QUANTIFYING RAINFALL-RUNOFF RELATIONSHIPS ON SELECTED BENCHMARK ECOTOPES IN ETHIOPIA: A PRIMARY STEP IN WATER HARVESTING RESEARCH

by

Worku Atlabatchew Welderufael

(M.Sc. Wageningen Agricultural University)

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Department of Soil, Crop and Climate Sciences,

University of Free State

Bloemfontein.

Promoter: Dr. P.A.L. Le Roux

Co-promoter: Dr. M. Hensley

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DECLARATION

I declare that the dissertation hereby submitted by me for the Doctor of Philosophy in Soil Science degree at the University of the Free State is my own independent work and has not previously been submitted by me at another university/faculty. I furthermore cede copyright of the dissertation in favour of the University of the Free State.

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ABSTRACT

Large areas of cultivated land in Ethiopia frequently suffer from drought, causing low crop yields and food insecurity. It was hypothesized that it may be possible to alleviate this problem by employing infield rain water harvesting (IRWH). Three representative semi-arid ecotopes in the Rift Valley were selected to test this hypothesis. They were the Melkassa Hypo Calcic Regosol, The Dera Calcic Fluvic Regosol and the Mieso Hypo Calcic Vertisol. The climate, topography and soils of the ecotopes were characterized in detail.

Rainfall runoff studies were carried out over two rain seasons on replicated plots on these ecotopes comparing two soil surface treatments. They were conventional tillage (CT), simulating the initially fairly rough surface which results after normal tillage; and no tillage (NT), simulating the flat crusted surface expected on the runoff strip of the IRWH system. Rainfall amounts, rainfall intensity at one minute intervals, and runoff, were measured for each storm during the two rain seasons on each ecotope. The results were used to calibrate and validate the Morin & Cluff runoff model in order to enhance the extrapolation capability of the study results to other similar ecotopes.

The study yielded the following useful results.

- The rainfall pattern on all the ecotopes was characterized by occasional storms with fairly high amounts and high intensities (Pi) which greatly exceeded the final infiltration rates of the soil, causing a high proportion of the rain (P) to runoff (R), i.e. producing a high R/P ratio. For the NT treatment final overall R/P values for the two seasons on the Melkassa, Dera and Mieso ecotopes were 0.45, 0.52 and 0.32, respectively. These high values indicate that IRWH should produce a significant increase in yield due to its ability to reduce R to zero while concentrating the runoff in the basin area and increasing the water available for transpiration and therefore increasing yield.
- Because of the textural and mineralogical properties of the topsoils, particularly the two Regosols soils; they disperse and form crusts easily when impacted by high

intensity rain. The result was that after cultivation at the start of the rain season the surface of the CT treatment soon became very similar to that of the NT treatment. Accordingly no significant difference was found between the runoff from the NT and CT plots on the Melkassa Regosol and Dera Regosol. There was, however, a significant difference in this respect on the Mieso Vertisol with a more stable surface.

- Runoff prediction in all the ecotopes were well done by the M & C model.
- Two separate strategies were developed to estimate the maize yield increase that could be expected on the Melkassa Regosol by employing IRWH. From the nearby Melkassa Research Station it was possible to obtain maize yields for 15 seasons (1989-2003). These were used together with climate data, the CROPWAT model, and the runoff measurements, to estimate the benefit of IRWH. The two strategies produced yield increase estimates of 33% and 40% compared to CT.

UITTREKSEL

Groot dele van die gewasproduserende streek van Ethiopië is dikwels onderhewig aan droogte. Dit veroorsaak swak oeste en ʼn tekort aan voedselsekuriteit. Die hipotese is dat die sukses met die gewasverbouingstegniek bekend as "infield rain water harvesting" (IRWH) ook hier van toepassing is en dus verligting kan bring. Drie verteenwoordigende semi-ariede ekotope in die Skeurvallei is gekies vir navorsing om hierdie hipotese te toets. Die ekotope Melkassa Hypo Calcic Regosol, Dera Calcic fluvic Regosol en Mieso Hypo Calcic Vertisol is gekies. Die ekotope is deeglik gekarakteriseer deur gedetaileerde beskrywings van die klimaat, topografie en grond.

Die reënval-afloop eienskappe van die drie ekotope is bestudeer deur middel van aflooppersele, met herhalings, met twee soorte grondbewerkings praletyke as behandelings. Die bewerkings praletyke was: konvensioneel (CT), ʼn simulasie van die redelike rowwe grondoppervlakte toestand wat op ʼn land voorkom na konvensionele algemene skaarploeg bewerking; geenbewerking (NT), ʼn simulasie van die gelyk oppervlakte met ʼn kors wat voorkom op die afloopstrook van die IRWH tegniek. Vir elke reënbui gedurende twee reënseisoene is die volgende gemeet: hoeveelheid reën, reënvalintensiteit op een minuut intervalle en afloop is gemeet. Resultate is gebruik om die Morin & Cluff afloopmodel te kalibreer en te valideer. Die doel hiervan was om dit moontlik te maak om die resultate van die studie na ander vergelykbare ekotope in Ethiopië te ekstrapoleer.

Die studie het die volgende waardevolle resultate gelewer:

- Op al die ekotope was daar nou en dan swaar reënbuie met Pi hoër as die infiltrasie vermoeë van die grond. Afloop het dan plaasgevind, soms met hoë waardes van R/P. Vir die NT behandeling was die finale R/P waardes vir die twee seisoene 0.45, 0.52 en 0.32. vir die Melkassa, Dera en Mieso ekotope, onderskeidelik. Hierdie hoë waardes gee ʼn aanduiding dat IRWH ʼn betekenisvolle verbetering in opbrengs behoort te gee weens die vermoeë van die sisteem om afloop te verminder na zero,

asook om meer water beskikbaar te maak vir transpirasie deur opgaring van afloopwater in die bakkies naby die gewas.

- Kluit degradasie en korsvorming vind maklik plaas op hierdie gronde deur dispergerende en kompakterende invloed van hoë intensiteit reën. Tekstuur en kleimineralogie speel 'n belangrike rol. Die gevolg van goeie dispersie en korsvorming was dat die oppervlakte van die CT behandeling, na bewerking aan die begin van die seisoen, vinnig verander het om amper vergelykbaar te wees met die oppervlakte van die NT en CT behandeling. Dié eienskap is sterker ontwikkel op die twee Regosols as op die Vertisol. Die resultaat was dat afloop nie betekenisvol verskil het tussen die NT en CT behandelings op die twee Regosols nie, maar wel so 'n op die Vertisol verskil.

- Die Morin en Cluff model het afloop op al drie ekotope goed gesimuleer.

- Twee prosedures is ontwikkel om 'n beraming te kry van 'n verwagte verbetering in mielie opbrengs op die Melkassa Hypo Calcic Regosol deur gebruik van IRWH. Mielie opbrengsdata van 15 seisoene (1989 – 2003) is verkry van die Melkassa Navorsingstasie. Hierdie data is saam met klimaatdata gebruik en die CROPWAT model ingespan om saam met die resultate van die afloop metings op hierdie ekotoop, die IRWH voordeel te beraam. Die twee prosedures het opbrengs verhogings van 33% en 40% bokant CT voorspel.

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LIST OF ABBREVIATIONS AND SYMBOLS

ACT	Almanac characterization tool
AI	Aridity index
CA	Contributing area
Cl	Clay content
CMUL	Crop modified upper limit
CO_2	Carbon dioxide
CT	Conventional tillage
CWPF	Crop water productivity function
CWR	Crop water requirement
D	Deep drainage
Db	Bulk density
Dg	Deep drainage during the growing season
D-index	Agreement index
DoY	Day of the year
DUL	Drainage upper limit
EARO	Ethiopian Agricultural Research Organization
Eg	Evaporation from the soil surface during the growing season
EIAR	Ethiopian Institute of Agricultural Research
Eo	Free water surface evaporation
Es	Evaporation from the soil surface
ET	Evapotranspiration
ETo	Potential evapotranspiration
ETr	Evapotranspiration rate
GM	Graphical method
HARC	Holetta Agricultural Research Center
I	Instantaneous infiltration rate
IB	Infiltration basin
Ic	Cumulative infiltration rate
I_f	Final infiltration rate
I_i	Initial infiltration rate
IRWH	Infield rainwater harvesting
k	Transpiration efficiency coefficient
kc	Crop coefficient
LL	Lower limit
M & C	Morin and Cluff (1980) runoff model
m.i.p.	Major intense period
MAPE	Mean absolute percentage error
MARC	Melkassa Agricultural Research Center
MCWH	Micro-catchment water harvesting
MoA	Ministry of agriculture
MSE	Mean square error
MSS	Minimum surface storage
MWD	Mean weight diameter
NT	No tillage

OM	Organic matter
P	Precipitation
PAW	Plant available water
P_f	Precipitation during the fallow period
Pg	Precipitation during the growing period
Pi	Rainfall intensity
PUE	Precipitation use efficiency
R	Runoff
R/P	Runoff rainfall ratio ($P \geq 9$ mm)
R^2	Coefficient of distribution
RFWH	Runoff farming water harvesting
Rg	Runoff during the growing season
RMSE	Root mean square error
RMSEs	Systematic root mean square error.
RMSEu	Unsystematic root mean square error.
RPA	Runoff producing area
RRA	Runoff receiving area
RSF	Rainfall storage efficiency
RWP	Rainwater productivity
RWPn	rainwater productivity over a year
s	Soil stotage
Sa	Sand content
SD_m	Maximum soil storage and detention
Si	Silt content
SPAC	Soil-plant-atmosphere continuum
T	Transpiration
TDR	Time domain reflectometer
TST	Conventional total tillage
TSTM	Conventional total tillage with mulch
WC	Water conservation
WHB	Water harvesting basin
WHBM	Water harvesting basin with mulch
WRB	World Resource Base
WUE	Water use efficiency
γ	Empirical soil parameter representing surface aggregate resistance to dispersion
ΔW	Change in root zone water
θa	Antecedent soil water content
θm	Gravimetric soil water content
θr	Root zone water content
ΣEi	Cumulative evaporation during the 1st phase
ΣEp	Cumulative potential evaporation

1. INTRODUCTION

1.1 Motivation

More than 80% of Ethiopia's population is involved in agriculture, the backbone of the country's economy. In Ethiopia, crop production mostly occurs under rainfed conditions, most of which is marginalized by moisture stress. The optimum utilization of rainwater is therefore of the utmost importance. Because of global environmental change, the normal rainfall amount and distribution in Ethiopia have been affected from year to year, especially in the low rainfall areas. This has greatly influenced the sustainability of crop production in most parts of the country. Nowadays even areas which previously had sufficient rainfall for crop production are experiencing unreliable amounts and distribution. Rainfed crop production is becoming a risky venture in Ethiopia and the frequent droughts are a serious threat to those engaged in agriculture.

Because of these facts, a stepwise modification of the traditional crop production strategies is urgently required. These include amongst others the improvement of rain water productivity (RWP). This is especially important i.e., "more crop per drop" as appropriately stated recently by the UN President Kofi Annan in areas where the seasonal rainfall amount is insufficient for optimum crop production.

Rainfall, especially in moisture stressed areas, is mainly lost through evaporation from the soil surface (Es) and runoff (R). Under semi-arid climatic conditions Es can be 60-70 % of the annual rainfall (Bennie & Hensley, 2001). Mwakalila & Hatibu (1993) also reported that the main loss of water from paddy fields is through Es amounting to 4 to 5 mm per day. Berry & Mallett (1988) found that a maize residue that covers more than 70% of the soil surface only decreased Es losses for wetting frequencies shorter than 14 days under sub-humid climatic conditions. In addition, they calculated that the amount of crop residue needed for 70% ground cover was a minimum of 6000 kg ha^{-1}. This of course, is not possible to achieve in practice by an average Ethiopian farmer. In Ethiopia most materials used for mulching are scarce because they are mostly used to feed animals, to make fires or to build houses.

Studies carried out in the semi-arid zone of Israel showed that runoff is initiated primarily by soil crust formation and intense rainfall (Morin & Benyamini, 1977; Morin & Cluff, 1980). Studies also showed that soils of the semi-arid zones are very susceptible to crust formation. This slows down infiltration. A study that was carried out by Morin (1967) to model the infiltration rate of five major soils in Israel in the laboratory showed a good correlation between calculated and measured infiltration rates for different rainfall intensities. The model was further tested in the field by Morin & Benyamini (1977) on bare sandy loam soils. Their study confirmed that the major factor reducing infiltration rate of the soil was crust formation. According to their study, the model also successfully predicted the potential infiltration rate of the bare crusted soil. Based on the above studies, Morin & Cluff (M & C) (1980) further evaluated the infiltration rate model on semi-arid watersheds in Arizona, in an effort to quantify the rainfall-runoff relationship under crust forming conditions. A model that can predict the runoff amount from crust forming soils was then developed. The model showed a good relationship between the measured and estimated values. Predicting runoff amounts with models enables researchers to quantify the benefits of water harvesting techniques in terms of crop yield for different ecotopes (Morin, Rawitz, Hoogmoed & Benyamini, 1983; Beukes, Bennie & Hensley, 1998; Hensley, Botha, Anderson, Van Staden & Du Toit, 2000; Botha, Van Rensburg, Anderson, Hensley, Macheli, Van Staden, Kundhandle, Groenewald, Baiphethi, 2003).

It is well documented that rainfall distribution in the arid and semi-arid regions of Ethiopia is erratic and low in amount resulting in soil water deficits at some critical stages of crop growth (Ministry of Agriculture (MoA), 2000). This contributes to low crop yields and sometimes total crop failure with no grain yield. Hence crop variety selection and plant breeding alone become unsuccessful strategies for the achievement of optimum crop production and sustainability. It is therefore necessary to seek suitable water conservation techniques which could combat the soil water shortage problem and improve RWP. These strategies are particularly important for critical crop growth stages, as well as for the whole growing period.

One way of increasing RWP and decreasing production risk in dry areas, is through water harvesting. Many types of water conservation techniques, that show significant crop yield increases, have been tested worldwide (Kronen, 1994; Gicheru, Gachene & Biahmah, 1998; Mwakalila & Hatibu, 1993; Berry & Mallett, 1988 and Ojasvi, Goyal & Gupta 1999). However, farmers in Ethiopia very seldom make use of these techniques such as tied ridges or potholes. Even if tied ridge and mulching techniques could substantially increase maize grain yields in water stressed areas in Ethiopia, their acceptability by small-scale farmers is still unproven. Recently a tide ridger that can be attached to local farmer's ox drawn ploughs was developed by the Melkassa Agricultural Research Center, Agricultural Research Mechanization Program (Temesgen, Georgis, Goda & Abebe, 2001). The implement was tested on the research station as well as on farmers' fields. It performed well. Its wide scale acceptance by small-scale farmers has not yet been proved. A one-year research report in this regard is nevertheless encouraging (Temesgen *et al.*, 2001). It is clear that all studies related to effective water conservation techniques in crop production systems that are acceptable and practical for Ethiopian farmers need to be encouraged.

A technique that showed good potential in a semi-arid area of South Africa is in-field rain water harvesting (IRWH) as described by Hensley *et al.* (2000). The objective of this technique is to maximize RWP. The technique is also known as mini-catchment runoff farming (Owies, Hachum & Kijne, 1999). The technique is illustrated in Figure 1.1.

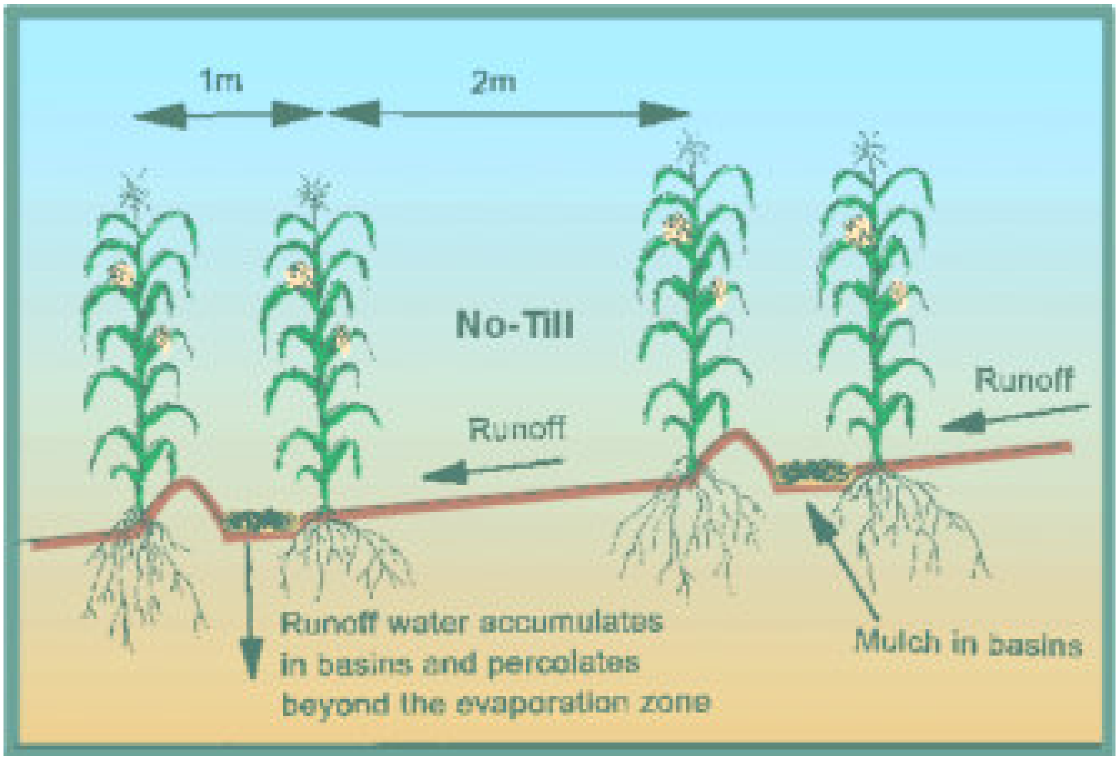


Figure 1. 1 A diagrammatic description of the no-till, mulching, basin tillage, in-field rain water harvesting (IRWH) production technique (Hensley *et al.*, 2000)

The IRWH technique has led to significant increases in RWP. Maize grain yield increases of between 25 and 50% compared to conventional tillage practices were reported. It has already been shown that the technique is suited to semi-arid areas with crusting soils that have a high water storage capacity (Hensley *et al*., 2000). If rainfall-runoff relationships for suitable ecotopes in Ethiopia can be determined, it will enable researchers there to quantify the extent to which the technique will result in increased yields.

1.2 Hypothesis

1. The in-field rain water harvesting technique illustrated in Figure 1.1 will result in increased crop yields on certain semi-arid ecotopes of Ethiopia.
2. The M & C (1980) model will satisfactorily predict runoff on the chosen ecotopes.

3. It will be possible to make reasonable estimates of yield increases, following IRWH on the selected ecotopes, by simulating the amount of runoff collected in the basins, and therefore increasing the amount of water available for crop growth.

1.3 Objectives

1. To quantify rainfall-runoff relationships on three selected dry crop ecotopes of Ethiopia.
2. To calibrate the M & C (1980) runoff model for these ecotopes.
3. To estimate for these ecotopes the maize yield benefit, using the IRWH technique described in Figure 1.1, compared to conventional tillage. Data from the first objective will be used to do this.

2. LITERATURE REVIEW

2.1 The ecotope

The land resource of any country can be subdivided into a number of agro-ecosystems further most subdivided into more homogenous land units called ecotopes (Troll, 1971; MacVicar, Scotney, Skinner, Niehaus & Loubser, 1974 and Van der Watt & Van Rooyen, 1995). Wikipedia (2006) defines ecotopes as the smallest ecologically-distinct landscape features in a landscape mapping and classification system. They represent relatively homogeneous, spatially explicit landscape units that are useful for stratifying landscapes into ecologically distinct units for the measurement and mapping of landscape structure, function and change. The first definition regarding an ecotope was made by Tansley (1939) as “the particular portion of the physical world that forms a home for the organisms which inhabit it”. In agriculture different sub-classifications of the agro-ecosystem have been, and still are, in use. In crop production especially, the smallest sub division becomes important for efficient resource utilization. In this respect the ecotope is the appropriate unit (MacVicar *et al.,* 1974; Van der Watt & Van Rooyen, 1995 and Hensley *et al.*, 2000). Troll (1971) first applied the term to landscape ecology “the smallest spatial object or component of a geographical landscape”.

More recently the term ecotope has been defined specifically for agricultural purposes by MacVicar *et al.* (1974) as follows: “An ecotope is a class of land defined in terms of its macro climate (including, where necessary, aspect), soil and soil surface characteristic (mainly slope) such that, in terms of the farming enterprises that can be carried out on it, the potential yield class for each enterprise or the production techniques needed for each enterprise, there is a significant difference between one ecotope and any other”. A more recent definition by Van der Watt & Van Rooyen (1995) reads as follow: “A particular habitat within a region. Used in South Africa for a class of land within which the variation of natural resources is insufficient to influence significantly the agricultural products that can be produced on it, their potential yield (both quantity and quality) and the required production techniques”. From the above mentioned definitions, it is clear that similar ecotopes are generally considered to have homogeneous soil, topography and climate (Hensley *et al.,* 2000).

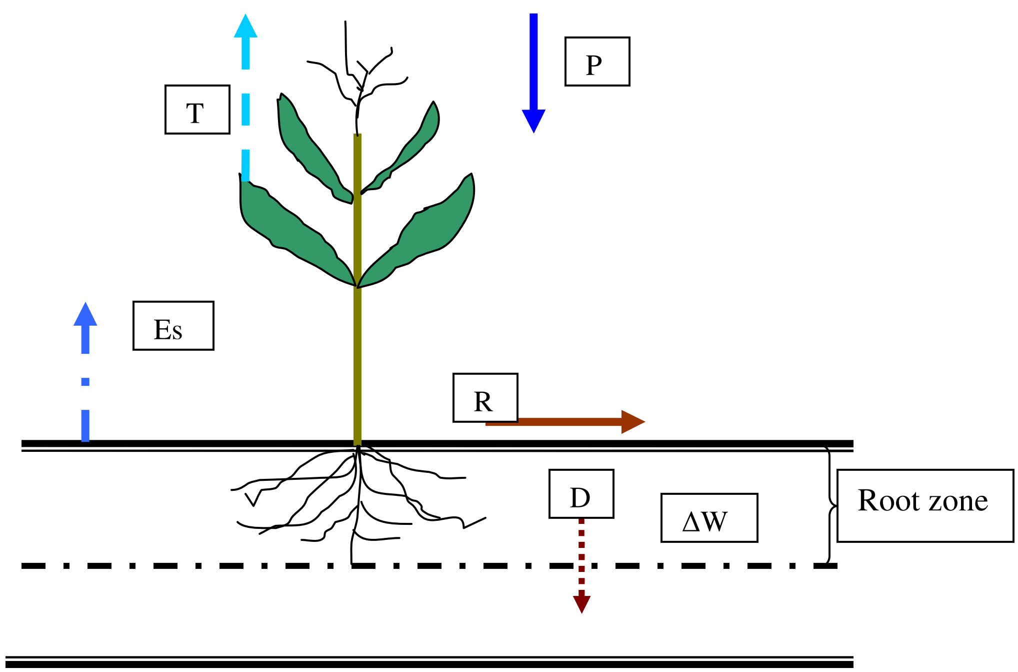
In agriculture the most important natural resource components determining the production potential of land are climate, soil and water. Currently, environmental degradation has become one of the most challenging problems to human beings universally. The destruction of forests for the production of different materials and for the expansion of croplands, encouraged by the constantly increasing population, remains a major environmental degradation threat. It is believed that global environmental change has been caused by the combined effect of the sum of multiple minor environmental degradations (Hillel & Rosenzweig, 2002 and Darkoh, 2003). Results such as flooding, desertification and similar processes are examples. These cause serious agricultural problems especially to those settled in arid and semi-arid regions of the world. Therefore, to manage and minimize the artificially induced harmful man made processes, it is important to understand and characterize the natural resources of each agro-ecosystem.

On the other hand, under utilized potential resources of an ecotope contributes towards unsustainable economy. It is therefore necessary to characterize the natural resources within a particular agro-ecosystem to determine its potential. Well characterized natural resources will promote wise and optimum utilization. This facilitates for the appropriate design and plan of research and development projects in agriculture.

Ecology is the branch of science that studies habitats and the interactions between living things and the environment. Agroecology is the science of applying ecological concepts and principles to the design, development, and sustainable management of agricultural systems. Therefore, an agro-ecosystem is a generalized system which encompasses and defines all the natural resources of an area. An important aspect is the dynamic relationships between the living things and the environment needed for sustainability.

2.2 Water deficits and crop production

Water deficit to crops is a common phenomenon in arid and semi-arid regions due to low and erratic rainfall (Biamah, Gichuki and Kaumbutho, 1993). The low precipitation problem is aggravated by the high evaporative demand of the atmosphere in these regions. Crops need water in different amounts during different stages of their growing period (Rushton, Eilers & Carter 2006 and Passioura, 2006). Generally, most of them have four different stages which require different amounts of water viz. (initial, developmental, middle and late stages). Crops use water mostly for transpiration, and relatively little for cell development. Water from the soil is used by plants not only to produce biomass yield through transpiration, but also serves as a nutrient transport system to the different parts of the plant. The natural system in which plants grow is termed the soil-plant-atmosphere continuum (SPAC) (Figure 2.1).



P = precipitation, T = transpiration, R = runoff, Es = soil evaporation, D = deep drainage and ΔW = change of root zone water content

Figure 2. 1 Diagrammatic representation of the SPAC water balance (adapted from Hillel, 1980)

Water also provides plant turgidity, which keeps the plant erect and therefore suitably positioned towards the sunlight (Kiazolu, Donker, Bitsang & Ramolemana, 1993).The guard cells of the stomata in the leaves need to be turgid to allow stomata to open and allow the important entrance of CO_2, needed for photosynthesis. The amount of water that is needed by crops during their whole growing season is known as crop water requirement or consumptive use (Allen, Pereira, Raes & Smith, 1998). It comprises the amount transpired (T) by plants plus that which evaporates (Es) from the soil surface (i.e. evapotranspiration). Many scientists have reported relationships between crop yield and water use by transpiration or evapotranspiration. They have discovered that water use by plants for T is directly related to the total dry matter yield of the crop (Tanner & Sinclair, 1983; Walker 1986; Hattingh, 1993 and Passioura, 2006).

In order for crops to produce the optimum dry matter yield they need to get the required amount of water during their growing period. They not only need to get the total consumptive use amount, but also need to have it suitably distributed among their different growth stages. Deficit of water from the total consumptive use, or deficit of water at one of the critical growth stages, will cause a reduction in the total dry matter yield (Passioura, 2006).

Table 2.1 shows the aridity index (AI) at Melkassa, Ethiopia and at Glen, South Africa respectively. Although both are semi-arid, the two climates have marked differences. Different agronomic strategies need to be selected in order to optimize productivity on these two ecotopes. The best growing season for summer crops at Glen is clearly November to March, whereas at Melkassa it is from June to September. In both cases about two thirds of this rainfall that fell during the best growing season is the only way in which sustainable crop production will be possible on these ecotopes. Crops with short growing seasons will be needed especially at Melkassa. Apart from the average climate at Melkassa during July and August ($AI > 1.0$) there is a well defined water deficit ($AI << 1.0$) during all the months at both ecotopes.

Table 2. 1 Aridity index (AI) at two semi-arid ecotopes in Africa (After Hensley *et al.,* 2000 & Melkassa Agricultural Research Center (MARC), Agrometeorology section)

Month	Melkassa/Ethiopia			Glen Bonheim/South Africa[1]		
	Rainfall (mm)	ETo (mm)	AI	Rainfall (mm)	Evap. (mm)[1]	AI
January	14	167	0.08	82	313	0.26
February	26	167	0.16	79	216	0.37
March	51	189	0.27	84	186	0.45
April	52	180	0.29	51	129	0.40
May	52	186	0.28	19	118	0.16
June	68	177	0.38	9	84	0.11
July	186	149	1.25	8	96	0.08
August	181	140	1.30	12	143	0.08
September	82	135	0.61	19	219	0.09
October	42	164	0.25	48	248	0.19
November	8	171	0.04	67	264	0.25
December	11	171	0.06	67	301	0.22
Total	**772**	**1994**	**0.39**	**545**	**2317**	**0.24**

1. Class A pan

Losses of rain water by runoff (R) and deep drainage (D) create an extra challenging water stress problem for crops in these regions. Soil nutrient supplies to crops are also greatly affected by soil water deficits since the nutrients are taken up in solution. A large fraction of crop roots are always located in the topsoil. This is therefore the layer that is subjected to intensive drying out due to water extraction for transpiration. It is however, also the layer subjected to severe water losses by Es. The result is that for cropping in semi-arid areas plants can easily be subjected to nutrient deficiencies at far higher nutrient levels in the soil than in humid regions. This aspect has possibly received too little research attention in the past. Stroosnijder (2003) working in semi-arid Burkina Faso, West Africa, on Ferric Lixisol soils on a 1.5% slope reported a non significant sorghum grain yield increase from water conservation (WC) treatment compared to the control treatment without WC practices. The WC treatment consisted of stone rows and grass strips without any type of fertilizer amendments. However sorghum grain yield increases of 180 % were obtained when similar WC practices were used in combination with compost or manure. The same WC treatments in combination with mineral fertilizers induced a 70% increase in sorghum grain yield. Similarly Ofori (1994) described fertilizer usage as one of the management practices for efficient soil water use.

According to him fertilizer usage enhances plant growth resulting in rapid vegetative growth with the advantage of decreased Es, R and soil erosion. He concluded that the efficient soil water utilization was due to root proliferation and good vegetative growth from the application of fertilizer. Ofori (1994) recommended that an appropriate balance needs to be maintained between the fertilizer level and the water availability. This aspect needs to receive more attention, especially in water stressed ecotopes. A considerable number of researchers have demonstrated the efficient utilization of fertilizers by crops when the soil water is improved by different WC techniques. Table 2.2 shows the improved grain yield of five maize varieties using fertilized WC practices on one of the semi-arid ecotopes of Ethiopia. Enormous improvements in yield of well over 100% were shown in the interaction when both limiting factors were ameliorated (Table 2.2).

Table 2. 2 Mean grain yield (kg ha^{-1}) of five improved maize varieties in the semi-arid eastern region of Ethiopia produced with and without fertilizer and water conservation practices; the experimental period was 1981 to 1983 (After Tamirie Mitiku, Huluf & Yohannes, 1984)

Varieties	Without WC		With WC		Influence of improved production on yield (%)*				
	Unfert. (A)	Fert (B)	Unfert. (C)	Fert. (D)	Fx	WCx	Fy	WCy	Fert. + WC
Alemaya composite	2815	5365	4812	7142	91	71	48	33	154
KCC	2556	4709	4283	6567	84	68	53	39	157
EAH-75	2597	4805	3601	5984	85	39	66	25	130
Ca 5	2285	3840	2889	4731	68	26	64	23	107
Bukuri	1972	3668	2911	4013	86	48	38	9	104
Mean	2445	4470	3699	5680	83	51			130

*Fx and WCx improvement by each factor on its own; i.e. [(B-A)/A * 100] or [(C-A)/A * 100]
Fy and WCy improvement by each factor when superimposed on the other factor; i.e. [(D-C)/C * 100] or [(D-B)/B * 100]

Kronen (1994) reported that increased water availability obtained by no-tillage practices lead to increased demand of nitrogen by cotton in Zimbabwe. Others, e.g. Passioura (2006), have reported negative consequences of too much fertilizer usage under water stressed conditions. In another study carried out in a semi-arid area of South Africa for four consecutive years, Van Averbeke & Marais (1992) showed that the critical plant density of maize increased from 4444 plants ha^{-1} to 50, 000 plants ha^{-1} through improved water storage in the root zone. They used the following treatments: rainfall only (mean 294 mm per season); irrigated to field capacity when 70 mm of water had been lost from a 1500 mm deep soil; irrigated to field capacity when a negative water balance occurred due to evapotranspiration. In accordance with the increased water storage and plant density, maize dry matter and grain yield were increased significantly (at $p = 0.05$ level) when water supply was increased from 349 mm to 650 mm. Plant density increased from 35,000 plants ha^{-1} to 75,000 plants ha^{-1}, while maize grain yield increased from 4599 kg ha^{-1} to 13,000 kg ha^{-1}. Thus, in water stressed areas, improving the water supply could also improve maize yield by allowing increased plant density.

Generally, all these studies have proved the negative consequences of a water deficit in semi-arid ecotopes. Improving the water content in the root zone by different water conservation techniques promotes improved crop yields. Improving the available soil water also helps to upgrade and improve different agronomic practices such as fertilizer rates and plant densities, which in turn contribute towards the maximum utilization, or improving an ecotope's potential.

2.3 Quantifying the water balance

The water balance equation provides insight regarding the relative portions of the rainfall that infiltrates into the soil and becomes available for root extraction (ΔW), evaporates from the surface (Es), flows over the surface and becomes lost as runoff (R), is lost by deep drainage (D), or is used for promoting crop growth by transpiration (T) (Figure 2.1).

The following is a simplified form (adapted from Hillel, 1982) appropriate for infield rainwater harvesting in dry areas where no water table is present within capillary rise distance from the bottom of the root zone and no significant lateral water movement (interflow) occurs in the root zone.

Water for yield = water gains – water losses

$T + Es = (P \pm \Delta W) - (R + D)$

$$T = (P \pm \Delta W) - (R + Es + D) \qquad (2.1)$$

ΔW is negative if it is more at harvesting than at planting. Bennie & Hensley (2001) used the subscripts 'g' or 'f' for each of the parameters in order to differentiate the growing season from the fallow period.

One can measure (T + Es) in the field together as evapotranspiration (ET). Measuring T alone in the field is difficult. All the other components can be measured or estimated in a satisfactory way. Tanner & Sinclair (1983) showed how to separate (T + Es) using the transpiration efficiency coefficient (k) which enables one to estimate T from the total plant biomass. In Gregory (1989) k is given by the equation:

$$k = \frac{N}{T} * \frac{Do}{D} \quad \text{kg ha}^{-1} \text{ mm}^{-1} \qquad (2.2)$$

Where N = total biomass (kg ha^{-1}), T = transpiration (mm); D = the mean saturation deficit of the atmosphere during the sunshine hours of the growing season and Do (1 kPa) is used to eliminate the awkward pressure dimension of k. Dividing N by 10 results in more suitable units for k, i.e. g m^{-2} mm^{-1}. Equation 2.2 is therefore used to express transpiration efficiency in a physically appropriate unit. Tanner & Sinclair (1983) in USA including an estimate of root biomass in their calculation reported a k value for maize of 9.5 g m^{-2} mm^{-1}. Using only above ground biomass in their calculations Walker (1986) in Canada, and Hattingh (1993) at Glen obtained k values for maize of 7.4 and 8.2 g m^{-2} mm^{-1}, respectively. Applying the Tanner & Sinclair (1983) factor of 1.2 for including root biomass to these two estimates yields values of 8.9 and 9.8 g m^{-2} mm^{-1} respectively, the average of the two giving the same value as Tanner & Sinclair. It seems therefore that 9.5 g m^{-2} mm^{-1} is a reasonable k value to use for maize until further research results are available.

2.4 Water productivity functions

Water productivity can be described by a variety of functions. Tanner & Sinclair (1983), Gregory (1989) and Bennie & Hensley (2001) defined water use efficiency (WUE) as:

$$WUE = \frac{Y}{ET} \qquad \text{kg ha}^{-1} \text{ mm}^{-1} \qquad (2.3)$$

Where Y = Crop yield (kg ha^{-1})

ET = Evapotranspiration (T + Es).

However, according to Gregory (1989), WUE in equation 2.2 is not strictly an efficiency term as the units of the numerator and denominator are not the same and therefore its value does not vary between 0 and 1 as in a true "efficiency" term. WUE as defined in equation 2.3, actually expresses the water productivity i.e. the crop yield obtained per each mm of water. Therefore, the term used by Passioura (2006) crop water productivity function (CWPF) appropriately suites the relationship in equation 2.3. On the other hand, the relationship of Y to (T + Es) is known as the crop production function, and is expressed by the linear equation:

$$Y = a\,(T + Es) + b \qquad (2.4)$$

It is considered that the intersection of the line described by the function with the horizontal (T + Es) axis describes the total amount of Es when R and D are negligible (Hanks, Gardner & Florian, 1969 and Passioura, 2006). CWPF, therefore, measures the ability of a particular crop to convert the available water into yield but does not take into account the total precipitation ($P_g + P_f$) during the growing and fallow periods (Hensley *et al.,* 2000). ($P_g + P_f$) includes water that may be lost due to R, Es and D (see Figure 2.1). Gregory (1989) used the water balance equation to relate the yield to the total amount of rainfall during the growing period of a crop. Since CWPF gives only the insight of the biological ability of a particular crop or genotype to convert the water available for T + Es into yield, it has a limitation regarding its use to evaluate different water conservation production techniques.

To study the benefits of different water conservation production techniques, Hensley, Snyman & Potgieter (1990) proposed a holistic type of approach to rainwater productivity which takes into account all the losses (R + Es + D) during the growing and fallow seasons. It is known as precipitation use efficiency (PUE).

$$\text{PUE} = \frac{Y}{P_g + P_f\,(Q_{h(n-1)} - Q_{h(n)})} \qquad (2.5)$$

Where, PUE = precipitation use efficiency (kg ha^{-1} mm^{-1})

P_g = precipitation during the growing season (mm)

P_f = precipitation during the fallow season (mm)

$Q_{h(n-1)}$ = water content of the root zone at harvest of the year n-1

$Q_{h(n)}$ = water content of the root zone at harvest of the year n.

Hensley *et al.* (1990) expanded equation 2.5 by including equation 2.2 and Mathews & Army's (1960) equation describing rainfall storage efficiency (RSE_f) during the fallow season; i.e. :

$RSE_f = \frac{W_{p(n)} - W_{h(n-1)}}{P_f}$ to get equation 2.6

$$PUE = \frac{Y}{Eg + Dg + Rg + (Y / WUE) + (W_{p(n)} - W_{h(n-1)} / RSE_f)} \qquad 2.6$$

Where Eg = evaporation from the soil during the growing season

Dg = deep drainage during the growing season

Rg = runoff during the growing season

Equation 2.6 shows that increasing WUE and RSF_f will lead to increased PUE and that decreases in Eg, Dg, and Rg result in increases in PUE.

In semi-arid areas the term ($Q_{h(n-1)} - Q_{h(n)}$) in equation 2.5 is generally very small compared to Pg and P_f. It also loses its significance when WC field experiments are conducted over a number of seasons on the same ecotope. Because of the extreme rainfall variations that occur in semi-arid areas field experiments to test WC practices need to be conducted over a number of years. Where results of such experiments are available the following simplified "multiple year" form of equation 2.7 is appropriate (Botha, 2007). It has also been considered convenient to exclude the undesirable word "efficiency" and use rain water productivity (RWP) instead.

$$\mathbf{RWPn} = \frac{\sum Y}{\sum Pn} \quad \mathbf{(2.7)}$$

Where RWPn = rain water productivity over a year

ΣYn = sum of grain yields over n year

ΣPn = total rainfall over n year

Table 2.3 and 2.4 show result reported by Hensley *et al.* (2000) and Botha (2007) regarding WC techniques and RWP. Table 2.3 presents CWPF and RWP of maize under different water conservation techniques at Glen Bonheim ecotope-Onrus ecotope, South Africa. The result shows an increase in CWPF and RWP by using IRWH described as water harvesting basin (WHB) and water harvesting basin with mulch (WHBM). Decreasing one or more of the losses (R, Es, and D) resulted in an increase of T and Es on WHB and WHBM treatments. Thus, increasing T means increase of grain yield of maize which in turn shows increase in CWPF and RWP. When there are no losses in R and D, the two terms crop water production function calculated based on evapotranspiration ($CWPF_{ET}$) and the rain water productivity during the growing season (RWPg) have the same value. On the other hand, when there is a loss due to R, D, or both, RWPg values are lower than $CWPF_{ET}$. This shows that RWPg takes into account the losses. The values for crop water productivity function calculated based on transpiration ($CWPF_T$) are large and do not show a trend to increase beyond some upper limit value (in this case ~ 27 mm ha^{-1} mm^{-1}) during 1997/98, even though T continued increase. On the other hand, RWPg in the same season keeps on increasing with the reduction of the losses by IRWH practices. This shows the advantage of RWPg for evaluating water conservation (WC) technologies. Since IRWH practices (WHB & WHBM) improved the stored soil water (ΔW), there was an increase in Es, especially during 1998/99 cropping season.

Table 2. 3 Water balance, CWPE and RWP data at Glen/Bonheim, South Africa taking maize grain yield

Season	Treatment*	Water productivity calculated over 3 years (kg ha^{-1} mm^{-1})			
		$CWPF_{ET}$	$CWPF_T$	RWP_g	RWP_{fg}
1996/97	TST (A)	6.3	24.3	6.1	ND
	WHB (A)	6.0	21.5	6.0	ND
1997/98	TST (A)	7.4	26.1	6.5	ND
	WHB (A)	8.9	26.9	8.6	ND
	WHBM (A)	10.0	24.9	9.6	ND
1998/99	TST (A)	-	-	-	-
	WHB (A)	0.13	0.80	0.13	0.08
	WHBM (A)	0.45	2.32	0.45	0.28
	WHB (B)	1.86	7.87	1.86	0.68
	WHBM (B)	2.17	7.66	2.17	0.87

* TST = conventional total tillage
TSTM = conventional total tillage with mulch
WHB = IRWH and basin tillage
WHBM = IRWH and basin tillage with mulch
(A) or (B) indicates annual, or bi-annual (long fallow) planting respectively

Table 2. 4 Various water use efficiencies for maize as affected by mulch treatments at Glen Bonheim ecotope (After Botha *et al.,* 2003)

CWPF indicators	Season	Treatment*				
		ObBr	ObOr	ObSr	SbOr	Mean
RSE (%)	99/00	57[a]	42[a]	46[a]	51[a]	49
	00/01	-4[a]	-23[b]	-13[ab]	-15[ab]	-14
	01/02	26[a]	51[a]	25[a]	25[a]	32
	Mean	26	23	19	20	22
RWP_{fg}	99/00	8.7[a]	9.7[a]	10.8[a]	9.5[a]	9.7
(kg ha^{-1} mm^{-1})	00/01	5.9[a]	7.5b[c]	7.9[c]	6.9[b]	7.1
	01/02	4.9[a]	4.9[a]	5.3[a]	4.9[a]	5.0
	Mean	6.5	7.4	8.0	7.1	7.3
**RWPa	99/00	9.0[a]	9.1[a]	10.3[a]	9.1[a]	9.4
(kg ha^{-1} mm^{-1})	00/01	5.0[a]	5.7[bc]	6.0[c]	5.3[b]	5.5
	01/02	5.4[c]	5.5[a]	5.9[a]	5.4[a]	5.6
	Mean	6.5	6.7	7.4	6.6	6.8
$CWPF_{ET}$	99/00	10.9[b]	12.0[ab]	13.2[a]	14.4[b]	12.0
(kg ha^{-1} mm^{-1})	00/01	9.4[a]	12.4[bc]	12.9[b]	11.2[ac]	11.5
	01/02	9.6[a]	10.0[ab]	10.7[b]	9.7[ab]	10.0
	Mean	10.0	11.5	12.3	10.8	11.2

* ObBr = IRWH with organic mulch in basin and a bare runoff area
ObOr = IRWH with organic mulch both in basin and runoff area
ObSr = IRWH with organic mulch in basin and stone mulch on the runoff area
SbOr = IRWH with stone mulch in basin and organic mulch on the runoff area
**RWPa = RWP annual

In another experiment, IRWH practice was combined with different mulch materials in order to reduce water loss by Es and R (Table 2.4). The result shows that RWPa values between 5 and 10.3 with an increasing trend in the order of ObSr > ObOr > SbOr > ObBr. Besides, the experiment shows the advantage of using mulch on the runoff strip area. Annual rain water productivity (RWPa), during the season 00/01 showed a significant deference of ObSr than ObBr. RWP_{fg} and $CWPF_{ET}$ showed the same increasing trend as that of RWPa but without non significant difference among the treatments except during the season 00/01. Generally, the experiment showed that the higher values of the water production functions when IRWH practice is further improved with mulch materials (Botha *et al.*, 2003).

In arid and semi-arid regions of the world where water is the major limitation factor for rainfed agriculture, many traditionally as well as improved WC tillage practices are in use. Some of the traditional as well as the introduced WC tillage practices were reported by many studies to improve RWP and crop yield in water deficit marginal areas.

Hensley *et al.* (2000) reported a maize grain yield increase of 13% and 35% in a study conducted during 1996/97 and 1997/98 respectively, on IRWH treatment compared to the conventional tillage treatment at Glen Bonheim ecotope. The yield increase during 1997/98 is also significant at p = 0.05 level. At Glen Swartland ecotope, during the two years maize grain yield increase on IRWH is 69% and 43%, and both are significantly (at p = 0.05 level) higher than the conventional tillage treatment. Similarly, sunflower and sorghum grain and biomass yields showed that a significant increase than the conventional treatment. Sunflower grain yield increased by 15% and 32% during 1996/97 and 1997/98 cropping season respectively. Correspondingly, at Swartland sorghum yield increased by 4% and 68%.

Bennie, Strydom & Vrey (1994) studied the effect of different tillage practices on the yield, RWP_{fg} and ET of maize, wheat and grain sorghum under optimal soil fertility condition for four years on sandy Bainsvlei soils in South Africa. The tillage treatments were conventional mouldboard ploughing and shallow time harrowing leaving the surface bare (CT), shallow sweep tillage retaining crop residue on the surface (SM) and no-tillage with chemical weed control (NT). Their result for both wheat and grain sorghum showed that higher yield and ET on the more sandy Bainsvlei soil. Both yield and ET were in the order of CT > SM > NT for both wheat and grain sorghum. Eventually, CT demonstrated the best performance in improving RWP in the prevailing ecotope. However, according to them, the less RWP by SM and NT was attributed by the limited root growth of the crops. On the other hand, since the introduction of tied ridging in water stressed ecotopes a lot of success stories were reported elsewhere (Kronen, 1994; Gicheru *et al*., 1998; Temesgen *et al*., 2001; Berry & Mallett, 1988) Tied ridge, by its basin like shape, trap all the rainfall dropped inside the basin (can be assumed as small closed watershed). If rainfall is not too much to overflow the ridges, the water will be hold inside the basin (tied ridge) ponded till consumed by the crop, lost by evaporation and/or drain dawn beyond the root zone.

Kronen (1994) reported that in Zimbabwe tied ridge increased the grain yield and RWP by 49% and 29% respectively compared to the traditional flat planting system. She reported that tied ridges (furrow) was advantageous to conserve and concentrate water and results good crop yield response especially in high clay content soils such as Vertisols, paragneiss and alluvium soils. In contrary, she also reported that in lighter soils with low water retention ability, the advantage was not more evident than the clayey soils. On the other hand, Gicheru *et al.* (1998) reported the ineffectiveness of tied ridges in clayey Ultisols in Kenya semi-arid region with annual rainfall of 711 mm. It is common to find a contradictory reports regarding WC efficiency in tied ridging efficiency in WC. For instance, Kronen (1994) in her review work reported that tied ridging is effective on light soils if combined with appropriate fertilizer rate and rainfall amount. For driest rainfall region, she reported average potential yield increase of 19%. She also showed 20% profit increase compared to the usual flat planting. For the relatively wetter zone, it obtained 49 and 43% increase in yield and profit respectively. From the different research results reported one can understand that some tillage practices including tied ridges are sensitive to the type of soil and rainfall amount as well as the distribution.

2.5. Water loss processes and production techniques to reduce them

2.5.1 Evaporation from the soil surface (Es)

The estimation of Es is found to be more complicated than the other water balance components due to:

a. Different canopy coverage of various crops and growth stages as well as different plant densities.
b. Soil surface conditions (e.g. Crusting by sealing the soil surfce, self mulching, cracking) and soil colours.
c. Different soil textures, which react differently due to their different hydraulic conductivity.
d. Variations in the evaporative demand of the atmosphere.

A number of different models have been developed to estimate Es. Ritchie (1972) proposed the following equation to predict Es from a bare soil:

$$\Sigma \text{ Es} = \Sigma \text{ Ei} + \alpha\ (t - t_i)^{1/2} \qquad \text{for } t > t_i \qquad (2.8)$$

Where Σ Ei = cumulative evaporation during the 1st phase = Σ Ep

Σ Ep = cumulative potential evaporation (mm)

t = timing after wetting (days)

t_i = period of phase one (days)

α = slope of the relationship for phase 2 between Σ Es and $t^{1/2}$

The 1st part of the equation (ΣEi) estimates the 1st stage of the evaporation during which Es is considered to be controlled solely by the evaporative demand of the atmosphere (Ep). The 2nd part of the equation estimates the second stage of soil evaporation. In this stage, Es is lower than Ep because of continually decreasing water content which causes a continually decreasing unsaturated hydraulic conductivity of the soil. Thus, Es is controlled during the 2nd phase mainly by the hydraulic properties of the soil. Ritchie (1972) reported α values of 5.08, 4.04, 3.50 and 3.34 mm $d^{-1/2}$ for Adelanto clay loam, Yolo loam, Houston black clay and Plainfield sand respectively. The mean of these α values, covering a wide range of soils is 4.0. Hensley *et al.* (2000) report α values of 2.75

and 6.57 mm $d^{-1/2}$ for Glen Bonheim and Glen Swartland ecotopes in South Africa respectively. The results obtained are in the same order as Ritchie's.

Stroosnijder & Koné (1982) and Stroosnijder (2003) developed a modified form of the Ritchie (1972) model for Burkina Faso and some parts of western Africa. They showed that cumulative soil evaporation (Σ Es) between showers in the growing season of a crop is described by the simple model:

$$\Sigma Es = f(LAI) * PEVAP + 3.5 * (t^{1/2} - 1) \quad (2.9)$$

Where f (LAI) = a correction term depending on the leaf area index of the cover

PEVAP = the potential evaporation (mm)

t = the number of days since the previous rain (days)

The 3.5 value in equation 2.9 is the equivalent of Ritchie's α value because it was found that this value was fairly constant for a range of soils with textures from sand to clay. Stroosnijder (2003) reported Es values of 2.5 mm d^{-1} and 1.5 mm d^{-1} for bare soil and for a soil with a vegetation cover (LAI = 1) respectively for the South-Sahelian region.

Hoffman (1997) compared four evaporation equations and found that the Richie (1972) model best predicted cumulative ΣEs using his measuring procedure. He recommended a slightly adapted version of the Ritchie model as:

$$\Sigma Es = [47.0497 (\theta_i - \theta_o) + 0.623]\, t^{1/2} \quad (2.10)$$

Where t = time after starting (days)

θ_i = soil water content at the start of the measurement (v/v)

θ_o = the soil water content at which Es ceases (v/v)

Hensley *et al.* (2000) tested equation (2.10) and found that the equation predicted ΣEs reasonably well on Glen Swartland and Glen-Bonhein ecotopes when θ_i was taken as the field determined drained upper limit for 0-300 mm layer. Hoffman (1997) reported that Es remained constant for only a few hours after wetting. He described this period as the constant evaporation stage. In another experiment, Hensley *et al.* (2000) found that the 1st stage evaporation ranged between 2 and 5 days on the Bonheim and Swartland ecotopes, depending on their different soil textures.

There are many reports from arid and semi-arid regions where the highest water loss was through Es (Bennie *et al.,* 1994; Berry & Mallett, 1988; Hoffman, 1997, Hensley *et al.,* 2000; Bennie & Hensley, 2001 and Passioura, 2006). Bennie *et al.* (1994) reported Es losses of 60 – 75% of the rainfall in South Africa under semi-arid climatic conditions from bare soils during a fallow period. They measured Es from three tillage treatments on winter wheat and summer maize cropping systems: conventional mouldboard planting (CT); shallow sweep tillage retaining crop residue on surface (SM); and no tillage (NT). Their results did not show a significant difference in Es from the different treatments over four years of experimentation. Bennie & Hensley (2001) ascribed the high evaporation loss from the SM treatment to be due the low amount of residue retained (30%) on the surface. Their results showed that Es was higher when the top soil was higher in clay. Hoffman (1997) in a lysimeter experiment also reported higher Es losses on soils with higher silt plus clay contents.

Hensley *et al.* (2000) reported Es losses of 60% of ET, or more on experiments carried out on the Glen Bonheim ecotope and Glen Swartland ecotopes in South Africa on conventional (TST) and IRWH tillage (Figure 1.1) practices (Table 2.4). The IRWH treatments are designed as WHBM and WHB in Table 2.5, indicating with and without mulch in the basins, respectively.

Table 2. 5 Experimental data of T and Es at two ecotopes in South Africa on maize crop (After Hensley *et al.,* 2000).

Season	Treatment *	Glen Bonheim ecotope					Glen Swartland ecotope				
		Es	T	Es + T	% Es*2	Es/T	Es	T	Es + T	% Es	Es/T
1996/97	TST	269	94	363	74	2.86	252	83	335	75	3.04
	WHB	273	106	379	72	2.58	259	102	361	72	2.54
1997/98	TST	326	120	446	73	2.72	327	117	444	74	2.79
	WHB	322	158	480	67	2.04	327	161	488	67	2.03
	WHBM	280	188	468	60	1.49	304	196	500	61	1.55
1998/99	TST	218	23	241	91	9.48	263	37	300	88	9.81
	WHB	230	44	274	84	5.23	215	61	276	78	3.52
	WHBM	237	57	294	81	4.16	238	62	300	79	3.84

*1 Defined similarly to table 2.3
*2 Es as % of (Es+T)

Es varies between 61 and 91% depending on the treatment and climatic conditions during the growing season. All the Es's values are large accentuating the importance of water losses by this process. Es losses were always lower from the IRWH treatments than from

TST. This shows that IRWH, besides reducing runoff to zero also minimizes the loss of water by Es compared to the conventional tillage practices. In the same experiment, IRWH practices improved RWP (Table 2.3) compared to the conventional tillage treatment. To improve RWP in semi-arid ecotopes it is clear that Es needs to be minimized.

Mulches and crop residues also proved to reduce soil water loss (Es) by protecting the soil from direct sunshine radiation (Hillel, 1980; Berry & Mallett, 1988; Hensley *et al.,* 2000 and Botha *et al.,* 2003). In a lysimeter experiment carried out in the Sudano-Sahelian zone of Burkina Faso with a Chromic Luvisol, it was found that Es from a bare soil was significantly ($p < 0.0001$) more than from the mulched treatment with 6 Mg ha^{-1} dry matter (Stroosnijder, 2003). Hoffman (1997) suggested a minimum of 80% shading in order to significantly decrease the cumulative evaporation within the first 10 days after wetting under dry climatic conditions.

Berry & Mallett (1988) after conducting an experiment on interaction of tillage with residue cover on a well drained clay loam soils, found a high water reserve in the mulched soils throughout the maize growing period. But they reported insignificant grain yield difference. This probably attributed by the lower plant population on mulched soils due to the poor performance of the planter which was not designed for mulched soils. They also concluded that mulching was only effective in reducing stage-one evaporation. If the rainless period exceeds more than 2 weeks, the evaporation on mulched soils often exceeds from well ploughed bare soils. In addition, Kronen (1994) and Gicheru *et al.* (1998) reported low seedling emergence and poor crop stand on mulched plots due to cooler and wetter micro climate condition created by the mulch. They also reported low nitrogen fixation by soil micro flora.

A study conducted by Hensley *et al.* (2000) on Glen Swartland and Glen-Bonhein, South Africa showed the advantage obtained by applying mulch on IRWH system. They showed an increase of maize grain yield by 10% and 76% during 1998 and 1999 cropping season respectively than the non–mulched basin treatment of IRWH. Similarly, Botha *et al.* (2003) showed that IRWH when combined with different mulch materials improved T and reduced Es (Table 2.6).

Table 2. 6 Cumulative evaporation (Es) and transpiration (T) for the fallow period (Fp) and growing period (Gp) on IRWH treatments planted with maize as influenced by mulching at Glen Bonheim ecotope, South Africa (After Botha *et al.,* 2003).

Period	Parameter	Season	Treatment*				
			ObBr	ObOr	ObSr	SbOr	Mean
Fp	Es	99/00	82[a]	70[a]	69[a]	62[a]	71
		00/01	158[a]	163[a]	143[a]	151[a]	154
		01/02	330[a]	345[a]	341[a]	316[a]	333
		Mean	190	193	184	176	186
Gp	T	99/00	84[a]	82[a]	88[a]	80[a]	84
		00/01	99[a]	115[b]	123[b]	113[b]	113
		01/02	113[a]	123[a]	121[a]	116[a]	118
		Mean	99	107	111	103	105
	Es	99/00	233[a]	212[a]	212[a]	228[a]	221
		00/01	171[b]	111[a]	127[ba]	130[ba]	135
		01/02	230[a]	208[b]	217[ba]	222[ba]	219
		Mean	211	177	185	193	192
	T + Es	99/00	317[a]	294[a]	300[a]	308[a]	305
		00/01	270[a]	226[a]	250[a]	243[ba]	247
		01/02	343[b]	331[a]	338[ab]	338[ab]	338
		Mean	310	284	296	296	

1. ObBr = IRWH with organic mulch in basin and a bare runoff area
2. ObOr = IRWH with organic mulch both in basin and runoff area
3. ObSr = IRWH with organic mulch in basin and stone mulch on the runoff area
4. SbOr = IRWH with stone mulch in basin and organic mulch on the runoff area

They also showed that on IRWH treatments, when both the basin as well as the runoff strip surfaces was covered with mulches, Es values are reduced significantly compared to the bare runoff strip (ObBr) during the season 01/02. Generally, they found that mean values of the same treatments of ObSr and ObOr reduced Es by 10% and 12%, respectively, compared to ObBr. The ObBr treatments produced the highest T + Es in all the seasons while ObOr had the lowest.

2.5.2 Runoff loss (R)

Runoff is an important water balance component in semi-arid areas. Studies show that runoff from a particular storm is mainly a function of the soil infiltration rate, surface storage and storm intensity (Morin *et al.,* 1983 and Lēonard, Ancelin, Ludwig & Richard 2005). Studies carried out in arid and semi arid regions show a runoff loss of up to 50% of the rainfall can occur on bare untilled lands (Haylett, 1960 and Stroosnijder, 2003). Especially on bare tilled soils R is aggravated by crusts where soils are susceptible to crust formation (Morin & Benyamini, 1977; M & C, 1980; Morin *et al.,* 1984; Rao, Steenhuis, Cogle, Srinivasan, Yule & Simith, 1998 and Hensley *et al.,* 2000).

Haylett (1960) measured runoff from runoff plots on a red, well drained sandy loam soil, with a slope of 3.8%, at Pretoria, South Africa for 27 years (1931-1957). Two of the many treatments were:

a) Bare, flat, crusted, untilled plots; and
b) Annual maize with conventional tillage.

At the end of the experiment it was found that the mean annual runoff expressed as a percentage of the mean annual rainfall amounted to 49% and 27% for the two treatments respectively. The importance of runoff as a water loss, and the potential it offers being harnessed beneficially by means of the IRWH water conservation technique (Figure 1.1) is accentuated.

On an experiment carried out in central Senegal on sandy loam soils with a surface slope of 1%, Babacar, Esteves, Van der Vaer, Lapetite & Vauclin (2005) found a runoff coefficient (ratio of total R to P during the experiment) ranging between 8 and 24% on plots ploughed perpendicular to the slope while the equivalent value for plots ploughed parallel to the slope was between 18 and 61%. They used simulated storms having cumulative amounts of between 34 and 179 mm, and 40 to 163 mm per event for perpendicular and parallel ploughed plots respectively. Others like Rao *et al.* (1998) and Lēonard & Andreux (1998) observed runoff coefficients of about 30% in the semi arid tropics of India and Mediterranean regions respectively. Rao *et al.* (1998) studying Alfisols of the semi-arid tropics of India reported runoff of 30% of the annual rainfall on a bare surface, 16.5% from a surface amended with farmyard manure, and 9.5% on rice straw covered surfaces. A study carried out at Cedara in South Africa on a highly weathered soil, very low in smectites and high in organic carbon (> 1.8%), the mean runoff over 10 consecutive years (1983 – 1993) on a bare fallow treatment was found to be 129 mm from a mean rainfall amount of 843 mm (i.e. R = 15.3% of P). The rainfall pattern is described as non intense (Gibbs, 1993).

Remains of crop residue and mulches were proved to reduce the direct raindrop impact on the soil surface and prevent soil crusting which in turn decreases runoff and increases rainwater infiltration. Stroosnijder (2003) reported 35% less R on plots mulched with 6 Mg ha^{-1} compared to non-mulched ones in semi-arid Africa. Snyman & Van Rensburg (1986) reported that runoff from veld was more affected by basal cover than slope. In their experiment carried out on a Valsrivier soil form near Bloemfontein there was an insignificant difference in runoff on slopes ranging between 2 – 6%. On the other hand, they reported a significant ($P \leq 0.01$) relationship between basal and canopy cover and runoff. Similarly, in a recent study carried out in northern Ethiopia on steep slopes (> 20%) Descheemaeker, Muys, Nyssen, Poesen, Raes, Haile & Dekkers (2006) found that runoff become negligible when vegetation cover exceeds 65% of the surface.

Table 2.7 shows the effect of mulch in soil final infiltration rate (I_f) and infiltrated rain. The mulched soil infiltrated the entire rainfall amount while the bare soil infiltrates 55.4 and 1.1% of the rainfall during the first and second storms respectively. It also shows the increase of runoff with the progressive increase of crust strengthening and stability. Lang & Mallett (1984) reported in an experiment conducted at Cedara on a Hutton Doveton clay loam soil on 3.5% slope, a minimum of 30% residue ground cover was able to keep runoff and soil loss within the limit of acceptable range. They also found with the same rate of residue ground cover that infiltration rate and percent of infiltrated water increased by 25.6 and 22% respectively compared with zero residue ground cover.

Table 2. 7 Infiltration of Bare and Mulched soil for first and second storms after 60 minute of rain (After Morin & Benyamini, 1977)

	Soil Type	I_f (mm hr^{-1})	Infiltrated water (mm)
First Storm	Bare soil	8	31
	Mulched soil	56*	56
Second Storm	Bare soil	5	6
	Mulched soil	56*	56

* = I_f = Rainfall

More over, Botha *et al.* (2003) showed that a 37% and 35% decrease of runoff coefficient on a runoff plot mulched with organic mulch compared to a bare one at the Glen Bonheim ecotope and Glen Swartland ecotope respectively (Table 2.8). In another study carried out at Bloemfontein, on a sandy soil of the Bainsvlei form Amalia family, Woyessa & Bennie (2004) found significantly higher runoff on no till plots compared with mulched and deeply ploughed plots.

Du Plessis & Mostert (1965) measured runoff and soil loss generated by natural rainfall at Glen for 18 years (1937-1955) on runoff plots. There were 12 different treatments which included different vegetation covers and tillage practices. The two treatments of most interest for the study were: (a) a flat bare crusted surface which was never tilled; and (b) annual maize with conventional tillage. At the end of the experiment it was found that the average annual runoff expressed as a percentage of the annual average rainfall amounted to 31.9% and 8.5% for the two treatments respectively. The slope of the site where the old runoff plots were located found to be 5%. The soil was classified as loamy fine sand Tukulu Dikeni (Soil Classification Working Group, 1991 & Zere, 2003).

Zere, Van Huysteen and Hensley (2005) used the rainfall-runoff data of Du Plessis & Mostert (1965) to calibrate and validate the M & C (1980) runoff model. Tsubo, Walker & Hensley (2005) used 30 years of daily rainfall and rainfall intensity data from Bloemfontein to calibrate and validate the stochastic model of Bonta (1997) for predicting rainfall intensity from daily rainfall data. Because of the proximity of Glen to Bloemfontein (20 km) Zere *et al.* (2005) assumed that the validated model for Bloemfontein would also be valid for Glen rainfall. They used the model to predict rainfall intensity for the 18 years of the Du Plessis & Mostert experiment. The information obtained from the soil profile description and analytical data (Zere, 2003) was used to make a first approximation of the parameter values needed by the M & C (1980) runoff model. A portion of the runoff data and the generated rainfall intensity during the period runoff was collected was used to calibrate the model and the remaining used for validation. The model predicted runoff from the bare and cultivated plots with R^2 of 0.74 and 0.68, respectively. In terms of IRWH the bare plots can be considered to represent the runoff strip in Figure 1.1, and the cultivated plots the condition pertaining to conventional tillage. The value of the exercise described is therefore that it provides a procedure for estimating runoff for any ecotope for which the rainfall data are available, and therefore contributing towards estimating yield increases possible with IRWH compared to conventional tillage practice.

Hensley *et al.* (2000) in a study carried out for three seasons (1996/97 to 1998/99) found runoff coefficients of 19.5%, 13.7% and 13.1% from a total rainfall of 452 mm, 589 mm and 462 mm respectively on a treatment which simulated the no-till crusted surface (minimum surface storage or MSS) of the runoff strip area in Figure 1.1 on the Glen Bonheim ecotope. The equivalent results on the nearby Glen Swartland ecotope were 31.2%, 18.0% and 13.0% (Table 2.8). R on the conventional treatment (total soil tillage or TST) is very low, the maximum not exceeding 7.3% of the total rainfall.

The decreased runoff on this treatment is due to increased surface storage caused by a relatively rough surface caused by annual cultivation. They also reported an accentuated difference between the two treatments (e.g. 1998/99) when most of the storms were less than 10 mm.

Hensley *et al.* (2000) showed that ex-field runoff was reduced to zero on IRWH (Figure 1.1) tillage practices (WHB & WHBM) compared to the conventional tillage practice (TST) (Table 2.3). They found ex-field R of 14 mm and 33 mm on the TST treatment in the 1996/97 and 1997/98 seasons, respectively. Similar R results were obtained on the Glen Swartland ecotope.

Table 2. 8 Runoff plots on the Glen Bonheim ecotope and Glen Swartland ecotopes (After Hensley *et al.,* 2000)

Ecotope	Soil tillage treatment	1996/97			1997/98			1998/99			Mean
		P[1] (mm)	R (mm)	R[3] (%)	P (mm)	R (mm)	R (%)	P (mm)	R (mm)	R (%)	R (%)
Bo	MSS[2]	452	88	19.5	589	80	13.7	462	60.7	13.1	15.4
	TST	452	ND[4]	-	589	33	5.6	462	7.4	1.6	3.6
Sw	MSS	452	141	31.2	589	106	18.0	462	59.3	12.8	20.7
	TST	452	ND	-	589	43	7.3	462	2.4	0.005	3.9

1. Precipitation
2. Minimum surface storage, which simulates the no-till crusted surface on the IRWH runoff strip in Figure 1.1
3. Runoff as % of precipitation
4. Not determined

Table 2.9 presents results obtained by Botha *et al.* (2003) on the Glen Bonheim and Glen Swartland ecotopes in South Africa. In both ecotopes, bare crusted soil produced the highest runoff coefficients followed by stone and organic mulch treatments. On the Bonheim, the average R over the three seasons was 43%, 25% and 6% on bare, stone mulch and organic mulch treatments respectively. Correspondingly, at Swartland R was 39%, 20% and 4%.

Table 2. 9 Rainfall and in-field runoff on 2m by 3m runoff plots on two Glen ecotopes with three surface treatments (After Botha *et al.,* 2003)

Ecotope	Glen Bonheim ecotope							Glen Swartland ecotope						
Season	Rain	Runoff						Rain	Runoff					
		Bare		Stone		Organic			Bare		Stone		Organic	
	mm	mm	%[1]	mm	%[1]	mm	%[1]	mm	mm	%[1]	mm	%[1]	mm	%[1]
99/00	479	110	30[2]	59	12	16	3	489	167	38[3]	80	16	11	2
00/01	544	255	47	175	32	26	5	544	214	39	124	23	16	3
01/01	591	280	47	168	28	54	9	567	228	40	115	20	32	6
Average	538	215	43	134	25	32	6	533	203	39	106	20	20	4

1. Runoff as % of rainfall
2. Percentage (%) based on a total rainfall of 362.6 mm
3. Percentage (%) based on rainfall of 444 mm

Runoff on semi-arid ecotopes therefore contributes a great deal towards precipitation water losses. To improve RWP it is therefore necessary to minimize runoff. Runoff can be reduced by implementing water conserving agronomic and tillage practices. Using the

IRWH technique runoff can be reduced to zero (e.g. Table 2.3). This improves RWP significantly (Tables 2.3 and 2.5).

2.5.3 Deep drainage (D)

Deep drainage (D) is one of the water loss processes. High D losses from the root zone have a significant effect on RWP and crop yield (Passioura, 2006). D can only occur when soil water content of the root zone (θr) exceeds drainage upper limit (DUL) (Hensley, Hatting & Bennie, 1993; Hensley *et al.,* 2000 and Botha *et al.,* 2003). D can be measured using lysimeter and soil water measuring equipments such as neutron probe and TDR. Hensley *et al.* (1993) described how D rate of a root zone can be estimated by determining the drainage curve of the root zone starting from saturation. The procedure to determine the drainage curve and its equation is described in detail in Chapter 3.

DUL of a soil is the highest field measured water content of a soil layer after it has been thoroughly wetted and allowed to drain until drainage from the soil layer becomes practically negligible, i.e. when the water decrease in the layer is about 0.1 to 0.2% per day (Ratliff, Richie & Cassael, 1983). LL is the lowest field measured water content of a soil after plants have stopped extracting water and are at or near premature death, or has become dormant as a result of water stress (Ratliff *et al.,* 1983). It can be estimated by the equation:

PAW = DUL – LL, where PAW is plant available water.

In cropped fields, DUL is affected by the root water extraction rate. To compensate for the extra amount of extracted by roots before D to occur, Hattingh (1993) introduced the concept of crop modified upper limit (CMUL). CUML value is greater than DUL. According to Hattingh (1993), CUML concept is based on equating the drainage rate of the root zone as a whole in relation to the evapotranspiration rate (ETr) of the growing crop. CMUL therefore expressed quantitatively by integration of the equation which describes the drainage curve as:

Evaporation rate = dy/dt (equation 3.3), where dy/dt = drainage rate.

CMUL of different crops can be computed by finding the time at which ETr of a crop equals to the drainage rate (derivative of equation 3.3). This gives the time at which soils acquiring the CMUL value on the drainage curve. Therefore, substituting the value of time (t) in the drainage curve equation (equation 3.3) gives CMUL value.

According to Hensley *et al.* (2000), calculating CMUL with the concept of Hattingh (1993) is misleading, because it calculates CMUL for the whole root zone. Hensley *et al.* (2000) found higher root density and root water extraction rates for maize in the upper soil layer of the root zone on the Glen Bonheim ecotope, and both decreasing with depth. At Glen Bonheim ecotope during 1997/98, between 65 and 79 days after planting, they found water extraction rates of 2.3, 2.4, 1.1 and 0 mm day^{-1} to the soil layers 0-300, 300-600, 600-900 and 900-1200 mm, respectively. The CMUL to the whole depth was 37 mm above DUL. They reported that D to next layer occurs only when θr value of the layer exceeds CMUL. Therefore, they suggested a modification to the previous concept of CMUL. They recommended CMUL to be calculated for each layer separately. They also concluded that D not necessarily starts when θr > DUL but rather it occurs when θr > CMUL.

Bennie *et al.* (1994) reported D losses of 20% of the seasonal rainfall under semi-arid conditions on a well drained sandy aeolian soil. Hensley *et al.* (2000) reported D losses of 0, 15 and 18 mm on the TST, WHB and WHBM treatments, respectively, cropped to maize during 1997/98 season on the Glen Bonheim ecotope (Table 2.3). During the season rainfall was 451 mm. In the same season, on the Glen Swartland ecotope also cropped to maize they found D of 1, 9 and 11 mm for treatments TST, WHB and WHBM respectively. It was noticed that D was more on treatments of IRWH (WHB & WHBM).

Figure 2.2 shows the rainfall distribution and root zone soil water content of the different tillage treatments after planting for the season 1997/98 on the Glen Swartland ecotope. In Figure 2.2, it can be seen that the water content of the root zone much more exceeded DUL on the IRWH treatments on the days between 10 and 50 after planting. In this period, the rainfall distribution was closely cropped and had higher amounts compared to

TST without mulch treatment. During the period, R was also zero on the IRWH treatments. This resulted in more rainwater infiltration on the IRWH treatments. Consequently, the large amount of the infiltrated rainwater increased the θr during the period considered. On the other hand, on the TST (without mulch) treatment, θr hardly exceeded DUL during the same period due to the loss of rainwater by R that limited the cumulative infiltration to the root zone. According to Hensley *et al*. (2000), this resulted in negligible D on the TST treatment. More over, it proofed that D is occurring only when θr exceeding DUL due to skewed rainfall distribution and amount in a certain period of the season. From the report, one can deduce the effect of different tillage practices on D losses. In this case, in order for D to happen, soil surface vertical water flux must also be greater than Es and R rates. Bennie & Hensley (2001) also noted the influence of antecedent soil water content and amount of seasonal rainfall on the magnitude of D. They also reported low D on soils with high water holding capacity.

The fact that D can only occur when the root zone water content (θr) > CMUL provides a guide line for combating this problem. It is generally not possible to stop D from ever occurring on a particular semi-arid ecotope due to the rare but inevitable short periods of high rainfall. The frequency of D events can, however, is minimized by selecting soils for IRWH which have high soil water holding capacity and slow internal drainage. Also, soils which have a drainage impeding layer towards the bottom of the root zone are particularly suitable.

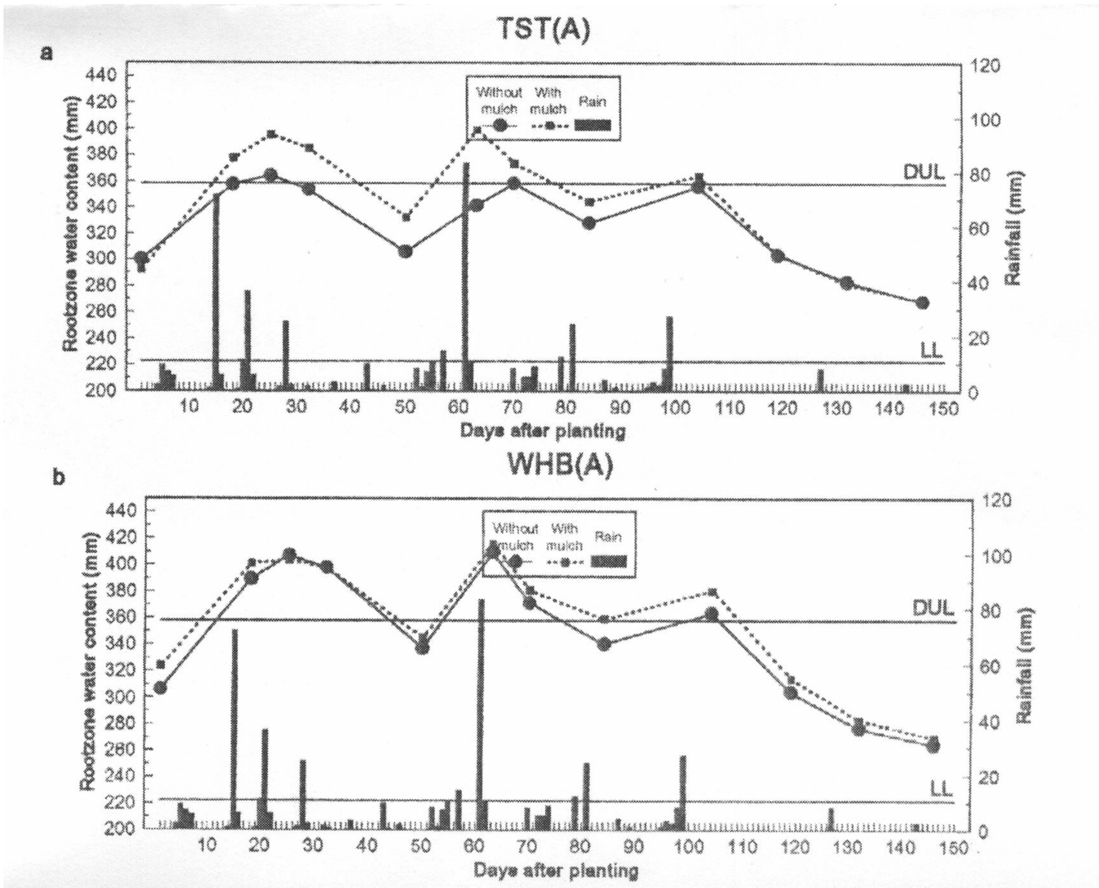


Figure 2. 2 Soil water and rainfall distributions during the growing period of maize on the Glen/Swartland ecotope (1997/98) (After Hensley *et al.,* 2000).

2.6 Rainwater harvesting

Rainwater harvesting is an age old practice used in water scarce rainfed crop production areas. It was practiced to supplement additional water for crops with insufficient amounts of rainfall for optimum yield production. It involves collecting rainwater from an area which is not in use and directs it to an area used for production, i.e. to an area where in most cases a crop is grown. Boers & Ben-Asher (1982) reviewed a number of literatures in rainwater harvesting and tried to establish a common definition. They defined it as a method to induce, collect, store, and conserve local surface runoff for agriculture in arid and semi-arid regions. Recently, Oweis & Hachum (2006) defined it in a simple way as "the process of concentrating precipitation through runoff and storing it for beneficial use". But, rainwater harvesting was found to be useful in all areas where rainfed agriculture is practiced and where critical water shortage is prevalent during the critical growing stages of crops. Passioura (2006) reported that maize grain yield have been significantly affected during grain filling stage when a critical water shortage was prevalent preceding sufficient supply of water and nitrogen before the flowering stage which enhanced too many flowers that need to be filled with grains in the succeeding stage. He also mentioned that water deficit during specific stages of floral development can severely damage seed set, or prematurely end grain filling through pollen sterility or abortion of embryos.

In rainwater harvesting, runoff inducement incorporates the techniques that improve runoff efficiency. Runoff efficiency/coefficient refers to the ratio of runoff to the total rainfall in a single rainfall event, or taken for a certain known period of time for a watershed. Boers & Ben-Asher (1982) described some of the important runoff inducement methods such as vegetation management, surface treatment and chemical treatment. They reported that surface pre-treatment mostly involved a combination of vegetation treatments (e.g. weeding) and practices to decrease infiltration and surface storage of the runoff contributing area or watershed. Smooth catchments improve runoff efficiencies up to 35% (Boers & Ben-Asher, 1982). Botha *et al.* (2003) also found high runoff efficiencies, 43% and 25% on bare crusted runoff strips and on surfaces covered by stone mulches, respectively (Table 2.8). In semi-arid soils, surface crusting was found to increase runoff efficiency by decreasing infiltration rate of the soil (M & C, 1980). Elsewhere research was also under taken to improve runoff efficiency using different chemicals in order to yield increased runoff. Among the chemicals that showed good prospects included sodium salt, paraffin wax and asphalt. Sodium salt disperses soil particles which in turn seal the soil surface while the paraffin wax and asphalt amendments clog the soil pores (Boers & Ben-Asher, 1982).

The other important aspect of rainwater harvesting is runoff collection. A number of traditional as well as improved rainwater collecting systems were used world wide. Boers & Ben-Asher (1982) tried to categorize the water collecting systems into two main divisions based on the runoff producing catchment area and the amount of water in production area: i.e. Micro-Catchement Water Harvesting (MCWH) and Runoff Farming Water Harvesting (RFWH). He defined MCWH as a method of collecting surface runoff from a contributing area (CA) over a flow distance of less than 100 meter and storing it for consumptive use in the root zone of an adjacent infiltration basin (IB). He included in this group water harvesting systems such as contour catchment water harvesting, desert strip farming, contour bench farming and runoff based pitcher farming. Hensley *et al.* (2000), introducing a rainwater harvesting system with a runoff strip (CA) 2 meter by 2 meter and an infiltration basin (IB) 1 meter wide by 2 meter long, and renamed it as infield rainwater harvesting (IRWH) (Figure 1.1). On the other hand, RFWH defined by Boers & Ben-Asher (1982) as a method of collecting surface runoff from a catchment area (CA), using channels dams, or diversion systems, and storing it in a surface reservoir (SR) or in the root zone of a farmed area (FA) for direct consumptive use.

Recent studies carried out on IRWH in South Africa, showed increased yields for maize, sunflower and sorghum (Hensley *et al.,* 2000 and Botha *et al.,* 2003). The system also increased CWPF and RWP significantly compared to the conventional cultivation practice. IRWH reduces runoff to zero and Es to some degree (Table 2.3). This improves the soil water to be available for transpiration in the semi-arid areas where there is a deficit of rainwater. According to Hensley *et al.* (2000), IRWH not only reduces runoff to zero, but also adds twice the total rainfall amount to the basin if infiltration of the runoff strip is assumed zero. In this system, the crop root zone is located in the premises of the basin where runoff is stored in (Figure 1.1). Therefore, IRWH could be used as one of the best practices to improve RWP and boast crop production in semi-arid ecotopes.

Water harvesting techniques are further improved to reduce Es by combining them with different surface cover and mulches (Ojasvi *et al.,* 1999; Hensley *et al.,* 2000; Botha *et al.,* 2003). Ojasvi *et al.* (1999) reported significantly higher root zone soil water content in a 1 meter radius conical rainwater harvesting watershade (slope 15% towards the center) surface covered with different materials compared to without any cover (control) and planted with jujube (Zizyphus mauritiana) in Barmer district of western

Rajasthan, India. In their first year of the experiment, after 15 days of the last rain, they found soil water contents of 22.2, 26.4, 32.6, 40.9 and 37.8 mm per 60 cm soil profile for the treatments control, and covered with polythene, paper, stone and marble respectively. The soil water content of the stone and marble covered treatments was 40% of the available water content while that of the control was near the wilting point. The place has a mean annual rainfall of 264 mm. The upper 15-30 cm soil is sandy with field capacity of 12% and wilting point of 2.3% (in gravimetric base). Similarly Hensley *et al.* (2000) and Botha *et al.* (2003) showed decreased Es on IRWH treatments covered by different mulches (Table 2.3). This eventually increased RWP and crop yield.

2.7. Soil crusting and infiltration

Infiltration can be defined as the rate at which water enters the soil through its soil-atmosphere interface (Horton, 1940 and Morin & Cluff, 1980). Quantitatively, infiltration rate (I) is the flux or volume of water entering the soil per unit area in unit time. The following were major factors affecting I:

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

Factors included in No. 1 are considered to be intrinsic factors while those in No. 2 are taken as extrinsic factors (Lado & Ben-Hur, 2004).

In arid and semi-arid regions, where water scarcity is the major limitation for rainfed crop production, soil infiltration rate plays the priority role in determining the cumulative infiltration amount to be available in the soil root zone during a particular rainfall event that can be used by crops. Studies carried out over a long period of time in arid and semi-arid regions have showed that soil crusting is a major cause for low infiltration. (Morin, 1967 and Seginer & Morin, 1970). Morin & Benyamini (1977) developed an infiltration model that can account for soil susceptibility to crust formation (equation 2.19). In their first field experiment carried out on Hamar soil (13% clay & 2% silt) in Israel under different soil moisture regimes it was showed that soil crusting played the major roll in determining the final infiltration rate (I_f), rather than the antecedent soil moisture. The effect of the latter in crusted soils was found to be minimal (Table 2.10). Similar results were also obtained by Morin *et al.* (1983) on a study carried out in the Sha'ar Hanegev region of southern Israel on Calcic Haploxeralf soil (FAO classification) (Table 2.11). Table 2.10 and 2.11 both showed a higher value for I_f before the crust was formed. Once the crust was formed, I_f value remained constant at different antecedent soil moisture conditions. Complementary I_f values (6-7 mm hr^{-1}) were obtained by Hoogmoed & Stroosnijder (1984) in Sahel, West Africa loamy fine sand (5% clay & 20% silt), wet crusted soil and by Hensley *et al.* (2000) in South Africa, Glen semi-arid ecotope on 11.2% clay soil (Tukulu Dikeni soil type). Zere *et al.* (2005) predicted I_f of 5 mm hr^{-1} and 10 mm hr^{-1} on bare untilled and maize cropped treatments at the Glen ecotope, respectively.

In the infiltration model (Equation 2.19), γ represents aggregate stability, i.e. resistant to the reorientation of the crust particles due to raindrop impact. High γ value explains more stable crust. Both tables show high γ values after the 24 hour storm reflecting the strength of the crust when the crust is relatively wet. On the dry crust, the γ value is low and shows a constant nature (Table 2.10). In addition, Table 2.11 showed increased I_f values when gypsum was added to the Alumim loess soil (36% silt & 17% clay). The addition of gypsum resulted in low γ and high I_f values compared without the gypsum treatment. In this case the gypsum caused stable aggregates which better resisted reorientation of soil particles and dispersion by raindrop impact. The relatively high I_i and I_f in the dry soil may be attributed to sorptivity. Bonsu, (1993) described sorptivity as the ability of a soil to absorb water without reference to gravitational effects, while Stroosnijder & Hoogmoed (1984) described it as the soils ability to absorb water as a sponge without interference of gravity. Eldridge, Zaady & Shachak (2000) reported sorptivity measured at -40 mm soil tension using disc infiltrometer. He found that sorptivity was significantly ($P < 0.001$) greater than on crust scalped plots, i.e. crust surface removed (mean ± SEM = 295.5 ± 21.5 mm $hr^{-0.5}$) than on crusted plots (46.0 ± 2.9 mm $hr^{-0.5}$) of a sandy soil at

Nizzana, Israel. Similarly, they got higher significant differences ($P < 0.001$) between the crust scalped surfaces and those crusted for locations at Sayeret Shaked and Sede Zin in Israel. Particle size distribution for the former soil was 14% clay and 27% silt.

Table 2. 10 Values of parameters for the various drying regimes (After Morin & Benyamini, 1977)

Drying regime	I_i, mm/hr	I_f, mm/hr	γ, mm^{-1}
Dry soil, first rainfall[1]	320	8	0.106
Wet soil second rainfall[2]	50	5	0.70
Six days after first rain[3]	160	8	0.16
Eleven days after first rain[4]	170	8	0.16

1: Prepared seedbed
2: Twenty- four hours after first rain
3: Six days after first rain
4: Eleven days after first rain

Table 2. 11 Values of I_i, I_f and Υ for the experimental soils (After Morin *et al.*, 1983)

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

Therefore, in the absence of a soil crust, the antecedent soil water content (θa) will have an influence on the infiltration rate. In the first few hours of infiltration, θa will probably be the major factor determining the infiltration rate. Stroosnijder & Hoogmoed (1984) reported that for permanently crusted soils the effect of different θa on infiltration was only on the time elapsed to attain I_f.

Valentin and Bresson (1992) classified crust types by morphologically characterizing the different types of layers that make up the soil crust. They studied and classified the crust types after collecting samples from temperate zone (France), humid tropics and arid regions (West Africa). The temperate zone soils were dominated by illite and vermiculities clay type. The arid soils were dominated by kaolinite and smectites clay type while the humid tropics soils were dominated only by kaolinite clay type. Texture of the soil samples included sand, sandy loam, loamy sand, loam, silty clay loam and clay loam. They identified three main groups of crusts each divided into a number of sub-groups. The main groups are: structural crusts, depositional crusts and erosion crusts (Table 2.12). Table 2.12 also shows decreasing I_f values when crust development goes on to the higher stages. It also shows some degree of consistency between the thickness of the crust and I_f with the exception of erosion crust. Erosion crust is very thin and smooth with low I_f (Table 2.12).

Valentin & Bresson (1989) also studied the pattern of crust formation through time in a rainfall season. They reported that in a loamy soil the pattern of crust formation was always the same, sealing of the surface by structural crust and development of depositional crust. Generally, for loam and sandy soils, they reported a pattern of crust stage change through time from structural to depositional followed by erosion crusts. Bresson & Boiffin (1990) and Cerdan, Souchere, Locomte, Couturier & Le Bissonnais (2002) also reported similar trends of crust formation. Change of crust to the next stage is mostly associated with decrease of I_f (Table 2.12). Hardy, Shainberg & Keren (1983), in a laboratory study in Israel, found that sandy loam soil reach I_f value of 1.6 mm hr^{-1} after three storms from a rainfall simulator. Final infiltration rates (I_f) were 2.5 and 1.9 mm hr^{-1} during the first and second storms, respectively. In contrary, when they applied the same number of storms to a silty loam soil, I_f of 1.8 mm hr^{-1} was attained in the first storm and persisted with same value to the end. They also reported that both soils acquired I_f more rapidly in the second and subsequent storms. But crusts in the sandy loam soil continuing further development.

Table 2. 12 Main features and range of infiltration rates of the different crust types identified.

Crust type	Thickness (mm)	Total porosity	Other features (pore shape, pore continuity, size….)	I_f (mm hr^{-1})
Structural crusts				
Slaking	1-3	Moderate	Weak textural differentiation, week void interconnection	5-20
Infilling	2-5	Low	Porosity partly filled with bare soils	5-8
Coalescing	3-15+	Moderate	Increase of pores convexity from the bottom of the top	3-9
Sieving:				
-Two-layered	1-3	Moderate	Sandy layer at the top over a thin seal of finer particles	5-15
-Three-layered	1-3	Low	Coarse sandy layer at the top, vesicular fine sandy layer, seal of fine particles at the bottom	0-5
-Coarse pavement	2-30	Very low	Similar to the three-layered sieving crust including coarse fragments and much pronounced vesicular porosity	0-2
Depositional crust				
Runoff	2-50+	Low	Interbedding of sandy layers and seals of finer particles, possible vesicles	1-5
Still water	2-50+	Very low	Large particles at the top, finer particles at the bottom, possible vesicles	0-2
Erosion crusts	<1	Very low	Exposed seal made of fine particles, possible vesicles	0-2

An investigation into the factors responsible for crust formation revealed that crusts are primarily formed by extrinsic factors such as raindrop impact as well as by intrinsic factors such as organic carbon, clay content and mineralogy, silt content and exchangeable ions (Hardy *et al.,* 1983; Hoogmoed & Stroosnijder, 1984; Slattery & Bryan, 1992; Bloem & Laker, 1994; Mermut, Luk, Romkens & Poessen, 1995; Van Deventer, 2000; Graef & Stahr, 2000; Lado & Ben-Hur, 2004 and Miguel, Imhoff, Ghiberto & Marano, 2005). Others, such as Verreechia (1995) and Eldridge *et al.* (2000)

reported that physical crusts combined with biological crusts were dominant, especially in non-cultivated arid and semi-arid regions. Biological crusts are mostly formed by cyanobacteria and green algae, which agglomerates soil particles. Apart from rainfall intensity, most research results showed that clay mineralogy and silt plus clay content are influential in crust formation. The latter constitutes a larger portion of the crust.

Bennie & Hensley (2001) reported that soil surfaces with a silt plus clay content of more than 20% are susceptible to crust formation. Verrecchia, Yair, Kidron & Verreechia (1995) studied some of the physical properties of the psammophile cryptogamic crust of the sandy dunal area of Nizzana, northwestern Negev Desert, Israel (crust developed due to the presence of cyanobacteria, which agglomerate the sand grains and trap Aeolian dust particles). According to their findings, the crust grain size distribution shows a higher concentration of silt and clay in the crust (Silt + clay = 80%) compared to the sands just beneath the crust. They also studied water retention of the crust in the laboratory and found it retains approximately ten times more water compared to the other soil samples below the crust.

Van Deventer (2000) studied the effect of clay mineralogy, ESP and EC on soil aggregate stability, crust formation and cumulative infiltration rate with simulated irrigation application rates in South Africa. He reported that kaolinite dominated soils with no smectite in chemically stable soils. In these two soils, with an ESP of 1 and 15, he found a decrease of cumulative infiltration of 16 and 25 %, respectively. If these soils have some smectite, iron or manganese oxides, they will give rise to a further decrease in cumulative infiltration. He reported illitie soils as more dispersive than kaolinitic soils. He also found a decrease of cumulative infiltration of 17 and 36% for ESP values of 1 and 15 respectively. On the other hand, the smectite dominated soils exhibiting poor aggregate stability. Due to the swelling and shrinking character of these soils, he found unpronounced decrease in cumulative infiltration at lower ESP values. In the same cycle of infiltration, these soils gave 11% decrease of cumulative infiltration for an ESP of 1. On the other hand, he found a 52% decrease of cumulative infiltration for an ESP value of 15. This was ascribed due to higher dispersivity of smectite soil at high ESP values which strongly influences sealing, mainly in the sub-surface layer.

Lado & Ben-Hur (2004) based on a laboratory study on soils collected from Kenya and Israel reported higher dispersivity for montmorillonite compared to kaolinite. This give montmorillontic soils a lower aggregate stability compared to kaolinitic soils (Table 2.13). Mean weight diameter (MWD) was used to measure aggregate stability of the soils. The aggregate stability was related to the strength of the interaction between the primary soil particles (sand, silt and clay) in the aggregate. MWD was calculated as: MWD = $\sum_{i=1}^{n} \overline{Ei}\, wi$ Where wi is the weight fraction of aggregates in size class i with a diameter Ēi. Higher MWD implies a greater aggregate stability (Le Bissonnais, 1996). Lado & Ben-Hur (2004) found that the kaolinitic Tunyai (Kenya) had the highest aggregate stability, the montmorillonitic Neve Ya'ar and Netanya (Israel) the lowest, and non-phyllosilicate Molo and Njoro (Kenya) soils had intermediate levels of aggregate stability (Table 2.13). Although soil texture and organic matter content of the kaolinitic soil (Tunyai) and the montmorillonitic (Neve Ya'ar) were fairly similar, they had a significant difference in MWD after fast-wetting (Table 2.13). In contrast, despite the significant difference between soil textures and organic matter contents of the two montmorillonitic soils (Neve Ya'ar and Netanya), they had a similar MWD (Table 2.13). They concluded that the mineralogy of the studied soils had a dominant effect on soil aggregate stability. The high dispersivity of montmorillonite also resulted in an accumulation of clay particles in a washed-in zone.

Similar to Bloem & Laker (1994) Lado & Ben-Hur (2004) showed that kaolinitic and illitic soils, which do not contain smectite, are stable soils and are less susceptible to seal formation. In contrast, they found that koalinitic and illitic soils contain some smectitic material and were unstable. Lado & Ben-Hur (2004), using electron micrographs, found that seal in smectitic soils was thick (> 0.2 mm) and included a highly developed washed-in zone. In kaolinitic soils that didn't contain smectite, the seal was thin (~ 0.1 mm) and contained relatively large particles.

Table 2. 13 Mean weight diameter and total soil loss values for various soils studied (after Wakindiki and Ben-Hur, 2002)

Soil		MWD		Total soil loss ($kg\ m^{-2}$)	O.M gm kg^{-1}	(Silt + Clay) %
Location	Mineralogy	In fast-wetting test (mm)	In runoff (mm)			
Tunyai	Kaolinitic	2.80a	0.12a	0.33a	34.0	24+64
Neve Ya'ar	Montmorillonitic	0.25b	0.03b	1.24b	24.3	26+63
Netanya	Montmorillonitic	0.31b	0.20c	1.14b	9.0	0+10
Molo	Non-phyllosilicate	0.84c	0.18c	0.75c	40.1	30+38
Njoro	Non-phyllosilicate	0.87c	0.21c	0.80c	42.0	34+34

Lado & Ben-Hur (2004) also studied I_f values of soils divided them into two groups. They found a mean I_f value of 20.5 mm hr^{-1} for the first group which comprised of only kaolinitic Tunyai soil. In the second group, comprising the rest of the soils had an I_f of $\leq$ 9.3 mm hr^{-1} which was significantly different from that of the Tunyai group. In their conclusion, they reported that their results for I_f were not consistent relative to the MWD values in the fast-wetting test (Table 2.16). Thus, they concluded that aggregate stability of is not the only factor that affects seal formation but also the rearrangement of particles in the seal and its thickness.

2.8. Infiltration -runoff model calibration

2.8.1. Introduction

Models are used to articulate part of natural phenomenon mathematically or numerically. A model can be physical, conceptual or empirical (Gowing, Wyseure & Young, 1993). De Wit (1982) defined a model as a simplified representation of a system where a system is a part of a reality that contains interrelated elements. Therefore, a model built up of mathematical relationships is used to simulate the system's properties. Conceptual models are those models that can give an output without showing the mathematical manipulation of the physical processes that lead to the output. Such models are also known as 'black box models'. According to Madsen, Wilson & Ammentorp (2002), a lumped conceptual rainfall-runoff model consists of a set of linked mathematical equations, describing in a simplified form the behaviour of the land phase of the hydrological cycle with parameters that represent average values from physiographic, climatic and soil physical characters for the catchment under consideration. Physically based models (process and system simulation) simulate physical processes by using measurable input parameters (Gowing *et al.,* 1993). They are built of parameters that can be physically measured and calibrated for different ecotopes. On the other hand, empirical models are mostly statistical regression relationships. They need long term dataset for their development. They are also location specific and perform badly in unusual seasons (Gowing *et al.,* 1993).

Runoff simulating and predicting computer models came into existence in the late 1960's and early 1970's (Madsen *et al.,* 2002). Most of the models generally partitioned rainfall into infiltrated water and runoff (Chahinian, Moussa, Andrieux & Voltz, 2005; M & C, 1980; Madsen *et al.,* 2002; Horton, 1940; Morin *et al.,* 1983 and Xuefeng & Marino, 2005). Therefore, runoff models consist of two parts, first, the infiltration model that used to disaggregate rainfall into runoff and infiltration, on the other part models used to simulate the overland flow.

Until recently, several physical and conceptual infiltration models were developed to be used along with runoff models. The most widely used once includes: Green and Ampt (1911), Horton (1940), Philip (1957), Soil Conservation Service-USDA (1972), Morel-Seytoux (1978) and M & C (1980). Two of them, Philip (1957) and Morel-Seytoux (1978) are considered physical models while the others are conceptual or empirical models (Chahinian *et al.,* 2005). Since all the infiltration models mentioned are used for partitioning of the rainfall in excess of infiltration, it is appropriate to discuses some of them for further understanding their modus operandia.

1. The Green and Ampt model

The model bases the principle of Darcy's equation for saturated hydraulic conductivity. It assumes a homogenous soil condition. The model equation in its simplified form is:

$$I = Ks * t - C \qquad (2.11)$$

Where, I = Infiltration rate (LT^{-1})

Ks = Saturated hydraulic conductivity (LT^{-1})

t = Time (T)

C = Constant that depends on soil moisture content and hydraulic head difference between the saturated soil and dry soil (wetted front).

According to the model, when the wetted front became larger, C approaches a constant value and thus infiltration rate (I) become equals the saturated hydraulic conductivity of the soil (I = Ks).

2. Horton's equation.

Horton developed it in 1933 and improved it in 1940. Horton based his empirical formula on the fact that many natural processes move spontaneously to their final value at a rate determined by the difference between the initial and final values of that variable (Horton 1940). Therefore, Horton suggested that infiltration rate as a variable that begins with some initial infiltration rate (f_0) and exponentially decreases until it reaches a constant rate (f_c). Horton's infiltration equation is given as:

$$f(t) = f_c + (f_0 - f_c)\, e^{-kt} \qquad (2.12)$$

Where k = a decay constant (T^{-1})

f_c = the minimum infiltration capacity (LT^{-1})

f_0 = the infiltration rate at t = 0 (LT^{-1})

t = time from the start of the rainfall (T)

The negative sign of k indicates the decrease of the infiltration rate to its final value. As t approaches infinite, i approach i_f, a constant rate of infiltration. According to Horton (1940) the values f_0, f_c and k are associated with soil cover complexes.

3. Morel-Seytoux's equation

According to Chahinian *et al.* (2005), Morel-Seytoux's equation is a modification of Green and Ampt's (1911) equation. The effect of the capillary drive in the shape of the moisture profile as well as the simultaneous presence of water and air fluxes in the soil profile was adjusted by a correction parameter (β) introduced by Morel-Seytoux and Khanji (1974) as cited by Chahinian *et al.* (2005). In this model, β varies between 1 and 1.7 but mostly fixed at 1.3.

The model also based on the ponding time of the soil. Accordingly, runoff occurs only when the soil surface retention or storage potential is fulfilled. Therefore, the model needs to determine the ponding time (t_p) for the time step (t). For $t > t_p$, the cumulative infiltration equation F(t) is calculated from:

$$\mathbf{F(t) = F_p = [S_f + F_p(1 - 1/\beta)]\ Ln\ [(S_f + F(t))/(S_f + F_p)] = K_s(t - t_p)/\ \beta} \quad \textbf{(2.13)}$$

Where F_p = cumulative infiltration (L) when ponding occurs

S_f = storage and suction factor (L) that can be expressed as a function of the soil hydraulic properties (Morel-Seytoux, 1978).

$$\mathbf{S_f = (\Theta_s - \Theta_i)\ H_c\ [1\text{-}\ 1/3\ *(\Theta_i - \Theta_r)^6/(S_f - F_p)^6]} \quad \textbf{(2.14)}$$

Where H_c = the capillary height (L).

Θ_s = volumetric water content at saturation (L^3L^{-3})

Θ_r = the volumetric residual soil water content (L^3L^{-3})

Θ_i = the initial soil water content (L^3L^{-3})

4. Philip's equation

Philip's (1957) infiltration equation is a physical model where most of the parameters are associated with initial soil moisture conditions. The infiltration equation is given by:

$$\mathbf{f(t) = 1/2\ St^{-(1/2)} + 2/3K_s} \quad \textbf{(2.15)}$$

Where S ($LT^{-0.5}$) = sorptivity, which depends on the water potential.

5. The Soil Conservation Service (SCS) equation

The SCS (1972) gives empirical relationships between depth of direct runoff and the depth of precipitation after runoff begins:

$$\mathbf{Pe} = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{2.16}$$

$$\mathbf{F = P - Pe}$$

Where Pe = runoff (L)

P = precipitation (L)

F = the total infiltration depth (L)

S = soil retention capacity (L)

The value S is estimated from a P and Pe relationship curves which were obtained from various US catchments. The curves were standardized and defined such as: $0 \leq CN \leq 100$. The CN and S relationship is given by:

S = 1000/CN -10 (inches)

2.8.2 Morin & Benyamini's model

Morin & Benyamini, (1977) developed an infiltration model through a minor modification of the theoretical model described by Seginer & Morin (1970), which considers the effect of crust formation in the infiltration rate of soils. This first theoretical infiltration model developed by Seginer & Morin (1970) is centered in the main effect of the rain drop size and its impact on the soil surface area that forms soil crust which in turn contributes for the decreasing of soil infiltration capacity to the final constant rate. The theoretical infiltration rate of Seginer & Morin (1970) is given by the equation:

$$\mathbf{I_t = I_i \beta_n + (1 - \beta_n) [I_f + (I_i - I_f)^{-nati}]} \tag{2.17}$$

Where, I_t = instantaneous infiltration rate (mm hr^{-1})

I_i = initial infiltration rate of the soil (mm hr^{-1})

I_f = final infiltration rate of the soil (mm hr^{-1})

β_n = that part of the soil crust which is broken by the impact of n drops and returns to its initial infiltration rate (-)

n = number of median drops which hit 1 mm^2 of the soil surface in 1 hour.

a = average size of the area sealed by the impact of one median drop, causing the infiltration rate of the area to decreases from I_t to I_f (mm^2)

t_i = time from the beginning of rain (hr)

Morin & Benyamini (1977) considered the difficulty of measuring the raindrop size in Seginer & Morin (1970) infiltration model. Therefore, they modified the model into Horton type equation by using the accumulated rainfall instead of the less accessible rain drop size as follows:

$$\mathbf{I_t = I_f + (I_i - I_f)\, e^{-\gamma P t_i}} \qquad \textbf{(2.18)}$$

Where,

I_t = Instantaneous infiltration rate, millimetre per hour

I_f = Final infiltration rate of the soil, millimetre per hour

I_i = Initial infiltration rate of the soil, millimetre per hour

P= Rain intensity, millimetre per hour

t_i = Time from the beginning of rain, hour

γ = Empirical soil parameter representing surface aggregate resistance to dispersion

M & C (1980), tested the modified infiltration rate model in a field experiment in Israel at a sandy soil with two types of seed bed preparation (cultivated and smoothed; and straw mulched) under different antecedent soil moisture condition (1^{st} storm on dry seed bed, 2^{nd} after 24 hours of drying, 2^{nd} storm after 6 days of drying and 2^{nd} storm after 11 days of drying). The result showed that in all soil moisture conditions, the smoothed and compacted bare seed bed was very well predicted the infiltration rate curve as a function of the depth of the rainfall (Table 2.7 and 2.8). In the different soil moisture regimes, they found R^2 ranged between 0.91 and 0.98 among the measured and model predicted infiltration rates. Most importantly, their result showed that in crusting soils, the final infiltration rate could be controlled by the crust rather than by the antecedent soil moisture condition. This finding was also substantiated by recent research in semi-arid Spain (Castillo, Gomez-Plaza & Martinez-Mena, 2003), which implicitly explained that soil infiltration rate would mostly control by crust seal in semi-arid regions where high intensity rainfall is frequent. Antecedent soil moisture mostly affects the infiltration rate at medium and low intensity rainfall areas. However, it doesn't mean that the antecedent soil moisture has no contribution in the M & C (1980) rainfall-runoff model; rather it is controlled by the soil water storage and detention parameter (SD_m) that will be discussed in the succeeding paragraphs.

2.8.3 M & C's (1980) model

The M & C's (1980) runoff model is a conceptual model which integrates the infiltration model developed by Morin & Benyamini (1977) and runoff. It calculates the storm runoff by dividing the rainfall intensity segment by segment over the total storm duration. The model is given by the equation:

$$\Sigma R_i = \sum_{i=1}^{n} (P_i \Delta t_i + SD_{i-1} - F_{\Delta ti} - SD_m) \qquad (2.19)$$

Where, R_i = surface runoff during segment i of the storm (mm)

SD_i = surface storage and detention for the time segment t_i (mm)

SD_m = maximum surface storage and detention (mm)

P_i = rainfall intensity (mm hr^{-1})

$F_{\Delta ti}$ = the potential infiltration during any time segment Δt_i (mm)

Δt_i = Any time segment

$F_{\Delta ti}$ is calculated by integrating the infiltration equation of Morin & Benyamini (1977) with time which becomes:

$$F_{\Delta ti} = I_f \Delta t_i + (I_i - I_f)/-\gamma P_i * (e^{-\gamma Di} - e^{-\gamma Di-1}) \qquad (2.20)$$

And $D_i = \Sigma P_i \Delta t_i$ (the cumulative rainfall up to the time ti (mm))

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

2.8.4 Model calibration

The parameters of a model need to be calibrated and validated by randomly or systematically selected sets of observed data from a specific ecotope. The performance of the model must also be evaluated to the extent where it became good enough in predicting the intended output. The performance of a rainfall-runoff model depends on how best the model parameters are calibrated using appropriate objective functions. Willmott (1981) recognized the insufficient indices and objective functions used in evaluation of geographical models in most of prior published articles. Therefore, in addition to F-test and coefficient of distribution (R^2), he recommended an alternative set of indices and objective functions to be included in any model that compares simulated and observed values. These recommended indices and objective functions are as follows:

1. Observed and predicted means and standard deviations
2. Slope and intercept of a least square regression between the predicted (dependent variable) and observed (independent variable);
3. Systematic and unsystematic components of the root mean squared error (RMSEs and $RMSE_u$ respectively);
4. Index of agreement (d).

The process of model calibration is normally done either manually or by using computer-based automatic procedures. In manual calibration, a trial-and-error parameter adjustment is made.

2.10 Integrated runoff-crop models

Young, Gowing, Wyseure & Hariby (2002) reported the lack of combined runoff and crop models. Quite recently, researchers such as Young *et al.* (2002) and Walker & Tsubo (2003a & 2003b) developed a model that lumped together runoff and crop growth models. Walker & Tsubo (2003b) developed a model known as PUTURUN which incorporates M & C (1980) runoff model and Putu crop growth model. Similarly, Young *et al.* (2002) developed a model known as Parched-Thrist (P-T). This model incorporates the Green & Ampt (1911) infiltration model and SCS (USDA, 1972) runoff routing model to estimate runoff; and two crop models, Parch for simulation of sorghum, millet and maize and for the simulation of rainfed, lowland rice.

Both models were developed for low rainfall semi-arid areas in order to evaluate the benefit of different rainwater harvesting practices through crop performance (growth and yield). Both models consider the following aspects:

- Estimating runoff from runoff producing area (RPA).
- Estimating soil moisture storage and use within runoff receiving area (RRA).
- Estimating crop yield.

In addition, the models are equipped with long-term climate generators that help to generate long-term daily climate data. The models also have rainfall intensity disaggregators that enable them to have rainfall intensities of short durations from rainfall data depending on the need of the models. For instance, PUTURUN uses input of one minute rainfall intensity while P-T uses five minute rainfall intensity. Moreover, both models software are user-friendly and can be run on recent windows operating system (See details in Young *et al.,* 2002 and Walker & Tsubo, 2003a & b).

The performances of the infiltrations and runoff models incorporated with the models were discussed in previous sections. The Green & Ampt (1911) infiltration equation is limited to layered soils such as crusted soils (Xuefeng & Mariño, 2005). Moreover, recently Chahinian *et al.* (2005) showed the poor performance of SCS (1972) runoff model.

According to Young *et al.* (2002), P-T was tested from three years micro catchments experimental data at Morogoro, Tanzania. Measured daily and seasonal runoff data for a bare, compacted soil was compared with model predicted once. The regression analysis between observed and predicted daily runoff gave R^2 of 0.60. The slope has a value of 0.97 which is not significantly different from 1 (0.97 ± 0.06; P < 0.0001) and an intercept of -0.02 which is also not significantly different from zero (-0.02 ± 0.03; P + 0.01). In predicting the seasonal runoff, it was found that R^2 = 0.99. The regression fitted line also have a slope of (1.02 ± 0.03; P < 0.0001) and an intercept of (15.6 ± 4.2; P = 0.01). The runoff model incorporated in P-T model predicted the daily runoff satisfactorily. On the other hand, the performance of M & C (1980) runoff model in accounting crust effect in the infiltration rate is well described in the previous sections.

Although the separate models (infiltration, runoff and crop) performed well independently, the performance evaluation of the comprehensive models (P-T and PUTURUN) in simulating crop yields for different rainwater harvesting practices is limited. Young *et al.* (2002) reported the performance of the P-T model in predicting maize yield from data obtained at Morogoro, and Kisangara, Tanzania and Zimbabwe. The observed and predicted regression analysis of the combined 3 locations' data gave them R^2 of 0.73 and a fitted line that have a slope of 0.9 (± 0.11; P < 0.0001) and an intercept of 0.31 (± 0.2 P; 0.12). According to Young *et al.* (2002), the model was developed for east Africa semi-arid regions.

Regarding the comprehensive PUTURUN model performance for simulating crop yield is not yet available. Recently, Zere *et al.* (2005) evaluated the performance of the rainfall intensity generator and the M & C (1980) runoff model incorporated in the model. They used the long term annual rainfall and runoff data (1937/38 to 1954/55) measured at Glen ecotope by Du Plessis & Mostert (1965). They analyzed the runoff data measured from runoff plots cropped with maize and bare untilled one. Rainfall intensity of one minute interval was not available. Therefore, they used model generated rainfall intensity. The model uses Huff's curves to generate rainfall intensities stochastically. In the model, Huff's curves were generated by the method described by Bonta (1977). The rainfall intensity generator as well programmed to generate rainfall intensities to two specific locations in South Africa (Bloemfontein and Pretoria). Zere *et al.* (2005), considering the nearness and similarity of Glen with Bloemfontein, they used the calibrated parameters of Bloemfontein to generate the Glen rainfall intensity.

The result of the performance statistics between the measured and simulated runoff is presented in Table 2.14. During calibration they reported the best fit parameters values for Eq. (2.19 & 2.20). In maize plots they found I_i = 25 mm hr $^{-1}$, I_f = 10 mm hr^{-1}, γ = 0.2 mm $^{-1}$ and SD_m = 6 mm while in bare plots they found I_i = 25 mm hr^{-1}, I_f = 5 mm hr^{-1}, γ = 0.2 mm^{-1} and SD_m = 0.1 mm. Annual runoff from the bare, untilled treatment was better predicted by the model (Table 2.14). In both treatments, the model test shows that the model estimated the annual runoff of the ecotope fairly well based on the generated intensities by the model.

Table 2. 14 Performance test of PUTURUN runoff model (After Zere *et al.,* 2005)

Indices	Maize plot		Bare, untilled	
	Calibration	Validation	Calibration	Validation
RMSE	25	56	24	51
MAE	18	46	18	48
RMSEs	16	26	16	13
$RMSE_u$	19	50	17	49
D-index	0.85	0.90	0.85	0.90
R^2	0.49	0.68	0.59	0.74

2.11 Soils of Ethiopia

The soils of Ethiopia are diverse because the features controlling the formation are diverse. The physiography of Ethiopia has extreme variability (Abebe, 1980 and MoA, 2000). Ethiopia consists of five elevation ranges based on traditionally divided climatic zones (Table 2.15). The variability in climate, with annual rainfall varying from < 200 mm to > 2200 mm, and altitude varying from < 500 m to > 3000 m (Table 2.15).

The diversity of altitude has contributed to the diversity of climates. The country lies wholly within the tropics, but its nearness to the equator is counter balanced by the elevation. On the higher mountains (> 3000 m.a.s.l.) the climate is Alpine. On the other hand, the eastern and southeastern plains (< 500 m.a.s.l.) are characterized by desert climate. MoA (2000), divided the country into 18 agroecological zones (AEZ) and 49 sub-zones. Approximately 35% of the country lies in arid and semi-arid zones (Appendix 7).

Table 2. 15 Traditional climatic zones and their physical characteristics (Ministry of Agriculture 2000)

Traditional zone	Climate	Altitude (m)	Average annual temperature (^oC)	Average annual rainfall (mm)
Bereha	Hot arid	< 500	> 27.5	< 200
Kola	Warm semi-arid	500-1800	20-27.5	200-800
Woinadega	Cool sub-humid	1800-2400	16-20	800-1200
Dega	Cool and humid	2400-3200	11.5-16	1200-2200
Wurch	Cold and Moist	> 3200	< 11.5	> 2200

The Great Eastern Africa Rift Valley divides Ethiopia into two approximately equal portions (Figure 2.3). It is one of the important features that contribute to the diversified nature of Ethiopia. It forms a corridor approximately from southwest to northeast (Figure 2.3).

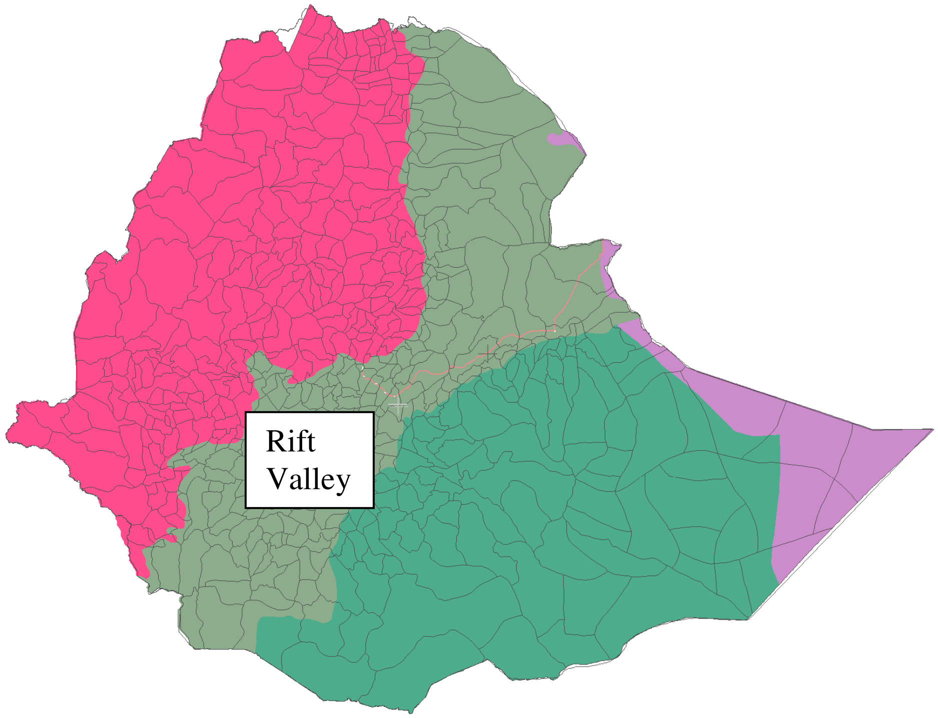


Figure 2. 3 The Rift Valley of Ethiopia

Residual soils are associated to geological formation. In Ethiopia, the geology is represented by the following formations:

- Sedimentary and Metamorphic
    - Recent: Coral, alluvium and sand
    - Tertiary: Lime stones of Harrar
    - Jurassic: Antalo lime stones
    - Triassic: Adigrat sand stones
    - Archaean: Gneisses, schists and slaty rocks
- Igneous
    - Recent: Aden volcanic series
    - Tertiary, Cretaceous: Magdala group
    - Jurassic: Ashengi group

Archaean: The northern portion, lying between 10^0 and 15^0 N, consists a huge mass of Archaean rocks with a mean height of 2200 meter. The metamorphic rocks compose the main mass of the Table land, an extension of the East African Table Land. They are exposed in every deep valley of northern Ethiopia and along the Blue Nile valley.

Triassic: In the northern region of the country, at Adigrat, the metamorphic rocks invariably overlain by white and brown sandstones, unfossiliferous, and attaining a maximum thickness of 303 meter. They are overlain by the fossiliferous limestones of the Antalo group. Around Chelga and Adigrat (North) coal bearing beds occur, which supposed may be of the same age as the coal bearing strata of India. The Adigrat sandstone possibly represents some portion of the Karoo formation of South Africa.

Jurassic: The fossiliferous limestones of Antalo are generally horizontal. In some places interstratified with trap rocks (a form of plutonic igneous rock). The fossils are Dolite forms and include species of Hemicidaris, Pholadomya, Ceromya, Trigonia and Alaria.

Igneous rocks: Above a height of 2400 meter, the country consists of bedded traps belonging to two distinct groups. The lower (Ashangi group) which consists of basalts and dolerites, and often amygdaloidal; and the upper (Magdala group) which contains much trachytic rock of considerable thickness, lying perfectly horizontal. In central Ethiopia, they gave rise to a series of terraced ridges. They are also inter-bedded with unfossiliferous sandstones and shales. The more recent igneous rocks (probably Tertiary), rich in alkalis occurred in certain localities in southern Ethiopia. The older igneous rocks show a prominent feature of suffering from denudation. They have been worn into deep and narrow ravines, sometimes to a depth of 2100 meter.

The diversity of climatic conditions as well as the geologic formations has contributed towards a wide range of soil types being present in Ethiopia. About 43 soil units have been defined in the legend of the Soil Association Map of Ethiopia (FAO, 1984). Table 2.16 shows the major soil types in Ethiopia and their area coverage.

Table 2. 16 Soils groups and their area coverage in Ethiopia (After Mitku, 1987 & FAO, 1984).

Soil group (FAO/UNSCO)	Area (%)
Lithosols	16.0
Nitosols	12.0
Cambisols	11.5
Vertisols	10.0
Regosols	10.0
Xerosols	8.5
Solonchaks	7.0
Fluvisols	6.0
Luvisols	6.0
Acrisols	3.0
Yermosols	3.0
Phaeozems	2.0
Rendzinas	2.0
Andosols	1.0
Arenosols	0.5
Gleysols	0.5
Histosols	< 0.3
Chernozems	< 0.1

2.12 Water balance research in Ethiopia

Water balance research in Ethiopia is limited. Compared to the large mass of arid and semi-arid area, the work done is immaterial. Moreover, Ethiopia considered having a large portion of the land mass (> 66%) under dryland prevalent in drought. These consists of the arid zone < 45 days of length of growing period (LGP) to sub humid and humid zones with LGP of 60 – 120 days (Georgis, Temesgen & Goda, 2001).

Research attention given to this region has not been satisfactory. Reasons are: a limited number of scientists focusing on water balance research; the fact that previous policy gave most emphasis to high potential areas. Nevertheless some relevant research has been carried out. Most of this has been concerned with breeding and seeking drought tolerant crops, and water conservation tillage (Mandefro, Hussein, Gelana, Gezahegne, Yosef, Hailemichael & Aderajew, 2001 and Georgis *et al.,* 2001).

As in most arid and semi-arid areas of the world, in Ethiopia, maize, sorghum and beans are the dominant crops. Mandefro *et al.* (2001) reports that the drought stressed maize growing areas occupy about 40% of the total maize growing area, but contribute less than 20% to the total maize production. The research concentrated on different tillage practices that proved better elsewhere in improving the available soil water. Despite Ethiopian farmers are deprived of appropriate farm power unit and excess crop residue that can be used for mulching, most of the research were done on different tillage practices, mulch and residue management. Some of the major research findings were reviewed by Georgis & Woldeyesus (1993), Haile & Reda (1996) and Georgis *et al.* (2001).

In experiments conducted at four selected semi-arid ecotopes (Babile, eastern Ethiopia; Kobo, northern Ethiopia and Melkassa, central Rift Valley) to evaluate the effect of tied ridges on the yields of maize and sorghum showed a substantial yield increase with tied ridge tillage practice (Table 2.17- 2.20).

Table 2. 17 Effect of land preparation methods and planting pattern on the grain yield of sorghum grown at Kobbo (1980-1982) (After Adjei-Twum *et al.,* 1984)

Soil preparation methods	Yield (kg ha^{-1})			
	1980	1981	1982	Mean
Planting on the flat	1315	1551	1855	1583
Planted in the furrows of open ridges	1148	2111	3018	1580
Planted on open ridges	1213	1649	3718	2193
Planted in the furrows of tie ridges	2618	1639	2741	2332
Planted on tie ridges	2918	2039	3784	2913
L.S.D. (0.05)	5.12	N.S.	8.03	

At Kobo, on the experiment carried out during 1980-1982, tied ridge planted on the ridge gave a mean grain yield advantage of 84% over the normal flat planting (Table 2.17). The grain yield during 1981 doesn't show significant differences among the different land preparation and planting methods. It also shows planting on the ridges gave better yield than planting inside the basin. At Melkassa, tied ridge planted inside the furrow and at the top of the ridge gave mean sorghum grain yield advantages of 123% and 116% respectively, compared to the normal flat planting during the experiments carried out between 1982 and 1984 (Table 2.18).

Table 2. 18 Effect of seedbed types on grain yield of sorghum at Melkassa Hypo Calcic Regosol ecotope 1982-1984

Seedbeds and position of seed[1]	Grain yield (kg ha^{-1})			
	1982	**1983**	**1984**	**Mean**
Flat	1890	670	850	1136.7
Furrows/open ridges	3020	770	1180	1656.7
Top/open ridges	3720	780	1130	1876.7
Furrows/tie ridges	3740	1000	2860	2533.3
Top/tie ridges	3780	910	2690	2460.0
L.S.D. (P<0.05)	8.0	NS	1.7	
Crop season rainfall (mm)	474	466	787	

1: Ridge height = 35 cm; row spacing = 75 cm; ridges tied at 6 m interval

The yield and the seasonal rainfall in the three seasons don't show any consistence relationship. Although the rainfall amount in 1982 and 1983 are almost similar, the yields obtained in 1983 are far less than that of 1982. This may be happened due to the rainfall distribution. Contrary to Kobo, at Melkassa, planting inside the furrows of tied ridges gave a relatively better yield than planting on the top of the ridges (Table 2.17).

In experiments carried out at Babile during 1988 and 1989, the different tillage practices (open end planting on ridges, open end planting in furrows, closed end planting on ridges and closed end planting in furrows) doesn't show significant grain yield difference of maize from the normal flat planting (2.19). Grain yields are better on tied ridges giving rise to 26% and 17% increases on tied ridges planted on the ridges and in the furrows respectively, than on the flat planting.

Table 2. 19 Effect of land preparation methods on yield of maize grown at Babile (After G/Kidan & Haile 1990)

Land preparation method	Grain yield (kg ha^{-1})		
	1988	**1989**	**Mean**
Flat planting	7640a	8830a	8240
Open end planting on ridges	8350a	8930a	8640
Open end planting in furrows	8230a	1167bc	9950
Closed end planting on ridges	11020b	9780ab	10400
Closed end planting in furrows	6670a	1260c	9640

On the other hand, in experiments carried out in eastern Ethiopia semi-arid regions on five different maize cultivars, tied ridge without fertilizer gave a mean yield advantage of over 51% than the flat planting. When it is combined with fertilizer, the yield advantage is 83%. But the mean absolute grain yields on fertilized and non fertilized tied ridges were 5680 kg ha^{-1} and 3699 kg ha^{-1} respectively (Table 2.20).

Table 2. 20 Mean grain yield (kg ha^{-1}) of five improved maize varieties in the semi-arid eastern region of Ethiopia produced with and without fertilizer and water conservation practices; the experimental period was 1981 to 1983 (After Tamirie *et al.,* 1984).

Varieties	Without WC		With WC		Increment (%)	
	Unfert.	Fert	Unfert.	Fert.	Fert.	WC
Alemaya composite	2815	5365	4812	7142	91	71
KCC	2556	4709	4283	6567	84	68
EAH-75	2597	4805	3601	5984	85	39
Ca 5	2285	3840	2889	4731	68	26
Bukuri	1972	3668	2911	4013	86	48
Mean	**2445**	**4470**	**3699**	**5680**	**83**	**51**

Some mulching experiments carried out in some selected semi-arid regions were also reported by Haile & Reda (1996) and Georgis *et al.* (2001) in improving soil moisture condition and crop yields. A preliminary study carried out at Melkassa research center during 1988 to see the effect of different mulch materials and rates on the yield of maize and sorghum grain yield showed a promising result in improving the soil moisture content as well as the yields of maize and sorghum (Table 2.21). It was found that stone mulch (scoria or red ash) which is abundant in the Rift Valley applied 137 tons ha^{-1} gave the highest grain yield for both maize and sorghum. It gave 46% and 63% of grain yield advantage over the non mulched one for maize and sorghum respectively. In the same experiment, tef straw mulch at a rate of 3 tons ha^{-1} gave the second best result with yield increase of 19% and 65% for maize and sorghum respectively. In similar experiment carried out in the vicinity of Zeway, (Rift Valley) during 1990, it was obtained similar yield advantage with scoria mulch at a rate of 137 tons ha^{-1}.

Table 2. 21 The effect of different mulch rates and materials on the yield of maize and sorghum at Melkassa Hypo Calcic Regosol ecotope during 1988 (After MARK, 1989).

Treatments	**Grain yield (kg ha^{-1})**	
	Maize	**Sorghum**
Control (no mulch)	2450	1350
3 tons ha^{-1} (tef straw)	3590	3340
5 tons ha^{-1} (tef straw)	3160	4020
137 tons ha^{-1} or 3 cm depth of scoria (red ash)	4570	3830
222 tons ha^{-1} or 5 cm depth of scoria (red ash)	3530	3650

Water conservation tillage researches carried out in semi-arid regions of Ethiopia resulted in a substantial crop yield increases. However, there is still a need to do much more work.

Thus, to fill the gaps which in previous studies were not covered and to provide alternative options in improving RWP and crop yields in the semi-arid ecotopes of Ethiopia, it is necessary to seek more suitable WC technologies which are also more practical to Ethiopian farmers. The technique should also be more effective and can be easily transferable to similar ecotopes with minimum resource. In this regard, IRWH appears to have a bright prospect to improve crop production and capable of to cover large areas with short time. With this understanding, a study was initiated and conducted at three representative semi-arid ecotopes of Ethiopia. The study includes a detail ecotope characterization in order to extrapolate the results to other similar areas with minimum cost.

3. MATERIALS AND METHODS

3.1 Ecotope selection

Three ecotopes representative of the semi-arid areas of the Rift Valley of Ethiopia were selected (Figure 3.1 and Table 3.1). They were located at Melkassa, Dera and Mieso (Figure 3.1). The Melkassa Hypo Calcic Regosol ecotope is located 15 km south of Nazaret city on the Melkassa Agricultural Research Center (MARC) located in the middle of the Rift Valley. It is one of the largest research centers of the Ethiopian Agricultural Research Organization (EARO), now Ethiopian Institute of Agricultural Research (EIAR).

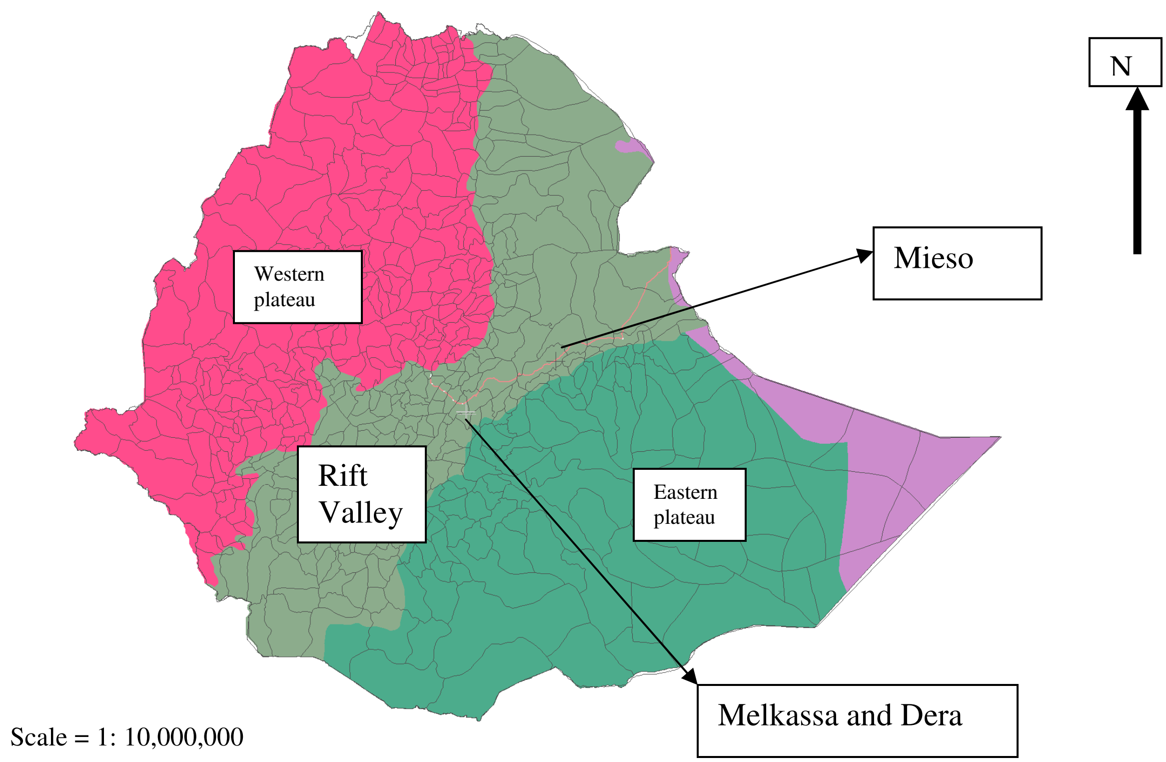


Figure 3. 1 The Rift Valley of Ethiopia (lighter coloured area) and the experimental ecotopes

The Dera Calcic Fluvic Regosol ecotope is located about 10 km south of the Melkassa center. The experiment was carried out on a farmer's field. The third ecotope Mieso is located about 270 km east of Melkassa. Details about the three ecotopes are presented in Table 3.1

Table 3. 1 Soil and climatic characteristics of the selected ecotopes

Characteristics	Selected Ecotopes		
	Dera	Melkassa	Mieso
Soil classification WRB (1989)	Calcic Fluvic Regosol	Hypo Calcic Regosol	Hypo Calcic Vertisol
FAO	Regosol	Regosol	Vertisol
SA	Dundee 1120 Sabie	Etosha 2111 Vetkuil	Arcadia 1200
Latitude	8.36^0 N	8.43^0 N	9.23^0 N
Longitude	39.34^0 E	39.31^0 E	40.8^0 E
Altitude (meters asl)	1500	1550	1352
Slope (%)	1	1	1 - 2
Texture(A1 horizon)	Sandy loam	Clay loam	Clay
Effective depth	> 150 cm	50 –100 cm	50 – 100cm
Climate			
Annual precipitation (mm)	765	772	737
Annual evaporation (mm)	1505	1994	1656
Aridity index (AI) = P/PE	0.50	0.39	0.45
Mean max. temperature (^oC)	28.3	28.5	30.5
Mean min. temperature (^oC)	14.2	13.8	14.8

3.2 Ecotope characterization

3.2.1 Climate

All ecotopes are situated in the semi-arid region of Ethiopia described as the AEZ sub-zone, ‘hot to warm semi-arid lakes and Rift Valley’, (SA1-2). The sub-zone ‘sub-moist lakes and Rift Valleys, tipped to cool’ (SM2-2), also fits the Melkassa Hypo Calcic Regosol and Dera Calcic Fluvic Regosol ecotopes.

Recently Mamo (2006) divided the Rift Valley into four agro-climatic zones depending on the rainfall amount and risk assessment in crop production. He categorized Melkassa and Dera under zone 3 characterized by an annual rainfall ranging between 600 – 800 mm. This zone is characterized as being relatively wet with 75 % of the years getting optimum rainfall. Drought is severe in the spring season (March – April – May).

According to Mamo (2006), the Mieso Hypo Calcic Vertisol ecotope is categorized in zone 4. This zone has an annual rainfall which ranges between 500 – 600 mm. This area is characterized as being hot and dry during most of the year, with fairly dependable rainfall during June to August.

3.2.2 Soil

3.2.2.1 Soil classification and analysis

At each ecotope a profile pit was dug deep enough to include most of the crop root zone. The soil profile was then described and classified according to the WRB (FAO, 1998b), South Africa (Soil classification working group (SCWG), 1991) and FAO soil classification systems, and samples were taken for the following chemical analysis. The analyses were made according to the standard methods described by the Non-Affiliated Soil Analysis Work Committee, (1990):

- Soil pH, (H_2O and KCl methods).
- Ca, K, Na, Mg, CEC, EC and organic carbon.

3.2.2.2 Soil physical properties

The following soil physical properties were determined:

3.2.2.2.1 Soil texture

Textural analysis was done using the hydrometer and pipette method while particle size distribution was carried out by sieving method (Non-Affiliated Soil Analysis Work Committee, 1990).

3.2.2.2.2 Infiltration rate

Infiltration rate, including initial (I_i) and final (I_f) infiltration rate were determined by using a sprinkler infiltrometer. At each ecotope a 6m X 6m plot was prepared with a flat surface, like on the no till (NT) treatment described under 3.3. The determination was carried out according to the prescribed method (Division of Agricultural Engineering, 1984). The procedure was replicated two to three times and the results averaged (Figure 3.2).

Figure 3. 2 Sprinkler infiltrometer and infiltration rate measurement photograph at Melkassa Hypo Calcic Regosol ecotope.

The amount of water intercepted at each rain gauge at ponding represents the cumulative infiltration (Ic) water into the soil before runoff starts. The data obtained was plotted as Ic (mm) against time taken t (minutes). This gives the power function of the cumulative infiltration graph. The regression curve fitted to this graph also provides the constants c and k in equation 3.1 and 3.2 which are used to calculate I. The equations 3.1 and 3.2 are the basic mathematical equations that describe I and Ic.

$$I = c\ k\ (t)^{k-1} \qquad (3.1)$$

$$Ic = c\,(t)^{k} \tag{3.2}$$

Where, Ic = cumulative infiltration (mm)

I = infiltration rate (mm hr^{-1})

t = time in minutes

c and k = constants obtained by plotting the measured data

Once the equation for the infiltration rate was determined I_i and I_f values were determined by taking the points at t = 1 minute for I_i and where the decrease in infiltration rate equals about 0.1 mm hr^{-1} for I_f. The I_i and I_f values at each site were used as the first approximation values for calibration in the Morin & Benyamini (1977) infiltration model (equation 2.18) and M & C (1980) runoff model (equation 2.19) to simulate runoff at each ecotope.

3.2.2.2.3 Drainage curve

This was done following the procedure described by Hensley *et al.* (1993). An area of 2 m X 2 m near by experimental plots was used. It was surrounded by a low sheet metal “wall” driven into the soil 20 cm deep and protruding 30 cm above the surface to form a dam. Water was continually added until all the horizons were saturated. The amount of water to be added was first predicted using estimated field capacity (FC) and bulk density (Db) values for each horizon. At saturation a plastic sheet was placed on the soil surface to prevent evaporation. Gravimetric soil water measurements of the potential root zone were converted to give volumetric values (θr) by multiplying by Db. These were then taken at appropriate time intervals, starting with one day intervals for a period of 5 days, followed by 5 and 10 days intervals until the decrease in θr became negligible. The drained upper limit (DUL) was considered to have been reached when Δθr became negligible. The θr vs. time data were used to construct a drainage curve for each ecotope. An exponential equation was used to describe the curve mathematically. The drainage curve equation that fit the drainage pattern of the soil is given by the equation:

$$Y = x - b\,(\ln t) \tag{3.3}$$

Where Y = water content of the soil layer at time t (mm) x = intercept of the drainage curve on the Y-axis, i.e. the point indicating field saturation.

b = slope of the drainage curve

t = time after saturation

3.2.2.2.4 Matric potential

Soil samples were collected from each ecotope's identified diagnostic horizons. For each horizon about one kilogram of composite sample was taken. The samples were prepared according to the procedures described by National Soil Research Center-EARO, (2000). They were subjected to pressures of 0.33, 5, 10 and 15 bars in a pressure plate apparatus in order to determine the matric suction.

3.2.2.2.5 Soil strength

Soil strength measurements (Kilo Newton) were made using a hand penetrometer (McKyes, 1989). In all ecotopes the strength was measured with the cone that has an area of 2 cm^2. Measurements were made on each plot at three points and two depths, at the surface of the soil and at 100 mm depth. Soil samples were taken at the time of measurement and the water content determined gravimetrically. The averages of the readings were taken for statistical analysis.

3.2.2.2.6 Bulk density (Db)

Db was determined in triplicate for the diagnostic horizons of each soil using a core sampler (Blake & Hartge, 1986). The cores had a diameter of 5 cm and height of 5 cm. The cores were oven dried for 24 hours at 105 ^{o}C and the dry mass determined. Db was calculated by dividing the dry soil mass by the volume of the core as:

Db = Dry mass of soil core/Volume of soil core (Mg m^{-3})

3.3 Experimental design and lay out

Experimental plots were laid out on sites with a slope of less than one percent. There were two treatments and three replications in a randomized complete block design (RCBD). The plot size was 2 meters by 2 meters (Figure 3.3). The treatments are (1) Conventional tillage (CT) i.e. the normal/traditional farmer's tillage practice; (2) No tillage on flat land (NT) i.e. simulating the runoff strip of IRWH (Figure 1.1). On both treatments weeds were controlled by hand weeding. The lower side of each plot was equipped with a runoff collecting device. Each plot was surrounded by a galvanized iron sheet protruding 20-30 cm above the surface of the soil, and inserted about 20 cm deep into the soil. This "wall" served to hydraulically isolate each plot. Runoff was collected in a gutter at a lower side of the plot. The gutter channelled the runoff water into a 200 litre barrel buried at the side of each plot (Figure 3.3).

3.4 Data collected

3.4.1 Rainfall measurements

Rainfall amount and intensity was measured by an automatic tipping bucket rain gauge (Hobo Event (C) Onset Computer Corp, Model No. 7, Version No. 4) installed at each experimental site to store detailed data for every storm. Each bucket tip measures 0.2 mm in a time interval determined by the intensity of the rainfall. It can measure as fast as 0.2 mm in 0.01 seconds. The rain gauge was equipped with a data logger with memory capacity of 32,768 bytes. The data was down loaded on to a lap top computer. The record included the starting date and time, as well as the terminating date and time of each storm. The data collected was analyzed to characterize each rainstorm at each ecotope during the measuring period.

3.4.2 Runoff data

Runoff data were collected for each rainfall event. M & C (1980) describe a rainstorm as a group of rain segments for which the breaks in the rain are less than 24 hours. Huff (1967) defines a storm, as a rain period separated from a preceding and succeeding rainfall event by 6 hours or more. The latter definition was used. During the 2003 rainfall season, runoff collected in the barrel was emptied into a graduated cylinder by successive steps until the drum had been emptied. In the following year (2004), runoff was simply measured by recording the height of the runoff inside the barrel. In 2004, as part of maintenance, new barrels with a diameter of 58 cm were installed at all the sites.

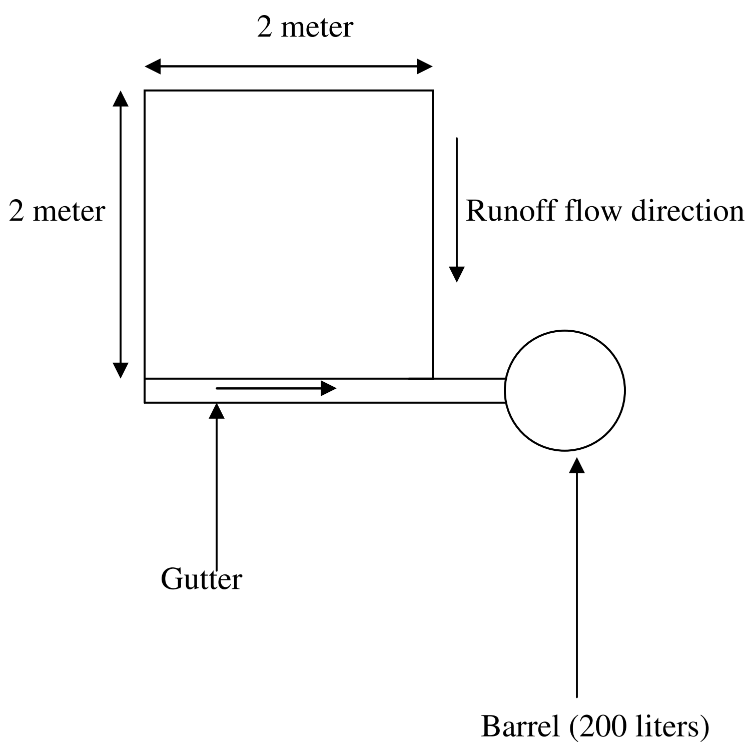


Figure 3. 3 Layout of a runoff plot.

The measured runoffs were used to calibrate and validate the M & C runoff model. Once the values of I_i, and I_f had been determined for a particular ecotope, and the rainfall intensity data collected, the remaining parameters in the runoff model, soil storage and detention (SD_m), and γ were fixed by calibration. To fix the values, a sensitivity analysis method was used. Once the models were calibrated and the parameters fixed, validation was carried out. In the model calibration and validation process, a computer programme known as RUNOFF, that incorporates both the infiltration and runoff equations, was used. The programme uses the inputs I_i, I_f, SD_m and γ together with the file that has the storm data arranged at minute intensities. This gave the output of the runoff of individual storms. Model validation was performed by using the procedure of (Willmot, 1981). The recommended indices and objective functions are as follows:

1. Observed and predicted means and standard deviations.
2. Slope and intercept of a least square regression between the predicted (dependent variable) and observed (independent variable).
3. Systematic and unsystematic components of the root mean squared error ($RMSE_s$ and $RMSE_u$ respectively).
4. Index of agreement (d).

4. DERA

4.1 Ecotope characterization

4.1.1 Climate

The experiment was carried out on a farmer's field. There is therefore no permanent climate station. The rainfall, temperature and PET data presented is from the almanac characterization tool (ACT), GIS data base software developed by the Blackland Research and Extension Center of the Texas A & M University System (Table 4.1, Figures 4.1 and 4.2).

According to MoA (2000), Dera is classified in the semi-arid agro-ecological zone of Ethiopia. The rainfall–evapotranspiration monthly distribution (Figure 4.2) is a bi-modal type of rainfall distribution. The best growing period amounts to approximately 115 days. This period covers June to September with a seasonal rainfall of 528 mm and a peak in August with 182 mm. The mean annual AI is 0.5. The maximum temperatures occur in the months March to June, the peak reaching 31^{o}C in May. Minimum temperatures occur during November to January, with the lowest in December at 11^{o}C.

Table 4. 1 Climate data of Dera (After ACT Ethiopia data base)

Month	Precipitation (mm)	PET (mm)	Min. T (^{o}C)	Max. T (^{o}C)	AI
January	10	118	12	27	0.085
February	21	117	13	28	0.180
March	44	142	15	30	0.310
April	58	138	16	30	0.420
May	44	141	16	31	0.312
June	72	137	17	30	0.526
July	178	119	16	26	1.496
August	182	114	16	27	1.597
September	96	117	16	28	0.821
October	39	129	13	28	0.302
November	13	120	12	27	0.108
December	8	113	11	26	0.071
Annual total/average	**765**	**1505**	**14**	**28**	**0.508**

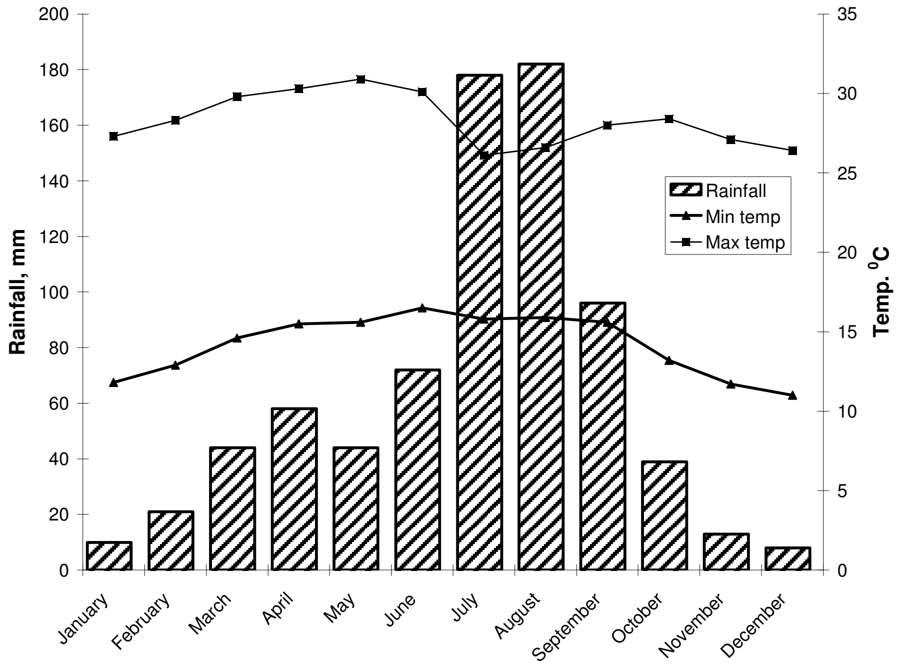


Figure 4. 1 Monthly variation of rainfall and temperature at Dera.

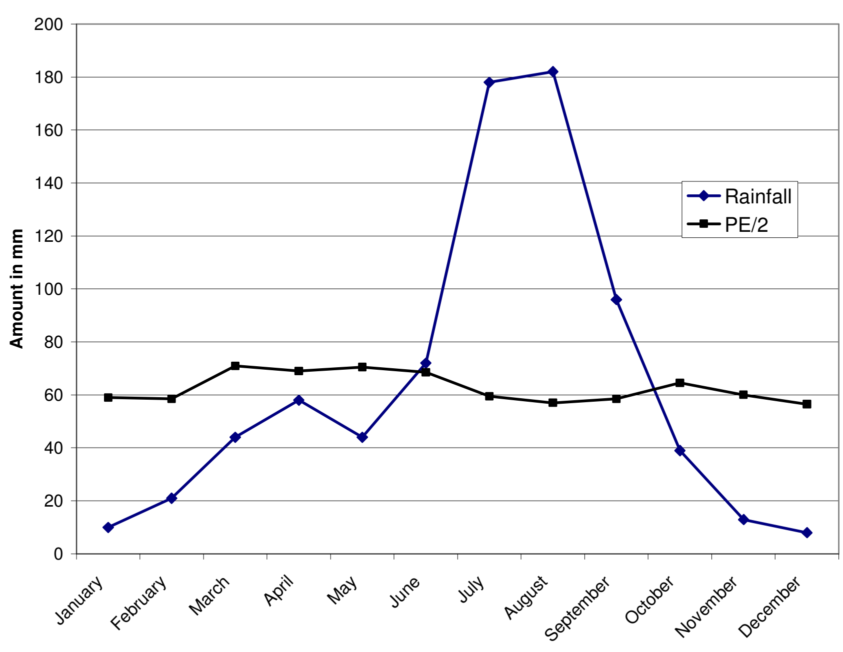


Figure 4. 2 Optimum moisture for crop production available period at Dera.

4.1.2 Topography

The ecotope is located at the foot slope of the Rift Valley, a flat land that stretches towards the river Awash. Its slope ranges between 1-5%. The experimental site had a slope of 1% and a northerly aspect.

4.1.3 Soil

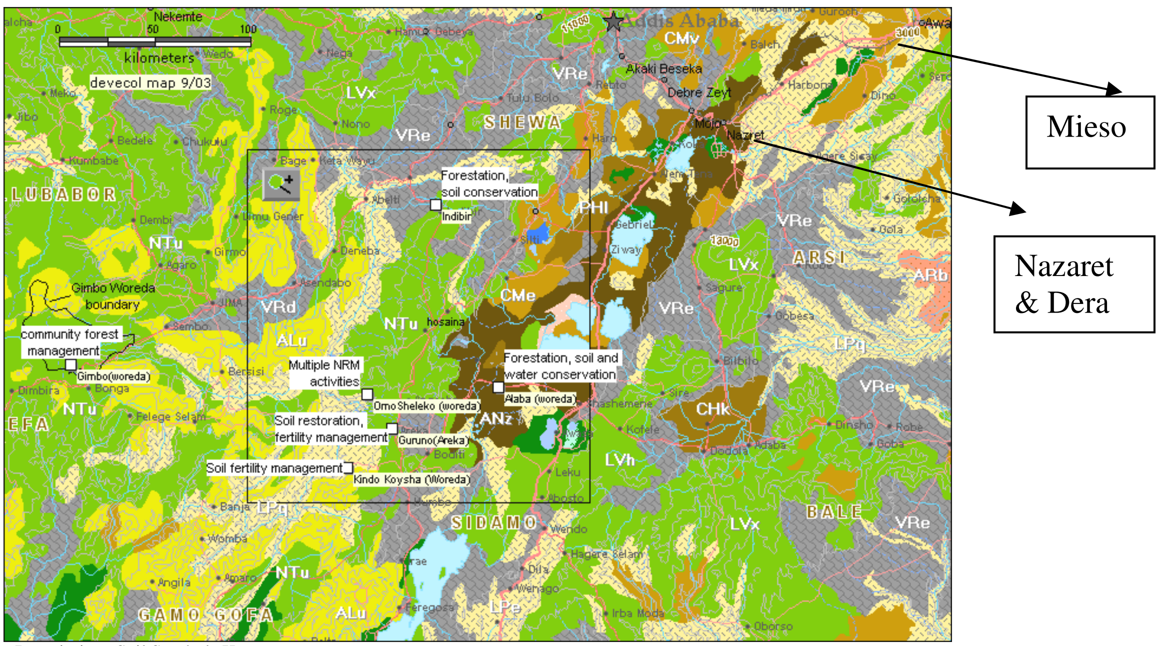
4.1.3.1 Morphology and classification

The soil of Dera was classified as a Calcic Fluvic Regosol in WRB, (FAO, 1998b) and Dundee Sabie (1120) (Soil Classification Working Group, 1991). A soil map (FAO, 1998) of the Rift Valley in this vicinity shows the dominance of the Regosols (Figure 4.3). The detailed profile description is presented in appendix 1.

At Dera, four horizons were identified. These are Ap, A1, AB and A2 with thicknesses of 0-200, 200-600, 600-1300 and 1300-1700 mm, respectively (Table 4.2). The parent material was identified as unconsolidated material. The soil effective depth is estimated at 600 mm.

Table 4. 2 Dera Calcic Fluvic Regosol: particle size distribution.

Horizon	Depth (mm)	% Particle size distribution			Textural class
		Clay	Silt	Sand	
Ap	0-200	17.5	30.6	51.9	Sandy loam
A1	200-600	20.9	31.6	47.5	Loam
AB	600-1300	15.7	24.8	59.5	Sandy loam
A2	1300-1700	22.5	46.3	31.3	Loam

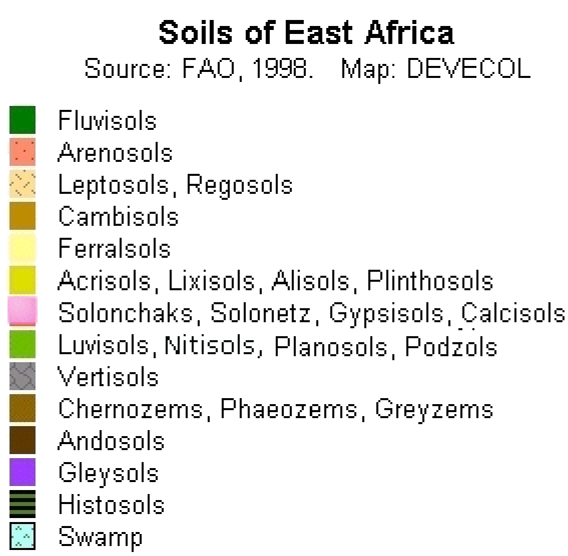


Soil Group Descriptions Soil Symbols Key

www.67.95.153.93/…/RiftValley_soils.php

Figure 4. 3 Soil map of the Rift Valley (FAO, 1998).

Soil Group Descriptions Soil Symbols Key



4.1.3.2 Chemical properties

The chemical analyses show that Ca is the dominant cation in all horizons, contributing on average about 80% of the sum of the exchangeable/extractable cations (Table 4.3 A & B). The soil in all horizons has a pH of 8 or more. The presence of large amounts of Ca results in a high pH and high base saturation. Although the large amount of Ca presence, the soil surface exhibited hard and strong crust. The large amount of Ca in all the horizons indicates low leaching conditions during pedognesis. The CEC of the soil increases with depth. This is advantageous for IRWH as it improves the water holding capacity of the root zone. It is, however, necessary to keep in mind the fact that these analyses were made on the fine earth fraction of the soil, whereas the total soil contains much gravel below 200 mm (Appendix 1).

Table 4. 3 Chemical analysis of the Dera Calcic Fluvic Regosol.

A.

Horizons	Depth (mm)	pH H_2O	pH KCl	OC (%)
1	0 - 200	8.07	7.14	0.94
2	200 - 600	7.97	7.14	1.06
3	600 - 1300	8.59	7.36	
4	1300 - 1700	8.89	7.23	

B.

Depth (mm)	Exchangeable/extractable cations ($cmol_c\ kg^{-1}$)					CEC ($cmol_c\ kg^{-1}$)		Base saturation (%)
	Ca	K	Mg	Na	Sum	Soil	Clay	
0 - 200	48.1	5.2	2.8	0.7	56.9	18.4	27.5	309
200 - 600	66.1	4.0	3.7	1.6	75.3	23.7	71.8	318
600 - 1000	39.6	4.1	3.5	6.6	53.8	27.8	103.0	194

4.1.3.3 Physical properties

4.1.3.3.1 Matric potential

The bulk density (Db) decreases with depth from 1.26 to 1.17 Mg m^{-3} (Table 4.4). $\theta_{0.33}$ and θ_{15} were lower at both the sandy loam horizons compared to the loam horizons (Table 4.4 & Figure 4.4). The water content at $\theta_{0.33}$ to the effective depth (600 mm) is 187 mm while the water content at 15 bar (θ_{15}) and $\Delta\theta$ ($\theta_{0.33}$ - θ_{15}) are 89.1 and 97.8 mm, respectively.

Table 4. 4 Matric suction data for the Dera Calcic Fluvic Regosol (% values are gravimetric).

Horizon	Depth (mm)	Db (Mg m^{-3})	$\theta_{0.33}$		θ_{15}		$\Delta\theta$	
			%	mm	%	mm	%	mm
1	0-200	1.26	21	53	10	25	11	28
2	200-600	1.24	27	134	13	64	14	70
3	600-1300	1.17	24	197	11	88	13	109
4	1300-1700	1.17	33	154	18	84	15	70
Total	1700			538		261		277

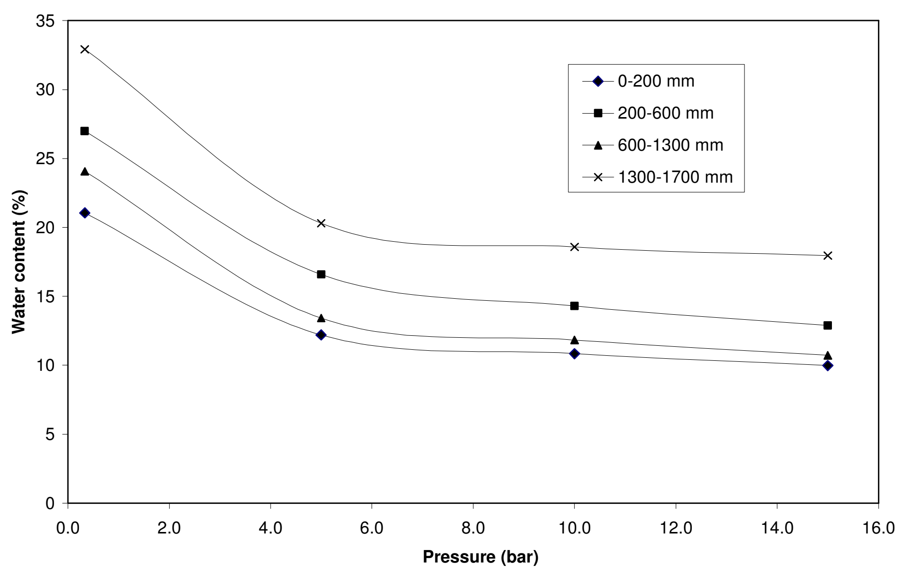


Figure 4. 4 Matric suction curves for the Dera Calcic Fluvic Regosol.

4.1.3.3.2 Penetrometer resistance

Table 4.5 shows the results of soil penetrometer resistance measurements on the two cultivation treatments after the crust had been formed, and at $\theta m = 22.7\%$. The result shows a significant difference between the two cultivation methods at the crust surface. There was also a significant difference on both treatments between the surface measurement and that at 100 mm depth. No significant difference was found at 100 mm depth between the two cultivation methods. This may be attributed to the type of crust formed. It has the finer part and the bedding located at the lower side.

Table 4. 5 Penetrometer resistances for the different cultivation methods, Dera Calcic Fluvic Regosol.

Depth	Resistance in Kilo Newton	
	NT mean	CT mean
At the surface	0.20	0.15
At 100 mm depth	0.32	0.33

4.1.3.3.3 Crust morphology

The first type of crust formed at Dera was classified as a sieving structural crust. The crust then undergoes different crust formation processes that take place particularly in sandy soils of arid and semi-arid tropics. The sieving type of crust is characterized by having the coarser particles at the top side and the finer particles at the lower side. This type of crust is formed by raindrop impact especially on sandy loam soils (Valentin & Bresson, 1992 and Graef & Stahr, 2000). It is a reorientation of the soil particles with minimum translocation due to raindrop impact on the bare soil. In due course depositional and erosion crusts were also formed so that finally the crust became changed to exhibit a rigid, hard, smooth surface. These types of crusts have very low infiltration rates (5-15 mm hr^{-1}), and low water storage capacity (Valentin & Bresson, 1992).

4.1.3.3.4 Drainage Curve

A drainage curve determination was carried out to a depth of 1300 mm. The data was arranged so that separate curves could be plotted for the 0-600 mm (DUL_{600}) layer, and 0-1300 mm layer (DUL_{1300}). DUL_{1300} and DUL_{600} were found to be 225 mm and 125 mm respectively. DUL was reached at around 45 and 50 days after saturation (Figure 4.5). There is a large difference between the so called ‘field capacity’ water content estimate at 0.33 bar of 384 mm for the 0-1300 mm layer (Table 4.4), and the field determined DUL value of 225 mm. This emphasizes the need to use field determinations for reliable soil water studies. The equations that fit the drainage curves are as follows:

$$DUL_{600} = -40.243 \text{Ln}(T) + 253.84 \quad (4.1)$$

$$R^2 = 0.885$$

DUL_{1300} = -65.605Ln (T) + 463.9 (4.2)

$R^2 = 0.841$

Considering estimations of field saturation based on Db values, it may seem that the starting points of the graphs are rather low. It is necessary, however, to realize that because of the considerable amount of gravel in the profile the measured water contents should be lower than expected for the textures given in Table 4.2.

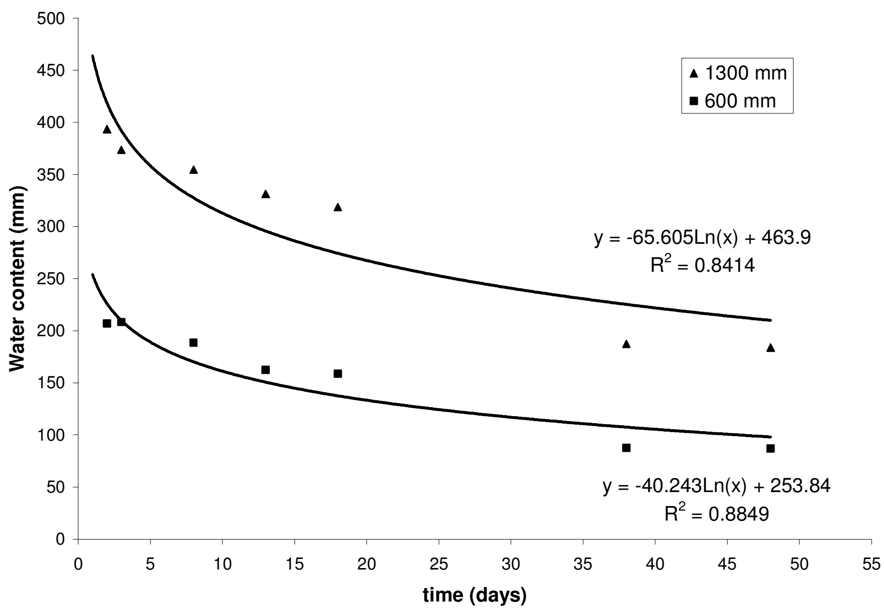
CMUL was calculated (see detailed procedure in Chapter 5) using an estimated ET rate of 5.1 mm day^{-1} for maize as follows:

Evaporation rate = $\frac{dy}{dt}(-65.61Ln(T)+463.9)$, which gives

5.1 = 65.61/T

T = 13 days

Substituting 13 days in the DUL_{1300} depth equation will yield a CMUL value of 296 mm. 296 – 225 gives 71 mm of water that can be extracted by maize roots while the layer 0-1300 mm drains from field saturation to DUL.



Note: y = θ and x = t

Figure 4. 5 Drainage curves for Dera Calcic Fluvic Regosol.

4.2 Infiltration rate

Infiltration rate measurements were carried out one day after a rainfall event. Results are presented in Table 4.3 and Figure 4.6. The power fit equation for the Ic curve was found as:

$(Ic) = 2.3078\ T^{0.4059}$ $R^2 = 0.9898$

The equation provided c and k values of 2.3078 and 0.4059, respectively. Substituting these values in equation 3.1 enable the calculation of I as follows:

$I = 2.3078 * 0.4059\ T^{0.4059-1}$

$= 56.204\ T^{-0.5941}$ mm hr^{-1}

Using this equation it is possible to estimate I_i and I_f by calculating I at say T = 1 minute and T = 40 minute, respectively. Results are I_i = 56 mm hr^{-1} and I_f = 6.3 mm hr^{-1}. T = 40 minute is the point where the decrease in I_f equals 0.1 per minute. Similar I_f values (6-7 mm hr^{-1}) were obtained by Hoogmoed & Stroosnijder (1984) for West African sandy wet crusted soils. Hensley *et al.* (2000) also reported an I_f value of 6 mm hr^{-1} on the Glen/Boheim ecotope in South Africa. Figure 4.7 shows the graph of infiltration rate using the Morin & Benyamini (1977) equation. It shows the time to reach I_f for different rainfall intensities. The Morin & Benyamini (1977) infiltration equation was found to be:

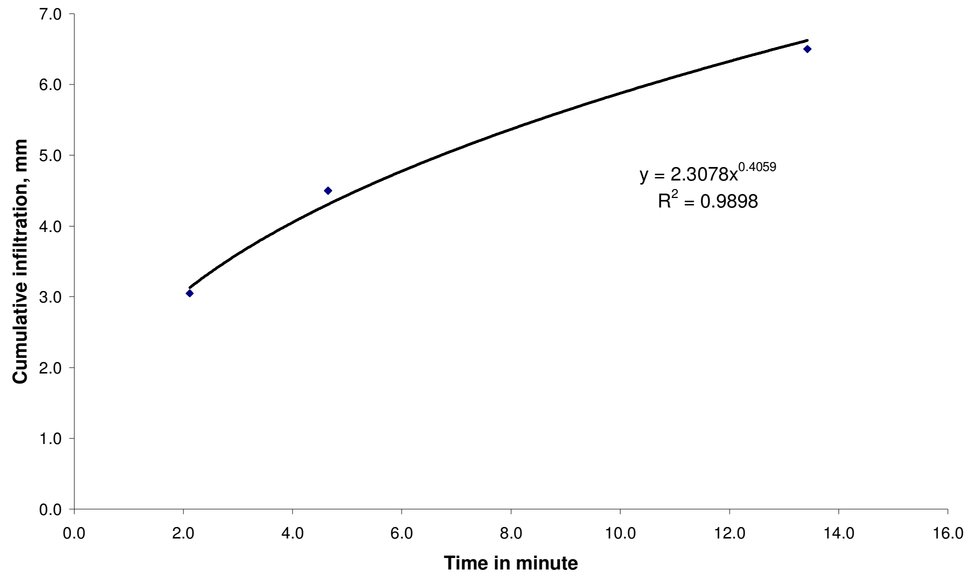
$I(t) = 54\ e^{-0.6Pi} + 6$

Where, Pi = rainfall intensity in mm hr^{-1}

High intensity rainfall events result in I_f being reached sooner than with lower intensity rainfall.

Table 4. 6 Measurements of infiltration rate with the sprinkler infiltrometer**.**

1st run		**2nd run**		**Average**	
T (min)	Ic (mm)	T (min)	Ic (mm)	T (min)	Ic (mm)
2.10	3.6	2.13	2.5	2.12	3.1
4.97	5.0	4.33	4.0	4.65	4.5
18.48	8.0	8.37	5.0	13.43	6.5



Note: y = Ic and x = t

Figure 4. 6 Cumulative infiltration curve for the Dera Calcic Fluvic Regosol.

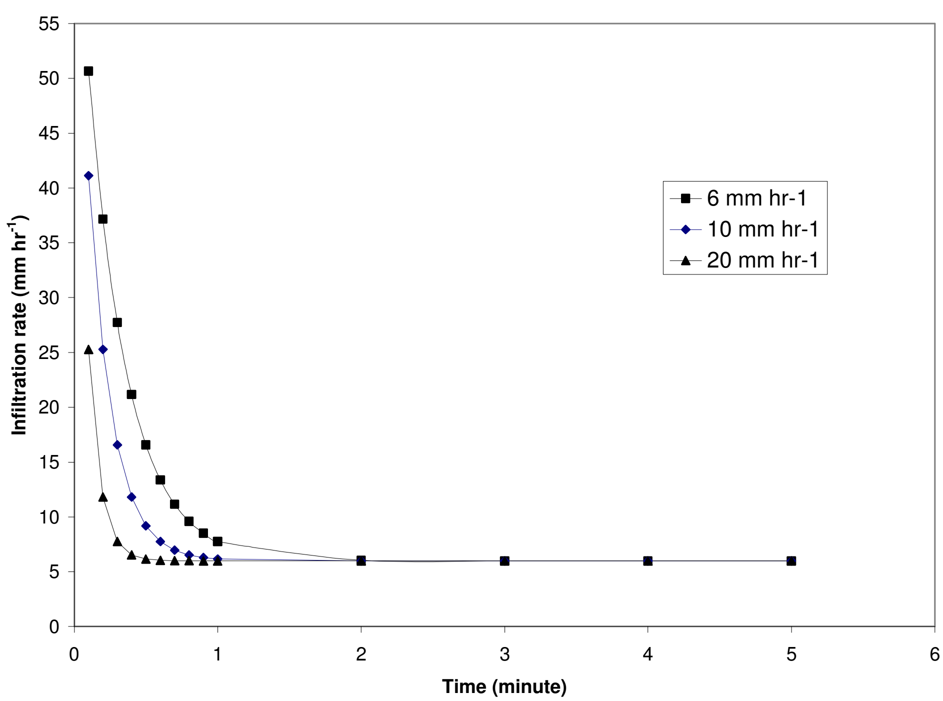


Figure 4. 7 Infiltration rate curves for different rainfall intensities calculated using the equation of Morin & Benyamini (1977) on the Dera Calcic Fluvic Regosol.

4.3 Rainfall–runoff relationships

4.3.1 M & C model calibration and validation

Runoff data observed during the two seasons were combined and equally divided into two with random selection for calibration and validation purpose of the M & C model. During the experimental seasons, 25 runoff data sets were obtained from rainfall storms with amounts of 9 mm or more. From the two year storm data sets, 12 were randomly selected for calibration while 12 were used for validation of the model.

The calibration was done using a computer program that incorporates the following M & C model input parameters: one minute storm intensity (Pi), I_i, I_f, γ, and surface storage (s= SD_m). Since, I_i and I_f were determined in the field, most of the optimizing calibration was done for γ and s. The value of γ is varies between 0 and 0.9 and its effect on the runoff is minimal compared to I_f and SD_m. Final infiltration rate (I_f) had a major influence on runoff. Sensitivity optimization analysis was done to identify the best I_f value. Most of the sensitivity analysis was concerned with s. Because the runoff plot was small ($4m^2$), the discharge and other flows rates were not measured during the experiment. Only one objective function was therefore considered to calibrate and validate the model, i.e. the runoff volume.

Model calibration was carried out by changing the values of γ between 0.1 and 0.9 and s between 0 and 10 mm, while keeping the measured and first approximation infiltration rates fixed (I_i = 56 mm hr^{-1} and I_f = 6.3 mm hr^{-1}). Once the optimum values for γ and s were obtained and fixed, then sensitivity analysis for measured I_f values were conducted manually and expertly (Madsen *et al.,* 2002) until the performance evaluation objective functions had reached their optimum level and the observed and simulated runoff matches reasonably well.

During the calibration process, the best performance was obtained when I_f = 6 mm hr^1; γ = 0.6 mm^{-1}; and s = 0.4 mm and 0.3 mm for CT and NT plots, respectively (Tables 4.7). Similar results (s = 0.5 mm) were reported by Morin & Cluff, (1980) on an experiment carried out on a semi-arid soil at Tucson, Arizona, and similarly in Israel for smooth and compacted soils. The ratio of the systematic residual mean square error (RMSEs) to the total residual mean square error (RMSE) reveals the minimum values where the best s values were achieved. Using these s values the R^2 and D-index values were 0.98 and 0.99 for CT and 0.94 and 0.98 for NT (Table 4.7).

Table 4. 7 Dera runoff model calibration: statistical evaluation parameters with different s values; a = CT plots, b = NT plots.

a. CT plot calibration: In all cases, I_i = 60 mm hr^{-1}, I_f = 6 mm hr^{-1} and γ = 0.6 mm^{-1}

Indices	**s values**					
	3 mm	2 mm	1 mm	0.5 mm	**0.4 mm***	0.3 mm
RMSE	3.63	3.16	2.93	1.88	**1.68**	2.42
RMSEs	3.20	2.70	2.40	1.05	**0.08**	1.37
$RMSE_u$	1.71	1.66	1.68	1.57	**1.68**	1.99
MAE	2.17	1.64	1.63	1.24	**1.08**	1.61
R^2	0.97	0.97	0.97	0.98	**0.98**	0.98
D-index	0.97	0.98	0.98	0.99	**0.99**	0.99
Slope (b)	0.80	0.81	0.81	0.92	**1.00**	1.11
Intercept (a)	-0.42	0.14	0.58	0.26	**-0.04**	-0.35
RMSEs/RMSE	0.88	0.85	0.82	0.56	**0.05**	0.57

b. NT plots

Indices	**s values**						
	3 mm	2 mm	1 mm	0.5 mm	0.4 mm	**0.3 mm***	0.15 mm
RMSE	5.38	4.84	4.53	3.67	3.37	**3.50**	5.29
RMSEs	4.86	4.28	3.89	2.68	1.91	**1.25**	3.04
$RMSE_u$	2.29	2.26	2.32	2.51	2.77	**3.26**	4.33
MAE	3.88	3.24	2.86	2.31	2.01	**2.23**	3.25
R^2	0.94	0.94	0.94	0.95	0.94	**0.94**	0.92
D-index	0.94	0.95	0.96	0.97	0.98	**0.98**	0.96
Slope (b)	0.75	0.77	0.77	0.87	0.94	**1.04**	1.25
Intercept (a)	-1.36	-0.81	-0.37	-0.78	-1.16	**-1.58**	-1.97
RMSEs/RMSE	0.90	0.88	0.86	0.73	0.57	**0.36**	0.57

* selected s (=SD_m) values

The slope of the equation during calibration shows a perfect correlation condition with the slope values of 1 and 1.04 for CT and NT plots respectively. A perfectly simulated graph has a slope of 1 and an x-intercept of 0 (Willmott, 1981 and 1982). The model therefore is shown to have performed well. The next step was to use the values of I_f, s and γ, which had proved to be the best during calibration, in the validation test on the remaining 12 storms Pi vs. R data sets. Statistical results are presented in Table 4.8. Although the R^2 and D-index values are good the RMSEs/RMSE ratio is excessively high for unknown reason. In spite of this when the model was used on the whole data set of 25 storms satisfactory results were obtained (Figures 4.8 and 4.9) with R^2 values of 0.95 and 0.94 for the CT and NT treatments, respectively.

Table 4. 8 Validation of M & C model for the selected s values.

Indices	CT	NT
RMSE	3.60	3.51
RMSEs	2.35	2.94
$RMSE_u$	2.72	1.92
MAE	2.40	2.22
R^2	0.93	0.96
D-index	0.97	0.98
Slope (b)	0.80	0.80
Intercept (a)	2.13	0.84
RMSEs/RMSE	0.65	0.84

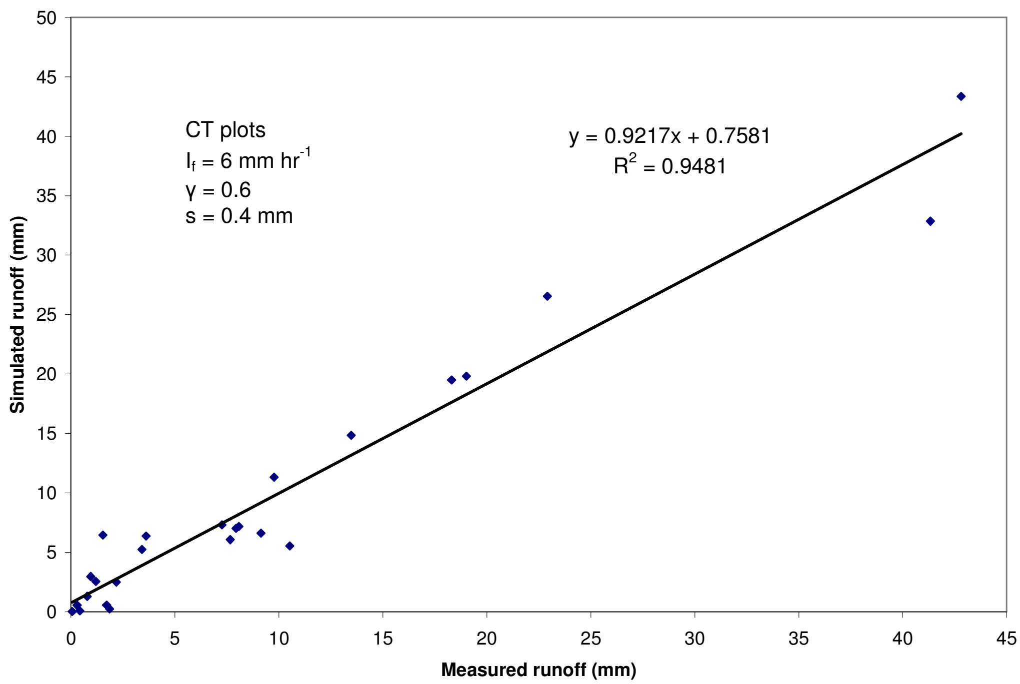


Figure 4. 8 Measured and simulated runoff during the two years on CT plots.

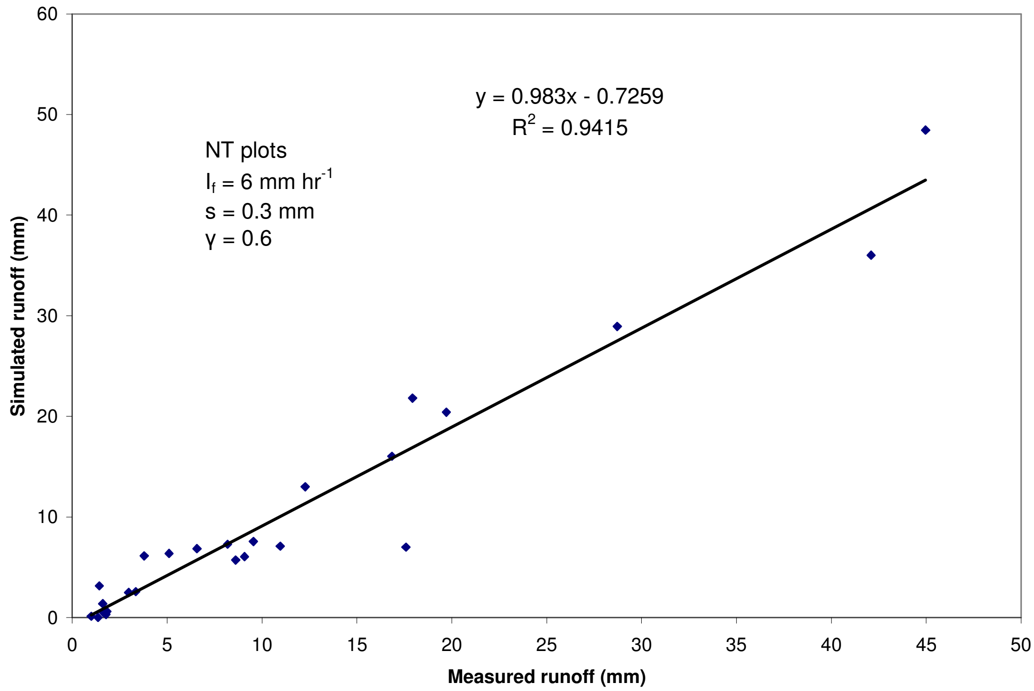


Figure 4. 9 Measured and simulated runoff during the two years on NT plots.

At Dera two seasons (2003 and 2004) rainfall-runoff data was collected (Tables 4.9 and 4.10). The rainfall in 2003 season seems to have been evenly distributed throughout the main rain season compared to 2004. In both years a total of 25 storms ≥ 9 mm occurred. In 2003, the number of storms includes the period July 01 to September 30 with a total of 327 mm. In 2004 the period was longer by a month, i.e. June 10 to September 30 with a total rainfall of 306 mm. The relatively large amounts and intense rain storms resulted in more rapid crust formation on the CT plots compared to 2004. In 2003 land preparation was carried out after the beginning of the rainy season on June 15. This may have caused the clods on the CT plots to disperse and slake quickly, promoting faster crust formation (Figure 4.10).

Figure 4. 10 Close views of crusts on NT and CT plots at Dera (NT at front side with minimum surface storage).

The result of statistical analysis reveals a non significant difference between the two treatments and the three replications. However, there is a significant difference in runoff amounts between the two years at $p = 0.01$ level. Rao *et al.* (1998) also reported no significant difference in runoff between no till and conventional tillage plots on an Alfisol soil in the semi-arid tropics of India. However, the R/P in both seasons was higher on NT plots than on the CT plots, i.e. 0.59 and 0.51 for 2003, respectively; and 0.45 and 0.47 for 2004, respectively. During the two seasons the total rainfall ($P > 9$ mm) recorded was 533 mm, and R/P was 0.44 and 0.52 for CT and NT plots, respectively.

The rainfall intensity analysis of the storms during the two experimentation seasons showed that from all the storms that caused runoff, 67% of them exhibited an intensity > 6 mm hr^{-1} in more than a quarter of their total storm period.

Table 4. 9 Rainfall-runoff relationships on the Dera Calcic Fluvic Regosol ecotope 2003.

Date	DoY	Rainfall (mm)	Observed R (mm)		Simulated R (mm)	
			CT	NT	CT	NT
19/07	200	20.2	10.52	8.61	5.5	5.7
21/07	202	10.6	1.19	3.35	2.6	2.6
26/07	207	54.8	41.34	42.10	32.9	36.0
31/07	212	14.6	0.95	1.43	3.0	3.2
02/08	214	16.0	1.85	1.78	0.2	0.3
06/08	218	9.6	2.18	2.97	2.5	2.5
13/08	225	31.8	19.02	17.93	19.8	21.8
24/08	236	20.2	1.53	6.57	6.5	6.9
27/08	239	11.4	0.06	1.36	0	0
30/08	242	22.0	7.93	17.58	7.0	7.0
06/09	248	47.0	42.81	44.97	43.4	48.5
24/09	266	21.8	13.47	16.84	14.8	16.0
Total		**280.0**	**142.9**	**165.6**	**138.2**	**150.5**
R/P			**0.51**	**0.59**	**0.49**	**0.54**

Table 4. 10 Rainfall-runoff relationships on the Dera Calcic Fluvic Regosol ecotope; 2004.

Date	DoY	Rainfall (mm)	Observed R (mm)		Simulated R (mm)	
			CT	NT	CT	NT
01/07	183	9.4	0.78	1.60	1.3	1.4
12/07	194	49.4	22.91	28.72	26.5	28.9
15/07	197	14.6	9.77	12.28	11.3	13.0
21/07	203	11.6	0.29	1.63	0.6	0.6
29/07	211	16.9	3.61	5.10	6.4	6.4
30/07	212	24.9	9.13	10.96	6.6	7.1
07/08	220	12.8	0.43	1.00	0.1	0.1
08/08	221	18.0	7.65	9.08	6.1	6.1
10/08	223	42.5	18.30	19.71	19.5	20.4
19/08	232	12.4	8.07	9.54	7.2	7.6
23/08	236	9.0	3.41	3.79	5.2	6.1
18/09	262	10.0	1.71	1.83	0.6	0.6
03/10	277	21.6	7.26	8.19	7.3	7.3
Total		**253.1**	**93.4**	**113.1**	**98.7**	**105.6**
R/P			**0.37**	**0.45**	**0.39**	**0.42**

Sorptivity is the soils ability to absorb water as a sponge without interference of gravity (Stroosnijder & Hoogmoed, 1984). Babacar *et al.* (2005) reported that sorptivity, infiltration rate and hydraulic conductivity became similar on CT and NT plots after 160 mm of cumulative rainfall on sandy loam soils of central part of Senegal. This showed the short lived effect of tillage. Similar results are also reported by Rao *et al.* (1998) in India on tropical Alfisols. Slattery & Bryan (1992) in a laboratory experiment found a rapid seal formation (< 3 minute) in a sandy loam soil. The two tillage practices reach almost at equal level of crust formation. The soil surfaces formed on the CT and NT plots following high intensity rainfall showed a similar SD_m and I_f values, resulting in similar amounts of runoff. This phenomenon was observed in both experimental years (Table 4.9 & 4.10). Simulated runoff values also vary from too low to too high. These variations may be caused by one or more of the following factors:

1. Experimental errors
2. Storage change of the soil at 2nd cultivation especially carried out in 2003 on August 14 for CT plots
3. Variations in I_f caused by differences in antecedent moisture and sorptivity due to different dry spell intervals between storms
4. Change in I_f during crust development.

For calibration purpose it was necessary to use average I_f, s and γ values relevant to the whole range of different crust formation processes and rainfall intensities. It is obvious that the soil storage at the beginning of the rainfall season had been high, until the crust was well established and stabilized. But, once the structural crust is formed and followed by formation of the successive depositional and erosion crusts, most of the depression smoothed. During the process, the storage acquires variable values temporally. Accordingly this may caused some deviation in the simulated runoff.

4.3.2 Well simulated storms

Most of the runoff at Dera was well simulated by the M & C model, on both the NT and CT plots (Tables 4.9 and 4.10). In particular runoffs from intense rainfall events were well simulated. During 2004 cultivation on CT was only carried out once, at the beginning of the experiment. The first three storms, on DoY 163 (5.5 mm), 179 (8.5 mm) and 183 (9.4 mm) virtually only wet the surface soil and initiated crust formation. The storms were small and their intensity smaller than I_f in most of the storm's duration (Figures 4.11, 4.12 and 4.13). The first two were not able to produce runoff due to the high sorptivity value on both treatments and the high s value on the CT treatment due to the recent cultivation. It seems, however, that even the short bursts of relatively high Pi are sufficient to promote considerable crust formation and reduction in surface storage (s). This is probably particularly true for storms on DoY 179 and DoY 183 (Figures 4.12 & 4.13), where Pi reached > 50 mm hr^{-1} for a few minutes. Support for this conclusion is provided by the results for storm on DoY 194 of 49.9 mm which fell 11 days after storm on DoY 183. It caused a large amount of runoff, 29 and 23 mm on NT and CT plots respectively (Table 4.9 & Figure 4.14).

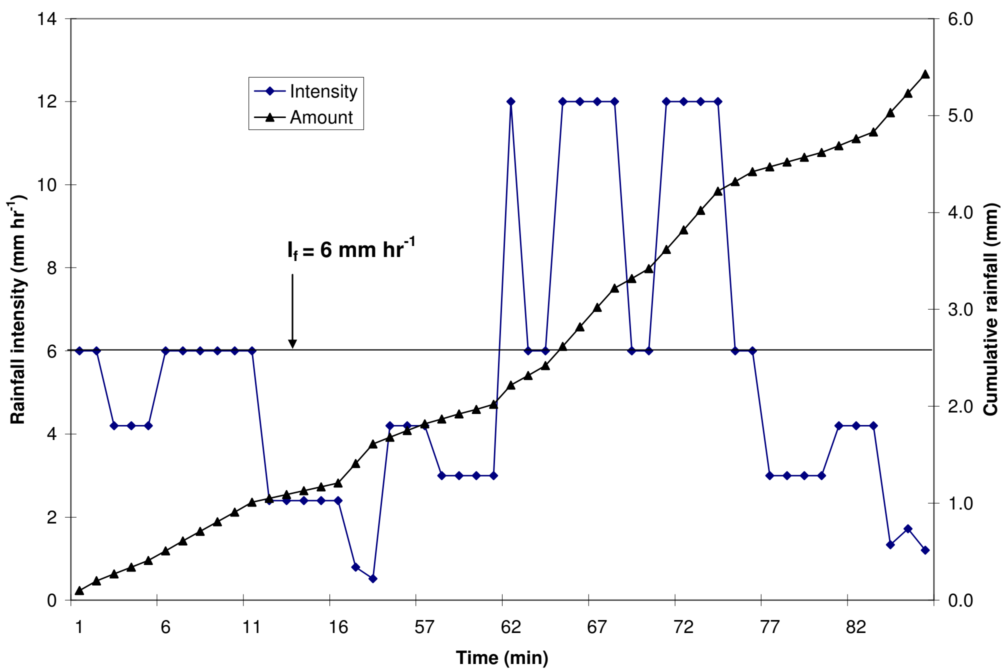


Figure 4. 11 Storm on DoY 163 of 2004 on the Dera Calcic Fluvic Regosol ecotope.

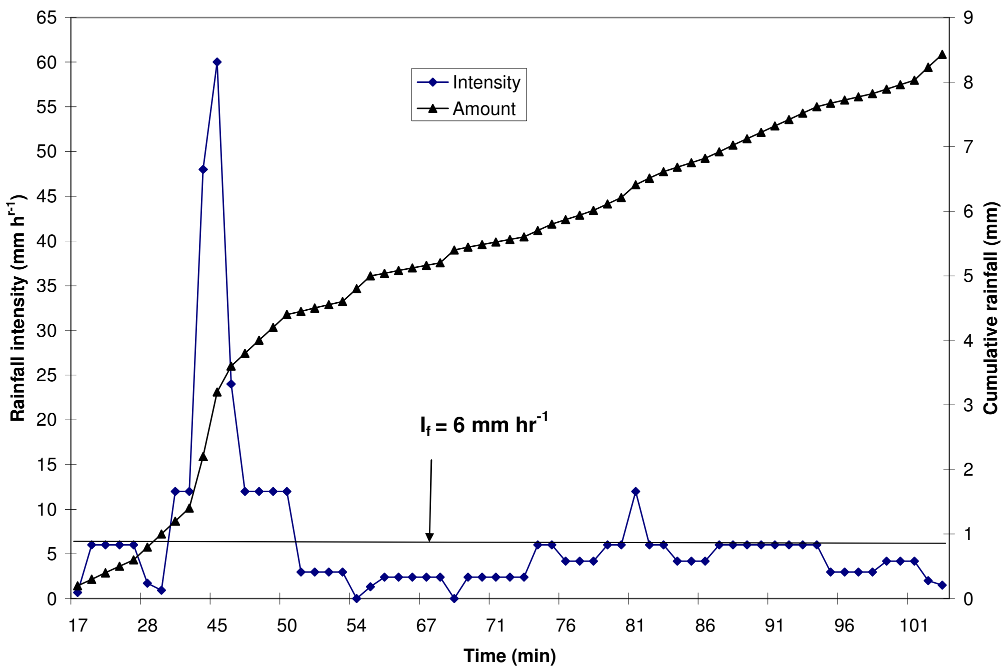


Figure 4. 12 Storm on DoY 179 of 2004 on the Dera Calcic Fluvic Regosol ecotope.

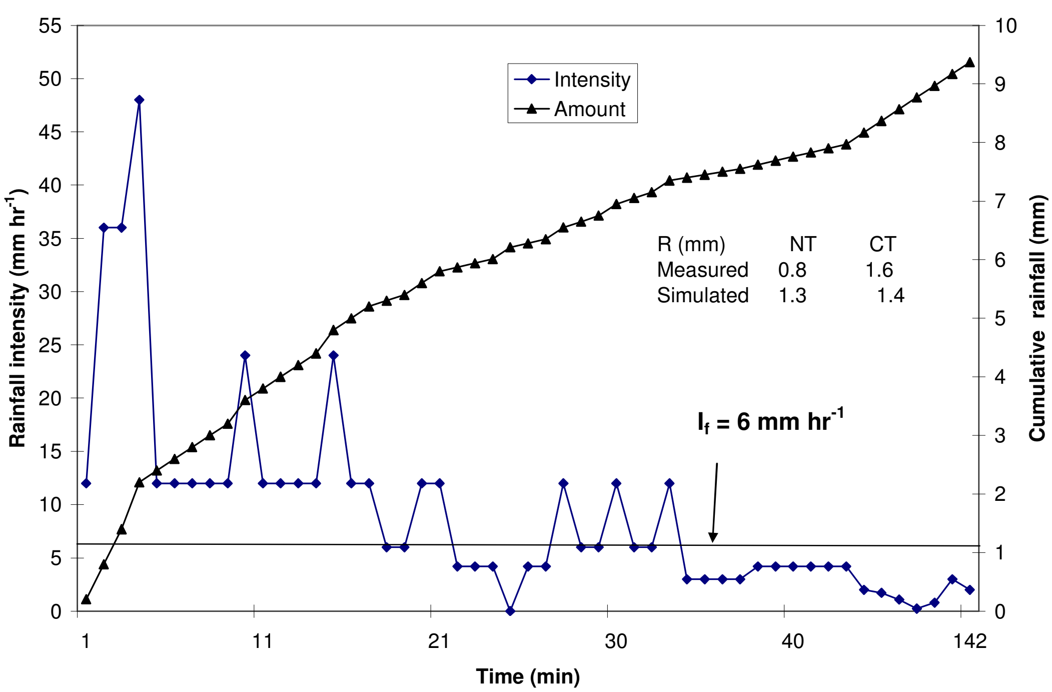


Figure 4. 13 Storm on DoY 183 of 2004 on the Dera Calcic Fluvic Regosol ecotope.

This was a storm of high intensity (Figure 4.14). More than 73 % of the runoff probably occurred during the first quartile of the storm or 26 % of the total duration. Its limit is shown by an arrow line in the intensity-cumulative graph (Figure 4.14). Storm on DoY 194 probably completed crust formation and reduced the infiltration rate to its final value of (I_f) was Pi > 6 mm hr^{-1} for the first 80 minutes, during which cumulative rainfall amounts to 36 mm or 73.5% of the total storm (shown by arrowed line in Figure 4.13). After 80 minutes, the intensity decreased to 6 mm hr^{-1} and lasted for a further 191 minutes contributing only 13 mm of rain. Thus, once the crust is formed and stabilized on both treatments, runoff was closely simulated by the model. Small differences in runoff from the two treatments were also explainable by the rapid crusting and collapse of the clods on the CT treatment due to the high Pi periods during the storms. One also sees small runoff differences between the two cultivation practices up to the end of the rain season on 2004 (Table 4.10). This proves that the storage difference that had been created at the beginning by cultivation had been largely eliminated early in the season. This is therefore an important characteristic of this soil and explains the no significant difference statistically between the runoff treatments.

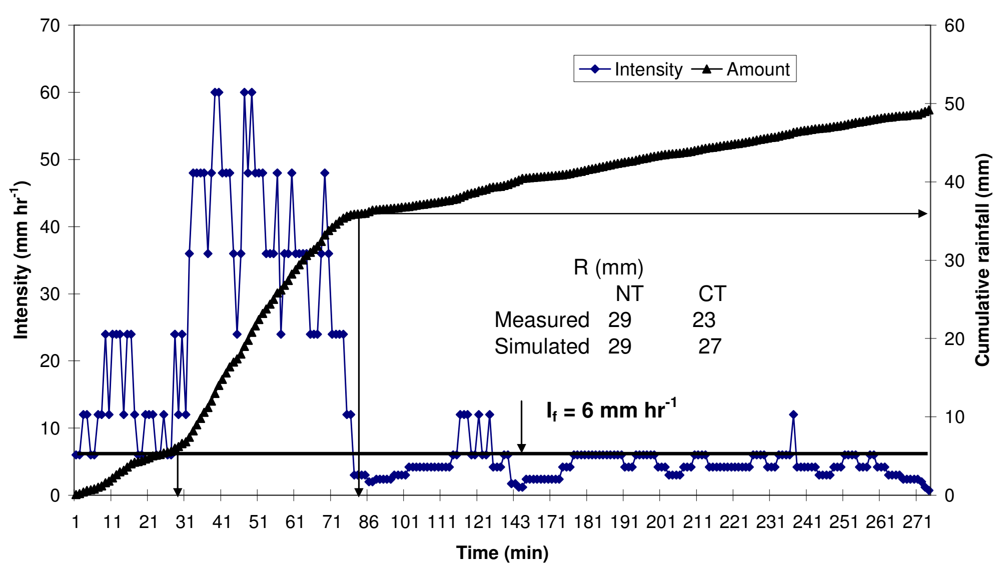


Figure 4. 14 Storm on DoY 194 of 2004 on the Dera Calcic Fluvic Regosol ecotope.

4.3.3 Storms not well simulated

These storms include mostly those from CT plots; especially those events happening after cultivation was done. For example storm on DoY 236 (Figure 4.15) occurred 10 days after the 2nd cultivation during 2003. Pi was > I_f during the first 26 minutes during which about 10 mm of rain fell. The measured and simulated values on the NT plot are very similar, 6.6 and 6.9 mm, respectively. On the CT plot however there is a large difference between the measured and simulated values, i.e. 1.5 and 6.5 mm respectively. This indicates that s had been temporarily greatly increased by the depressions created by the second cultivation on the CT plots. It is impractical to have a separate s value for each storm. Models are developed to solve such kind of problems. They calculate and assign an average value to such parameters which vary spatially and temporally by selecting those which minimize the standard deviation. In this way a reasonably good output is produced, as in this study.

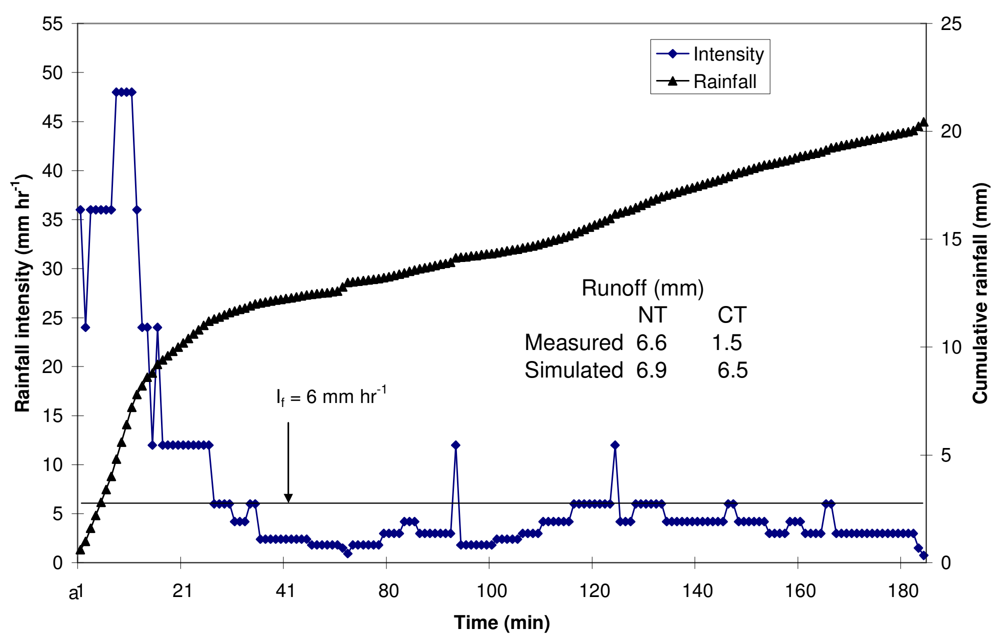


Figure 4. 15 Storm on DoY 236 of 2003 on the Dera Calcic Fluvic Regosol ecotope.

4.4 Conclusions

In this study rainfall-runoff relationship were quantified for a semi-arid water stressed ecotope in Ethiopia. The soil of the Dera Calcic Fluvic Regosol ecotope is a Calcic Fluvic Regosol with a sandy loam texture of the 0-200 mm depth. Ca is the dominant cation, the pH is around 8.0 in the depths 0 to 600 mm, and is around 9.0 below 600 mm. The exchange complex is saturated with bases below 200 mm depth. Leaching has clearly been minimal in this soil. The drainage curve gave a DUL value of 225 mm for the 0 – 1300 mm profile. This soil is very susceptible to crust formation caused by high rainfall intensity. The crusts are in general very hard and smooth. These crusts are known as sieving structural type.

In this study it was found that the averages R/P over the two rainy seasons R/P were 0.52 and 0.44 on the NT and CT treatments, respectively. These are very high values. Soil crusting is shown to be the main factor reducing I_f. The crusting was produced by soil dispersion caused by the high intensity storms which dominate in these semi-arid ecotopes.

During the calibration process an appropriate I_f value was found to be 6 mm hr^{-1}, appropriate s value were found to be 0.3 and 0.4 mm for NT and CT treatments, respectively, and the best γ value found to be 0.6 mm^{-1}. The calibrated M & C model simulated the observed runoff well over the two seasons giving R^2 = 0.94, D-index = 0.98, and slope of the correlation equation 1 for both cultivation practices. This result confirms how influential the soil crust is in depressing I_f on certain soils in the semi-arid areas, regardless of the antecedent soil moisture conditions.

The result confirms one of the hypotheses of this study, i.e. "the Morin & Cluff (1980) runoff model will satisfactorily predict runoff on the chosen ecotopes". This model should therefore be valuable for extrapolating results to similar ecotopes. Most importantly, the result is encouraging with regard to introducing the practice infield water harvesting in similar ecotopes. On frequently cultivated fields the M & C model is not expected to give good results since it operates best after the crust has been formed. Storms with rapid fluctuation in intensities are also not well simulated.

5. MELKASSA

5.1. Ecotope characterization

5.1.1. Climate

The Melkassa Hypo Calcic Regosol ecotope is located about 15 km north of Dera. The climate is similar to that of Dera. The main rainy season is during the months June to September, during which 68% of the annual rainfall occurs (Table 5.1 and Figure 5.1). The measured class A pan evaporation data (Eo) and the potential evapotranspiration (ETo), calculated using the Penman-Montieth equation, correlate well as indicated by R^2 0.92 (Figure 5.2). The highest evaporative demand occurs during the months of March, April and May. During these months, the mean maximum temperature (Txm) is around 30^{o}C while the mean relative humidity (RHm) drops to 51%. During the main crop growing season of June to September conditions are more favourable with Txm and RHm approximately 27^{o}C and 64% respectively.

According to the recent agroecological zones classification of Ethiopia (MoA, 2000), the Melkassa Hypo Calcic Regosol ecotope falls in the zone termed hot to warm semi-arid lowlands (SA1). Alternatively, according to Engida (2000), Melkassa is classified under areas with two growing seasons and termed TS 221. This belt exhibits two growing seasons of 50 and 100 days in length for the 1st and 2nd seasons, respectively, and has an annual rainfall and PET of about 772 mm and 1994 mm, respectively. The AI of 0.39 (Table 5.1) identifies this as a semi-arid area.

Table 5. 1 Long-term (1977 – 2003) mean monthly climatic data of Melkassa meteorological station. ETo is Penman-Monteith reference ET.

Month	Rainfall (mm)	MinT (^oC)	MaxT (^oC)	RH (%)	Sshine (Hr)	Wind Sp (K/hr)	ETo (mm)	A.I
J	14	12	28	52	8.9	11	167	0.084
F	26	13	29	50	8.7	12	167	0.156
M	51	15	30	52	8.3	11	189	0.270
A	52	15	30	51	8.3	10	180	0.289
M	52	16	31	51	8.9	10	186	0.080
J	68	16	30	53	8.4	12	177	0.384
J	186	16	27	67	7.0	12	149	1.248
A	181	15	26	69	7.2	10	140	1.293
S	82	14	27	65	7.3	6	135	0.607
O	42	12	29	50	8.6	8	164	0.256
N	8	11	28	46	9.7	11	171	0.047
D	11	11	28	49	9.5	11	171	0.064
Total	772						1994	
Mean		14	29	55	8.4	10		**0.387**

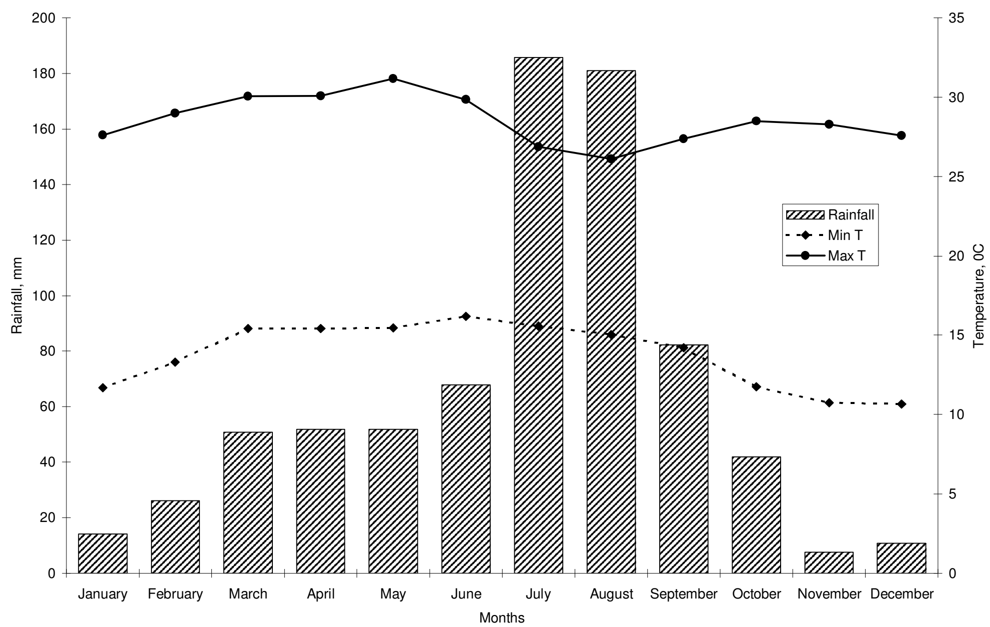


Figure 5. 1 Melkassa ecotope rainfall and temperature distribution (1977-2003).

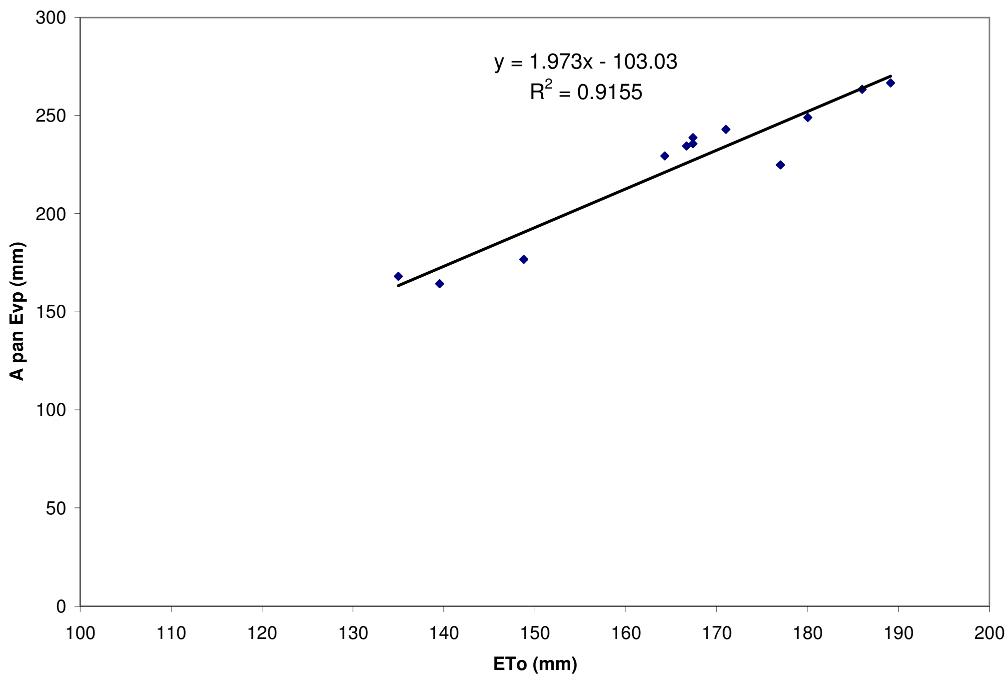


Figure 5. 2 Relationship of A pan evaporation (Eo) and ETo at Melkassa.

5.1.2 Topography

The ecotope, located at the middle of the Rift Valley, is dominated by gently sloping, flat areas. Generally, the normally cultivated crop lands have a slope of < 5%. The slope at the experimental site was 1% southeast.

5.1.3 Soil

5.1.3.1 Morphology and classification

A soil profile description was made at a profile pit 3 meters deep near the experimental site. The detailed profile description and analytical results are presented in Appendix 2 and Table 5.3. The soil is classified as Hypo Calcic Regosol in WRB (FAO, 1998b) and Etosha Vetkuil (2111) (Soil Classification Working Group, 1991). This soil differs from the Dera Regosol due to the position of secondary carbonates in the soil profile. The parent material is fluvial deposit.

Table 5. 2 Melkassa Hypo Calcic Regosol: particle size distribution (%).

Horizon	Depth (mm)	coSi	fiSi	Cl	coSa	meSa	fiSa	Texture
Ap	0-200	19	19	33	5	9	17	Clay loam
AI1	200-500	13	27	33	2	7	17	Clay loam
AI2	500-1000	10	31	34	3	6	13	Clay loam
AI3	1000-1500	12	30	34	2	4	16	Clay loam

5.1.3.2 Chemical properties

The chemical properties show a trend of increasing increments to the 3rd horizon with the exception of Na, Ca and Mg, which continued increasing to the 4th horizon (Table 5.3). The abundance of Ca indicates minimal leaching during pedogensis. It also indicates minimum deep drainage under natural conditions. Results include Ca domination of the cation suite, with high pH and base saturation (Table 5.3). The high CEC of the soil, and especially of the clay, shows that smectites dominate the clay mineralogy. This is also the reason for the high water holding capacity of the soil. The total amount of Na in each horizon is very low. The high organic carbon content is unusual for semi-arid surface soils.

Table 5. 3 Chemical properties of the Melkassa Hypo Calcic Regosol.

Depth (mm)	Extractable/Exchangeable bases ($cmol_c\ Kg^{-1}$)					CEC ($cmol_c\ kg^{-1}$)		Base saturation (%)
	Ca	K	Mg	Na	Sum	Soil	Clay	
0-200	19.4	4.3	3.7	0.3	27.8	32.5	98.5	86
200-500	26.6	5.1	4.1	0.4	36.3	30.0	90.9	121
500-1000	31.8	10.0	3.9	0.6	46.3	36.3	106.8	128
1000-1500	61.1	6.7	5.7	1.4	75.0	29.5	86.8	254

Table 5.3 continued

Depth (mm)	pH (H_2O)	pH (KCl)	ESP (%)	OC (%)	OM (%)
0-200	7.79	6.71	0.9	1.60	2.75
200-500	8.36	7.19	1.3	1.29	2.21
500-1000	8.51	7.49	1.7		
1000-1500	8.05	7.46	4.7		

5.1.3.3 Physical properties

5.1.3.3.1 Matric potential

Matric suction data for the four layers are similar due to the uniformity of the texture with depth (Table 5.4 and Figure 5.3).

Table 5. 4 Melkassa Hypo Calcic Regosol: Matric suction data. (The % values are gravimetric).

Horizon	Depth (mm)	Db (Mg m^{-3})	θ at -0.33 bar		θ at -15 bar		Δθ
			%	mm	%	mm	mm
Ap	0-200	1.19	30	71	16	39	33
AI1	200-500	1.20	30	108	17	61	47
AI2	500-1000	1.14	33	188	16	90	98
AI3	1000-1500	1.16	34	196	17	101	96
Total				564		290	274

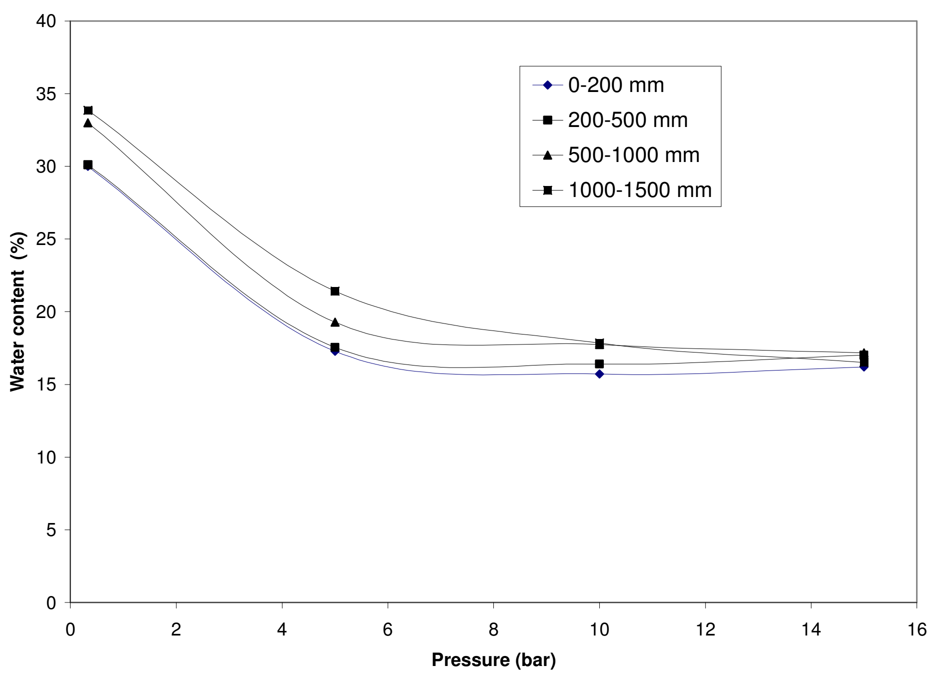


Figure 5. 3 Matric suction curves for the Melkassa Hypo Calcic Regosol**.**

5.1.3.3.2 Penetrometer resistance

During the measurement of penetrometer resistance θm (gravimetric water content) was 32.7%. The cone had an area of 2 cm^2. The crusts formed on the NT and CT plots showed different penetrometer resistances at the surface of the soil and at 100 mm depth, but with no significant differences between the two cultivation methods (Table 5.5).

Table 5. 5 Penetrometer resistances of the different cultivation methods.

Sampled depth	Soil resistance in Kilo Newton	
	NT mean	CT mean
At the surface	0.17	0.12
At 100 mm depth	0.26	0.23

However, there is a significant difference (at $p = 0.05$ level) between depths for both tillage practices. The soil resistance was slightly lower than that on the Dera Calcic Regosol for all measurements.

5.1.3.3.3 Crust morphology

The crust of the soil is a depositional type and formed by raindrop impact (Valentin & Bresson, 1992). It is about 5 mm thick with finer particles on the top side. During drying the crust develop cracks between plates of 15-20 cm in diameter (Figure 5.7). Similar observations were also reported in loess soils in Israel by Eldridge *et al.* (2000).

5.1.3.3.4 Drainage curve

DUL was found to be 390 mm, after a drainage period of 50 days (Figure 5.4). The difference between the field measured value for the amount of water which the soil profile can hold against gravity (390 mm) and the so called “field capacity” estimate at 0.33 bars of 564 mm (Table 5.2), reveals the unreliability of the latter procedure for soil water studies.

The drainage curve is described by equation 3.3:

$$Y = -60.284 \, \text{Ln}(t) + 626.16 \quad \text{mm} \qquad (5.1)$$

$R^2 = 0.95$

Where Y = water content at time t (mm)

t = days after saturation

Equation 5.1 can be used to estimate what is termed the crop modified upper limit (CMUL) of available water (Hattingh, 1993 & Hensley *et al.*, 1993). CMUL provides an estimate of the amount of water which a crop can extract from a very wet soil while it is draining from field saturation to DUL. The procedure equates the rate at which water is extracted by ET to the drainage rate. Differentiation of equation 5.1 gives the drainage rate at any time t after saturation for this profile, viz:

$dy/dt = 60.284 * 1/t \quad mm\ d^{-1}$

Using the data in Table 5.1 and the appropriate Kc value in Table 7.1 an average ET value for maize during the months July to September is estimated at 5.1 mm d^{-1}. Substituting this value for dy/dt makes it possible to calculate the time at which the ET rate equals the drainage rate

$5.1 = 60.284 * 1/t$

$t = 11.8$ days

Substituting this value for t in equation 5.1 gives the value of CMUL.

$Y = 626 – 60.284Ln(11.8) \quad mm$

$Y = CMUL = 477$ mm

The amount of water which a mature maize crop can extract from a very wet soil while it is draining between field saturation and DUL is therefore estimated as being 477-390 = 87 mm. Under maize production condition DUL is estimated to be reached after 11.8 days.

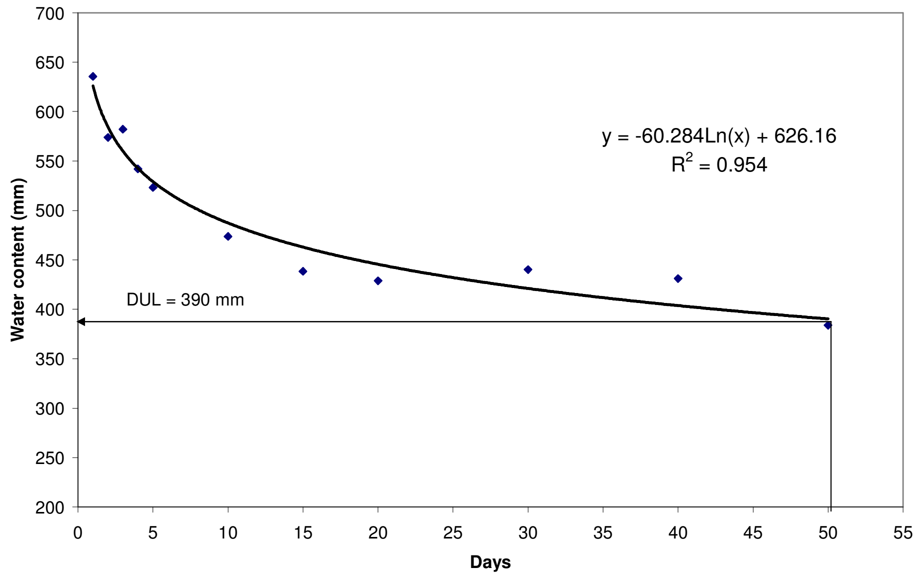


Figure 5. 4 Measured and fitted drainage curve for the Melkassa Hypo Calcic Regosol.

5.2. Infiltration rate

The cumulative infiltration (Ic) and the infiltration rate (I) of this soil are calculated using equations 3.1 and 3.2. The results are presented in Table 5.6 and Figure 5.5.

Table 5. 6 Measured cumulative infiltration (Ic).

Sprinkler infiltrometer					
1st Run		2nd Run		Average	
T (min)	Ic (mm)	T (min)	Ic (mm)	T (min)	Ic (mm)
3.65	3.00	3.18	3.00	3.42	3.00
9.18	5.00	5.58	4.00	7.38	4.50
16.77	5.00	17.97	6.00	17.37	5.50

The exponential cumulative infiltration curve was obtained with regression analysis (Figure 5.5). From this curve, the constants c and k were determined. Their values are c = 1.985 and k = 0.370. Substitution of these values in equation 3.1 allows the calculation of I as fallows:

$I = 1.985 * 0.730\ T^{0.370-1}$ mm min^{-1}

Or $I = 44.074\ T^{-0.6299}$ mm hr^{-1}

$I = 44.074/T^{0.630}$ mm hr^{-1}

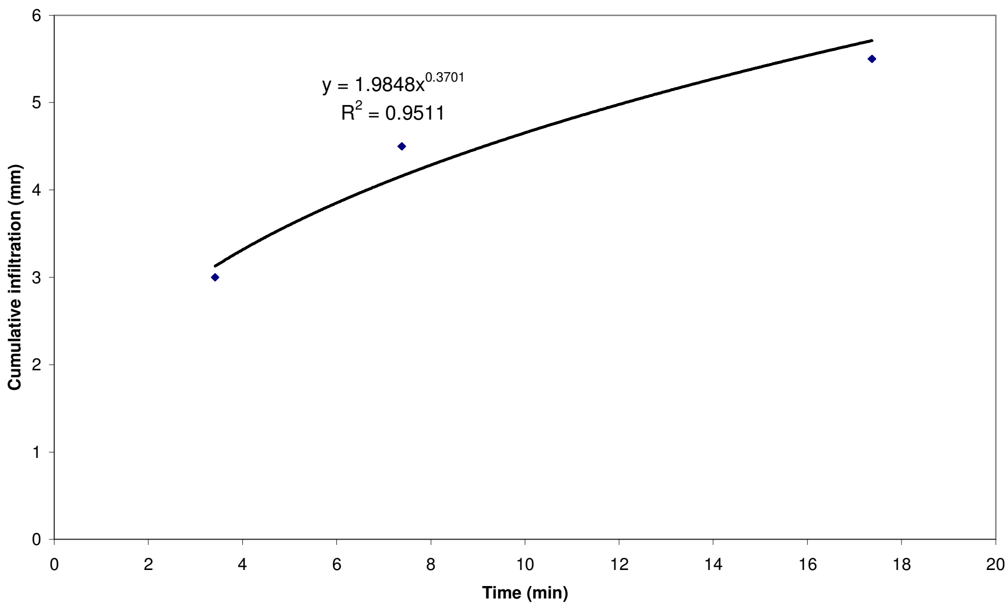


Figure 5. 5 Measured and plotted cumulative infiltration**.**

This equation enables the estimation of I_i at say t = 0.5, and I_f at say t = 20 minutes. Results are I_i = 68 mm hr^{-1} and I_f = 6.7 mm hr^{-1}. These were used as first approximation values for the M & C model calibration procedure. In practice I_f values will vary depending on a number of factors such as the degree to which the crust has formed and the antecedent water content of the soil. The best fit I_f value will be an average one for the season.

The equation after Morin & Benyamini (1977) was found to be:

$I(t) = 64\ e^{-0.6Pi} + 6$, where Pi = rainfall intensity in mm hr^{-1}.

Figure 5.6 shows the plot of the infiltration rate for the Morin & Benyamini (1977) infiltration equation. The graph shows infiltration rate (I) against time for rainfall intensities of (Pi) 6, 10 and 20 mm hr^{-1}. The parameter γ was found as 0.6 mm^{-1} during the calibration process of the runoff model. The graph shows that the higher the rainfall intensity the sooner I_f is reached.

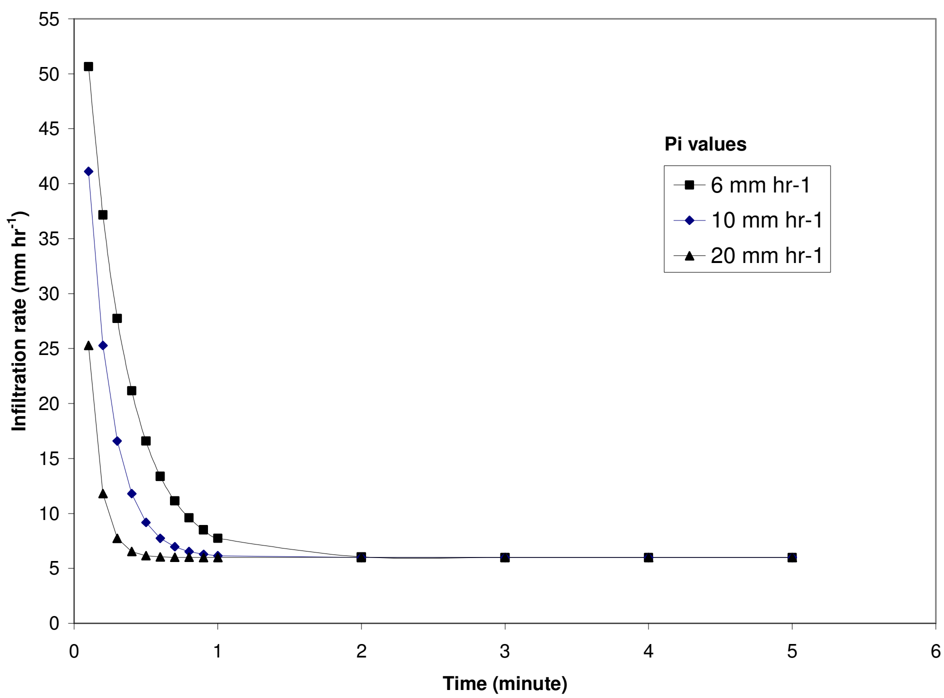


Figure 5. 6 Infiltration curve of Melkassa Hypo Calcic Regosol using the Morin & Benyamni (1977) model.

5.3 Rainfall–runoff relationships

5.3.1 M & C model calibration and validation

Rainfall amounts (P) and intensities (Pi) were measured during the main rainy seasons of 2003 and 2004 (Appendix 5). Runoff (R) measurements are only available for 2004. The M & C model was calibrated and validated using the rainfall-runoff measurements for 2004. The validated model was then used to predict R for each storm of the 2003 season. It was found that storms with amounts ≥ 9.0 mm were potentially capable of producing a significant amount of runoff, provided their rainfall intensity exceeds I_f for some time during the storm period.

A similar procedure for model calibration and validation to that used at Dera was followed. Results are presented in Tables 5.7 A and B and Table 5.8. Appropriate values for I_f and γ were found to be 6 mm hr^{-1} and 0.6 mm^{-1}, respectively. These are the same as those selected for Dera.

Table 5. 7 Melkassa runoff calibration using the fixed parameters: I_i = 70 mm hr^{-1}, I_f = 6 mm hr^{-1} and γ = 0.6 mm^{-1}.

A. NT plots

Objective functions & indices	s = 5 mm	s = 4 mm	s = 3 mm	s = 2 mm	s = 1.5 mm	**s = 1 mm***	s = 0.5 mm
RMSE	3.60	3.12	2.72	2.51	2.45	**2.41**	3.07
RMSEs	3.22	2.76	2.32	2.03	1.90	**1.78**	1.31
$RMSE_u$	1.60	1.46	1.43	1.49	1.54	**1.63**	2.78
MAE	3.10	2.70	2.38	2.32	2.30	**2.29**	2.77
R^2	0.98	0.98	0.99	0.99	0.98	**0.98**	0.95
D-index	0.98	0.98	0.99	0.99	0.99	**0.99**	0.98
Slope (b)	0.93	0.95	0.98	1.01	1.01	**1.02**	1.04
Intercept (a)	-2.37	-2.26	-2.14	-2.12	-2.03	**-1.93**	-1.63
RMSEu/RMSE	0.44	0.47	0.52	0.59	0.63	**0.68**	0.90

B. CT plots

Objective functions & indices	s = 8 mm	s = 7 mm	**s = 6 mm***	s = 5 mm
RMSE	1.79	1.77	**1.88**	1.92
RMSEs	1.14	0.87	**0.82**	0.97
RMSEu	1.39	1.54	**1.69**	1.65
MAE	1.24	1.24	**1.32**	1.48
R^2	0.98	0.98	**0.98**	0.98
D-index	0.99	0.99	**0.99**	0.99
Slope (b)	0.98	1.02	**1.06**	1.09
Intercept (a)	-1.02	-1.00	**-0.96**	-0.80
RMSEu/RMSE	0.77	0.87	**0.90**	0.86

Note: s = SD_m of the M & C model
* Selected s value

Table 5. 8 Validation of M & C model using the s values selected during calibration phase Table 5.7.

Objective functions & indices	NT plots	CT plots
RMSE	1.91	2.52
RMSEs	1.89	2.33
RMSEu	0.28	0.96
MAE	1.47	2.17
R^2	0.99	0.96
D-index	0.99	0.90
Slope (b)	1.10	1.70
Intercept (a)	-1.50	-6.70
RMSEu:RMSE	0.15	0.38

The calibration procedure revealed that the s values (= SD_m) which gave the best results with M & C model were 1 mm and 6 mm for the NT and CT plots respectively. These values, and their assessment parameters, are printed in bold (Table 5.7). Results of the validation test using these values, and the I_i, I_f and γ values (Table

5.7) are presented in Table 5.8. Significant aspects for both NT and CT are the relatively low RMSE values, very high D-index and R^2 values, and very low RMSEu:RMSE values. The latter is an unsatisfactory feature for which an explanation is not available. However, this is not considered to be a serious short coming because of the good overall correlation finally between measured and predicted runoff values for the 2004 season for both the NT and CT treatments; R^2 values were 0.86 and 0.94, respectively. The small number of observations (4) available for validation was probably also a factor which contributed to the low RMSEu:RMSE value.

Melkassa storms generally exhibited intense rainfall during the first and second quartiles of the events. Huff (1967) in his study at Illinois in the USA also found a similar pattern. In the 2003 rainy season the total amount of the rainfall for events ≥ 9 mm was 297 mm. It was uniformly distributed throughout the season. There were six storms in July, seven in August and four in September, with 103 mm, 114 mm and 80 mm rainfall amounts, respectively (Table 5.9 A). The M & C model predicted R/P as 0.3 and 0.16 on NT and CT plots respectively. Most of R (57%) came from the three big storms on DoY 199, 236 and 249. For 2004, rainfall events ≥ 9 mm totalled 210 mm, producing R/P values of 0.6 and 0.4 on the NT and CT plots respectively. Unlike 2003, the rainfall distribution in 2004 was non-uniform with two large storms in July followed by one large storm in August, and one large storm each in September and October. This pattern would have caused a shortage of water during the flowering and maturity stage of the cropping period. For 2004 there was a significant difference ($p = 0.05$ level) between the runoff on the two cultivation practices, with an overall means per storm of 15.5 mm and 10.5 mm on the NT and CT plots respectively. The significant difference is attributed to the larger SD_m values of the CT plots, presumably due to the two cultivation practices carried out on them during the season, and also the relatively few heavy storms capable of producing a similar crusted surface to that on the NT plots. The CT plot was cultivated at the beginning of the study and after storm on DoY 212. This left a rough surface with considerable depressions that persisted for a longer period throughout the rainy season (Figure 5.7).

Table 5. 9 Measured and simulated runoff during the 2003 (A) and 2004 (B) rainy seasons at Melkassa.

A

Date	DoY	P (mm)	NT simulated R (mm)	CT simulated R (mm)
July 19	199	26.9	13.9	10.2
July 21	202	9.8	1.4	0.0
July 22	203	10.2	1.0	0.0
July 24	205	12.9	1.4	0.0
July 26	207	26.6	4.1	0.0
July 29	210	17.0	8.9	5.2
Aug 02	214	12.1	0.0	0.0
Aug 03	215	11.1	1.0	0.0
Aug 13	225	13.2	3.3	0.0
Aug 20	232	14.2	5.2	1.8
Aug 24	236	34.6	17.0	12.9
Aug 27	239	11.0	0.0	0.0
Aug 30	242	17.6	0.9	0.0
Sept 06	249	30.8	18.2	14.3
Sept 08	251	18.6	5.6	1.5
Sept 23	266	14.2	5.2	1.8
Sept 29	272	16.3	0.6	0.0
Sum		**297.1**	**87.7**	**47.7**
R/P			**0.30**	**0.16**

B

Date	DoY	P (mm)	Measured R (mm)		Simulated R (mm)	
			NT	CT	NT	CT
July 12	194	57.5	36.9	30.3	34.5	30.6
July 30	212	42.3	25.4	20.5	25.0	21.2
Aug. 7	220	12.4	1.8	0.2	0.0	0.0
Aug. 8	221	11.7	2.3	0.3	0.2	0.0
Aug 10	223	31.6	25.9	10.5	12.2	7.6
Aug 19	232	10.2	7.4	4.2	3.4	0.1
Sept. 8	252	22.0	16.4	11.4	18.2	13.8
Oct. 3	277	21.9	8.0	6.5	8.2	3.8
Sum		**209.6**	**124.1**	**83.9**	**102.4**	**77.1**
R/P			**0.59**	**0.40**	**0.49**	**0.37**

Figure 5. 7 Runoff plots at Melkassa during 2004 showing the development of crust and high SD_m condition on the CT plots (front and rear plots).

Once the M & C model had been calibrated and validated, it was used to simulate the runoff of each storm during both years (Table 5.9 and Figures 5.8 and 5.9). The R^2 values of 0.86 and 0.94 for the NT and CT plots, respectively, reflects the good agreement between the measured and predicted values.

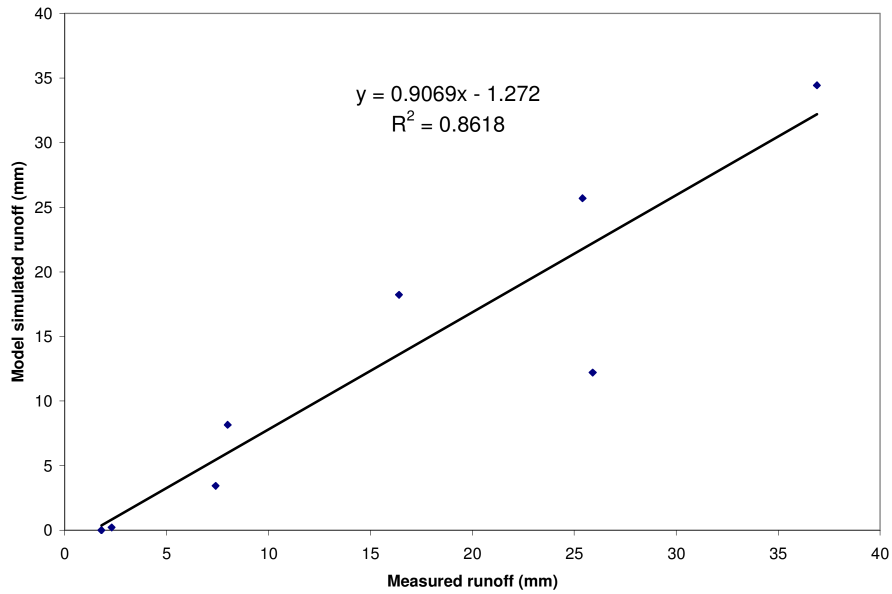


Figure 5. 8 Relationships between measured and model simulated runoff on NT plots for 2004; Melkassa Hypo Calcic Regosol.

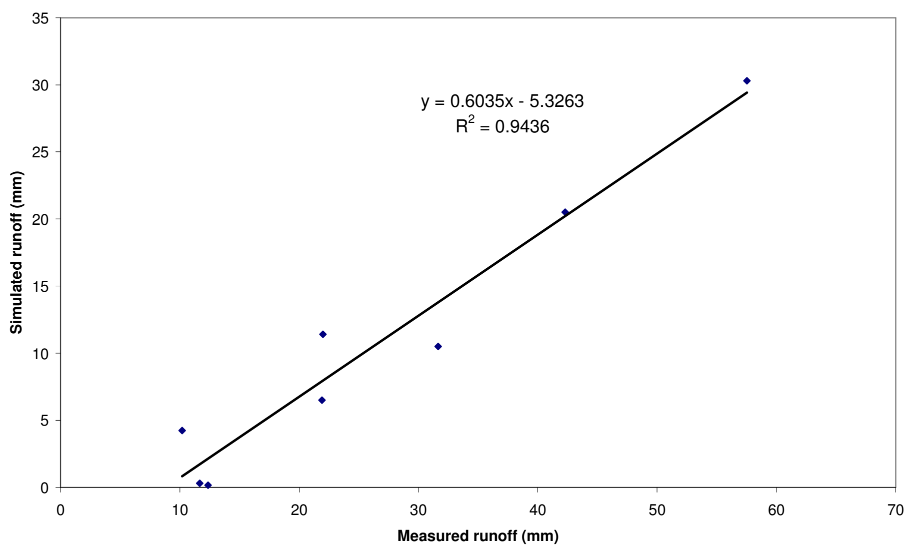


Figure 5. 9 Relationships between measured and model simulated runoff on CT plots for 2004; Melkassa Hypo Calcic Regosol.

5.3.2 Well simulated storms

Included are storms that start with intense rainfall ($P_i > I_f$), and those storms that acquire high intensities ($P_i > I_f$) later than in the first quartile, and continued with $P_i > I_f$ for sufficient time to fulfil the sorptivity and SD_m demand of the soil. A study of the rainfall vs. time graphs for a number of storms of this type indicates that about 4 mm of rain is needed to satisfy the requirements of sorptivity and SD_m (1mm) on the NT plots. Therefore, subtracting 4 mm from the cumulative rainfall value at the point where P_i becomes less than I_f, or at the point where the steepest part of the cumulative rainfall line terminates, will directly give an estimated amount of runoff on the NT plots.

Figure 5.10 and 5.11 show storms that begin with high intensity, during 2003 and 2004 respectively. For storm on DoY 199 of year 2003, the point where $P_i < I_f$ is indicated by an arrowed line. The $P_i > I_f$ part of the storm lasted for about 48 minutes. The arrow gives a value of 18 mm on the y-axis of the cumulative rainfall. Therefore, subtracting 4 mm (the value of sorptivity + SD_m) from 18 mm will give 14 mm. This is a similar result to the amount of runoff simulated by the M & C (1980) runoff model for NT plot which equals 13.9 mm (Table 5.9). Similarly, for CT plots if we subtract 3 mm plus the value of SD_m for CT plots (3 + 6 = 9), we will obtain 9 mm of runoff. Again the result is very close to the one estimated by the model as 10.2 mm (Table 5.9). Since no measurements of runoff were recorded during 2003, this analysis enables us to further validate the M & C model.

The storm on DoY 252 of 2004 (Figure 5.11) had $Pi > I_f$ throughout its 22 minute duration giving 22 mm of cumulative rainfall. Subtracting 4 mm from 22 mm gives an expected runoff of 18 mm on NT plots. The measured runoff was 16.4 mm, while the model simulated 18.2 mm. Using the same calculation as for storm on DoY 199; the expected runoff on CT plots is 13 mm. The measured and simulated values were 11.4 and 13.8 mm respectively. Storms with $P_i < I_f$ were also well simulated giving in all cases zero runoff.

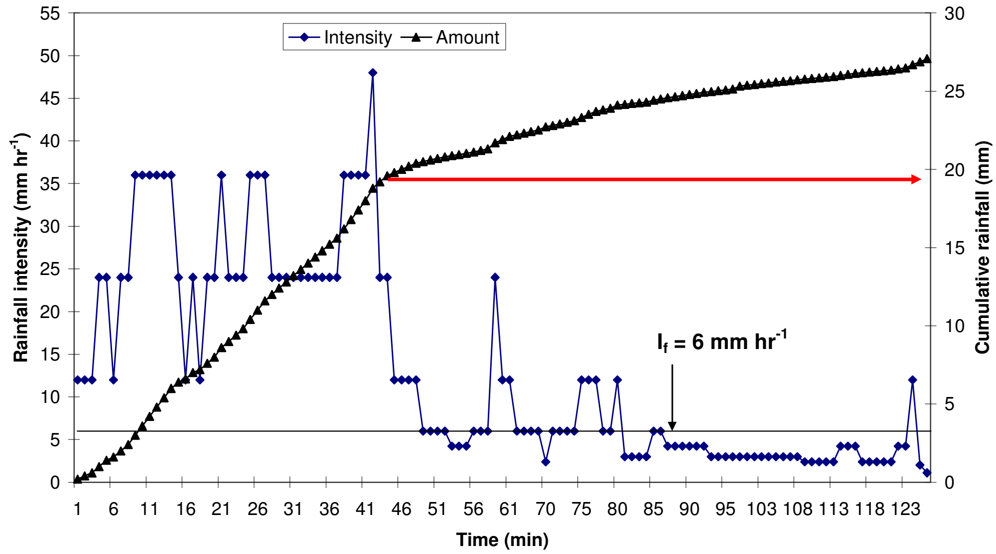


Figure 5. 10 Storm on DoY 199 of 2003 on the Melkassa Hypo Calcic Regosol ecotope.

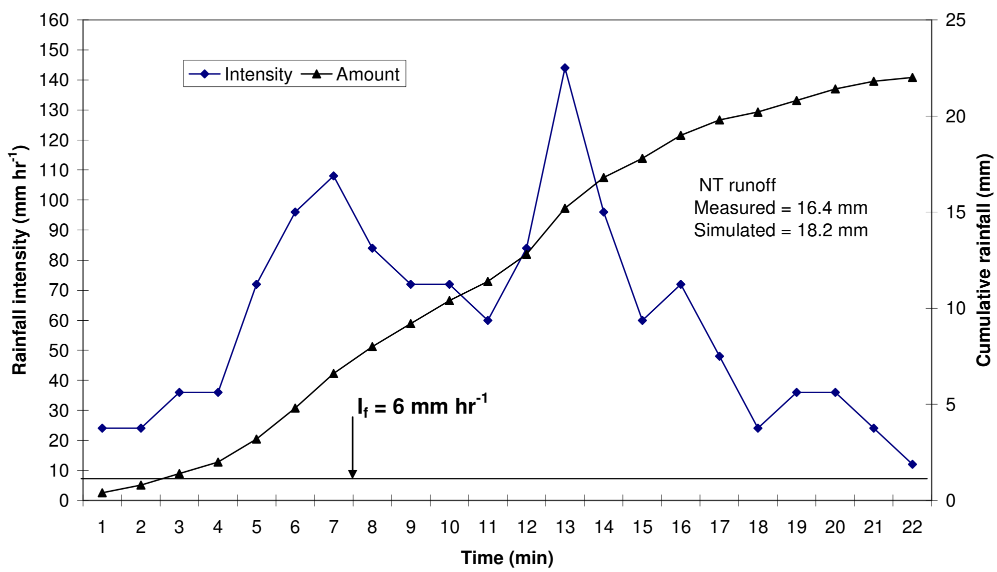


Figure 5. 11 Storm on DoY 252 of 2004 on the Melkassa Hypo Calcic Regosol ecotope.

The 2nd group of storms that were well simulated were characterized by $P_i > I_f$ for a certain period during the middle of the storm's duration (2nd, 3rd or 4th quartiles). It can be assumed that the sorptivity and SD_m demand for these storms was satisfied by the rain that fell before the intense part started, or else by bursts of intense rains ($P_i > I_f$) that occurred before or after the major intense period (m.i.p.). Huff (1967) defined "burst" as a cessation in rainfall or an abrupt, persistent change in rainfall rate. But here "burst of intense rain" was taken as part of the storm that show $P_i > I_f$ for a short time interval compared to the m.i.p. of $P_i > I_f$. At Melkassa this type of storm was rare. Figure 5.12 shows one of these storms (DoY 277) during 2004. In this storm the starting and ending of the m.i.p. is indicated by the arrowed lines giving 14 and 6 mm of rainfall on the cumulative rainfall y–axis. Thus, by subtraction, 14mm minus 6 mm, gives 8 mm of expected runoff, the same as the measured value. The model simulated 8.2 mm. Similarly, for storm on DoY 249 of 2003 (Figure 5.13) the arrowed lines indicate 26 mm and 7 mm of the cumulative rainfall as boundary values of the m.i.p. This gives 19 mm of expected runoff on NT plots, while the model simulated 18.2 mm.

It is clear that a long dry period between storms will increase the sorptivity of the soil. Storms which occurred immediately after cultivation on CT plots encounter high SD_m values. Both these factors will influence the accuracy of simulations. Unlike the Dera Calcic Fluvic Regosol ecotope, the CT plots on the Melkassa Hypo Calcic Regosol ecotope retained an almost similar SD_m value (6 mm) throughout the 2004 rain season. This may be due to the smaller number of intense rains after the second cultivation practice carried out on DoY 215.

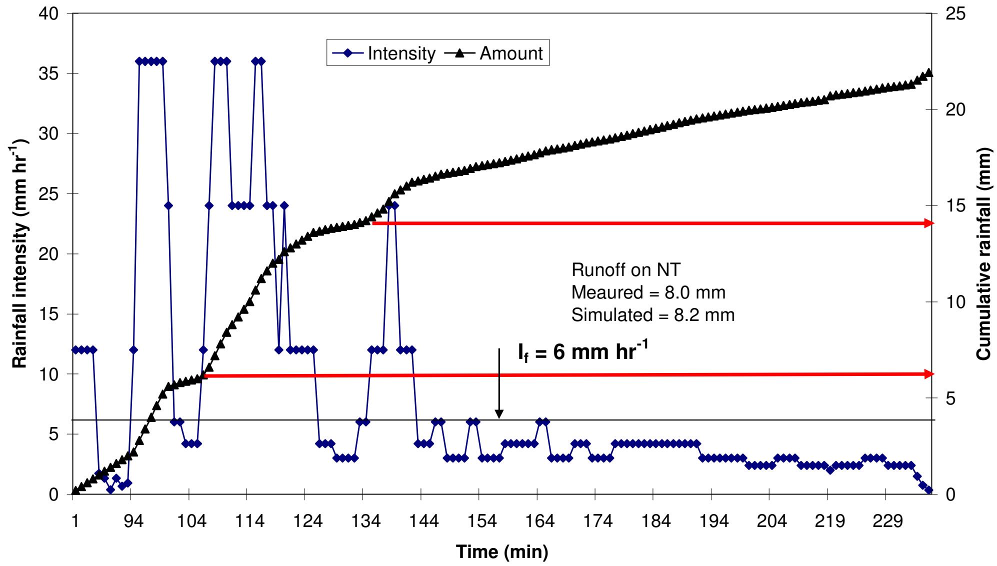


Figure 5. 12 Storm on DoY 277 of 2004 on the Melkassa Hypo Calcic Regosol ecotope.

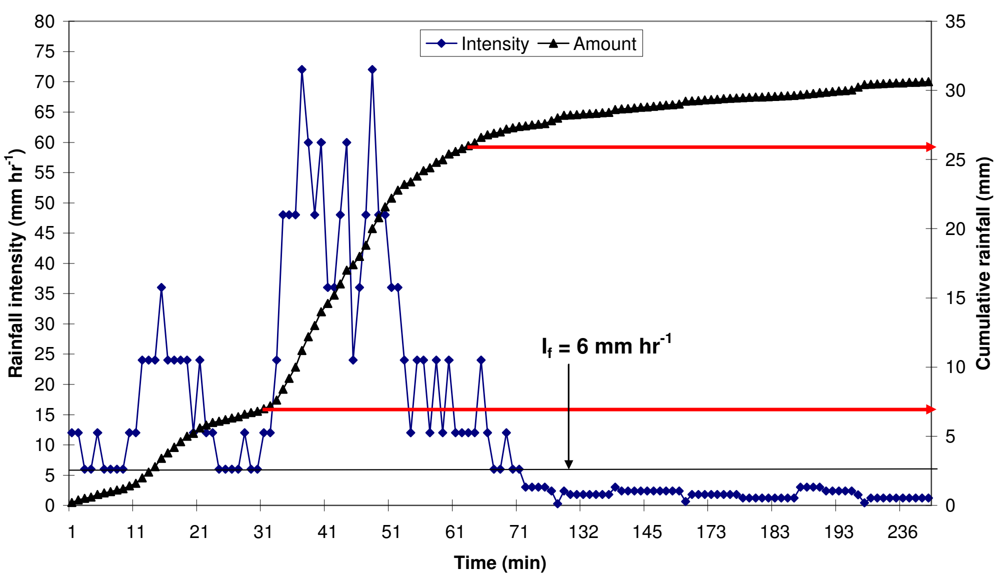


Figure 5. 13 Storm on DoY 249 of 2003 on the Melkassa Hypo Calcic Regosol ecotope.

5.3.3 Storms not well simulated

No runoff was over estimated during 2004. Storm on DoY 223 of 2004 gave an exceptionally high measured runoff value on the NT plot of 25.9 mm whereas the simulated value was only 12.2 mm (Figure 5.14). The high measured R was probably due to the fact that it occurred 48 hours after two continuous storms on DoY 220 and 221. Although these storms produced little R (1.8 and 2.3 mm from NT) they probably contributed enough water to leave the surface of the soil wet after 48 hours. As a result the demand for sorptivity was minimized. The other relevant factor was the occurrence of continuous small bursts of $P_i > I_f$ that lasted for about 80 minutes, between 78 to 158 minutes (Figure 5.14). They covered approximately a quarter of the storm's duration. These bursts may not have been considered by the model as significant time segments to produce runoff. Similarly storms on DoY 232 and 251 of 2004 and 2003, respectively, were under simulated by the model (Appendix 5).

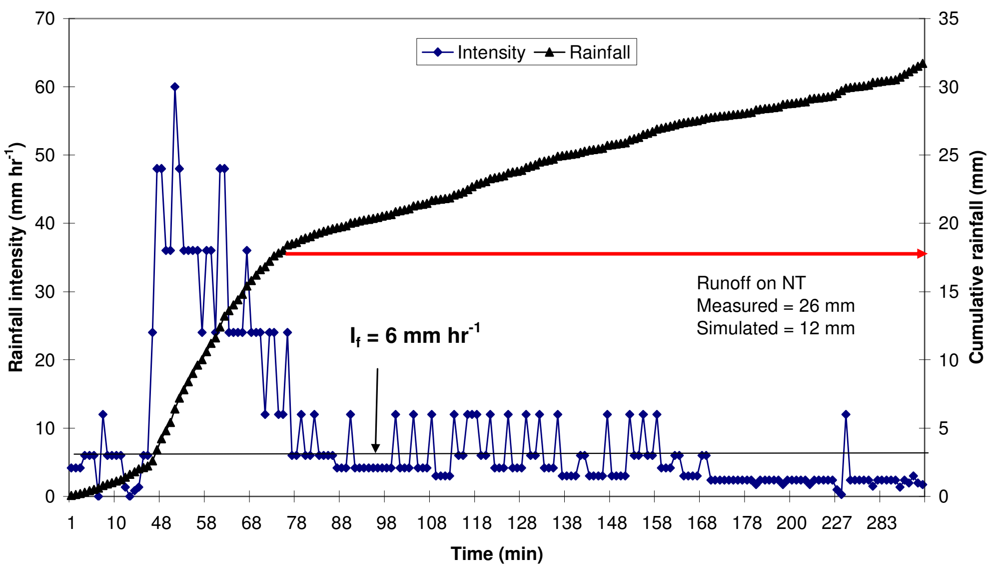


Figure 5. 14 Storm on DoY 223 of 2004 on the Melkassa Hypo Calcic Regosol ecotope.

5.4 Conclusions

The soil of the Melkassa Hypo Calcic Regosol ecotope is a Hypo Calcic Regosol with a clay loam texture throughout. Ca is the dominant cation, the pH is around 8.0 and the exchange complex is saturated with bases below 200 mm depth. Leaching of Ca has clearly been minimal in this soil. The drainage curve gave a high value of DUL for the 0 – 1500 mm profile of 390 mm. This soil is susceptible to crust formation caused by high rainfall intensity and due to inherited high silt content. As expected the infiltration rate test gave a low I_f value of 6 mm hr^{-1}. Over the two rain seasons during which measurements were made mean R/P values were 0.44 and 0.28 on the NT and CT plots, respectively. The M & C (1980) runoff model, after being calibrated and validated, simulated the measured runoff reasonably well. The calibration result gave the values of the model parameters as $\gamma = 0.6$ mm^{-1}; and SD_m 1 mm and 6 mm on NT and CT plots respectively. The assessment of model performance by correlating measured and simulated runoff for the 2004 season gave R^2 value of 0.86 and 0.94 for the NT and CT treatments, respectively. The slope of the correlation graph was approximately one for both NT and CT plots.

More than 90% of the storms were characterized by high intensity during the 1st and 2nd quartiles. This results in rapid crust formation which in turn leads to rapid attainment of I_f.

Like Dera, the Melkassa Hypo Calcic Regosol ecotope showed a large loss of rain water by runoff. Runoff was well simulated by the M & C (1980) runoff model.

6 MIESO

6.1 Ecotope characterization

6.1.1 Climate

The climatic data of Mieso is compiled from class A weather station records comprising different datasets: 1967 to 2003 for rainfall, 1989-2003 for temperature and; 1998-2003 for relative humidity, wind speed and sunshine hours. Table 6.1 shows the monthly mean climatic data while Figure 6.1 presents the distribution and variability of rainfall and temperature through out the year. The rainfall has two peak seasons during the year, March-April and July-August. Even though it consists of two peak periods, the March – April one has less than a month growing period which is insufficient to support crop production. The July – August season has a growing period of about 105 days (Figure 6.2). The annual total rainfall is about 737 mm. ACT (1980) data base also gave annual rainfall of the area as 736 mm and the potential evapotranspiration (ETo) of 1656 mm which gives a mean annual AI of 0.44. The site, according to the agro-ecological zones of Ethiopia (MoA, 2000), is located in the sub-agroecological zone of 'hot to warm semi-arid lakes and Rift Valley' (SA1-2) while recently Mamo (2006) classified it under zone 4, a medium risk area of the Rift Valley for crop production.

Table 6. 1 Climatic data for the Mieso Hypo Calcic Vertisol ecotope.

Month	Rainfall (mm)	MaxT (^oC)	MinT (^oC)	RH, (%)	Wind (km hr^{-1})	Sshhr (hr)
January	15.0	28.2	11.7	43.7	1.5	8.7
February	30.8	29.6	12.8	37.4	1.6	9.2
March	71.2	30.7	15.4	40.3	1.7	7.4
April	85.8	31.5	16.6	36.1	1.8	7.9
May	49.9	33.1	17.2	32.2	2.0	8.1
June	42.0	33.3	17.6	33.9	2.5	7.8
July	123.8	31.2	17.2	44.0	2.8	6.7
August	151.9	30.1	17.1	49.9	2.4	6.4
September	87.1	30.4	16.3	48.2	1.5	6.6
October	48.9	30.2	14.1	40.8	1.3	7.7
November	14.8	29.3	11.0	32.2	1.4	9.3
December	15.6	28.0	10.6	38.1	1.3	9.0
Annual Total	736.7					

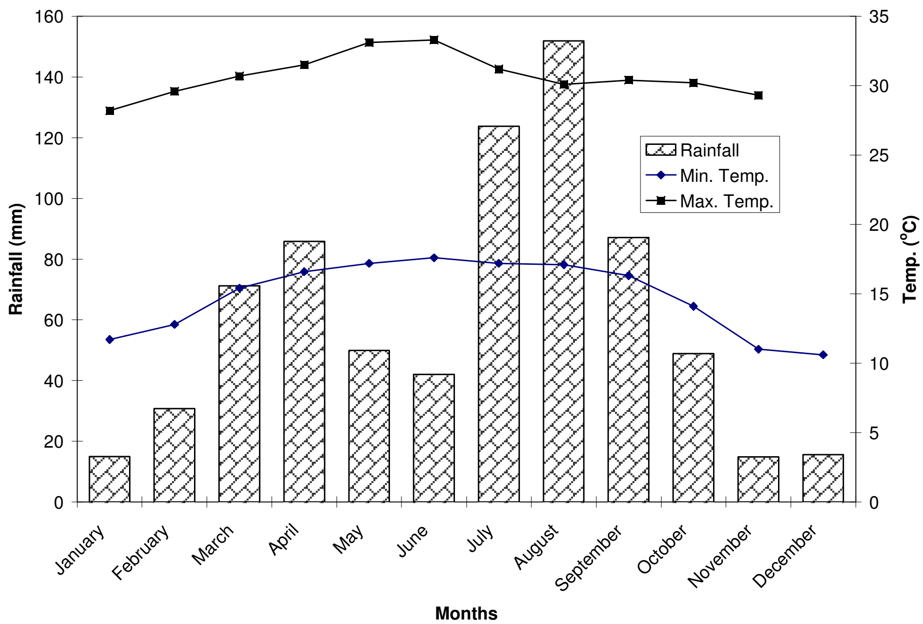


Figure 6. 1 Monthly rainfall and temperature distribution at Mieso.

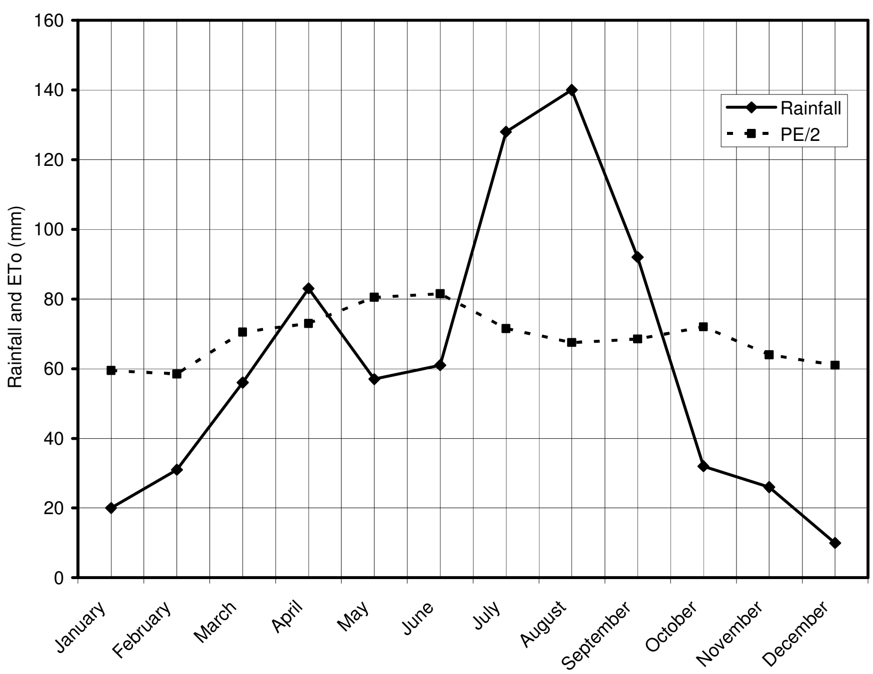


Figure 6. 2 Monthly rainfall and potential evapotranspiration at Mieso.

6.1.2 Topography

The ecotope is located at the north side of the Churcher highlands, at the foot of the mountains immediately before ascending to the peaks. The experimental field has a slope that ranges between 1% and 2% with aspect of northeasterly that drains towards the Awash River.

6.1.3 Soil

6.1.3.1 Morphology and classification

A soil profile pit dug near by the experimental plots was used to characterize the soil at Mieso. A detailed profile description is presented in Appendix 3. The soil is classified as a Hypo Calcic Vertisol in WRB (FAO, 1998b) and a clayey Arcadia Rustenburg (1200) (Soil Classification Working Group, 1991). The Hypo Calcic describes the presence of secondary carbonates in the top 100 cm of the soil profile. Vertisols have the same characteristics in both FAO (1984) and WRB (FAO, 1998b) soil classification systems. In the FAO (1989) soil map the soil is classified as a Eutric Vertisol. The FAO (1984) report gave the land mass coverage of Vertisols as 10% in Ethiopia. In another report Itanna (2005) described Vertisols as the commonest soil type in the Rift Valley, with coverage 19.2% (Chapter 4). The FAO (1998) soil map also clearly shows the dominance of the Vertisol in the Rift Valley (Figure 4.1).

At the site of the experiment five horizons were identified in the deep soil profile of at least 2100 mm. The texture is clay throughout, with (60-67% clay). The Ap horizon which is continuously pulverized by cultivation and has a depth of 100 mm (Table 6.2).

Table 6. 2 Mieso Hypo Calcic Vertisol: particle size distribution.

Depth (mm)	coSi (%)	fiSi (%)	Cl (%)	coSa (%)	meSa (%)	fiSa (%)	Texture	Db (Mg m^{-3})
0-100	6	20	61	3.8	1.7	4.7	Clay	1.29
100-500	4	19	63	1.7	2.7	6.1	Clay	1.44
500-1200	6	22	61	2.1	1.5	5.3	Clay	1.54
1200-1600	4	18	63	5.9	2.9	5.3	Clay	1.71
1600-2100	4	18	67	3.6	1.6	4.4	Clay	1.58

Generally, Vertisols have unique physicochemical characteristics. They swell during wetting and crack while drying. They are very sticky and heavy when moist and becoming very hard when dries. They exhibit a gilgai microrelief that forms small depressions and mounds in a circular form (Abebe, 1998; FAO, 1984; FOA, 1998b and Beukes *et al.*, 1998). Their main disadvantage is concerned with tillage difficulties due to the power required for cultivation, which needs careful timing and heavy machineries. In addition, their low hydraulic conductivity and infiltration rate is also a disadvantage for crop production, especially in high rainfall areas. In spite of all of the mentioned negative characteristics for crop production, Vertisols in Ethiopia are believed to have a good agricultural potential if proper soil and water management systems are practiced (Abebe, 1998). Beukes *et al.* (1998), support this contention for Vertisols in the dry farming areas of South Africa. Advantages are their high values of cation exchange capacity, base saturation, organic carbon and inorganic carbon. Continuous cultivation of Vertisols causes a relatively slow decrease in organic carbon and structural degradation. These are the main causes of soil crusting and increased runoff (Beukes *et al.,* 1998).

6.1.3.2 Chemical properties

The soil of the Mieso Hypo Calcic Vertisol is relatively homogeneous regarding some of the chemical properties. The pH (KCl) shows almost a neutral soil condition (about 6.8) throughout all the horizons. The pH in water (1:1 H_2O) showed a slightly alkaline condition with an increasing trend with depth, with values ranging from 7.8 to 8.3. Calcium is very high compared to the Dera and Melkassa soils (Table 6.3). This contributed to the high pH and base saturation. Because of the high water holding capacity of the soil, plus the low permeability and relatively low rainfall, deep drainage is expected to be minimal. This in turn has contributed to the large accumulation of $CaCO_3$ in the region of major root development, i.e. 0-500 mm (Table 6.3).

Table 6. 3 Chemical properties of Mieso Hypo Calcic Vertisol ecotope soil.

Horizon	Depth (cm)	pH 1:1 (H_2O)	pH (KCl)	OC (%)	OM (%)	ESP (%)
1	0-10	7.78	6.78	1.48	2.55	1.7
2	10-50	7.91	6.75	1.04	1.79	1.1
3	50-120	8.29	6.77			1.8
4	120-160	8.44	6.79			3.8
5	160-210	8.27	6.82			3.2

Table 6.3 continue

Depth (mm)	($cmol_c$ kg^{-1})					CEC ($cmol_c$ kg^{-1})		Base saturation (%)
	Ca	K	Mg	Na	Sum	Soil	Clay	
0-100	87.8	2.1	8.8	1.7	100.3	48.9	80.2	205
100-500	78.6	1.3	8.6	1.0	89.5	41.8	66.3	214
500-1200	70.5	1.3	9.2	1.5	82.5	45.2	74.1	183
1200-1600	67.4	1.5	10.7	3.1	82.6	40.5	64.3	204
1600-2100	67.5	1.4	9.8	2.6	81.4	39.2	58.5	208

6.1.3.3 Physical properties

6.1.3.3.1 Matric potential

The soil has high $\theta_{0.33}$ and θ_{15}, water contents. This estimate of the total water holding capacity to the effective soil depth (1600 mm) was found to be 1239 mm, and the estimate of plant available water ($\Delta\theta$) 467 mm (Table 6.4 and Figure 6.3).

Db was found to be larger for the depths below the Ap horizon, increasing at 100 mm from 1.44 to 1.58 Mg m^{-3} (Table 6.4). Similar result was reported by Abebe (1998) in Ethiopia for the Sheno and Bale Vertisols where the plough depth is frequently pulverized by continuous cultivation.

Table 6. 4 Mieso Hypo Calcic Vertisol soil water holding capacities.

Horizon	Depth, (mm)	Db (Mg m^{-3})	$\theta_{0.33}$		θ_{15}		$\Delta\theta$
			%	mm	%	mm	mm
1	0-100	1.29	45.6	59	28.9	37.4	22
2	100-500	1.44	48.7	281	31.6	184.3	99
3	500-1200	1.54	49.3	532	30.4	289.8	204
4	1200-1600	1.71	53.6	367	32.9	338.6	142
5	1600-2100	1.58	49.1	388	31.9	252.8	136
Total				1606			603

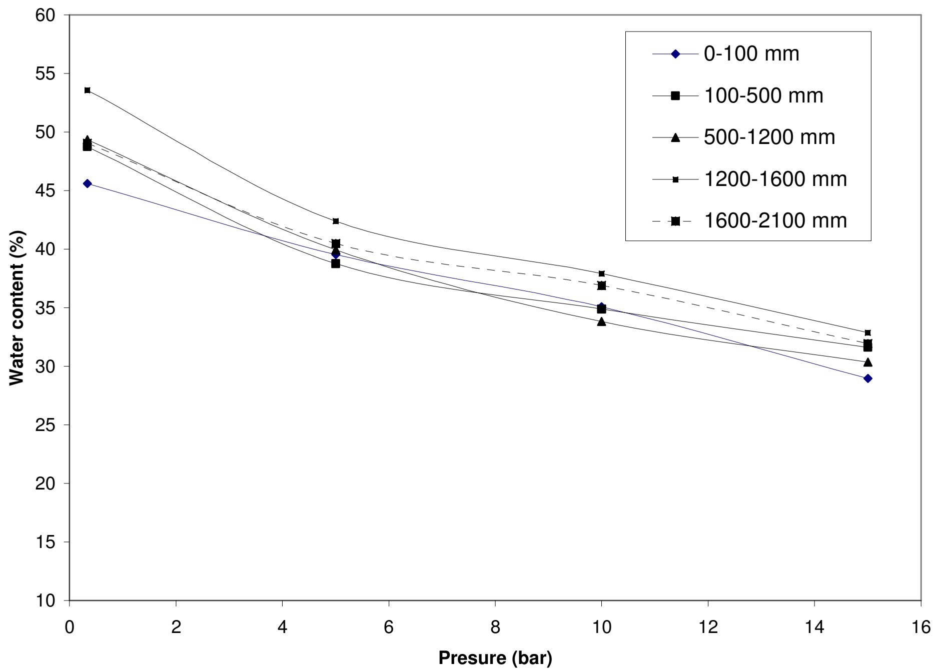


Figure 6. 3 Matric suction curves of the Mieso Hypo Calcic Vertisol.

6.1.3.3.2 Crust morphology

At Mieso the soil crust formed had a thickness of 5 to 6 mm. The finer particles are located at the top side of the crust. In contrast to the crusts at Dera and Melkassa, this one is not strong and hard. It is also not ridged or continuous. It consists of small platelets, 50-100 mm in diameter separated by cracks 5 to 10 mm wide. The platelets have curling up character when dry (Figures 6.8 & 6.9). Valentin & Bresson (1992) classified this type of crust as still depositional crusts. According to Valentin & Bresson (1992), these types of crusts are formed by the combined effect of rain drop impact and the resulting deposition due to runoff.

6.2 Infiltration rate

Infiltration rate measurements were carried out at one and five days after the last rainfall event. Each measurement consisted of two runs for which the results were averaged. Results are presented in Table 6.5. Graphs of Ic vs. t are presented in Figure 6.4.

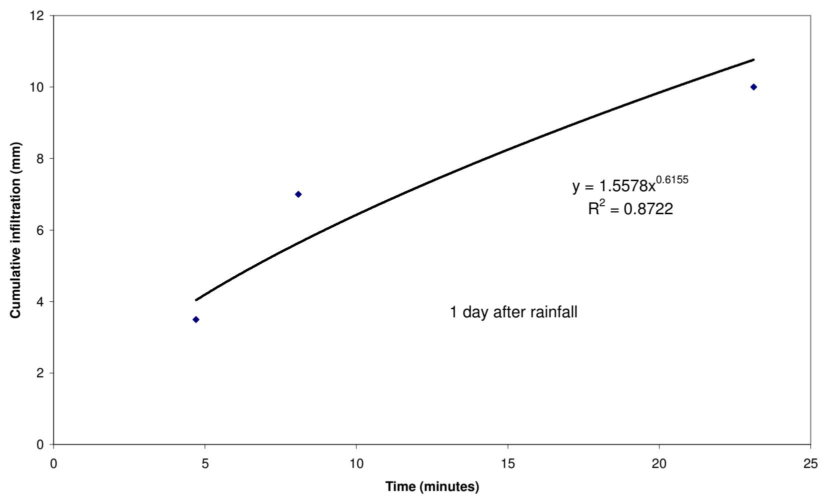
Table 6. 5 Cumulative infiltration (a) After one day and (b) after five days.

(a)

1st run		2nd run		Average	
T (min)	Ic (mm)	T (min)	Ic (mm)	T (min)	Ic (mm)
5.56	3.0	4.70	3.50	5.13	3.25
8.85	9.0	8.08	7.00	8.47	8.00
29.50	11.0	23.12	10.00	26.31	10.50

(b)

1st run		2nd run		Average	
T (min)	Ic (mm)	T (min)	Ic (mm)	T (min)	Ic (mm)
		6.93	5.00	6.93	5.00
10.70	8.50	8.82	6.50	9.76	7.50
26.17	12.00	23.77	11.00	24.97	11.50



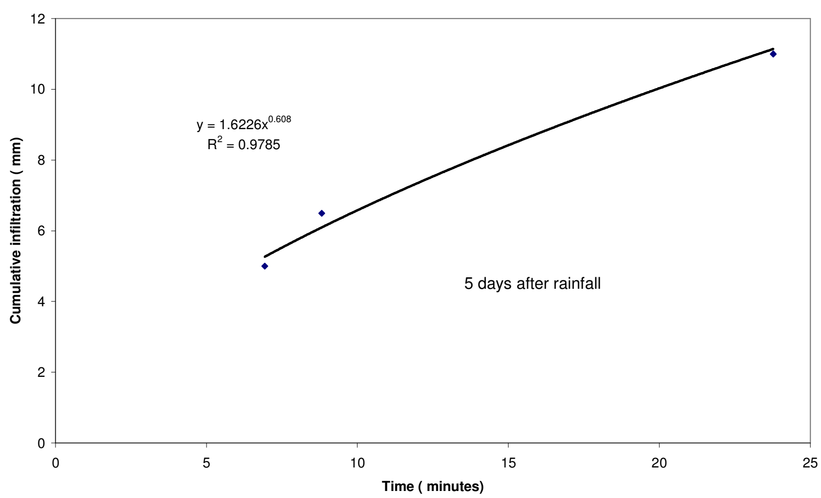


Figure 6. 4 Fitted cumulative infiltration curves at Mieso; Y = Ic and x = T.

The curve fitting regression analysis produced the following equations:

Cumulative infiltration (Ic)

One day after rainfall $Ic = 1.5578\ T^{0.6155}$ mm; c = 1.6, and k = 0.62

Five days after rainfall $Ic = 1.6226\ T^{0.608}$ mm; c = 1.6, and k = 0.61

Infiltration rate:

One day after rainfall, $I = 59.192\ T^{-0.392}$ mm hr^{-1}

Five days after rainfall, $I = 57.53\ T^{-0.3845}$ mm hr^{-1}

I_i and I_f were calculated when t = 0.5 minute and when the rate of decrease in I_f became 0.1 mm min^{-1}, respectively. Both equations gave I_f values of 10 mm hr^{-1}. The resultant average I_i value was 76 mm hr^{-1}. These first approximation I values were used in the M & C model calibration. The time to reach an I_f was found similar for both measurement procedures. The Morin & Benyamini (1977) infiltration equation predicted that I_f reaching at different times for different rainfall intensities, i.e. short time for high intensities (Figure 6.5). These results indicate that the antecedent soil water content will probably generally have an insignificant influence on I_f as well as on the time required to reach I_f. The Morin & Benyamini (1977) infiltration rate is given by the following equation: $I(t) = 70\ e^{-0.4Pi} + 10$, where, Pi = rainfall intensity in mm hr^{-1}.

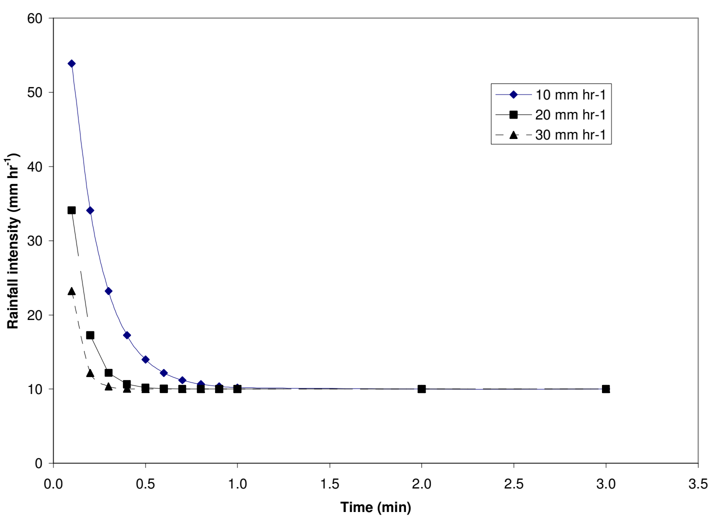


Figure 6. 5 Mieso Hypo Calcic Vertisol soil infiltration rate for different rainfall intensities according to the equation of Morin & Benyamini (1977).

6.3 Rainfall–runoff relationships

6.3.1 M & C model calibration and validation

For the calibration of the M & C (1980) model, only storms with amounts > 9 mm were used. Exceptions were considered for high rainfall intensity events that yielded high runoff amounts. From a total of 24 storms obtained during the two years, 12 were used to calibrate the model and the other 12 used to validate the model. Rainfall and measured runoff results are presented in Tables 6.6 and 6.7. Similar sensitivity analysis procedures as those used for the Dera and Melkassa Hypo Calcic Regosol ecotopes were followed to select appropriate I_f, s and γ values.

Model calibration and validation results showed a good performance in simulating the observed runoff (Table 6.7). Best results for the calibration were obtained using I_i and I_f values of 80 mm hr^{-1} and 10 mm hr^{-1} respectively; $\gamma = 0.4$ mm^{-1} for both treatments; and s = 5 mm for CT plots and s = 2 mm for NT plots. The statistical results of the performance test of the calibrated model for different s values are given in Table 6.7. The calibration results show that runoff was well predicted with D-index values of 0.96 and 0.97 for NT and CT plots, respectively; R^2 values of 0.89 and 0.90 for NT and CT plots, respectively; and encouragingly low RMSEs/RMSE values of 0.54 and 0.27 for NT and CT plots, respectively.

Validation results are presented in Table 6.8. The M & C model performed well giving similar statistical results to those obtained for the calibration test. The validated model was then used to predict the runoff for all the 24 storms studied over the two rainfall seasons. Results are presented in Tables 6.9 and 6.10 for the 2003 and 2004 seasons, respectively. The results are presented in graphical form in Figures 6.7 and 6.8 showing high R^2 values of 0.91 and 0.86 for the NT and CT plots, respectively.

Table 6. 6 Mieso Hypo Calcic Vertisol ecotope runoff calibration statistics, I_i = 80 mm hr^{-1}, I_f = 10 mm hr^{-1} and γ = 0.4: A for CT plots, B for NT plots.

A

Objective function	**CT plots, I_f = 10 mm hr^{-1}, I_i = 80 mm hr^{-1} and γ = 0.4**				
	s=8mm	**s=7mm**	**s=6mm**	**s = 5 mm**	**s = 4 mm**
RMSE	3.70	3.56	3.40	**3.32**	3.34
RMSEs	2.53	2.07	1.54	**0.91**	
RMSEu	2.69	2.90	3.03	**3.19**	3.36
MAE	2.13	2.28	2.40	**2.50**	2.49
R^2	0.90	0.89	0.89	**0.89**	0.89
D-index	0.96	0.96	0.97	**0.97**	0.97
slope (b)	0.80	0.83	0.86	**0.88**	0.90
intercept (a)	-0.34	-0.07	0.28	**0.74**	1.17
RMSEs/RMSE	0.68	0.58	0.45	**0.27**	

B

Objective function	**NT plots I_f = 10 mm hr^{-1}, I_i = 80 mm hr^{-1} and γ = 0.4**					
	s=8mm	**s = 5 mm**	**s = 4 mm**	**s = 3 mm**	**s = 2 mm**	**s=1.5mm**
RMSE	5.96	4.81	4.51	4.31	**4.16**	4.43
RMSEs	5.42	3.89	3.38	2.87	**2.24**	0.90
RMSEu	2.47	2.84	2.99	3.21	**3.51**	4.34
MAE	3.78	3.24	3.07	2.91	**2.63**	3.06
R^2	0.92	0.91	0.91	0.90	**0.90**	0.87
D-index	0.92	0.95	0.96	0.96	**0.96**	0.96
slope (b)	0.67	0.73	0.75	0.76	**0.78**	0.84
intercept (a)	-0.85	0.21	0.63	1.02	**1.49**	1.78
RMSEs/RMSE	0.91	0.81	0.75	0.67	**0.54**	0.020

Table 6. 7 Validation of M & C model with the selected s values

Indices	CT	NT
RMSE	3.32	4.08
RMSEs	0.91	2.14
RMSEu	3.19	3.47
MAE	2.49	2.43
R^2	0.89	0.91
D-index	0.97	0.97
slope (b)	0.88	0.77
intercept (a)	0.75	1.78
RMSEs/RMSE	0.27	0.52

During 2003, measurements could only be started in mid July, hence the fewer measurements than those for the complete rainy season of 2004. In 2003 the 7 storms monitored produced a runoff amount of 55 mm and 70 mm on CT and NT plots, respectively, from the total rainfall of 150 mm, giving R/P values of 0.37 and 0.47 for the CT and NT plots respectively. In 2004 runoff amounted to 72 mm and 112 mm on

CT and NT plots, respectively from a total rainfall of 431 mm, giving R/P values of 0.17 and 0.26, respectively. The 2004 rain season was wetter than the 14 year average amount for the same period, i.e. 405 mm. In both years, relatively high amounts of runoff were obtained from large storms for example in 2003, storms on DoY's 207 and 238 together produced 68% of the total annual runoff from the NT plots. Similarly in 2004, storms on DoY 196, 229 and 281 produced 65% of the total annual runoff from the NT plots.

Table 6. 8 Rainfall and runoff measured at Mieso Hypo Calcic Vertisol ecotope during 2003.

Date	DoY	Rainfall (mm)	Measured R (mm)		Simulated R (mm)	
			NT	CT	NT	CT
18/07	195	9.0	2.59	1.09	3.2	1.1
26/07	207	22.4	6.29	4.12	3.7	1.1
05/08	217	15.8	6.08	4.18	4.3	2.7
16/08	228	9.4	3.41	0.26	0.0	0.0
26/08	238	55.4	41.21	34.12	29.3	26.6
08/09	251	20.4	5.10	4.53	4.9	2.8
14-15/09	257	17.8	5.46	6.62	5.0	2.1
Total		**150.2**	**70.14**	**54.92**	**50.4**	**36.4**
R/P			**0.47**	**0.37**	**0.34**	**0.24**

Table 6. 9 Rainfall and runoff measured at Mieso Hypo Calcic Vertisol ecotope during 2004.

Date	DoY	Rainfall (mm)	Measured R (mm)		Simulated R (mm)	
			NT	CT	NT	CT
09/06	161	16.6	4.54	4.19	9.3	7.3
01/07	183	17.8	7.65	5.17	12.0	9.4
14/07	196	29.2	19.45	10.54	18.0	15.6
15/07	197	17.4	0.21	0.34	0.0	0.0
21/07	203	24.2	1.57	0.54	7.6	4.9
25/07	207	16.8	0.00	0.05	0.0	0.0
26/07	208	9.2	0.46	0.08	2.5	0.0
04/08	216	20.8	0.53	0.41	2.9	0.1
08/08	221	17.8	0.04	0.04	0.0	0.0
10/08	223	21.2	1.08	0.29	1.5	0.0
11/08	224	27.0	3.93	1.82	7.3	5.7
16/08	228+229	58.0	31.11	23.91	30.4	27.8
21/08	233+234	21.0	3.53	2.44	8.2	5.9
28/08	241	12.6	2.28	0.78	1.4	0.0
02/09	246	10.2	0.62	0.33	0.0	0.0
03/09	247+248	40.2	0.10	0.18	0.0	0.0
14/09	258	11.4	2.90	1.32	2.6	0.5
18/09	262	16.8	8.84	5.54	9.1	6.7
07/10	281	35.2	22.71	13.23	20.6	18.5
Total		**431.62**	**112.14**	**71.65**	**133.4**	**102.4**
R/P			**0.26**	**0.17**	**0.31**	**0.24**

During the two seasons, it was found that the length of non-rain period varied from less than a day to more than 10 days. Among the total storms recorded, 57% have less than one to five days of a dry spell between them while 30% of them have five to ten days of dry spell, and 13% have greater than ten days of dry spell. The results also show that most of the storms in 2004 had lower rainfall intensities than during 2003. This gave significantly lower runoff in 2004. The storms generally showed higher intensity during the 1st and 2nd quartiles of their duration. This is a similar characteristic to the Dera and Melkassa Hypo Calcic Regosol ecotopes. Walker & Tsubo (2003a) reported a similar characteristic for storms at Pretoria and at Bloemfontein in South Africa. Huff (1967) in his study also found in Illinois, USA, that high intensity during the first and second quartiles occurred more frequently than high intensities during the fourth quartile. Due to the high surface storage (s) difference between NT and CT plots (Table 6.7), at Mieso Hypo Calcic Vertisol ecotope the amounts of runoff on CT and NT plots, in contrast to Dera, showed a significant difference (at $p = 0.05$).

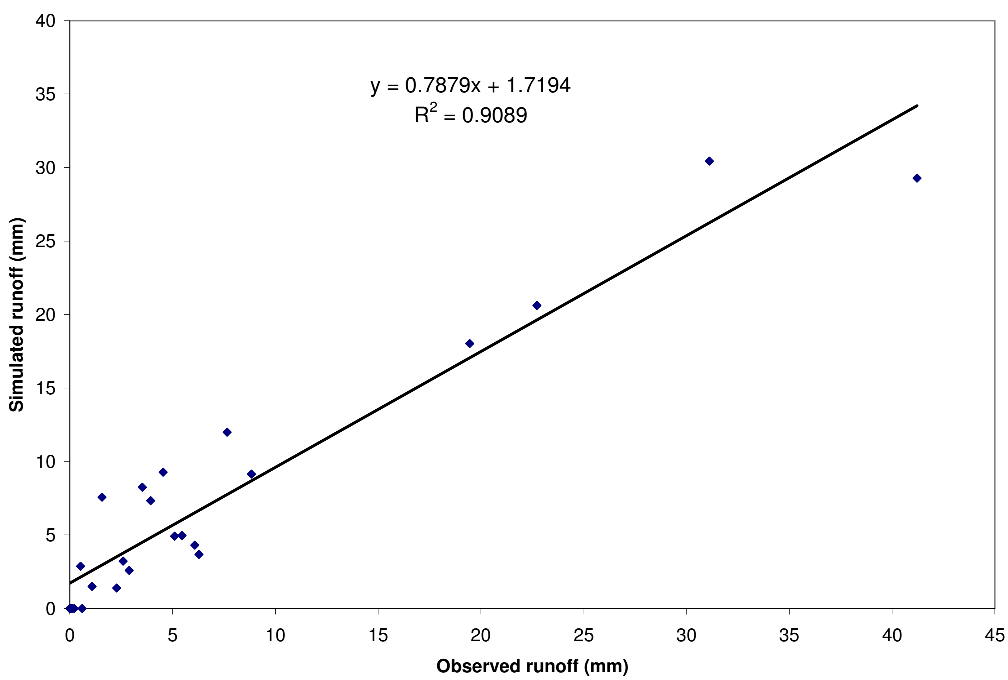


Figure 6. 6 Relationships between observed and simulated runoff on NT plots over the 2003 and 2004 rain seasons: Mieso Hypo Calcic Vertisol.

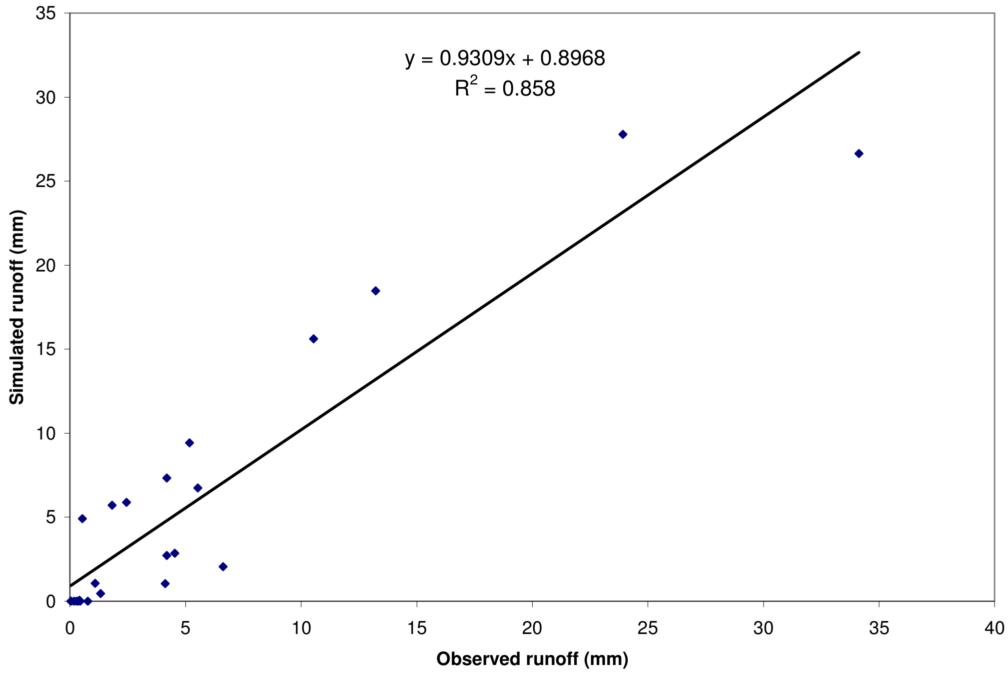


Figure 6. 7 Relationships between observed and simulated runoff on CT plots over the 2003 and 2004 rain seasons: Mieso Hypo Calcic Vertisol.

Vertisols are characterized by swelling and shrinking properties upon wetting and drying due to their high content of montmorillonite and smectite clays. The swelling and shrinking process results in the formation of multiple surface cracks (Figures 6.8 and 6.9). Due to their high content of swelling clay large clods and angular blocky structures resulted when cultivating Vertisols in both dry and wet conditions. This occurred on the CT plots. However, on the NT plots the clods were broken down to small aggregates in order to smooth the soil surface and create an artificial NT condition. The clods on the CT plots took a much longer time to disperse and to form a crust compared to NT. It was also found that the sorptivity was higher in the cloddy dry soils. Sorptivity is governed by surface soil properties such as texture, degree of aggregation and aggregate stability (Shaver, Peterson & Sherrod, 2003). All these factors promoted high sorptivity on the CT plots. The result was the lower s value on the NT plots, promoting significantly higher runoff on these plots. Although the two treatments showed a significant difference in total runoff the differences became less after large storms. The large storms caused the clods on CT plots to be dispersed, prompting a similar surface condition to that on the NT plots. Similar results are reported by Rao *et al.* (1998) and Babacar *et al.* (2005). For instance, this happened during storms on Doy's 238 and 229 in years 2003 and 2004 respectively (Tables 6.8 and 6.9).

Tarchitzky, Bann, Morin & Chen (1984), Lado & Ben-Hur (2004) and Miguel *et al.* (2005) also showed that the impact of high intensity rainfall on soil aggregates was one of the main factors contributing to aggregate dispersion leading to sealing by soil crusting. This is especially true when soils high in montmorillonitic clay, have ESP values >10% and high silt contents, which facilitated aggregate breakdown by the raindrop impact and the swelling, dispersion and slaking of the soil surface. This in turn decreases the hydraulic conductivity and infiltration rate of the soil. The Mieso Hypo Calcic Vertisol is therefore inherently susceptible to crusting. The relatively lower γ value (0.4) at Mieso was also an indicator of the susceptibility of the soil to aggregate dispersion. These features help to explain the rainfall-runoff characteristics on this ecotope.

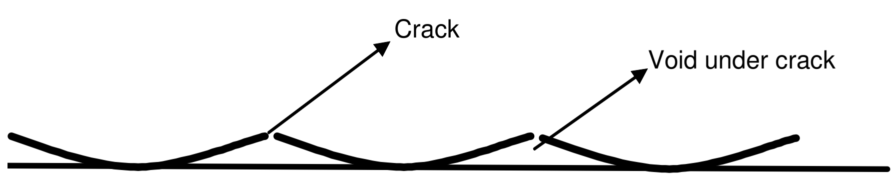


Figure 6. 8 Diagram showing cross section of the soil crust with the cracks and voids.

Figure 6. 9 Crust formation of the Mieso Hypo Calcic Vertisol.

6.3.2 Well simulated storms

Well simulated storms include most of those beginning with high intensities ($P_i > I_f$). Storms on DoY's 196 and 229 for 2004 are presented as examples for the purpose of detailed analysis. Storm on DoY 196 had a total duration of 55 minutes (Figure 6.10), 78% of which had Pi > I_f (I_f = 10 mm hr^{-1}, Table 6.7). During this period about 23 mm or 80% of the total rainfall was received. The measured runoff amounted to 19.5 and 10.5 mm from the NT and CT plots respectively, and simulated amounts of 18 mm and 15.6 mm, respectively (Figure 6.10).

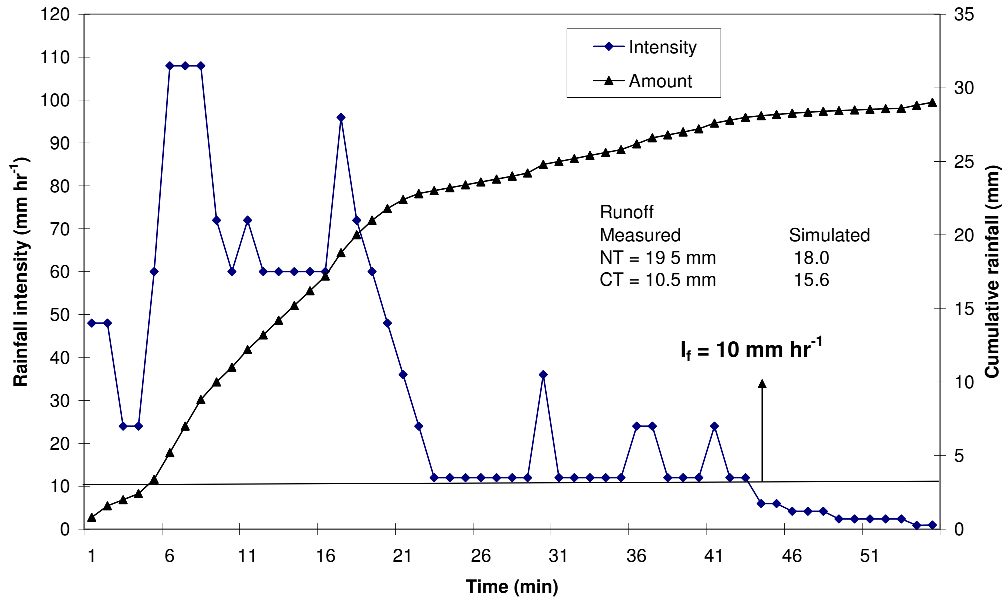


Figure 6. 10 Storm on DoY 196 of year 2004 on the Mieso Hypo Calcic Vertisol.

The graph for storm on DoY 196, at the lower and upper boundaries of the Pi portion (i.e. between 2 and 22 minutes) shows the steepest part of the cumulative rainfall line. Taking the soil infiltration rate line that equals 10 mm/hr as a reference point for runoff initiation and termination (Table 6.7), we find approximately 23 and 3 mm on the curve representing the rainfall cumulative line. Therefore, subtracting 3 mm from 23 mm gives about 20 mm of runoff. Subtracting the calibrated storage values of 2 mm and 5 mm for NT and CT plots, gives 18 and 15 mm runoff on the NT and CT plots, respectively, a similar result to that of the model. Runoff form the NT plots was well predicted by the model. The model over predicted R for CT. The low amount of measured runoff on CT was promoted by the previous cultivation that increased s. Furthermore, the long preceding dry period prevented the formation of a stabilized crust on CT like that on NT. The NT plots were favoured by the artificially smoothed surface condition that enhanced the formation of a well established crust by the proceeding storms on DoY 161and 183 (Table 6.10).

Based on Figure 6.11 and the graphical interpretation previously used the expected runoff of storm on DoY 229 from NT is 35 mm. If the NT and CT s values of 2 mm and 5 mm, respectively are subtracted from this expected amount, R values would be 33 mm and 30 mm for the NT and CT plots, respectively. The correspondingly measured values were 31 mm and 24 mm. The model also predicted the runoff for storms on DoY 195, 217, 234, 251 and 258 of year 2003; and most of the storms from 2004, in a satisfactory way (Table 6.9 and appendix 6).

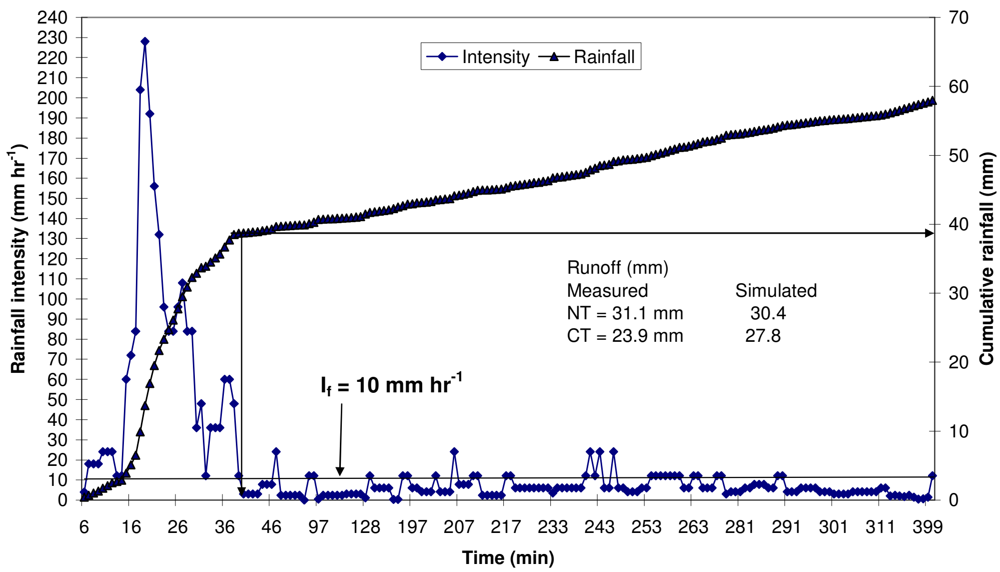


Figure 6. 11 Storm on DoY 229 of year 2004 on the Mieso Hypo Calcic Vertisol.

The model also simulated runoff well for those storms with low intensities ($P_i < I_f$) throughout the storm period. Therefore, it is not surprising to see storms that have high amounts of rain ending with trivial or negligible amounts of runoff. Such storms include storms on DoY 247+248, 197 and 207 from year 2004 (Table 6.10); and 214 and 234 from year 2003 (appendix 6). Storm on DoY (247+248) of year 2004 (Figure 6.12) serves as an example. The importance of Pi as a factor determining runoff is clearly shown. The storm had Pi < I_f throughout the three days of its duration, resulting in virtually no measured or predicted runoff.

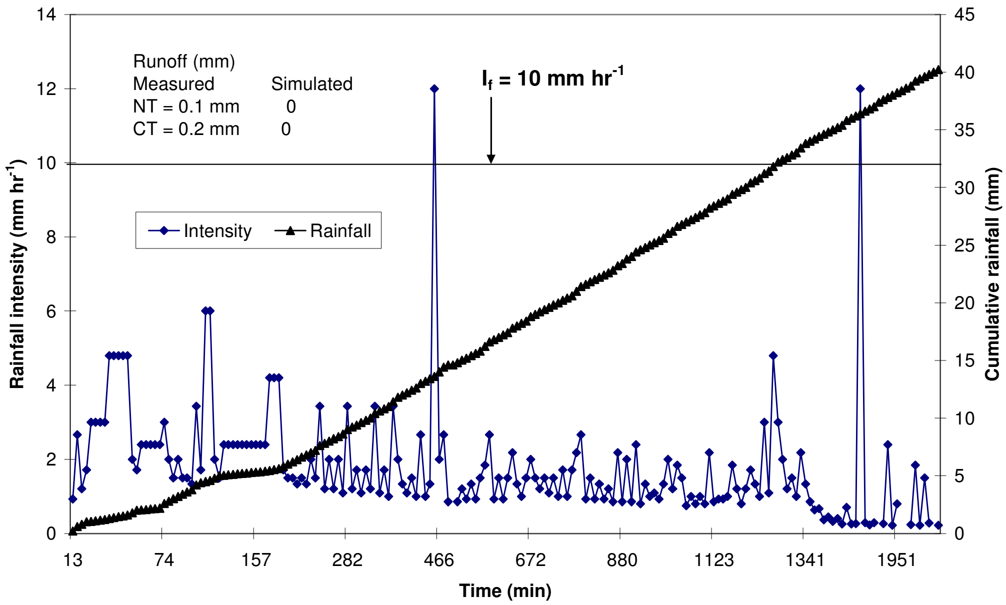


Figure 6. 12 Storm on DoY 247+248 of 2004 on the Mieso Hypo Calcic Vertisol.

6.3.3 Storms not well simulated

The M & C model over predicted runoff when storms exhibited rapidly fluctuating Pi. Examples are storms on DoY 203, 224 and 233+234 in 2004. During 2003 no storms showed these characteristics.

High fluctuation of Pi during storms may cause continuous rearrangement of aggregates that affect the stability of crusts by breaking and remoulding them. These storms may have two or more major periods of $P_i > I_f$. I_f may remain high due to the turbulence and scouring effect caused by Pi fluctuation and which may break the sealed crust into smaller aggregates enhancing infiltration and reducing R. It is clear that M & C model could not cope satisfactorily with these variations in I_f and assumed too low on I_f value causing R values to be too high (Figures 6.13, 6.14 and 6.15 and Table 6.10).

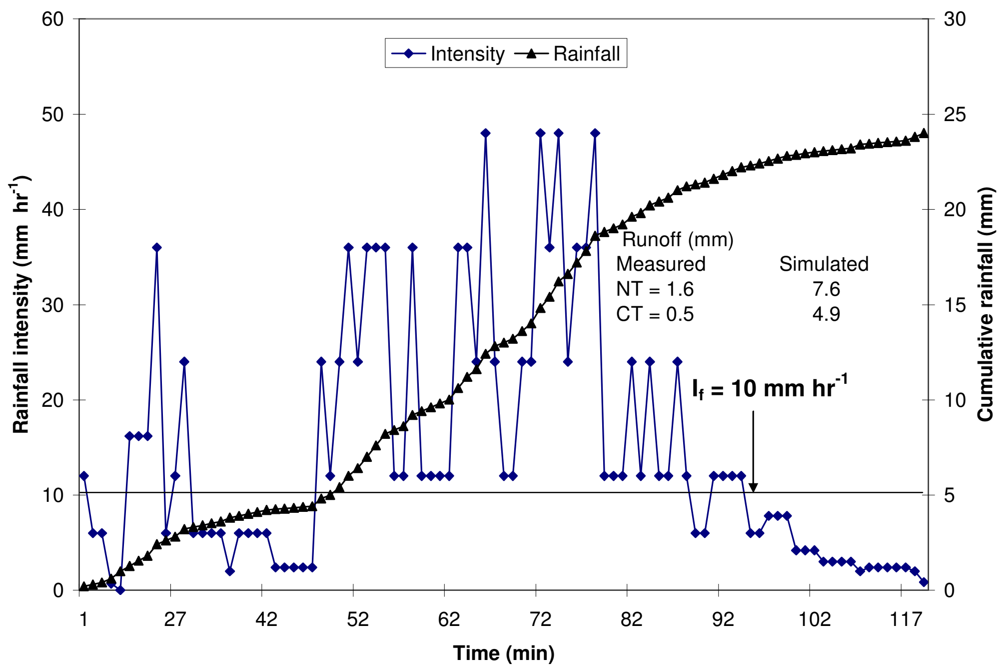


Figure 6. 13 Storm on DoY 203 of year 2004 on the Mieso Hypo Calcic Vertisol.

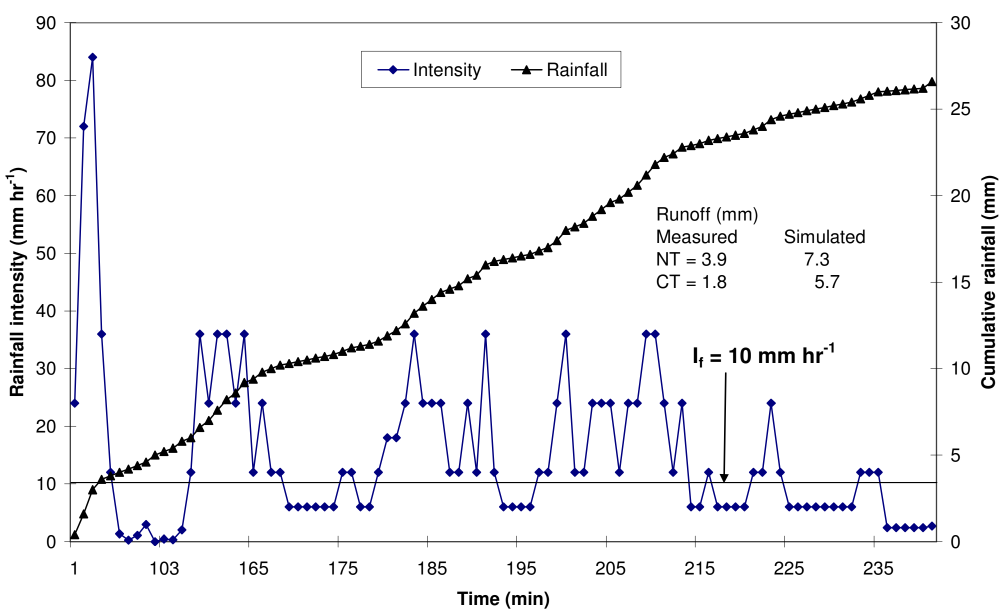


Figure 6. 14 Storm on DoY 224 of year 2004 on the Mieso Hypo Calcic Vertisol.

Valentin & Bresson (1992) reported the formation of well-sorted micro-beds when there was laminar flow, whereas poorly sorted dense micro-beds occurred where there was turbulent flow. The flow type depends on runoff conditions (velocity, solid charges, and surface roughness/γ-value) as well as on rain drop splash which is a cause of turbulence. Since the crust type at Mieso Hypo Calcic Vertisol ecotope was classified as a still depositional crust with γ-value of 0.4, the stability of the crust was probably affected by the highly fluctuating rainfall intensity which might have caused frequent micro-aggregation of the crust (Valentin & Bresson, 1992). In the process of this frequent micro-aggregation, the soil I_f value may have became greater than the average Pi of the fluctuating storm, resulting in decreased runoff. Consequently, the model which tries to account for each time segment of the fluctuating Pi may easily over predict or under predict R depending on the frequency of the fluctuating Pi. At Mieso, muddy runoff conditions were seldom observed and recorded. This observation substantiates the suggestion of Valentin & Bresson (1992) regarding the occurrence of micro-aggregates in the lower sedimentary micro-beds (crusts) during high raindrop and turbulence runoff.

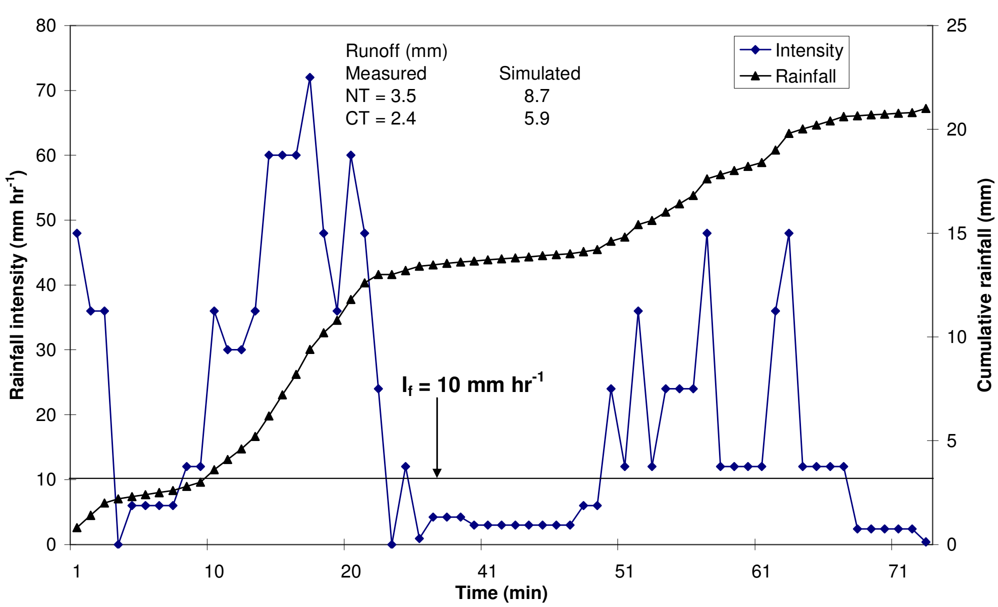


Figure 6. 15 Storm on DoY 233+234 in 2004 on the Mieso Hypo Calcic Vertisol.

6.4 Conclusions

The Mieso Hypo Calcic Vertisol has a texture throughout the profile with mean clay and silt contents of 66 and 24%, respectively to the depth of 2100 mm. The pH (water) varies between 7.8 and 8.4.

The soil showed a high dispersablity when exposed to intense rainfall, resulting in the formation of a quick seal that decreases the infiltration rate. Final infiltration rate (I_f) at 10 mm hr^{-1} was, however, considerably higher than the equivalent values of 6 mm hr^{-1} for the Melkassa and Dera Regosols. The type of crust formed was identified as a still depositional crust. This crust cracks into small plates with diameter ranging between 50 and 100 mm and thickness up to 10 mm in places. The plate-shaped crusts curl upwards upon drying. Depending on the antecedent soil water content the sorptivity demand varies between 2 and 5 mm. The NT plots were found to have average s values of 2 mm whereas the equivalent value for the CT plots was 5 mm. The s value of the CT plots approached that of NT towards the end of the rain season.

During the two years, the rain storms showed a similar Pi distribution pattern to those of Melkassa and Dera, with high Pi mainly during the 1st and 2nd quartiles. The high Pi periods were generally and for a short duration, continuing for less than half of the storm period. During the two years, from the total rainfall > 9 mm, R/P of 0.37 and 0.27 was found on the NT and CT plots, respectively.

The M & C model, after calibration and validation, simulated the runoff of the two treatments in a satisfactory way. During the calibration process, the best result was obtained when I_f = 10 mm hr^{-1}, γ = 0.4 mm^{-1} and SD_m = 2mm for NT and 5 mm for CT. The model has a limitation to simulate runoff well until crust is formed and well stabilized.

7 EXPECTED MAIZE YIELD IMPROVEMENT WITH IRWH

7.1 Introduction

Maize yields are expected to increase with IRWH. A water production function is a linear relationship between yield and water used by the crop for evapotranspiration (Es + T), or transpiration (T). During photosynthesis water evaporates and CO_2 is absorbed through the stomata, when they are open. The amount of water evaporated has a major effect to the total biomass produced by the crop because of its close relationship with CO_2 absorption (Passioura, 2006). If water is limited the growth and yield of the crop will be decreased. Based on this concept, researchers have established a direct relationship between crop biomass and T (Tanner & Sinclair 1983, Walker, 1986 and Hattingh, 1993). Because of the difficulty of separating Es and T for a growing season, attempts are also made to establish a relationship between evapotranspiration (Es + T) and biomass yield (Yb) as in Equation 7.1

$$Yb = a\,(Es + T) + b \qquad (7.1)$$

Since Es + T is dependent on climatic and soil factors, it varies with the ecotope being studied. Thus, the relation of Yb versus (Es + T) is ecotope specific. In this study, the ecotope being studied was the Melkassa Hypo Calcic Regosol ecotope described in Chapter 4.2.

7.2 Procedure

Empirical procedures were followed to estimate the benefit of IRWH to maize production on the Melkassa Hypo Calcic Regosol ecotope. Maize yields and climate data for 16 growing seasons (1988-2003) were used. Historical climate data was obtained from the Melkassa Agricultural Research Center (MARC) (Table 7.1). It includes rainfall (P), temperature (T), relative humidity (RH), sunshine hours (SH), wind speed (WS) and Penman-Monteith reference evapotranspiration (ETo). Maize yield data (1988 - 2003) was acquired from the center's farm management program. Important agronomic crop data was also obtained from the center's maize programme and literature (Table 7.1). The agronomic practices listed have been similar for all the years for which maize yields are reported.

Crop modelling with CROPWAT

The CROPWAT programme developed by FAO was used for making the Es + T estimates. Es + T is termed ET in the program. The programme flow chart is presented in figure 7.1.

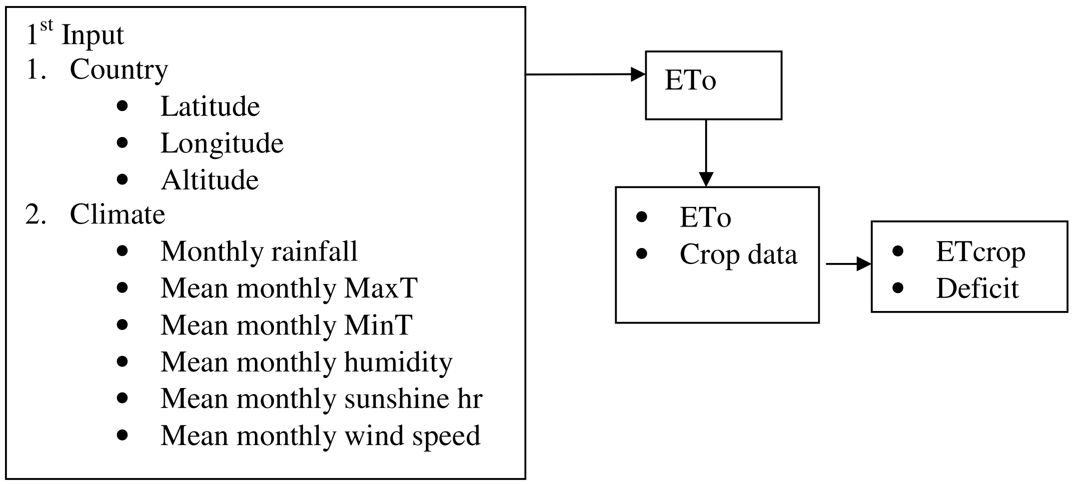


Figure 7. 1 Flow chart for the CROPWAT program.

The programme first makes use of the climatic data needed (i.e. P, T, RH, SH, and WS) to calculate ETo for each day of the growing season using the Penman-Monteith equation. In the second step the programme combines the crop coefficient (Kc) shown in Table 7.1 with ETo to estimate the potential ET of maize (Kc*ETo) for each growth stage i.e. the amount of water it would require for ET to attain maximum yield.

The program then uses daily rainfall to estimate effective rainfall for each event using Equation 7.2 developed by the USDA soil conservation service (USDA, 1972).

$$Peff = Ptot * (125 - 0.2 * Ptot)/125 \quad (7.2)$$

For Ptot < 250 mm

$$Peff = 125 + 0.1 * Ptot$$

For Ptot > 250 mm

Table 7. 1 Maize production practices at MARC and cultivar characteristics.

Cultivar characteristics	1st stage	2nd stage	3rd stage	4th stage	Total
Growing period (days)	20	28	32	25	105
Crop coefficient (Kc)	0.45	1.1	1.1	0.55	

Tillage practice: furrow and ridges
Approximate growing season: 105 days, June 15 – September 28
Plant population: 53,333 ha^{-1}, planted 25 cm apart in rows 75 cm apart
Cultivar: Katumani

CROPWAT then uses this effective rainfall to simulate the water deficit suffered by a maize crop for each growth stage of a particular season, and therefore the total deficit for the growing season. Subtraction of this amount from the (Kc*ETo) value for the growing season provides an estimate of the actual ET (ETactual) of the crop for that season.

7.3 Results and Discussion

Model No 1.

Results are presented in Table 7.3. Water productivity in terms of water used for ET (WP_{ET}) was calculated for each growing season by dividing grain yield by ET giving kg ha^{-1} mm^{-1}. Because of the high water holding capacity of the Melkassa Regosol (see Chapter 5), and the fact that there is much $CaCO_3$ in the lower parts of the profile, it is reasonable to assume that deep drainage is generally negligible in this soil. Runoff loss (R) for each growing season can therefore be estimated as rainfall–ETactual, giving the results in the 8th column (Rest) in Table 7.2. Had the tillage practice been IRWH this loss would not have occurred, and the runoff would have been stored in the basins (Figure 1.1). Results were extracted from Hensley *et al.* (2000) and Botha (2007) for maize grown with IRWH on the Glen Bonheim ecotope-Onrus ecotope over seven seasons. The ratio of (ET_{IRWH}/ET_{CT}), where CT refers to conventional tillage, to the estimated runoff which occurred from the runoff strip into the basins (R_{if} = infield runoff) was calculated for each season. The mean value was 0.62. This indicates that on average, on the Glen Bonheim ecotope with maize, ET_{IRWH} can be expected to be increased to the extent of ($0.62*R_{if}$) above the ET of maize with conventional tillage.

Table 7. 2 Maize grain yields and seasonal rainfall for 16 years on the Melkassa Hypo Calcic Regosol ecotope, parameters estimated in order to predict yield increases using IRWH (Model No. 1).

Year	Grain yield (kg ha^{-1})	Seasonal rainfall (mm)	Kc*ETo (mm)	Deficit (mm)	ETactual (mm)	WP_{ET} *1 (Kg ha^{-1} mm^{-1})	Rest *2 (mm)	ER*3 (0.62*Rest)	ER*WP_{ET} (Kg)	Estimated % > due to IRWH
1988	2707	439	391	31	360	7.5	79	49	368	14
1989	2957	466	405	61	343	8.6	123	76	654	22
1990	3800	525	398	88	310	12.2	215	133	1622	43
1991	1444	450	401	119	281	5.1	169	105	536	37
1992	1190	515	425	58	367	3.2	148	92	294	25
1993	2479	463	399	116	284	8.7	179	111	966	39
1994	1388	502	386	99	288	4.8	214	133	638	46
1995	2396	695	423	84	339	7.1	356	221	1569	65
1996	2709	558	401	53	348	7.8	210	130	1014	37
1997	2187	637	375	68	307	7.1	330	205	1456	67
1998	1460	695	406	63	343	4.3	352	218	937	64
1999	2346	558	406	85	321	7.3	237	147	1073	46
2000	2346	555	394	70	324	7.2	231	143	1030	44
2001	1876	521	367	71	296	6.3	225	140	882	47
2002	262	277	324	101	223	1.2	54	33	40	15
2003	2300	552	410	40	370	6.2	182	113	701	30
MEAN	2115	526								40

*1 WP_{ET} = water productivity in terms of ET
*2 Rest = estimated runoff (seasonal rainfall – ETactual)
*3 ER = effective runoff, i.e. the ET increment expected from the estimated runoff

Since runoff characteristic of the Melkassa Hypo Calcic Regosol ecotope have been shown to be similar to those of Glen Bonheim ecotope, it is reasonable as a first approximation to employ this relationship on the Melkassa Hypo Calcic Regosol ecotope.

Multiplying R_{est} by 0.62 gives the results in the column designated as ER (effective runoff) in Table 5.2. The multiplication ER * WP_{ET} provides a logical estimate of the increase in yield resulting from IRWH. Results are recorded in the 10^{th} column. As is to be expected there is a wide variation (14% to 67%) depending on the conditions which prevailed during the different seasons. The mean percentage increase in yield due to IRWH is shown to be 40%. This is comparable to the equivalent mean value over seven seasons of 57% from the combined results of Hensley *et al.* (2000) and Botha (2007) on the Glen Bonheim ecotope.

Model No 2

The following is the description of an alternative procedure used to estimate the expected maize yield increment with IRWH. Results are presented in Table 7.3. The rainfall-runoff measurements made on the Melkassa Hypo Calcic Regosol ecotope during 2003 and 2004 are described in Chapter 5. From these measurements it was possible to develop an empirical equation relating runoff from the no-till plots (NT) to rainfall events > 9 mm. The equation is $R = 0.714P – 6.8959$ ($R^2 = 0.87$), where R is the estimated runoff in mm and P is the amount (> 9 mm) of the rainfall event. Applying this equation to each rainfall event during each growing season provides an estimate of what the runoff (R_{if}) would have been from the runoff strip (Figure 1.1) had IRWH been employed. Multiplication of this value by 0.62, as in the 1^{st} procedure, gives an estimate of the expected ET increment (ETinc). The multiplication of ETinc*WP_{ET} provides a logical estimate of the increased yield with IRWH. Results are presented in Table 7.3. Values vary from 13% to 49%. The mean increase is shown to be 33%.

An attempt was also made to determine a water production function relating maize grain yield to ETactual. The result is presented in Figure 7.2. Eleven points lie on a line described by the equation $Y = 19.343x – 3976.8$ with an R^2 value of 0.945. The other five points are widely scattered about this line. A similar wide scatter is obtained with the results of Hensley *et al.* (2000) and Botha (2007) for maize on the Glen Bonheim ecotope. A consistent relationship between ET and yield cannot be expected on a semi-arid ecotope because of the widely varying conditions between seasons. The line on Figure 7.2 is however reassuring for two reasons. Firstly, it passes very approximately in a central way between all the points, and secondly, the intercept on the ET axis at 210 mm indicates a reasonable limiting value below which zero yields can be expected. It was therefore considered that the given equation gives a very approximate water production function for maize on the Melkassa Regosol ecotope.

Table 7. 3 Maize grain yields and estimates of parameters needed to predict yield increases using IRWH (Model No 2).

Year	Grain Yield ($Kg\ ha^{-1}$)	R_{if} [*1] (mm)	ETinc [*2] R * 0.62	WP_{ET} [*3] ($kg\ ha^{-1}\ mm^{-1}$)	WP * ET (kg)	Yield increase (%)
1988	2707	93.6	58.0	7.5	436.3	16.1
1989	2957	128.2	79.5	8.6	684.8	23.2
1990	3800	190.0	117.8	12.2	1442.8	38.0
1991	1444	138.7	86.0	5.1	441.3	30.6
1992	1190	172.2	106.8	3.2	346.3	29.1
1993	2479	129.6	80.3	8.7	702.1	28.3
1994	1388	157.9	97.9	4.8	472.4	34.0
1995	2396	266.7	165.4	7.1	1167.4	48.7
1996	2709	194.0	120.3	7.8	937.1	34.6
1997	2187	242.8	150.5	7.1	1072.4	49.0
1998	1460	266.7	165.4	4.3	704.3	48.2
1999	2346	194.0	120.3	7.3	878.5	37.4
2000	2346	180.1	111.7	7.2	808.1	34.4
2001	1876	175.2	108.6	5.9	645.6	34.4
2002	262	47.5	29.4	1.2	34.6	13.2
2003	2300	162.8	101.0	6.2	626.9	27.3
				Mean	712.6	32.9

*1 R_{if}= estimate of infield runoff based on measurements made on this ecotope during 2003 and 2004 (Chapter 5)
*2 ETinc = estimate of the increase in ET due to R_{if}
*3 WP_{ET} = as in Table 7.2

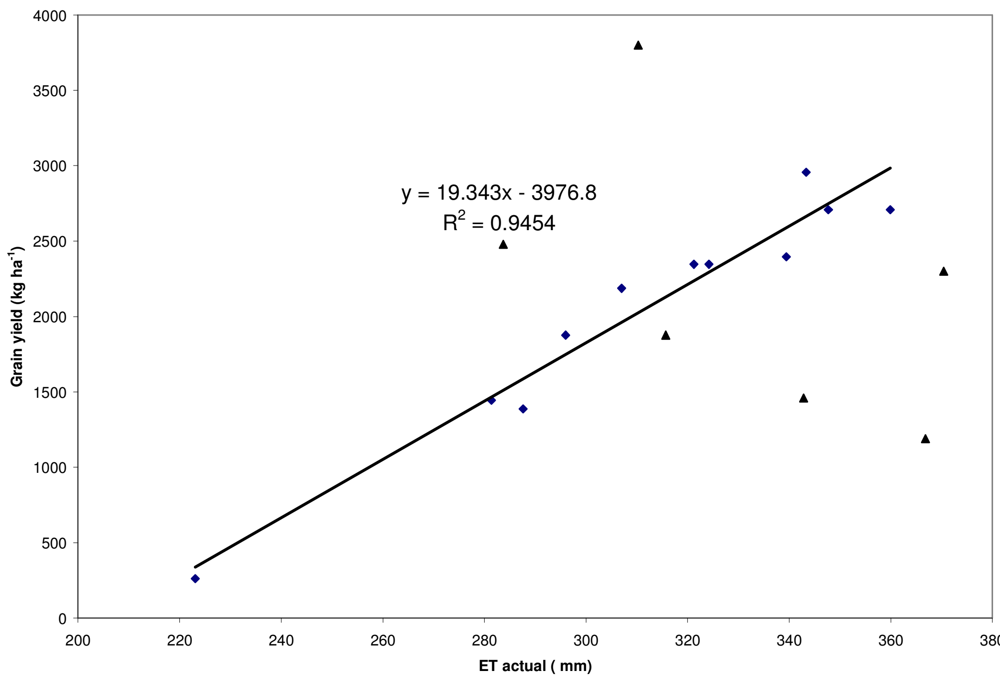


Figure 7. 2 Relationship between maize grain yields and ETactual on the Melkassa Hypo Calcic Regosol ecotope for the years 1988-2003.

7.3 Conclusions and recommendations

The CROPWAT computer programme was able to compute useful estimates of ETo and ETactual for each of the 16 growing seasons for which climate and yield data were available for the Melkassa Hypo Calcic Regosol ecotope. ETactual was used to make an estimate of water productivity in terms of ET (WP_{ET}) for each of the growing seasons. This basic data was used to formulate two models for predicting the extent to which IRWH would increase maize yields. Model No 1 predicted increases varying from 14% to 67% for the different seasons with an overall average of 40%. Model No 2 predicted increases varying from 13% to 49% with an overall average of 33%. These results are comparable to those for maize on the Glen Bonheim ecotope of 57% reported by Hensley *et al.* (2000) and Botha (2007). The lower values for the Melkassa Hypo Calcic Regosol ecotope are surprising because growing conditions seem to be far more favourable there than on Glen Bonheim ecotope. For example the mean growing season rainfall over the 16 years on the former ecotope was 526 mm whereas on the latter ecotope over seven years it was only 275 mm. Rain water productivity (RWP) values, using only growing season rainfall for the two ecotopes over the respective growing periods, works out as 4.03 kg ha^{-1} mm^{-1} and 6.22 kg ha^{-1}

mm^{-1} for Melkassa Hypo Calcic Regosol ecotope and Glen Bonheim ecotope respectively, using conventional tillage. The large amount of runoff (Tables 7.2 and 7.3) on the Melkassa Hypo Calcic Regosol ecotope is probably an important contributing factor for its low RWP values. The excessively high plant population of 55,000 plants ha^{-1} might also have been a disadvantage.

It was not possible to compute a reliable water production function relating ET to yield for the Melkassa Hypo Calcic Regosol ecotope due to the large variations between seasons.

8. SUMMARY AND CONCLUSION

In Ethiopia more than 95% of crop production is under rainfed conditions, and more than 80% of the population is engaged in agricultural production as small scale farmers. The country's economy depends greatly on this sector which provides about 90% of the GDP. The amount and distribution of the rainfall is generally unreliable for sustainable crop production in the arid and semi-arid regions. These areas also experience high runoff and evaporation losses which aggravate the problem of water stress in crop production. As a consequence, drought and famine in these areas has become prevalent, occurring almost every other year. In order to address the problem, a modification of the traditional crop production system is required.

To improve crop production in these areas, it is necessary to improve rain water productivity (RWP). Infield rainwater harvesting (IRWH) had been found to improve RWP in some semi-arid ecotopes of South Africa. The system is appropriate for small scale farmers and resulted in significant increases in crop yield. It was hypothesized that IRWH will improve the RWP and boost crop production in the water stressed semi-arid ecotopes of Ethiopia.

In order to test the hypothesis, a study was launched to quantify the rainfall-runoff relationships on three selected semi-arid ecotopes in Ethiopia during the 2003 and 2004 main rain seasons. The ecotopes are Dera Calcic Fluvic Regosol, Melkassa Hypo Calcic Regosol and Mieso Hypo Calcic Vertisol. They are located in the central Rift Valley of Ethiopia. They have an annual rainfall that ranges between 600 – 800 mm. Their AI is also less than 0.5. In these ecotopes drought is a common phenomena, happening once in every three years. In order to be able to extrapolate the results obtained, a detailed ecotope characterization was undertaken at each of the ecotopes. These include soil, climate and topography.

The study was conducted on runoff plots of 2 meter by 2 meter in size. Runoff initiated on the 2 meter strip was collected and measured for every storm. The rainfall intensity of each storm at minute interval was measured by a tipping bucket type rain gauge. At each ecotope the experiment was laid out with two soil surface treatments, conventional tillage (CT) simulating the relatively rough surface of a conventionally tilled land, and no-till (NT) simulating the flat crusted surface on the runoff strip of the IRWH system (Figure 1.1), There were three replications, in a randomized complete block design. The Morin & Cluff (1980) runoff model was selected to simulate runoff. The model was calibrated and validated using measured rainfall-runoff data during the two experimental seasons. The Morin & Cluff (1980) runoff model simulated the runoffs of each ecotope reasonably well. Measured runoff vs. simulated runoff for the combined seasons gave R^2 values of 0.94, 0.86 and 0.91 for Dera, Melkassa and Mieso, respectively, on the NT treatment. Equivalent values for the CT treatment were 0.95, 0.94 and 0.86, respectively. In all cases the D-index was found to be > 0.98. During the calibration and validation process, I_f values were found to be 6 mm hr^{-1} for Dera and Melkassa, and 10 mm hr^{-1} for Mieso. It was found that I_f was affected more by the soil surface character rather than by the antecedent soil water content. Appropriate soil storage values (s) on NT plots were found to be 0.3, 1.0 and 2.0 mm for Dera, Melkassa and Mieso, respectively. High storage conditions created by cultivation were found to be short lived after heavy storms on all ecotopes.

Maize grain yields from the nearby Melkassa Research Station under conventional tillage were used to obtain an estimate of the yields which would have been produced by using IRWH. Fifteen years (1989-2003) of maize yield data were used. Two related empirical models were used to simulate maize grain yield using IRWH. Basic water balance data were calculated using the Penman-Monthieth equation which is available in a software program of CROPWAT. Rainfall-runoff relationships for the Melkassa Hypo Calcic Regosol obtained during the two seasons of measurements were also used to provide basic input data for the models. Estimated maize grain yield increments using IRWH by the two models revealed 33 and 40% compared to CT.

The ratio of runoff (R) to rainfall (P), i.e. R/P was used as an integrated parameter to quantify the rainfall-runoff relationship for each ecotope. The R/P values were high for all ecotopes, viz. 0.52, 0.45 and 0.32 for Dera, Melkassa and Mieso, respectively, on the NT plots. At Dera and Melkassa runoff from the two treatments didn't show a statistically significant difference. Due to fairly stable clods on the Mieso Vertisol CT treatment, that increased soil storage, there was a significant difference in runoff between the treatments. The crust formed on the Dera and Melkassa Regosols are hard and smooth, and continuously became more stable after every storm. The Mieso Vertisol crust cracks on drying and is renewed by every storm.

Similar ecotopes can benefit from the output of this study. The stopping of runoff completely and the additional water which will be collected in the basins of the IRWH system should help to decrease the water deficit in the soil root zone and increase RWP. This will in turn contribute towards sustainable crop production on these semi-arid ecotopes.

9. REFERENCES

ABEBE, M., 1998. Nature and management of Ethiopian soils. ILRI, Addis Ababa

ABEBE, M., 1980. State of the soil science development for agriculture in Ethiopia. *Ethiopian J. of Agri Sci*. 2, 139-155.

ADJEI-TWUM, D.C., GEORGIS K. & TEKELE, A., 1984. Effect of cultivar, population density, planting date and tillage methods on yield of sorghum under dryland farming condition at Kobo. In: proceedings of the 15th National Crop Conference, Addis Ababa, Ethiopia.

ALLEN, R.G., PEREIRA, L.S., RAES, D. & SMITH, M., 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. FAO, Rome.

BABACAR, N., ESTEVES M., VAN DER VAER J.P., LAPETITE J. & VAUCLIN M., 2005. Effect of rainfall and tillage direction on the evaluation of surface crust, soil hydraulic properties and runoff generation for a sandy loam soil. *J.Hydrology* 307, 294-311.

BENNIE, A.T.P. & HENSLEY M., 2001. Maximizing precipitation utilization in dry land agriculture in South Africa. *J. Hydrology* 241. Elsevier Science Publishers B.V, Amsterdam, The Netherlands.

BNNIE, A.T.P., STRYDOM, J.E & VREY, H.S., 1994. Opgaring en benutting van reënwater in grond vir die stabilisering van plantproduksie in halfdroë gebiede. Waternavorsingskommisie verslag no. 227/1/94, Pretoria.

BERRY, W A. J, & MALLETT, J. B, 1988. The effect of Tillage: Maize residue interactions upon soil water storage. *S. Afri J. Plant Sci*.5,

BEUKES, D. J, BENNIE, A T P & HENSLEY, M, 1998. Optimization of soil water use in the dry crop production areas of South Africa: A review.

BEVEN, K., 2004. Infiltration excess at the Harton Hydrology Laboratory (or not?). *J. Hydrology* 293, 219-234.

BIAMAH, E.K., GICHUKI F.N. & KAUMBUTHO, P.G., 1993. Tillage methods and soil and water conservation in Eastern Africa. *Soil & Tillage Res*. 27, 105-123.

BLAKE, G.R. & HARTGE, K.H., 1986. Methods of soil analysis. Part 1. Physical and mineralogical methods. In: A. Klute (ed.). 2nd ed. ASA, Madison.

BLOEM, A.A. & LAKER, M.C., 1994. Criteria for adaptation of the design and management of centre-pivot irrigation systems to the infiltrability of soils. *Water South Africa* 2, 20, 127-132.

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

BONTA, J. V., 1997. Proposed use of Huff curves for hyetograph characterization. In: Richardson *et.al.* (eds.). Proceedings of Workshop on Climate and Weather Records. Denver, Colorado. 17-19 July 1995. USDA-Agricultural Research Service, 1996-03.

BOTHA, J.J., 2007. Evaluating maize and sunflower production in a semi-arid area using infield rainwater harvesting. PhD thesis in press. University of the Free State. Bloemfontein.

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

BRESSON, L.-M. & BOIFFIN, J., 1990. Morphological characterization of soil crust development stages on an experimental field. Geoderma 47, 301-325.

CASTILLO, V. M., GOMEZ-PLAZA A., & MARTINEZ-MENA M., 2003. The role of antecedent soil water content in the runoff response of semiarid catchments. A simulation approche. *J. Hydrology* 284, 114-130.

CERDAN, O., SOUCHÈRE, V., LECOMTE, V., COUTURIER, A. & LE BISSONNAIS, A., 2002. Incorporating soil surface crusting processes in an expert-based runoff model. Sealing and transfer by runoff and erosion related to agricultural management. CATENA 46, 189-205.

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

DARKOH, M.B.K., 2003. Regional perspectives on agriculture and biodiversity in the dryland of Africa. *J. Arid Environ.* 54, 261-279.

DESCHEEMAEKER, K., MUYS, B., NYSSEN, J., POESEN, J., RAES, D., HAILE, M. & DECKERS, J., 2006. Runoff on slopes with restoring vegetation: A case study from the Tigray highlands. *J. Hydrology*. In press. doi:10.1016/j.jhydrol.2006.05.015

DIVISION OF AGRICULTURAL ENGINEERING, 1984. Infiltration: measurements and use. Department of technical Services, Silverton, South Africa.

DE WIT, C.T., 1982. Simulation of plant growth and crop production. In: F.W.T. Penning De Vries and H.H. VanLaar (eds.), 3-8. Agricultural Publishing and Documentation (Pudoc), Wageningen.

DU PLESSIS, M.C. & MOSTERT, J.W.C., 1965. Runoff and soil losses at the Agricultural Research Centre, Glen. *S. Afr. J. Agri. Sci.* 8, 1051-1061.

DUAN, Q., SOROOSHIAN S. & GUPTA V.K., 1994. Optimal use of the SCE-UA global optimization method for calibrating watershed models. *J. Hydrology* 158, 265-284.

DUNIN, F.X., SIMITH, C.J., ZEGELIN, S.J., LEUNING, R., DENMEAD, O.T. & POSS, R., 2001. Water balance changes in a crop sequence with lucerne. *Aus. J. Agri. Res.* 52, 247-261.

ELDRIDGE, D.J., ZAADY, E. & SHACHAK, M., 2000. Infiltration through three contrasting biological soil crusts in patterned landscapes in the Negev, Israel. *Catena*, 40, 3, 323-336.

ENGIDA, M., 2000. Agro-climatic belts of Ethiopia – Potentials and constraints. In: Engida Mersh (ed.). Proceedings of the national sensitization workshop on Agrometeorology and GIS held in Addis Ababa, 17-18 December 2001.

FAO, 1984. "Provisional Soil Association Map of Ethiopia (1:2,000,000)" based on the work of H.Y. Wijntje-Bruggeman, AG:DP/ETH/82/010, Field Document 6, Addis Ababa.

FAO, 1989. Physiography and Soils of the Hykoch and Butajira and Yerer and Kereyu Awerajas (Shewa). By Dr. L.A. Vansleen with the assistance of Misbah Abudulatif, Alemayehu Neway and Senbeta Esata. FAO/AG : DP/ET/87/006, Field Document 37. Addis Ababa.

FAO, 1998. Soils of East Africa. www.67.95.153.93/RiftValley_soils.php.

FAO, 1998b. World Reference Base for Soil Resources. World Soil Resource Reports 84. FAO, Rome.

GEORGIS, K., TEMESGEN, M. & GODA, S., 2001. On-farm evaluation of soil moisture conservation techniques using improved germplasm. In: proceedings of Seventh Eastern and Southern Africa Regional Maize Conference, 11th – 15th February, 2001. 313-316.

GEORGIS, K. & WOLDEYESUS, S., 1992. Tillage, soil and water conservation research on maize in Ethiopia. In. T Benti & J.K. Ransom (eds.). Proceedings of the First National Maize Workshop of Ethiopia. 5-7 May 1992, Addis Ababa, Ethiopia. IAR/CIMMYT, Addis Ababa. 56-61.

GIBBS, M.D., 1993. Erosion studies using natural plots. Unpublished data, personal communication.

GICHERU, P.T., GACHENE, C.K.K. & BIAMAH, E.K., 1998. Effects of tillage and mulching on soil moisture conservation and crop production. *Applied Plant Sci.* 12

G/KIDAN, H., & HAILE M., 1990. Soil Science Research Programme, Annual Research Report.

GOWING, J.W., WYSEURE G.C.L. & YOUNG , M.D.B. 1993. A Holistic modeling approach as a framework for evaluating rainwater harvesting in semi-arid environments. In: Proceedings of the Fourth Annual Conference of SADC-Land Water Management Research Program. Windhoek, Namibia, Oct 11-14, 1993. 127-138.

GRAEF, F. & STAHR, K., 2000. Incidence of soil surface crust types in semi-arid Niger. *Soil & Tillage Res*. 55, 213-218.

GREEN, W.H. & AMPT, G. A., 1911. Studies on soil physics: 1. The flow of air and water through soils. Journal of Agricultural Science. V (4), Issue (1-24).

GREGORY, P.J., 1989. Concepts of water use efficiency. In: Proceedings of an international ICARDA workshop. Turkey. May 1989. 9-19

HAILE, M & REDA F., 1996. Soil and moisture conservation in the semi-arid areas of Ethiopia. In: Proceedings of the third Ethiopian Soil Science Society, February 28-29, 1996. Addis Ababa, Ethiopia. 60-66.

HANKS, R.J., GARDNER, H.R. & FLORIAN, R.L., 1969. Plant growth-evapotranspiration relations for several crops in the central Great Plains. *J. Agron.* 61, 30-34.

HARDY, N., SHAINBERG, I., GAL, M. & KEREN R., 1983. The effect of water quality and storm sequence upon infiltration rate and crust formation. *J. Soil. Sci.* 34, 677-691.

HATTINGH, H.W., 1993. Die beraming van grondoppervlakverdamping by droëlandkoring en –mileieverbouing. M.Sc. Thesis. University of the Orange Free State. Bloemfontein.

HAYLETT, D.G., 1960. Runoff and soil erosion studies at Pretoria. *S. Afri J. of Agri. Sci.* 3, 379-394.

HENSLEY, M., BOTHA, J.J., ANDERSON, J.J., VAN STADEN, P.P. & DU TOIT, A., 2000. Optimizing rainfall use efficiency for developing farmers with limited access to irrigation water. WRC Report No. 878/1/00. Water Research Commission, Pretoria, South Africa.

HENSLEY, M., HATTINGH, H. & BENNIE, A.T.P., 1993. A water balance modeling problem and a proposed solution. In: Proceedings of the Fourth Annual Scientific Conference, October 11-14, 1993. Windhoek, Namibia. 479-482.

HENSLEY, M., SNYMAN, P.J. & POTGIETER, H.L.J., 1990. A parameter for describing the efficiency of water use in rainfed cropping. Poster paper presented at International Symposium held in Brisbane, Australia. July 1990.

Hillel, D., 1980. Fundamentals of soil physics. Academic Press, London.

Hillel, D., 1982. Introduction to soil physics. Academic Press, London.

HILLEL, D., 1972. The field water balance and water use efficiency. In: Optimizing the soil physical environment towards greater crop yields. D. Hillel (ed.). Academic Press, London.

HILLEL, D. & ROSENZWEIG, C., 2002. Desertification in relation to climate variability and change. *Adv. Agron*. 77, 1-38.

HOFFMAN, J.E., 1997. Kwantifisering en voorspelling van grondwaterverdamping by droēlandgewasproduksie. Ph.D. thesis, U.O.V.S. Bloemfontein.

HOOGMOED, W.B. & STROOSNIJDER, L., 1984. Crust formation on sandy soils in the Sahel. I. Rainfall and infiltration. *Soil & Tillage Res*. 4, 5-23.

HORTON, R.E., 1940. An approach toward a physical interpretation of infiltration capacity. *Soil Sci.Soc. Am Proc*. 5, 399-417.

HUFF, F.A., 1967. Time distribution of rainfall in heavy storms. *Water Resource Research*. 3, 1007-1019.

ITANNA, F., 2005. Sulphur distribution in five Ethiopian Rift Valley soils under humid and semi-arid climate. *J. of Arid Environ,* article in press. www.elsevier/locate/jnlabr/yjare.

KIAZOLU, J.S., DONKER, S.M.K., BITSANG, M. & RAMOLEMANA, G. 1993. Effect of soil moisture tension on the availability of nitrogen and phosphorus to maize in two soils of Botswana. In: Proceedings of the Fourth Annual Scientific Conference, October 11-14, 1993. Windhoek, Namibia. 468-478.

KRONEN, M. 1994. Water harvesting and conservation techniques for smallholder crop production system. *Soil & Tillage Res.* 32. Elsevier Science Publishers B.V, Amsterdam, The Netherlands.

LADO, M., & BEN-HUR M., 2004. Soil mineralogy effects on seal formation, runoff and soil loss. Allied Clay Science 24, 209-224.

LE BISSONNAIS, Y., 1996. Aggregate stability and assessment of soil crusting and erodibility: 1. Theory and methodology. *Euro. J. of Soil Sci.* 47, 425-437.

LĒONARD, J., ANCELIN, O., LUDWIG, B. & RICHARD, G., 2005. Analysis of the dynamics of soil infiltrability of agricultural soils from continuous rainfall-runoff measurements on small plots. *Journal of Hydrology*, 326, 1-4, 122-134.

LĒONARD, J. & ANDREUX, P., 1998. Infiltration characteristics of soils in Mediterranean vineyard in Southern France. Catena 32, 209-223.

MACVICAR, C.N., SCOTNEY, D.M., SKINNER, T.E., NIEHAUS, H.S. & LOUBSER, J.H., 1974. A classification of land (climate, terrain form, soil) primarily for rainfed agriculture. *S. Afri. J. of Ext.*

MADSEN, H., WILSON G. & AMMENTORP H.C., 2002. Comparison of different automated strategies for calibration of rainfall-runoff models. *J. Hydrology* 261, Issue (1-4). 48-59.

MCKYES, E., 1989. Agricultural engineering soil mechanics. Elsevier, Amsterdam.

MAMO, G., 2006. Using seasonal climate outlook to advice on sorghum production in the central Rift Valley of Ethiopia. PhD. Agric. Dissertation, University of the Free State, Bloemfontein.

MANDEFRO, N., HUSSIEN, M., GELANA, S., GEZAHEGNE, B., YOSEF, B., HAILEMICHAEL, S. & ADERAJEW, H., 2001. Maize improvement for drought stressed areas of Ethiopia. In: Mandefro N., D. Tanner, and S. Twumasi-Afriyie (eds.). Enhancing the Contribution of Maize to Food Security in Ethiopia. Proceeding of the Second National Maize Workshop of Ethiopia. 12-16 November 2001. Addis Ababa, Ethiopia. 15-26.

MARK, 1989. Annual Report Agricultural Research Center. Melkkasa, Ethiopia.

MATHEWS, O.R. & ARMY, T.J., 1960. Moisture storage on followed wheat land in the Great Plains. *Soil Sci. Am. Proc*., 24, 414-418.

MERMUT, A.R., LUK, S.H., RÖMKENS, M.J.M. & POESEN, J.W.A., 1995. Micromorphological and mineralogical components of surface sealing in loess sols from different geographic regions. Geoderma 66, 71-84.

MIGUEL, A.P., IMHOFF, S., GHIBERTO, P. & MARANO, R.P., 2005. Change in some physical properties of Mollisols induced by supplemental irrigation. Geoderma doi:10.1016/j.geoderma.2005.08.007 (article in press).

MINISTRY OF AGRICULTURE (MoA), 2000. Agro-Ecological Zones of Ethiopia, Natural Resource Management and Regulatory Department, Addis Ababa.

MITKU, H., 1987. Genesis, characteristics and classification of the soils of Central Highlands of Ethiopia. PhD thesis, State University of Ghent, Ghent.

MOREL-SEYTOUX, 1978. Derivation of equations for variable rainfall infiltration. *Water Resource Research*, 14, 4, 561-568.

MOREL-SEYTOUX & KHANJI, J., 1974. Derivation of an equation of infiltration. Water Resource Research, 10, 4, 795-800.

MORIN, J. & BENYAMINI Y., 1977. Rainfall infiltration into bare soils. *Water Resource Research* 3, American Geophysical Union.

MORIN, J. & CLUFF, C. B., 1980. Runoff calculation on Semi-Arid watersheds using a Rotadisk Rainulater. *Water Resource Research* 16, University of Arizona, Tucson, Arizona 85721.

MORIN, J., 1967. The kinetic of raindrop impact and its influence on infiltration capacity and erosion of soils. PhD thesis, Hebrew University, Jerusalem.

MORIN, J., RAWITZ E., HOOGMOED, W.B. & BENYAMINI, Y., 1983. Tillage practice for soil and water conservation in the Semi-Arid Zone III: Runoff modelling as a tool for conservation tillage design. Elsevier Science Publishers B.V, Amsterdam, The Netherlands.

MWAKALILA, S.S. & HATIBU, N., 1993. Rain water harvesting for crop production in Tanzania. Proceedings of the third annual scientific conference of the SADC – Land Water Management Research.

NATIONAL SOIL RESEARCH CENTER-EARO, 2000. Procedures for soil and plant analysis. In: S. Sertsu and T. Bekele (eds.). Technical paper No. 74. NFIA, Addis Ababa, Ethiopia.

OFORI, C., 1994. Soil management for increased water and fertilizer use efficiency in the semi-arid environment. In: Water harvesting for improved agricultural production. Proceedings of the FAO Expert Consultation, Cairo, Egypt, November 1993. FAO, Rome.

OJASVI, P.R, GOYAL, R.K., & GUPTA, J. P., 1999. The Micro-Catchment water harvesting technique for the plantation of jujube (Zizyphus mauritiana) in an agroforestry system under arid conditions. *Agricultural Water Management* 41. Elsevier Science Publishers B.V, Amsterdam, The Netherlands.

OWEIS, T., HUCHUM, A., 2006. Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. *Agricultural Water management*, 80, 1-3, 57-73.

OWEIS, T., HUCHUM, A. & KIJNE, J., 1999. Water harvesting and supplementary irrigation for improved water use efficiency in dry areas. IWMI contribution (no. 7) to System-Wide Initiative on Water Management (SWIM).

PASSIOURA J., 2006. Increasing crop productivity when water is scarce- from breeding to field management. *Agricultural Water Management* 80, 176-196.

PHILIP, J.R., 1957. Theory of infiltration: 1. The infiltration equation and its solution. *J. of Soil Sci.* 83, 345-357.

RAO, K.P.C., STEENHUIS, T.S., COGLE, A.L., SRINIVASAN, S.T., YULE, D.F. & SIMITH, G.D., 1998. Rainfall infiltration and runoff from an Alfisol in semi-arid tropical India. II: Tilled systems. *Soil & Tillage Res*. 48, 61-69.

RATLIFF, L.F., RITCHIE, J.T. & CASSEL, D.K., 1983. Field measured limits of soil water availability as related to laboratory measured properties. *Soil Sci Soc. Am. J.* 47, 770-775.

RITCHIE, J.T., 1972. Model for predicting evaporation from a row crop with incomplete cover. *Water Resource Research* 18, 1204-1211.

RUSHTON, K.R., EILERS, V.H.M. & CARTER, R.C., 2006. Improved soil moisture balance methodology for recharge estimation. *J. Hydrology* 318, 379-399.

SEGINER, I. & MORIN J., 1970. A model of surface crusting and infiltration of bare soils. *Water Resource Research* 6, 629.

SHAVER, T.M., PETERSON, G.A. & SHERROD, L.A., 2003. Cropping intensification in dry land systems improves physical properties: regression relations. Geoderma 116, 149-164.

SLATTERY, M. C. & BRYAN, R.B., 1992. Laboratory experiments on surface seal development and its effect on interrill erosion processes. *J. Soil Sci*. 43, 517-529.

SNYMAN, H.A, & VAN RENSBURRG W.L.J, 1986. Effect of slope and plant cover on runoff, soil loss and water use efficiency of natural Veld. *J. of Grass. Soc. of S.Afri.* 4, 153-158.

SOIL CLASSIFICATION WORKING GROUP, 1991. Soil Classification-A taxonomy system for South Africa. Mem. Agric. Nat. Resour. S. Afr. No. 15. Dept. Dev., Pretoria.

SOIL CONSERVATION SERVICE-USDA, 1972. Estimation of direct runoff from storm rainfall. National Engineering Handbook, Section 4-Hydrology, 10.1-10.24.

STROOSNIJDER, L. & HOOGMOED, W.B., 1984. Crust formation on sandy soils in the Sahel. II. Tillage and its effect on the water balance. *Soil & Tillage Res*. 4, 321-337.

STROOSNIJDER, L. & KONE D., 1982. Le bilan d'eau du sol. In «La Productivité des Pâturages Sahéliens: Une Etude des Sols, des Végétations et de l'Exploitation de cette Ressource Naturelle (1 ére édition)». Penning de Vries, F.W.T. & Djiteye M.A. (eds.), PUDUC, Wageningen. 133-165.

STROOSNIJDER, L., 2003. Technologies for improving rainwater use efficiency in semi-arid Africa. In : Proceedings of Water Conservation Technologies for Sustainable Dryland Agriculture, Symposium and Workshop, Bloemfontein, South Africa, 8-11 April 2003.

TAMIRIE H., MITIKU, H., HELUF, G. & YOHANNES, U., 1984. Summary results of on-going Soil science Research Projects. Hararghe Highlands. Eastern Ethiopia. AAU.

TANNER, C.B. & SINCLAIR, T.R., 1983. Efficient water use in crop production. In: T.R. Jordan & H.M. Tayler (Eds). Efficient water use in crop production. *Am. Soc. of Agron*. Inc, Madison, Wisconsin, USA.

THE NON-AFFILATED SOIL ANALYSIS WORK COMMITTEE, 1990. Handbook of standard soil testing methods for advisory purposes. SSSSA, Pretoria.

TANSLEY, A.G., 1939. The British Isles and their vegetation. Vol. 1 of 2. Cambridge, United Kingdom. 494.

TARCHITZKY, J., BANIN, A., MORIN, J. & CHEN, Y., 1984. Nature, formation and effects of soil crusts formed by water drop impact. Geoderma 33, 135-155.

TEMESGEN, M., GEORGIS, K., GODA, S. & ABEBE, H., 2001. Development and evaluation of tillage implements for maize production in the dryland areas of Ethiopia. In: Proceedings of Seventh Eastern and Southern Africa Regional Maize Conference, 11 – 15 February, 2001. 308-312.

TROLL, C., 1971. Landscape ecology (geoecology) and biogecenology: A terminological study. Geoforum 8, 43-46.

TSUBO, M., WALKER, S. & HENSLEY, M., 2005. Quantifying risk for water harvesting under semi-arid conditions: Part 1. Rainfall intensity generator. Agricultural Water Management 76, 77-93.

VALENTIN, C. & BRESSON, L. M., 1992. Morphology, genesis and classification of surface crusts in loamy and sandy soils. Geoderma 55, 225-245.

VAN AVERBEKE, W. & MARAIS J.N., 1992. Maize response to plant population and soil water supply: I. Yield of grain and total above-ground biomass. *S. Afr. J. PlantSoil*, 9, 4, 187-192.

VAN DER WATT, H.V.H. & VAN ROOYEN, T.H., 1995. A glossary of soil science. (Second edition). *Soil Sci. Soc.* SA, Pretoria.

VAN DEVENTER, P.W., 2000. Die invloed van uitruilbare natriumpersentasie enkleimineralogie op die infiltreerbaarheid van gronde wat reeds as gevolg van sikliese besproeiing verseël is.; WRC Report No. 499/1/00. Water Research Commission, Pretoria, South Africa.

VERRECCHIA, E., YAIR, A., KIDRON, G.J. & VERREECHIA, K., 1995. Physical properties of the psammophile cryptogamic crusts and their consequences to the water regime of sandy soils, north western Negev Desert. *Israel J. of Arid Environ*. 29, 427-437.

WAKINDIKI, I.I.C. & BEN-HUR, M., 2002. Soil mineralogy and texture effects on crust micromorphology, infiltration and erosion. *J. of Soil Sci. Soc. of Am*. 66, 897-905.

WALKER, G.K., 1986. Transpiration efficiency of field-grown maize. *Field Crops Res*. 14, 29-38.

WALKER, S. & TSUBO, M., 2003a. Estimation of rainfall intensity for potential crop production on clay soil with in-field water harvesting practices in a semi-arid area. Report to the Water Research Commission. The University of Free State, Bloemfontein, South Africa.

WALKER, S. & TSUBO, M., 2003b. PUTURUN: A simulator for rainfall-runoff-yield processes with infield water harvesting. WRC report (Project no. K8/486). Department of Soil, Crop and Climate Sciences, The University of the Free State, Bloemfontein, South Africa.

WANG, Q. J., 1991. The genetic algorithm and its application to calibrating conceptual rainfall-runoff models. *Water Resource Research* 27, 2467-2471.

WIKIPEDIA, 2006. In *Wikipedia, The Free Encyclopedia*. Retrieved November 13, 2006, from http://en.wikipedia.org/wiki/Ecotope

WILLMOTT, C.J., 1981. On the validation of models. Physical Geography 2, 184-194.

WILLMOTT, C.J., 1982. Some comments on the evaluation of model performance. *Am. Met. Soc*.63, 1309-1313.

WOYESSA, Y.E. & BENNIE, A.T.P., 2004. Factors affecting runoff and soil loss under simulated rainfall on a sandy Bainsvlei Amalia soil. *S. Afri. J. of Plant Soil* 21, 203-207.

XUEFENG, C. & MARIŇO, M.A., 2005. Determination of ponding condition and infiltration into layered soils under unsteady rainfall. *Journal of Hydrology*, 313, 3-4, 195-207.

YOUNG, M.D.B., GOWING, J.W., WYSEURE, G.C.L. & HATIBU, N., 2002. Parched-Thirst: development and validation of a process-based model of rainwater harvesting. *Agricultural Water Management* 55, 122-140.

ZERE, T.B., 2003. Evaluating maize production potential of selected semi-arid ecotopes using a water balance model. M.Sc. Agric. Dissertation, University of the Free State, Bloemfontein.

ZERE, T.B., VAN HUYSSTEEN C.W. & HENSLEY M., 2005. Estimation of runoff at Glen in the Free State Province of South Africa. Water SA.31, 17-21.

Appendix 1

Dera ecotope profile description
Soil Type (WRB, 1998): Calcic Fluvic Regosols
South Africa: Dundee 1120 Sabie
Location: Dera, (Ethiopia)

Profile : Dera Calcic Fluvic Regosol ecotope	**Date: 13/01/04**
Location : • Lat: 8.36^0 N • Long: 39.34^0 E • Altitude: 1500 meters m.a.s.l.	Drainage class: Well drained • Internal drainage: Never saturated • Hydraulic conductivity: Rapid • External drainage: Receiving • Water table depth: Very deep • Moisture condition: Dry
Topography • Land form: Rift Valley plain • Land element: Terrace • Position: Intermediate part • Slope gradient/form: 1 %, concave • Micro-topography: Farm furrow	. Stone size: 120 mm Stone abundance: Very few
Land use/Vegetation: Peasant farm • Grass cover (%):	Rock outcrop: None • Quantity: • Distance: • Height:
Surface cracks: None • Width: • Distance:	Human influence: plowing Type/Degree of erosion: None Evidence of erosion: Gully near profile
Phase Flood frequency/duration: None Parent material/Rock: Unconsolidated (unspecified)	Area affected: Activity of erosion: Effective soil depth: 600 mm

Ap 0-200 mm Brown (7.5YR 5/2, dry), dark brown (7.5YR 3/4, moist); sandy loam; moderate fine sub angular blocky; soft dry, soft moist, slightly plastic and slightly sticky with very few fine roots; strongly calcareous; clear smooth transition to

A1 200-600 mm Brown (7.5YR 4/3, dry), dark brown (7.5YR 3/4, moist); loam weak fine sub angular blocky; soft dry, friable moist, non plastic and non sticky wet; many rounded gravels and calcium carbonate nodules; strongly calcareous; clear smooth transition to

AB 600-1300 mm Gravel layer; sandy loam, strongly calcareous; abrupt smooth transition to

A1 1300-1700 mm Pinkish grey (7.5YR 6/2, dry), dark brown (7.5YR 3/4, moist); loam; moderate medium sub angular blocky; soft, friable, slightly plastic, slightly sticky; few rounded gravels and calcium carbonate nodules; strongly calcareous.

Appendix 2

Melkassa ecotope profile description
Soil Type (WRB, 1998): Hypo Calcic Regosols
South Africa: Etosha 2111 Vetkuil
Location: Malkassa Research Centre, Nazareth (Ethiopia)

Profile : Melkassa Hypo Calcic Regosol ecotope	**Date: 13/01/04**
Location : • Lat: 8.43^0 N • Long: 39.31^0 E • Altitude: 1550 meters m.a.s.l.	Drainage class: Well drained • Internal drainage: Never saturated • Hydraulic conductivity: Slow • External drainage: Receiving • Water table depth: Very deep • Moisture condition: Dry
Topography • Land form: Rift Valley plain • Land element: Terrace • Position: Foot slope • Slope gradient/form: 1 %, concave • Micro-topography: Farm furrow	. Stone size: None Stone abundance: Very few
Land use/Vegetation: Research farm • Grass cover (%):	Rock outcrop: None • Quantity: • Distance: • Height:
Surface cracks: None • Width: • Distance:	Human influence: plowing Type/Degree of erosion: None Evidence of erosion: None
Phase Flood frequency/duration: None Parent material/Rock: Fluvial deposit (unspecified)	Area affected: Activity of erosion: Effective soil depth: 1000 mm

Ap 0-200 mm Brown (7.5YR 5/2, dry), dark brown (7.5YR 3/2, moist); clay loam; moderate fine sub-angular blocky; soft dry, soft moist, slightly plastic, slightly sticky; few fine roots; clear smooth transition to

A1 200-500 mm Brown (7.5YR 5/3, dry), dark brown (7.5YR 3/1, moist); clay loam; moderate fine sub angular blocky; soft dry, soft moist, slightly plastic, slightly sticky; fine horizontal cracks; very few very fine roots; slightly calcareous; clear smooth transition to

A1 500-1000 mm Brown (7.5YR 5/3, dry), dark brown (7.5YR 3/2, moist); loam; moderate fine sub angular blocky; slightly hard, soft, slightly plastic, slightly sticky; very few rounded gravels; very few very fine roots; slightly calcareous; clear smooth transition to

A1 1000-1500+ mm Pinkish white (7.5YR 8/2, dry), dark brown (7.5YR 3/2, moist); clay loam; moderate coarse platy; slightly hard, soft, non plastic, slightly sticky; few rounded gravels and calcium carbonate nodules; strongly calcareous.

Appendix 3

Mieso ecotope profile description
Soil Type (WRB, 1998): Hypo Calcic Vertisol
South African: Arcadia 1200
Location: Mieso, Ethiopia

Profile : Mieso Hypo Calcic Vertisol ecotope	**Date: 13/01/04**
Location :	Drainage class: Well drained
• Lat: 9.23^0 N	• Internal drainage: Never saturated
• Long: 40.77^0 E	• Hydraulic conductivity: Slow
• Altitude: 1352 meters m.a.s.l.	• External drainage: Receiving
	• Water table depth: Very deep
	• Moisture condition Slightly moist
Topography	.
• Land form: Rift Valley plain	Stone size: Fine $CaCO_3$ gravels
• Land element: Alluvial plain	Stone abundance: Very few
• Position: Lower part	
• Slope gradient/form: 2 %, concave	
• Micro-topography: Farm furrow	
Land use/Vegetation: Research farm	Rock outcrop: None
• Grass cover (%):	• Quantity:
	• Distance:
	• Height:
Surface cracks: None observed due to moisture	Human influence: plowing
• Width:	Type/Degree of erosion: None
• Distance:	Evidence of erosion: Gully near profile
Phase	Area affected:
Flood frequency/duration: None	Activity of erosion:
Parent material/Rock: Alluvial deposit material	Effective soil depth: 1600 mm

Ap 0-100 mm Brown (7.5YR 2/2, dry), very dark gray (7.5YR 3/1, moist); clayey; strong medium sub angular blocky; firm, hard; plastic, sticky; moderately calcareous; clear smooth transition to

A1 100-500 mm Brown (7.5YR 4/2, dry), very dark gray (7.5YR 3/1, moist); clayey; strong coarse sub angular blocky; hard, extremely firm, very plastic, very sticky; very few calcium carbonate nodules; moderately calcareous; clear smooth transition to

A2 500-1200 mm Brown (7.5YR 4/2, dry), very dark gray (7.5YR 3/2, moist); clayey; strong coarse angular blocky; very hard, extremely firm, very plastic, very sticky; very few calcium carbonate nodules; very fine cracks; strongly calcareous; clear smooth transition to

Bss 1200-1600 mm very dark grey (7.5YR 3/1, dry), black (7.5YR 2.5/1, moist); clayey; strong coarse angular blocky; extremely hard, firm, extremely plastic, extremely sticky; slightly shining slickensides; few calcium carbonate nodules; strongly calcareous; gradual smooth transition to

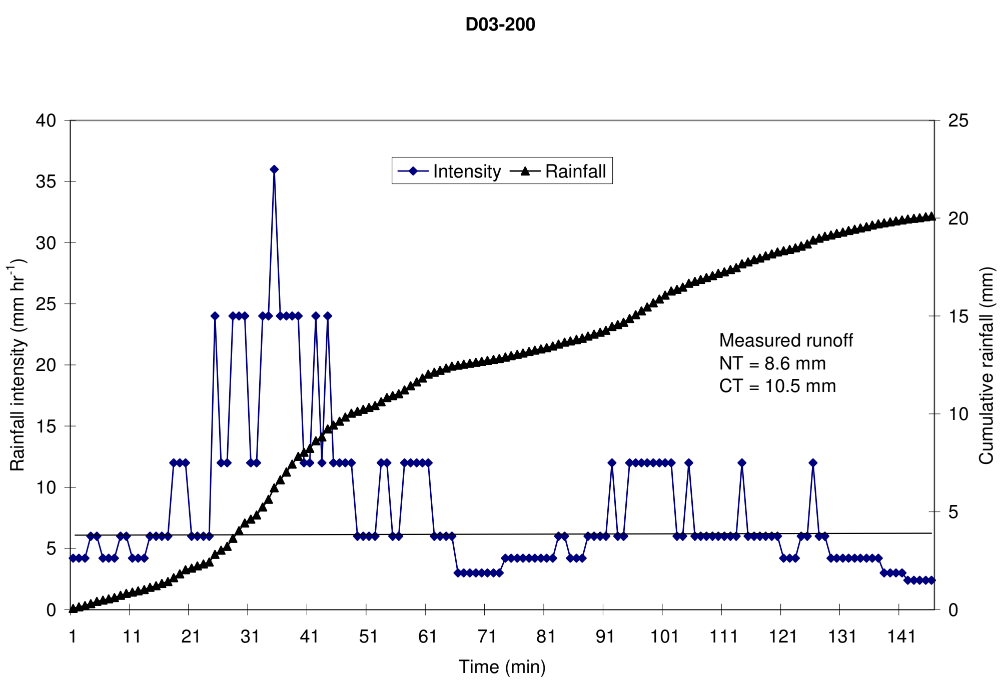
Bss 1600-2100+ mm very dark grey (7.5YR 3/1, dry), very dark brown (7.5YR 2.5/2, moist); clayey; strong coarse platy; slightly hard, firm, slightly plastic, sticky; slightly shining slickensides; many calcium carbonate nodules; extremely calcareous.

Appendix 4

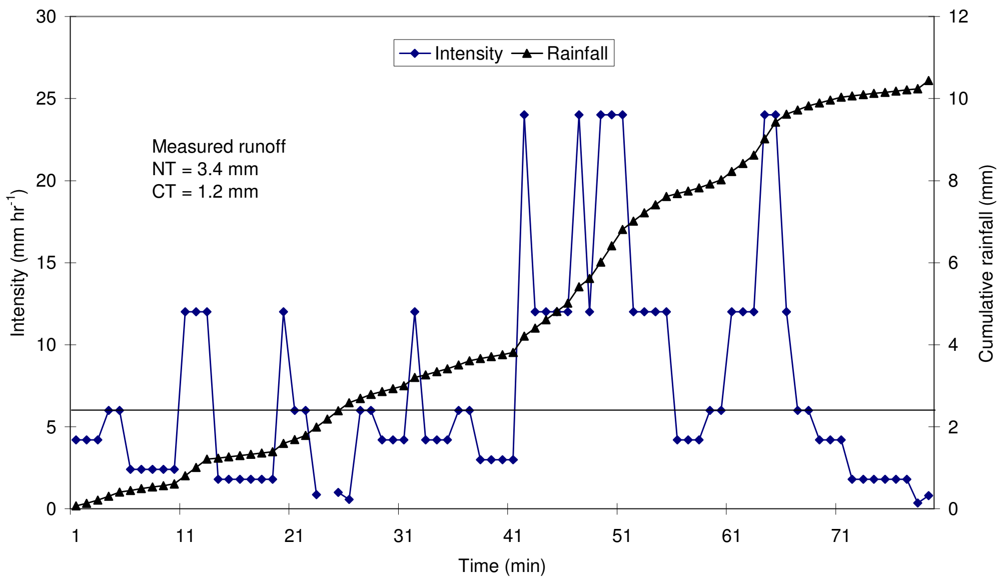
Dera ecotope rainfall intensity and cumulative rainfall

A. 2003 storms

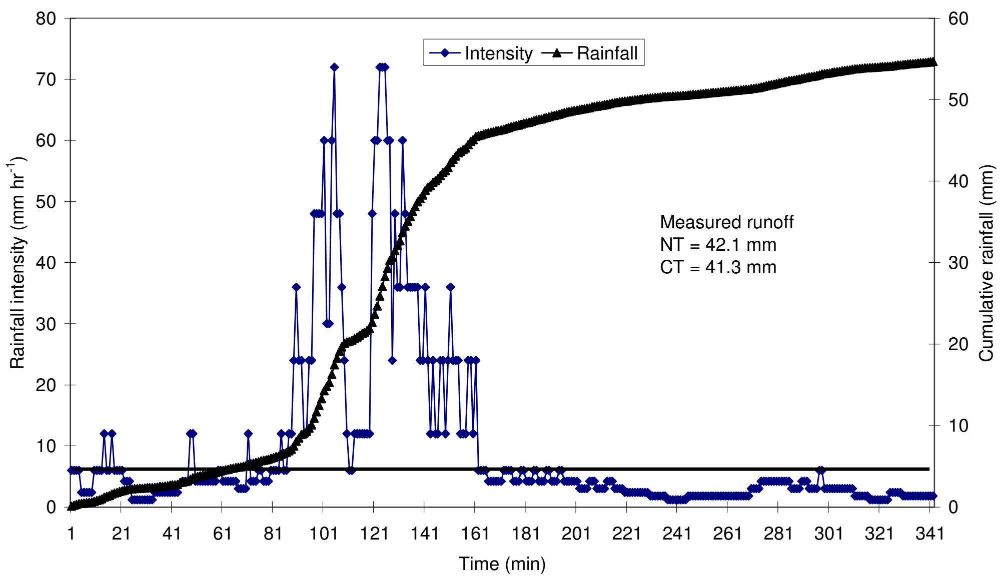
Each storm is labeled site (D), year (03) and day of the year (200) as D03-200
Horizontal line I_f = 6 mm hr^{-1} for Dera Calcic Fluvic Regosol ecotope



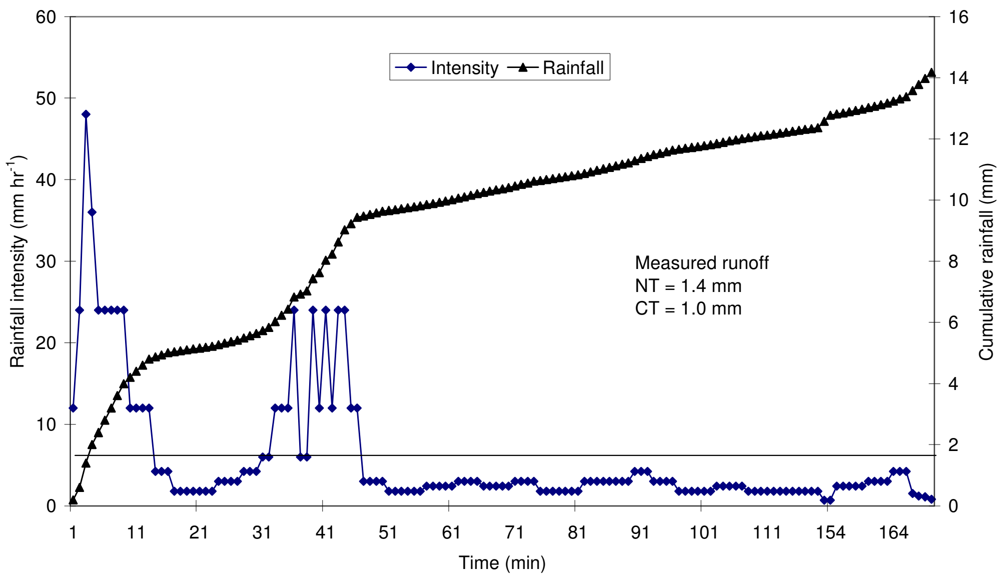
D03-202



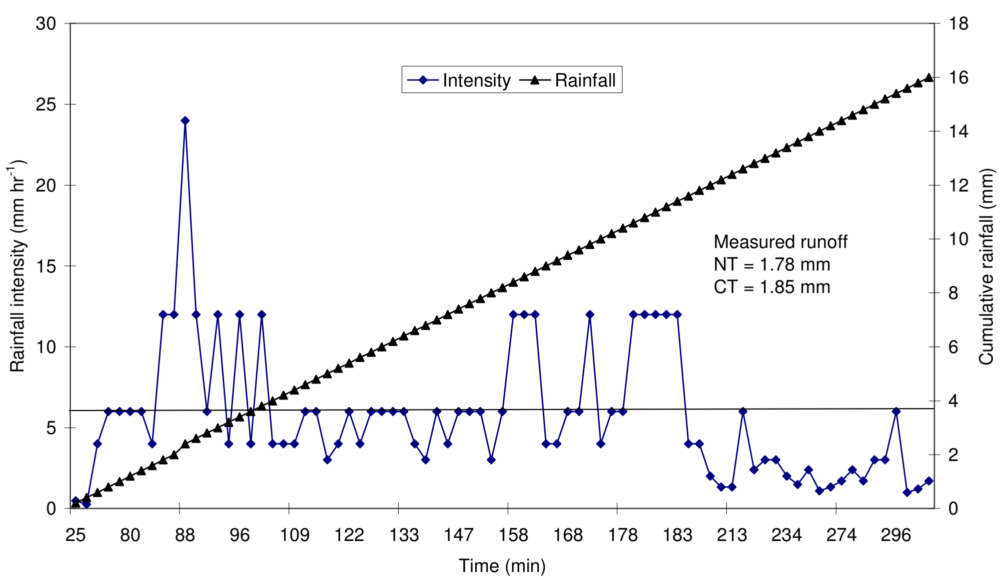
D03-207



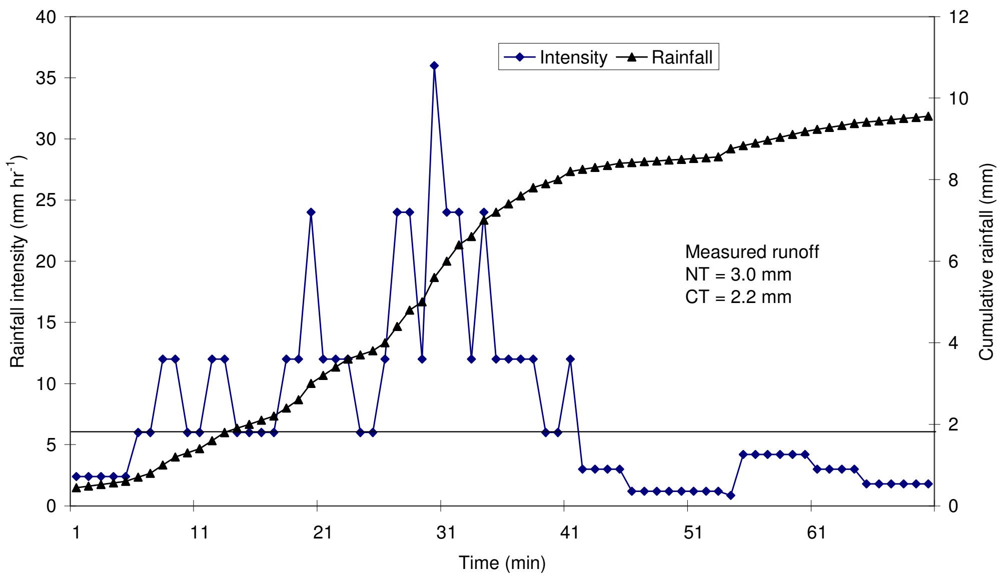
D03-212



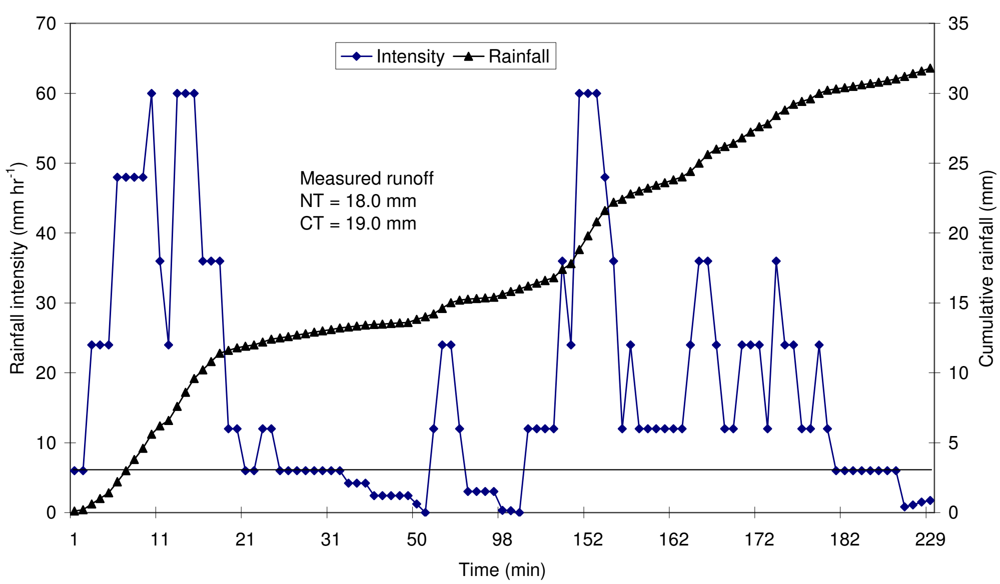
D03-214



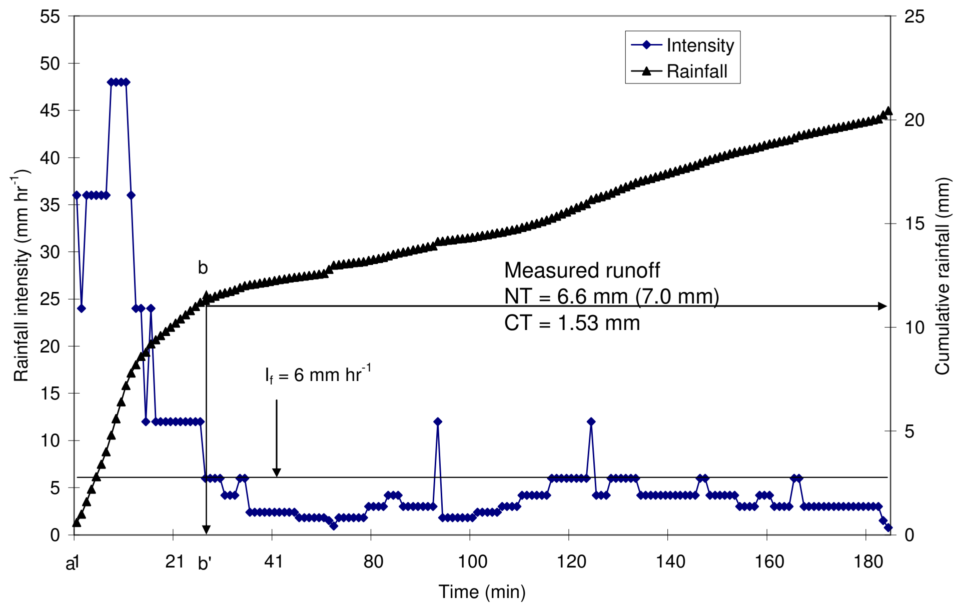
D03-218



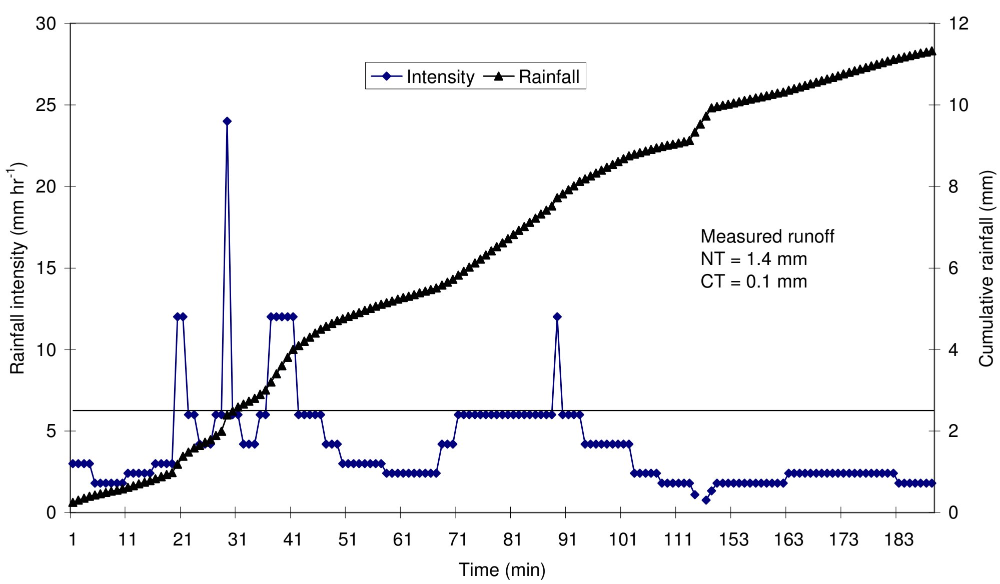
D03-225



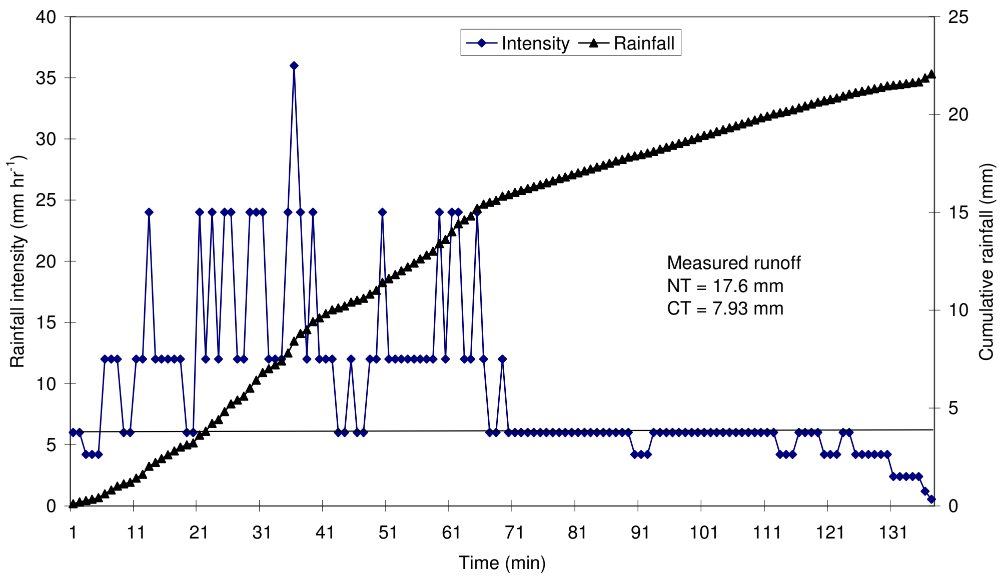
D0-236



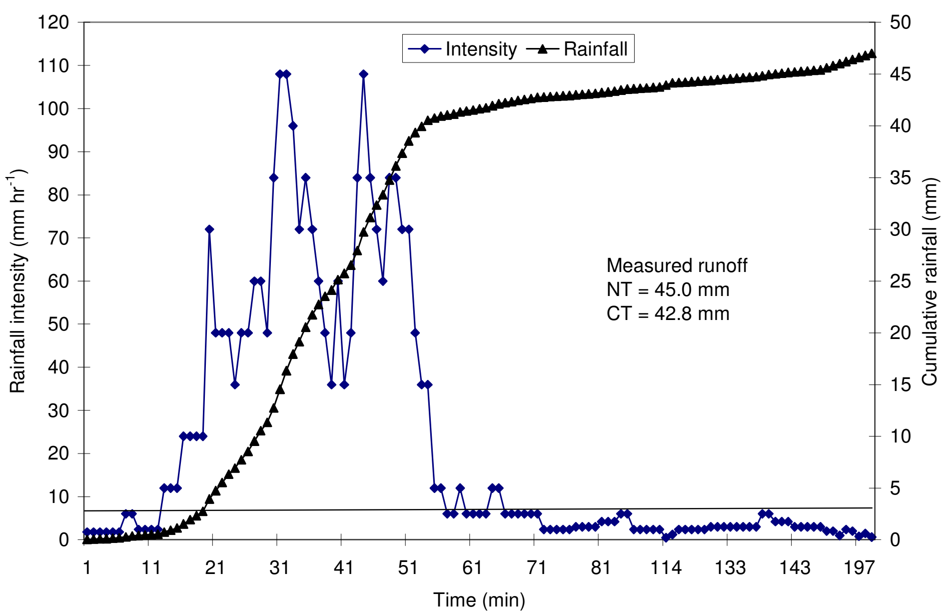
D03-239



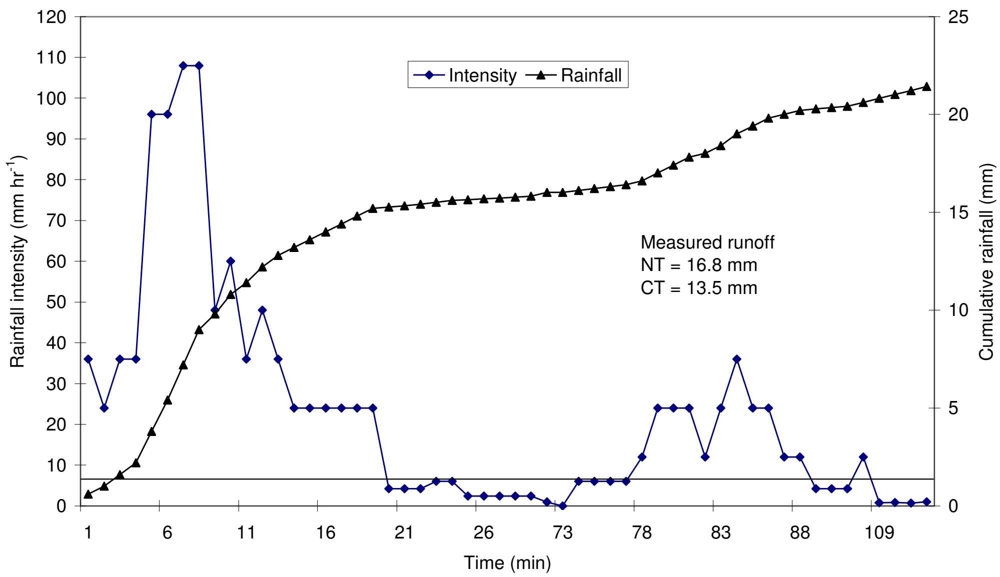
D03-242



D03-248

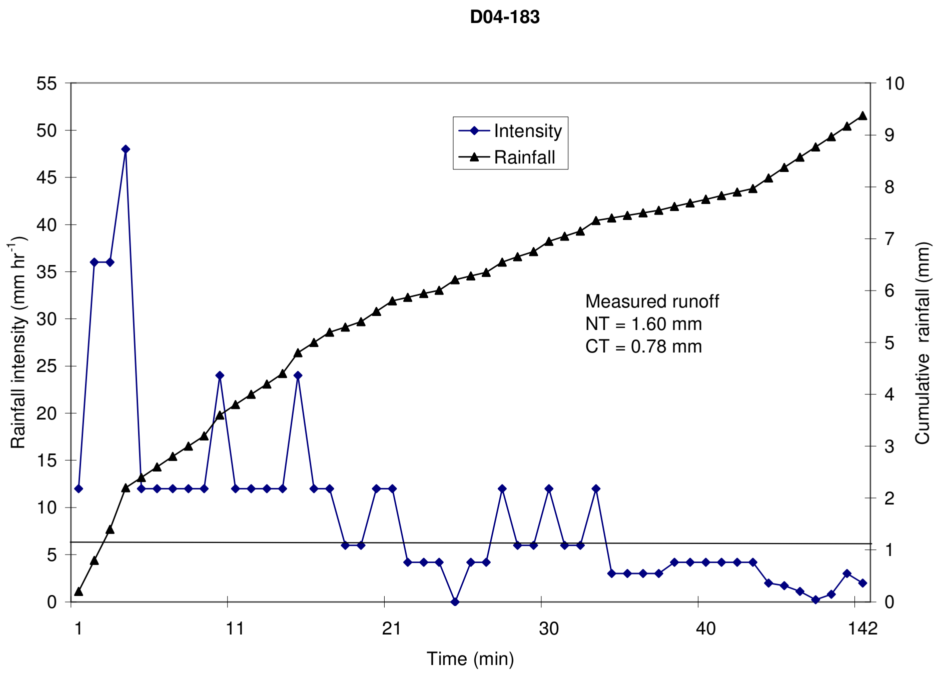


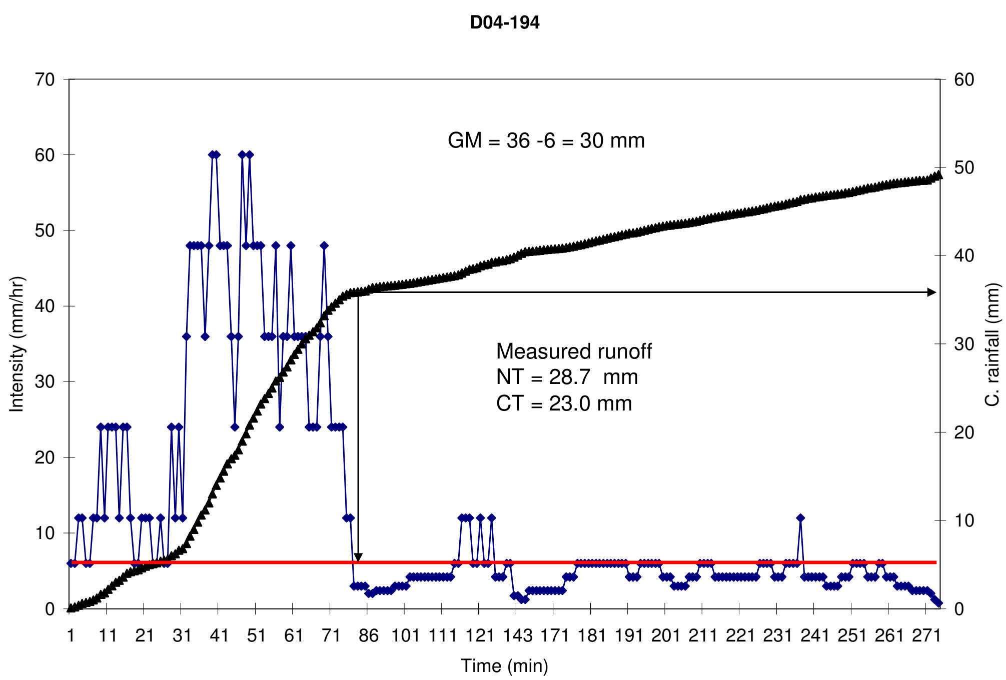
D03-266



120
110
100
90
80
70
60
50
40
30
20
10
0
Rainfall intensity (mm hr-1)
25
20
15
10
5
0
Cumulative rainfall (mm)
Intensity
Rainfall
Measured runoff
NT = 16.8 mm
CT = 13.5 mm
1
6
11
16
21
26
73
78
83
88
109
Time (min)

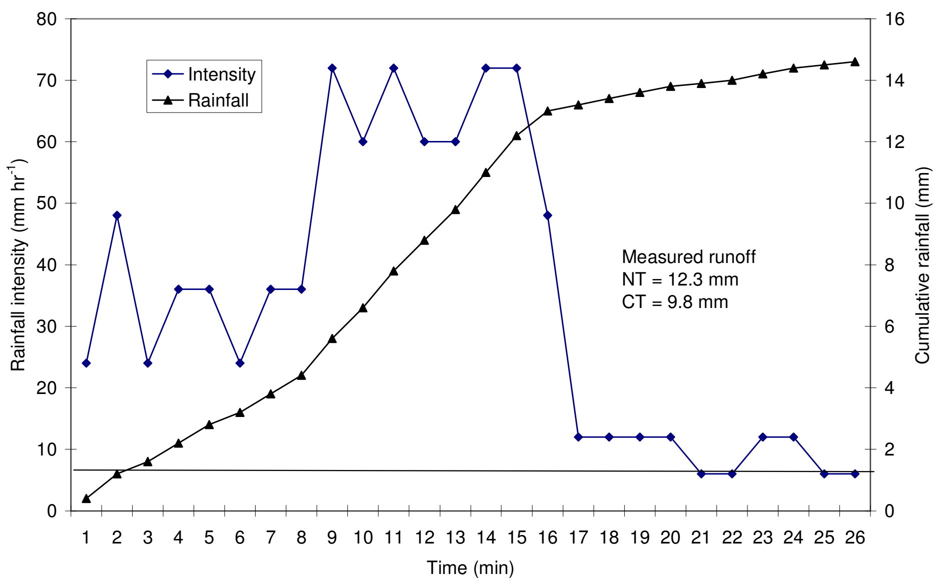
B. 2004 Storms



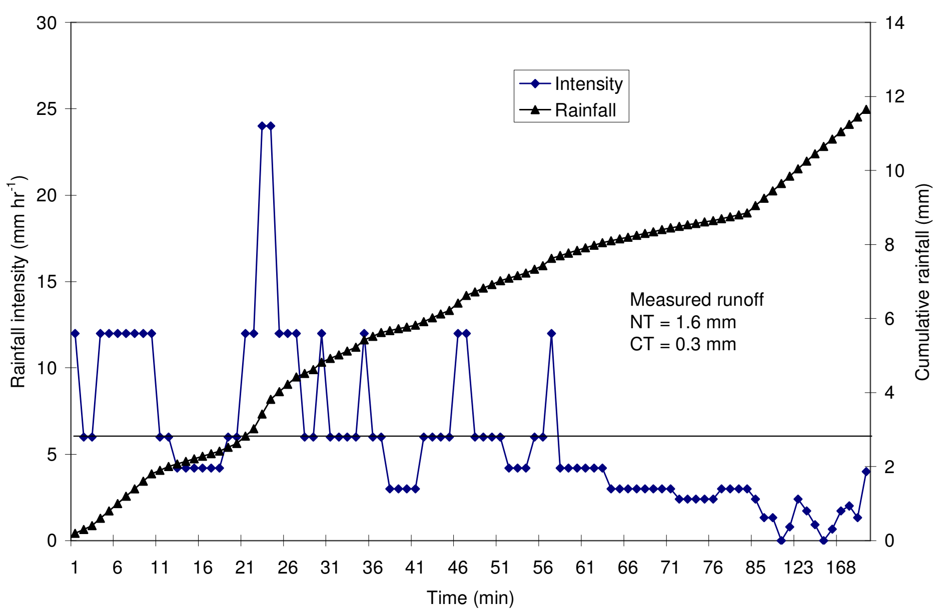


GM = Graphical method (Simulated by GM)

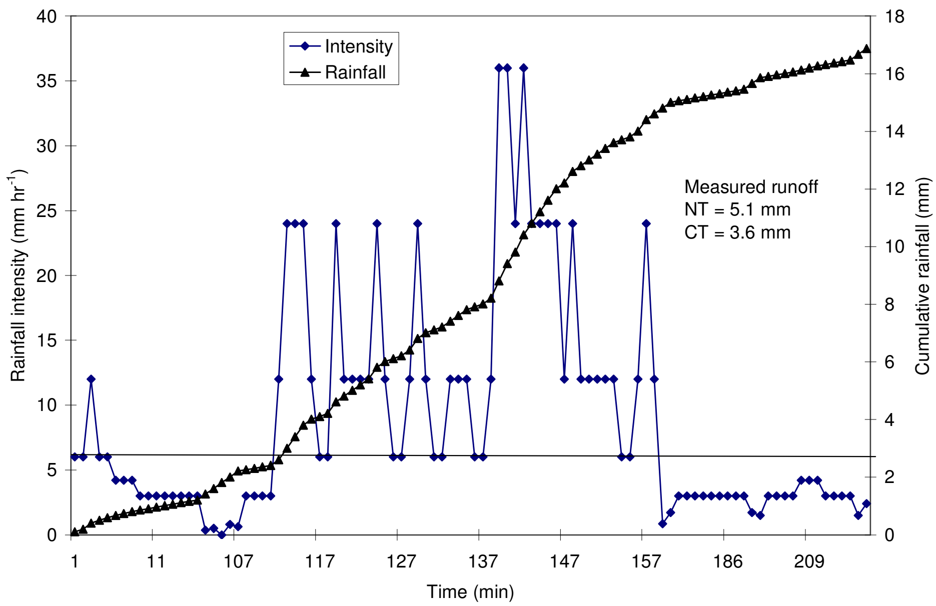
D04-197



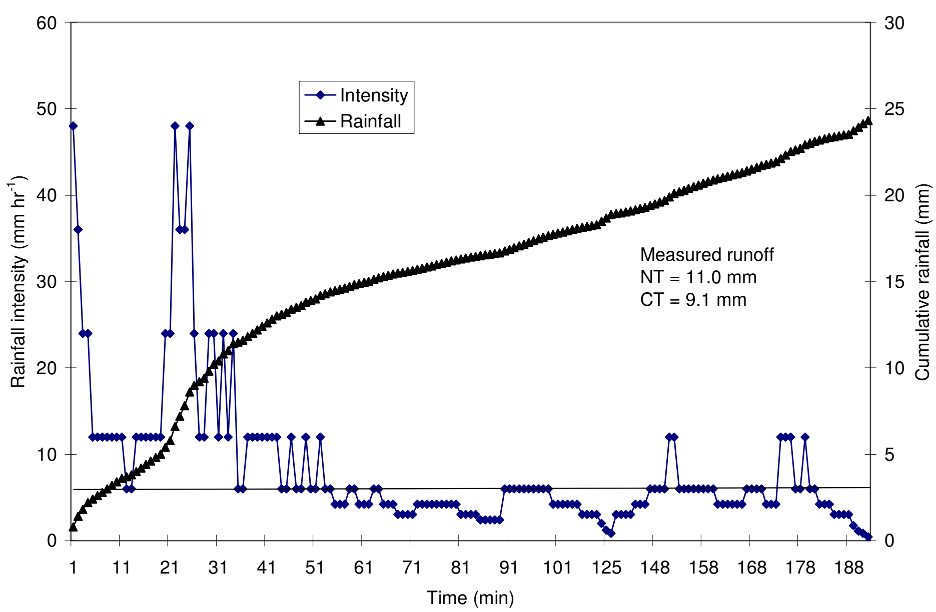
D04-203



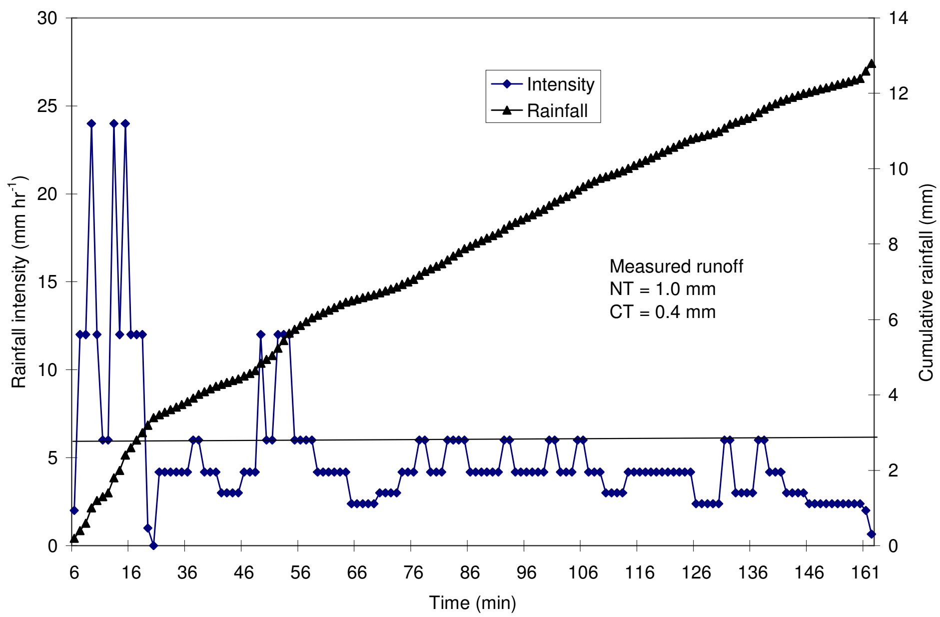
D04-211



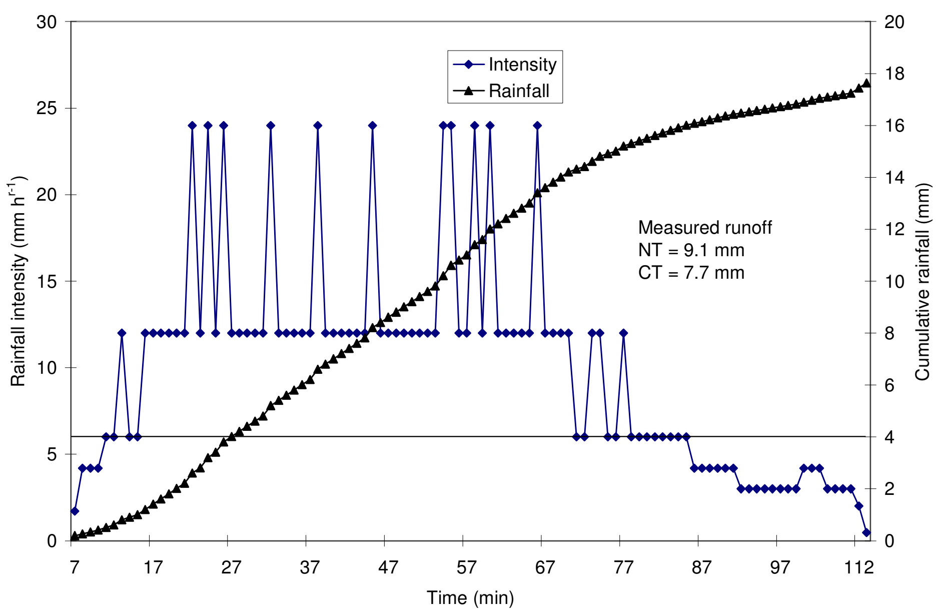
D04-212



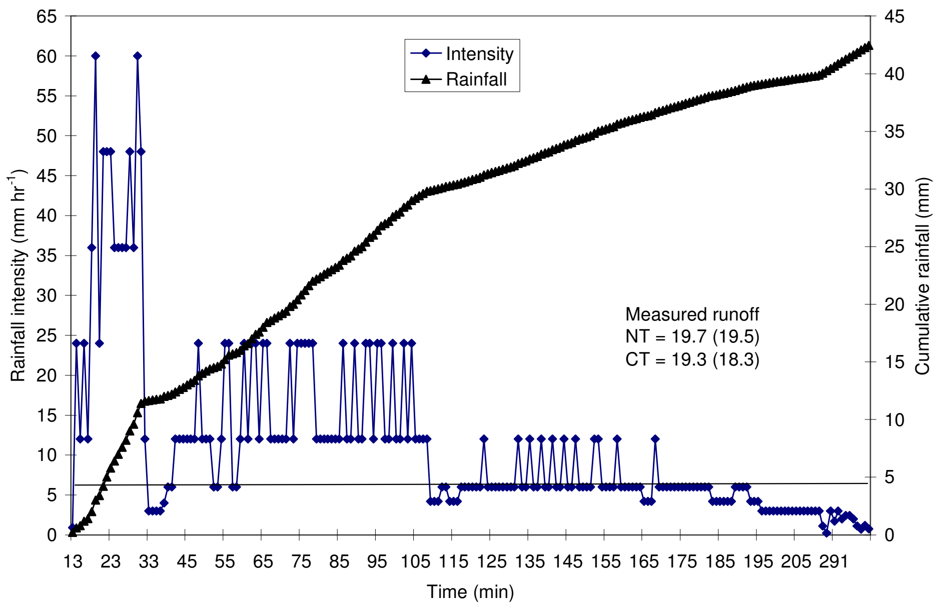
D04-220



D04-221

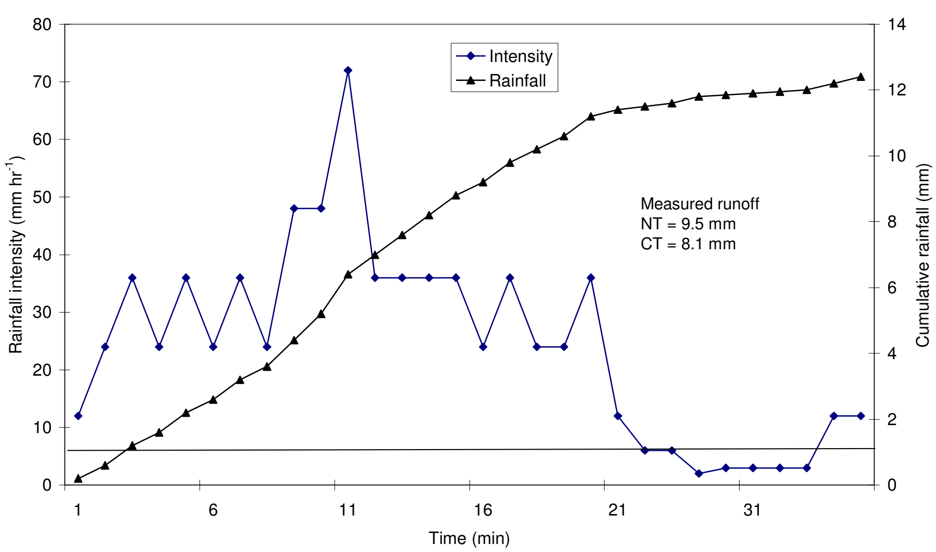


D04-223

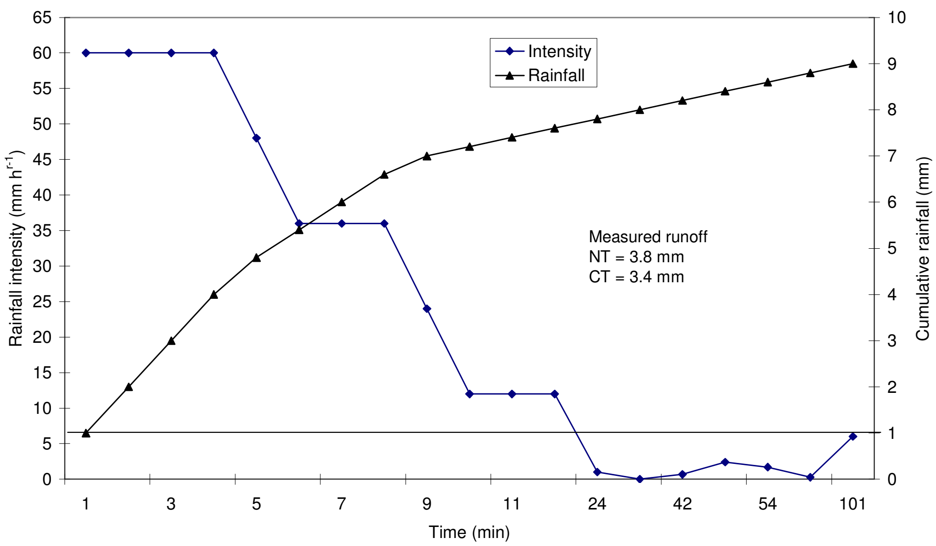


Note: Figures in brackets are simulated runoff by Morin & Cluff model

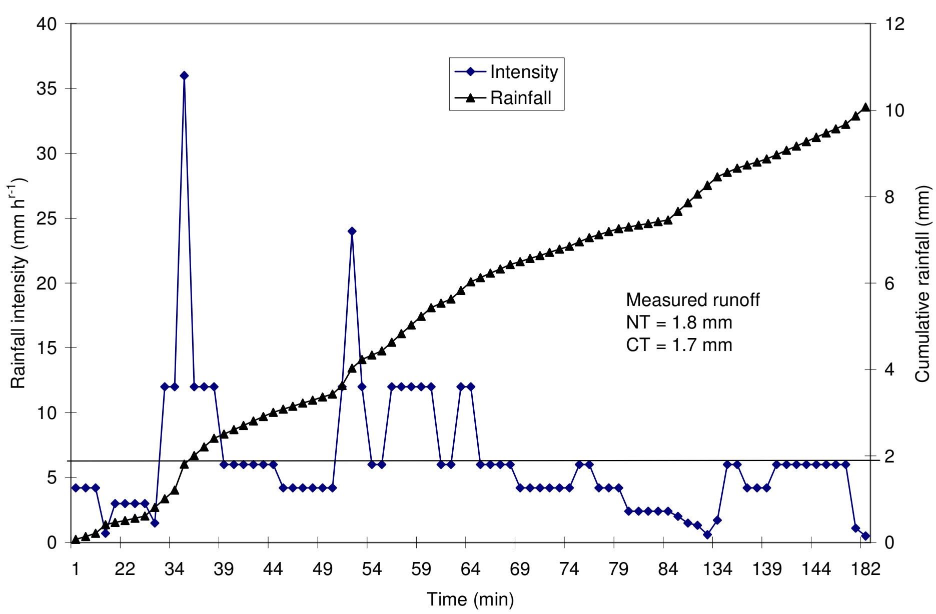
D04-232



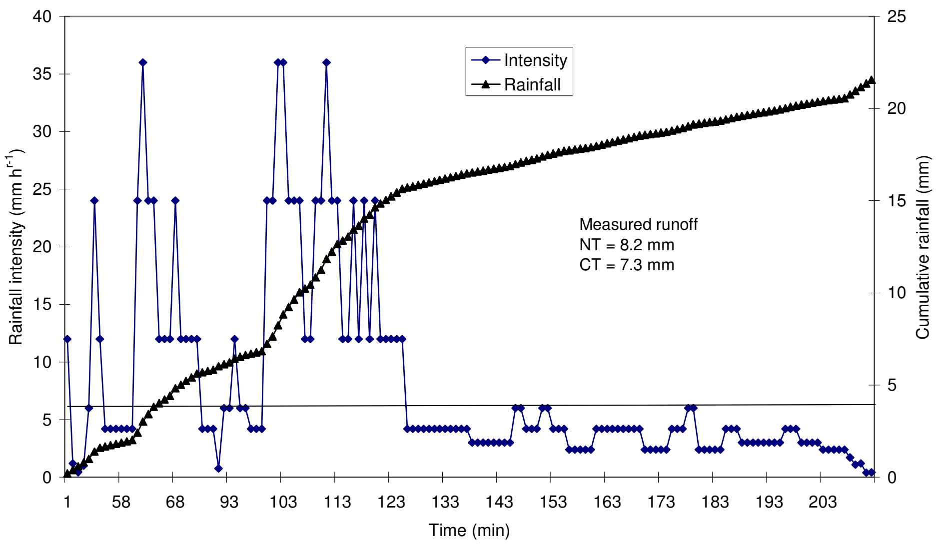
D04-236



D04-262



D04-277

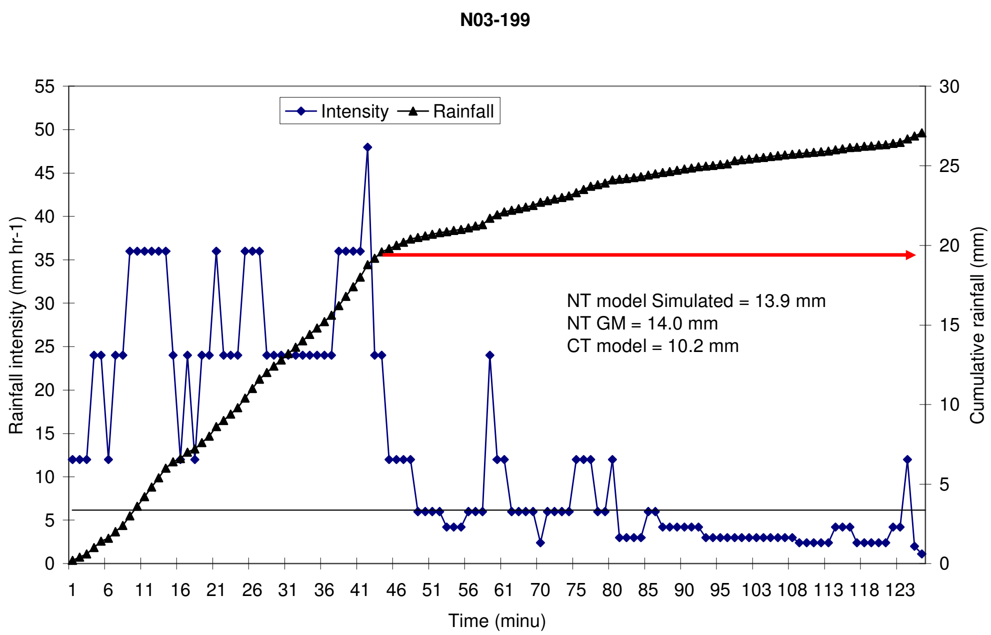


Intensity
Rainfall
Measured runoff
NT = 8.2 mm
CT = 7.3 mm
Rainfall intensity (mm h-1)
Cumulative rainfall (mm)
Time (min)
40
35
30
25
20
15
10
5
0
25
20
15
10
5
0
1
58
68
93
103
113
123
133
143
153
163
173
183
193
203

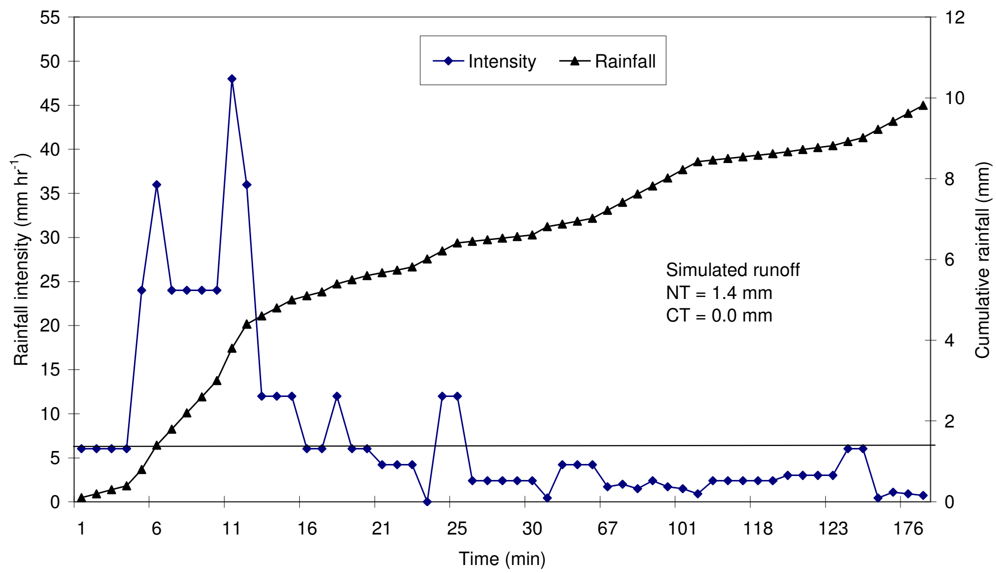
Appendix 5
Nazaret/Melkassa ecotope rainfall intensity and cumulative rainfall

A. 2003 Storms

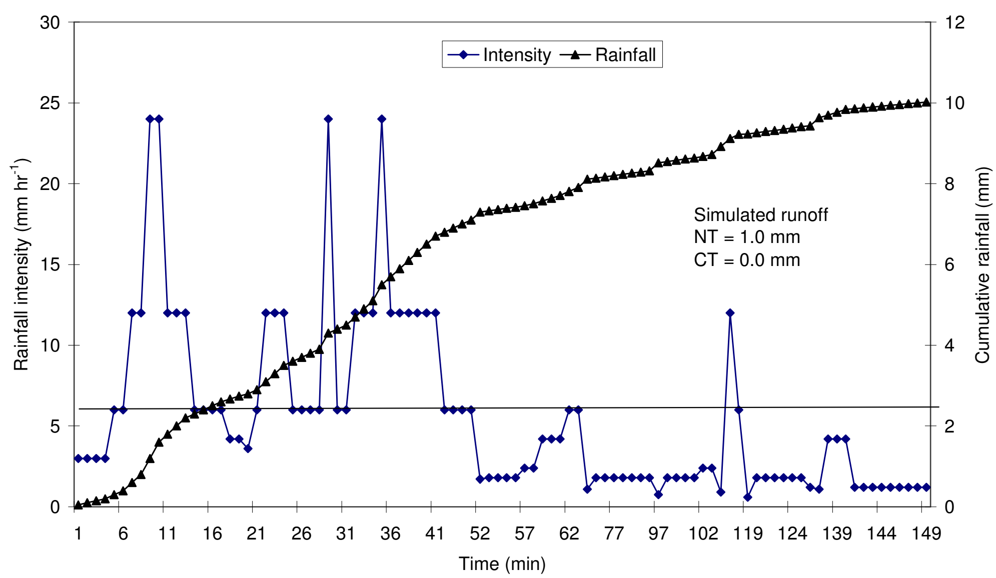
If = 6 mm hr-1
To differentiate from Mieso (M) Nazaret (N) is used.
In 2003 no measured runoff was recorded for Melkassa.



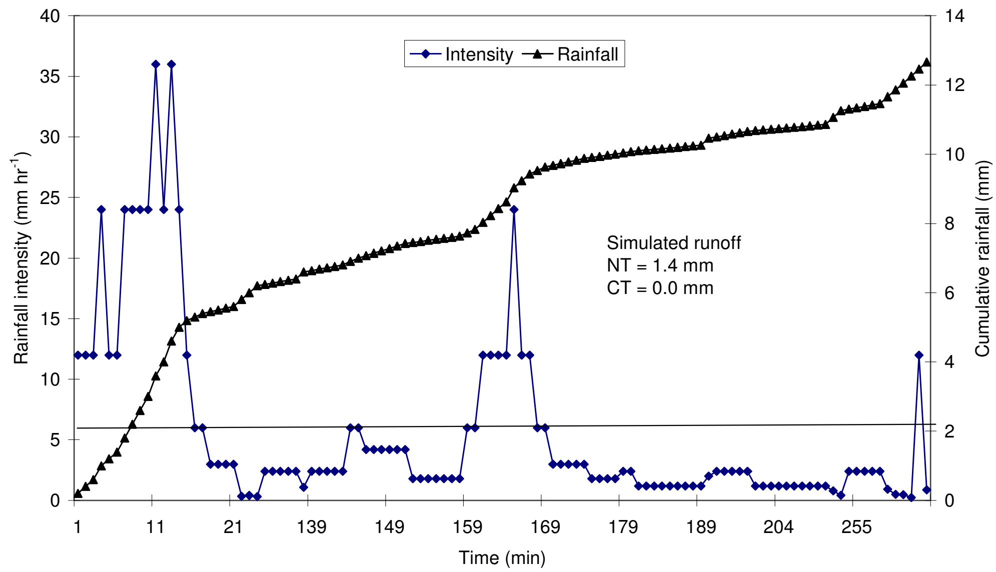
N03-202



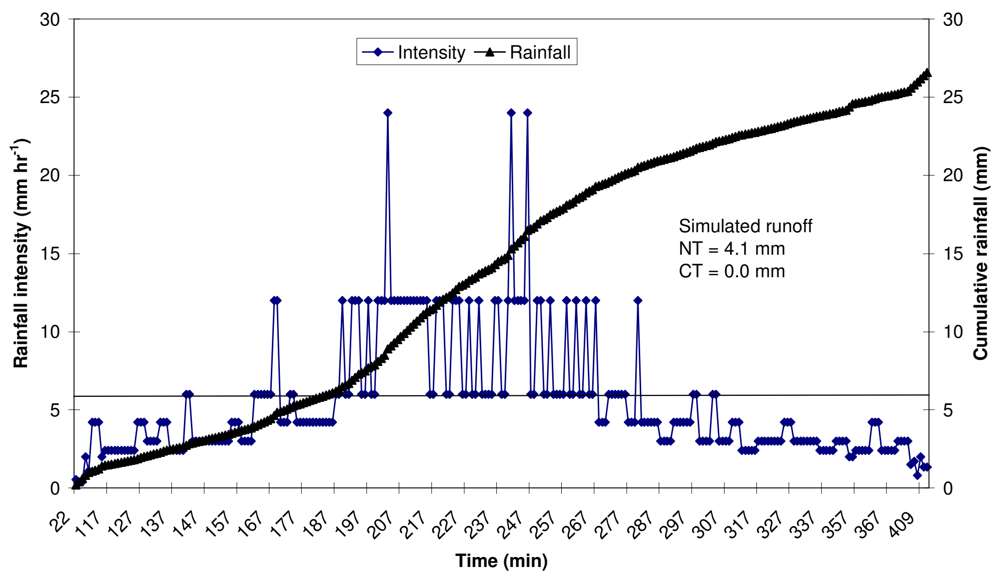
N03-203



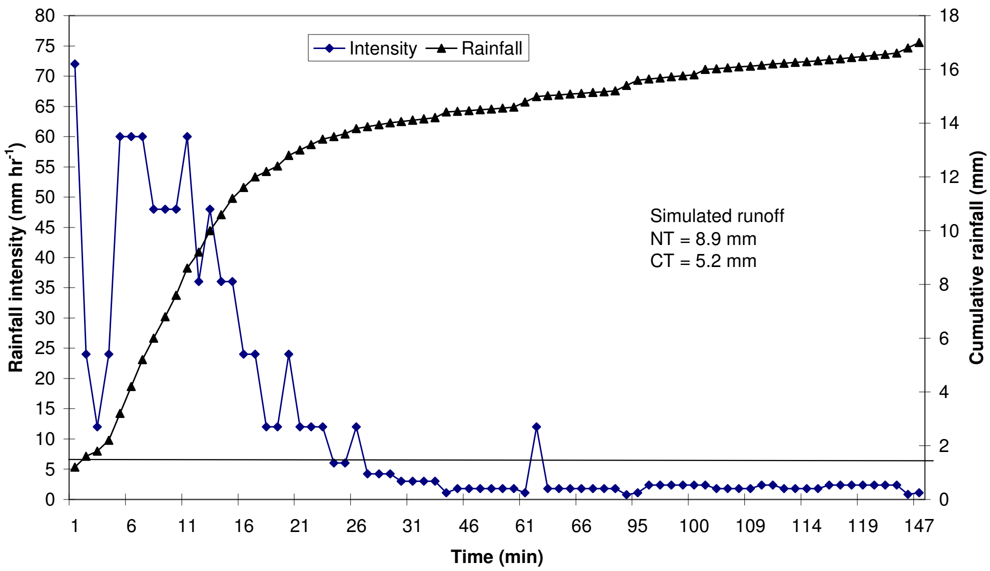
N03-205



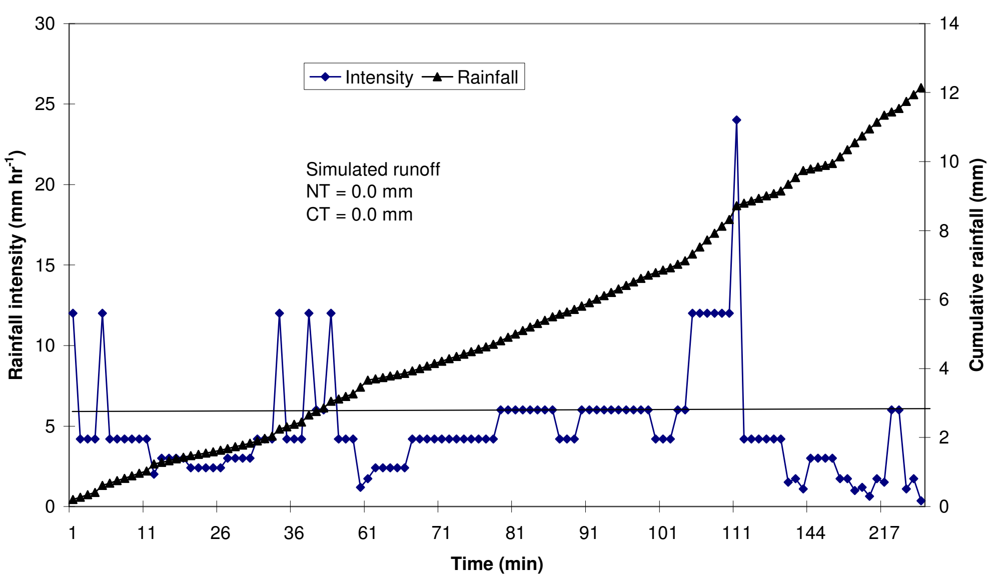
N03-207



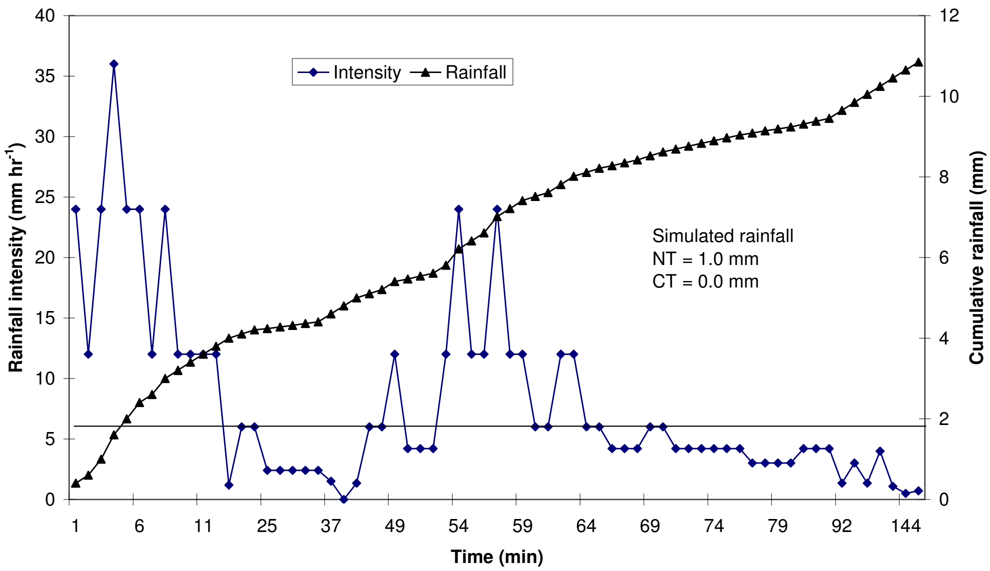
N03-210



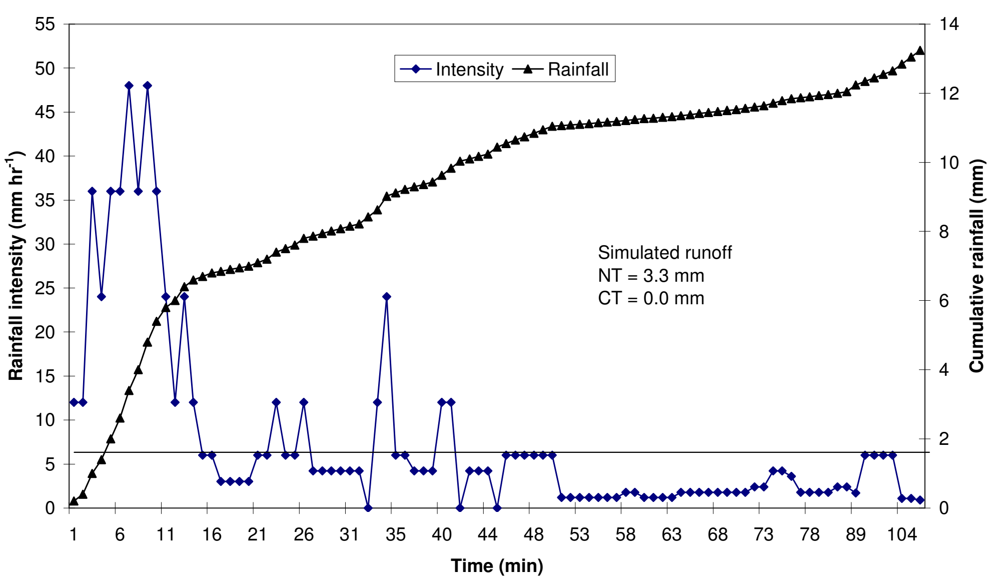
N03-214



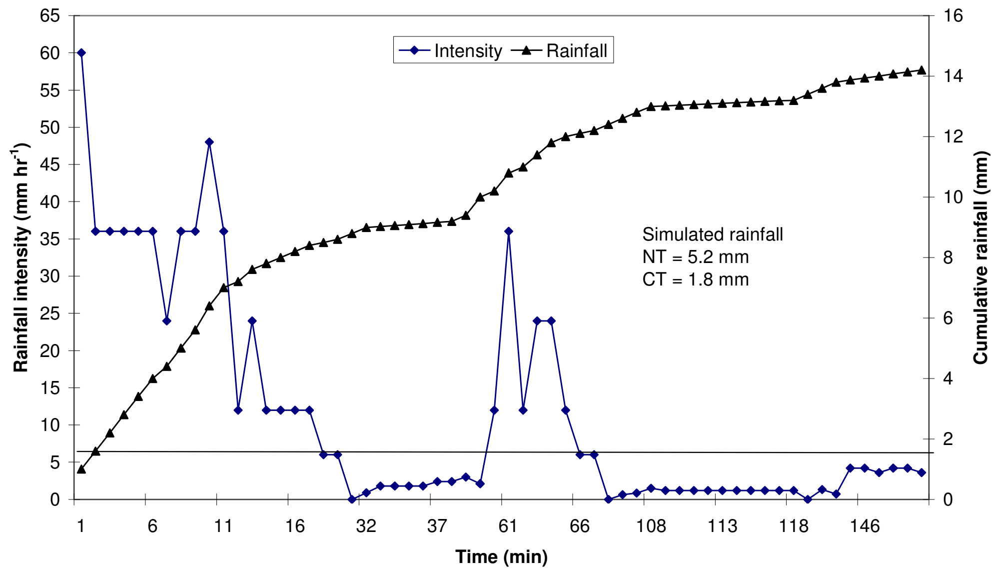
N03-215



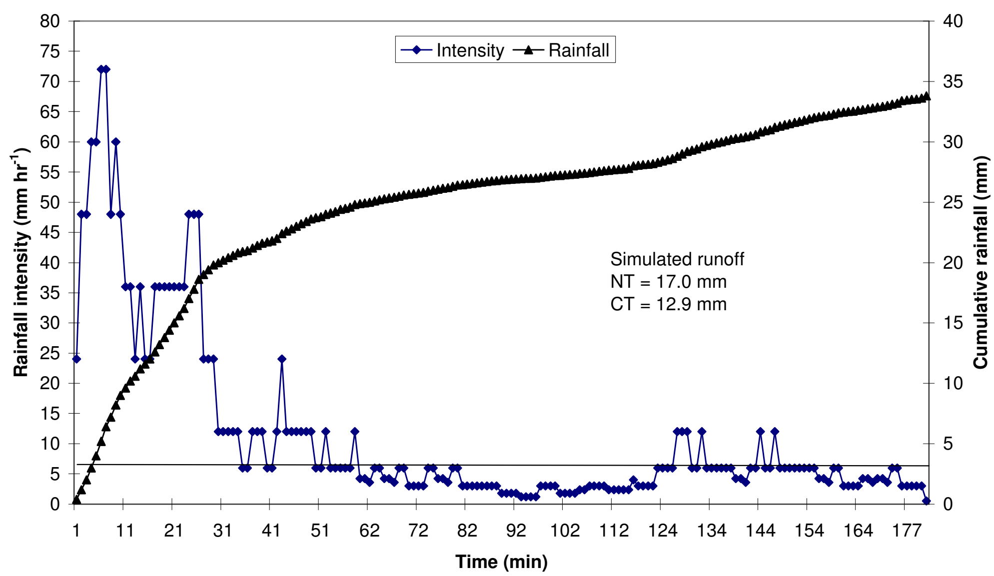
N03-225



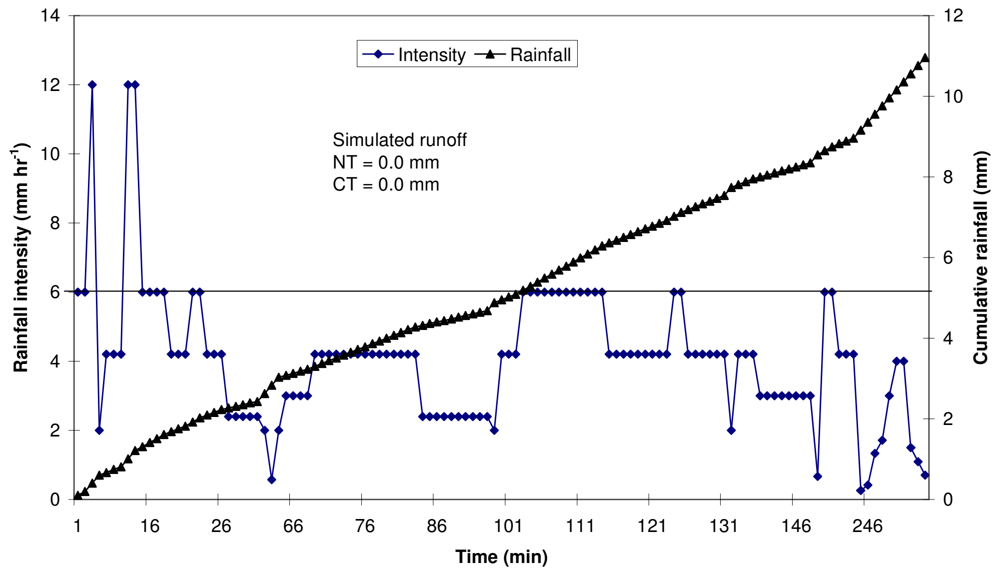
N03-232



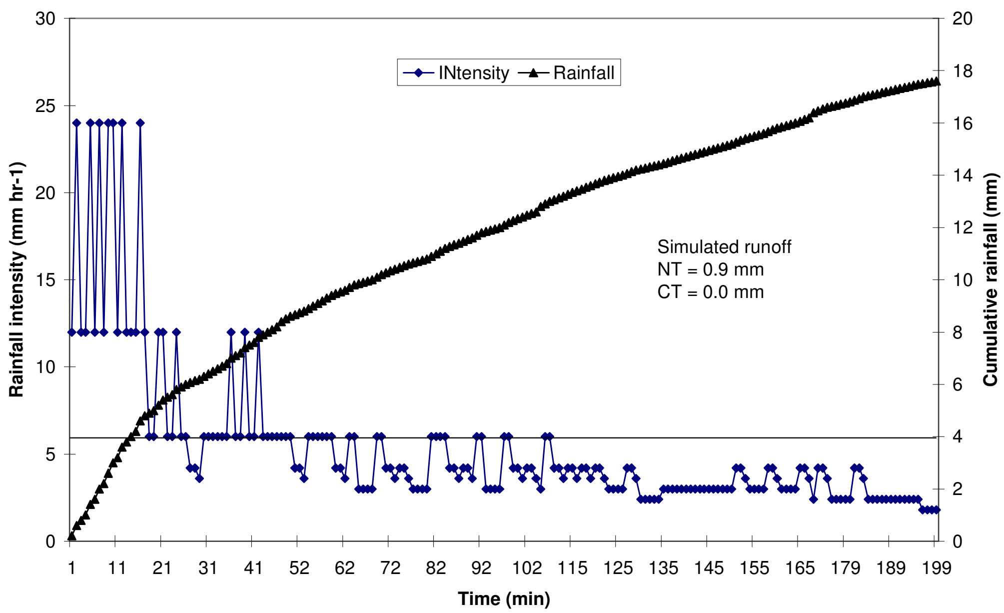
N03-236



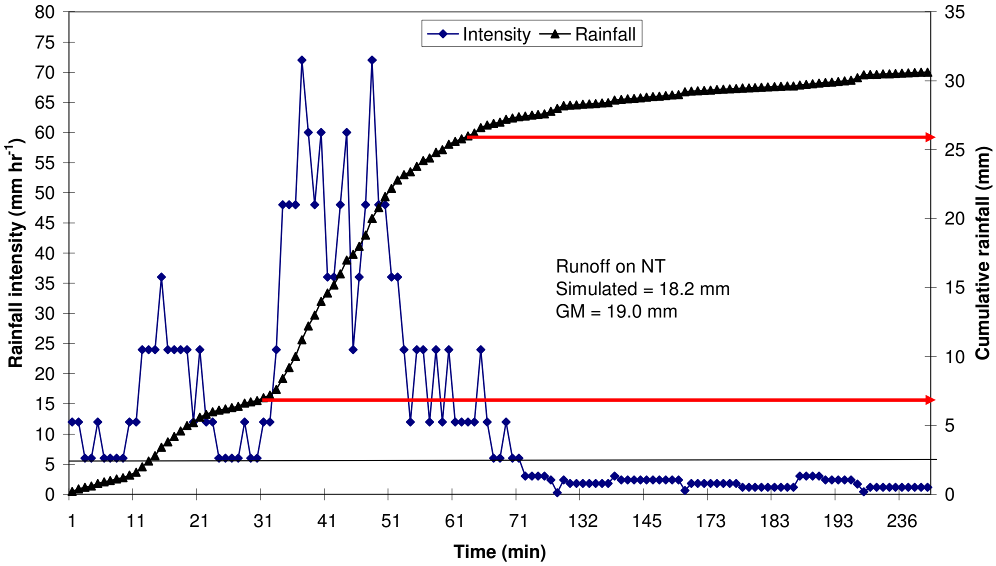
N03-239



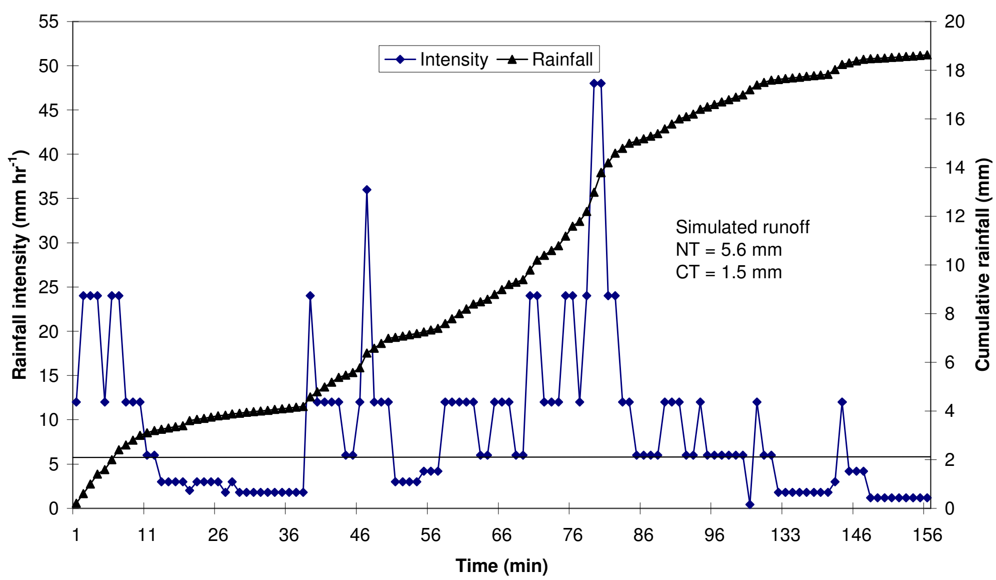
N03-242



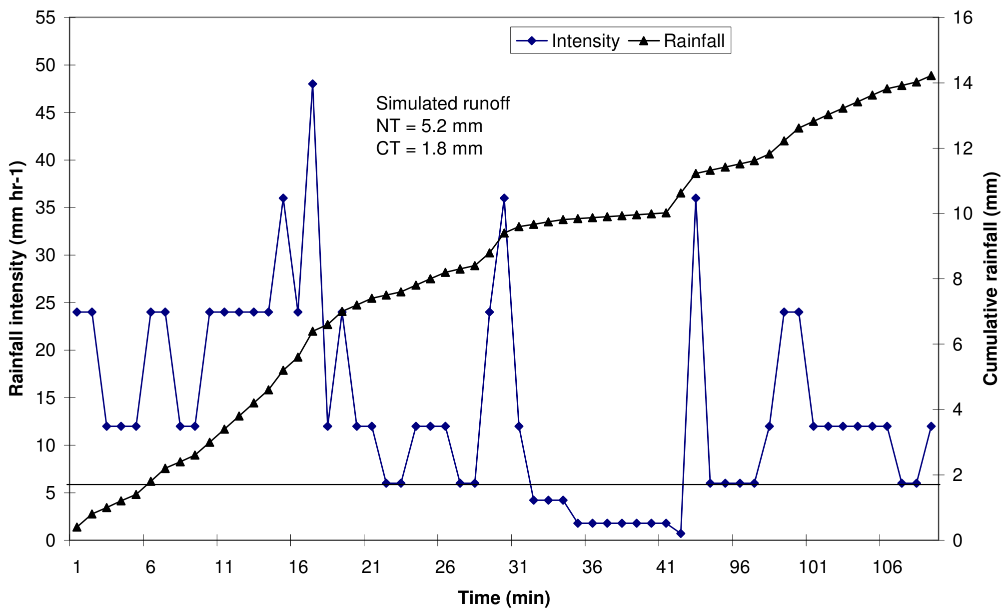
N03-249



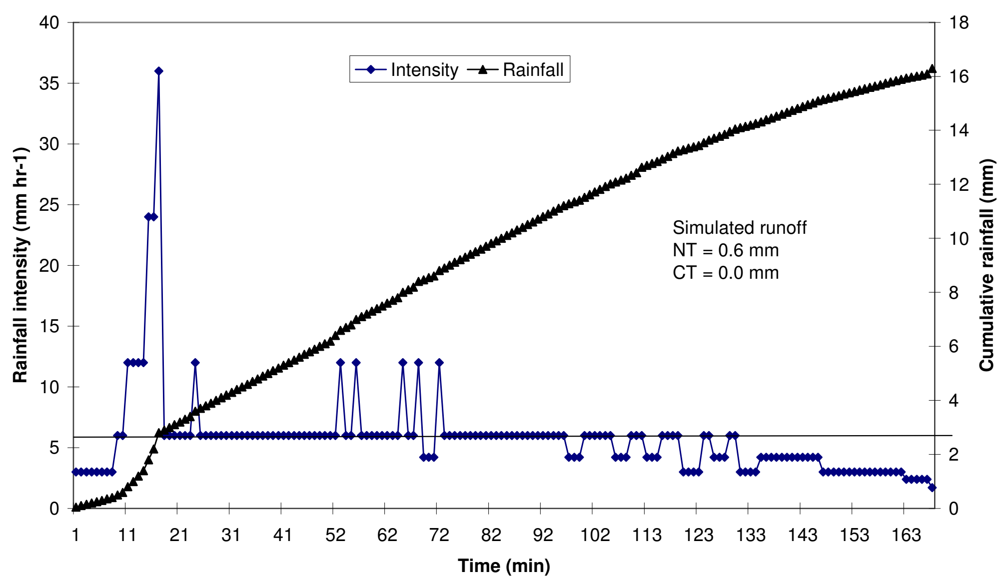
N03-251



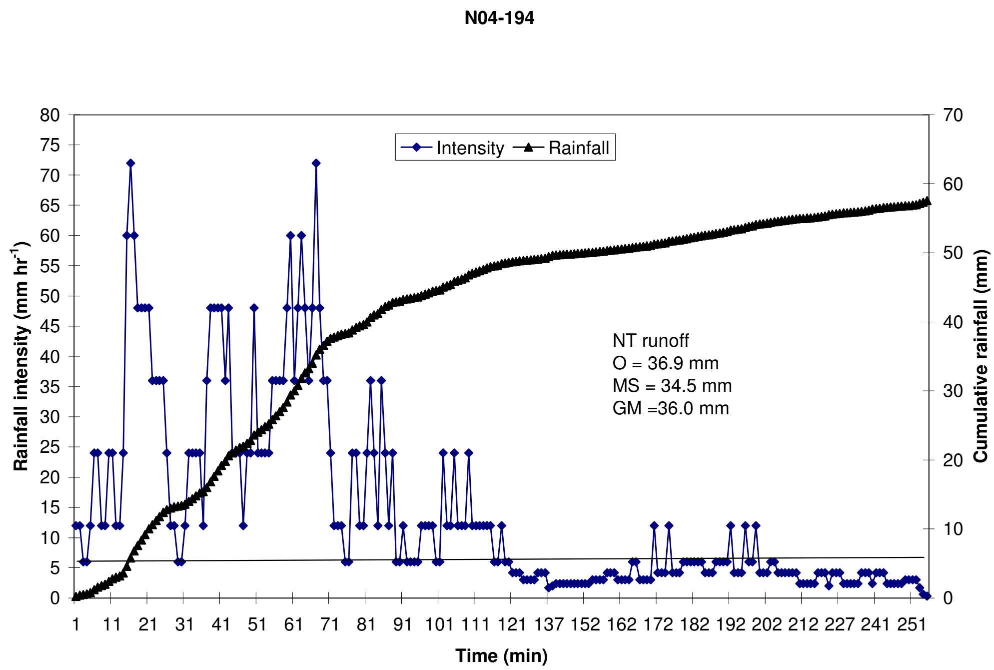
N03-266



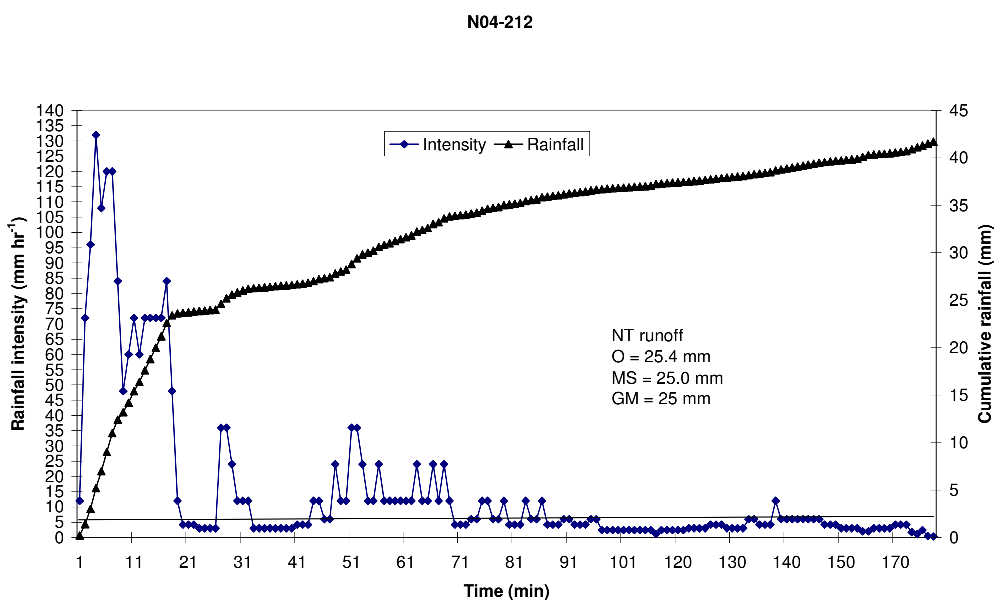
N03-272



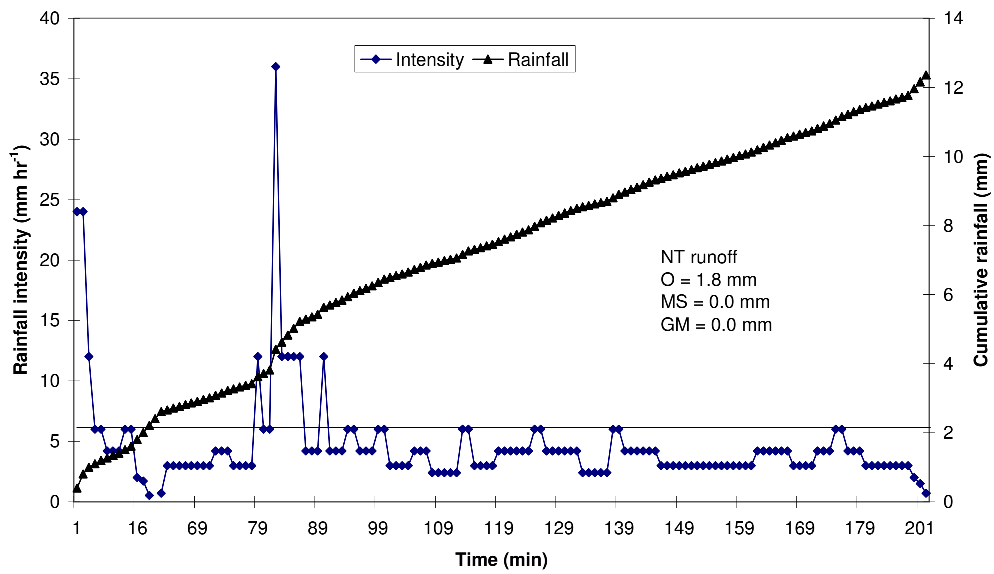
B. 2004 storms



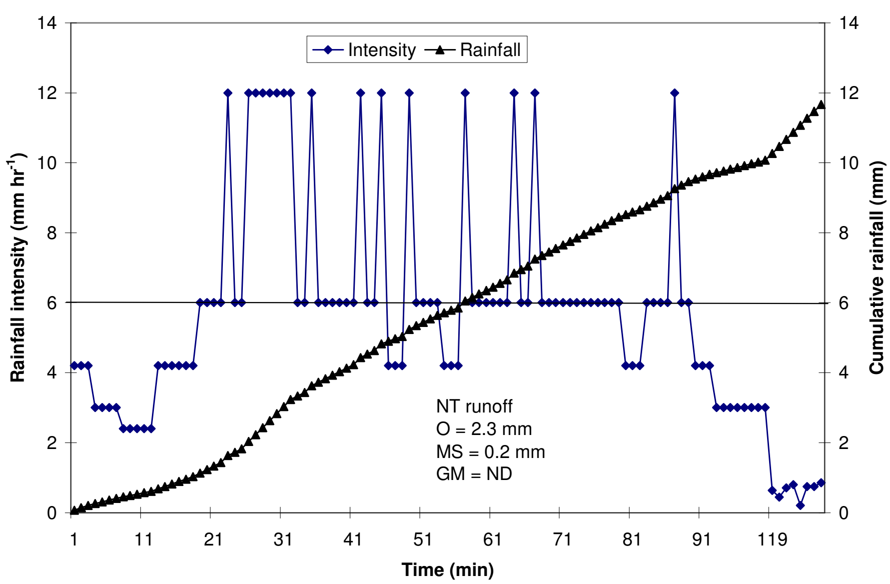
Note: O = Observed; MS = Model simulated; GM = Graphical method



N04-220

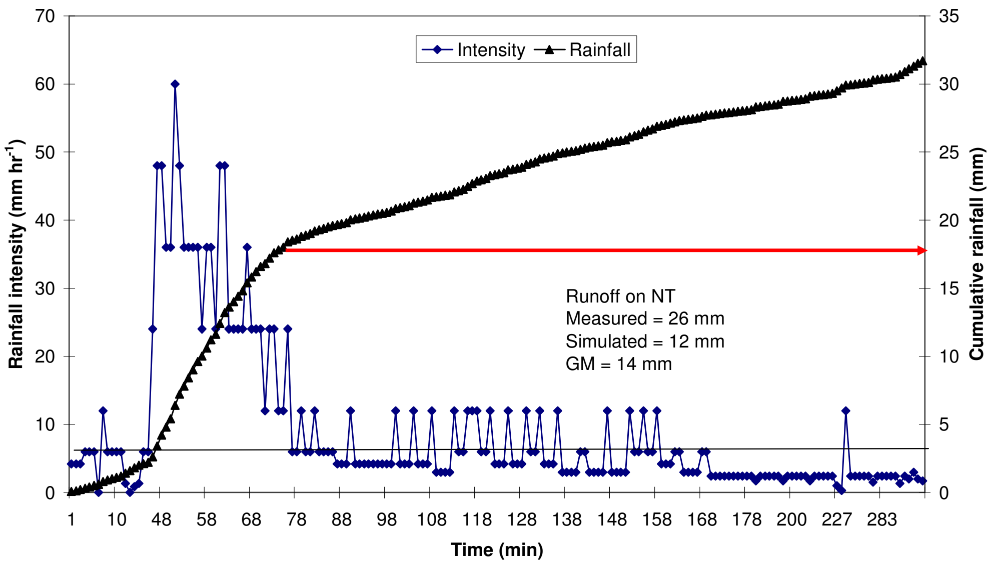


N04-221

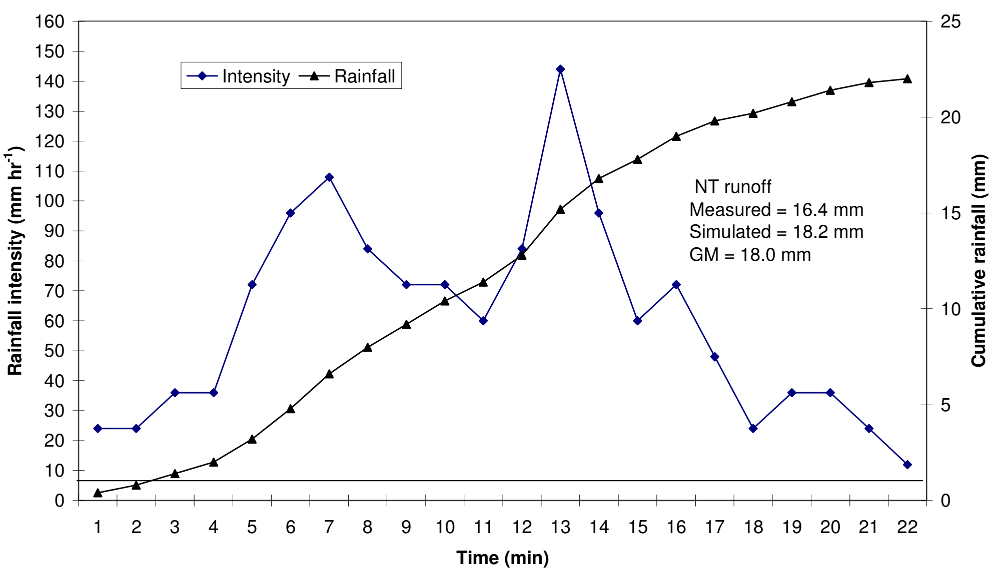


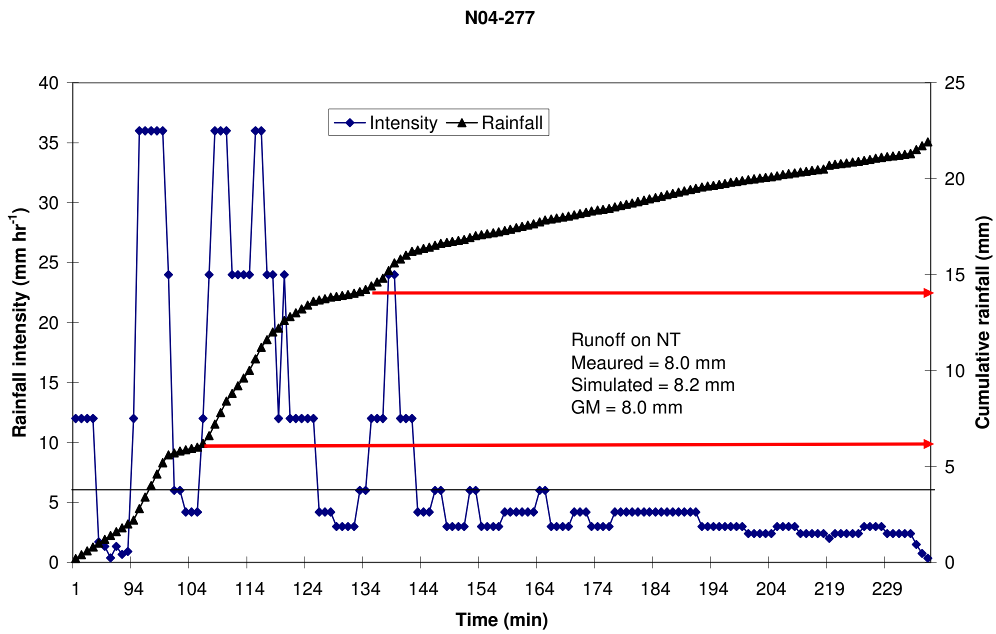
ND=not determined

N04-223



N04-252

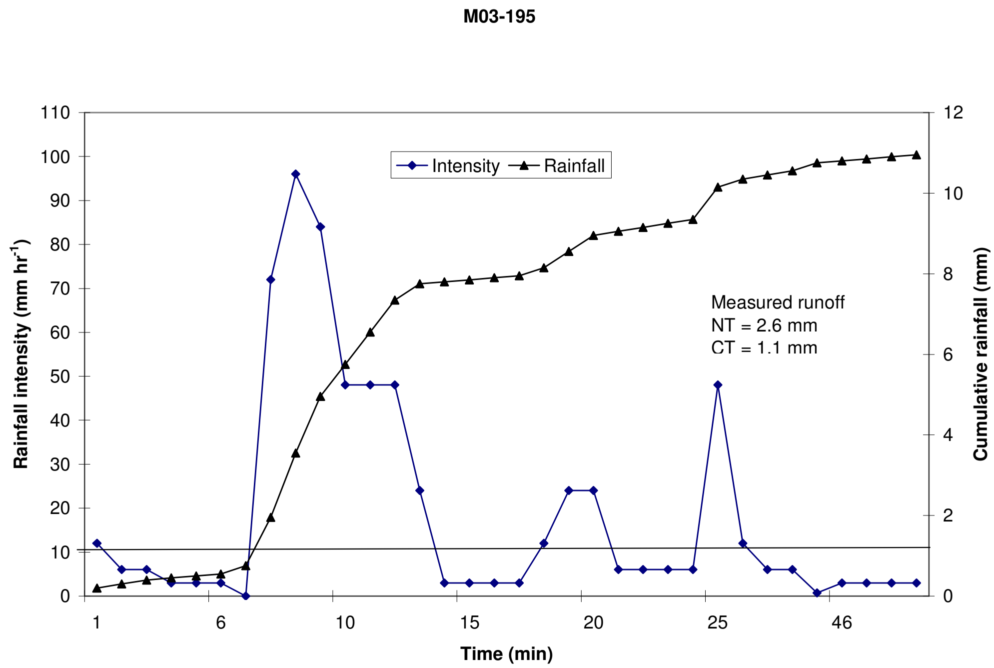


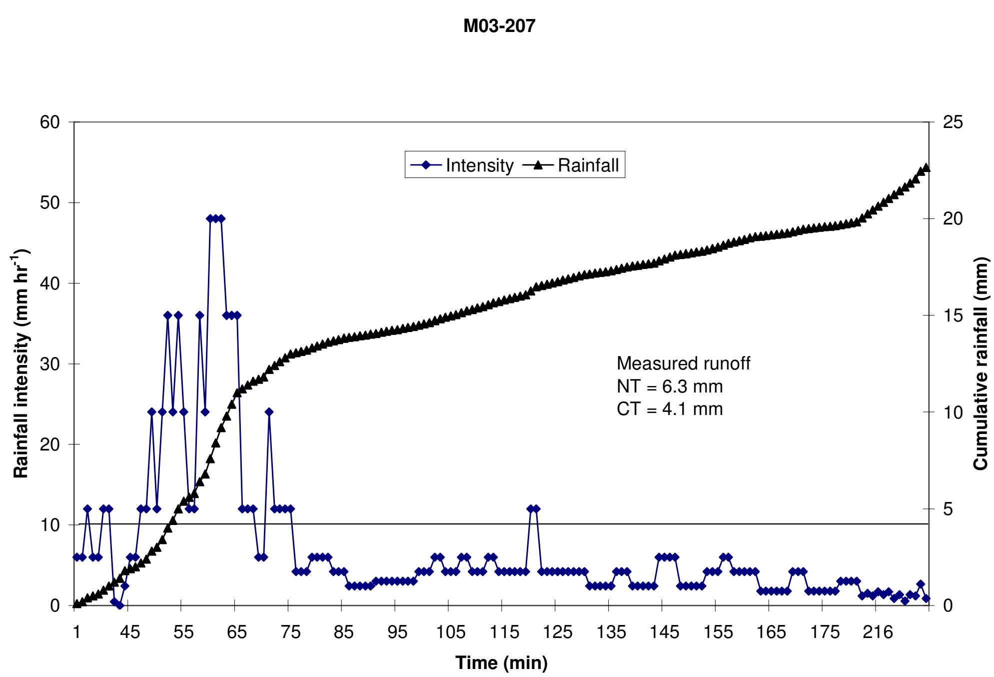

N04-277
Intensity
Rainfall
Rainfall intensity (mm hr-1)
Cumulative rainfall (mm)
Time (min)
Runoff on NT
Meaured = 8.0 mm
Simulated = 8.2 mm
GM = 8.0 mm
0
5
10
15
20
25
30
35
40
1
94
104
114
124
134
144
154
164
174
184
194
204
219
229

Appendix 6
Mieso ecotope rainfall intensity and cumulative rainfall

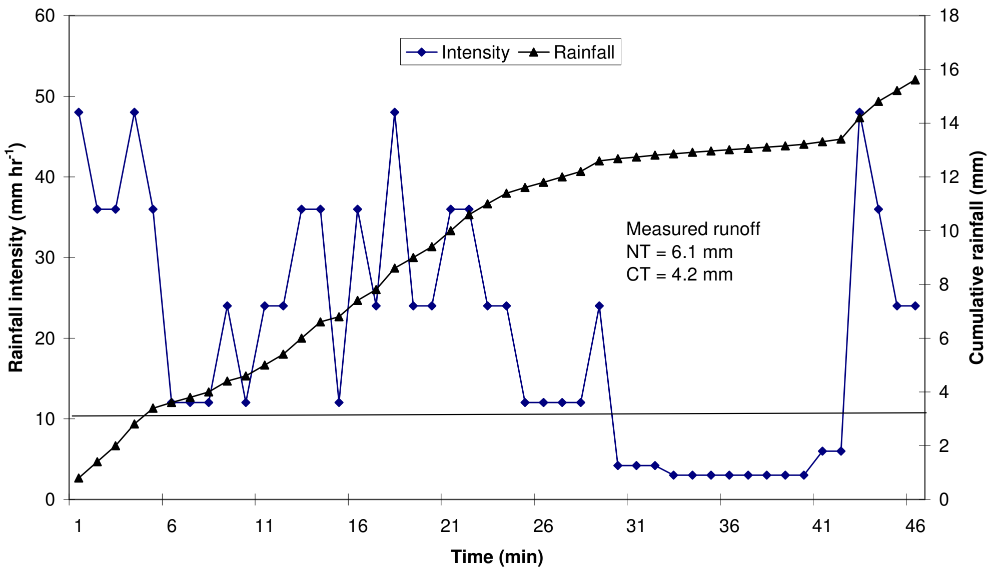
A. 2003 storms

I_f = 10 mm hr-1

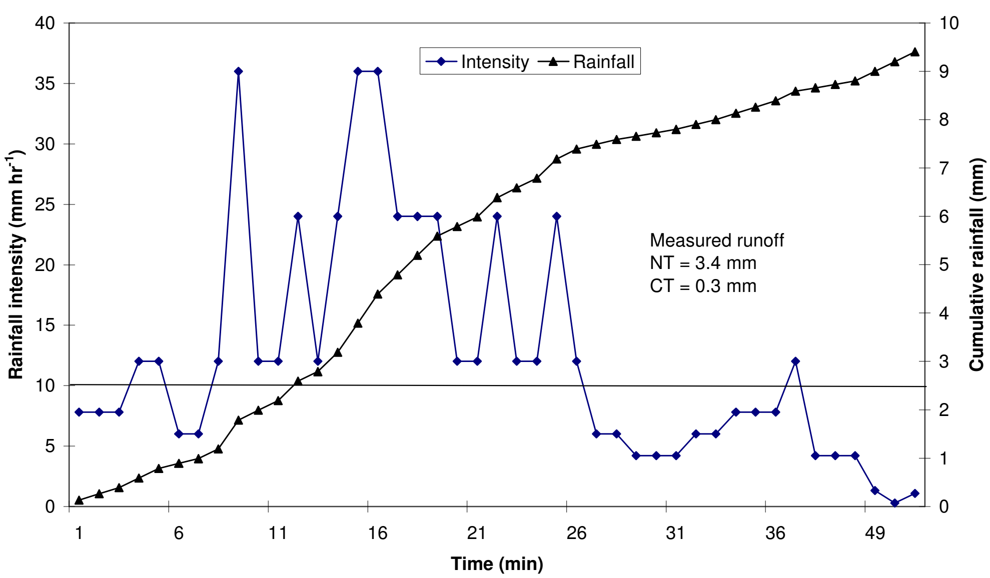




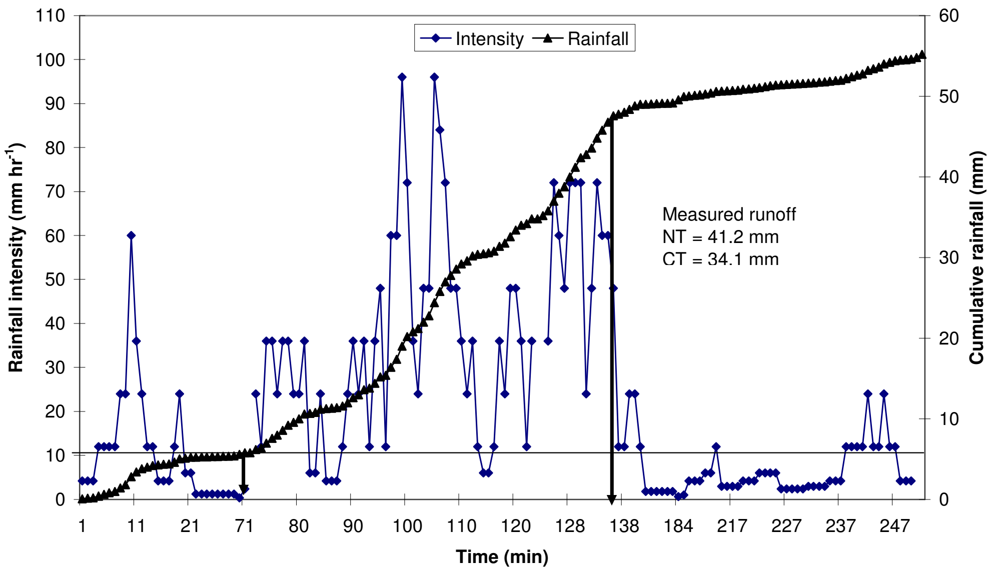
M03-217



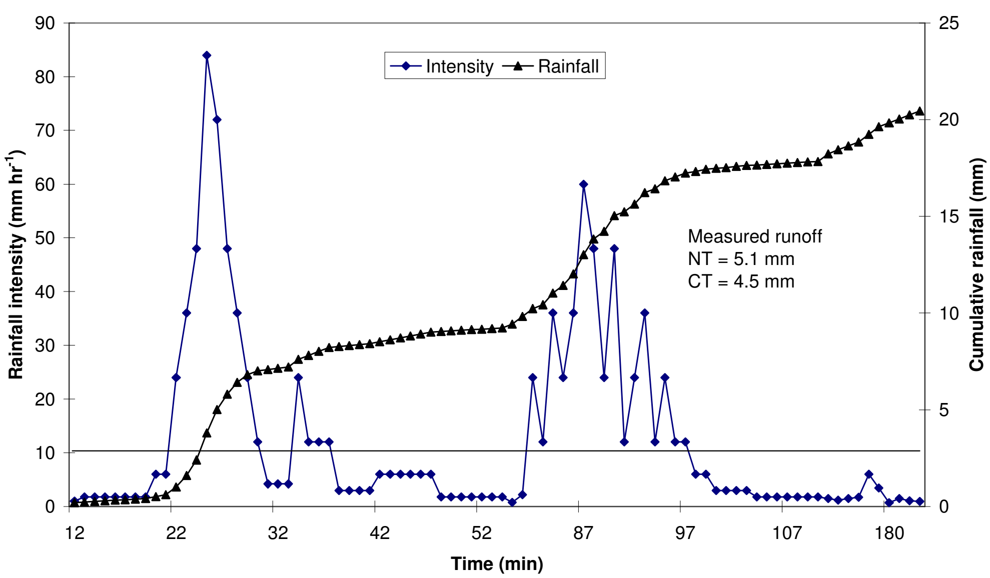
M03-228



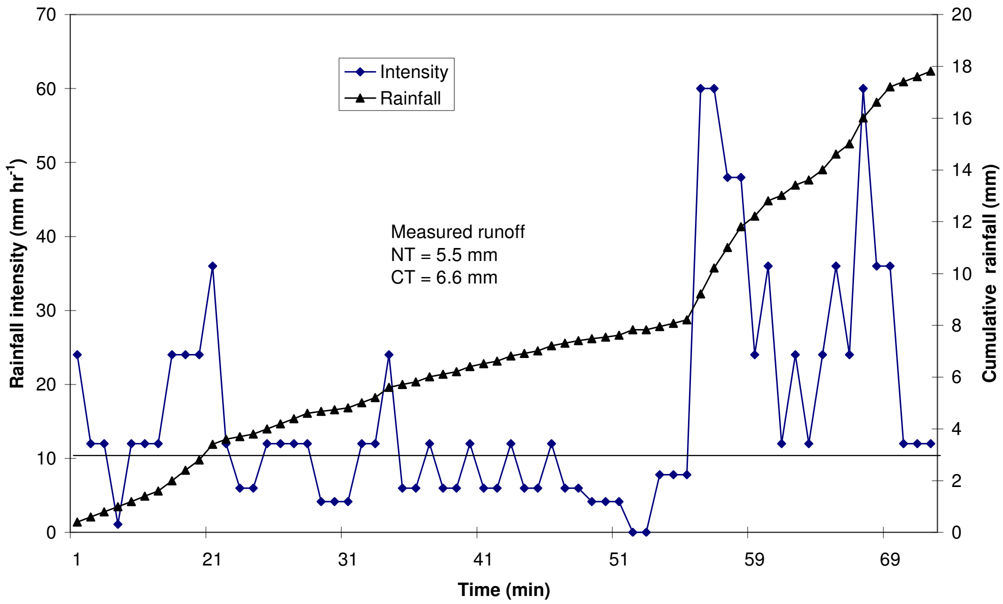
M03-238



M03-251



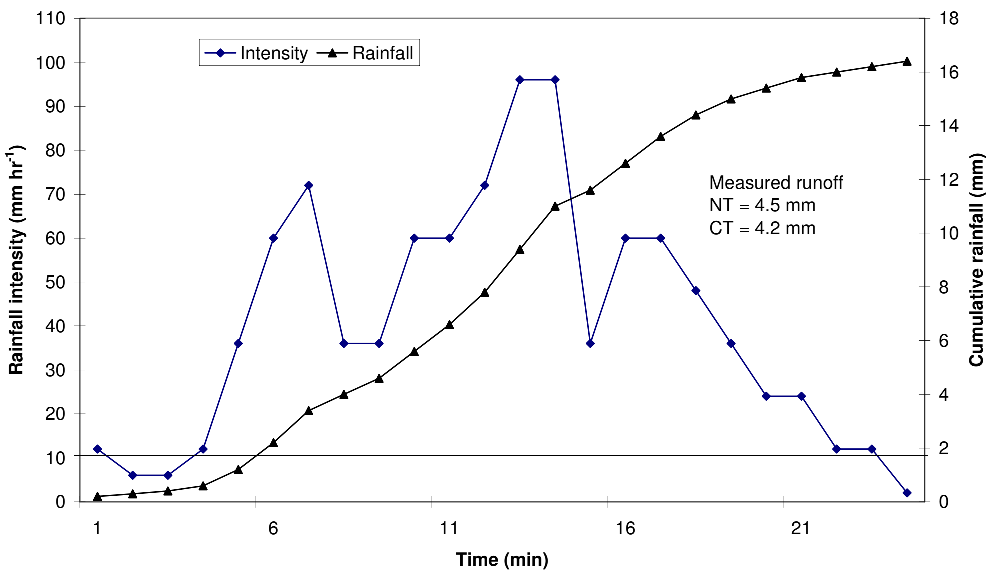
M03-257



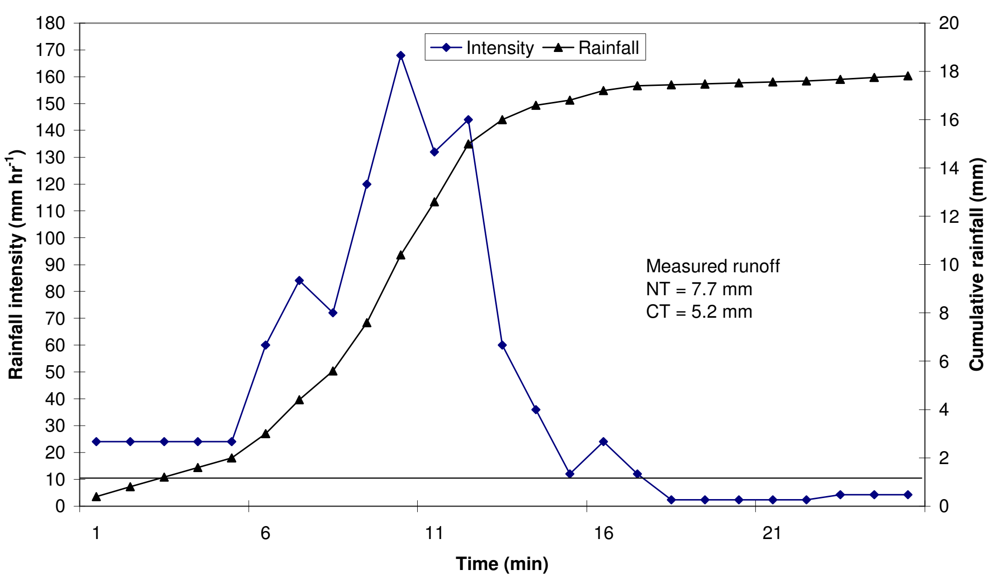
Intensity
Rainfall
Measured runoff
NT = 5.5 mm
CT = 6.6 mm
Rainfall intensity (mm hr-1)
Cumulative rainfall (mm)
Time (min)
70
60
50
40
30
20
10
0
20
18
16
14
12
10
8
6
4
2
0
1
21
31
41
51
59
69

B. 2004 storms

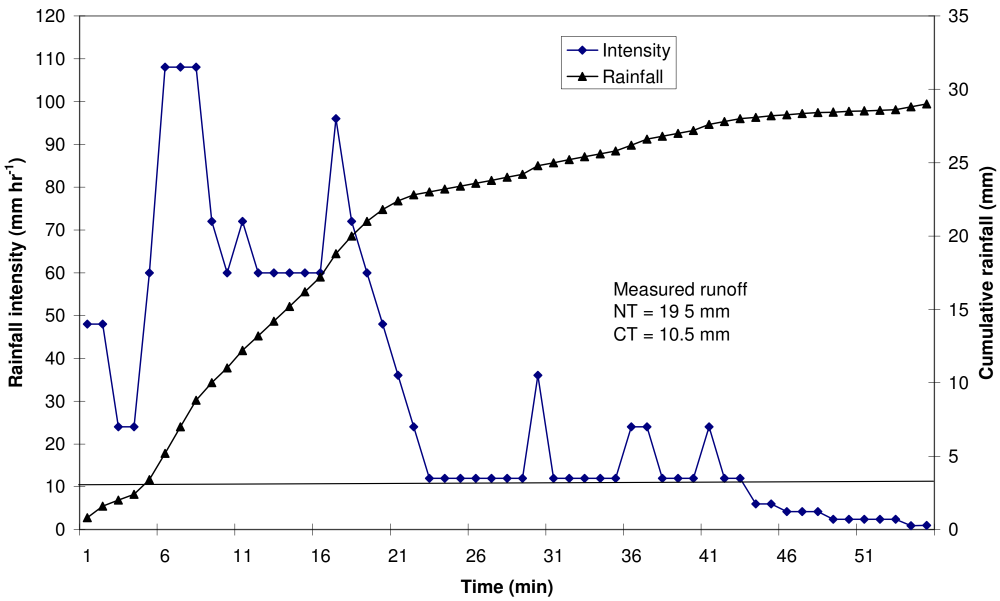
M04-161



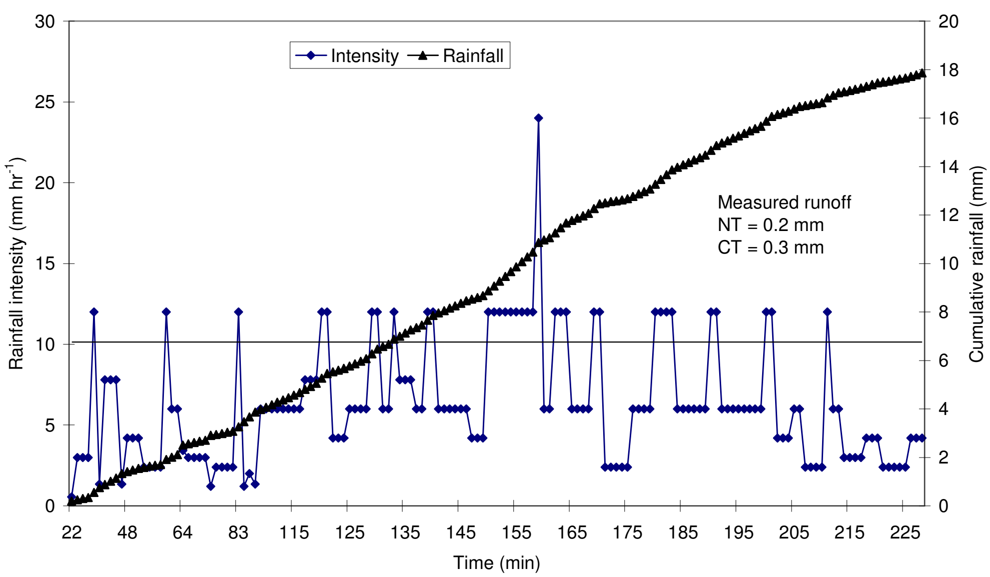
M04-183



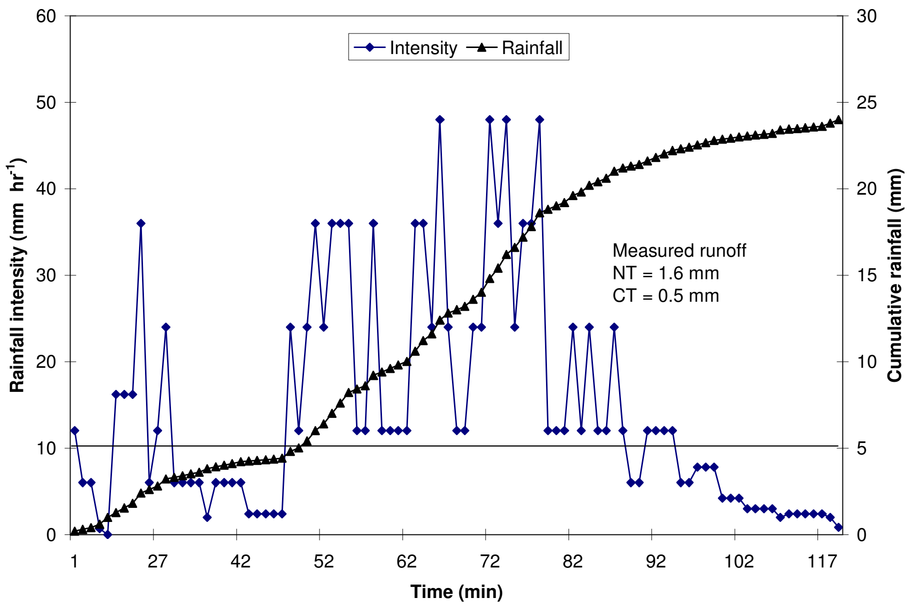
M04-196



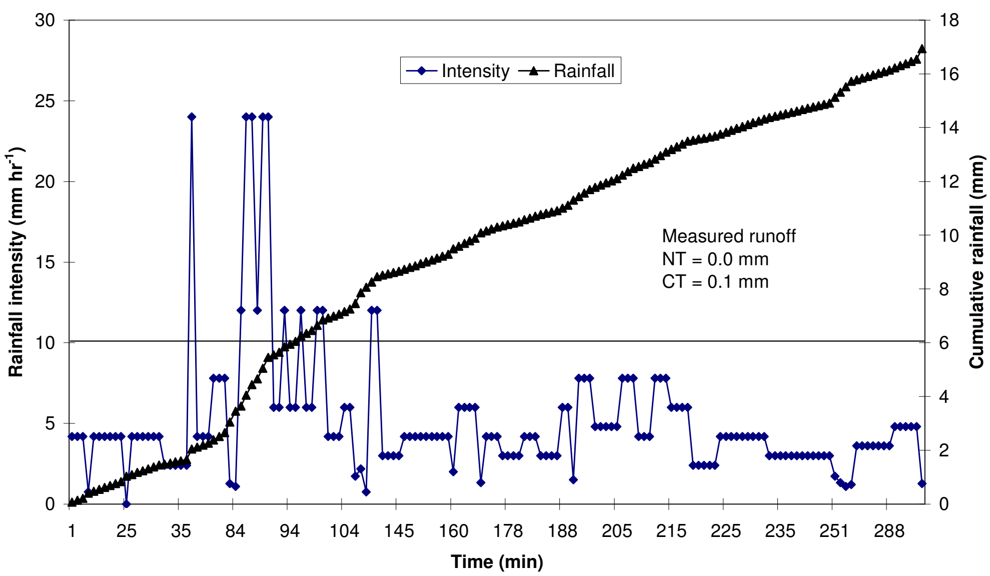
M04-197



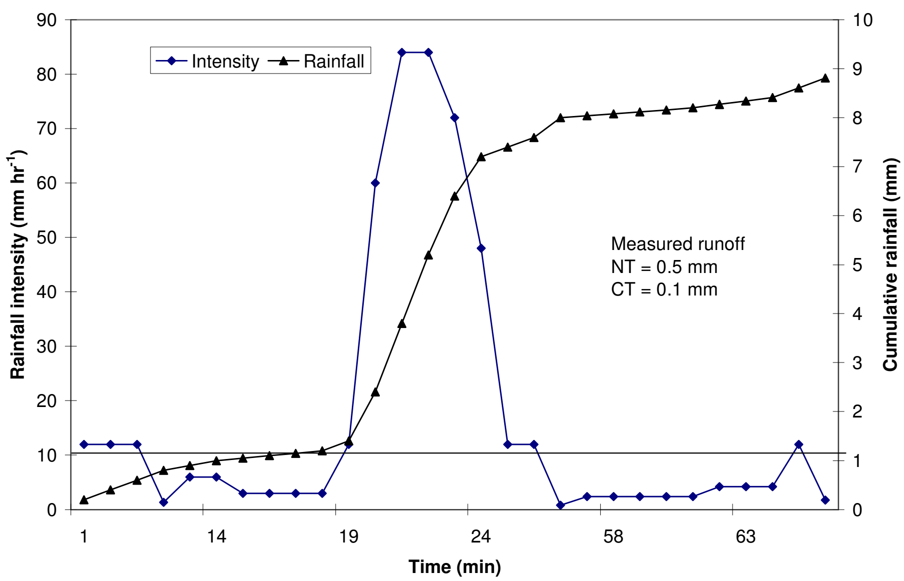
M04-203



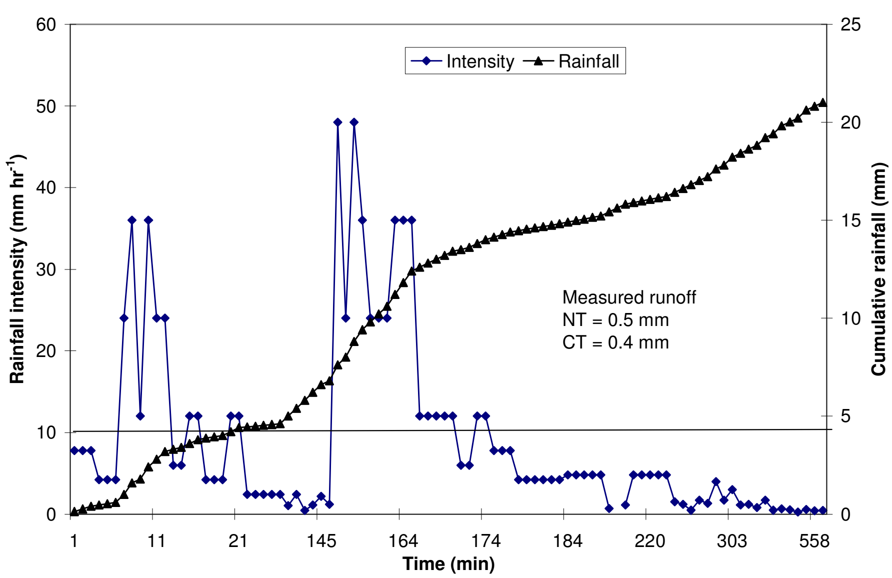
M04-207



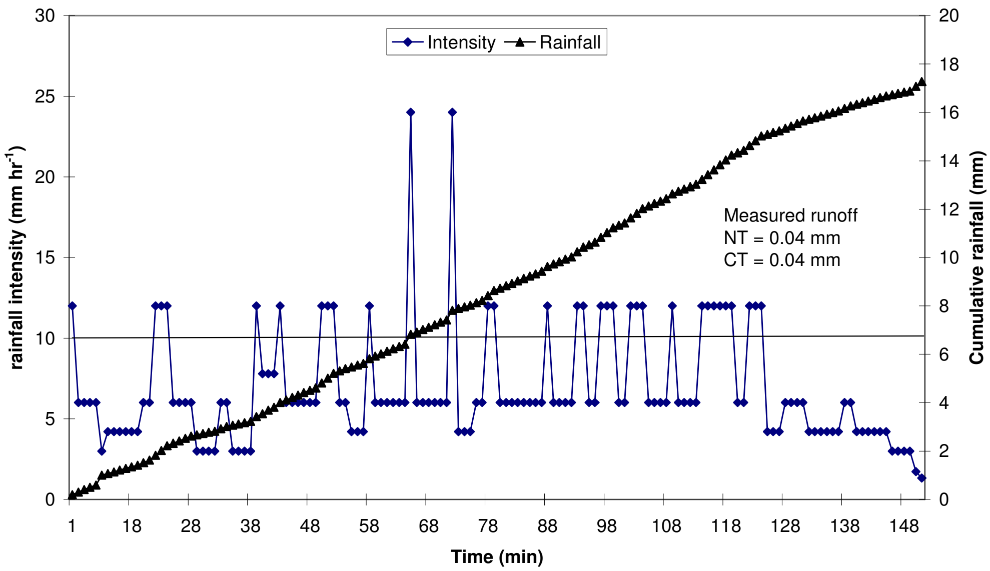
M04-208



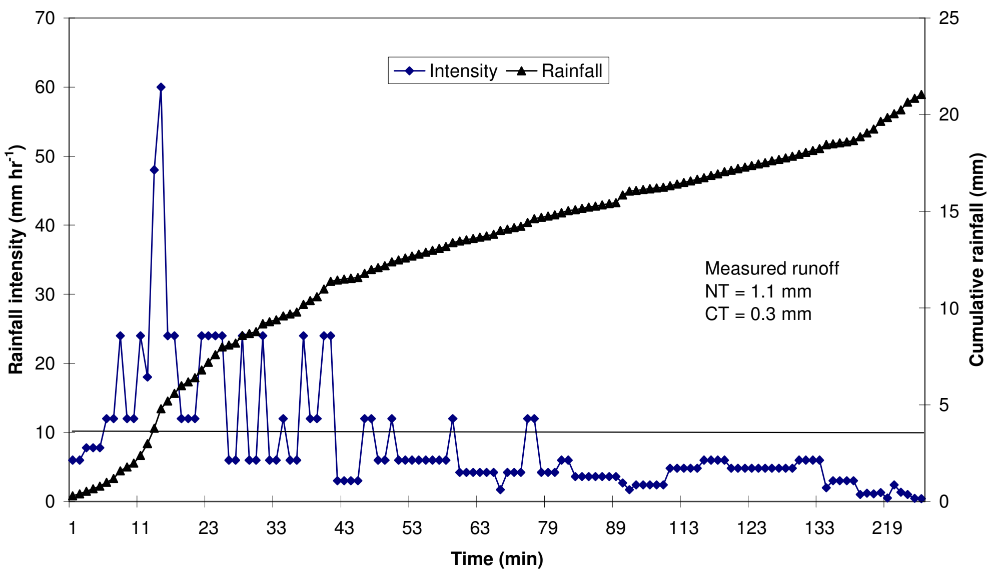
M04-216



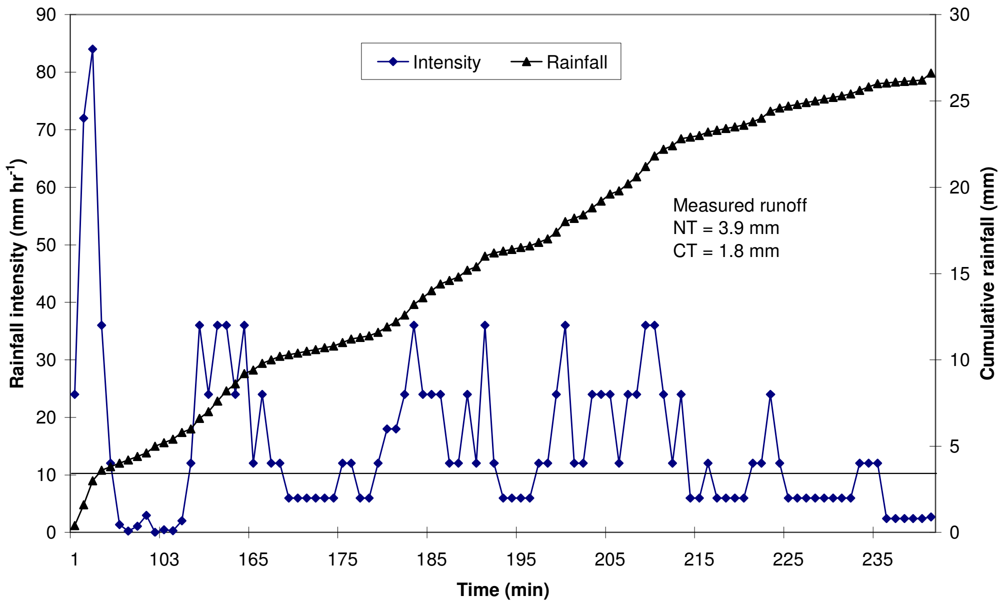
M04-221



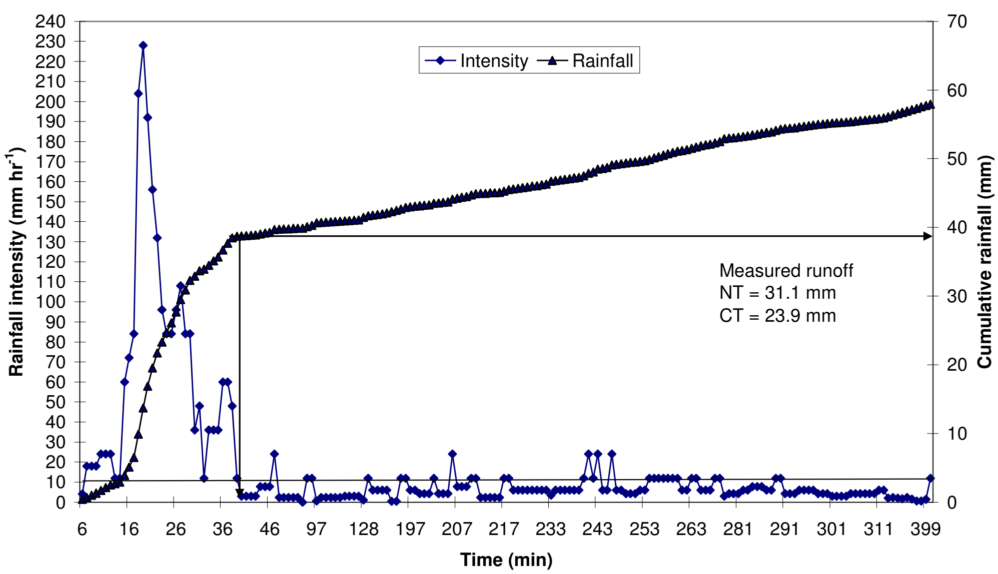
M04-223



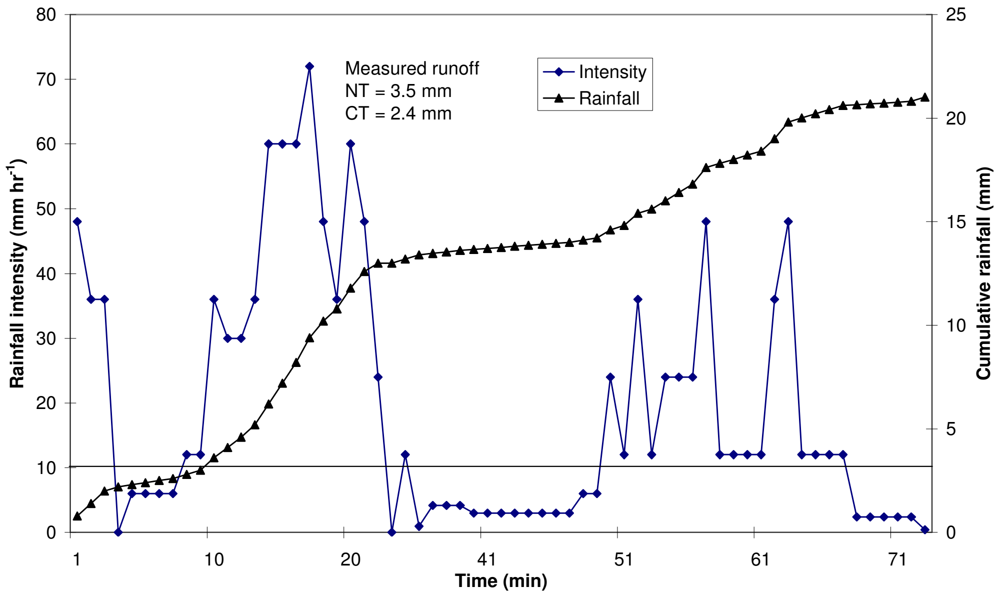
M04-224



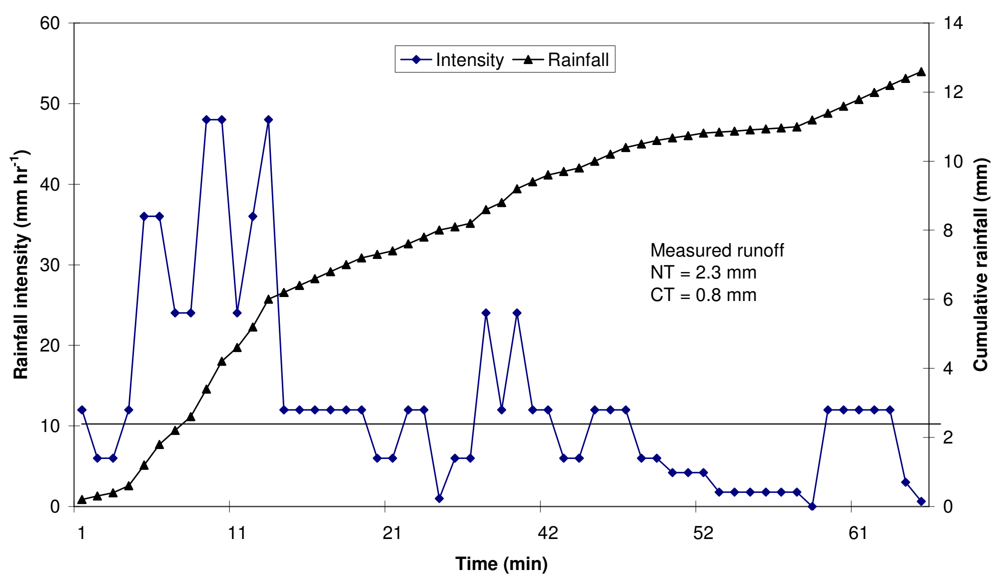
M04-228+229



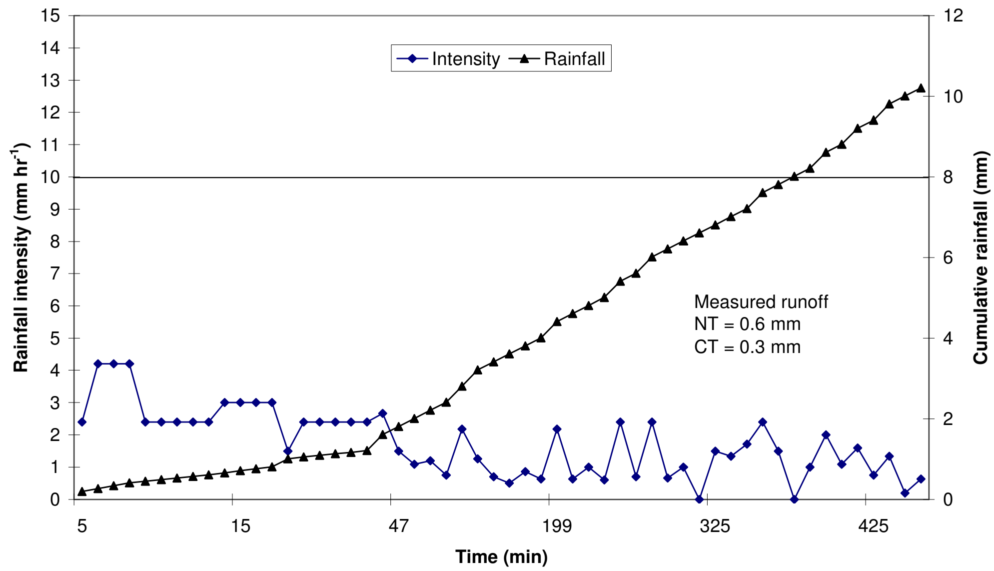
M04-233+234



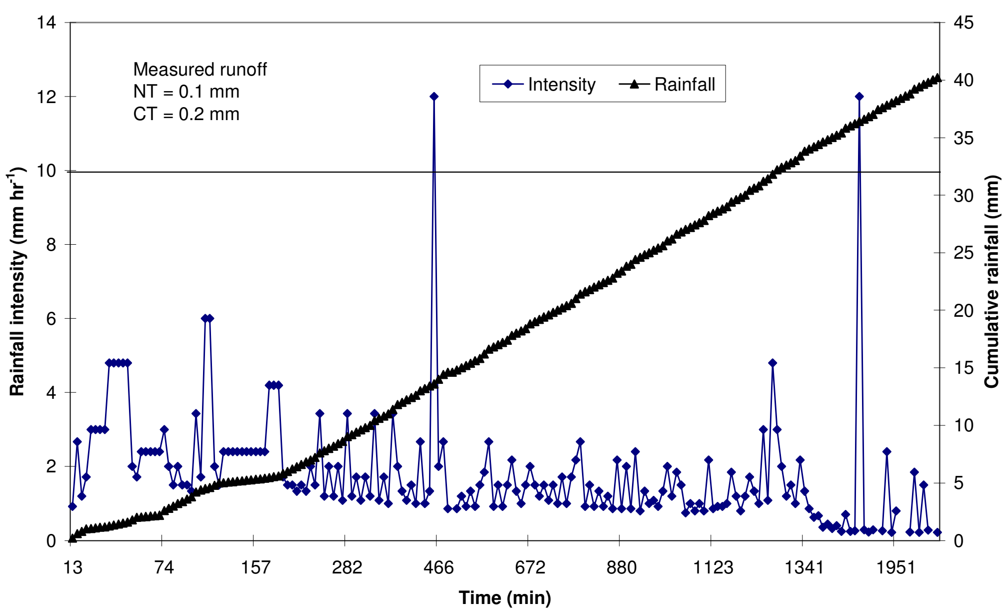
M04-241



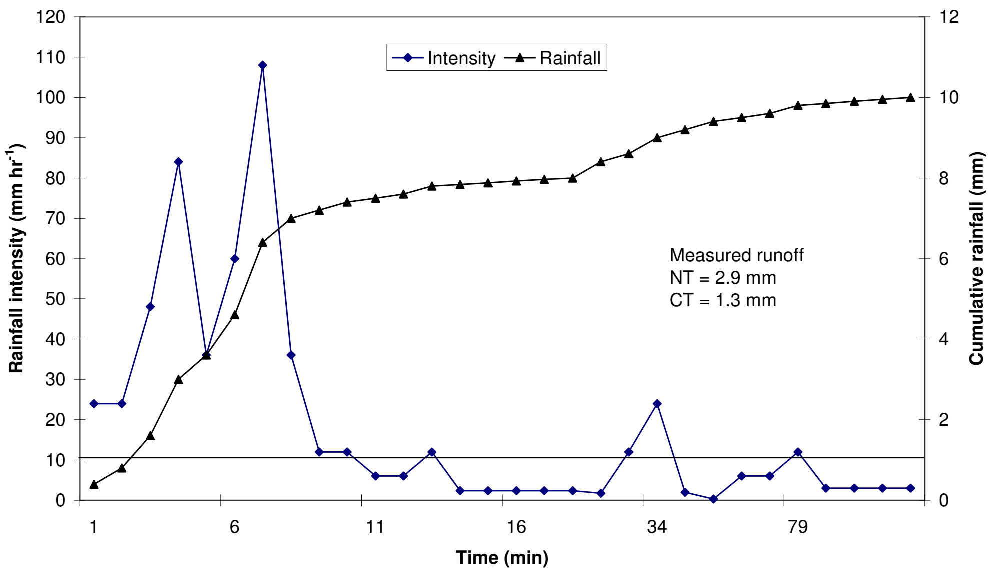
M04-246



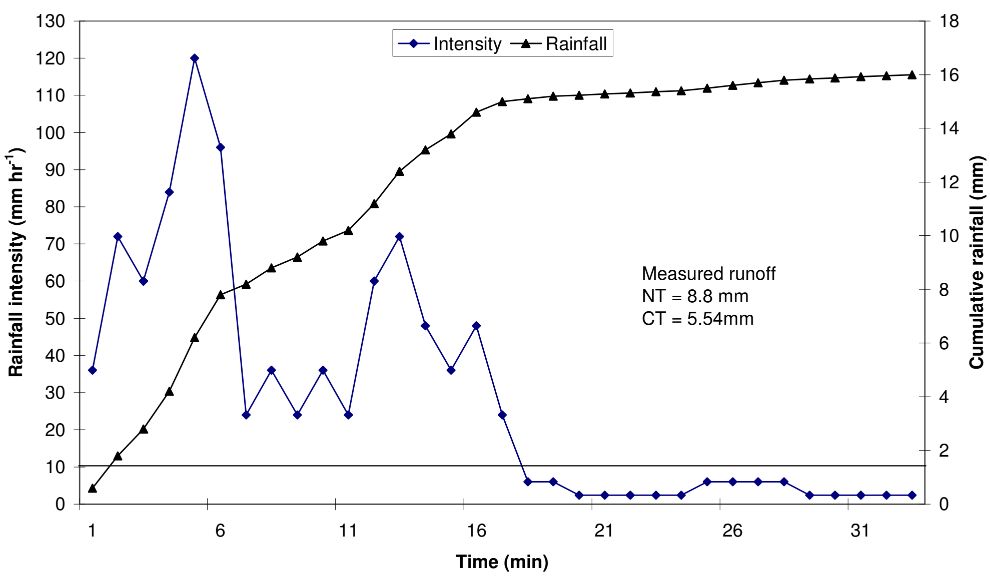
M04-247+248



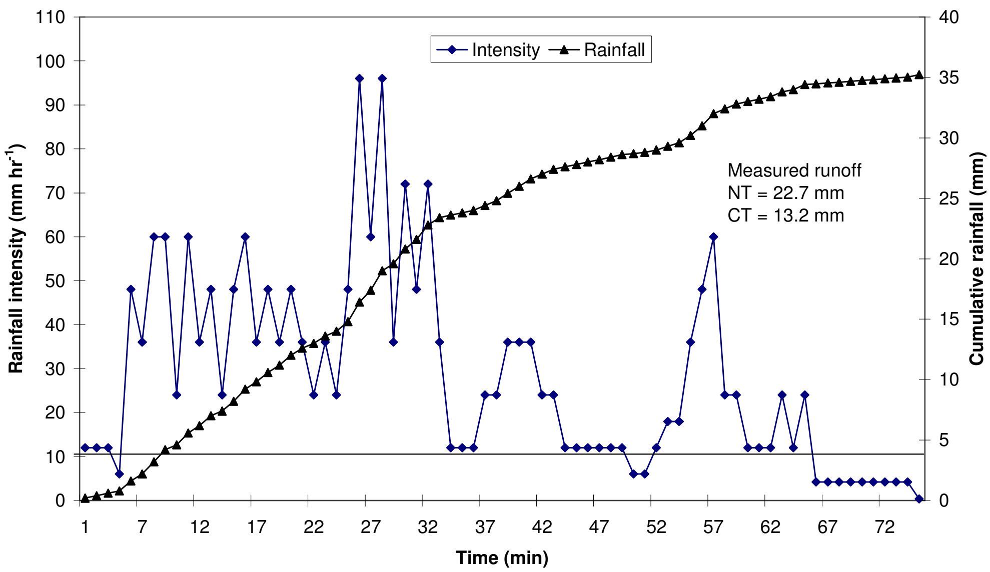
M04-258



M04-262



M04-281



Intensity
Rainfall
Measured runoff
NT = 22.7 mm
CT = 13.2 mm
Rainfall intensity (mm hr^{-1})
Cumulative rainfall (mm)
Time (min)
110
100
90
80
70
60
50
40
30
20
10
0
40
35
30
25
20
15
10
5
0
1
7
12
17
22
27
32
37
42
47
52
57
62
67
72

Appendix 7

Table Description of arid and semi-arid AEZs of Ethiopia

Major AEZs and symbols	Sub AEZs and symbols	Brief description	Area (ha)	Area (%)
Hot to warm arid low land plains **(A1)**	Hot to warm arid plains **(A1-1)**	• Location: plain of the Afar and Somalie Regional States • Altitude: ranges 126 m below sea level to 1200 m asl. • Soils: Calcicsol, Gypsisol, Regosol, Vertisol and Fluvisol. • Mean annual temperature (MAT) : > 27^0c • Mean annual rainfall (MAR): 100-400 mm • PET: 1700 – 3000 mm • GP: no growing period from rainfall • Crops: cotton maize and sorghum	33,848,000.0	30.03
	Hot to warm arid valleys and escarpments **(A1-3)**	• Location: valleys and escarpments in ARS • Altitude: 0 – 1200 m asl. • Soils: Leptosol, Cambisol and Fluvisol • MAT: > 28 ^{0}c • MAR: 100 – 600 mm • PET: 2000 – 2600 mm • GP: no growing period from rainfall • Crops: maize and sorghum	440,000.0	0.39
	Hot to warm arid mountains **(A1-7)**	• Location: East of Dire Dawa, SNRS and in the Dire Dawa Administration Counsel • Altitude: 1000 – 1400 m asl. • Soils: Cambisol, Regosol, Lithosol and Solonchac. • MAT: 16 -21 ^{0}c • MAR: 300 - 800 mm • PET: na • GP: less than 45 days • Crops: pastoral farming		

Tepid to cool arid mid highlands **(A2)**	Tepid to cool arid plains **(A2-1)**	• Location: in SNRS between Kebri Beya & Artshek. • Altitude: 1200 - 1600 m asl. • Soils: Randzine, Vertisol and Cambisol. • MAT: 16 - 21 ^{0}c • MAR: 500 - 600 mm • PET: na • GP: less than 45 days • Crops: nomadic pastoralist.	240,000.0	0.21
	Tepid to cool arid mountains **(A2-7)**	• Location: in SNRS between Jijiga & Kebri Beya. • Altitude: 1400 - 2200 m asl. • Soils: Lithosol, Regosol, cambisol, Arenosol and Fluvisol. • MAT: 16 - 21 ^{0}c • MAR: 350 - 800 mm • PET: na • GP: less than 45 days • Crops: pastoral farming sorghum and chat.	380,000.0	0.34
Total			620,000.0	0.55

Hot to warm semi-arid lowlands **(SA-1)**	Hot to warm semi-arid plains **(SA1-1)**	• Location: Western Tigray, plains of Humara area. • Altitude: 500 - 1600 m asl. • Soils: Vertisol. Fluvisol and Leptosol occur in minor extent. • MAT: 21 - 28 ^{0}c • MAR: 300 - 800 mm • PET: 1900 – 2100 mm • GP: about 60 days • Crops: sesame, tef and sorghum.	720,000.0	0.64
	Hot to warm semi-arid lakes and Rift Valley **(SA1-2)**	• Location: Centeral part of the country in ONRS, north east of Alem Tena. • Altitude: 1000 - 2000 m asl. • Soils: Phaeozem, Andosol, Lithosol and Regosol. • MAT: 16 – 27.5 ^{0}c • MAR: 650 - 700 mm • PET: na • GP: 46 - 60 days • Crops: pastoralism, tef, sorghum, maize vegetables and to some extent papaya and banana.	66,000.0	0.06
	Hot to warm semi-	• Location: Includes areas	2,920,000.0	2.59

	arid mountains and plateau **(SA1-5)**	around hamerbako, SNNPRS. • Altitude: 400 - 1600 m asl. • Soils: Luvisol, cambisol plus Lithosol, Andisol, Solonchak, Fluvisol and Regosol. • MAT: > 21 ^{0}c • MAR: 300 - 700 mm • PET: na • GP: 46 - 60 days • Crops: nomadic pastoralism, and sorghum.		
Total			**3,706,000.0**	**3.29**

Tepid to cool semi-arid mid highlands **(SA2)**	Tepid to cool semi-arid lakes and Rift Valleys **(SA2-2)**	• Location: southern part of Rift Valley around Bulbula in ONRS. • Altitude: 1600 - 2200 m asl. • Soils: Andisol Lithosol, and Regosol. • MAT: 16 – 27.5 ^{0}c • MAR: 600 - 800 mm • PET: na • GP: 46 - 60 days • Crops: maize.	320,000.0	0.28
Total			**320,000.0**	**0.28**