01	1.10
1816	0.05	4.00	0.10	7.80	2.00	0.07	27.65	0.03	1.13
1821	0.08	4.08	0.10	7.90	1.20	0.11	27.76	0.00	1.13
1823	0.03	4.12	0.10	8.00	3.00	0.04	27.80	0.06	1.19
1826	0.05	4.17	0.10	8.10	2.00	0.07	27.87	0.03	1.22
1829	0.05	4.22	0.10	8.20	2.00	0.06	27.93	0.04	1.26
1910	0.68	4.90	0.10	8.30	0.15	0.88	28.82	0.00	1.26

Rainstorm of March 29th, 2008

i	Δt_i (hr)	$\sum\Delta t_i$ (hr)	P_i (mm)	$\sum P_i$ (mm)	I_i ($mmhr^{-1}$)	$Id_{\Delta ti}$ (mm)	$\sum Id_{\Delta ti}$ (mm)	R_i (mm)	$\sum R_i$ (mm)
1426	0.008	0.008	0.100	0.100	12.000	0.010	0.010	0.000	0.000
1426	0.008	0.017	0.100	0.200	12.000	0.087	0.097	0.000	0.000
1427	0.008	0.025	0.100	0.300	12.000	0.048	0.146	0.000	0.000
1427	0.008	0.033	0.100	0.400	12.000	0.029	0.175	0.000	0.000
1428	0.006	0.039	0.100	0.500	18.000	0.013	0.188	0.000	0.000
1428	0.006	0.044	0.100	0.600	18.000	0.010	0.198	0.000	0.000
1428	0.006	0.050	0.100	0.700	18.000	0.008	0.206	0.000	0.000

1429	0.006	0.056	0.100	0.800	18.000	0.007	0.213	0.000	0.000
1429	0.006	0.061	0.100	0.900	18.000	0.007	0.220	0.000	0.000
1429	0.006	0.067	0.100	1.000	18.000	0.007	0.227	0.000	0.000
1430	0.006	0.072	0.100	1.100	18.000	0.007	0.234	0.000	0.000
1430	0.006	0.078	0.100	1.200	18.000	0.007	0.241	0.000	0.000
1430	0.006	0.083	0.200	1.400	36.000	0.007	0.248	0.000	0.000
1431	0.003	0.087	0.100	1.500	30.000	0.004	0.252	0.000	0.000
1431	0.003	0.090	0.100	1.600	30.000	0.004	0.256	0.000	0.000
1431	0.003	0.093	0.100	1.700	30.000	0.004	0.260	0.000	0.000
1431	0.003	0.097	0.100	1.800	30.000	0.004	0.264	0.000	0.000
1431	0.003	0.100	0.100	1.900	30.000	0.004	0.268	0.000	0.000
1432	0.006	0.106	0.100	2.000	18.000	0.007	0.275	0.000	0.000
1432	0.006	0.111	0.100	2.100	18.000	0.007	0.281	0.000	0.000
1432	0.006	0.117	0.100	2.200	18.000	0.007	0.288	0.000	0.000
1433	0.003	0.119	0.100	2.300	36.000	0.003	0.291	0.000	0.000
1433	0.003	0.122	0.100	2.400	36.000	0.003	0.295	0.000	0.000
1433	0.003	0.125	0.200	2.600	72.000	0.003	0.298	0.000	0.000
1433	0.003	0.128	0.100	2.700	36.000	0.003	0.301	0.097	0.097
1433	0.003	0.131	0.200	2.900	72.000	0.003	0.305	0.197	0.293
1433	0.003	0.133	0.100	3.000	36.000	0.003	0.308	0.097	0.390
1434	0.003	0.136	0.200	3.200	80.000	0.003	0.311	0.197	0.587
1434	0.003	0.138	0.200	3.400	80.000	0.003	0.314	0.197	0.784
1434	0.003	0.141	0.100	3.500	40.000	0.003	0.317	0.097	0.881
1434	0.003	0.143	0.300	3.800	120.000	0.003	0.320	0.297	1.178
1434	0.003	0.146	0.200	4.000	80.000	0.003	0.323	0.197	1.375
1434	0.003	0.148	0.200	4.200	80.000	0.003	0.326	0.197	1.572
1434	0.003	0.151	0.200	4.400	80.000	0.003	0.329	0.197	1.769
1435	0.003	0.153	0.200	4.600	80.000	0.003	0.332	0.197	1.966
1435	0.003	0.156	0.200	4.800	80.000	0.003	0.335	0.197	2.163
1435	0.003	0.158	0.100	4.900	40.000	0.003	0.338	0.097	2.260
1435	0.003	0.161	0.100	5.000	40.000	0.003	0.341	0.097	2.357

1435	0.003	0.163	0.200	5.200	80.000	0.003	0.344	0.197	2.554
1435	0.003	0.166	0.200	5.400	80.000	0.003	0.347	0.197	2.751
1435	0.003	0.168	0.200	5.600	80.000	0.003	0.350	0.197	2.948
1435	0.003	0.171	0.300	5.900	120.000	0.003	0.353	0.297	3.245
1436	0.002	0.173	0.100	6.000	45.000	0.003	0.356	0.097	3.342
1436	0.002	0.175	0.100	6.100	45.000	0.003	0.359	0.097	3.439
1436	0.002	0.178	0.300	6.400	135.000	0.003	0.362	0.297	3.736
1436	0.002	0.180	0.100	6.500	45.000	0.003	0.364	0.097	3.834
1436	0.002	0.182	0.100	6.600	45.000	0.003	0.367	0.097	3.931
1436	0.002	0.184	0.100	6.700	45.000	0.003	0.370	0.097	4.028
1436	0.002	0.186	0.200	6.900	90.000	0.003	0.372	0.197	4.226
1436	0.002	0.189	0.200	7.100	90.000	0.003	0.375	0.197	4.423
1437	0.003	0.191	0.100	7.200	40.000	0.003	0.378	0.097	4.520
1437	0.003	0.194	0.100	7.300	40.000	0.003	0.381	0.097	4.617
1437	0.003	0.196	0.100	7.400	40.000	0.003	0.384	0.097	4.714
1437	0.003	0.199	0.200	7.600	80.000	0.003	0.387	0.197	4.911
1437	0.003	0.201	0.200	7.800	80.000	0.003	0.390	0.197	5.108
1437	0.003	0.204	0.200	8.000	80.000	0.003	0.393	0.197	5.305
1437	0.003	0.206	0.100	8.100	40.000	0.003	0.396	0.097	5.402
1438	0.002	0.208	0.200	8.300	90.000	0.003	0.399	0.197	5.599
1438	0.002	0.211	0.100	8.400	45.000	0.003	0.402	0.097	5.696
1438	0.002	0.213	0.200	8.600	90.000	0.003	0.404	0.197	5.894
1438	0.002	0.215	0.200	8.800	90.000	0.003	0.407	0.197	6.091
1438	0.002	0.217	0.100	8.900	45.000	0.003	0.410	0.097	6.188
1438	0.002	0.219	0.100	9.000	45.000	0.003	0.412	0.097	6.286
1438	0.002	0.222	0.200	9.200	90.000	0.003	0.415	0.197	6.483
1438	0.002	0.224	0.200	9.400	90.000	0.003	0.418	0.197	6.680
1439	0.002	0.226	0.100	9.500	45.000	0.003	0.420	0.097	6.778
1439	0.002	0.228	0.300	9.800	135.000	0.003	0.423	0.297	7.075
1439	0.002	0.231	0.200	10.000	90.000	0.003	0.426	0.197	7.272
1439	0.002	0.233	0.100	10.100	45.000	0.003	0.428	0.097	7.370

1439	0.002	0.235	0.300	10.400	135.000	0.003	0.431	0.297	7.667
1439	0.002	0.237	0.200	10.600	90.000	0.003	0.434	0.197	7.864
1439	0.002	0.239	0.200	10.800	90.000	0.003	0.437	0.197	8.062
1439	0.002	0.242	0.200	11.000	90.000	0.003	0.439	0.197	8.259
1440	0.002	0.244	0.100	11.100	45.000	0.003	0.442	0.097	8.356
1440	0.002	0.246	0.300	11.400	135.000	0.003	0.445	0.297	8.653
1440	0.002	0.248	0.100	11.500	45.000	0.003	0.447	0.097	8.751
1440	0.002	0.251	0.100	11.600	45.000	0.003	0.450	0.097	8.848
1440	0.002	0.253	0.100	11.700	45.000	0.003	0.453	0.097	8.945
1440	0.002	0.255	0.300	12.000	135.000	0.003	0.455	0.297	9.243
1440	0.002	0.257	0.100	12.100	45.000	0.003	0.458	0.097	9.340
1440	0.002	0.259	0.100	12.200	45.000	0.003	0.461	0.097	9.437
1440	0.002	0.262	0.200	12.400	90.000	0.003	0.463	0.197	9.635
1441	0.003	0.265	0.100	12.500	30.000	0.004	0.467	0.096	9.731
1441	0.003	0.268	0.100	12.600	30.000	0.004	0.471	0.096	9.827
1441	0.003	0.272	0.100	12.700	30.000	0.004	0.476	0.096	9.923
1441	0.003	0.275	0.100	12.800	30.000	0.004	0.480	0.096	10.018
1441	0.003	0.278	0.100	12.900	30.000	0.004	0.484	0.096	10.114
1442	0.004	0.283	0.100	13.000	24.000	0.005	0.489	0.095	10.209
1442	0.004	0.287	0.100	13.100	24.000	0.005	0.494	0.095	10.304
1442	0.004	0.291	0.100	13.200	24.000	0.005	0.499	0.095	10.399
1442	0.004	0.295	0.100	13.300	24.000	0.005	0.504	0.095	10.494
1443	0.004	0.299	0.100	13.400	24.000	0.005	0.509	0.095	10.589
1443	0.004	0.303	0.200	13.600	48.000	0.005	0.514	0.195	10.784
1443	0.004	0.308	0.100	13.700	24.000	0.005	0.519	0.095	10.879
1443	0.004	0.312	0.100	13.800	24.000	0.005	0.524	0.095	10.974
1444	0.004	0.316	0.100	13.900	24.000	0.005	0.529	0.095	11.069
1444	0.004	0.320	0.300	14.200	72.000	0.005	0.534	0.295	11.364
1444	0.004	0.324	0.100	14.300	24.000	0.005	0.539	0.095	11.459
1444	0.004	0.328	0.100	14.400	24.000	0.005	0.544	0.095	11.554
1445	0.017	0.345	0.100	14.500	6.000	0.020	0.564	0.080	11.634

1446	0.017	0.362	0.100	14.600	6.000	0.020	0.584	0.080	11.714
1447	0.017	0.378	0.100	14.700	6.000	0.020	0.605	0.080	11.793
1511	0.400	0.778	0.100	14.800	0.250	0.484	1.089	0.000	11.793
1538	0.450	1.228	0.100	14.900	0.222	0.545	1.633	0.000	11.793

Rainstorm of March 13th, 2008

i	Δt_i (hr)	$\sum \Delta t_i$ (hr)	P_i (mm)	$\sum P_i$ (mm)	I_i ($mmhr^{-1}$)	$Id_{\Delta ti}$ (mm)	$\sum Id_{\Delta ti}$ (mm)	R_i (mm)	$\sum R_i$ (mm)
1855	0.017	0.017	0.100	0.100	6.000	0.020	0.020	0.000	0.000
1856	0.017	0.033	0.100	0.200	6.000	0.409	0.429	0.000	0.000
1857	0.017	0.050	0.100	0.300	6.000	0.382	0.811	0.000	0.000
1859	0.033	0.083	0.100	0.400	3.000	0.716	1.527	0.000	0.000
1900	0.017	0.100	0.100	0.500	6.000	0.335	1.862	0.000	0.000
1901	0.017	0.117	0.100	0.600	6.000	0.314	2.176	0.000	0.000
1902	0.017	0.133	0.100	0.700	6.000	0.294	2.470	0.000	0.000
1903	0.008	0.142	0.100	0.800	12.000	0.138	2.608	0.000	0.000
1903	0.008	0.150	0.100	0.900	12.000	0.129	2.737	0.000	0.000
1904	0.017	0.167	0.100	1.000	6.000	0.242	2.979	0.000	0.000
1905	0.017	0.183	0.100	1.100	6.000	0.227	3.206	0.000	0.000
1906	0.017	0.200	0.100	1.200	6.000	0.213	3.419	0.000	0.000
1907	0.017	0.217	0.100	1.300	6.000	0.200	3.620	0.000	0.000
1908	0.017	0.233	0.100	1.400	6.000	0.188	3.807	0.000	0.000
1909	0.008	0.242	0.100	1.500	12.000	0.088	3.896	0.000	0.000
1909	0.008	0.250	0.100	1.600	12.000	0.083	3.979	0.000	0.000
1911	0.033	0.283	0.100	1.700	3.000	0.312	4.291	0.000	0.000
1912	0.008	0.292	0.100	1.800	12.000	0.073	4.365	0.000	0.000
1912	0.008	0.300	0.100	1.900	12.000	0.069	4.434	0.000	0.000
1913	0.006	0.306	0.100	2.000	18.000	0.043	4.477	0.000	0.000
1913	0.006	0.311	0.100	2.100	18.000	0.041	4.518	0.000	0.000

1913	0.006	0.317	0.100	2.200	18.000	0.039	4.557	0.000	0.000
1914	0.008	0.325	0.100	2.300	12.000	0.055	4.612	0.000	0.000
1914	0.008	0.333	0.100	2.400	12.000	0.052	4.663	0.000	0.000
1915	0.017	0.350	0.100	2.500	6.000	0.098	4.761	0.000	0.000
1916	0.006	0.356	0.100	2.600	18.000	0.031	4.792	0.000	0.000
1916	0.006	0.361	0.100	2.700	18.000	0.029	4.821	0.071	0.071
1916	0.006	0.367	0.100	2.800	18.000	0.028	4.849	0.072	0.143
1917	0.004	0.371	0.100	2.900	24.000	0.020	4.869	0.080	0.223
1917	0.004	0.375	0.100	3.000	24.000	0.019	4.887	0.081	0.305
1917	0.004	0.379	0.100	3.100	24.000	0.018	4.905	0.082	0.387
1917	0.004	0.383	0.100	3.200	24.000	0.017	4.922	0.083	0.470
1918	0.008	0.392	0.100	3.300	12.000	0.032	4.954	0.068	0.538
1918	0.008	0.400	0.100	3.400	12.000	0.031	4.985	0.069	0.607
1919	0.006	0.406	0.100	3.500	18.000	0.020	5.005	0.080	0.687
1919	0.006	0.411	0.100	3.600	18.000	0.019	5.023	0.081	0.769
1919	0.006	0.417	0.100	3.700	18.000	0.018	5.041	0.082	0.851
1920	0.008	0.425	0.100	3.800	12.000	0.026	5.067	0.074	0.925
1920	0.008	0.433	0.100	3.900	12.000	0.025	5.092	0.075	1.000
1921	0.017	0.450	0.100	4.000	6.000	0.047	5.139	0.053	1.053
1922	0.017	0.467	0.100	4.100	6.000	0.046	5.185	0.054	1.107
1924	0.033	0.500	0.100	4.200	3.000	0.088	5.272	0.000	1.107
1925	0.017	0.517	0.100	4.300	6.000	0.042	5.314	0.058	1.165
1927	0.033	0.550	0.100	4.400	3.000	0.081	5.396	0.000	1.165
1928	0.017	0.567	0.100	4.500	6.000	0.039	5.435	0.061	1.226
1929	0.008	0.575	0.100	4.600	12.000	0.019	5.454	0.081	1.307
1929	0.008	0.583	0.100	4.700	12.000	0.018	5.473	0.082	1.388
1930	0.008	0.592	0.100	4.800	12.000	0.018	5.490	0.082	1.471
1930	0.008	0.600	0.100	4.900	12.000	0.017	5.508	0.083	1.553
1931	0.017	0.617	0.100	5.000	6.000	0.034	5.541	0.066	1.620
1932	0.008	0.625	0.100	5.100	12.000	0.016	5.558	0.084	1.703
1932	0.008	0.633	0.100	5.200	12.000	0.016	5.574	0.084	1.787

1934	0.033	0.667	0.100	5.300	3.000	0.062	5.636	0.000	1.787
1935	0.017	0.683	0.100	5.400	6.000	0.030	5.666	0.070	1.857
1937	0.033	0.717	0.100	5.500	3.000	0.059	5.726	0.041	1.898
1938	0.017	0.733	0.100	5.600	6.000	0.029	5.755	0.071	1.969
1939	0.008	0.742	0.100	5.700	12.000	0.014	5.769	0.086	2.054
1940	0.008	0.750	0.100	5.800	12.000	0.014	5.783	0.086	2.140
1940	0.008	0.758	0.100	5.900	12.000	0.014	5.796	0.086	2.227
1941	0.017	0.775	0.100	6.000	6.000	0.027	5.823	0.073	2.300
1942	0.017	0.792	0.100	6.100	6.000	0.026	5.850	0.074	2.373
1943	0.017	0.808	0.100	6.200	6.000	0.026	5.876	0.074	2.447
1945	0.008	0.817	0.100	6.300	12.000	0.013	5.889	0.087	2.535
1945	0.008	0.825	0.100	6.400	12.000	0.013	5.901	0.087	2.622
1946	0.006	0.831	0.100	6.500	18.000	0.008	5.909	0.092	2.714
1946	0.006	0.836	0.100	6.600	18.000	0.008	5.918	0.092	2.806
1946	0.006	0.842	0.100	6.700	18.000	0.008	5.926	0.092	2.897
1947	0.006	0.847	0.100	6.800	18.000	0.008	5.934	0.092	2.989
1947	0.006	0.853	0.100	6.900	18.000	0.008	5.942	0.092	3.082
1947	0.006	0.858	0.100	7.000	18.000	0.008	5.949	0.092	3.174
1948	0.008	0.867	0.100	7.100	12.000	0.012	5.961	0.088	3.262
1948	0.008	0.875	0.100	7.200	12.000	0.012	5.973	0.088	3.351
1949	0.006	0.881	0.100	7.300	18.000	0.008	5.980	0.092	3.443
1949	0.006	0.886	0.100	7.400	18.000	0.008	5.988	0.092	3.535
1949	0.006	0.892	0.100	7.500	18.000	0.008	5.995	0.092	3.628
1950	0.004	0.896	0.100	7.600	24.000	0.006	6.001	0.094	3.722
1950	0.004	0.900	0.100	7.700	24.000	0.006	6.006	0.094	3.817
1950	0.004	0.904	0.100	7.800	24.000	0.006	6.012	0.094	3.911
1950	0.004	0.908	0.100	7.900	24.000	0.005	6.017	0.095	4.006
1951	0.004	0.913	0.100	8.000	24.000	0.005	6.023	0.095	4.100
1951	0.004	0.917	0.100	8.100	24.000	0.005	6.028	0.095	4.195
1951	0.004	0.921	0.100	8.200	24.000	0.005	6.034	0.095	4.289
1951	0.004	0.925	0.100	8.300	24.000	0.005	6.039	0.095	4.384

1952	0.004	0.929	0.100	8.400	24.000	0.005	6.045	0.095	4.479
1952	0.004	0.933	0.100	8.500	24.000	0.005	6.050	0.095	4.573
1952	0.004	0.938	0.100	8.600	24.000	0.005	6.055	0.095	4.668
1952	0.004	0.942	0.100	8.700	24.000	0.005	6.060	0.095	4.763
1953	0.003	0.945	0.100	8.800	30.000	0.004	6.065	0.096	4.859
1953	0.003	0.948	0.100	8.900	30.000	0.004	6.069	0.096	4.954
1953	0.003	0.952	0.100	9.000	30.000	0.004	6.073	0.096	5.050
1953	0.003	0.955	0.100	9.100	30.000	0.004	6.077	0.096	5.146
1953	0.003	0.958	0.100	9.200	30.000	0.004	6.081	0.096	5.242
1954	0.004	0.962	0.100	9.300	24.000	0.005	6.087	0.095	5.337
1954	0.004	0.967	0.100	9.400	24.000	0.005	6.092	0.095	5.431
1954	0.004	0.971	0.100	9.500	24.000	0.005	6.097	0.095	5.526
1954	0.004	0.975	0.100	9.600	24.000	0.005	6.102	0.095	5.621
1955	0.004	0.979	0.100	9.700	24.000	0.005	6.107	0.095	5.716
1955	0.004	0.983	0.100	9.800	24.000	0.005	6.113	0.095	5.811
1955	0.004	0.987	0.100	9.900	24.000	0.005	6.118	0.095	5.906
1955	0.004	0.992	0.100	10.000	24.000	0.005	6.123	0.095	6.000
1956	0.003	0.995	0.100	10.100	30.000	0.004	6.127	0.096	6.096
1956	0.003	0.998	0.100	10.200	30.000	0.004	6.131	0.096	6.192
1956	0.003	1.002	0.100	10.300	30.000	0.004	6.135	0.096	6.288
1956	0.003	1.005	0.100	10.400	30.000	0.004	6.139	0.096	6.384
1956	0.003	1.008	0.100	10.500	30.000	0.004	6.143	0.096	6.480
1957	0.004	1.013	0.100	10.600	24.000	0.005	6.148	0.095	6.575
1957	0.004	1.017	0.100	10.700	24.000	0.005	6.154	0.095	6.670
1957	0.004	1.021	0.100	10.800	24.000	0.005	6.159	0.095	6.765
1957	0.004	1.025	0.100	10.900	24.000	0.005	6.164	0.095	6.859
1958	0.006	1.031	0.100	11.000	18.000	0.007	6.171	0.093	6.953
1958	0.006	1.036	0.100	11.100	18.000	0.007	6.177	0.093	7.046
1958	0.006	1.042	0.100	11.200	18.000	0.007	6.184	0.093	7.139
1959	0.008	1.050	0.100	11.300	12.000	0.010	6.194	0.090	7.229
1959	0.008	1.058	0.100	11.400	12.000	0.010	6.204	0.090	7.319

2000	0.017	1.075	0.100	11.500	6.000	0.020	6.225	0.080	7.399
2001	0.008	1.083	0.100	11.600	12.000	0.010	6.235	0.090	7.488
2001	0.008	1.092	0.100	11.700	12.000	0.010	6.245	0.090	7.578
2002	0.017	1.108	0.100	11.800	6.000	0.020	6.265	0.080	7.658
2003	0.008	1.117	0.100	11.900	12.000	0.010	6.275	0.090	7.748
2003	0.008	1.125	0.100	12.000	12.000	0.010	6.286	0.090	7.838
2004	0.017	1.142	0.100	12.100	6.000	0.020	6.306	0.080	7.917
2005	0.017	1.158	0.100	12.200	6.000	0.020	6.326	0.080	7.997
2006	0.008	1.167	0.100	12.300	12.000	0.010	6.336	0.090	8.087
2006	0.008	1.175	0.100	12.400	12.000	0.010	6.346	0.090	8.177
2007	0.017	1.192	0.100	12.500	6.000	0.020	6.367	0.080	8.257
2008	0.008	1.200	0.100	12.600	12.000	0.010	6.377	0.090	8.347
2008	0.008	1.208	0.100	12.700	12.000	0.010	6.387	0.090	8.436
2009	0.008	1.217	0.100	12.800	12.000	0.010	6.397	0.090	8.526
2009	0.008	1.225	0.100	12.900	12.000	0.010	6.407	0.090	8.616
2010	0.008	1.233	0.100	13.000	12.000	0.010	6.417	0.090	8.706
2010	0.008	1.242	0.100	13.100	12.000	0.010	6.427	0.090	8.796
2011	0.008	1.250	0.100	13.200	12.000	0.010	6.437	0.090	8.886
2011	0.008	1.258	0.100	13.300	12.000	0.010	6.447	0.090	8.976
2012	0.008	1.267	0.100	13.400	12.000	0.010	6.458	0.090	9.066
2012	0.008	1.275	0.100	13.500	12.000	0.010	6.468	0.090	9.156
2013	0.017	1.292	0.100	13.600	6.000	0.020	6.488	0.080	9.235
2014	0.008	1.300	0.100	13.700	12.000	0.010	6.498	0.090	9.325
2014	0.008	1.308	0.100	13.800	12.000	0.010	6.508	0.090	9.415
2015	0.008	1.317	0.100	13.900	12.000	0.010	6.518	0.090	9.505
2015	0.008	1.325	0.100	14.000	12.000	0.010	6.528	0.090	9.595
2016	0.017	1.342	0.100	14.100	6.000	0.020	6.548	0.080	9.675
2017	0.008	1.350	0.100	14.200	12.000	0.010	6.559	0.090	9.765
2017	0.008	1.358	0.100	14.300	12.000	0.010	6.569	0.090	9.855
2019	0.033	1.392	0.100	14.400	3.000	0.040	6.609	0.060	9.914
2020	0.017	1.408	0.100	14.500	6.000	0.020	6.629	0.080	9.994

2021	0.017	1.425	0.100	14.600	6.000	0.020	6.649	0.080	10.074
2023	0.033	1.458	0.100	14.700	3.000	0.040	6.690	0.060	10.134
2025	0.033	1.492	0.100	14.800	3.000	0.040	6.730	0.060	10.193
2026	0.017	1.508	0.100	14.900	6.000	0.020	6.750	0.080	10.273
2028	0.033	1.542	0.100	15.000	3.000	0.040	6.791	0.060	10.333
2029	0.017	1.558	0.100	15.100	6.000	0.020	6.811	0.080	10.412
2031	0.033	1.592	0.100	15.200	3.000	0.040	6.851	0.060	10.472
2032	0.017	1.608	0.100	15.300	6.000	0.020	6.871	0.080	10.552
2033	0.017	1.625	0.100	15.400	6.000	0.020	6.891	0.080	10.632
2035	0.033	1.658	0.100	15.500	3.000	0.040	6.932	0.060	10.691
2036	0.017	1.675	0.100	15.600	6.000	0.020	6.952	0.080	10.771
2037	0.017	1.692	0.100	15.700	6.000	0.020	6.972	0.080	10.851
2039	0.033	1.725	0.100	15.800	3.000	0.040	7.013	0.060	10.911
2040	0.017	1.742	0.100	15.900	6.000	0.020	7.033	0.080	10.991
2041	0.017	1.758	0.100	16.000	6.000	0.020	7.053	0.080	11.070
2042	0.017	1.775	0.100	16.100	6.000	0.020	7.073	0.080	11.150
2043	0.017	1.792	0.100	16.200	6.000	0.020	7.093	0.080	11.230
2044	0.017	1.808	0.100	16.300	6.000	0.020	7.113	0.080	11.310
2045	0.017	1.825	0.100	16.400	6.000	0.020	7.134	0.080	11.390
2046	0.017	1.842	0.100	16.500	6.000	0.020	7.154	0.080	11.469
2047	0.017	1.858	0.100	16.600	6.000	0.020	7.174	0.080	11.549
2048	0.017	1.875	0.100	16.700	6.000	0.020	7.194	0.080	11.629
2049	0.017	1.892	0.100	16.800	6.000	0.020	7.214	0.080	11.709
2050	0.017	1.908	0.100	16.900	6.000	0.020	7.234	0.080	11.789
2052	0.033	1.942	0.100	17.000	3.000	0.040	7.275	0.060	11.848
2053	0.017	1.958	0.100	17.100	6.000	0.020	7.295	0.080	11.928
2055	0.033	1.992	0.100	17.200	3.000	0.040	7.335	0.060	11.988
2057	0.033	2.025	0.100	17.300	3.000	0.040	7.376	0.060	12.048
2059	0.033	2.058	0.100	17.400	3.000	0.040	7.416	0.060	12.107
2104	0.083	2.142	0.100	17.500	1.200	0.101	7.517	0.000	12.107
2109	0.083	2.225	0.100	17.600	1.200	0.101	7.618	0.000	12.107

2113	0.067	2.292	0.100	17.700	1.500	0.081	7.698	0.019	12.127
2117	0.067	2.358	0.100	17.800	1.500	0.081	7.779	0.019	12.146
2120	0.050	2.408	0.100	17.900	2.000	0.061	7.839	0.039	12.185
2123	0.050	2.458	0.100	18.000	2.000	0.061	7.900	0.039	12.225
2124	0.017	2.475	0.100	18.100	6.000	0.020	7.920	0.080	12.305
2126	0.033	2.508	0.100	18.200	3.000	0.040	7.961	0.060	12.364
2128	0.033	2.542	0.100	18.300	3.000	0.040	8.001	0.060	12.424
2129	0.017	2.558	0.100	18.400	6.000	0.020	8.021	0.080	12.504
2130	0.017	2.575	0.100	18.500	6.000	0.020	8.041	0.080	12.584
2131	0.017	2.592	0.100	18.600	6.000	0.020	8.061	0.080	12.664
2132	0.017	2.608	0.100	18.700	6.000	0.020	8.082	0.080	12.743
2134	0.033	2.642	0.100	18.800	3.000	0.040	8.122	0.060	12.803
2135	0.017	2.658	0.100	18.900	6.000	0.020	8.142	0.080	12.883
2136	0.017	2.675	0.100	19.000	6.000	0.020	8.162	0.080	12.963
2137	0.017	2.692	0.100	19.100	6.000	0.020	8.182	0.080	13.043
2138	0.017	2.708	0.100	19.200	6.000	0.020	8.203	0.080	13.122
2139	0.017	2.725	0.100	19.300	6.000	0.020	8.223	0.080	13.202
2140	0.017	2.742	0.100	19.400	6.000	0.020	8.243	0.080	13.282
2141	0.017	2.758	0.100	19.500	6.000	0.020	8.263	0.080	13.362
2142	0.008	2.767	0.100	19.600	12.000	0.010	8.273	0.090	13.452
2142	0.008	2.775	0.100	19.700	12.000	0.010	8.283	0.090	13.542
2143	0.017	2.792	0.100	19.800	6.000	0.020	8.303	0.080	13.622
2144	0.017	2.808	0.100	19.900	6.000	0.020	8.324	0.080	13.701
2145	0.017	2.825	0.100	20.000	6.000	0.020	8.344	0.080	13.781
2146	0.017	2.842	0.100	20.100	6.000	0.020	8.364	0.080	13.861
2147	0.017	2.858	0.100	20.200	6.000	0.020	8.384	0.080	13.941
2148	0.017	2.875	0.100	20.300	6.000	0.020	8.404	0.080	14.021
2149	0.017	2.892	0.100	20.400	6.000	0.020	8.424	0.080	14.101
2150	0.017	2.908	0.100	20.500	6.000	0.020	8.445	0.080	14.180
2152	0.033	2.942	0.100	20.600	3.000	0.040	8.485	0.060	14.240
2153	0.017	2.958	0.100	20.700	6.000	0.020	8.505	0.080	14.320

2154	0.017	2.975	0.100	20.800	6.000	0.020	8.525	0.080	14.400
2156	0.033	3.008	0.100	20.900	3.000	0.040	8.566	0.060	14.459
2157	0.017	3.025	0.100	21.000	6.000	0.020	8.586	0.080	14.539
2159	0.033	3.058	0.100	21.100	3.000	0.040	8.626	0.060	14.599
2201	0.033	3.092	0.100	21.200	3.000	0.040	8.666	0.060	14.659
2202	0.017	3.108	0.100	21.300	6.000	0.020	8.687	0.080	14.738
2203	0.017	3.125	0.100	21.400	6.000	0.020	8.707	0.080	14.818
2205	0.033	3.158	0.100	21.500	3.000	0.040	8.747	0.060	14.878
2206	0.017	3.175	0.100	21.600	6.000	0.020	8.767	0.080	14.958
2207	0.017	3.192	0.100	21.700	6.000	0.020	8.787	0.080	15.038
2208	0.017	3.208	0.100	21.800	6.000	0.020	8.808	0.080	15.117
2209	0.017	3.225	0.100	21.900	6.000	0.020	8.828	0.080	15.197
2210	0.017	3.242	0.100	22.000	6.000	0.020	8.848	0.080	15.277
2211	0.017	3.258	0.100	22.100	6.000	0.020	8.868	0.080	15.357
2212	0.017	3.275	0.100	22.200	6.000	0.020	8.888	0.080	15.437
2213	0.017	3.292	0.100	22.300	6.000	0.020	8.908	0.080	15.517
2214	0.017	3.308	0.100	22.400	6.000	0.020	8.929	0.080	15.596
2215	0.017	3.325	0.100	22.500	6.000	0.020	8.949	0.080	15.676
2216	0.017	3.342	0.100	22.600	6.000	0.020	8.969	0.080	15.756
2217	0.017	3.358	0.100	22.700	6.000	0.020	8.989	0.080	15.836
2218	0.017	3.375	0.100	22.800	6.000	0.020	9.009	0.080	15.916
2219	0.017	3.392	0.100	22.900	6.000	0.020	9.029	0.080	15.996
2220	0.017	3.408	0.100	23.000	6.000	0.020	9.050	0.080	16.075
2221	0.017	3.425	0.100	23.100	6.000	0.020	9.070	0.080	16.155
2222	0.017	3.442	0.100	23.200	6.000	0.020	9.090	0.080	16.235
2223	0.017	3.458	0.100	23.300	6.000	0.020	9.110	0.080	16.315
2224	0.017	3.475	0.100	23.400	6.000	0.020	9.130	0.080	16.395
2225	0.017	3.492	0.100	23.500	6.000	0.020	9.150	0.080	16.475
2226	0.017	3.508	0.100	23.600	6.000	0.020	9.171	0.080	16.554
2227	0.017	3.525	0.100	23.700	6.000	0.020	9.191	0.080	16.634
2228	0.017	3.542	0.100	23.800	6.000	0.020	9.211	0.080	16.714

2229	0.017	3.558	0.100	23.900	6.000	0.020	9.231	0.080	16.794
2231	0.033	3.592	0.100	24.000	3.000	0.040	9.271	0.060	16.854
2232	0.017	3.608	0.100	24.100	6.000	0.020	9.292	0.080	16.933
2233	0.017	3.625	0.100	24.200	6.000	0.020	9.312	0.080	17.013
2234	0.017	3.642	0.100	24.300	6.000	0.020	9.332	0.080	17.093
2236	0.033	3.675	0.100	24.400	3.000	0.040	9.372	0.060	17.153
2237	0.017	3.692	0.100	24.500	6.000	0.020	9.392	0.080	17.233
2238	0.017	3.708	0.100	24.600	6.000	0.020	9.413	0.080	17.312
2240	0.033	3.742	0.100	24.700	3.000	0.040	9.453	0.060	17.372
2241	0.017	3.758	0.100	24.800	6.000	0.020	9.473	0.080	17.452
2243	0.033	3.792	0.100	24.900	3.000	0.040	9.513	0.060	17.512
2245	0.033	3.825	0.100	25.000	3.000	0.040	9.554	0.060	17.571
2246	0.017	3.842	0.100	25.100	6.000	0.020	9.574	0.080	17.651
2248	0.033	3.875	0.100	25.200	3.000	0.040	9.614	0.060	17.711
2249	0.017	3.892	0.100	25.300	6.000	0.020	9.634	0.080	17.791
2251	0.033	3.925	0.100	25.400	3.000	0.040	9.675	0.060	17.850
2252	0.017	3.942	0.100	25.500	6.000	0.020	9.695	0.080	17.930
2253	0.017	3.958	0.100	25.600	6.000	0.020	9.715	0.080	18.010
2254	0.017	3.975	0.100	25.700	6.000	0.020	9.735	0.080	18.090
2256	0.033	4.008	0.100	25.800	3.000	0.040	9.776	0.060	18.149
2258	0.033	4.042	0.100	25.900	3.000	0.040	9.816	0.060	18.209
2300	0.033	4.075	0.100	26.000	3.000	0.040	9.856	0.060	18.269
2302	0.017	4.092	0.100	26.100	6.000	0.020	9.876	0.080	18.349
2303	0.017	4.108	0.100	26.200	6.000	0.020	9.897	0.080	18.428
2304	0.017	4.125	0.100	26.300	6.000	0.020	9.917	0.080	18.508
2305	0.017	4.142	0.100	26.400	6.000	0.020	9.937	0.080	18.588
2306	0.017	4.158	0.100	26.500	6.000	0.020	9.957	0.080	18.668
2308	0.033	4.192	0.100	26.600	3.000	0.040	9.997	0.060	18.728
2310	0.033	4.225	0.100	26.700	3.000	0.040	10.038	0.060	18.787
2311	0.017	4.242	0.100	26.800	6.000	0.020	10.058	0.080	18.867
2313	0.033	4.275	0.100	26.900	3.000	0.040	10.098	0.060	18.927

2314	0.017	4.292	0.100	27.000	6.000	0.020	10.118	0.080	19.007
2315	0.017	4.308	0.100	27.100	6.000	0.020	10.139	0.080	19.086
2317	0.033	4.342	0.100	27.200	3.000	0.040	10.179	0.060	19.146
2318	0.017	4.358	0.100	27.300	6.000	0.020	10.199	0.080	19.226
2320	0.033	4.392	0.100	27.400	3.000	0.040	10.239	0.060	19.286
2321	0.017	4.408	0.100	27.500	6.000	0.020	10.260	0.080	19.365
2322	0.017	4.425	0.100	27.600	6.000	0.020	10.280	0.080	19.445
2323	0.017	4.442	0.100	27.700	6.000	0.020	10.300	0.080	19.525
2324	0.017	4.458	0.100	27.800	6.000	0.020	10.320	0.080	19.605
2325	0.017	4.475	0.100	27.900	6.000	0.020	10.340	0.080	19.685
2326	0.017	4.492	0.100	28.000	6.000	0.020	10.360	0.080	19.765
2327	0.017	4.508	0.100	28.100	6.000	0.020	10.381	0.080	19.844
2328	0.017	4.525	0.100	28.200	6.000	0.020	10.401	0.080	19.924
2329	0.017	4.542	0.100	28.300	6.000	0.020	10.421	0.080	20.004
2330	0.017	4.558	0.100	28.400	6.000	0.020	10.441	0.080	20.084
2331	0.017	4.575	0.100	28.500	6.000	0.020	10.461	0.080	20.164
2332	0.017	4.592	0.100	28.600	6.000	0.020	10.481	0.080	20.244
2334	0.033	4.625	0.100	28.700	3.000	0.040	10.522	0.060	20.303
2337	0.050	4.675	0.100	28.800	2.000	0.061	10.582	0.039	20.343
2339	0.033	4.708	0.100	28.900	3.000	0.040	10.623	0.060	20.402
2340	0.017	4.725	0.100	29.000	6.000	0.020	10.643	0.080	20.482
2342	0.033	4.758	0.100	29.100	3.000	0.040	10.683	0.060	20.542
2344	0.033	4.792	0.100	29.200	3.000	0.040	10.723	0.060	20.602
2347	0.050	4.842	0.100	29.300	2.000	0.061	10.784	0.039	20.641
2350	0.050	4.892	0.100	29.400	2.000	0.061	10.844	0.039	20.681
2356	0.100	4.992	0.100	29.500	1.000	0.121	10.965	0.000	20.681

Rainstorm of May 4th, 2008

i	Δt_i (hr)	$\sum\Delta t_i$ (hr)	P_i (mm)	$\sum P_i$ (mm)	I_i (mmhr^{-1})	$Id_{\Delta ti}$ (mm)	$\sum Id_{\Delta ti}$ (mm)	R_i (mm)	$\sum R_i$ (mm)

724	0.100	0.100	0.100	0.100	1.000	0.121	0.121	0.000	0.000
730	0.100	0.200	0.100	0.200	1.000	2.452	2.573	0.000	0.000
734	0.100	0.300	0.100	0.300	1.000	2.295	4.868	0.000	0.000
737	0.050	0.350	0.100	0.400	2.000	1.074	5.942	0.000	0.000
738	0.017	0.367	0.100	0.500	6.000	0.335	6.277	0.000	0.000
739	0.017	0.383	0.100	0.600	6.000	0.314	6.591	0.000	0.000
740	0.017	0.400	0.100	0.700	6.000	0.294	6.885	0.000	0.000
741	0.017	0.417	0.100	0.800	6.000	0.275	7.161	0.000	0.000
742	0.017	0.433	0.100	0.900	6.000	0.258	7.419	0.000	0.000
743	0.017	0.450	0.100	1.000	6.000	0.242	7.661	0.000	0.000
744	0.017	0.467	0.100	1.100	6.000	0.227	7.888	0.000	0.000
746	0.008	0.475	0.100	1.200	12.000	0.107	7.995	0.000	0.000
746	0.008	0.483	0.100	1.300	12.000	0.100	8.095	0.000	0.000
747	0.017	0.500	0.100	1.400	6.000	0.188	8.283	0.000	0.000
748	0.008	0.508	0.100	1.500	12.000	0.088	8.371	0.000	0.000
748	0.008	0.517	0.100	1.600	12.000	0.083	8.454	0.000	0.000
749	0.008	0.525	0.100	1.700	12.000	0.078	8.532	0.000	0.000
749	0.008	0.533	0.100	1.800	12.000	0.073	8.605	0.000	0.000
750	0.008	0.542	0.100	1.900	12.000	0.069	8.675	0.000	0.000
750	0.008	0.550	0.100	2.000	12.000	0.065	8.740	0.000	0.000
751	0.008	0.558	0.100	2.100	12.000	0.061	8.801	0.000	0.000
751	0.008	0.567	0.100	2.200	12.000	0.058	8.859	0.000	0.000
752	0.017	0.583	0.100	2.300	6.000	0.110	8.969	0.000	0.000
753	0.017	0.600	0.100	2.400	6.000	0.103	9.072	0.000	0.000
754	0.017	0.617	0.100	2.500	6.000	0.098	9.170	0.000	0.000
757	0.033	0.650	0.100	2.600	3.000	0.185	9.355	0.000	0.000
758	0.017	0.667	0.100	2.700	6.000	0.088	9.443	0.012	0.012
759	0.017	0.683	0.100	2.800	6.000	0.083	9.526	0.017	0.029
800	0.017	0.700	0.100	2.900	6.000	0.079	9.605	0.021	0.050
801	0.008	0.708	0.100	3.000	12.000	0.037	9.642	0.063	0.113
801	0.008	0.717	0.100	3.100	12.000	0.036	9.678	0.064	0.177

802	0.008	0.725	0.100	3.200	12.000	0.034	9.712	0.066	0.243
802	0.008	0.733	0.100	3.300	12.000	0.032	9.744	0.068	0.311
803	0.017	0.750	0.100	3.400	6.000	0.062	9.806	0.000	0.311
804	0.017	0.767	0.100	3.500	6.000	0.059	9.864	0.041	0.352
805	0.008	0.775	0.100	3.600	12.000	0.028	9.892	0.072	0.424
805	0.008	0.783	0.100	3.700	12.000	0.027	9.919	0.073	0.497
807	0.008	0.792	0.100	3.800	12.000	0.026	9.945	0.074	0.572
807	0.008	0.800	0.100	3.900	12.000	0.025	9.970	0.075	0.647
809	0.033	0.833	0.100	4.000	3.000	0.095	10.064	0.005	0.652
810	0.017	0.850	0.100	4.100	6.000	0.046	10.110	0.054	0.707
811	0.017	0.867	0.100	4.200	6.000	0.044	10.154	0.056	0.763
812	0.017	0.883	0.100	4.300	6.000	0.042	10.196	0.058	0.821
813	0.008	0.892	0.100	4.400	12.000	0.020	10.216	0.080	0.901
813	0.008	0.900	0.100	4.500	12.000	0.020	10.236	0.080	0.981
814	0.017	0.917	0.100	4.600	6.000	0.038	10.274	0.062	1.043
815	0.017	0.933	0.100	4.700	6.000	0.037	10.311	0.063	1.106
816	0.017	0.950	0.100	4.800	6.000	0.036	10.346	0.064	1.170
819	0.050	1.000	0.100	4.900	2.000	0.104	10.450	0.000	1.170
821	0.033	1.033	0.100	5.000	3.000	0.067	10.518	0.033	1.203
824	0.050	1.083	0.100	5.100	2.000	0.098	10.616	0.002	1.205
827	0.050	1.133	0.100	5.200	2.000	0.096	10.712	0.004	1.209
830	0.050	1.183	0.100	5.300	2.000	0.093	10.805	0.007	1.216
831	0.017	1.200	0.100	5.400	6.000	0.030	10.835	0.070	1.285
832	0.008	1.208	0.100	5.500	12.000	0.015	10.850	0.085	1.371
832	0.008	1.217	0.100	5.600	12.000	0.015	10.865	0.085	1.456
834	0.008	1.225	0.100	5.700	12.000	0.014	10.879	0.086	1.542
834	0.008	1.233	0.100	5.800	12.000	0.014	10.893	0.086	1.628
836	0.017	1.250	0.100	5.900	6.000	0.027	10.920	0.073	1.701
837	0.017	1.267	0.100	6.000	6.000	0.027	10.947	0.073	1.774
838	0.008	1.275	0.100	6.100	12.000	0.013	10.960	0.087	1.860
838	0.008	1.283	0.100	6.200	12.000	0.013	10.973	0.087	1.947

839	0.017	1.300	0.100	6.300	6.000	0.026	10.999	0.074	2.022
840	0.017	1.317	0.100	6.400	6.000	0.025	11.024	0.075	2.097
841	0.008	1.325	0.100	6.500	12.000	0.012	11.036	0.088	2.184
841	0.008	1.333	0.100	6.600	12.000	0.012	11.049	0.088	2.272
843	0.033	1.367	0.100	6.700	3.000	0.049	11.097	0.051	2.323
844	0.017	1.383	0.100	6.800	6.000	0.024	11.121	0.076	2.399
845	0.017	1.400	0.100	6.900	6.000	0.024	11.145	0.076	2.476
846	0.017	1.417	0.100	7.000	6.000	0.023	11.169	0.077	2.552
847	0.017	1.433	0.100	7.100	6.000	0.023	11.192	0.077	2.629
848	0.017	1.450	0.100	7.200	6.000	0.023	11.215	0.077	2.706
850	0.033	1.483	0.100	7.300	3.000	0.046	11.261	0.054	2.760
852	0.033	1.517	0.100	7.400	3.000	0.045	11.306	0.055	2.815

Rainstorm of March 16th, 2008

i	Δt_i (hr)	$\sum \Delta t_i$ (hr)	P_i (mm)	$\sum P_i$ (mm)	I_i (mmhr^{-1})	$Id_{\Delta ti}$ (mm)	$\sum Id_{\Delta ti}$ (mm)	R_i (mm)	$\sum R_i$ (mm)
53	0.150	0.150	0.100	0.100	0.667	0.182	0.182	0.000	0.000
102	0.150	0.300	0.100	0.200	0.667	3.679	3.860	0.000	0.000
110	0.133	0.433	0.100	0.300	0.750	3.060	6.920	0.000	0.000
119	0.150	0.583	0.100	0.400	0.667	3.222	10.142	0.000	0.000
121	0.033	0.617	0.100	0.500	3.000	0.670	10.812	0.000	0.000
124	0.050	0.667	0.100	0.600	2.000	0.942	11.753	0.000	0.000
125	0.017	0.683	0.100	0.700	6.000	0.294	12.047	0.000	0.000
127	0.033	0.717	0.100	0.800	3.000	0.551	12.598	0.000	0.000
129	0.033	0.750	0.100	0.900	3.000	0.516	13.115	0.000	0.000
131	0.033	0.783	0.100	1.000	3.000	0.484	13.599	0.000	0.000
132	0.017	0.800	0.100	1.100	6.000	0.227	13.826	0.000	0.000
134	0.033	0.833	0.100	1.200	3.000	0.426	14.252	0.000	0.000

136	0.033	0.867	0.100	1.300	3.000	0.400	14.653	0.000	0.000
138	0.033	0.900	0.100	1.400	3.000	0.376	15.028	0.000	0.000
139	0.017	0.917	0.100	1.500	6.000	0.177	15.205	0.000	0.000
141	0.033	0.950	0.100	1.600	3.000	0.332	15.537	0.000	0.000
143	0.033	0.983	0.100	1.700	3.000	0.312	15.849	0.000	0.000
146	0.050	1.033	0.100	1.800	2.000	0.441	16.290	0.000	0.000
150	0.067	1.100	0.100	1.900	1.500	0.554	16.844	0.000	0.000
153	0.050	1.150	0.100	2.000	2.000	0.391	17.235	0.000	0.000
154	0.008	1.158	0.100	2.100	12.000	0.061	17.296	0.000	0.000
154	0.008	1.167	0.100	2.200	12.000	0.058	17.354	0.000	0.000
155	0.017	1.183	0.100	2.300	6.000	0.110	17.464	0.000	0.000
156	0.017	1.200	0.100	2.400	6.000	0.103	17.567	0.000	0.000
157	0.017	1.217	0.100	2.500	6.000	0.098	17.665	0.000	0.000
158	0.017	1.233	0.100	2.600	6.000	0.093	17.758	0.000	0.000
159	0.017	1.250	0.100	2.700	6.000	0.088	17.845	0.012	0.012
200	0.017	1.267	0.100	2.800	6.000	0.083	17.928	0.017	0.029
201	0.017	1.283	0.100	2.900	6.000	0.079	18.007	0.021	0.050
202	0.017	1.300	0.100	3.000	6.000	0.075	18.082	0.025	0.075
204	0.033	1.333	0.100	3.100	3.000	0.142	18.225	0.000	0.075
206	0.033	1.367	0.100	3.200	3.000	0.135	18.360	0.000	0.075
209	0.050	1.417	0.100	3.300	2.000	0.194	18.554	0.000	0.075
215	0.067	1.483	0.100	3.400	1.500	0.246	18.800	0.000	0.075
217	0.033	1.517	0.100	3.500	3.000	0.117	18.917	0.000	0.075
218	0.017	1.533	0.100	3.600	6.000	0.056	18.973	0.044	0.119
219	0.017	1.550	0.100	3.700	6.000	0.054	19.027	0.046	0.166
220	0.017	1.567	0.100	3.800	6.000	0.051	19.079	0.049	0.214
221	0.017	1.583	0.100	3.900	6.000	0.049	19.128	0.051	0.265
222	0.008	1.592	0.100	4.000	12.000	0.024	19.152	0.076	0.341
222	0.008	1.600	0.100	4.100	12.000	0.023	19.174	0.077	0.418
223	0.006	1.606	0.100	4.200	18.000	0.015	19.189	0.085	0.504

223	0.006	1.611	0.100	4.300	18.000	0.014	19.203	0.086	0.590
223	0.006	1.617	0.100	4.400	18.000	0.014	19.217	0.086	0.676
224	0.008	1.625	0.100	4.500	12.000	0.020	19.236	0.080	0.757
224	0.008	1.633	0.100	4.600	12.000	0.019	19.255	0.081	0.838
225	0.006	1.639	0.100	4.700	18.000	0.012	19.267	0.088	0.925
225	0.006	1.644	0.100	4.800	18.000	0.012	19.279	0.088	1.013
225	0.006	1.650	0.100	4.900	18.000	0.012	19.291	0.088	1.102
226	0.017	1.667	0.100	5.000	6.000	0.034	19.325	0.066	1.168
227	0.008	1.675	0.100	5.100	12.000	0.016	19.341	0.084	1.252
227	0.008	1.683	0.100	5.200	12.000	0.016	19.357	0.084	1.336
228	0.008	1.692	0.100	5.300	12.000	0.016	19.372	0.084	1.420
228	0.008	1.700	0.100	5.400	12.000	0.015	19.388	0.085	1.505
229	0.017	1.717	0.100	5.500	6.000	0.030	19.417	0.070	1.575
230	0.008	1.725	0.100	5.600	12.000	0.015	19.432	0.085	1.661
230	0.008	1.733	0.100	5.700	12.000	0.014	19.446	0.086	1.747
231	0.017	1.750	0.100	5.800	6.000	0.028	19.474	0.072	1.819
232	0.008	1.758	0.100	5.900	12.000	0.014	19.488	0.086	1.905
232	0.050	1.808	0.100	6.000	2.000	0.081	19.568	0.000	1.905
233	0.017	1.825	0.100	6.100	6.000	0.026	19.595	0.074	1.979
235	0.033	1.858	0.100	6.200	3.000	0.052	19.647	0.048	2.027
237	0.033	1.892	0.100	6.300	3.000	0.051	19.698	0.049	2.075
241	0.067	1.958	0.100	6.400	1.500	0.101	19.799	0.000	2.075
243	0.033	1.992	0.100	6.500	3.000	0.050	19.849	0.050	2.126
247	0.067	2.058	0.100	6.600	1.500	0.098	19.947	0.002	2.127
253	0.100	2.158	0.100	6.700	1.000	0.146	20.092	0.000	2.127
300	0.117	2.275	0.100	6.800	0.857	0.168	20.260	0.000	2.127
316	0.267	2.542	0.100	6.900	0.375	0.380	20.640	0.000	2.127
320	0.067	2.608	0.100	7.000	1.500	0.094	20.734	0.006	2.133
325	0.083	2.692	0.100	7.100	1.200	0.116	20.851	0.000	2.133
330	0.083	2.775	0.100	7.200	1.200	0.115	20.966	0.000	2.133

332	0.033	2.808	0.100	7.300	3.000	0.046	21.012	0.054	2.188
334	0.033	2.842	0.100	7.400	3.000	0.045	21.057	0.055	2.242
335	0.017	2.858	0.100	7.500	6.000	0.023	21.079	0.077	2.320
336	0.017	2.875	0.100	7.600	6.000	0.022	21.102	0.078	2.397
337	0.017	2.892	0.100	7.700	6.000	0.022	21.124	0.078	2.475
338	0.017	2.908	0.100	7.800	6.000	0.022	21.146	0.078	2.553
339	0.017	2.925	0.100	7.900	6.000	0.022	21.168	0.078	2.631
340	0.017	2.942	0.100	8.000	6.000	0.022	21.190	0.078	2.709
341	0.017	2.958	0.100	8.100	6.000	0.022	21.212	0.078	2.788
343	0.033	2.992	0.100	8.200	3.000	0.043	21.255	0.057	2.845
344	0.017	3.008	0.100	8.300	6.000	0.022	21.276	0.078	2.923
345	0.017	3.025	0.100	8.400	6.000	0.021	21.298	0.079	3.002
346	0.017	3.042	0.100	8.500	6.000	0.021	21.319	0.079	3.080
348	0.033	3.075	0.100	8.600	3.000	0.043	21.361	0.057	3.138
349	0.017	3.092	0.100	8.700	6.000	0.021	21.383	0.079	3.217
350	0.017	3.108	0.100	8.800	6.000	0.021	21.404	0.079	3.295
351	0.017	3.125	0.100	8.900	6.000	0.021	21.425	0.079	3.374
353	0.033	3.158	0.100	9.000	3.000	0.042	21.467	0.058	3.432
354	0.017	3.175	0.100	9.100	6.000	0.021	21.488	0.079	3.512
356	0.033	3.208	0.100	9.200	3.000	0.042	21.529	0.058	3.570
358	0.033	3.242	0.100	9.300	3.000	0.042	21.571	0.058	3.628
400	0.033	3.275	0.100	9.400	3.000	0.042	21.613	0.058	3.687
402	0.033	3.308	0.100	9.500	3.000	0.041	21.654	0.059	3.745
403	0.017	3.325	0.100	9.600	6.000	0.021	21.675	0.079	3.824
404	0.017	3.342	0.100	9.700	6.000	0.021	21.696	0.079	3.904
406	0.033	3.375	0.100	9.800	3.000	0.041	21.737	0.059	3.962
407	0.017	3.392	0.100	9.900	6.000	0.021	21.757	0.079	4.042
408	0.017	3.408	0.100	10.000	6.000	0.021	21.778	0.079	4.121
410	0.033	3.442	0.100	10.100	3.000	0.041	21.819	0.059	4.180
411	0.017	3.458	0.100	10.200	6.000	0.021	21.840	0.079	4.260

412	0.017	3.475	0.100	10.300	6.000	0.020	21.860	0.080	4.339
413	0.017	3.492	0.100	10.400	6.000	0.020	21.881	0.080	4.419
414	0.017	3.508	0.100	10.500	6.000	0.020	21.901	0.080	4.498
415	0.017	3.525	0.100	10.600	6.000	0.020	21.922	0.080	4.578
417	0.033	3.558	0.100	10.700	3.000	0.041	21.962	0.059	4.637
418	0.017	3.575	0.100	10.800	6.000	0.020	21.983	0.080	4.717
420	0.033	3.608	0.100	10.900	3.000	0.041	22.024	0.059	4.776
422	0.033	3.642	0.100	11.000	3.000	0.041	22.064	0.059	4.835
424	0.033	3.675	0.100	11.100	3.000	0.041	22.105	0.059	4.894
426	0.033	3.708	0.100	11.200	3.000	0.041	22.146	0.059	4.954
428	0.033	3.742	0.100	11.300	3.000	0.041	22.186	0.059	5.013
432	0.067	3.808	0.100	11.400	1.500	0.081	22.268	0.019	5.032
441	0.150	3.958	0.100	11.500	0.667	0.183	22.450	0.000	5.032
447	0.100	4.058	0.100	11.600	1.000	0.122	22.572	0.000	5.032
451	0.067	4.125	0.100	11.700	1.500	0.081	22.653	0.019	5.051
459	0.133	4.258	0.100	11.800	0.750	0.162	22.816	0.000	5.051
505	0.100	4.358	0.100	11.900	1.000	0.122	22.937	0.000	5.051
508	0.050	4.408	0.100	12.000	2.000	0.061	22.998	0.039	5.090
510	0.033	4.442	0.100	12.100	3.000	0.041	23.039	0.059	5.149
512	0.033	4.475	0.100	12.200	3.000	0.041	23.079	0.059	5.209
514	0.033	4.508	0.100	12.300	3.000	0.040	23.120	0.060	5.268
516	0.033	4.542	0.100	12.400	3.000	0.040	23.160	0.060	5.328
518	0.033	4.575	0.100	12.500	3.000	0.040	23.201	0.060	5.387
519	0.017	4.592	0.100	12.600	6.000	0.020	23.221	0.080	5.467
520	1.000	5.592	0.100	12.700	0.100	1.214	24.434	0.000	5.467
521	0.017	5.608	0.100	12.800	6.000	0.020	24.455	0.080	5.547
523	0.033	5.642	0.100	12.900	3.000	0.040	24.495	0.060	5.606
524	0.017	5.658	0.100	13.000	6.000	0.020	24.515	0.080	5.686
525	0.017	5.675	0.100	13.100	6.000	0.020	24.536	0.080	5.766
527	0.033	5.708	0.100	13.200	3.000	0.040	24.576	0.060	5.825

528	0.017	5.725	0.100	13.300	6.000	0.020	24.596	0.080	5.905
529	0.017	5.742	0.100	13.400	6.000	0.020	24.616	0.080	5.985
530	0.017	5.758	0.100	13.500	6.000	0.020	24.637	0.080	6.065
531	0.008	5.767	0.100	13.600	12.000	0.010	24.647	0.090	6.155
531	0.008	5.775	0.100	13.700	12.000	0.010	24.657	0.090	6.245
532	0.017	5.792	0.100	13.800	6.000	0.020	24.677	0.080	6.324
533	0.017	5.808	0.100	13.900	6.000	0.020	24.697	0.080	6.404
534	0.017	5.825	0.100	14.000	6.000	0.020	24.717	0.080	6.484
535	0.008	5.833	0.100	14.100	12.000	0.010	24.727	0.090	6.574
535	0.008	5.842	0.100	14.200	12.000	0.010	24.738	0.090	6.664
536	0.033	5.875	0.100	14.300	3.000	0.040	24.778	0.060	6.724
537	0.017	5.892	0.100	14.400	6.000	0.020	24.798	0.080	6.803
538	0.017	5.908	0.100	14.500	6.000	0.020	24.818	0.080	6.883
539	0.017	5.925	0.100	14.600	6.000	0.020	24.838	0.080	6.963
540	0.008	5.933	0.100	14.700	12.000	0.010	24.849	0.090	7.053
540	0.008	5.942	0.100	14.800	12.000	0.010	24.859	0.090	7.143
541	0.017	5.958	0.100	14.900	6.000	0.020	24.879	0.080	7.223
542	0.008	5.967	0.100	15.000	12.000	0.010	24.889	0.090	7.313
542	0.008	5.975	0.100	15.100	12.000	0.010	24.899	0.090	7.402
543	0.008	5.983	0.100	15.200	12.000	0.010	24.909	0.090	7.492
543	0.008	5.992	0.100	15.300	12.000	0.010	24.919	0.090	7.582
544	0.008	6.000	0.100	15.400	12.000	0.010	24.929	0.090	7.672
544	0.008	6.008	0.100	15.500	12.000	0.010	24.939	0.090	7.762
545	0.017	6.025	0.100	15.600	6.000	0.020	24.960	0.080	7.842
546	0.008	6.033	0.100	15.700	12.000	0.010	24.970	0.090	7.932
546	0.008	6.042	0.100	15.800	12.000	0.010	24.980	0.090	8.022
547	0.017	6.058	0.100	15.900	6.000	0.020	25.000	0.080	8.102
548	0.017	6.075	0.100	16.000	6.000	0.020	25.020	0.080	8.181
549	0.008	6.083	0.100	16.100	12.000	0.010	25.030	0.090	8.271
549	0.008	6.092	0.100	16.200	12.000	0.010	25.040	0.090	8.361

550	0.008	6.100	0.100	16.300	12.000	0.010	25.050	0.090	8.451
550	0.008	6.108	0.100	16.400	12.000	0.010	25.060	0.090	8.541
551	0.008	6.117	0.100	16.500	12.000	0.010	25.070	0.090	8.631
551	0.008	6.125	0.100	16.600	12.000	0.010	25.081	0.090	8.721
552	0.017	6.142	0.100	16.700	6.000	0.020	25.101	0.080	8.801
553	0.008	6.150	0.100	16.800	12.000	0.010	25.111	0.090	8.891
553	0.008	6.158	0.100	16.900	12.000	0.010	25.121	0.090	8.981
554	0.017	6.175	0.100	17.000	6.000	0.020	25.141	0.080	9.060
555	0.017	6.192	0.100	17.100	6.000	0.020	25.161	0.080	9.140
556	0.017	6.208	0.100	17.200	6.000	0.020	25.181	0.080	9.220
557	0.017	6.225	0.100	17.300	6.000	0.020	25.202	0.080	9.300
558	0.017	6.242	0.100	17.400	6.000	0.020	25.222	0.080	9.380
559	0.017	6.258	0.100	17.500	6.000	0.020	25.242	0.080	9.460
600	0.017	6.275	0.100	17.600	6.000	0.020	25.262	0.080	9.539
601	0.017	6.292	0.100	17.700	6.000	0.020	25.282	0.080	9.619
602	0.017	6.308	0.100	17.800	6.000	0.020	25.302	0.080	9.699
603	0.017	6.325	0.100	17.900	6.000	0.020	25.323	0.080	9.779
604	0.017	6.342	0.100	18.000	6.000	0.020	25.343	0.080	9.859
606	0.033	6.375	0.100	18.100	3.000	0.040	25.383	0.060	9.918
607	0.017	6.392	0.100	18.200	6.000	0.020	25.403	0.080	9.998
609	0.033	6.425	0.100	18.300	3.000	0.040	25.444	0.060	10.058
610	0.017	6.442	0.100	18.400	6.000	0.020	25.464	0.080	10.138
611	0.017	6.458	0.100	18.500	6.000	0.020	25.484	0.080	10.218
612	0.017	6.475	0.100	18.600	6.000	0.020	25.504	0.080	10.297
613	0.017	6.492	0.100	18.700	6.000	0.020	25.524	0.080	10.377
615	0.033	6.525	0.100	18.800	3.000	0.040	25.565	0.060	10.437
616	0.017	6.542	0.100	18.900	6.000	0.020	25.585	0.080	10.517
618	0.033	6.575	0.100	19.000	3.000	0.040	25.625	0.060	10.576
619	0.017	6.592	0.100	19.100	6.000	0.020	25.645	0.080	10.656
621	0.033	6.625	0.100	19.200	3.000	0.040	25.686	0.060	10.716

622	0.017	6.642	0.100	19.300	6.000	0.020	25.706	0.080	10.796
624	0.033	6.675	0.100	19.400	3.000	0.040	25.746	0.060	10.855
625	0.017	6.692	0.100	19.500	6.000	0.020	25.766	0.080	10.935
627	0.033	6.725	0.100	19.600	3.000	0.040	25.807	0.060	10.995
628	0.017	6.742	0.100	19.700	6.000	0.020	25.827	0.080	11.075
629	0.017	6.758	0.100	19.800	6.000	0.020	25.847	0.080	11.154
630	0.017	6.775	0.100	19.900	6.000	0.020	25.867	0.080	11.234
631	0.017	6.792	0.100	20.000	6.000	0.020	25.887	0.080	11.314
632	0.017	6.808	0.100	20.100	6.000	0.020	25.907	0.080	11.394
633	0.017	6.825	0.100	20.200	6.000	0.020	25.928	0.080	11.474
634	0.017	6.842	0.100	20.300	6.000	0.020	25.948	0.080	11.554
635	0.017	6.858	0.100	20.400	6.000	0.020	25.968	0.080	11.633
636	0.017	6.875	0.100	20.500	6.000	0.020	25.988	0.080	11.713
637	0.017	6.892	0.100	20.600	6.000	0.020	26.008	0.080	11.793
638	0.017	6.908	0.100	20.700	6.000	0.020	26.028	0.080	11.873
639	0.017	6.925	0.100	20.800	6.000	0.020	26.049	0.080	11.953
640	0.017	6.942	0.100	20.900	6.000	0.020	26.069	0.080	12.033
641	0.017	6.958	0.100	21.000	6.000	0.020	26.089	0.080	12.112
642	0.017	6.975	0.100	21.100	6.000	0.020	26.109	0.080	12.192
643	0.008	6.983	0.100	21.200	12.000	0.010	26.119	0.090	12.282
643	0.008	6.992	0.100	21.300	12.000	0.010	26.129	0.090	12.372
644	0.017	7.008	0.100	21.400	6.000	0.020	26.149	0.080	12.452
645	0.008	7.017	0.100	21.500	12.000	0.010	26.160	0.090	12.542
645	0.008	7.025	0.100	21.600	12.000	0.010	26.170	0.090	12.632
646	0.006	7.031	0.100	21.700	18.000	0.007	26.176	0.093	12.725
646	0.006	7.036	0.100	21.800	18.000	0.007	26.183	0.093	12.818
646	0.006	7.042	0.100	21.900	18.000	0.007	26.190	0.093	12.912
647	0.008	7.050	0.100	22.000	12.000	0.010	26.200	0.090	13.002
647	0.008	7.058	0.100	22.100	12.000	0.010	26.210	0.090	13.091
648	0.006	7.064	0.100	22.200	18.000	0.007	26.217	0.093	13.185

648	0.006	7.069	0.100	22.300	18.000	0.007	26.223	0.093	13.278
648	0.006	7.075	0.100	22.400	18.000	0.007	26.230	0.093	13.371
649	0.008	7.083	0.100	22.500	12.000	0.010	26.240	0.090	13.461
649	0.008	7.092	0.100	22.600	12.000	0.010	26.250	0.090	13.551
650	0.006	7.097	0.100	22.700	18.000	0.007	26.257	0.093	13.644
650	0.006	7.103	0.100	22.800	18.000	0.007	26.264	0.093	13.738
650	0.006	7.108	0.100	22.900	18.000	0.007	26.270	0.093	13.831
651	0.004	7.113	0.100	23.000	24.000	0.005	26.276	0.095	13.926
651	0.004	7.117	0.100	23.100	24.000	0.005	26.281	0.095	14.021
651	0.004	7.121	0.100	23.200	24.000	0.005	26.286	0.095	14.116
651	0.004	7.125	0.100	23.300	24.000	0.005	26.291	0.095	14.211
652	0.006	7.131	0.100	23.400	18.000	0.007	26.297	0.093	14.304
652	0.006	7.136	0.100	23.500	18.000	0.007	26.304	0.093	14.397
652	0.006	7.142	0.100	23.600	18.000	0.007	26.311	0.093	14.491
653	0.006	7.147	0.100	23.700	18.000	0.007	26.318	0.093	14.584
653	0.006	7.153	0.100	23.800	18.000	0.007	26.324	0.093	14.677
653	0.006	7.158	0.100	23.900	18.000	0.007	26.331	0.093	14.770
654	0.006	7.164	0.100	24.000	18.000	0.007	26.338	0.093	14.864
654	0.006	7.169	0.100	24.100	18.000	0.007	26.344	0.093	14.957
654	0.006	7.175	0.100	24.200	18.000	0.007	26.351	0.093	15.050
655	0.006	7.181	0.100	24.300	18.000	0.007	26.358	0.093	15.144
655	0.006	7.186	0.100	24.400	18.000	0.007	26.365	0.093	15.237
655	0.006	7.192	0.100	24.500	18.000	0.007	26.371	0.093	15.330
656	0.006	7.197	0.100	24.600	18.000	0.007	26.378	0.093	15.423
656	0.006	7.203	0.100	24.700	18.000	0.007	26.385	0.093	15.517
656	0.006	7.208	0.100	24.800	18.000	0.007	26.391	0.093	15.610
657	0.008	7.217	0.100	24.900	12.000	0.010	26.402	0.090	15.700
657	0.008	7.225	0.100	25.000	12.000	0.010	26.412	0.090	15.790
658	0.008	7.233	0.100	25.100	12.000	0.010	26.422	0.090	15.880
658	0.008	7.242	0.100	25.200	12.000	0.010	26.432	0.090	15.970

659	0.017	7.258	0.100	25.300	6.000	0.020	26.452	0.080	16.049
700	0.008	7.267	0.100	25.400	12.000	0.010	26.462	0.090	16.139
700	0.008	7.275	0.100	25.500	12.000	0.010	26.472	0.090	16.229
701	0.017	7.292	0.100	25.600	6.000	0.020	26.492	0.080	16.309
702	0.017	7.308	0.100	25.700	6.000	0.020	26.512	0.080	16.389
703	0.017	7.325	0.100	25.800	6.000	0.020	26.533	0.080	16.469
704	0.017	7.342	0.100	25.900	6.000	0.020	26.553	0.080	16.549
706	0.033	7.375	0.100	26.000	3.000	0.040	26.593	0.060	16.608
707	0.017	7.392	0.100	26.100	6.000	0.020	26.613	0.080	16.688
709	0.033	7.425	0.100	26.200	3.000	0.040	26.654	0.060	16.748
710	0.017	7.442	0.100	26.300	6.000	0.020	26.674	0.080	16.828
711	0.017	7.458	0.100	26.400	6.000	0.020	26.694	0.080	16.907
713	0.033	7.492	0.100	26.500	3.000	0.040	26.734	0.060	16.967
714	0.017	7.508	0.100	26.600	6.000	0.020	26.754	0.080	17.047
716	0.033	7.542	0.100	26.700	3.000	0.040	26.795	0.060	17.107
718	0.033	7.575	0.100	26.800	3.000	0.040	26.835	0.060	17.166
720	0.033	7.608	0.100	26.900	3.000	0.040	26.875	0.060	17.226
722	0.033	7.642	0.100	27.000	3.000	0.040	26.916	0.060	17.286
723	0.017	7.658	0.100	27.100	6.000	0.020	26.936	0.080	17.365
724	0.017	7.675	0.100	27.200	6.000	0.020	26.956	0.080	17.445
725	0.017	7.692	0.100	27.300	6.000	0.020	26.976	0.080	17.525
726	0.017	7.708	0.100	27.400	6.000	0.020	26.996	0.080	17.605
727	0.017	7.725	0.100	27.500	6.000	0.020	27.017	0.080	17.685
730	0.050	7.775	0.100	27.600	2.000	0.061	27.077	0.039	17.724
732	0.033	7.808	0.100	27.700	3.000	0.040	27.117	0.060	17.784
736	0.067	7.875	0.100	27.800	1.500	0.081	27.198	0.019	17.803
739	0.050	7.925	0.100	27.900	2.000	0.061	27.259	0.039	17.843
741	0.033	7.958	0.100	28.000	3.000	0.040	27.299	0.060	17.902
743	0.033	7.992	0.100	28.100	3.000	0.040	27.339	0.060	17.962
745	0.033	8.025	0.100	28.200	3.000	0.040	27.380	0.060	18.022

747	0.033	8.058	0.100	28.300	3.000	0.040	27.420	0.060	18.081
749	0.033	8.092	0.100	28.400	3.000	0.040	27.460	0.060	18.141
752	0.050	8.142	0.100	28.500	2.000	0.061	27.521	0.039	18.181
756	0.067	8.208	0.100	28.600	1.500	0.081	27.601	0.019	18.200
758	0.033	8.242	0.100	28.700	3.000	0.040	27.642	0.060	18.260
800	0.033	8.275	0.100	28.800	3.000	0.040	27.682	0.060	18.319
802	0.033	8.308	0.100	28.900	3.000	0.040	27.722	0.060	18.379
806	0.067	8.375	0.100	29.000	1.500	0.081	27.803	0.019	18.398
812	0.100	8.475	0.100	29.100	1.000	0.121	27.924	0.000	18.398
817	0.083	8.558	0.100	29.200	1.200	0.101	28.025	0.000	18.398
822	0.083	8.642	0.100	29.300	1.200	0.101	28.126	0.000	18.398
907	0.750	9.392	0.100	29.400	0.133	0.908	29.033	0.000	18.398
911	0.067	9.458	0.100	29.500	1.500	0.081	29.114	0.019	18.418
1027	1.267	10.725	0.100	29.600	0.079	1.533	30.647	0.000	18.418
1034	0.117	10.842	0.100	29.700	0.857	0.141	30.788	0.000	18.418
1037	0.050	10.892	0.100	29.800	2.000	0.061	30.848	0.039	18.457
1039	0.033	10.925	0.100	29.900	3.000	0.040	30.889	0.060	18.517
1041	0.033	10.958	0.100	30.000	3.000	0.040	30.929	0.060	18.576
1043	0.033	10.992	0.100	30.100	3.000	0.040	30.969	0.060	18.636
1045	0.033	11.025	0.100	30.200	3.000	0.040	31.010	0.060	18.696
1048	0.050	11.075	0.100	30.300	2.000	0.061	31.070	0.039	18.735
1051	0.050	11.125	0.100	30.400	2.000	0.061	31.131	0.039	18.775
1053	0.033	11.158	0.100	30.500	3.000	0.040	31.171	0.060	18.834
1056	0.050	11.208	0.100	30.600	2.000	0.061	31.231	0.039	18.874
1057	0.017	11.225	0.100	30.700	6.000	0.020	31.252	0.080	18.954
1059	0.033	11.258	0.100	30.800	3.000	0.040	31.292	0.060	19.013
1103	0.067	11.325	0.100	30.900	1.500	0.081	31.373	0.019	19.033
1107	0.067	11.392	0.100	31.000	1.500	0.081	31.453	0.019	19.052
1112	0.083	11.475	0.100	31.100	1.200	0.101	31.554	0.000	19.052
1119	0.117	11.592	0.100	31.200	0.857	0.141	31.695	0.000	19.052

1122	0.050	11.642	0.100	31.300	2.000	0.061	31.756	0.039	19.092
1126	0.067	11.708	0.100	31.400	1.500	0.081	31.836	0.019	19.111
1136	0.167	11.875	0.100	31.500	0.600	0.202	32.038	0.000	19.111
1146	0.167	12.042	0.100	31.600	0.600	0.202	32.240	0.000	19.111
1213	0.450	12.492	0.100	31.700	0.222	0.545	32.784	0.000	19.111
1217	0.067	12.558	0.100	31.800	1.500	0.081	32.865	0.019	19.130
1219	0.033	12.592	0.100	31.900	3.000	0.040	32.905	0.060	19.190
1222	0.050	12.642	0.100	32.000	2.000	0.061	32.966	0.039	19.229
1224	0.033	12.675	0.100	32.100	3.000	0.040	33.006	0.060	19.289
1226	0.033	12.708	0.100	32.200	3.000	0.040	33.046	0.060	19.349
1227	0.017	12.725	0.100	32.300	6.000	0.020	33.067	0.080	19.429
1229	0.033	12.758	0.100	32.400	3.000	0.040	33.107	0.060	19.488
1231	0.033	12.792	0.100	32.500	3.000	0.040	33.147	0.060	19.548
1233	0.033	12.825	0.100	32.600	3.000	0.040	33.188	0.060	19.608
1234	0.017	12.842	0.100	32.700	6.000	0.020	33.208	0.080	19.687
1235	0.017	12.858	0.100	32.800	6.000	0.020	33.228	0.080	19.767
1236	0.017	12.875	0.100	32.900	6.000	0.020	33.248	0.080	19.847
1237	0.017	12.892	0.100	33.000	6.000	0.020	33.268	0.080	19.927
1239	0.033	12.925	0.100	33.100	3.000	0.040	33.309	0.060	19.987
1240	0.017	12.942	0.100	33.200	6.000	0.020	33.329	0.080	20.066
1242	0.033	12.975	0.100	33.300	3.000	0.040	33.369	0.060	20.126
1244	0.033	13.008	0.100	33.400	3.000	0.040	33.409	0.060	20.186
1245	0.017	13.025	0.100	33.500	6.000	0.020	33.430	0.080	20.266
1247	0.033	13.058	0.100	33.600	3.000	0.040	33.470	0.060	20.325
1249	0.033	13.092	0.100	33.700	3.000	0.040	33.510	0.060	20.385
1251	0.033	13.125	0.100	33.800	3.000	0.040	33.551	0.060	20.445
1253	0.033	13.158	0.100	33.900	3.000	0.040	33.591	0.060	20.504
1255	0.033	13.192	0.100	34.000	3.000	0.040	33.631	0.060	20.564
1256	0.017	13.208	0.100	34.100	6.000	0.020	33.651	0.080	20.644
1258	0.033	13.242	0.100	34.200	3.000	0.040	33.692	0.060	20.703

1259	0.017	13.258	0.100	34.300	6.000	0.020	33.712	0.080	20.783
1301	0.033	13.292	0.100	34.400	3.000	0.040	33.752	0.060	20.843
1302	0.017	13.308	0.100	34.500	6.000	0.020	33.772	0.080	20.923
1303	0.008	13.317	0.100	34.600	12.000	0.010	33.783	0.090	21.013
1303	0.008	13.325	0.100	34.700	12.000	0.010	33.793	0.090	21.103
1304	0.017	13.342	0.100	34.800	6.000	0.020	33.813	0.080	21.182
1305	0.017	13.358	0.100	34.900	6.000	0.020	33.833	0.080	21.262
1306	0.017	13.375	0.100	35.000	6.000	0.020	33.853	0.080	21.342
1307	0.008	13.383	0.100	35.100	12.000	0.010	33.863	0.090	21.432
1307	0.008	13.392	0.100	35.200	12.000	0.010	33.873	0.090	21.522
1308	0.008	13.400	0.100	35.300	12.000	0.010	33.883	0.090	21.612
1308	0.008	13.408	0.100	35.400	12.000	0.010	33.893	0.090	21.702
1309	0.017	13.425	0.100	35.500	6.000	0.020	33.914	0.080	21.782
1310	0.008	13.433	0.100	35.600	12.000	0.010	33.924	0.090	21.872
1310	0.008	13.442	0.100	35.700	12.000	0.010	33.934	0.090	21.961
1311	0.008	13.450	0.100	35.800	12.000	0.010	33.944	0.090	22.051
1311	0.008	13.458	0.100	35.900	12.000	0.010	33.954	0.090	22.141
1312	0.017	13.475	0.100	36.000	6.000	0.020	33.974	0.080	22.221
1313	0.017	13.492	0.100	36.100	6.000	0.020	33.994	0.080	22.301
1314	0.017	13.508	0.100	36.200	6.000	0.020	34.014	0.080	22.381
1315	0.017	13.525	0.100	36.300	6.000	0.020	34.035	0.080	22.461
1316	0.017	13.542	0.100	36.400	6.000	0.020	34.055	0.080	22.540
1317	0.017	13.558	0.100	36.500	6.000	0.020	34.075	0.080	22.620
1318	0.017	13.575	0.100	36.600	6.000	0.020	34.095	0.080	22.700
1319	0.017	13.592	0.100	36.700	6.000	0.020	34.115	0.080	22.780
1320	0.017	13.608	0.100	36.800	6.000	0.020	34.135	0.080	22.860
1321	0.017	13.625	0.100	36.900	6.000	0.020	34.156	0.080	22.940
1323	0.033	13.658	0.100	37.000	3.000	0.040	34.196	0.060	22.999
1324	0.017	13.675	0.100	37.100	6.000	0.020	34.216	0.080	23.079
1326	0.033	13.708	0.100	37.200	3.000	0.040	34.256	0.060	23.139

1328	0.033	13.742	0.100	37.300	3.000	0.040	34.297	0.060	23.198
1330	0.033	13.775	0.100	37.400	3.000	0.040	34.337	0.060	23.258
1332	0.033	13.808	0.100	37.500	3.000	0.040	34.377	0.060	23.318
1334	0.033	13.842	0.100	37.600	3.000	0.040	34.418	0.060	23.377
1336	0.033	13.875	0.100	37.700	3.000	0.040	34.458	0.060	23.437
1339	0.050	13.925	0.100	37.800	2.000	0.061	34.519	0.039	23.477
1342	0.050	13.975	0.100	37.900	2.000	0.061	34.579	0.039	23.516
1346	0.067	14.042	0.100	38.000	1.500	0.081	34.660	0.019	23.535
1348	0.033	14.075	0.100	38.100	3.000	0.040	34.700	0.060	23.595
1350	0.033	14.108	0.100	38.200	3.000	0.040	34.740	0.060	23.655
1351	0.017	14.125	0.100	38.300	6.000	0.020	34.761	0.080	23.735
1352	0.017	14.142	0.100	38.400	6.000	0.020	34.781	0.080	23.814
1354	0.033	14.175	0.100	38.500	3.000	0.040	34.821	0.060	23.874
1355	0.017	14.192	0.100	38.600	6.000	0.020	34.841	0.080	23.954
1356	0.017	14.208	0.100	38.700	6.000	0.020	34.861	0.080	24.034
1357	0.017	14.225	0.100	38.800	6.000	0.020	34.882	0.080	24.114
1359	0.033	14.258	0.100	38.900	3.000	0.040	34.922	0.060	24.173
1400	0.017	14.275	0.100	39.000	6.000	0.020	34.942	0.080	24.253
1402	0.033	14.308	0.100	39.100	3.000	0.040	34.982	0.060	24.313
1403	0.017	14.325	0.100	39.200	6.000	0.020	35.003	0.080	24.393
1405	0.033	14.358	0.100	39.300	3.000	0.040	35.043	0.060	24.452
1407	0.033	14.392	0.100	39.400	3.000	0.040	35.083	0.060	24.512
1409	0.033	14.425	0.100	39.500	3.000	0.040	35.124	0.060	24.572
1412	0.050	14.475	0.100	39.600	2.000	0.061	35.184	0.039	24.611
1415	0.050	14.525	0.100	39.700	2.000	0.061	35.245	0.039	24.651
1417	0.033	14.558	0.100	39.800	3.000	0.040	35.285	0.060	24.710
1418	0.017	14.575	0.100	39.900	6.000	0.020	35.305	0.080	24.790
1421	0.050	14.625	0.100	40.000	2.000	0.061	35.366	0.039	24.830
1423	0.033	14.658	0.100	40.100	3.000	0.040	35.406	0.060	24.889
1425	0.033	14.692	0.100	40.200	3.000	0.040	35.446	0.060	24.949

1427	0.033	14.725	0.100	40.300	3.000	0.040	35.487	0.060	25.009
1429	0.033	14.758	0.100	40.400	3.000	0.040	35.527	0.060	25.068
1430	0.017	14.775	0.100	40.500	6.000	0.020	35.547	0.080	25.148
1431	0.017	14.792	0.100	40.600	6.000	0.020	35.567	0.080	25.228
1432	0.017	14.808	0.100	40.700	6.000	0.020	35.587	0.080	25.308
1434	0.033	14.842	0.100	40.800	3.000	0.040	35.628	0.060	25.367
1435	0.017	14.858	0.100	40.900	6.000	0.020	35.648	0.080	25.447
341436	0.017	14.875	0.100	41.000	6.000	0.020	35.668	0.080	25.527
1438	0.033	14.908	0.100	41.100	3.000	0.040	35.708	0.060	25.587
1441	0.050	14.958	0.100	41.200	2.000	0.061	35.769	0.039	25.626
1443	0.033	14.992	0.100	41.300	3.000	0.040	35.809	0.060	25.686
1445	0.033	15.025	0.100	41.400	3.000	0.040	35.850	0.060	25.746
1447	0.033	15.058	0.100	41.500	3.000	0.040	35.890	0.060	25.805
1449	0.033	15.092	0.100	41.600	3.000	0.040	35.930	0.060	25.865
1451	0.033	15.125	0.100	41.700	3.000	0.040	35.971	0.060	25.925
1453	0.033	15.158	0.100	41.800	3.000	0.040	36.011	0.060	25.984
1454	0.017	15.175	0.100	41.900	6.000	0.020	36.031	0.080	26.064
1456	0.033	15.208	0.100	42.000	3.000	0.040	36.071	0.060	26.124
1458	0.033	15.242	0.100	42.100	3.000	0.040	36.112	0.060	26.183
1500	0.033	15.275	0.100	42.200	3.000	0.040	36.152	0.060	26.243
1502	0.033	15.308	0.100	42.300	3.000	0.040	36.192	0.060	26.303
1506	0.067	15.375	0.100	42.400	1.500	0.081	36.273	0.019	26.322
1509	0.050	15.425	0.100	42.500	2.000	0.061	36.334	0.039	26.362
1512	0.050	15.475	0.100	42.600	2.000	0.061	36.394	0.039	26.401
1515	0.050	15.525	0.100	42.700	2.000	0.061	36.455	0.039	26.441
1517	0.050	15.575	0.100	42.800	2.000	0.061	36.515	0.039	26.480
1519	0.033	15.608	0.100	42.900	3.000	0.040	36.555	0.060	26.540
1523	0.067	15.675	0.100	43.000	1.500	0.081	36.636	0.019	26.559
1526	0.050	15.725	0.100	43.100	2.000	0.061	36.697	0.039	26.599

1530	0.067	15.792	0.100	43.200	1.500	0.081	36.777	0.019	26.618
1534	0.067	15.858	0.100	43.300	1.500	0.081	36.858	0.019	26.637
1539	0.083	15.942	0.100	43.400	1.200	0.101	36.959	0.000	26.637
1542	0.050	15.992	0.100	43.500	2.000	0.061	37.019	0.039	26.677
1545	0.050	16.042	0.100	43.600	2.000	0.061	37.080	0.039	26.716
1547	0.033	16.075	0.100	43.700	3.000	0.040	37.120	0.060	26.776
1550	0.050	16.125	0.100	43.800	2.000	0.061	37.181	0.039	26.815
1553	0.050	16.175	0.100	43.900	2.000	0.061	37.241	0.039	26.855
1557	0.067	16.242	0.100	44.000	1.500	0.081	37.322	0.019	26.874
1601	0.067	16.308	0.100	44.100	1.500	0.081	37.402	0.019	26.894
1605	0.067	16.375	0.100	44.200	1.500	0.081	37.483	0.019	26.913
1609	0.067	16.442	0.100	44.300	1.500	0.081	37.564	0.019	26.932
1612	0.050	16.492	0.100	44.400	2.000	0.061	37.624	0.039	26.972
1615	0.050	16.542	0.100	44.500	2.000	0.061	37.685	0.039	27.011
1617	0.033	16.575	0.100	44.600	3.000	0.040	37.725	0.060	27.071
1620	0.050	16.625	0.100	44.700	2.000	0.061	37.786	0.039	27.110
1622	0.033	16.658	0.100	44.800	3.000	0.040	37.826	0.060	27.170
1624	0.033	16.692	0.100	44.900	3.000	0.040	37.866	0.060	27.230
1627	0.050	16.742	0.100	45.000	2.000	0.061	37.927	0.039	27.269
1629	0.033	16.775	0.100	45.100	3.000	0.040	37.967	0.060	27.329
1631	0.033	16.808	0.100	45.200	3.000	0.040	38.007	0.060	27.389
1633	0.033	16.842	0.100	45.300	3.000	0.040	38.048	0.060	27.448
1635	0.033	16.875	0.100	45.400	3.000	0.040	38.088	0.060	27.508
1637	0.033	16.908	0.100	45.500	3.000	0.040	38.128	0.060	27.568
1639	0.033	16.942	0.100	45.600	3.000	0.040	38.169	0.060	27.627
1641	0.033	16.975	0.100	45.700	3.000	0.040	38.209	0.060	27.687
1644	0.050	17.025	0.100	45.800	2.000	0.061	38.270	0.039	27.726
1646	0.033	17.058	0.100	45.900	3.000	0.040	38.310	0.060	27.786
1648	0.033	17.092	0.100	46.000	3.000	0.040	38.350	0.060	27.846
1651	0.050	17.142	0.100	46.100	2.000	0.061	38.411	0.039	27.885

1653	0.033	17.175	0.100	46.200	3.000	0.040	38.451	0.060	27.945
1655	0.033	17.208	0.100	46.300	3.000	0.040	38.491	0.060	28.005
1657	0.033	17.242	0.100	46.400	3.000	0.040	38.532	0.060	28.064
1659	0.033	17.275	0.100	46.500	3.000	0.040	38.572	0.060	28.124
1702	0.050	17.325	0.100	46.600	2.000	0.061	38.633	0.039	28.163
1705	0.050	17.375	0.100	46.700	2.000	0.061	38.693	0.039	28.203
1708	0.050	17.425	0.100	46.800	2.000	0.061	38.754	0.039	28.242
1711	0.050	17.475	0.100	46.900	2.000	0.061	38.814	0.039	28.282
1713	0.033	17.508	0.100	47.000	3.000	0.040	38.854	0.060	28.342
1715	0.033	17.542	0.100	47.100	3.000	0.040	38.895	0.060	28.401
1718	0.050	17.592	0.100	47.200	2.000	0.061	38.955	0.039	28.441
1720	0.033	17.625	0.100	47.300	3.000	0.040	38.996	0.060	28.500
1722	0.033	17.658	0.100	47.400	3.000	0.040	39.036	0.060	28.560
1723	0.017	17.675	0.100	47.500	6.000	0.020	39.056	0.080	28.640
1725	0.033	17.708	0.100	47.600	3.000	0.040	39.096	0.060	28.700
1727	0.033	17.742	0.100	47.700	3.000	0.040	39.137	0.060	28.759
1728	0.017	17.758	0.100	47.800	6.000	0.020	39.157	0.080	28.839
1730	0.033	17.792	0.100	47.900	3.000	0.040	39.197	0.060	28.899
1731	0.017	17.808	0.100	48.000	6.000	0.020	39.217	0.080	28.979
1733	0.033	17.842	0.100	48.100	3.000	0.040	39.258	0.060	29.038
1735	0.033	17.875	0.100	48.200	3.000	0.040	39.298	0.060	29.098
1737	0.033	17.908	0.100	48.300	3.000	0.040	39.338	0.060	29.158
1740	0.050	17.958	0.100	48.400	2.000	0.061	39.399	0.039	29.197
1743	0.050	18.008	0.100	48.500	2.000	0.061	39.459	0.039	29.237
1747	0.067	18.075	0.100	48.600	1.500	0.081	39.540	0.019	29.256
1751	0.067	18.142	0.100	48.700	1.500	0.081	39.621	0.019	29.275
1754	0.050	18.192	0.100	48.800	2.000	0.061	39.681	0.039	29.315
1756	0.033	18.225	0.100	48.900	3.000	0.040	39.722	0.060	29.374
1758	0.033	18.258	0.100	49.000	3.000	0.040	39.762	0.060	29.434
1800	0.033	18.292	0.100	49.100	3.000	0.040	39.802	0.060	29.494

1803	0.050	18.342	0.100	49.200	2.000	0.061	39.863	0.039	29.533
1805	0.033	18.375	0.100	49.300	3.000	0.040	39.903	0.060	29.593
1807	0.033	18.408	0.100	49.400	3.000	0.040	39.943	0.060	29.653
1809	0.033	18.442	0.100	49.500	3.000	0.040	39.984	0.060	29.712
1811	0.033	18.475	0.100	49.600	3.000	0.040	40.024	0.060	29.772
1813	0.033	18.508	0.100	49.700	3.000	0.040	40.064	0.060	29.832
1815	0.033	18.542	0.100	49.800	3.000	0.040	40.105	0.060	29.891
1817	0.033	18.575	0.100	49.900	3.000	0.040	40.145	0.060	29.951
1818	0.017	18.592	0.100	50.000	6.000	0.020	40.165	0.080	30.031
1820	0.033	18.625	0.100	50.100	3.000	0.040	40.206	0.060	30.090
1822	0.033	18.658	0.100	50.200	3.000	0.040	40.246	0.060	30.150
1823	0.017	18.675	0.100	50.300	6.000	0.020	40.266	0.080	30.230
1826	0.050	18.725	0.100	50.400	2.000	0.061	40.327	0.039	30.269
1828	0.033	18.758	0.100	50.500	3.000	0.040	40.367	0.060	30.329
1831	0.050	18.808	0.100	50.600	2.000	0.061	40.427	0.039	30.369
1834	0.050	18.858	0.100	50.700	2.000	0.061	40.488	0.039	30.408
1839	0.083	18.942	0.100	50.800	1.200	0.101	40.589	0.000	30.408
1843	0.067	19.008	0.100	50.900	1.500	0.081	40.669	0.019	30.427
1848	0.083	19.092	0.100	51.000	1.200	0.101	40.770	0.000	30.427
1851	0.050	19.142	0.100	51.100	2.000	0.061	40.831	0.039	30.467
1854	0.050	19.192	0.100	51.200	2.000	0.061	40.891	0.039	30.506
1858	0.067	19.258	0.100	51.300	1.500	0.081	40.972	0.019	30.526
1903	0.083	19.342	0.100	51.400	1.200	0.101	41.073	0.000	30.526
1906	0.050	19.392	0.100	51.500	2.000	0.061	41.133	0.039	30.565
1909	0.050	19.442	0.100	51.600	2.000	0.061	41.194	0.039	30.605
1912	0.050	19.492	0.100	51.700	2.000	0.061	41.254	0.039	30.644
1916	0.067	19.558	0.100	51.800	1.500	0.081	41.335	0.019	30.664
1919	0.050	19.608	0.100	51.900	2.000	0.061	41.395	0.039	30.703
1922	0.050	19.658	0.100	52.000	2.000	0.061	41.456	0.039	30.743
1926	0.067	19.725	0.100	52.100	1.500	0.081	41.537	0.019	30.762

1931	0.083	19.808	0.100	52.200	1.200	0.101	41.637	0.000	30.762
1935	0.067	19.875	0.100	52.300	1.500	0.081	41.718	0.019	30.781
1940	0.083	19.958	0.100	52.400	1.200	0.101	41.819	0.000	30.781
1943	0.050	20.008	0.100	52.500	2.000	0.061	41.879	0.039	30.821
1946	0.050	20.058	0.100	52.600	2.000	0.061	41.940	0.039	30.860
1948	0.033	20.092	0.100	52.700	3.000	0.040	41.980	0.060	30.920
1952	0.067	20.158	0.100	52.800	1.500	0.081	42.061	0.019	30.939
1954	0.033	20.192	0.100	52.900	3.000	0.040	42.101	0.060	30.999
1958	0.067	20.258	0.100	53.000	1.500	0.081	42.182	0.019	31.018
2001	0.050	20.308	0.100	53.100	2.000	0.061	42.242	0.039	31.058
2005	0.067	20.375	0.100	53.200	1.500	0.081	42.323	0.019	31.077
2008	0.050	20.425	0.100	53.300	2.000	0.061	42.384	0.039	31.117
2011	0.050	20.475	0.100	53.400	2.000	0.061	42.444	0.039	31.156
2014	0.050	20.525	0.100	53.500	2.000	0.061	42.505	0.039	31.196
2019	0.083	20.608	0.100	53.600	1.200	0.101	42.605	0.000	31.196
2024	0.083	20.692	0.100	53.700	1.200	0.101	42.706	0.000	31.196
2030	0.100	20.792	0.100	53.800	1.000	0.121	42.827	0.000	31.196
2037	0.117	20.908	0.100	53.900	0.857	0.141	42.968	0.000	31.196
2114	0.617	21.525	0.100	54.000	0.162	0.746	43.715	0.000	31.196
2121	0.117	21.642	0.100	54.100	0.857	0.141	43.856	0.000	31.196
2127	0.100	21.742	0.100	54.200	1.000	0.121	43.977	0.000	31.196
2133	0.100	21.842	0.100	54.300	1.000	0.121	44.098	0.000	31.196
2140	0.117	21.958	0.100	54.400	0.857	0.141	44.239	0.000	31.196
2145	0.083	22.042	0.100	54.500	1.200	0.101	44.340	0.000	31.196
2148	0.050	22.092	0.100	54.600	2.000	0.061	44.400	0.040	31.235
2150	0.033	22.125	0.100	54.700	3.000	0.040	44.441	0.060	31.295
2153	0.050	22.175	0.100	54.800	2.000	0.061	44.501	0.040	31.334
2156	0.050	22.225	0.100	54.900	2.000	0.061	44.562	0.040	31.374
2203	0.117	22.342	0.100	55.000	0.857	0.141	44.703	0.000	31.374
2209	0.100	22.442	0.100	55.100	1.000	0.121	44.824	0.000	31.374

2214	0.083	22.525	0.100	55.200	1.200	0.101	44.925	0.000	31.374
2218	0.067	22.592	0.100	55.300	1.500	0.081	45.005	0.019	31.393
2223	0.083	22.675	0.100	55.400	1.200	0.101	45.106	0.000	31.393
2230	0.117	22.792	0.100	55.500	0.857	0.141	45.247	0.000	31.393
2352	0.367	23.158	0.100	55.600	0.273	0.444	45.691	0.000	31.393

Appendix 6.1: Specific maize growth parameters (cultivar PNR 6479) included in the SWB database

Specific growth parameters	
Canopy radiation extinction coefficient	0.56
Corrected dry matter-water ratio (Pa)	9
Radiation conversion efficiency (kg MJ^{-1})	0.0015
Base temperature (C^o)	10
Temperature for optimum crop growth (C^o)	25
Cutoff temperature (C^o)	30
Emergence day degrees (d C^o)	50
Day degrees at end of vegetative growth (d C^o)	900
Day degrees for maturity (d C^o)	1700
Transition period day degrees (d C^o)	10
Day degrees for leaf senescence (d C^o)	900
Maximum crop height (m)	2.2
Maximum root depth (m)	1.2
Fraction of total dry matter translocated to heads	0.05
Canopy storage (mm)	1
Leaf water potential at maximum transpiration (kPa)	-2000
Maximum transpiration (mm d^{-1})	9
Specific leaf area (m^2 kg^{-1})	15
Leaf stem partition parameter (m^2 kg^{-1})	0.8
Total dry matter at emergence (kg m^{-2})	0.0019
Fraction of total dry matter partitioned to roots	0.2
Root growth rate (m^2 $kg^{-0.5}$)	8
Stress index	0.95

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