THE EFFECT OF TILLAGE AND RESIDUE COVER ON RUNOFF AND SOIL LOSS FROM TWO LAND UNITS

by

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DECLARATION

I declare that the dissertation hereby submitted by me for the Philosophiae Doctor 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 for the dissertation in favour of the University of the Free State.

Signature:

Yali Edessa Woyessa

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ABSTRACT

Land degradation, due to soil erosion, is a serious problem in many parts of the world. Productivity of large areas of cultivated land is decreasing due to severe soil degradation. A major factor responsible for the degradation of this natural resource is accelerated soil erosion. Water erosion is responsible for the biggest share of this degradation, contributing about 50-60%. This shows that soil erosion by water is the most important form of human induced land degradation. Every year, erosion undermines the sustainable use of land and land resource and threatens the livelihood of those depending on agriculture and beyond. Choosing the most appropriate tillage practices for a particular soil often decreases soil erosion and increases available water for crops. A conservation tillage practice such as no-tillage is generally credited with reducing soil losses when compared with conventional tillage.

Field experiments were conducted on two land units. The first experiment was conducted at the University of the Free Sate (UFS) experimental site (South Africa) on a sandy soil with 8.4% clay in the topsoil under simulated rainfall conditions. The second field study was conducted at the Alemaya University (AU) experimental site (Ethiopia) on a clay soil with 45.1% clay in the topsoil. At both sites, the experiment consisted of three tillage practices, namely no-tillage, stubble mulch (traditional tillage for the experiment at AU) and conventional tillage with mouldboard ploughing, combined with four rates of wheat (*Triticum aestivum* L.) residue, namely 0, 2, 4 and 8t/ha. The experiment at AU was conducted for two consecutive main rainfall seasons.

The results of the experiment at the UFS showed that the type of tillage had a significant effect on the initial infiltration rate of soil whereas the final infiltration rate was affected by the residue amount. Runoff and soil loss were also affected by the residue rate. Both runoff and soil loss decreased significantly with an increase in residue rate. When averaged over the four rates of residue cover, no-tillage had the highest runoff and soil loss followed by the stubble mulch tillage. Conventional tillage had the lowest runoff and soil loss. Given the type of soil, which was sandy without structure, conventional tillage practice appeared to have created structure which increased the infiltration rate and consequently decreased runoff and soil loss. A substantial decrease in runoff and soil loss was obtained when conventional tillage practice was combined with residue cover. On conventional tillage practices with higher residue cover rates, such as 4 and 8t/ha, the infiltration rate remained close to the rain application rate, thus controlling runoff and soil loss. Generally it was observed that a residue cover rate of 2t/ha was sufficient to effectively reduce runoff and soil loss on all the three tillage practices.

The results of the experiment at the AU showed similar effects of tillage and residue cover on runoff and soil loss as that of the UFS. When averaged over the four rates of residue cover, no-tillage had a higher runoff and soil loss compared with the traditional and conventional tillage practices. It was also observed that rainfall characteristics in general and rainfall intensity in particular were found to be among the important factors affecting runoff and soil loss. The amount of residue cover required to effectively control runoff and soil loss was dependent on the rainfall intensity. Similar to the UFS site, a residue cover rate of 2t/ha was sufficient to effectively reduce runoff and soil loss for most of the erosive storms, with the exception of a single high intensity storm for which residue rates of 4t/ha and higher was required to control erosion. Soil loss was very well related to the rainfall erosivity index and accordingly classes of erosivity indices were defined where low to high soil losses may be expected.

Comparison of results from the two land units showed that, generally, both tillage and residue cover affected runoff and soil loss in a similar way, but to a different degree. The general tendency reported in literature towards the superiority of no-tillage compared with conventional tillage could not be found in this study. At the UFS site, conventional tillage was found to be more effective than no-tillage in reducing runoff and soil loss. Although results for more seasons are required to draw a final conclusion for the AU site regarding the effectiveness of tillage, it was found that no-tillage was less effective in conserving water and soil compared to traditional and conventional tillage. It was therefore recommended that farmers should use tillage practices consisting of loosening of the soil, combined with maintaining at least 2t/ha or 62% cover of wheat residue.

An attempt was made to predict runoff from rainfall characteristics (amount and intensity) for the AU site. Empirical relationships, established between runoff and rainfall amount, with the inclusion of all rainstorms and for erosive storms only, from the first year's data were used to predict runoff for the second year data. The predicted values agreed well with the measured ones for both conditions. The indices of agreement for the two approaches were 0.79 and 0.89, for the equation based on only erosive storms and on all storms respectively.

Another approach was followed for the prediction of runoff from rainfall intensities and infiltration rates of the soil. A procedure was developed, based on area under the curve method, for the first year's data and it was then used to predict runoff for the second year's data. The predicted runoff values, using the area under the curve method, were comparable to the measured values for the same season. The agreement was good as shown by the high index of agreement (D-index = 0.92) between the two sets of values. This procedure was also used to estimate runoff at the UFS site, from the simulated rainfall intensity and infiltration rate obtained from the double ring infiltrometer. It was found that runoff could be estimated using this procedure when the predicted values were corrected for the depth of tillage.

Key words: Tillage practices, Residue rates, Infiltration, Runoff, Soil loss, Rainfall characteristics

OPSOMMING

Land agteruitgang, as gevolg van gronderosie, is 'n ernstige probleem in baie dele van die wêreld. Dit lei tot 'n verlaging in die produktiwiteit van bewerkte gronde. Watererosie dra 50-60% by tot hierdie mensgeïnduseerde degradasie. Die keuse van die mees geskikte bewerkingspraktyk vir 'n spesifieke grond kan tot 'n verlaging in erosie en verhoging in die beskikbaarheid van water vir gewasse bydrae. Bewaringsbewerkingspraktyke soos geenbewerking het gewoonlik 'n vermindering in grondverliese, in vergelyking met konvensionele bewerking, tot gevolg.

Veldproewe is op twee landeenhede uitgevoer. Die eerste is op die navorsingsterrein van die Universiteit van die Vrystaat (UV) in Suid-Afrika, op 'n sanderige grond met 8.4% klei in die bogrond, met gesimuleerde reën uitgevoer. Die tweede is op die kampus van die Alemaya Universiteit (AU) in Ethiopië op 'n kleigrond met 45.1% klei in die bogrond, uitgevoer. By beide lokaliteite is drie bewerkingspraktyke, nl. geenbewerking, deklaagbewerking (tradisionele bewerking in Ethiopië) en konvensionele skaarploegbewerking, elk gekombineer met vier deklaagpeile van koringstrooi (*Triticum aestivum* L.) nl. 0, 2, 4 en 8 t/ha. By konvensionele bewerking is die strooideklae op die oppervlak uitgestrooi nadat die grond geploeg is. Die proewe by AU is vir twee opeenvolgende reënseisoene uitgevoer.

Die resultate van die eksperimente by die UV het getoon dat die tipe bewerking 'n beduidende effek op die aanvanklike infiltrasietempo gehad het terwyl die finale infiltrasievermoë 'n funksie van die hoeveelheid deklaag was. Afloop en grondverlies het betekenisvol met 'n verhoging in die hoeveelheid deklaag afgeneem. Wanneer die gemiddelde afloopwaardes van die deklaagpeile vergelyk word, het geenbewerking die hoogste en konvensionele bewerking die laagste afloop en grondverlies gehad, met deklaagbewerking tussenin. Dit was duidelik dat diepbewerking van hierdie sanderige grond 'n tydelike struktuur skep wat die infiltrasietempo verhoog, en afloop en grondverlies verlaag. Die uitstrooi van plantreste of instandhouding van 'n deklaag op

die losgemaakte grond, beskerm die tydelike struktuur en deklaagpeile van 4 en 8 t verseker dat die infiltrasietempo hoog bly. Strooideklae van 2 t/ha of hoër was voldoende om afloop en grondverliese effektief, op aldrie bewerkingspraktyke, te verminder.

Die resultate van die veldproef by AU het grootliks met dié van die UV-eksperimente ooreengestem, ten opsigte van die effek van die bewerkingspraktyke en deklaagpeile op afloop en grondverlies. Wanneer die gemiddelde afloop- en grondverliese van die bewerkspraktyke vergelyk word, was geenbewerking hoër as tradisionele en konvensionele bewerking. Die intensiteit en karakteristieke van 'n reënbui was van die belangrikste aspekte wat die afloop en grondverlies geaffekteer het. Die hoeveelheid deklaag wat benodig is om afloop te beheer was van die reënintensiteit afhanklik. Soos by die UV-terrein, was 'n deklaagpeil van 2 t/ha voldoende om afloop en grondverlies tydens meeste reënbuie te beheer maar tydens hoë intensiteit buie word minstens 4 t/ha deklaag vereis. Grondverlies was ook direk van die reënval erosiwiteitsindeks afhanklik en klasse van erosiwiteit is gedefinieër.

'n Vergelyking van die twee landeenhede het getoon dat die resultate vir beide bewerkingspraktyke en deklaagpeile dieselfde was, maar die grade het verskil. Anders as wat meestal in die literatuur berig word, was geenbewerking by beide terreine minder suksesvol as konvensionele bewerking om afloop en grondverliese te verminder. Hoewel resultate oor meer reënseisoene by die AU-terrein nodig is, wil dit voorkom of geenbewerking selfs op hierdie kleierige grond minder effektief as tradisionele of konvensionele bewerking is, om afloop en grondverlies te beheer. Die aanbeveling aan boere is dat hulle grondbewerkings sodanig moet wees dat die grond diep (<150 mm) losgemaak word en terselfdetyd moet 'n strooideklaag van minstens 2 t/ha of 60% grondbedekking behou word.

Pogings is ook aangewend om afloop vanaf die hoeveelheid en intensiteit van reënbuie, vir die AU-terrein te voorspel. Empiriese verwantskappe tussen afloop en hoeveelheid reënval van die eerste jaar is afgelei, waar alle reënbui en waar slegs reënbuie met afloop, ingesluit is. Hierdie verwantskappe is gebruik om die afloop vir die tweede reënseisoen

te voorspel. Die voorspelde waardes het goed met die werklike gemete waardes ooreengestem, met D-waardes van ooreenstemming van 0.79 en 0.89 vir die twee verwantskappe onderskeidelik. ’n Ander benadering wat gevolg is, was om afloop vanaf reënintensiteit en die infiltrasievermoë van die grond te voorspel. ’n Prosedure is met die data van die eerste reënseisoen ontwikkel, wat gebasseer is op die oppervlakte onder die reënintensiteitkurwe-metode. Hierdie metode is toe gebruik om die afloop vir die tweede reënseisoen te voorspel. Die voorspelde en gemete waardes het goed ooreengestem met ’n D-indeks van ooreenstemming gelyk aan 0.92. Dieselfde benadering is ook gebruik om afloop vir die UV-terrein te voorspel. Die voorspelde afloop het ook goed met die gemete waardes vergelyk mits, die voorspelde waardes gekorrigeer word vir die effek van bewerkingsdiepte.

Sleutelwoorde: Bewerkingspraktyke, oesreste peile, Infiltrasie, Afloop, Grondverlies, reënval karakteristieke.

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LIST OF SYMBOLS AND ABBREVIATIONS

A = Plot area
AU = Alemaya University
BBM = Broad Bed Maker
CT = Conventional Tillage
D = Interrill sediment delivery rate
da = Area increment
D-index = Index of agreement
E = Erosion rate
EARO = Ethiopian Agricultural Research Organization
EC = Electrical Conductivity
EI_{30} = Erosivity index based on the maximum 30-minute intensity
EIA = Rainfall erosivity factor
ET = Evapotranspiration
F = Depth of Infiltration
f = Infiltration rate
GLASOD = Global Assessment of Soil Degradation
i = Actual infiltration rate
I = Rainfall intensity
ILRI = International Livestock Research Institute
I_m = Mean maximum infiltration rate
k = Effective hydraulic conductivity
K = Relative erodibility
KE = Kinetic Energy
LSD = Least Square Difference
M = Residue mass
MAE = Mean Absolute Error
MUSLE = Modified Universal Soil Loss Equation
NT = No-Tillage

P = Rainfall depth

Pc = Percentage residue cover

Pe = Rainfall during an event

PET = Potential Evapotranspiration

PRR = Percent Runoff Reduction

Qe = Runoff amount for the event

Qm = Measured runoff

Qp = Predicted runoff

Qr = Runoff rate

Q_R = Runoff ratio

Qu = Total runoff amount

R = Rainfall excess rate

Rc = Runoff coefficient

Re = Erosivity factor for individual storm

RMF = Runoff Mulch Factor

RMSE = Root Mean Square Error

RTF = Runoff Tillage Factor

R_w = Erosivity factor for MUSLE

SC = Sediment Concentration

SCMF = Sediment Concentration Mulch Factor

SCRP = Soil Conservation Research Project

SD = Standard Deviation

S_f = Slope function

SL = Soil Loss

SLC = Soil Loss from Covered plots

SLe = Soil Loss from event storm

SLMF = Soil Loss Mulch Factor

SLR = Soil Loss Ratio

SLU = Soil Loss from Uncovered plots

SSE = Sum of Squared Errors

SSRR = Small Scale Runoff Routing

ST = Stubble Mulch Tillage

TT = Traditional Tillage

UFS = University of the Free State

USLE = Universal Soil Loss Equation

V = Runoff volume

WEPP = Water Erosion Prediction Project

γ = Crust coefficient

θ = Soil water content

Σ = Summation

CHAPTER 1

INTRODUCTION

1.1 Problems of Erosion and Land Degradation

1.1.1 A Global Perspective

The total land area of the world exceeds 13 billion hectares, but less than half of it can be used for agriculture, including grazing (Lal, 1990a). The world's potential arable land is estimated at 3031 million hectares, or 23% of the total land area. The potential cultivable land is distributed as 2154 and 877 million hectares, in developing and developed countries respectively, representing 28% and 15% of the land area (Dudal, 1982; cited by Lal, 1990a). Of the potentially cultivable land 36% and 77% is cultivated in developing and developed countries, respectively.

Productivity of large area of cultivated land is decreasing due to severe soil degradation. A major factor responsible for the degradation of this natural resource is accelerated soil erosion. It is estimated that accelerated soil erosion has irreversibly destroyed approximately 430 million hectares in different countries (Lal, 1990a). This is about 30% of the present cultivated land area of the world.

The severity of soil erosion is attributed to human activities. The effect of erosion, both on-site and off-site, is highly alarming. For instance, studies by GLASOD (1990), cited by Zeleke (2000), showed that about 2 billion hectares of land are affected by human induced land degradation. Water erosion is responsible for the biggest share of this degradation, contributing about 50-60%. This shows that soil erosion by water is the most important form of human induced land degradation. Every year, erosion undermines the sustainable use of land and land resource and threatens the livelihood of those depending on agriculture and beyond.

Of course, soil erosion is not a new phenomenon; it has been a problem since human beings started cultivating the land. Soil erosion by water is most severe in the tropical Africa, with estimated soil losses ranging from 0 to 10 t/ha/year (Lal, 1990a).

1.1.2 National Perspective

In Ethiopia the total cultivable land amounts to 13 million hectares. In 1975, some 9 to 9.5 million hectares of land have already been under cultivation, which is about 73% of the total cultivable area. Recently this figure is expected to be much higher. The severe erosion in Ethiopia is predominantly a human-created problem, resulting from continuous deforestation activities, uncontrolled grazing and unsuitable farming practices. Its drought-triggered famine is merely a symptom of soil degradation caused by erosion. Data from the Simien Mountains in the Gondar region revealed an average annual soil loss of approximately 20 metric tons per hectare (Lamb & Milas, 1983; cited by Lal, 1990a). The Ethiopian highlands lose more than one billion tons of topsoil every year (Brown, 1984), which is equivalent to stripping away one meter of topsoil from about 80,000 ha. Some indication of the extent of soil erosion in Ethiopia can be obtained from the results of research done by Hurni (1985) (Tables 1.1 and 1.2).

Table 1.1. Predicted mean annual soil losses from traditional Ethiopian cultivated fields (*Source*: Hurni, 1985).

Slope length (m)	Slope percentage						
	10	20	30	40	50	60	70
	Mean annual soil loss (t/ha)						
10	12	35	54	61	68	74	81
20	16	50	76	86	95	105	115
30	20	62	92	104	115	127	138
40	24	70	108	122	134	148	162
50	26	78	119	135	148	164	179

Table 1.2. Estimated average soil loss rate on slopes from different land use types in Ethiopia (*Source*: Hurni, 1986)

Land use type	Area (%)	Soil loss (t/ha/yr)	Soil loss (t/yr) (in millions)
Crop land	13.1	42	672
Perennial crops	1.7	8	17
Grazing & browsing	51.0	5	312
Currently unproductive	3.8	70	325
Currently uncultivable	18.7	5	114
Forests	3.6	1	4
Wood & bush land	8.1	5	49
Total	100.0		1493

As a consequence of land degradation, the productive capacity of the soils in the Ethiopian highlands is believed to be undermined at a rate of 2-3% annually (Hurni, 1993, cited by Zeleke, 2000). This is an increasing threat to the national food supply if allowed to continue unchecked.

Soil degradation is in effect the result of the interaction and interdependence of many biological and socio-economic factors, such as climate, the land and land use, and socio-economic factors as shown in Figure 1.1.

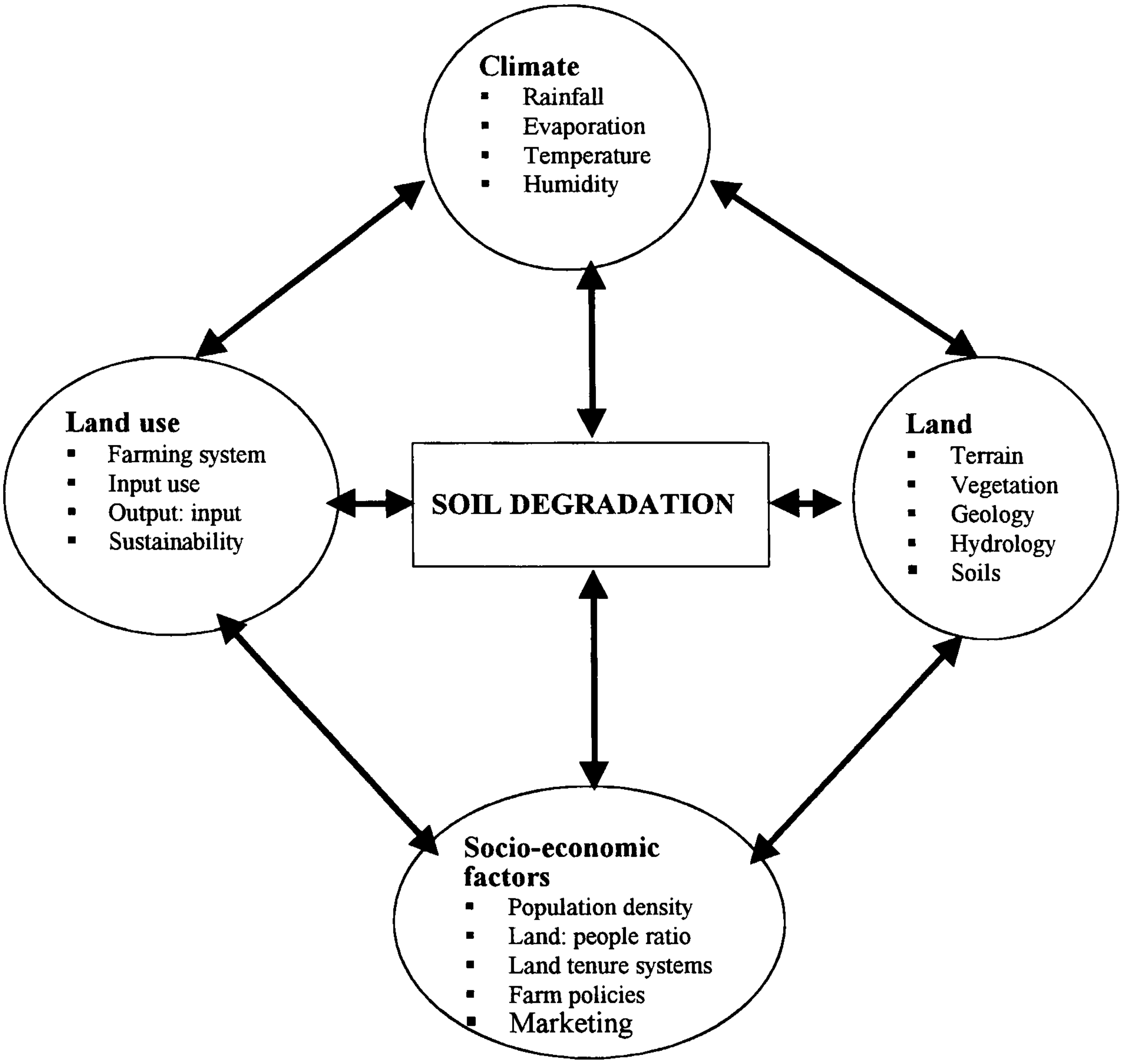


Figure 1.1. Interdependence of soil degradation on biological and socio-economic factors (from Lal & Stewart, 1990).

1.2 Developments in Conservation Tillage

The accelerating soil erosion, the increasing population pressure and the decline of land productivity has renewed the interest of most researchers in tillage systems. Most research acknowledged that tillage is responsible for a major part of soil structural deterioration. The adverse effect of tillage on soil structure are well established – enhanced oxidation of organic matter by exposure at the surface, mechanical dispersion by paddling through the action of implements and by raindrop impact on bare soil. The obvious results are soil erosion by water and wind, and the formation of crusts that seals the soil surface, which impedes air and water movement and seedling emergence, all that can be serious handicaps to crop growth (Periera, 1975; cited by Larson & Osborne, 1982).

Crops respond to changes in soil water content, soil temperature, nutrient supply, aeration, and to the strength of the soil. The specific tillage practice employed influences all these plant growth factors, although the effects may vary for different soils and weather conditions. Conservation tillage has been defined as a form of non-inversion tillage that retains protective amounts of crop residue on the soil surface (SCSA, 1982; cited by Andraski *et al.*, 1985). Its use as a means of reducing erosion by water and wind is increasing (Larson & Osborne, 1982). For instance, it has been estimated that conservation tillage will be used on 50 to 60% of the USA cropland by the year 2010 (Larson & Osborne, 1982).

1.3 Tillage Methods and Soil and Water Conservation in Ethiopia

In Ethiopia, about 85% of the population makes a living from agriculture, half of which is subsistence farmers on steep slopes (Hurni, 1988). The Ethiopian highlands, situated in the eastern Sahel belt, have a higher altitude with much more rainfall than the surrounding lowlands. As result, the Ethiopian highlands have been a centre of civilisation for many millennia. Major deforestation started 2,000 years ago and ox-plough agricultural systems developed first in the northern parts of the country spreading later to the south and west (Hamilton, 1977; cited by Hurni, 1988).

An estimation done fifteen years ago showed that the natural forests in Ethiopia have been reduced from an original 40 percent tree cover to 2.8% (Hurni, 1985) and it is expected to be much less presently. Much of the deforestation took place during the last

100 years. Soil degradation is extreme in the areas from where agriculture started, the northern regions of Ethiopia. It is not by chance that these areas experienced famine in 1973-1974 and in 1984-1985 (Hurni, 1988). Although a direct correlation of famine with soil erosion is difficult, the latter certainly undermined sustainable food production. Furthermore, the growing human population pressure and the degradation of cultivable land has forced small holder farmers in some areas of the central highlands of Ethiopia to expand into cultivating plots located on steep slopes (Goe, 1998), contributing further to soil degradation.

Tillage practices and cultivation of crops with animal drawn implements is a widespread practice in many parts of eastern Africa in general and in Ethiopia in particular. Tractor powered tillage implements are used to a limited extent, mainly on larger state and private commercial farms, but also sometimes for initial or primary tillage of small plots through rental agreements.

In Ethiopia, 90% of the land preparation for crop production by smallholder farmers is done with a traditional 'maresha' plough pulled by a pair of local zebu oxen (Appendix 1.1 &1.2). Three to five passes with maresha are required for all types of soils before a field is ready for planting. Each cultivation pass is perpendicular to the previous one. The first pass reaches 8 cm soil depth while with a last pass up to 20 cm depth can be attained (Astatke *et al.*, 2002). Land is usually prepared before the main rainy season, from June to August. When the crops sown during the rainy season are still small, the tilled soil is exposed to heavy rain resulting in high erosion. In response to this and other problems related to land degradation, efforts have been made to develop farm implements appropriate for land preparation by small-scale farmers. An animal drawn equipment, called the broad bed maker (BBM), has been developed by a research consortium in order to alleviate the waterlogging problem on vertisols in the Ethiopian highlands by modifying the local maresha. The BBM creates 80 cm wide beds separated by 40 cm wide furrows that remove excess water during heavy rains, allowing for early planting and taking advantage of a longer growing period, and resulting in higher yields and less erosion (Astatke *et al.*, 2002). However, the use of this technology has not been adopted on a wider scale.

The use of minimum tillage for crop production is an entirely new concept, which has not yet been accepted, even at a research level. However, it is worth mentioning that some research that was done jointly by the International Livestock Research Institute (ILRI) and Ethiopian Agricultural Research Organization (EARO) are showing promising results, both at the research station and in on-farm trials. The BBM - tillage implement was modified with an attachment to minimise the tillage passes (Appendix 1.3) (Astatke *et al.*, 2002).

The highlands of Ethiopia, which cover 44 percent of the country, include 95% of the cropped area and carry two thirds of the country's livestock. Approximately 88% of the population live in this area, at an average density of 64 people per km^2. In contrast, the lowlands comprise 56% of the land area, but accommodate only 12% of the population at a density of less than 10 people per km^2. Most of the highland terrain has slopes of more than 16%, and only a fifth of it is considered free from an erosion hazard. Most of the productive topsoil in the highlands has been degraded, resulting in chronic food shortages and persistent poverty. Serious erosion is estimated to have affected 25% of the area, and some estimates found that 4% of the highlands is so seriously eroded that it will not be economically productive again in the foreseeable future (SCRP, 1996).

The Ethiopian government first recognized the severity of the soil degradation problem after the 1973-74 famine. With heavy external support, the government initiated a massive soil conservation and rehabilitation program in the most highly degraded areas. Thousands of kilometers of terraces were constructed on cropland and hills, including re-vegetation of highly denuded land. In the 10 years to 1990 more than US $20 million has been disbursed annually as Food for Work (Cheatle, 1993). The money was mainly used to build terraces, bunds, and other physical measures in farmers' fields. Other donors in Ethiopia have committed funds to the approach of reducing land degradation through the control of soil and water movement by physical structures. The success of these projects appears to be limited, and some measures may have done more harm than good. Engineering structures for soil conservation are considered unnecessary by many people, and once erected at considerable costs they may be abandoned, neglected or removed, because people do not perceive the advantage. They do not want to loose the fifteen per cent of their land that is taken up by stone bunds. Because of these and other factors soil conservation achievements fell far below expectations, and despite considerable efforts, the country is still loosing an incredible amount of precious topsoil annually.

Environmental, socio-political and demographic factors contributed to this poor performance. Environmental factors include the dissected terrain, rugged topography, cultivation of steeper lands, erratic and erosive rainfall, and so on. Generally in Ethiopia the valleys and hills are a pleasure to view but a challenge to develop. Socio-political factors include the top-down approach adopted by intervening bodies to improve soil and water conservation. Farmers were minimally involved in soil conservation activities. As a result, soil and water conservation programs to date have proved to be highly unpopular among farmers. Demographically the high population per unit land exceeds the supporting capacity of the land in many regions.

In order to support the massive and extensive campaign of the government to control and reverse the process of soil degradation, a soil conservation research project (SCRP) was initiated in 1981, jointly by the Soil and Water Conservation Department of the Ministry of Agriculture of Ethiopia and the Institute of Geography of the University of Bern in Switzerland. Seven research units have been established since 1981, including the one in the present Eritrea, across different agro-ecological zones of Ethiopia representing average conditions of landscape, climate, land use, soil and population (Figure 1.2 and Table 1.3).

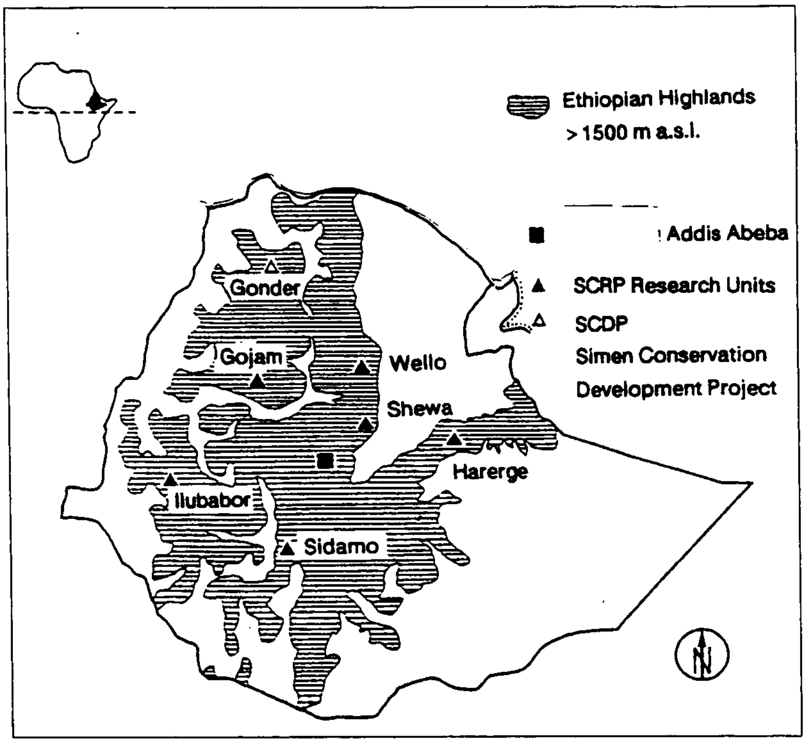


Figure 1.2. Location map of the Ethiopian highlands and SCRP research sites.

Table 1.3. Research Units of the SCRP and their agro-ecological information

Research Unit	Region	Establishment Year	Altitude (m.a.s.l.)	Agro-climatic Zonation
Maybar	Amhara, South Wello	1981	2500-2800	Moist Dega
Gununo	Southern, North Omo	1982	1980-2100	Wet Woyna Dega
Hunde Lafto	Oromia, West Harage	1982	1950-2300	Dry Woyna Dega
Andit Tid	Amhara, North Shewa	1982	3000-3500	Wet Dega/Wet Wurch
Anjeni	Amhara, West Gojam	1984	2350-2450	Wet Dega
Dizi	Oromia, Illubabor	1988	1560-1720	Wet Kolla/Wet Woyna Dega

1.4 Effect of Tillage and Residue Cover on Runoff and Soil Loss

Surface runoff from upland areas such as hillslopes is often accompanied by soil erosion. Soil particles may be detached when the impact of raindrops exceeds the consistency at the soil surface. Detachment may also occur when the shear stresses caused by flowing water exceed the ability of the soil's particles to resist these erosive forces. Vegetation as a canopy or as residue cover, or other surface covers such as gravel and rock fragments, protect the soil surface from direct raindrop impact, and also decrease surface flow reducing the shear stresses acting on the soil. Plant roots and incorporated plant residue increase cohesion and protect the soil by reducing the rate of soil particle detachment by flowing water and raindrop impact.

Once detachment has occurred, raindrop splash and overland flow transport sediment particles. Conditions, which limit detachment of soil by raindrop impact, such as tillage roughness and residue cover, limit the sediment supply that is available for transport by splash and flow mechanisms.

Choosing the most appropriate tillage practices for a particular soil often decreases soil erosion and increases available water for crops. A conservation tillage practice such as no-tillage is generally credited with reducing soil losses when compared with conventional tillage (Andraski *et al.*, 1985; Bradford & Huang, 1994; Choudhary *et al.*, 1997).

Conservation tillage systems are effective in reducing soil erosion because of the greater crop residue cover, greater soil resistance to soil detachment and transport, or reduced soil erodibility, often reducing runoff (Lindstorm & Onstad, 1984). Observed differences in total runoff due to tillage have not been consistent, apparently because of the effect of factors such as the degree of residue cover; rainfall intensity, amount and timing; soil texture and surface roughness (Unger, 1992). For example, Kinnel (1996) reported no differences among tillage practices on either sediment concentration or runoff amount. The reason being the high capacity of the soil to maintain it's tillage-induced surface roughness under rain following cultivation.

As a general rule, tillage is considered to encourage erosion through the degradation of soil physical properties, leading to an increase in runoff and sediment concentration, compared to untilled conditions with a higher aggregate stability and infiltration capacity resulting from biotic activity (Kinnel, 1996). Regional differences in soil physical properties explain most of the contradictory results from various runoff studies (Myer & Wagger, 1996).

The effect of crop residue on runoff and soil loss has been studied by several researchers (Mannering & Meyer, 1963; Lattanzi *et al.*, 1974; Gilley *et al.*, 1986; Gilley *et al.*, 1986a & 1986b; Stein *et al.*, 1986; Unger, 1992; Biamah *et al.*, 1993). Mannering & Meyer (1963) reported that the use of wheat straw at rates of 1, 2, and 4 tons per acre almost completely eliminated runoff and controlled erosion under simulated rainfall by providing sufficient protection from raindrop impact energy to prevent the destruction of the soil surface structure.

Residue management is reported to be much more important than soil management (Bradford & Huang, 1994). Because without adequate surface residue, even a no-tillage soil condition will seal, crust and erode. It is the combination of residue cover and improved soil management practices that causes reduced runoff and erosion.

Bradford & Huang (1994) reported further that differences in runoff and soil loss between conservation and conventional tillage practices is more pronounced before planting, until the crop canopy begins to protect the soil surface from raindrop impact, sealing and crusting. In effect, much of the soil loss from agricultural land takes place during the time of seedbed preparation and until such time that the plant canopy develops fully and takes the role of protecting the soil surface. For the time following full canopy cover, there will be small differences in infiltration and erosion between no-till and conventional tillage.

Andraski *et al.* (1985) reported that individual event runoff volumes and peak flows generated by natural and simulated rainfall were consistently reduced by conservation, compared with conventional tillage. The study found that natural runoff volumes for four large growing season rainfall events averaged 85, 77, and 77% less than conventional tillage for chisel, no-till, and till-plant, respectively.

Choudhary *et al.* (1997) reported that soil loss and runoff were in the order of *mouldboard ploughing* > *chisel ploughing* > *no-tillage* for long-term tillage treatments. They also showed that soil loss and runoff were higher when a rainstorm fell on a wet soil. In general it has been repeatedly shown that reduced tillage intensities decreased soil degradation through reducing soil splash and erosion.

Lattanzi *et al.* (1974) showed that both runoff and soil loss decreased significantly when the wheat (*Triticum aestivum* L.) straw mulch cover on interrill areas was increased. Runoff from 64.0 mm rainfall from a silt loam soil mulched at 8t/ha (95% cover) were only 10% of the amount from 2, 0.5, and 0 t/ha (61, 25, and 0% cover, respectively), which were similar. Soil loss decreased in an inverse exponential form to essentially zero as the mulch rate increased to 8t/ha. Singer *et al.* (1981), using similar techniques but on a clay loam rather than silt loam, found no significant decrease in runoff as the mulch cover increased, whereas soil loss decreased significantly as the mulch cover increased, in a linear rather than inverse exponential form. Zuzel & Pikul (1993) reported that the relationship between sediment loss and percentage cover of wheat residue was non-linear (a second-degree polynomial). This model is reported to have the advantage of a determinate intercept at zero cover that represents the data more realistically.

Zuzel & Pikul (1993) supported the hypothesis of little or no erosion protection from covers of 30% or less and suggested that more experimental data for cover less than 25% are needed in order to define the residue cover-soil loss relationship. Furthermore, they noted that the use of an exponential model such as, $MF = exp(bc)$ (Wishmeier, 1973, cited by Zuzel & Pikul, 1993) where MF is the mulch factor (equivalent to soil loss ratio in their analysis), b is an empirically determined coefficient, and c is percentage residue cover, is not justified because of a lack of verification data for covers less than 25%.

According to Van Doren & Allmaras (1978) less than 1t/ha of wheat straw is required to provide 30% surface cover, which in turn will reduce soil losses by about 70%. The relationship between the soil loss ratio (soil loss with cover divided by soil loss from bare soil) and percentage surface cover showed that small amounts of residue are highly effective for controlling erosion by wind and water. Because of the differences in residue density from different crops, the amounts required to provide protection equivalent to that provided by wheat straw will vary. For example, 1t/ha of wheat straw provides about 50% surface cover (Van Doren & Allmaras, 1978), but about 3 and 9 t/ha of grain sorghum (*Sorghum bicolor* L.) stover and cotton (*Gossypium hirsutum* L.) stalks, respectively, are needed to provide the same percentage cover when placed flat on the surface (Unger & Parker, 1976). Sallaway *et al.* (1988) established the following relationships between residue weight (t/ha) and surface cover (%).

> Projected cover (%) = $m(1-e^{-\text{residue weight}})$, with m being 98.1 for wheat, 64.7 for sorghum and 49.3 for sunflower (*helianthus annuus* L.).

Gilley *et al.* (1986) tested the effect of sorghum and soybean residue at different rates of cover on runoff and soil loss under simulated rainfall conditions. They reported that sorghum residue at rates of 0.84, 1.68, 3.36, 6.73 and 13.45 t/ha produced average surface covers of 4, 17, 26, 44 and 72%, respectively. Similarly, average surface covers of 17, 27, 36, 56 and 82% were produced by placement of soybean residue at rates of 0.84, 1.68, 3.36, 6.73 and 13.45 t/ha, respectively. From these data, relationships between surface cover and residue mass were established using regression analysis.

$$\text{Sorghum surface cover (\%)} = 100\,(1-e^{-0.091M}), \qquad r^2 = 0.96$$

$$\text{Soybean surface cover (\%)} = 100\,(1-e^{-0.135M}), \qquad r^2 = 0.94$$

Where, M = the mass of residue (t/ha)

A significant reduction in total runoff occurred at a sorghum residue rate of 3.36t/ha (26% cover), and at a soybean residue rate of 1.68t/ha (27% cover).

A runoff mulch factor was obtained by dividing the total average runoff for each of the residue treatments by the runoff from bare treatments without residue cover. Gilley *et al.* (1986) obtained the following runoff mulch factor-surface cover relationships for sorghum and soybean residue mulches.

$$\text{Sorghum runoff mulch factor} = e^{-0.031\,(\%cover)}, \qquad r^2 = 0.93$$

$$\text{Soybean runoff mulch factor} = e^{-0.019\,(\%cover)}, \qquad r^2 = 0.89$$

Gilley *et al.* (1986) reported that the sediment concentration mulch factor (SCMF), which is obtained by dividing sediment concentration for each of the residue treatments by sediment concentration for conditions without residue, is related to surface cover as shown below.

$$\text{Sorghum SCMF} = e^{-0.050\,(\%cover)}, \qquad r^2 = 0.99$$

$$\text{Soybean SCMF} = e^{0.035\,(\%cover)}, \qquad r^2 = 0.96$$

The soil loss mulch factor (SLMF), which is also called soil loss ratio, is obtained by dividing total soil loss for each of the residue treatments by the soil loss from the soil without residue cover.

$$\text{Sorghum SLMF} = e^{-0.073\,(\%cover)}, \qquad r^2 = 0.99$$

$$\text{Soybean SLMF} = e^{-0.045\,(\%cover)}, \qquad r^2 = 0.95$$

Mohamoud *et al.* (1990b) reported, while comparing no-tillage with tilled practices, both with surface residue removed, that runoff occurred sooner on no-till because of the rapid filling of surface pores and clogging of pores by raindrop splash. Runoff occurred later under tilled conditions because of a higher surface roughness and depression storage. Final runoff and infiltration were about the same for no-till and tilled treatments because surface sealing properties were primarily determining the runoff and infiltration rates. They concluded that: (1) no-till systems generally result in significantly higher rainfall infiltration than conventional tillage systems, (2) rainfall infiltration was directly related to percentage ground cover, (3) plots with rows on the contour generally have more rainfall infiltration than plots with rows up and down the slope, (4) no-tillage generally has less depression storage than conventional tillage, (5) conventional tillage generally resulted in a smaller effective hydraulic conductivity of a soil, than no-tillage.

Unger (1992) calculated infiltration rates for different tillage practices using the equation of Morin & Benyamini (1977) under field conditions and found that the type of tillage performed had an influence on runoff and water infiltration, and hence, on soil erosion. Soil measurements made in conjunction with the infiltration measurements indicated that different tillage methods resulted in soil surface conditions that differed with respect to aggregate stability, aggregate size distribution, organic matter concentration, amount of residues on the surface, surface roughness, all of which were related to water infiltration. Tillage methods also affected the length of time that water had to be applied to reach constant infiltration rates.

According to Unger (1992), tillage methods affect soil aggregate-size distribution and stability, surface roughness, and hence water infiltration. On the other hand Unger (1992) showed that the percentage of cover provided by surface residues was not closely related to infiltration rates of water applied with a rainfall simulator whereas soil-inverting tillage such as mouldboard ploughing resulted in lower final infiltration rates than non-inverting tillage.

1.5 Effect of Rainfall Intensity on Erosion

The relationship between rain intensity and sediment production rate is important for evaluating cropland erosion related problems and designing effective control practices. Rainfall characteristics are the dominant climatic factor affecting erosion rates (Meyer, 1981). An understanding of the effect of rainfall intensity on erosion makes it possible to analyse the changes in erosion rate as the intensity varies during rainstorms. Such knowledge is becoming increasingly useful for the evaluation of the progress of soil erosion from using average estimates to those for individual storms (Meyer, 1981).

The effect of rain intensity on the erosion from research plots has been expressed as the kinetic energy (a function of intensity greater than unity) times the maximum 30-minutes intensity (Wischmeir & Smith, 1958; cited by Meyer, 1981). According to Meyer (1981), the relationship between rain intensity and erosion followed a straight line for almost all conditions when soil losses per unit area per unit time (*E*) was plotted against rain intensity (*I*) on log-log paper. The appropriate equation is a power function,

$$E = aI^{b} \quad\text{[1.1]}$$

Where *a* and *b* are the coefficient and exponent of best fit respectively.

Meyer (1981) used the traditional technique for getting the *a*- and *b*- variables of the power equation by plotting log *E* against Log *I* and fitting a linear equation to the transformed data,

$$\log E = \log a + b \log I \quad\text{[1.2]}$$

For bare, tilled silt and silt loam soils, Meyer (1981) found values of b ranging from 1.85 to 2.21, which averaged 1.98. For clay and silty clay soils, b ranged from 1.63 –1.73, averaging 1.67. Equation 1.3 was derived for estimating b from the clay content of soils.

$$b = 2.1 - (0.01)*(\%clay), \text{ or } b = 2.1 - (clay\ fraction) \quad\text{[1.3]}$$

Thus, according to Meyer (1981), the influence of rainfall intensity on erosion is greater for low clay content soils than on those with higher clay contents. Meyer (1981) reported that the reason for the lesser effect of rainfall intensity on the clayey soils was not obvious, but it may be the greater soil cohesiveness slowing the rate of soil detachment and the production of a larger more heavily sediment concentration that is more difficult to transport.

In general terms the relationship between erosion and rainfall intensity can be described as:

$$D_i = K_i I^2 \qquad [1.4]$$

Where,

D_i = the interrill sediment delivery per unit area per unit time,

K_i = a relative erodibility parameter,

I = the rainfall intensity.

To account for runoff as well as infiltration effects on sediment transport, this equation was modified and used in the Water Erosion Prediction Project (WEPP) model (Flanagan & Nearing, 1995; cited by Zhang *et al.*, 1998) as

$$D_i = K_i IRS_f \qquad [1.5]$$

Where,

D_i = sediment delivery in mass per unit area per unit time (kg/m^2/hr)

R = rainfall excess rate (mm/hr),

S_f = slope function,

K_i = relative erodibility,

I = rainfall intensity (mm/hr).

The slope function can be estimated by using Equation 1.6.

$$S_f = 1.05 - 0.85e^{-4\sin\theta} \qquad [1.6]$$

Where θ is the slope angle (in degrees).

Using regression analysis, Huang (1995) found that sediment delivery related well to either runoff rate or slope steepness in a quadratic model. The interactive effects between slope and runoff on sediment delivery could be accommodated by regression coefficients in each model. Guy *et al.* (1987) found that sediment transport capacity was proportional to the square of rainfall intensity, which was similar to the relationships for sediment delivery proposed by Meyer (1981) (Equation 1.4) from their field experiments.

Models developed solely on rainfall characteristics, such as Equation 1.4 may produce a satisfactory prediction for steady state conditions when rainfall intensity is closely related to runoff rate at this state (Zhang *et al.*, 1998). Meyer (1981) suggested that, because the exponent in Equation 1.1 is close to 2.0, an equation of $E = cI^2$ would give a good relationship for all soils with the exception of high-clay soils. This equation can be fitted to non-transformed data, even for small E-values. The ratio between the c-coefficients of two soils can be used to quantify the relative interrill erodibility of the different soils or the relative erosion from different cropping systems for a given soil. For instance, the relative erodibility of two sandy soils, $A(E=23.1I^2)$ and $B(E=39.0I^2)$, is $\frac{23.1}{39.0} = 0.59$. The relative erosion from cotton at partly canopy cover as compared to full canopy cover was $\frac{20.4}{7.3} = 2.8$. The results from Meyer (1981) indicated that $E = cI^2$ gave good relationships for silt, silt loam, loam and sandy loam soils, since the exponent of best fit for these soils were generally between 1.9 and 2.1. The equation also fitted data from a wide range of crop covers and soil conditions well. Unfortunately, this equation is less satisfactory for soils with clay contents greater than about 20%.

Akan & Yen (1983) have shown that for the same antecedent conditions and the same final rate of infiltration, the infiltrability was different at different rainfall intensities. Naturally, large rainfall intensities resulted in higher infiltration rates early in the storm. A higher infiltration rate saturated the surface layers of the soil sooner, therefore the decline in infiltrability occurred earlier.

Akan & Yen (1983) also reported that the cumulative infiltration is independent of the intensity of the rain if the duration of the rainfall event is long. However, instantaneous infiltration rates as well as overland flow rates and volumes are affected by the rainfall intensity.

Rainstorm characteristics are also used to calculate the R-factor of the Universal Soil

Loss Equation (USLE). The *R*-factor of the USLE is dependent only on the product of storm energy (E) and the maximum 30-min rainfall intensity (I_{30}). The need to consider runoff directly in obtaining *R*-factors for individual storms has been demonstrated by Foster *et al.* (1982) and Kinnell (1997). Foster *et al.* (1982), in their analysis of USLE data, observed that lumped erosivity indices, which include rainfall amount, rainfall intensity, and runoff amount, were better predictors of erosivity than the EI_{30} index alone, which is the product of the total kinetic energy and the maximum 30-minute intensity of the storm. They showed that erosivity indices with separate terms for rainfall and runoff erosivity were better because it can be used to separate the contributions of rill and interrill erosion given (Equation 1.7).

$$R_e = 0.5EI_{30} + 0.5Q_e q_p^{0.33} \qquad [1.7]$$

Where,

R_e = Erosivity for individual rainstorms,

E = the kinetic energy of the rain expended on the ground during a rainstorm

I_{30} = the maximum 30-min rainfall intensity.

Q_e = runoff amount for the event

q_p = peak runoff rate observed during the event,

Both runoff rate and amount from a rainstorm also affect the erosivity of the storm. Foster *et al.* (1982) suggested a rainfall erosivity factor (EIA), which takes both the rainfall and runoff amount into account (Equation 1.8).

$$EIA = I_{30} (Q_e P_e)^{1/2} \qquad [1.8]$$

Where, Q_e and P_e are runoff (mm) and rainfall (mm) for the rainfall event, respectively.

Kinnell (1997) proposed an alternative erosivity index to the EI_{30} index, which includes runoff ratio,

$$Erosivity = Q_R EI_{30} \qquad [1.9]$$

Where Q_R is runoff ratio (ratio between runoff and rainfall).

Kinnell (1997) reported that this index was superior to the EI_{30} index in relation to its capacity to act as an event erosivity index where sheet and rill erosion occur either separately or together in a rainstorm.

1.6 Soil Physical and Hydraulic Properties as Affected by Tillage

Soil management practices, such as tillage, have a large effect on soil physical and hydraulic properties (Tollner *et al.*, 1984) and the processes of infiltration, runoff, water storage, soil temperature, and chemical transport. Soil tillage generally decreases soil bulk density and increases soil porosity by loosening up the soil (Cassel, 1982; Ahuja *et al.*, 1998; Xu & Mermoud, 2001). These changes are large with the initial primary tillage, but are moderated by the secondary tillage. The magnitude of these changes varies with the nature of the soil, tillage method, and soil water content. These changes in soil properties are not permanent, because they tend to revert over time to the original values before tillage.

During wetting by natural rainfall or irrigation, the soil is reconsolidated by three mechanisms (Ahuja *et al.*, 1998): (1) raindrop impact, (2) the effective stress in water saturated soil approaching zero, which cause the soil matrix to collapse under its own weight, thus reducing the size and number of macropores, and (3) the dynamic forces of water moving through the pores, which tend to condense the soil matrix.

During wetting, the tilled soil may also be subjected to changes in pore size distribution and the water retention characteristics due to slaking and dispersion of the temporary soil aggregates created by tillage. At the soil surface this process is enhanced by raindrop impact, which often results in the development of a surface crust (Ahuja *et al.*, 1998).
Generally, the modification of soil physical properties by tillage operations influences the amounts and rates of water infiltration into the soil. For example, Waddel & Weil (1996) estimated soil sorptivity with the Philip infiltration equation for no-till and ridge-till plots

and found that the sorptivity values were approximately twice as high for no-till as for ridge-till. This was attributed to higher surface residue mulch and an undisturbed macropore system in no-till plots.

1.7 Developments in Erosion and Runoff Models

The processes controlling sediment detachment, transport, and deposition are lumped under the term erosion processes and are complex and interactive. On-site measurement and monitoring of erosion is expensive and time consuming, but a knowledge of the extent and degree of soil erosion is essential for soil and water conservation planning and other agricultural development activities. This complexity leads to the need for erosion prediction models as tools in resource management. Erosion models can be classified into two basic categories: empirically based and physical process based models.

1.7.1 Empirically Based Models

Universal Soil Loss Equation

The Universal Soil Loss Equation (USLE) is the most widely used empirical model for overland flow or sheet-rill erosion. The equation was originally developed as a tool for soil conservationists for use in developing farm management plans to control erosion and maintain soil productivity. More recently, it has been used to estimate sediment yield and erosion's contribution to non-point source pollution. The equation is simple and is based on large data sets from natural runoff plots over several years (Foster, 1982).

The USLE is given by:

$$A = RKLSCP \qquad [1.10]$$

Where: A = Soil loss averaged over the slope length, R = combined erosivity of rainfall and runoff, K = soil erodibility, L = a slope length factor, S = slope steepness factor, C =

cover-management factor, P = supporting practices factor.

According to Foster (1982), three major limitations of the USLE restrict its application in many modelling analyses. Firstly, it is not intended to be used for estimating soil loss from single storm events. Secondly, it is an erosion equation, and consequently it doesn't estimate deposition. Thirdly, it doesn't estimate gully or channel erosion. The USLE is intended to estimate average soil loss over an extended period, e.g. average annual soil loss.

Models developed using the approach of multiplication-of-factors type, such as USLE, are generally reliable, simple, and easy to calibrate; however, these models usually don't delineate between transport and detachment processes explicitly (Zhang *et al.*, 1998).

Modified Universal Soil Loss Equation (MUSLE)

Sediment yield is sometimes obtained from estimating the gross erosion with the USLE and then multiplying it by a delivery ratio. However, Foster (1982) argued that this method is inadequate and can lead to false conclusions for small watersheds and that it can only be used as a first approximation.

The MUSLE, which is a modification of USLE by Williams (1975a), cited by Foster (1982), is used to estimate sediment yield for individual runoff events from a watershed by replacing the USLE, R-factor with:

$$R_w = 9.05(VQ_p)^{0.56} \qquad [1.11]$$

Where: V = volume of runoff (m^3) and Q_p = Peak discharge rate (m^3/s). The USLE with this R factor is referred to as the Modified USLE or MUSLE.

1.7.2 Process Based Models

Process based or physically based models have several advantages over empirical models. Foster (1982) notes that (i) they are physically based and consequently can be more accurately extrapolated; (ii) they more accurately represent the process, for example, rill and interrill erosion are considered separately rather than being lumped; (iii) they are more accurate for single storm events; (iv) they can consider more complex areas; (v) they consider deposition processes directly; and (vi) they can consider channel erosion and deposition.

Most of the process-based soil erosion models, particularly the WEPP model, were developed following the fundamental concept of Meyer & Wischmeier (1969, according to Nearing *et al.*, 1990), with an improvement over the empirically based USLE parameters. The WEPP model, which is considered to be an up to date erosion prediction technology, is based on the current knowledge of fundamentals of stochastic weather generation, infiltration theory, hydrology, soil physics, plant science, hydraulics, and erosion mechanics (Flanagan *et al.*, 1995, cited by Zelleke, 2000).

The model developed by Yu *et al.* (1997), called SSRRM (Small Scale Runoff Routing Model) is a physically based model for small plots. It consists of two components; the first component addresses infiltration and therefore rainfall excess, the second one deals with runoff routing down the slope length. At sufficiently small spatial scales, or for sufficiently large time intervals, the difference between rainfall intensity and infiltration rate, commonly known as excess rainfall rate, can be regarded as the runoff rate.

Yu *et al.* (1997) defined an apparent infiltration rate as the difference between the observed rainfall intensity and observed runoff rate. When this apparent infiltration was plotted against the rainfall intensity, using one-minute data for the same event, no simple relationship was identified, apart from the constraint that the apparent infiltration cannot be higher than the rainfall intensity. However, the relationship suggested that the apparent infiltration rate increase with rainfall intensity. The scatter between the two parameters was to some extent attributed to the lag between runoff and rainfall. Yu *et al.* (1997) concluded that, after inspection of a large number of events with respect to rainfall-runoff characteristics, the lag between runoff and rainfall is a significant feature even at plot scales. More importantly, they noted that the apparent infiltration rate is primarily a function of rainfall intensity.

Infiltration Component:

All classic theories of infiltration, such as the Green-Ampt infiltration equation, suggest two distinct infiltration phases. Initially the infiltration rate is high and in excess of rainfall intensity due to the sorptivity effect. The maximum rate of infiltration decreases rapidly as the soil becomes wetter to reach the saturated hydraulic conductivity. Yu *et al.* (1997) noted that as rainfall intensity increases, the proportion of the soil surface where the rainfall intensity exceeds the maximum infiltration rate would increase, hence the rainfall excess and surface runoff rate would increase. As a result, the apparent infiltration rate (the difference between rainfall and runoff) would increase as rainfall intensity increases.

The steps followed by Yu *et al.* (1997) to characterise the spatial variation of infiltration capacity is as follows. Let *f(I)* be the frequency distribution of a spatially variable maximum infiltration, *I*. This maximum infiltration rate can be interpreted in the sense that for a given rainfall intensity, P, at a given point within the plot, the actual infiltration, *i*, is no greater than *I*:

$$i = \begin{cases} P & \text{if } I > P \\ I & \text{if } I \le P \end{cases} \quad \text{[1.12]}$$

It follows that the rainfall excess at the point, *r*, is:

$$r = \begin{cases} 0 & \text{if } I > P \\ P - I & \text{if } I \le P \end{cases} \quad \text{[1.13]}$$

Thus for a given rainfall intensity, the rainfall excess can be regarded a function of the maximum infiltration rate which varies in space. This spatially variable rainfall excess resulting from the variable infiltration characteristics can be integrated to give average rainfall excess for the plot, R:

$$R = \frac{1}{A}\int_{plot} r\,da = \int_0^{\infty} r f(I)\,dI = \int_0^{p} (P - I) f(I)\,dI, \quad \text{[1.14]}$$

Since $r = 0$ when $I > P$

Where A is the plot area and da is the area increment. The assumption is that run-on from less permeable areas to more permeable areas within the plot can be ignored. Integrating Equation 1.14 yields:

$$R = \int_0^{p} F(I)\,dI \quad \text{[1.15]}$$

Where, $F(I)$ is the distribution function.

Hence, if the distribution function and its parameters are known, the rainfall excess rate for the plot can be uniquely determined for a given rainfall intensity. The spatial variation of the maximum infiltration rate can be characterised by a one-parameter exponential distribution function, i.e.:

$$F(I) = 1 - e^{-I/I_m} \quad \text{[1.16]}$$

Therefore, the rate of rainfall excess as a function of the rainfall intensity is given by:

$$R = P - I_m\left(1 - e^{-P/I_m}\right) \quad \text{[1.17]}$$

The parameter I_m is the mean maximum infiltration rate across the field when the whole is saturated and the entire plot generates runoff.

Runoff Routing Component:

The rainfall excess *(R)* is the water routed to the plot outlet using the kinematic wave approximation, for which the storage equation can be written:

$$\frac{ds}{dt} = R - Q \quad \text{[1.18]}$$

Where S is the equivalent depth of water stored on the soil surface and Q is the runoff.

Let Q_i and R_i be the average runoff rate and rainfall excess rate for the time interval i, then the storage equation can be written in a discrete form:

$$K(Q_i - Q_{i-1}) = (R_i - Q_i)\Delta t$$

Or ....[1.19]

$$Q_i = \alpha Q_{i-1} + (1 - \alpha)R_i$$

Where the parameter α is related to the lag (K) and time interval (Δt) by:

$$\alpha = \frac{K}{K + \Delta t} \quad \text{[1.20]}$$

The three model parameters that have been chosen to describe the variation in the plot scale runoff rate at small time intervals, namely F_o (the initial infiltration amount in mm before runoff occurs), I_m (a spatially averaged maximum infiltration rate in mm/h, which could be achieved if the entire plot produces it) and α (a dimensionless routing parameter between 0 and 1) can be estimated by minimising the sum of squared errors, SSE, between the observed (Q_o) and modelled (Q_m) runoff rates,

$$SSE = \sum_{i=1}^{N} \left(Q_o - Q_m \right)^2 \quad \text{[1.21]}$$

In summary, Yu *et al.* (1997) indicated that plot-scale runoff models need to take into account the spatial variation of the maximum infiltration rate, and the lag between rainfall intensity and runoff rate, which can be important at small time intervals. A simple exponential distribution of the maximum infiltration rate and a constant lag can satisfactorily describe the temporal variation of runoff within a rainfall event of a given data set. Modelling runoff rates at small time intervals is important because it helps to understand the infiltration characteristics at each site, and to identify predominant infiltration and runoff processes that need to be considered.

With the SSRR model three important aspects of the runoff processes were modelled at small temporal and spatial scales. Infiltration was separated into two distinct phases. Firstly, no runoff occurs during the first phase because the maximum infiltration rate is usually quite high in the beginning of a rainfall event. Secondly, an exponential distribution was used to model the spatial variation in the maximum infiltration over the plot once runoff commences. The net result is that once runoff begins, the runoff rate is closely related to the rainfall intensity.

Yu & Rose (1999) reported a methodology to predict runoff rates from rainfall intensity and runoff amount using a program called GOSH (Yu, 1997) so that a physically based model, called GUEST, can be used to determine the soil erodibility parameter using a program called GEUPS (Yu & Rose, 1997) and to predict the amount of soil loss on an event basis. The models have been used to predict consistent runoff rates, soil erodibility parameters and soil losses at six sites (Yu *et al.*, 1999).

Water balance and infiltration equation:

Mohamoud *et al.* (1990a) used a water balance model for computation of infiltration and depression storage from simulated rainfall events on small plots. They described the hydrologic component of a small plot by the following water balance model.

$$P = F + I + V + D + Q \quad \text{..........}[1.22]$$

Where

P = Accumulated depth of rainfall at any time since rainfall began (mm)

F = Accumulated depth of infiltration at any time since rainfall began (mm)

I = Accumulated depth of interception at any time since rainfall began (mm)

V = Accumulated depth of depression storage at any time since rainfall began (mm)

D = Accumulated depth of detention storage at any time since rainfall began (mm)

Q = Accumulated depth of runoff at any time since rainfall began (mm)

From the above model, the accumulated depth of excess rainfall can be expressed as:

$$R = P - F - I \quad \text{[1.23]}$$

Mohamoud *et al.* (1990a) used an infiltration model, namely a modified Philip equation, which was proposed by Swartzendruber (1974) and used by Swartzendruber & Hillel (1975), to represent the excess rainfall mathematically.

$$f = b(t - c)^{-\frac{1}{2}} + k \quad \text{[1.24]}$$

Where

f = infiltration rate (mm/h)

b = constant parameter that is related to soil sorptivity (mm/h$^{1/2}$)

c = constant parameter that adjusts time to account for rainfall limited infiltration (h)

t = time (h), and

k = effective hydraulic conductivity of the soil (mm/h).

The parameter b in the Equation 1.24 can be expressed in terms of the other parameters of the equation, because infiltration rate is assumed to be to equal the rainfall rate at the time of ponding. By substituting this condition into Equation 1.24, b can be expressed as:

$$b = (p-k)\,(t_p-c)^{1/2} \quad \text{[1.25]}$$

Where

P = rainfall rate (mm/h)

t_p = time of ponding (h)

By substituting b as given by Equation 1.25 into Equation 1.24, infiltration rate is expressed in terms of parameters c, k and t_p as:

$$f = (p-k)(t_p - c)^{1/2}(t-c)^{1/2} + k \qquad [1.26]$$

The rate of excess rainfall on the plot at any time during the rainfall event is equal to the rainfall intensity minus the sum of the infiltration rate plus the rate of change of interception storage before ponding. After the time of ponding the rate of change of interception storage equals zero. Therefore, the rate of excess rainfall can be written as:

$$\frac{dR}{dt} = p - f \quad for\ t \geq t_p \qquad [1.27]$$

After replacing f in Equation 1.27 with the right hand side of Equation 1.26 and knowing that $R = 0$ at $t = t_p$ and that $R = R$ at any time after the time of ponding, the modified Equation 1.27 can be integrated to obtain excess rainfall at any time after time of ponding as:

$$R = (p-k)[(t-c)^{1/2} - (t_p - c)^{1/2}]^2 \quad for\ t \geq t_p \geq c \qquad [1.28]$$

Excess rainfall is related to accumulated runoff, depression storage and detention storage as given in Equation 1.22. By substituting for R from Equation 1.28 into Equation 1.22 and rearranging equations describing runoff can be expressed as:

$$Q = (p-k)[(t-c)^{1/2} - (t_p - c)^{1/2}]^2 - V - D \quad for\ t \geq t_p \geq c \qquad [1.29]$$

In Equation 1.29 the independent variable is time (t) and the dependent variables are infiltration rate (f) and runoff rate (Q).

Morin & Benyamini (1977) proposed a model, based on a Horton type equation, which allows for the calculation of infiltration rate from easily obtainable variables (Equation 1.30).

$$I_t = (I_i - I_f)e^{-\gamma pt} + I_f \quad \text{[1.30]}$$

Where

I_t = infiltration rate at (mm/h) at t,

t = time from the beginning of rain (h),

p = rainfall intensity (mm/h),

I_i = Initial infiltration rate (mm/h),

I_f = final (constant) infiltration rate (mm/h),

γ = Crust coefficient (mm^{-1}).

Equation 1.30 is more suited for studies under variable rainfall intensities such as in the case of natural rainfall and for runoff calculation from event rainstorms (Morin & Cluff, 1980; Hauser & Chichester, 1987; Rao *et al.*, 1998a).

For constant rainfall intensities a modified Philip equation as proposed by Swartzendruber (1974), which is $I = s(t-c)^{1/2} + k$, where I = cumulative infiltration (mm), t = time (hr), s = sorptivity, c = constant parameter that adjusts time to account for rainfall limited infiltration (h), k = effective hydraulic conductivity of the soil (mm/hr), was found to perform well (Mohamoud *et al.*, 1990a).

1.8 Objectives of the Study

The study was conducted within the framework of a "sandwich" program following an agreement between the Alemaya University (AU) of Ethiopia and the University of the Free State (UFS) of South Africa. A rainfall simulation study was conducted in Bloemfontein, South Africa, at the University of the Free State (UFS) experimental site. A field experiment under natural rainfall was conducted in Alemaya, Ethiopia, at the Alemaya University (AU) experimental site, during two rainy seasons of the years 2000 and 2001.

The general objective of the study was to investigate the effect of different tillage methods and levels of residue cover on runoff and soil loss, and to determine the relationships between the different factors involved in runoff and erosion processes on these two different land units.

CHAPTER 2

MATERIALS AND METHODS

2.1 The Alemaya University Experimental Site

2.1.1 Description of the Site

Location

The Alemaya University experimental site was located on the Alemaya University Campus, which is situated 550 km, east of Addis Ababa, the capital city of Ethiopia. Alemaya University is in the Alemaya Woreda (District), Eastern Harerge Zone at an altitude of 1960 meter above sea level (Figure 2.1 and 2.2).

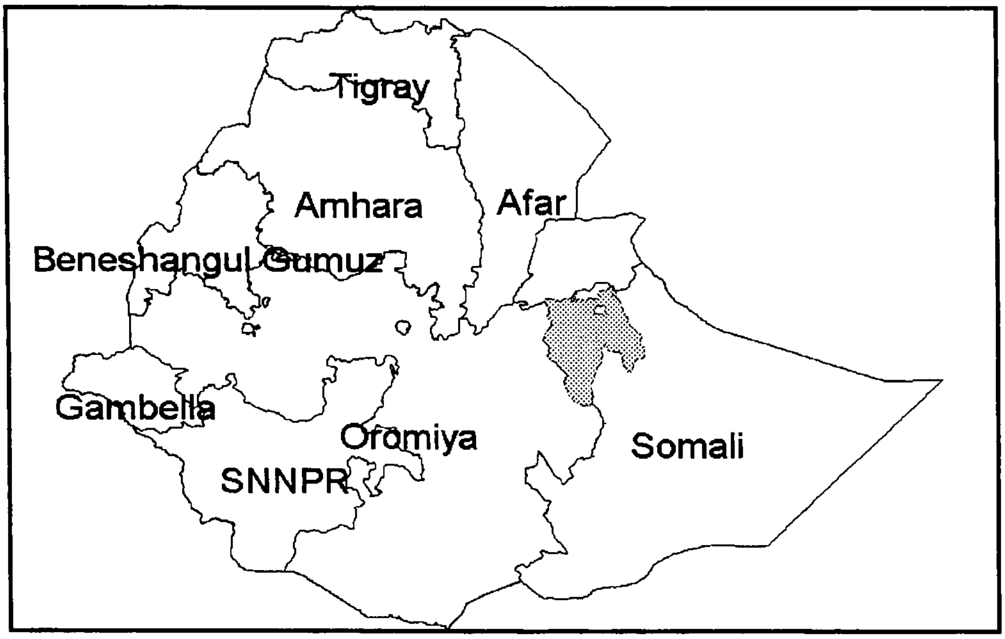


Figure 2.1. Map of Ethiopia showing the location of Eastern Harerge Zone (shaded area) in Oromiya National Regional State.

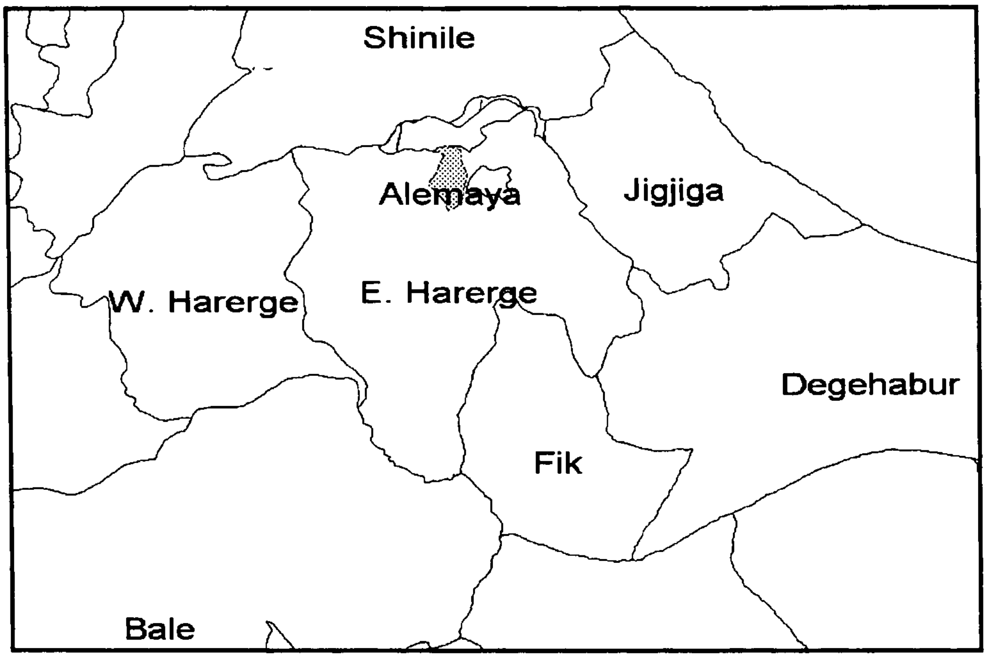


Figure 2.2. Location Map of Eastern Harerge Zone showing the location of Alemaya District, the study site (shaded area).

Climate

According to the agro-ecological zonation of Ethiopia, the climate of the study area is characterized as "Dry Weyna Dega" zone, which is based on the altitude and mean annual rainfall (altitude between 1500 - 2300 m.a.s.l. and annual rainfall of less than 900 mm) (Hurni, 1986). The altitude of the study site is 1960 meter above sea level and the mean annual rainfall is about 800 mm. The mean minimum and maximum temperatures are 10.1^{0}C and 23.6^{0}C, respectively. The rainfall pattern is bi-modal with a short rainy season from March to May and a long rainy season during the months of July, August and September. Long-term averages of rainfall, potential evapotranspiration, minimum and maximum temperatures are given in Figure 2.3.

Soil

The soil of the study area is characterized as a Regosol with good internal drainage. Some of the physical and chemical properties of the soil will be discussed in more detail.

Particle size distribution

The particle size distribution was determined using standard Pipette procedure as described by Day (1965). The topsoil is clayey with 45.1% clay, 22.2% silt and 32% sand. The detailed particle size distribution is given in Table 2.1.

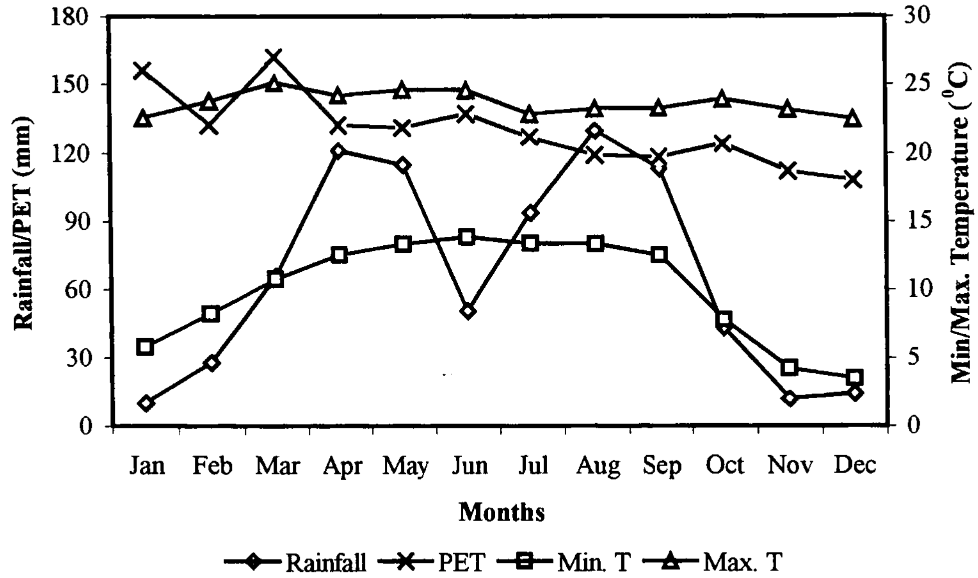


Figure 2.3. Long-term mean monthly rainfall, potential evapotranspiration (PET) and minimum and maximum temperatures at the AU site (1979-1997).

Electrical conductivity, organic matter content and pH

The electrical conductivity of the soil paste and organic matter content determined with Walkley-Black method as described by the Non-Affiliated Soil Analysis Work Committee (1990) and the pH in water (1:2.5) for the different topsoil samples are given in Table 2.2.

Bulk Density

The bulk density of the soil is a very good indicator of the structural status of the soil as affected by the soil management practices, such as tillage and residue management. The bulk density was measured for four depths (10, 20, 40 and 60 cm) using a core sampler with a dimension of 5 cm diameter and 5 cm long. The measurements were done in duplicates. The result showed very little variation between the different tillage practices, as shown in the Table 2.3.

Table 2.1. Mean percent particle size distribution of the topsoil at the AU experimental site

Tillage[1]	Coarse Sand	Medium Sand	Fine & very fine Sand	Coarse Silt	Fine Silt	Clay
	2.0-0.5	0.5-0.25	0.25-0.053	0.053-0.02	0.02-0.002	<0.002
NT-a	21.84	4.68	7.72	4.72	18.40	42.20
NT-b	20.72	4.88	8.32	5.08	15.00	45.20
TT-a	19.76	4.80	8.60	6.04	16.40	44.40
TT-b	17.68	5.40	9.36	4.20	16.40	43.80
CT-a	16.36	4.76	7.92	6.40	17.40	47.40
CT-b	16.40	4.92	7.80	4.88	18.40	47.60
Average	**18.79**	**4.91**	**8.29**	**5.22**	**17.00**	**45.10**
SD	**2.32**	**0.26**	**0.62**	**0.84**	**1.33**	**2.10**

[1] Tillages are: NT = No-tillage, TT = Traditional tillage, CT = Conventional tillage, *a* & *b* show the duplicate soil samples.

Table 2.2. Electrical Conductivity (EC), pH, and organic matter (OM) of the topsoil at the AU experimental site

Tillage	EC (mmhos)	OM (%)	PH (1:2.5)
NT-a	2.47	1.2	6.12
NT-b	2.33	1.1	6.14
TT-a	1.89	1.1	6.30
TT-b	1.79	1.1	6.30
CT-a	1.74	1.1	6.29
CT-b	1.67	1.1	6.24
Average	**1.98**	**1.1**	**6.23**
SD	**0.340**	**0.056**	**0.082**

Table 2.3. Bulk density (kg/m^3) for three tillage practices at four depths at the AU experimental site

Tillage[z]	Depth (cm)			
	10	20	40	60
	Bulk density (kg/m^3)			
TT-a	1260	1240	1090	1210
TT-b	1120	1050	1090	1090
Mean	**1190**	**1150**	**1090**	**1150**
SD	**100**	**140**	**0**	**80**
NT-a	1120	1090	1120	1210
NT-b	1130	1060	940	1130
Mean	**1120**	**1080**	**1030**	**1170**
SD	**10**	**20**	**120**	**50**
CT-a	910	1080	1090	1240
CT-b	980	990	1000	1330
Mean	**940**	**1030**	**1040**	**1280**
SD	**40**	**60**	**60**	**60**

[z] Tillage: NT = No-tillage, TT = Traditional tillage, CT = Conventional tillage and *a* & *b* are duplicate samples.

2.1.2 Experimental Methods

In this experiment, three tillage practices, namely no-tillage, traditional tillage, and conventional tillage (mouldboard ploughing) each with four levels of wheat (*Triticum aestivum* L.) residue cover, namely 0t/ha, 2t/ha, 4t/ha, and 8t/ha as treatments were compared. Traditional tillage is the land preparation method with a shallow tillage tool called "Maresha" pulled by a pair of oxen (Appendix 1.1 & 1.2). The experiment was laid out in a split plot design with tillage practices as main plots and residue cover rates as sub-plots. The size of each plot was 4 meters wide and 6 meters long. The total combinations of tillage and residue cover treatments were twelve. With duplicate replications of all treatments, there were 24 plots in total.

The experimental plots were laid on a field with homogenous soil and uniform slope of 5-6%. A topographic map of the field was prepared from which the slope was calculated. A corrugated iron sheet border was placed around each plot to measure runoff (Morgan, 1995; De Ploy *et al.*, 1974). Pieces of corrugated iron sheet were carefully attached to one another by rivets. The 40 cm corrugated iron sheets were inserted 20 cm deep into the soil in order to prevent run-on and runoff to and from the field. At the down slope side of each plot a trough made of iron sheet was installed which collected the runoff in a barrel with a capacity of 200 liters. During the course of the experiment growth of weeds within the plots was chemically controlled by spraying an herbicide (glyphosate).

During the second year (summer 2001) of the experiment, the same experimental plots were used with the same layout and replication. The tillage operation was conducted after carefully removing the corrugated iron sheet borders and the troughs. After completion of the tillage operations the metallic borders were re-installed.

2.1.3 Measurements

Runoff

Runoff amount and sediment mass were collected in a barrel for each plot. The volume of runoff in each barrel was measured after every rainfall event that produced runoff by inserting a steel tape into the barrel and measuring the depth of water. The depth of runoff in the barrel was converted into volume. After taking the runoff measurements a sample was taken to determine the sediment concentration where after the barrel was emptied and cleaned.

Soil Loss

The soil loss from each plot was calculated using the sediment concentration of the samples that were taken after every runoff event. The samples were put in an oven until all the water has evaporated in order to obtain the amount of sediment in the sample. The sediment was then weighed and the total soil loss per plot for the event was calculated from the total runoff (Morgan, 1995).

Soil Water Content

The gravimetric soil water content was measured weekly for each treatment at three depths, namely 20, 40 and 60 cm with a screw type auger. The samples were weighed and dried in an oven at 105°C for 24 hours. The percentage water content on a dry mass basis was converted to volumetric water content by multiplying it with the corresponding dry bulk density, assuming the density of water to be almost equal to 1.

Bulk Density

A profile was dug on one site of a plot for each of the three tillage practices. Soil cores were taken with a core sampler of 5 cm length and 5 cm diameter. The samples were taken in duplicate at depths of 10, 20, 40 and 60 cm. The samples were dried in an oven for 24 hours at 105°C and the dried samples were weighed and the dry bulk density was calculated as the ratio of the oven dry weight to the volume of the soil.

Percentage Surface Cover

Runoff and soil loss relate better to percentage surface cover than to residue weight. The measurement of the percentage surface cover was conducted with hand held piece of wood in which long nails were inserted as described by Lang & Mallett (1982). A flat 160 cm long bar of carpenter wood with fifteen 12-cm long nails inserted at a spacing of 10 cm was used. The measurement was conducted by placing the wood bar on the soil surface and by counting the number of nails in contact with crop residue. A total of six placements per plot were used. The percentage surface cover (*Pc*) was calculated using the following formula.

$$Pc = \frac{Total\ number\ of\ contacts}{15\,x\,Number\ of\ placements}$$

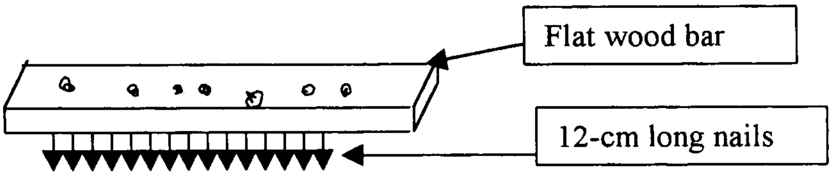


Figure 2.4. Schematic representation of the apparatus used to measure the percentage surface cover at the AU experimental site.

Rainfall

A recording type tipping bucket rain gauge was installed right in the middle of the experimental plots. The rain gauge was connected to a data logger from which the rainfall amount and intensity per event were downloaded on a computer.

2.2 The University of the Free State Experimental Site

2.2.1 Description of the site

Location

The University of Free State experimental site is located 15 km north of the University of the Free State main campus, South Africa (Latitude $26^0 08'50''$ and longitude $29^0 01'00''$). The then Department of Soil Science of the University of the Free State has established a long-term tillage experiment in order to evaluate appropriate and sustainable tillage systems for dry land crop production (Bennie, 2000).

Climate

The study area is characterized as semi-arid climate with a mean annual rainfall of about 510 mm and minimum and maximum temperatures of 7.46^{0}C and 24.35^{0}C. The main rainy season is during the months of November to March. Some rains also occur during the months of April and May and August to October. The long-term averages of the rainfall, reference evaporation (based on Penmann-Monteith method) and minimum and maximum temperatures are given in Figure 2.5.

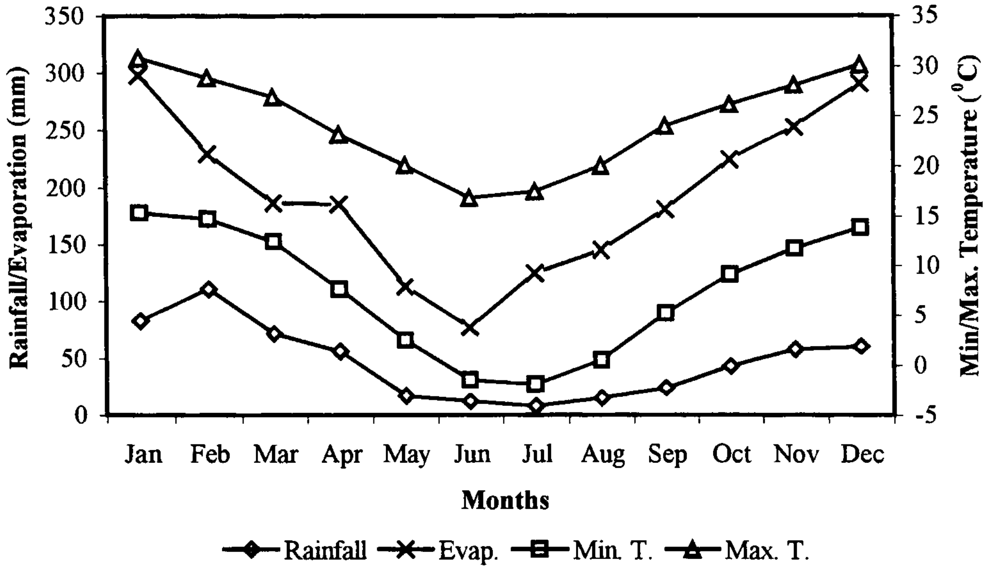


Figure 2.5. Long-term mean monthly rainfall, reference evaporation (Penmann-Monteith), and minimum and maximum temperatures at the UFS Experimental site.

Soil

The soil of the study area, with a slope of less than 1% is characterized as a Bainsvlei Form, Amalia Family according to the South African Soil Classification System (Soil

Classification Working Group, 1991). Some of the physical and chemical properties of the soil will be describe here.

Particle size distribution

The topsoil has a sandy texture with particle size distribution of 88.0% sand, 3.6% silt, and 8.4% clay. The detailed particle distribution for each plot is given in Table 2.4.

Table 2.4. Percentage particle size distribution of the soil for three tillage practices at three depths at the UFS experimental site

Tillage	Depth (cm)	Coarse sand (%)	Medium sand (%)	Fine & very fine sand (%)	Coarse silt (%)	Fine silt (%)	Clay (%)
No-tillage	0-10	0.38	5.33	80.42	4.65	2.60	8.85
	10-20	0.50	6.42	80.04	1.75	1.67	10.00
	20-30	0.56	6.92	79.69	1.85	2.71	9.79
Stubble mulch	0-10	0.52	5.44	84.96	2.60	1.67	7.29
	10-20	0.50	5.21	86.06	1.15	0.83	8.13
	20-30	0.34	5.84	82.88	1.67	1.77	8.96
Conventional	0-10	0.38	6.44	83.17	0.60	1.98	8.96
	10-20	0.38	6.23	83.19	0.98	1.25	8.85
	20-30	0.36	6.21	83.29	1.79	0.63	9.27

The soils of the experimental plots are slightly acidic with an average pH of 4.99, 4.88 and 4.91 at depths of 0-10, 10-20, and 20-30 cm, respectively. The electrical conductivity (EC), organic matter contents and pH are shown in Table 2.5.

Bulk density

The bulk density of the soil for the three tillage practices, measured at three depths of the topsoil, is shown in Table 2.6.

Table 2.5. Organic matter content (OM), pH and Electrical conductivity (EC) of the soil of the UFS experimental site

Tillage	Depth (cm)	EC (mmhos)	pH (H_2O)	OM (%)
No-tillage	10	0.20	4.93	0.15
	20	0.19	4.70	0.18
	30	0.22	4.90	0.14
Stubble mulch	10	0.13	5.10	0.07
	20	0.14	4.95	0.09
	30	0.15	4.83	0.09
Conventional	10	0.16	4.95	0.10
	20	0.19	4.98	0.12
	30	0.15	5.00	0.04

Table 2.6. Mean bulk density (kg/m^3) of the soil at the UFS experimental site at three depths of the topsoil. Numbers in the brackets are Standard Deviations.

Tillage	Depth (cm)		
	0-5	5 -10	10 -15
	Bulk density (kg/m^3)		
No-tillage	1280(50)	1390(60)	1400(70)
Stubble mulch	1210(60)	1210(100)	1290(70)
Conventional	1060(40)	1170(90)	1370(80)

2.2.2 Experimental Methods

Three tillage practices included in the long-term field experiment are:

1. Conventional tillage (CT): Mouldboard ploughing to a depth of 25 cm as a primary tillage, followed by shallow tine cultivator as secondary tillage operations.

2. Stubble mulch tillage (ST): shallow tillage to a depth of 15 cm with a minimum soil inversion using cultivator sweeps.
3. No-tillage (NT): Chemical weed control with direct drilling.

Runoff studies were done on parts of plots of each of the tillage treatments. Simulated rainfall in combination with four levels of wheat (*Triticum aestivum* L.) residue cover, namely 0t/ha, 2t/ha, 4t/ha and 8t/ha was used. The experimental design used was similar to the Alemaya experiment, i.e. split plot design arrangement where tillage treatments were as main plots and the levels of residue cover as sub-plots. All twelve treatment combinations were replicated twice.

The stubble mulch and conventional tillage practices were freshly tilled and ploughed respectively just few days before the start of the experiment. The no-tillage plots were sprayed with chemical herbicide (glyphosate) in order to prevent the growing of weeds.

The simulator used in this experiment was an oscillating type with intermittent application of water with a veejet nozzle as described by Claassens & van der Watt (1993). The kinetic energy of the simulated rain was similar to that of natural rain. The application rate of the simulator can be varied from 4 mm/hr to 192 mm/hr. For the constant rate studies an application rate of 60 mm/hr was selected because in many other rainfall simulator studies an intensity of 64 mm/hr was commonly used (Flanagan *et al.*, 1988). The chosen intensity was sufficient to generate runoff.

In the variable rainfall intensity experiment, which was conducted on the stubble mulch and conventional tillage practices, the intensities were 40, 60, 90, and 122 mm/hr. Each of the rainfall intensities was allowed to run for 20 minutes. The sequence of the simulation was from the lower (40 mm/hr) to the higher intensity (122 mm/hr) and then to the lower intensity (40 mm/hr), with a peak intensity at 122 mm/hr. The rainfall intensity, sequence of application and the duration of each application are given in Table 2.7.

Table 2.7. Rainfall intensity, sequence and duration of application

Sequence	Rainfall intensity (mm/hr)	Duration (min)
1	40	20
2	60	20
3	90	20
4	122	20
5	90	20
6	60	20
7	40	20

The runoff area under the simulator was one by one meter wide consisting of 100 x 12 cm steel walls welded together at the corners, and a collection gully connected to a plastic hose for collecting the runoff water in a container placed below ground level outside the rainfall simulator housing.

2.2.3 Measurements

Runoff

Runoff volumes were collected in a graduated bucket, which was placed below ground level at one corner of the metallic frame. The runoff rate was obtained by recording the time required for one liter of runoff to be generated. The recording of runoff amount was continued until a constant runoff rate was obtained. At this point it was assumed that the infiltration rate reached its final stage.

Soil Loss

The soil loss during the simulation was calculated from the sediment concentration of 500 cm^3 runoff samples, which were taken at constant intervals. The samples were taken to the laboratory and placed in an oven to dry after which it was weighed to determine the soil loss.

Infiltration

Measurement of infiltration rate at this experimental site was conducted using the rainfall simulator and double ring infiltrometer. For the rainfall simulation method, the infiltration rate at any given time was calculated as the difference between the rainfall rate and the runoff rate (Claassens & van der Watt, 1993). This method represents well the infiltration under natural rainfall conditions. It was conducted on all treatments with two replications.

The other method is the well-known ponding method using a double-ring infiltrometer. The double ring infiltrometer had dimensions of 40 cm diameter for the inner ring and 60 cm for the outer ring. Both rings were inserted into the soil to a depth of 5 cm. Water depth in both rings were allowed to remain constant at 2 cm above the soil surface. Measurements were done as the time taken for one liter of water to infiltrate from within the inner ring. The measurements were conducted only on the bare plots of the three tillage practices.

Bulk density

The measurement of bulk density from this experimental site was conducted in the same manner as at the Alemaya experimental site. Samples were taken at three places in each tillage practice for from the top 15 cm of the soil at three depths, namely 0-5 cm, 5-10 cm, and 10-15 cm with a core sampler having a diameter of 5 cm and height of 5 cm.

2.3 Methods of Statistical Analysis

Statistical analysis of the data was conducted using analysis of variance procedures (Steel *et al.*, 1997; MSTATC Software). Significance levels of $P \leq 0.05$ and $P \leq 0.01$ were used based on the variability associated with the type of measurements. Empirical relationships of the parameters were derived using regression procedures. Some of the values were fitted to physically based models. In addition to statistical methods, graphical and tabular representations were used to illustrate and compare between different variables of the treatments. The Willmott (1982) D-index of agreement was used for testing the model performance and the agreement between measured and predicted values.

CHAPTER 3

EFFECT OF TILLAGE AND RESIDUE COVER ON INFILTRATION AND RUNOFF UNDER SIMULATED RAINFALL (UFS EXPERIMENTAL SITE)

3.1 Introduction

There has been an increasing emphasis on maintaining crop residues on agricultural fields to protect the soil surface against erosion and to increase water storage during fallow periods (Foley *et al.*, 1991, Norwood, 1994, Unger & Jones, 1981, Unger, 1992). Tillage practices developed to achieve this include reduced tillage, zero or no-tillage and stubble mulching. Depending on the process that control infiltration, the response of soil infiltration to changes in tillage practice may vary.

Rainfall runoff often results from the formation of a soil surface crust or seal, which is formed by the combined action of the kinetic energy of the falling raindrops and the dispersive effect of rainwater that is devoid of electrolytes (Agassi *et al.*, 1981). Disintegration of aggregates and reorientation of soil particles at the soil surface result in a crust, which is the main factor causing infiltration to decrease under natural rainfall (Unger, 1992). The soil properties related to infiltration capacity can be characterized by using infiltration curves as shown in Figure 3.1 (Morin & Benyamini, 1977). The hatched area in Figure 3.1 represents the amount of rainfall that infiltrates into the soil, which can constitute only part of the total rainfall reaching the ground surface.

Unger (1992) indicated that tillage might increase infiltration when it loosens the surface crust, disrupts dense soil layers, or provides surface depressions for temporary storage of water. Tillage may also decrease infiltration when it smoothes the surface, disrupts aggregates, eliminate surface residues or causes compaction. Crop residues retained on or near the soil surface usually enhance infiltration by dissipating the raindrop energy, thus minimizing aggregate dispersion and surface sealing, and by retarding surface water flow, thus providing more time for infiltration.

Infiltration is also affected by the rainfall intensity. Naturally, larger rainfall intensities result in higher infiltration rates during the early part of the process. However, high infiltration rates saturate the surface layer of the soil sooner, and consequently, the decline in the infiltrability occurs earlier. On the other hand the final infiltration rate will remain nearly constant (Akan &Yen, 1983). The effect of rain intensity on infiltration rate is shown in Figure 3.2. The Figure shows infiltration rate as function of time at different rainfall intensities ranging from 60 mm/hr to 120 mm/hr.

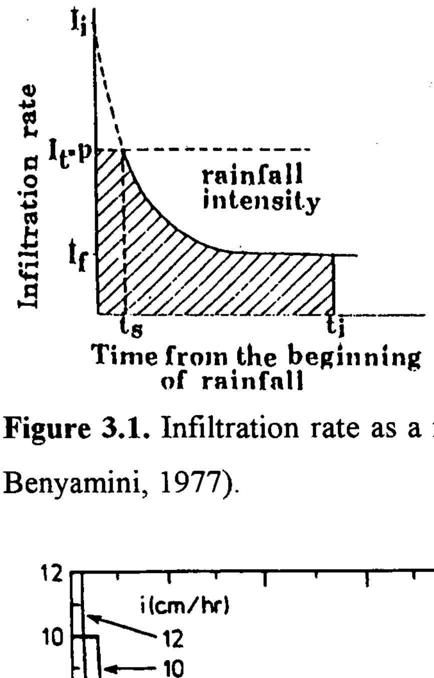


Figure 3.1. Infiltration rate as a function of time during a rainfall storm (after Morin & Benyamini, 1977).

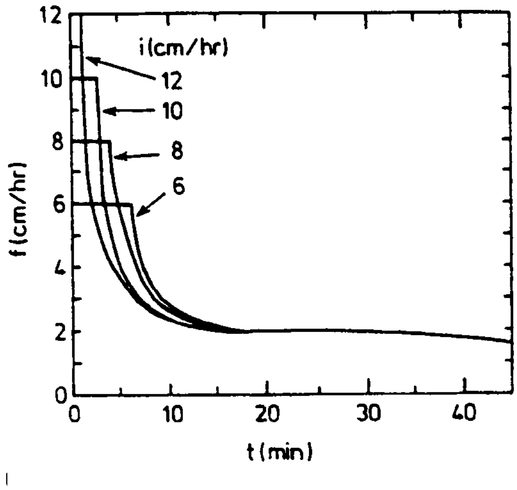


Figure 3.2. Effect of rainfall intensity on infiltration (after Akan &Yen, 1983).

3.2 Results and Discussion

3.2.1 Infiltration and Runoff under Simulated Rainfall with a Constant Intensity

Infiltration and runoff rates were determined for the three tillage practices; no-tillage (NT), stubble mulch tillage (ST) and conventional tillage (CT), each with four levels of residue cover using simulated rainfall with a constant intensity of 60 mm/hour (see Chapter 2, section 2.2.1). This experiment was conducted on plots of a long-term tillage experiment. It should be noted that the different amounts of wheat residue were applied on the surface of freshly ploughed (25 cm depth) soil on the conventional tillage treatments. On the stubble mulch treatments the soil was tilled to a depth of 15 cm with sweeps after which the old crop residue was removed and replaced with the required amounts of fresh residue. On the no-till plots also the old crop residue was removed and replaced with the different amounts of fresh residue cover.

The infiltration results were treated in two parts. The first section contains the infiltration results for the three tillage treatments without surface cover in order to compare the effect of tillage alone. The effect of residue cover on infiltration for the three tillage systems will be discussed in the second part.

3.2.1.1 Infiltration on three tillage practices under bare soil conditions

Firstly, the bare plots of the three tillage systems were compared separately to determine the effect of depth of tillage on the initial and final infiltration rates. The data was fitted to the equation of Morin & Benyamini (1977) (Equation 3.1) using the least square optimization technique.

$$I_t = (I_i - I_f)e^{-\gamma p t} + I_f \quad \text{..........} [3.1]$$

Where,

I_t = Infiltration rate (mm/hr)

I_i = Initial infiltration rate (mm/hr)

I_f = Final infiltration rate (mm/hr)

P = Rainfall intensity (mm/hr)

t = Time (hr)

γ = Crust coefficient

The final infiltration rates for each of the tillage systems were determined after the runoff rate became constant. The two unknown model parameters, namely the initial infiltration rate and the crust coefficient, γ, were estimated using the least square optimization technique. The results are presented in Figure 3.3 and Table 3.1.

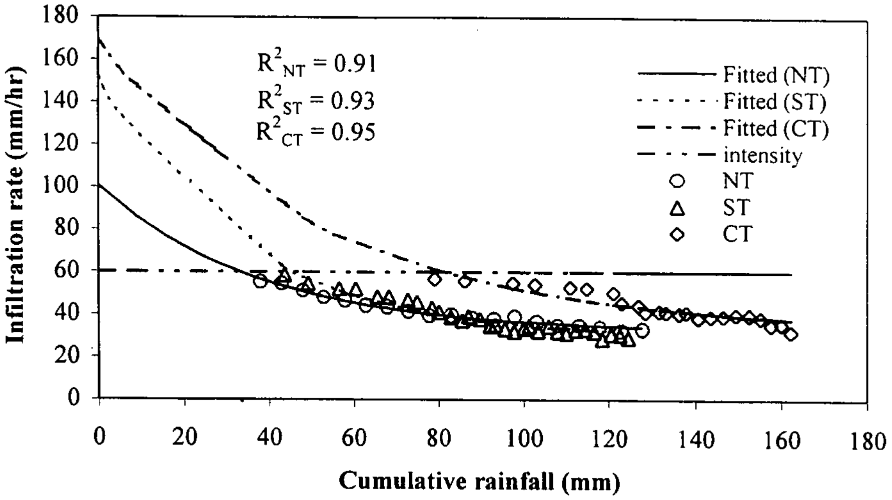


Figure 3.3. Infiltration rates as a function of cumulative rainfall on the bare plots of three tillage practices (depths) fitted to the equation of Morin & Benyamini (1977).

Table 3.1. Infiltration parameters of Morin & Benyamini model for three tillage practices (depths) under bare soil conditions

Tillage types	Tillage depth (mm)	Initial infiltration rate (I_i, mm/hr)	Final infiltration rate (I_f, mm/hr)	Crust coefficient, γ	R^2
NT	0	100.9	32	0.03	0.91
ST	150	151.3	29	0.03	0.93
CT	250	169.1	32	0.02	0.95

It is clear from Table 3.1 that under bare surface conditions the tilled treatments namely conventional and stubble mulch tillage had, as can be expected, higher initial infiltration rates than no-tillage.

As indicated in Figure 3.4 the predicted initial infiltration rates increased with increasing depth of primary tillage. The final infiltration rates did not differ significantly among the tillage treatments (Table 3.1). Mohamoud *et al.* (1990b) also reported, while comparing no-tillage with soil disturbing tillage practices, with surface residue removed, that runoff occurred sooner (lower initial infiltration rate) on no-till because of rapid filling of surface pores and clogging of pores by raindrop splash. Runoff occurred later (higher initial infiltration rate) for tilled conditions because of higher macro porosity, greater surface roughness and depression storage. Final runoff and infiltration rates were about the same for no-till and tilled treatments because of the same surface sealing properties.

Because of the increased porosity in the plow layer, infiltration rates in a newly tilled soil are initially high (Edwards, 1982). Although newly tilled soils tend to have rapid initial infiltration, crusting of the soil surface due to raindrop impact decreases the rate of water intake (Griffith *et al.*, 1986).

In another report, Unger (1992) showed, on a clay loam soil, higher initial infiltration rates for about 15-cm depth sweep tillage (284.5 mm/hr) after residues were removed than no-tillage (38.4 mm/hr) with residues left on the field, where values were derived by curve fitting.

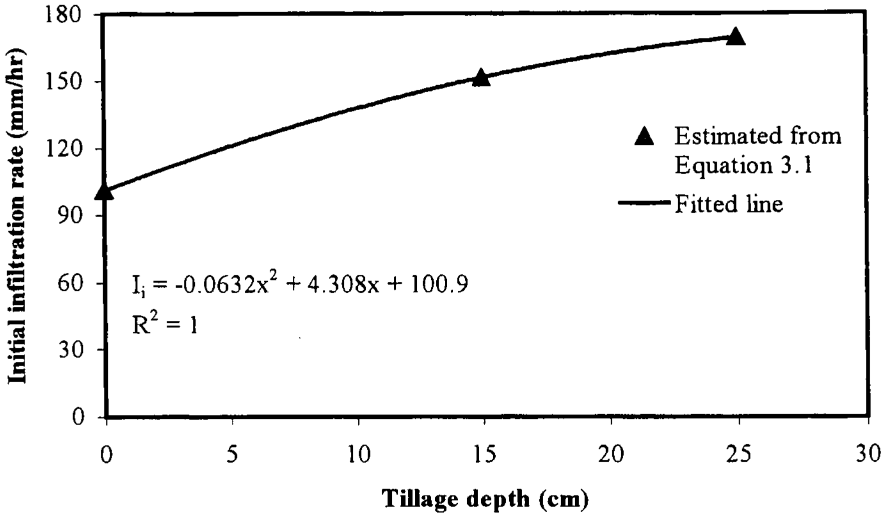


Figure 3.4. Initial infiltration rates (I_i) on bare plots as a function of tillage depth.

The difference in infiltration rate curves for the three tillage practices, under bare soil conditions (Figure 3.3), has shown that tillage on this particular soil type will result in higher rainfall infiltration during the early stage of infiltration. However, over a longer duration of rainfall it is the soil surface condition, i.e. the crust formation that controls rainfall infiltration and the type of tillage practice has little effect. The implication is that less runoff will occur from tilled fields after planting when there is insufficient crop cover, and higher runoff is expected to occur from bare no-tillage fields. But in either case, sooner or later, after a continuous rainfall in excess of 60 or 80 mm, the soil surface crust will be the factor determining the amount of runoff. There is a need to have the soil covered with residues until the plant takes the role of protecting the soil or regular loosening of the soil surface by tillage will be essential. The objective with the second part of this investigation was to determine the amount of surface residue required to reduce surface crusting on this soil.

3.2.1.2 Infiltration on different tillage practices and residue covers

Infiltration rates, plotted as a function of cumulative rainfall for the three tillage treatments at the four levels of residue cover, are presented in Figure 3.5. The four levels were 0t/ha (R0), 2t/ha (R1), 4t/ha (R2) and 8t/ha (R3). More information on the experimental procedure is given in Chapter 2, Section 2.2.1. A clear interaction between tillage practice and levels of residue cover can be observed in Figure 3.5. For instance on conventional tillage (Figure 3.5c) even the lowest level of residue cover (2t/ha) prevented crusting and the infiltration remained similar to the rainfall application rate of 58 mm/h, for more than three hours or 180 mm of rainfall. The bare treatment reached a final infiltration rate of 42.4 mm/hr and runoff commenced after 15 mm cumulative rain.

The no-tillage and stubble mulch tillage treatments have, however, shown a clear difference between the different amounts of residue cover as shown in Figure 3.5 (a) and (b). The cumulative rain where runoff started is indicated by arrows. For no-tillage, the plot with the highest rate of residue cover (8t/ha) started to generate runoff after about 60 mm of rainfall (one hour) whereas the one with 4t/ha has started to produce runoff after 30 mm of rainfall (30 minutes). The plots with 0t/ha and 2t/ha) started at more or less the same time, after 20 mm of rainfall (20 minutes).

The data is also illustrated in the form of a bar chart in Figure 3.6. The final or steady infiltration rates for the three tillage treatments varied according to the type of tillage and the amount of residue cover. The final infiltration rates for the three tillage systems under bare soil conditions were 38.6 mm/hr, 36.7 mm/hr and 45.5 mm/hr for no-tillage, stubble mulch and conventional tillage receptively. All residue-covered plots for the conventionally ploughed plots with added residue had higher final infiltration rates, ranging from 58 mm/hr to 58.6 mm/hr. The no-tillage plots covered with 4 and 8t/ha residue were both 50.1 mm/hr.

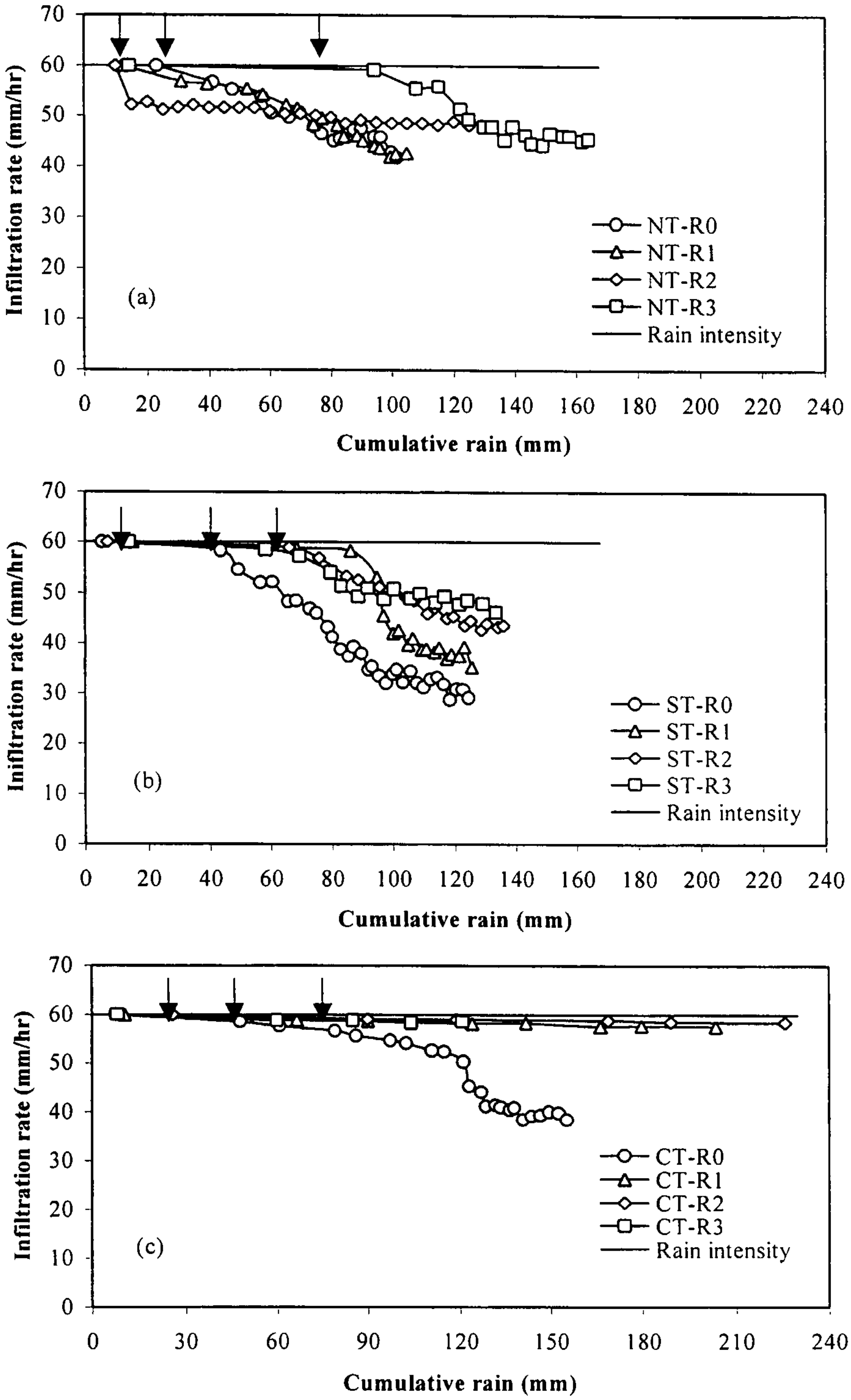


Figure 3.5. Infiltration as a function of cumulative rain on three tillage practices at four levels of residue cover for (a) No-tillage, (b) Stubble mulch tillage and (c) Conventional tillage practices.

The final infiltration rates increased linearly with an increase in residue amount for all the tillage treatments. This is shown in Figure 3.7 where the final infiltration rates were plotted against the levels of residue cover, expressed as percentage residue cover. For all three tillage practices it was found that there were strong linear relationships, with R^2 = 0.89, 0.86 and 0.92 for no-tillage, stubble mulch, and conventional tillage respectively, between the percentage residue cover and final infiltration rate. The linear relationships for both the no-tillage and stubble mulch lie more or less on the same line, with little deviation at the lower rates of residue cover.

The linear relationship between the final infiltration rate and the percentage residue cover is found to be much stronger when the mean final infiltration rate of the tillage treatments is plotted against the percentage residue cover. This strong linear relationship, (R^2 = 0.99) showed that there was a steady increase of 0.16 mm/h with each 1% increase in residue cover (Figure 3.8). Loch (2000) reported a similar linear relationship between the final infiltration rate and percentage surface vegetative cover.

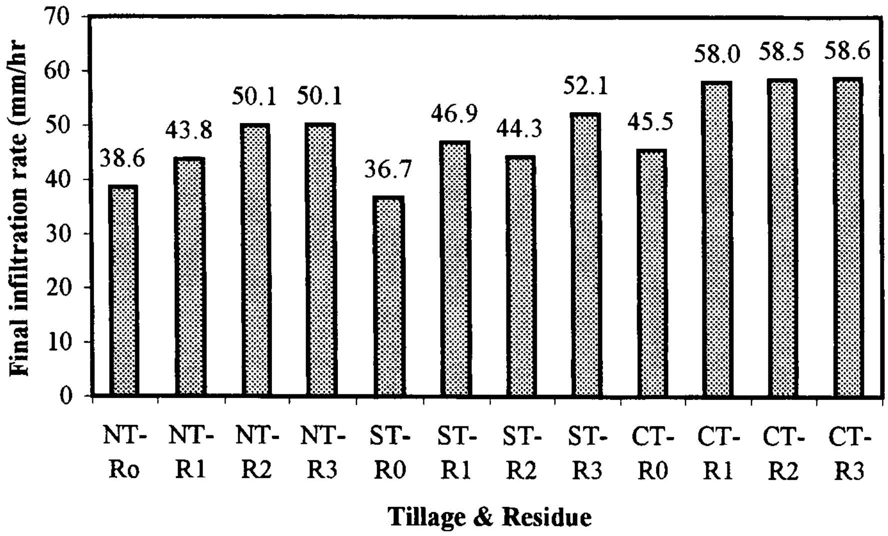


Figure 3.6. Final infiltration rates on three tillage practices with four levels of residue cover: NT = No-tillage, ST = Stubble mulch tillage, CT = Conventional tillage and four levels of residue cover: R0 = No residue, R1 = 2t/ha, R2 = 4t/ha and R3 = 8t/ha of wheat residue.

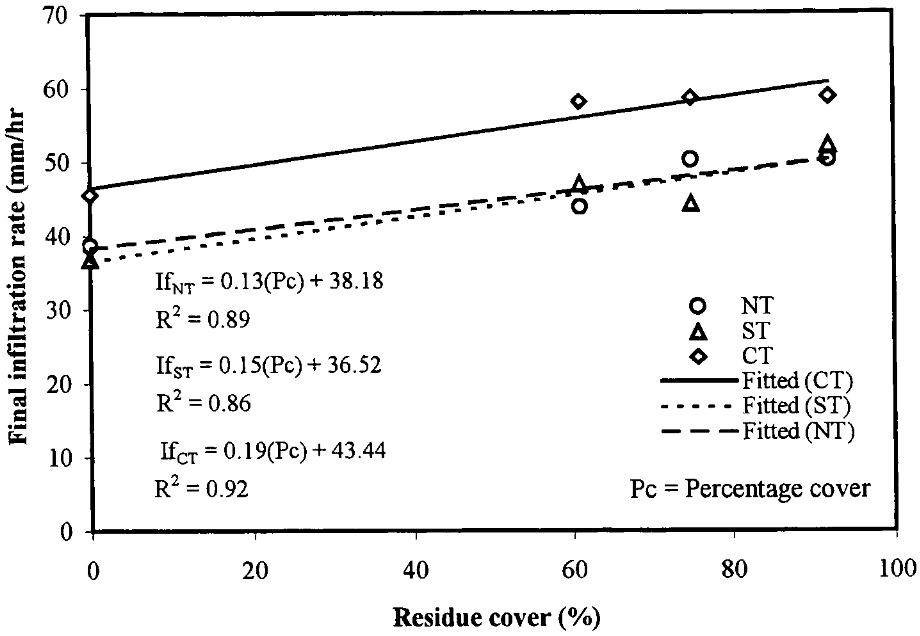


Figure 3.7. Relationships between the percentage residue cover and final infiltration rate for three tillage practices.

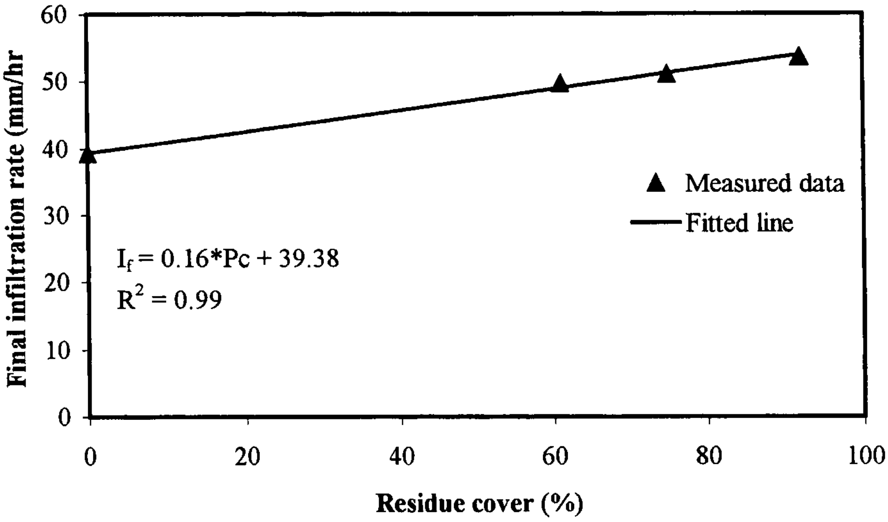


Figure 3.8. Mean final infiltration rate (I_f) as a function of percentage residue cover (Pc).

An analysis of variance was conducted to separate the effects of tillage and residue cover on final infiltration rates. The result of the analyses showed that tillage had no significant effect on final infiltration rate, whereas the residue cover effect have been significant at

5% probability level. The combined average final infiltration rates for all tillage practices across all rates of residue cover were 45.7 mm/hr, 45.0 mm/hr, and 54.4 mm/hr for no-tillage, stubble mulch, and conventional respectively. No-tillage and stubble mulch had similar final infiltration rates whereas the conventional had a higher rate.

A statistical analysis of the effect of residue cover revealed that the final infiltration rates on the bare plots have been significantly different from residue covered plots (Table 3.2) at 5% probability level. It can be seen from Table 3.2 that all residue-covered plots had similar final infiltration rates, but were significantly higher than the bare plots. These results are supported by findings of several researchers. Morin & Benyamini (1977) reported for a sandy soil, with 85% sand and 13% clay, that the final infiltration rates of the mulched soil was seven times higher than for bare soil. Yuxia Li *et al.* (2001) also reported that the final infiltration rate on a black clay soil type increased from 48 mm/hr for the bare soil to 102 mm/hr at 80% residue cover. Kouyate *et al.* (1988), cited by Papendick *et al.* (1990), reported that the final infiltration rate from a sandy soil with full residue covered was double the bare soil value. In another report, Freebrain & Gupta (1990) showed that soil cover and tillage frequency were the most important factors controlling infiltration rate. Bradford & Huang (1994) also reported that removing the residue cover greatly decreased the final infiltration rate, regardless of the tillage treatment.

Table 3.2. Mean final infiltration rates (I_f) at four levels of residue cover

Residue cover (t/ha)	Percentage cover (%)	Final infiltration rate (mm/hr)*
0	0	39.22^b
2	62	49.55^a
4	76	50.97^a
8	92	53.58^a
LSD		7.65

(*): Numbers in the same column followed by the same letter(s) are not significantly different at 5% probability level.

3.2.1.3 Infiltration as measured by the double ring infiltrometer

The infiltration rate was also measured with a double ring infiltrometer on the three tillage systems under bare soil conditions to compare the final infiltration rates obtained under conditions of simulated rainfall with ponding conditions. The measurements were conducted under dry and wet soil conditions. Both the two tillage practices, stubble mulch and conventional were respectively freshly sweep and mouldboard ploughed a few days before the measurements were taken. The results are presented in Figures 3.9 (a, b, and c).

The measured infiltration data were fitted to the Philip-equation using the least square optimization technique and the coefficient of determination showed that the data fitted well. The three curves illustrate that the depth of primary tillage (type of tillage) affected both the soil sorptivity and the final infiltration rate. The sorptivity for the three tillage systems as obtained from the fitted Philip-equations were 78.32, 112.20, 217.86 mm for no-tillage, stubble mulch and conventional respectively. Under this dry run condition the initial infiltration rate was higher for conventional than the rates for stubble mulch and no-tillage.

The final infiltration rates were derived from Figure 3.9. They were 40.9 mm/hr, 81.1 mm/hr, and 156.7 mm/hr for NT, ST and CT respectively. The reason for the high final infiltration rates on ST and CT is due to the fact that plots were freshly plowed, loosening the soil to depths of 15 and 25 cm respectively. The NT treatment, however, had a final infiltration rate close to the one obtained with rainfall simulation (Table 3.3). The final infiltration rate on the CT treatment was nearly four times higher than the NT treatment and ST treatment is twice as much as higher. The relationship between depth of tillage and the final infiltration rate is given in Figure 3.10.

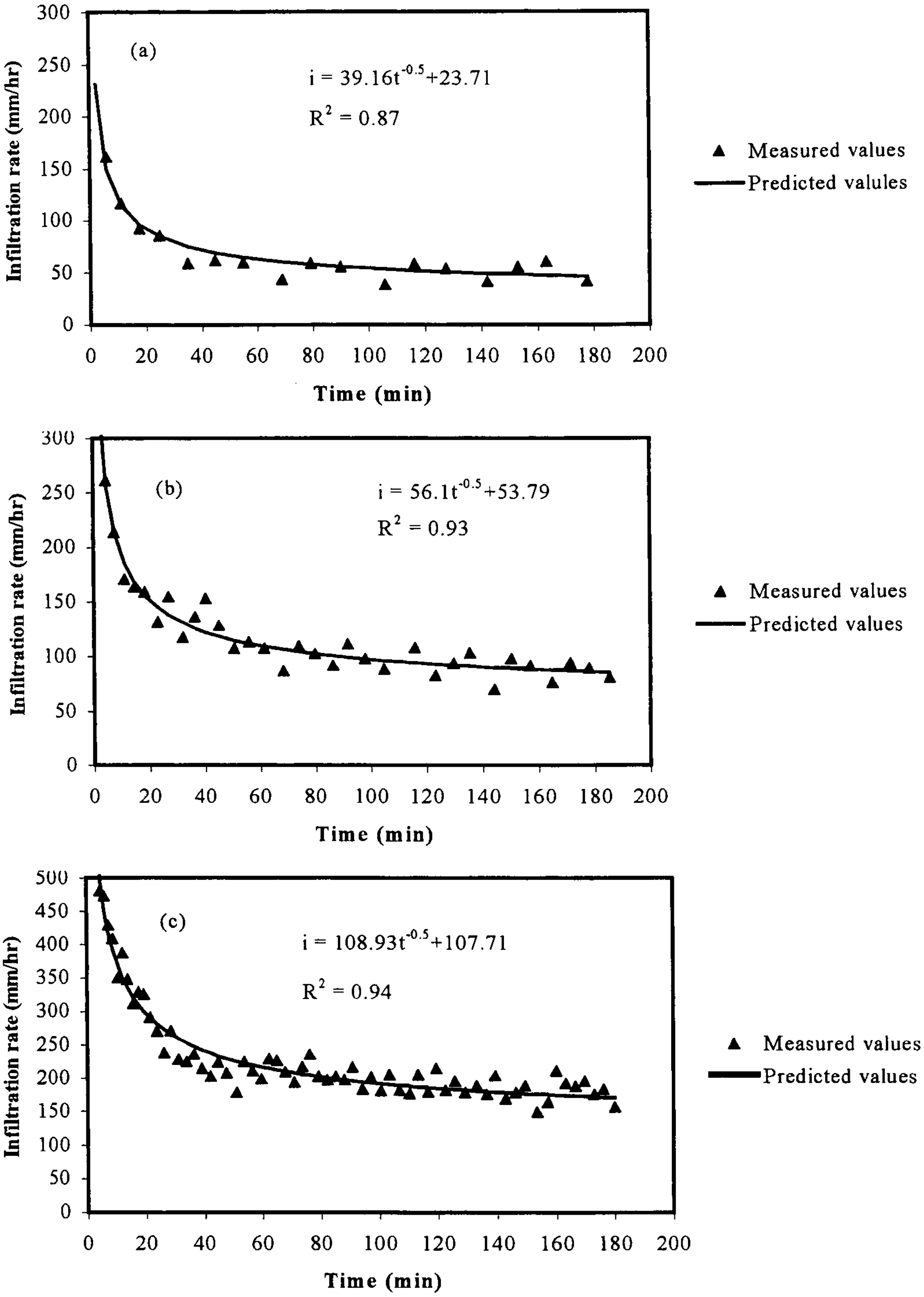


Figure 3.9. Infiltration rates (dry soil condition) as measured with the double-ring infiltrometer on three tillage practices under bare soil condition for (a) No-tillage, (b) Stubble mulch, and (c) Conventional tillage.

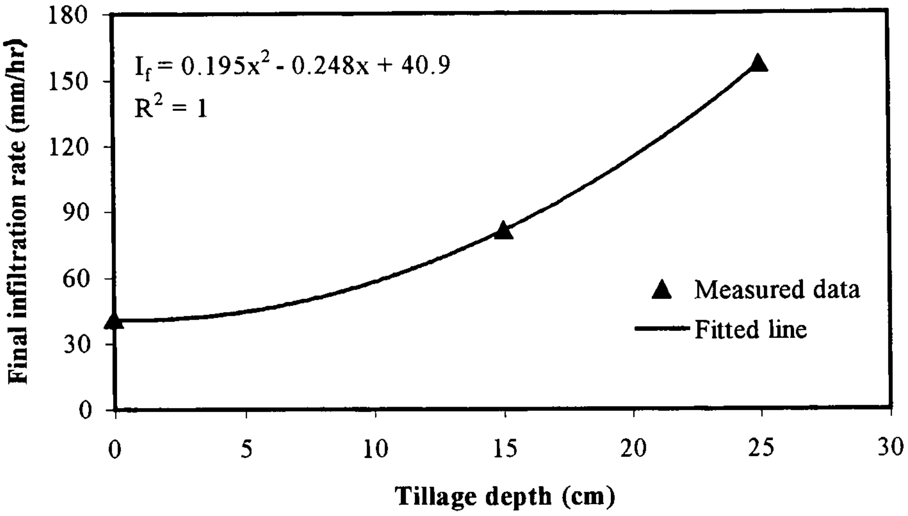


Figure 3.10. Increase in final infiltration rate with depth of tillage.

The cumulative infiltrations required to reach the final infiltration rate were 180 mm, 360 mm and 660 mm for the NT, ST, and CT treatments respectively. The amount of cumulative infiltration required for the infiltration rate to reach its steady state doubled on ST (360 mm) and nearly quadrupled on CT (660 mm) as compared to the NT (180 mm) treatment (Table 3.3).

Table 3.3. Final infiltration rate (mm/hr) and the corresponding cumulative infiltration for three tillage practices measured under rainfall simulation and with the double ring infiltrometer

	Infiltrometer method (I)		Simulator method (S)		Ratio
Tillage	Infiltration rate (mm/hr)	Cumulative Infiltration (mm)	Infiltration rate (mm/hr)	Cumulative Infiltration (mm)	I:S
NT	40.9	180	38.6	98.7	1.1
ST	81.1	360	36.7	115.3	2.2
CT	156.7	660	42.4	291.9	3.7

The ratios between the final infiltration rates with the infiltrometer and simulator methods show that the highest ratio (3.7) was obtained for CT and the lowest (1.0) for the NT treatment. Sidiras & Roth (1987) compared simulator and double ring infiltration rates and reported an average ratio of 5.6 for CT and 2.6 for NT on a clayey type of soil. This shows that under simulated rainfall conditions, the effect of tillage on the infiltration process lasted only during the initial infiltration period, after which a crust started to form. Thereafter the surface crust controlled the infiltration process and tillage method played a lesser role. An analysis of variance showed that tillage had no statistically significant effect on final infiltration rate whereas residue cover had a significant effect (Table 3.2).

Measurements of infiltration with the double ring infiltrometer were also conducted on wet soils for only the NT and CT treatments and the results are shown in Figure 3.11. The final infiltration rates on the two tillage practices were 41.2 mm/hr and 39.8 mm/hr for CT and NT respectively. The infiltration data were fitted to the Philip- equation and strong coefficients of determinations were obtained (R^2 = 0.92 for NT and 0.94 for CT). Under the wet condition the final infiltration rates were almost similar. The decrease in infiltration rate was much more distinct and uniform than under the dry condition because of the lower sorptivity. The sorptivity, as given by the fitted Philip-equations (Figure 3.11), were 58.2 and 74.18 mm for NT and CT treatments, respectively.

3.2.1.4 Runoff from simulated rainfall with a constant intensity

The amounts of runoff produced from the three tillage treatments and four levels of residue cover were measured using the procedure described in Chapter 2, Section 2.2.3. The runoff from 100 mm of cumulative rainfall was used to compare the different tillage and residue treatments. The results are given in Table 3.4.

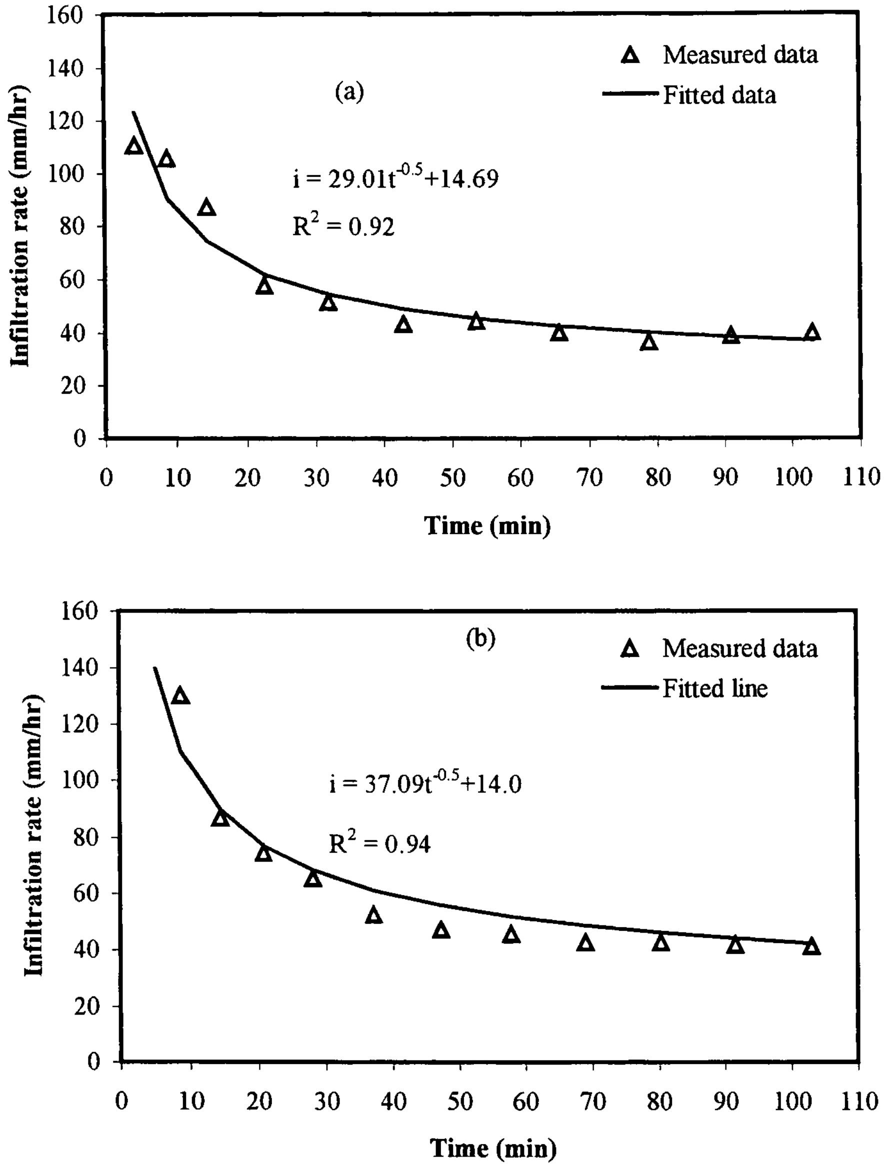


Figure 3.11. Infiltration rates (wet soil condition) as measured by double ring infiltrometer on two tillage practices for (a) No-tillage, and (b) Conventional tillage.

Table 3.4. Mean runoff (mm) from three tillage practices and four levels of residue cover at a cumulative rainfall of 100 mm

Residue rate (t/ha)	Tillage practices		
	No-tillage	Stubble mulch	Conventional
0	14.2	8.8	3.2
2	11.6	2.4	1.2
4	7.9	3.1	1.3
8	1.9	3.6	1.3

The results in Table 3.4 show that runoff decreased with an increase in the amount of residue cover and with the depth of tillage, i.e. from the no-tillage treatment to a maximum depth of 25 cm for conventional tillage.

An analysis of variance conducted on the effect of tillage treatments on runoff showed that the differences between tillage treatments were not significant at 5% probability level. However, significant differences have been observed for the four residue levels (0t/ha, 2t/ha, 4t/ha, and 8t/ha) at 5% probability level as indicated in Table 3.5. From Table 3.5, it can be seen that the runoff from the bare plots was significantly higher than from the covered plots at rates of 4t/ha and 8t/ha. However, differences among the three residue treatments have not been statistically significant.

The cumulative runoff was also plotted as a function of cumulative rainfall for the three tillage treatments and for each of the residue rates (Figures 3.12 (a), (b), and (c)). The Figures show that there is a non-linear relationship between cumulative runoff and cumulative rainfall that was fitted to a second-degree polynomial function for all treatments.

Table 3.5. Mean runoff amount (mm) and runoff coefficient, over the three tillage practices, from four residue rates during a single storm event at 60 mm/hr intensity

Residue rate (t/ha)	Residue cover (%)	Runoff (mm)*	Runoff coefficient (%)**
0	0	8.72^{a}	8.72
2	62	5.03^{ab}	5.03
4	76	4.08^{b}	4.08
8	92	2.25^{b}	2.25
LSD		4.21	

(*) Numbers in the same column followed by the same letter(s) are not significantly different at 5% probability level.

(**) Expressed as percentage runoff (mm) from 100 mm of cumulative rainfall.

Figure 3.12a indicates that a residue cover of 8t/ha with no-tillage delayed the onset of rapid runoff from 20 mm for the bare soil to 90 mm cumulative rainfall. For stubble mulching (Figure 3.12b) a 2t/ha residue cover was sufficient to delay the onset of rapid runoff from approximately 50 to 70 mm cumulative rainfall. A 2t/ha residue cover on the ploughed soil was sufficient to prevent runoff even after 200 mm cumulative rainfall (Figure 3.12c).

Graphical comparisons of the three tillage practices at the same rate of residue cover is presented in Figure 3.13 (a, b, c, and d). These Figures illustrate the interaction between tillage and level of residue cover. It was observed that the cumulative runoff for NT was higher than from ST and CT at the 0t/ha, 2t/ha and 4t/ha rates of residue cover. However, at a residue rate of 8t/ha the runoff curve for the ST treatment was higher than both the NT and CT treatments. In all the cases the cumulative runoff from the loose CT treatment was much lower than from the NT and ST treatments at all levels of residue cover.

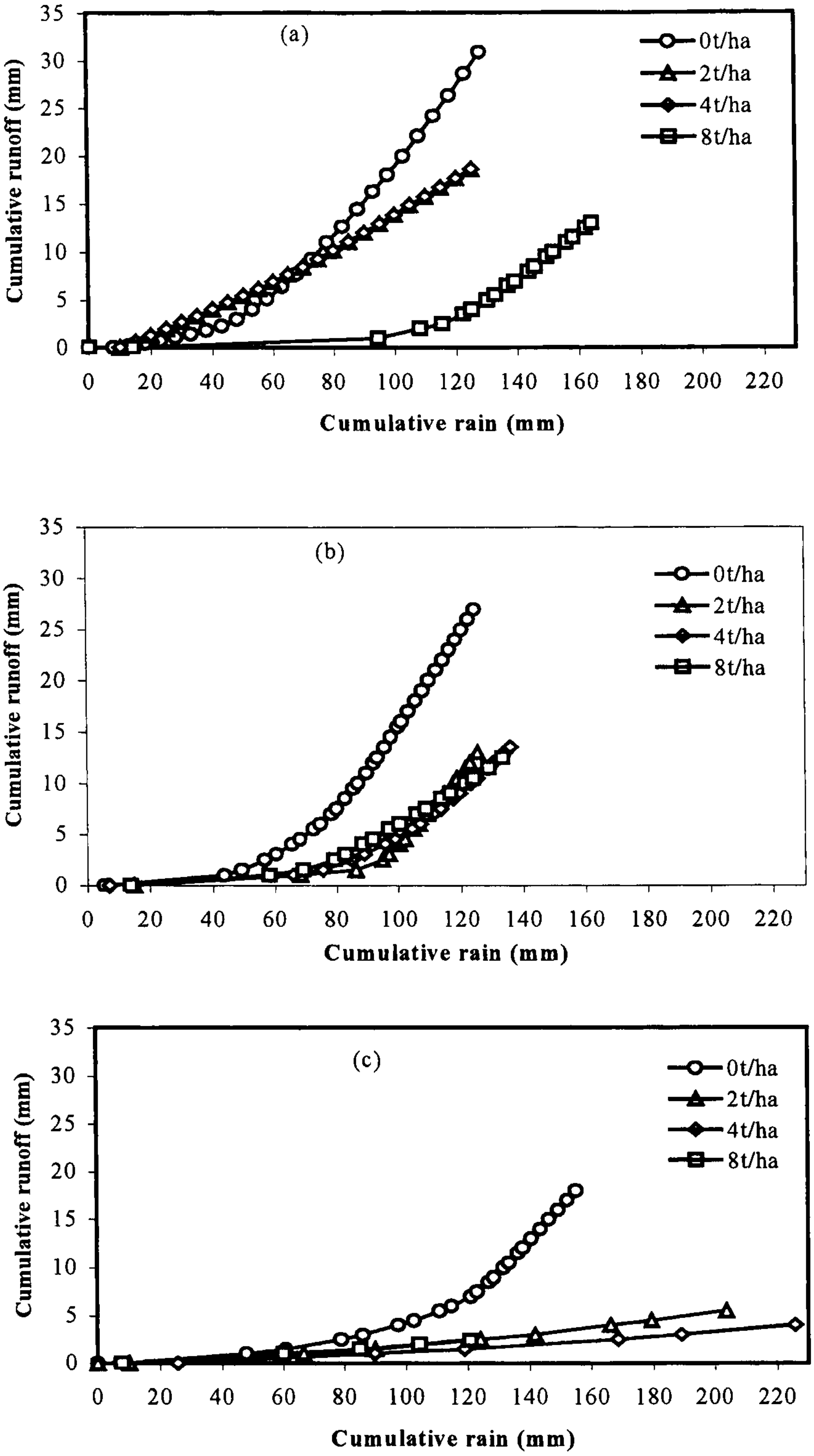


Figure 3.12. Relationships between cumulative runoff and rainfall at four rates of residue cover for (a) no-tillage, (b) stubble mulch tillage, and (c) conventional tillage.

The increase in the cumulative runoff from the bare conventional tillage plots (Figure 3.13a) has been very gradual until a cumulative rainfall of 120 mm, after which a sharp increase of runoff can be observed. This could be explained by the fact that the soil of the experimental site is sandy (about 90% sand) with no structure. Mouldboard ploughing, however, created a temporary structure and depression storage on the soil surface. The small aggregates created by mouldboard ploughing could withstand the energy of the falling raindrop impact and extend the time required for the formation of a crust on the soil the surface. The time at which a sharp increase of cumulative runoff, or a deflection point on the curve, occurred indicates when the soil surface crust began to decrease the infiltration rate and increase runoff. It is also obvious that a rate of 2t/ha residue cover absorbed sufficient raindrop energy to prevent crusting. In general, the hydrographs (Figures 3.12 and 3.13) demonstrate the substantial impact of both tillage and residue cover on runoff.

Bennie (2000) and Bennie & Hensley (2001) also reported, long term experiments showing that no-tillage systems were not beneficial compared to conventional and stubble mulch tillage in terms of both soil water conservation and crop yield on none and poorly structured soils.

The relationships between runoff and percentage residue cover, after 100 mm of simulated rain was applied, for the three tillage practices are shown in Figure 3.14. It can be seen from Figure 3.14 that there has been a negative relationship between the amount of runoff and percentage residue cover at a cumulative rainfall amount of 100 mm. The runoff amount decreased almost linearly with an increase in residue cover for all the tillage practices, up to 62% residue cover after which ST and CT remained constant. The runoff from NT decreased for residue covers higher than 62%. This negative linear relationship is shown to be much more prominent when the mean runoff over the three tillage practices is related to percentage residue cover (Figure 3.15).

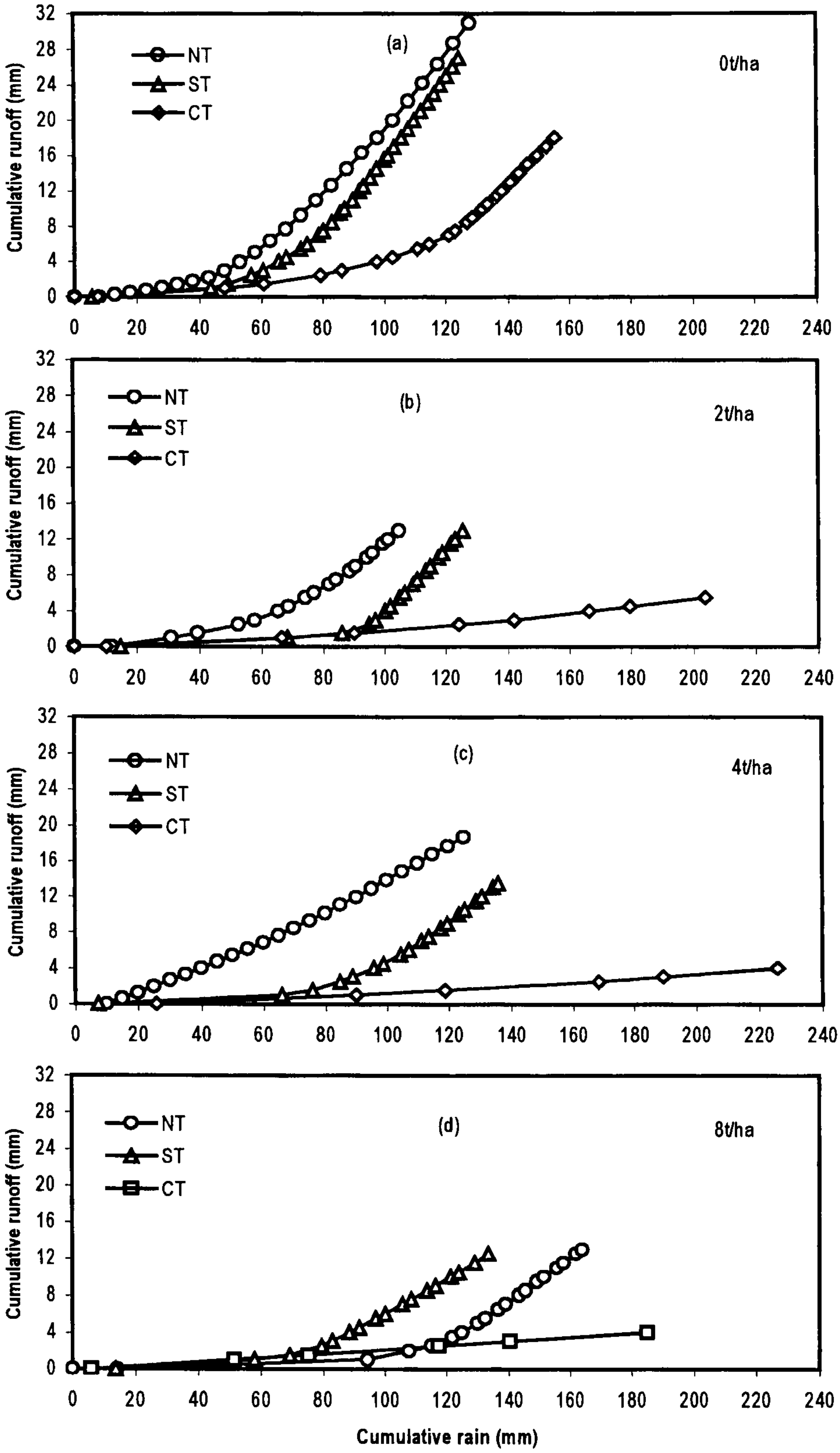


Figure 3.13. Cumulative runoff as a function of cumulative rainfall for three tillage practices at four levels of residue cover for residue rates of (a) 0t/ha, (b) 2t/ha, (c) 4t/ha and (d) 8t/ha.

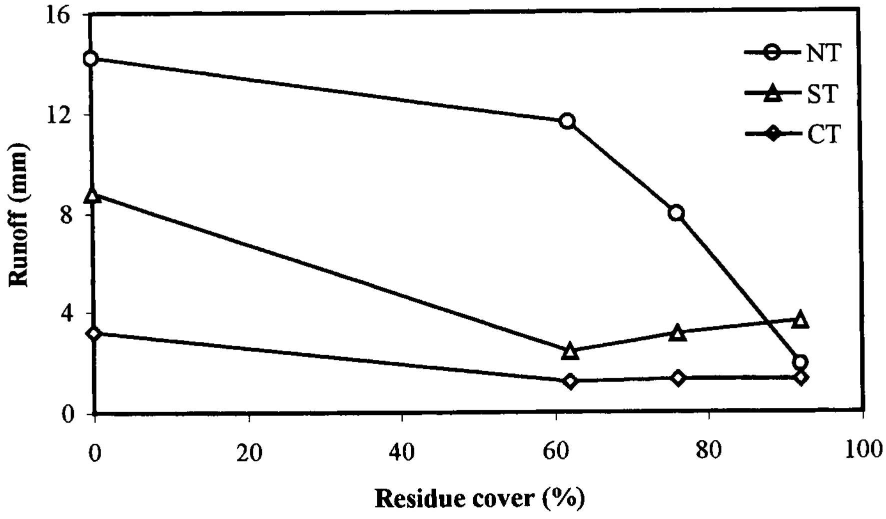


Figure 3.14. Mean runoff as a function of the percentage residue cover at a cumulative rainfall amount of 100 mm for three tillage practices.

The data from Table 3.5 has been fitted to a linear equation and is presented in Figure 3.15.

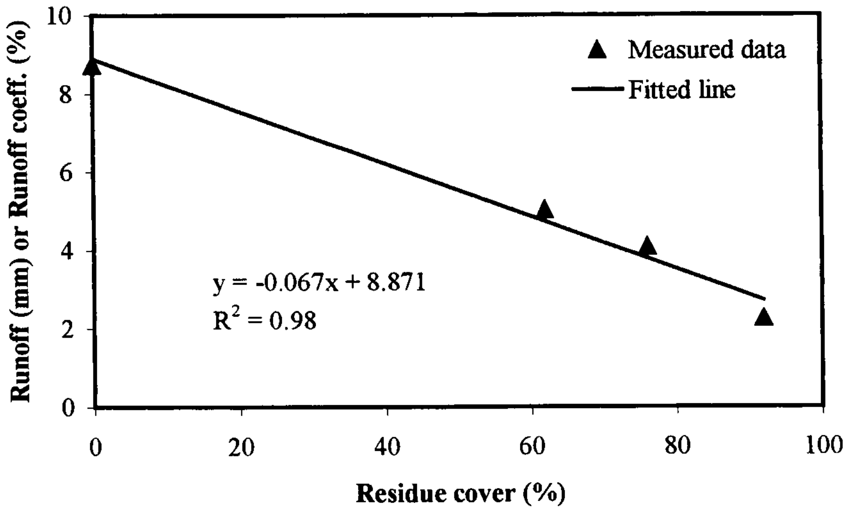


Figure 3.15. Mean runoff and runoff coefficient over the three tillage practices as a function of percentage residue cover at a cumulative rainfall of 100 mm.

The negative linear relationship between runoff and percentage residue cover shown in Figures 3.14 and 3.15 demonstrate that runoff amount for a given rainfall depends on surface cover conditions and that it decreased at a rate of 0.07 mm of runoff for every 1% increase in residue cover for this particular condition and an application intensity of 60 mm/hr.

When the depth of cultivation of these three tillage practices is taken into consideration (NT = 0 cm, ST = 15 cm, and CT = 25 cm), it was found that there was a decline in runoff with increasing tillage depth at the different levels of residue cover (Figure 3.16). The decline was linear for the treatments with residue covers of 0, 2 and 4t/ha. The treatments with 8t/ha residue cover, however, fitted to a second-degree polynomial function. The linear relationship was even much stronger (R^2 = 0.99) when the mean runoff over the four rates of residue cover was related to the depth of tillage as shown in Figure 3.16. The fitted equations for the average of the four rates of residue cover are given in Figure 3.16. The linear regression equation on the combined mean runoff as a function of tillage depth is given in Equation 3.2.

$$Q_u = -0.29x + 8.85 \qquad R^2 = 0.99 \ldots\ldots\ldots\ldots [3.2]$$

Where,

Q_u = Runoff amount (mm)

x = Tillage depth (cm)

From the relationship between runoff and tillage, a runoff tillage factor (RTF) can be introduced, similar to the runoff mulch factor. It is the ratio between runoff from tilled plots and runoff from the untilled plots. The runoff tillage factor could be used here as an indicator of the effectiveness of tillage operations in reducing runoff relative to the no-tillage practice for a type of soil at an experimental site. The result is given in Figure 3.17.

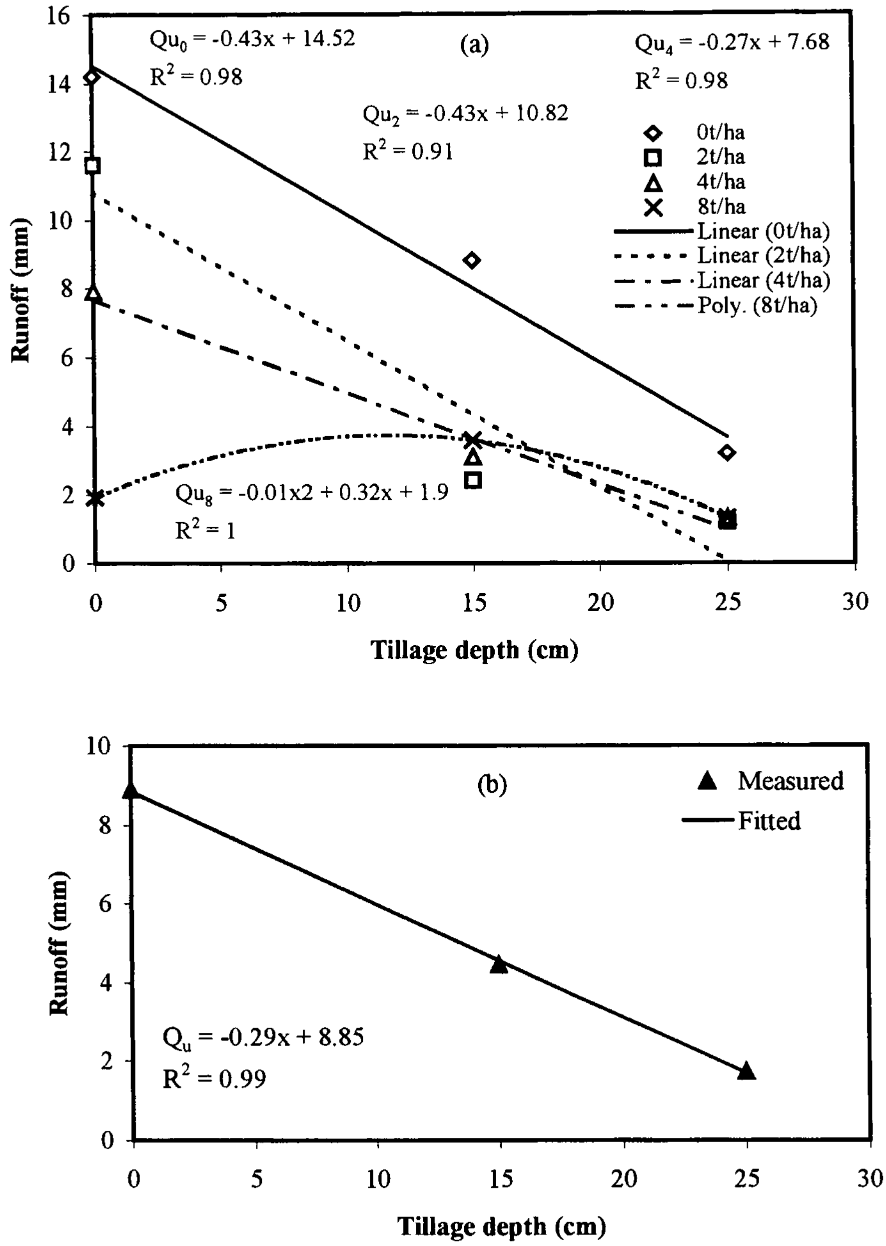


Figure 3.16. Mean runoff (mm) as a function of tillage depth for (a) four levels of residue cover and (b) for the mean over the four rates of residue cover, at a cumulative rainfall amount of 100 mm.

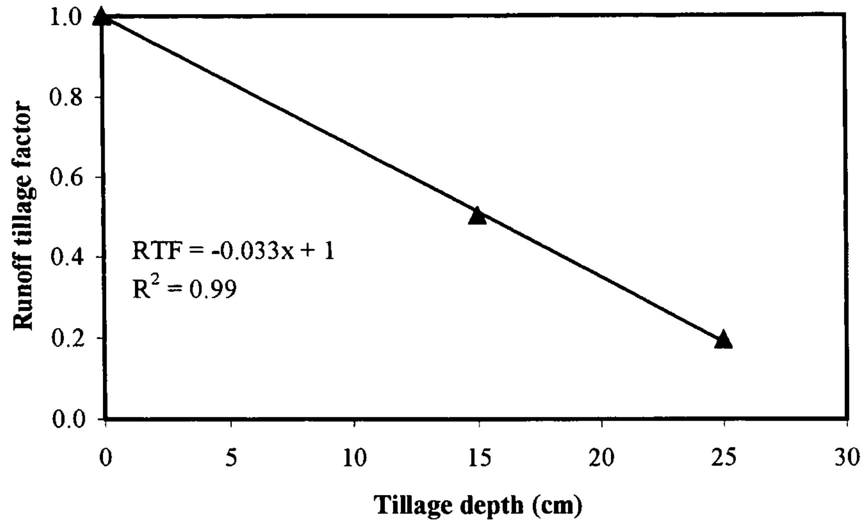


Figure 3.17. Relationships between the runoff tillage factor (RTF) and tillage depth.

Runoff Coefficient

The runoff coefficients (ratio of runoff amount to rainfall amount), which is also called runoff ratio (Kinnel, 1997), for the different residue covers at a cumulative rainfall amount of 100 mm are given in Table 3.5. It should be noted that runoff amount in Table 3.5 was obtained from a cumulative rainfall of 100 mm. For this reason, values of runoff amount and runoff coefficients were identical. It was observed that the runoff coefficients decreased steadily from 8.72% for 0t/ha residue rate to 2.25% for 8t/ha residue cover (Table 3.5). The data in Table 3.5 was fitted to a linear equation using a least square optimization technique (Equation 3.3 and Figure 3.15).

$$R_c = -0.07*P_c + 8.87, \qquad R^2 = 0.98 \ldots\ldots\ldots\ldots\ldots [3.3]$$

Where, R_c = Runoff coefficient (%)

P_c = Percent residue cover

Foster (1982) demonstrated the need to take runoff into account in obtaining the R-factor of the ULSE equation, which is defined as the product of storm rainfall energy (E) and the maximum 30-min rainfall intensity (I_{30}), for individual storms. Kinnel (1997) reported that the runoff ratio could be used to improve the R-factor in the empirical modeling of erosion by individual storms. The author proposed a combination of the runoff ratio and EI_{30} (R_cEI_{30}), which is reported to correlate better with the soil loss than the EI_{30} index alone.

The importance of including the runoff coefficient in calculating erosivity indexes can be illustrated using the results obtained in this study.

For tropical rain storms Hudson (1965), cited by Morgan (1995), gave the following equation for calculating the kinetic energy (KE) of a storm.

$$KE = 29.8 - (127.5/I) \quad \text{[3.4]}$$

Where, I is the rainfall intensity and KE is the unit kinetic energy per mm of rainfall (J/m^2/mm).

With the constant rainfall intensity of 60 mm/hr, the unit KE is equal to 27.68 J/m^2/mm. The total kinetic energy (E) for the cumulative rainfall amount of 100 mm is 2767.5 J/m^2. The EI_{30} (with I_{30} = 60 mm/hr) will then be equal to 166050 J mm/m^2/h. With the incorporation of the runoff ratio into the erosivity index we get values given in Table 3.6.

Table 3.6. Incorporation of runoff coefficient in calculating the erosivity indexes for a single storm at four levels of residue cover

Cover (%)	Runoff coefficient, *Rc*	EI_{30} (J mm m^{-2} h^{-1})	$RcEI_{30}$ (J mm m^{-2} h^{-1})
0	0.0872	166050	14479.56
62	0.0503	166050	8352.32
75	0.0408	166050	6774.84
92	0.0225	166050	3736.13

The reduction in runoff by the different rates of residue levels, relative to the runoff from the bare plots of the same tillage practice, is given in Table 3.7. The result shows that the reduction in runoff increased with increasing amounts of residue cover. The relationship between the percentage runoff reductions was fitted to an exponential function (R^2 = 0.99). The following regression equation was obtained from the data in Table 3.7.

$$PRR = 13.14e^{0.0188(Pc)}, \qquad R^2 = 0.99 \quad \text{[3.5]}$$

Where,

PRR = Percentage runoff reduction

Pc = Percentage residue cover

Table 3.7. Mean percentage runoff reduction by the different levels of residue cover relative to the runoff generated from a bare soil treatment at a cumulative rainfall of 100 mm

Residue (t/ha)	Percentage runoff reduction (%)
0	00.0
2	42.3
4	53.2
8	74.2

Runoff Mulch Factor

In order to quantify the effectiveness of residue cover in reducing runoff and soil loss as compared to bare fields, Wischmeier (1973), cited by Zuzel & Pikul (1993), proposed a mulch factor for combined rill and interrill erosion. This mulch factor was suggested to be proportional to an exponential function of percentage residue cover.

The runoff mulch factor (RMF) was obtained by dividing the total average amount of runoff at a specific residue cover by the runoff from bare soil for the same type of tillage. The relationship between the mean of the tillage practices runoff mulch factors and the corresponding residue surface covers is shown in Figure 3.18. The relationship indicates that the runoff mulch factor decreased exponentially with an increase in the percentage residue cover. The data was also fitted well to a linear equation. Gilley *et al.* (1986) obtained an inverse exponential relationship between runoff mulch factors and percentage surface cover for sorghum and soybean residues, which are given in Equations 3.6 and 3.7.

$$Sorghum\ RMF = e^{-0.031\,(Pc)},\quad R^2 = 0.938 \qquad [3.6]$$

$$Soybean\ RMF = e^{-0.019\,(Pc)},\quad R^2 = 0.885 \qquad [3.7]$$

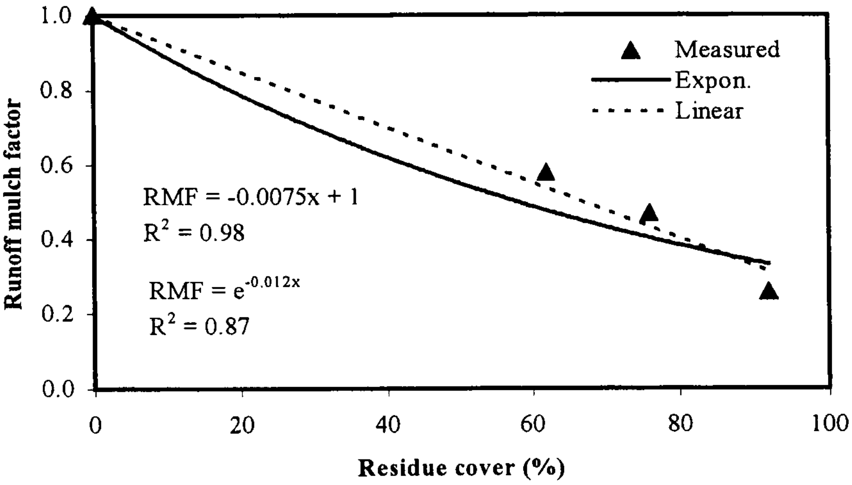


Figure 3.18. Mean runoff mulch factor (RMF) over the three tillage practices as a function of percentage residue cover.

3.2.2 Infiltration and Runoff under Simulated Rainfall with a Varying Intensity

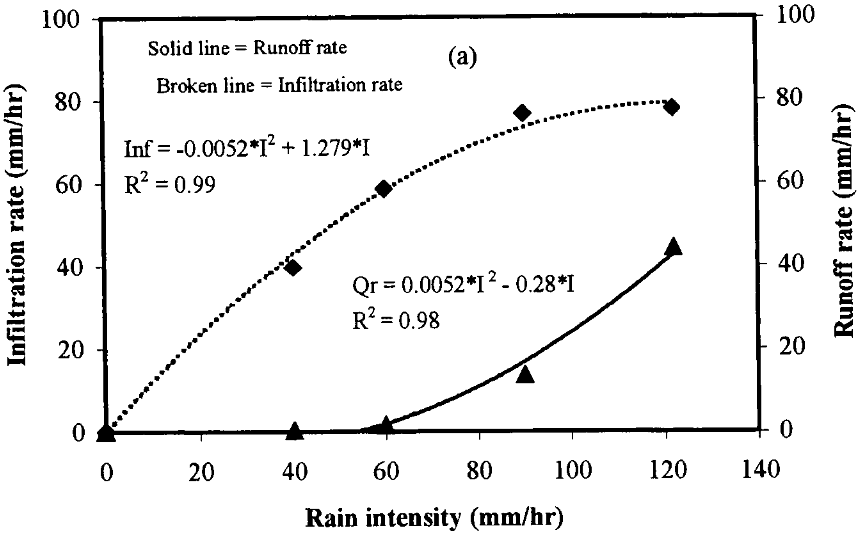
A relationship between rainfall intensity and sediment delivery rate from interrill areas is required for evaluating erosion and for designing effective erosion control practices (Meyer, 1981). An understanding of the effect of rainfall intensity on erosion processes makes it possible to quantify erosion rate with changes in rainfall intensity. The effect of rainfall intensity on erosion rate has been expressed as $E = aI^b$ (Meyer, 1981), where E is the erosion rate, and a and b are the coefficient and exponent of best fit, respectively. Meyer (1981) suggested that a fit to Equation 3.8 would give a good relationship for all, except clayey soils, because b equals 2.0 for most soils.

$$E = K_i I^2 \qquad [3.8]$$

Where, K_i is the relative erodibility parameter of the soil.

Two tillage practices, namely stubble mulch and conventional tillage were selected to determine the effect of rainfall intensity on the infiltration-runoff process. Four levels of rainfall intensity (40, 60, 90 and 122 mm/hr) were applied to each of the two tillage practices, each for duration of 20 minutes. The detail is discussed in Chapter 2, Section 2.2.2. The relationships between simulated rainfall intensity, and infiltration or runoff rates under these two tillage practices, without residue cover, are shown in Figure 3.19.

The infiltration and runoff rates for both tillage treatments were fitted to different equations showing the effect of tillage on the process. On stubble mulch tillage, runoff rate as well as infiltration rate was fitted to a second-degree polynomial function with strong coefficients of determination. In the case of conventional tillage runoff rate increased quadraticaly similar to the stubble mulch tillage while the infiltration rate increased linearly with an increase in the rainfall intensity. The reason for the differences between the infiltration rate – rainfall intensity curves for stubble mulch and conventional tillage could probably be ascribed to the effect of the depth of tillage. In the case of the stubble mulch tillage the infiltration rate increased with an increase in rainfall intensity but at a decreasing rate, in a parabolic form, indicating a possible decline or constant rate beyond a rainfall intensity of 120 mm/hr.



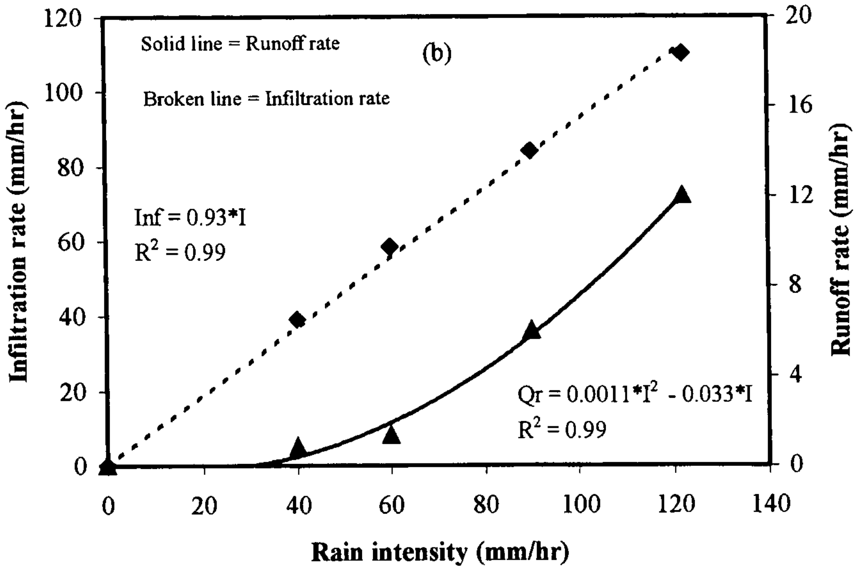


Figure 3.19. Infiltration (Inf) and runoff (Qr) rates as a function of rainfall intensity (I) on (a) stubble mulch and (b) conventional tillage practices without residue cover.

The results of the variation of infiltration, runoff rate and rainfall intensity with time, from the varying intensity simulated rainfall experiment, are presented in Figure 3.20. It can be observed from Figure 3.20 that runoff started after the rainfall rate exceeded the infiltration capacity of the soil. The cumulative infiltration and runoff represented by the area under the respective curves shows that stubble mulch tillage had a higher runoff (more than three times) compared with conventional tillage (Table 3.8). Figure 3.20 also shows that the selection of the time zero and the initial infiltration rate for use with simple infiltration equations becomes difficult if the rain intensity varies with time.

Moldenhauer *et al.* (1960), cited by Flanagan *et al.* (1988), reported a positive relationship between infiltration rates and rainfall intensities in their analysis of runoff from natural storms. Hawkins (1982), cited by Flanagan *et al.* (1988), also found similar increases in infiltration rates with rainfall intensity for several field data sets. Flanagan *et al.* (1988) reported that spatial variability of infiltration rates over the plots could cause this uncharacteristic behavior in measured infiltration rates, i.e. areas having higher infiltration rates would produce runoff only when the rainfall intensity is sufficiently high, while areas having lower infiltration rates would produce runoff earlier at low rainfall intensities.

Table 3.8. Average cumulative infiltration and runoff on two tillage practices under varying rainfall intensity

Tillage	Rain (mm)	Infiltration (mm)	Runoff (mm)
Stubble mulch	167.3	123.7	43.6
Conventional	167.3	155.5	11.8

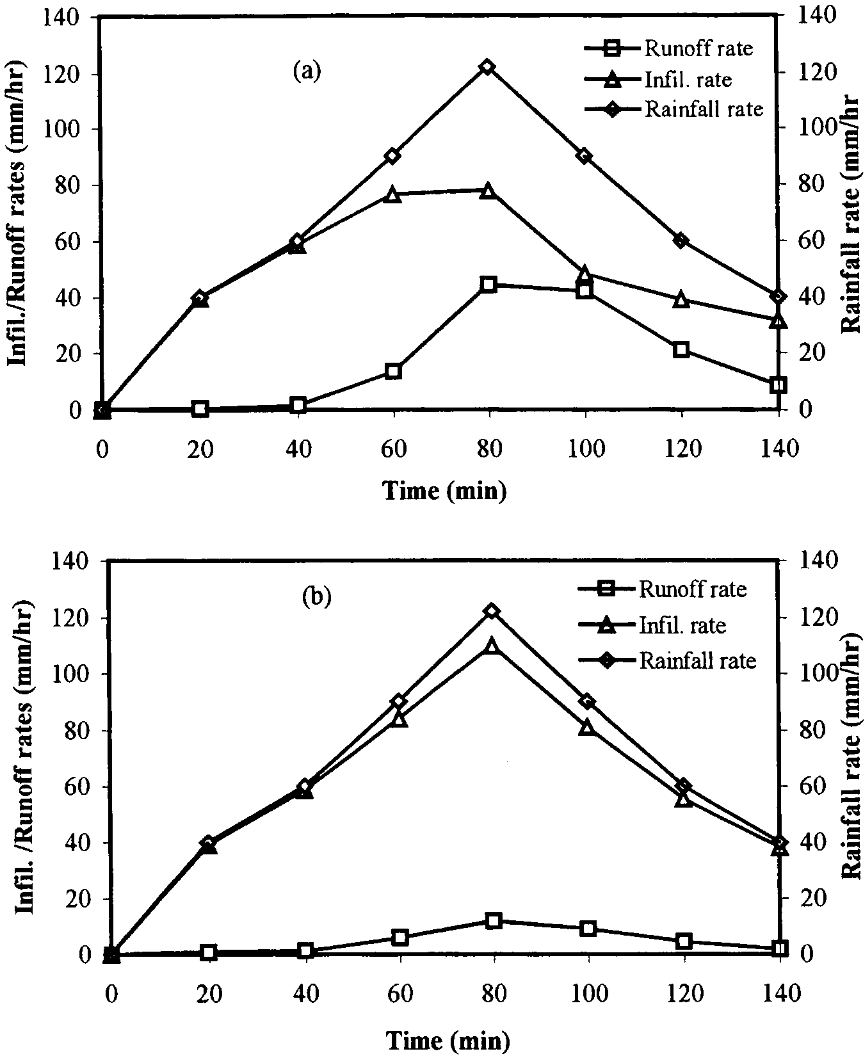


Figure 3.20. Infiltration and runoff rates as a function of time from varying rainfall intensities on (a) stubble mulch and (b) conventional tillage without residue cover.

3.3 Conclusions

The effect of conventional, stubble mulch and no-tillage, each with 0, 2, 4 and 8t/ha wheat straw as a residue cover, on the infiltration – runoff characteristics of a Bainsvlei soil was investigated in this chapter using a rainfall simulator. The infiltration data from the bare soils of the three tillage practices has been fitted to the Morin & Benyamini model and the results showed that the depth of tillage had a substantial effect on the initial infiltration rate of the soil. The bare 250 mm depth ploughed soil had the highest initial infiltration rate followed by the 150 mm tillage. The bare no-tillage had the lowest initial infiltration rate. The reason for this difference is believed to be due to the increase in porosity of the topsoil created by the tillage operations. Primary tillage, such as mouldboard ploughing, is reported to increase infiltration by increasing soil porosity and establishing channels or voids in the surface layer of soil that conduct water more readily into the soil profile (Edwards, 1982; Lindstrom & Onstad, 1984). Tillage can also increase infiltration when it loosens surface crusts, disrupts dense layers, or provides surface depressions for surface storage of water (Unger, 1992), and water entry is controlled to a greater degree by the surface seal formation (Glanville & Smith, 1988).

The levels of residue cover affected the time of runoff commencement and the final infiltration rate of the soil. The final infiltration rate of the soil increased with an increase of the amount of residue for all tillage treatments. With a residue cover the tillage treatments also affected the final infiltration rate. When the final infiltration rates are averaged over the different residue rates for the tillage practices, conventional tillage had the highest average final infiltration rate compared with stubble mulch and no-tillage, which had similar rates. The result of this study is in agreement with other findings, such as Morin & Benyamini (1977), who reported that the final infiltration rate of a mulched sandy soil was seven times higher than the bare soil. Yuxi Li *et al.* (2001) also reported a higher final infiltration rate on a residue covered black clay soil than the bare soil. Generally, crop residues retained on or near the soil surface enhance infiltration by dissipating raindrop drop energy, thus minimizing aggregate dispersion and surface sealing, and by retarding surface water flow, thus providing more time for infiltration (Unger, 1992).

Infiltration rate measurements on the bare soils of the three tillage treatments using a double ring infiltrometer also revealed differences between the tillage practices. Conventional tillage had a higher final infiltration rate as compared to the other two tillage practices. The final infiltration rate increased exponentially with an increase in tillage depth.

The runoff from the three tillage systems and four rates of residue cover, at a cumulative rainfall of 100 mm, have shown that runoff decreased linearly as the amount of residue cover increased from a rate of 0t/ha to 8t/ha. It should be noted that the different amounts of wheat residue were applied on the surface of freshly ploughed (25 cm depth) soil on the conventional tillage treatments. On the stubble mulch treatments the soil was tilled to a depth of 15 cm with sweeps after which the old crop residue was removed and replaced with the required amounts of fresh residue. On the no-till plots the old crop residue was removed and replaced with the different amounts of fresh residue cover. No-tillage generated more runoff than stubble mulch and conventional tillage practices. Conventional tillage had the lowest amount of runoff at all residue levels. Bennie *et al.* (1994), cited by Bennie & Hensley (2001) found, with studies on sandy soils, higher runoff from shallow tilled crop residue mulching and no-tillage than from the deeper tilled bare conventional mouldboard ploughing. The long-term studies reported by Bennie (2000) and Bennie & Hensley (2001) also suggested that a no-tillage practice with insufficient residue rates was not beneficial in terms of both soil water conservation and crop yield compared with conventional and stubble mulch tillage on soils similar to the one used in this study. In another study, Tullberg *et al.* (2001) reported that no-tillage with residue cover reduced mean annual runoff on a black clay soil and increased yield compared with stubble mulch tillage practice.

The presence of a residue cover on all three tillage treatments delayed the onset of rapid runoff. For instance, for stubble mulching a 2t/ha residue cover was sufficient to delay the onset of rapid runoff from approximately 50 to 70mm cumulative rainfall. The effect of tillage in delaying the commencement of runoff was much more visible on the conventional tillage than the other two. This could probably be due to the surface roughness created by mouldboard ploughing. Even under bare soil conditions, the runoff initiation time was delayed significantly by conventional tillage compared to no-tillage and stubble mulch tillage treatments.

Under bare soil conditions final runoff and infiltration became almost the same for no-till and the tilled treatments because of the degree of surface sealing starting to control these processes. Mohamoud *et al.* (1990b) also reported, while comparing no-tillage with other tillage practices, with the surface residue removed, that runoff occurred sooner on no-till because of rapid filling of surface pores and clogging of pores by raindrop splash. Runoff occurred later under tilled conditions because of greater surface roughness and depression storage. No-tillage systems generally have less depression storage than conventional tillage systems.

Although conservation tillage, compared to conventional tillage, enhances water conservation and crop yields in many cases, opposite results or no differences were reported by others (Bhatnagar *et al.*, 1983; Myers & Waggers, 1996; Ghidey & Alberts, 1998). Myers & Wagger (1996) reported that conventional tillage had 73% less runoff than no-tillage treatments in a simulation study on a sandy clay loam soil. Ghidey & Alberts (1998) reported on a silt loam soil that runoff from no-tillage was significantly higher compared with conventional or chisel ploughing. In India Rao *et al.* (1986), cited by Unger *et al.* (1991) under semi-arid conditions, conventional tillage was superior to no-tillage, reduced tillage or mulching for increasing soil water content and yields of some crops grown in the dry season with conserved soil water.

The result of this study suggests, under this particular experimental and soil conditions, that conventional tillage (mouldboard ploughing) is more appropriate in improving, albeit temporarily, the soil structure, which would increase the infiltration of rainwater into the soil until such time that too much rain causes the breakdown of aggregates and the formation of a surface crust. Moreover, the primary tillage with mouldboard ploughing creates roughness and surface depression storage, which can store more rainwater and increase the infiltration opportunity time. The presence of surface cover on conventionally tilled soils will protect the soil from raindrop impact and maintain a higher infiltration rate during the rainy period.

Loosening of this sandy soil below a residue mulch will decrease runoff substantially and the decrease will be a function of the depth of tillage, or the degree of loosening of the soil. Under commercial farming conditions this objective can be achieved by the non-inverting ripping of sandy soils while a crop residue mulch is maintained on the surface. When subsistence food production is practiced, on especially sandy soils, it is recommended that the soil be loosened to at least a depth of 15 cm before the crop residue is replaced.

CHAPTER 4

EFFECT OF TILLAGE AND RESIDUE COVER ON RUNOFF UNDER NATURAL RAINFALL (AU EXPERIMENTAL SITE)

4.1 Introduction

Low and erratic precipitation is the single most important climatic factor that limits crop yields in most semi-arid regions (Lal, 1990b). Soil productivity may be impaired if the degradation processes outweigh the conservation practices (Unger *et al.*, 1991). To avert continuing degradation, conservation practices that improve the soil productivity must be implemented. Two practices having a major impact on soil and water conservation are crop residue management and tillage (Unger *et al.*, 1991). The value of crop residues for water conservation has long been recognised, and today crop residue management forms the basis for conservation tillage systems that are gaining acceptance in most parts of the dry land farming areas (Willocks, 1988; Papendick *et al.*, 1990).

Numerous studies in various dryland areas around the world have shown that control of water erosion in areas of high potential runoff depends mainly on the amount of surface cover and roughness than on soil type and the tillage practices per se (Papendick *et al.*, 1990; Unger *et al.*, 1991). Crop residue management ranges from complete removal or destruction to a total retention on the soil surface, as with no-tillage systems.

Residue management should form part of improved soil management practices (Bradford & Huang, 1994) and should be aimed at increasing infiltration and reducing runoff. No-tillage without adequate surface residue can create soil conditions like sealing, crusting, and erosion. Observed differences in runoff and soil loss between conservation and conventional tillage systems is more pronounced immediately after tillage, and decreases when the crop canopy begins to protect the soil surface from rain drop impact, sealing and crusting (Bradford & Huang, 1994).

In effect, much of the soil loss from agricultural land takes place from seedbed preparation till full plant canopy development. With full canopy cover, there will be small differences between infiltration and erosion on no-tillage and conventional tillage.

In marginal rainfall areas of Ethiopia, recurrent dry soil conditions have been attributed to low infiltration of rainwater and high runoff due to soil surface sealing and crusting properties. Raindrop impact causes sealing and crusting of bare soils resulting in a very high runoff. This runoff water should be conserved in the soil in order to sustain crop growth. Both runoff and erosion is a serious problem on the Ethiopian highland soils. Most of the productive topsoil in the highlands of Ethiopia has been degraded, resulting in chronic food shortages and persistent poverty. Serious erosion is estimated to have affected some 25% of the area, and some estimates suggest that 4% of the highlands is so seriously eroded that it will not be economically productive again in the foreseeable future (SCRP, 1994). As a consequence of this land degradation, the production capacity of the soils of the Ethiopian highlands is believed to be declining at a rate of 2-3% annually (Hurni, 1993; cited by Zeleke, 2000). This is a potential threat to the national food supply if allowed to continue uncontrolled and every effort should be made to reverse the situation.

A study was conducted at the Alemaya University experimental site for two consecutive years (2000 and 2001) with the objective of evaluating the effect of tillage and residue cover on runoff and soil loss under natural rainfall. The experiment consisted of three tillage practices (no-tillage, traditional and conventional tillage) and four levels of wheat residue cover (0, 2, 4 and 8t/ha). The objective of this chapter is to discuss the runoff results from this experiment.

4.2 Results and Discussion

4.2.1 Surface Cover Measurements

In erosion studies, runoff and soil loss is found to correlate well with the percentage residue cover than with the residue mass per unit area. Several methods have been proposed to measure the percentage cover by residue, which was left on the field after tillage. These include the photographic method (Laflen *et al.*, 1981; Sallaway *et al.*, 1988), meter-stick method (Hartwig & Laflen, 1978; Laflen *et al.*, 1981) and line-transect method (Sloneker & Moldenhauer; 1977; Laflen *et al.*, 1981). From these measurements empirical relationships were established relating the residue mass per hectare to the percentage cover. A simple method (Lang & Mallett, 1982), similar to the line-transect method, was used to measure the percentage residue cover in this study. A detailed description of this method is reported in Section 2.1.3. The result of the measured percentage residue cover is given in Table 4.1.

Table 4.1. Mean percentage cover and standard deviation for different amount of residue

Residue mass (t/ha)	Mean cover (%)	Standard deviation S.D.	Number of measurements N
2	61.87	3.18	36
4	75.55	4.55	36
8	91.85	6.53	36

Using a photographic method, Lattanzi *et al.* (1974) reported percentage cover by wheat residue of 0, 25, 61, and 95% for residue rates of 0, 0.5, 2.0 and 8.0 t/ha, which is very similar to the results in Table 4.1. The data in Table 4.1 was fitted to different non-linear equations by regression analysis (Equations 4.1 to 4.3). The results are presented in Figures 4.1.

$$\%Cover = 81.02*(1-e^{-M}), \quad R^2 = 0.96 \quad [4.1]$$

$$\%Cover = 51.24*M^{0.28}, \quad R^2 = 0.99 \quad [4.2]$$

$$\%Cover = 91.17*(1-e^{-0.52M}), \quad R^2 = 0.99 \quad [4.3]$$

Where, M is the mass of wheat residue in t/ha.

As shown in Figure 4.1, the two curves represented by Equations 4.2 and 4.3 fitted the data very well with high coefficients of determination.

Sallaway *et al.* (1988) established a relationship, similar to Equation 4.1, between mass of residue and percentage residue cover, in which the percentage cover was given as $b*(1-e^{-M})$, where b is a coefficient for the type of residue, and M is the residue mass in t/ha. The coefficient b was 98.1 for wheat (the coefficient b in this study was 81.2 from Equation 4.1, 64.7 for sorghum and 49.3 for sunflower. Gilley *et al.* (1986) reported similar relationships between sorghum and soybean residue mass and percentage cover which are: *Sorghum surface cover (%)* = $100(1-e^{-0.091*M})$ and *Soybean surface cover (%)* = $100(1-e^{-0.135*M})$.

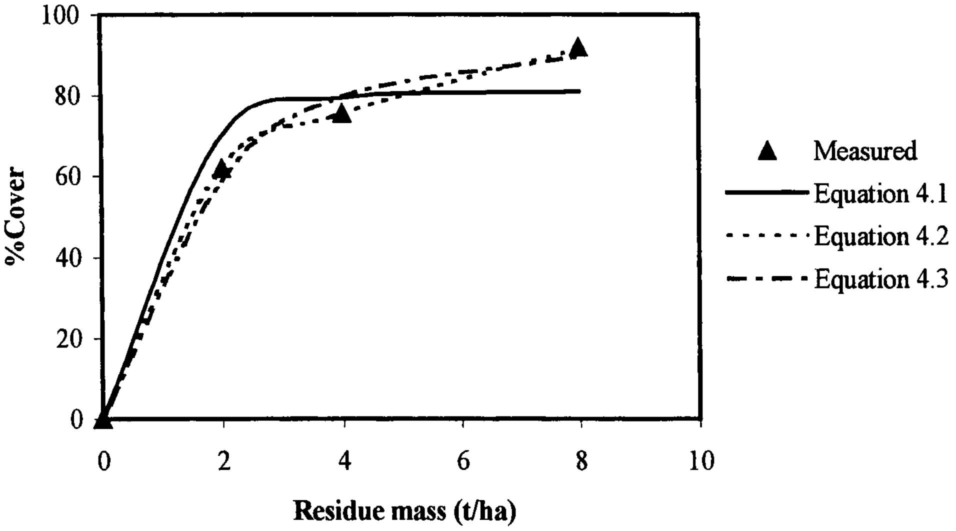


Figure 4.1. Percentage residue cover as a function of residue mass fitted to exponential and power functions.

4.2.2 Characteristics of Erosive Rainstorms

A natural rainstorm is characterized by its intensity distribution, duration, drop size distribution, and rainfall energy (Agassi & Bradford, 1999). Rainfall intensity is an important factor in soil erosion since interrill soil erosion varies with the square of rainfall intensity (Meyer, 1981). The kinetic energy of a raindrop is related to the rainfall intensity. As the kinetic energy of a storm increases with an increase in rainfall intensity the infiltration rate of a soil is reported to decrease sharply (Karen, 1990; Bradford & Huang, 1992)), thus increasing runoff. Soil loss is also related to runoff and because of the interrelationship between rainfall and runoff, one would expect storm intensity and its distribution during a storm to be an important factor in determining runoff and the associated soil loss (Foster, 1982).

The rainfall intensity and amount have been monitored at the experimental site with a recording rain gauge, connected to a data logger. This data was used to calculate the rainfall intensities during each rainfall event. The erosive rainstorm intensities for the main rainfall seasons of 2000 and 2001 are presented here.

The first erosive storm during the 2000 rainy season was that of the 8th of July, which was 19.6mm. The rainfall intensities during this storm are presented in Figure 4.2. The storm lasted for about 32 minutes (from 18:20:00 to 18:52:00). The average maximum 30-minute intensity (I_{30}) was 28.8 mm/hr. This storm had two peak intensities, reaching up to 150 mm/hr and then declined to zero towards the end of the storm. The rainfall erosivity index (EI_{30}) was calculated using Equation 3.4. Equation 3.4 shows that at intensities greater than 75 mm/hr, the kinetic energy became constant at a value of about 29 J/m^2/mm, which seems to be representative for many locations (Kinnel, 1987; cited by Morgan, 1995). The total kinetic energy (E) was calculated to be 380.2 J/m^2. The erosion index (EI_{30}) is equal to the product of E and I_{30}, which was 10949.8 J mm/m^2/hr.

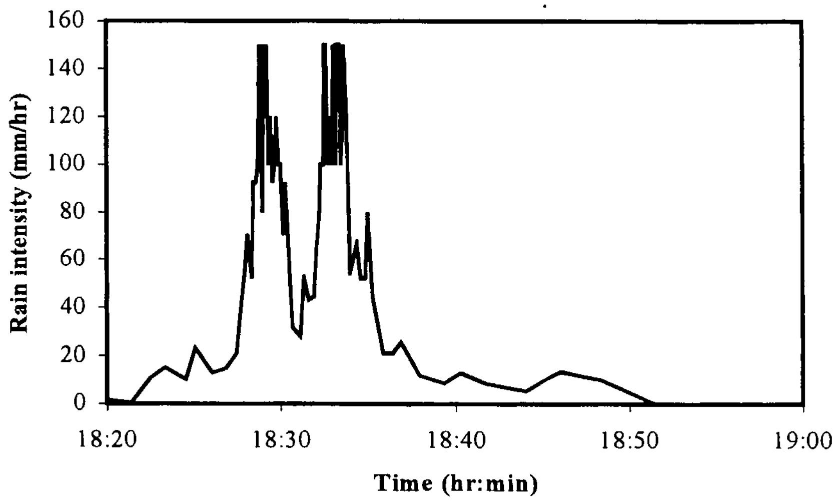


Figure 4.2. Rainfall intensity during a storm of 19.6mm on the 8th of July 2000.

The second storm of the 2000 rainy season was that of the 12th of July, which was 18.6mm. It lasted for about one hour and forty minutes. The intensities are given in Figure 4.3. As shown in Figure 4.3, the storm had two peak intensities, reaching up to 100mm/hr few minutes into the start of the storm. The maximum 30-minute intensity (I_{30}) and the erosion index (EI_{30}) were 32.4 mm/hr and 13561.99 J mm/m^2/hr, respectively.

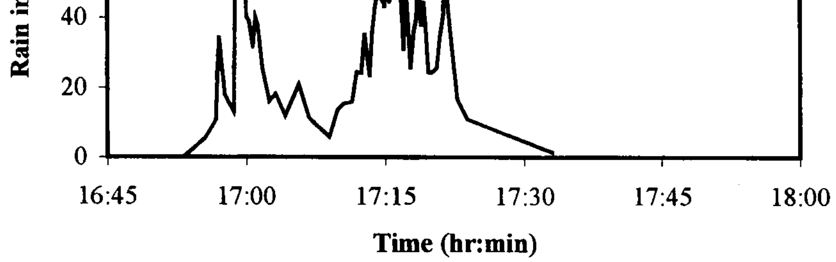


Figure 4.3. Rainfall intensity during a storm of 18.6mm on the 12th of July 2000.

The third and most intense rain was received on the 12th of August 2000, which was 35.6 mm. The intensity of rain during this rainfall event is given in Figure 4.4. The rainfall lasted for about two hours. The most intense part of the storm was received only for about 35 minutes into the beginning of the storm, during which 65% of the total rainfall was received. The rainfall intensity was well above 60 mm/hr reaching up as high as 240 mm/hr during this period. The I_{30} and the erosion index for this storm were 40.8 mm/hr and 32280.96 J mm/m^2/hr, respectively.

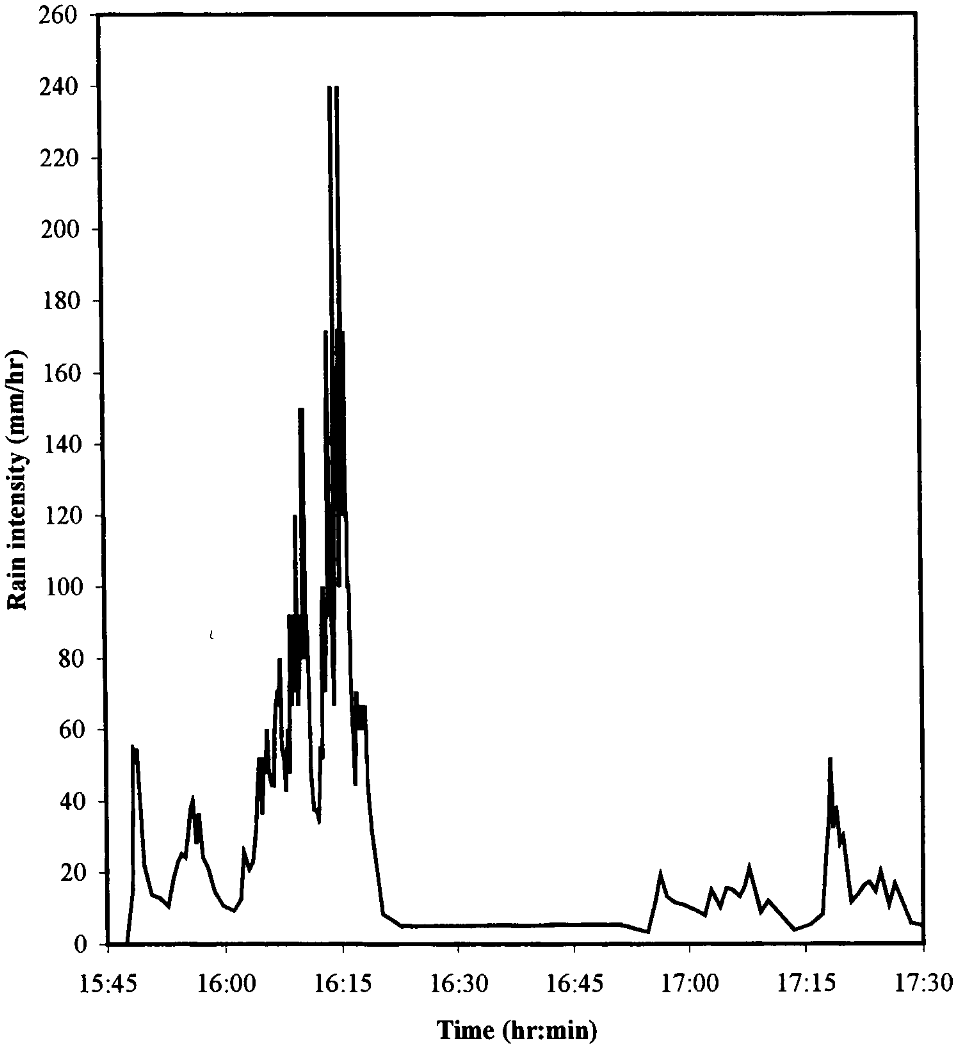


Figure 4.4. Rainfall intensity during a storm of 35.6 mm on the 12th of August 2000.

A storm of 9.6 mm was received on the 13th of August. This storm, though small in amount, was able to generate runoff from some of the treatments, due to the fact that the soil was sufficiently wet because of a heavy storm on the day before, the 12th of August. Morgan (1995) indicated that erosion is related to two types of rainfall events, the short-lived intense storm where the infiltration capacity of the soil is exceeded, and the prolonged storm of low intensity that saturates the soil. Moreover, the previous rainfall and the initial soil conditions may also determine the response of the soil to rainfall. The duration of this storm was well over 2 hours. The I_{30} and erosion index were 8.4 mm/hr and 879.48 J mm/m^2/hr, respectively. The intensities for this storm are given in Figure 4.5.

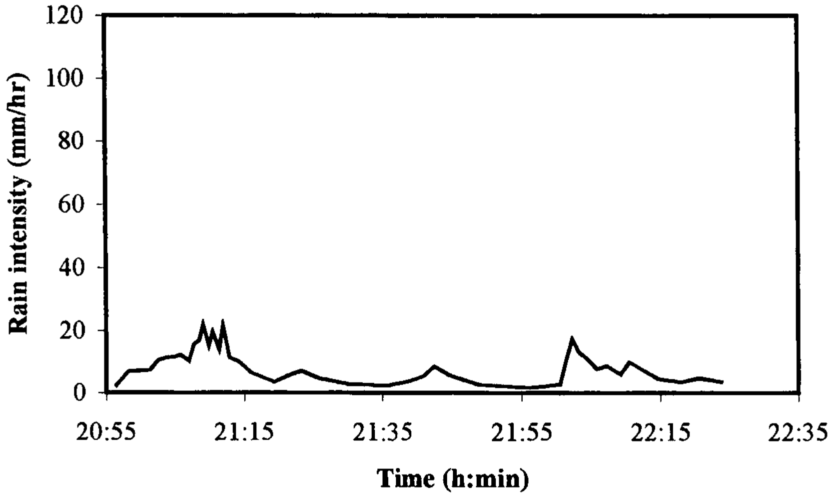


Figure 4.5. Rainfall intensity during a storm of 9.6 mm on the 13th of August 2000.

The storm of the 25th of August 2000 was 27.4 mm. It lasted for about 8 hours with an interruption for about a hour and half, after the first two hours of the storm. The intensities were quite low with the I_{30} and erosion index of 9.6 mm/hr and 2037.1 J mm/m^2/hr, respectively. The rainfall intensities for this storm are given in Figure 4.6.

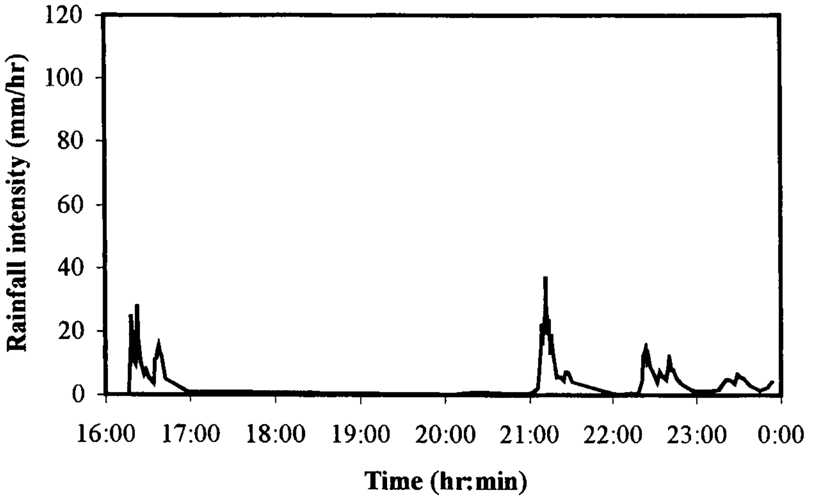


Figure 4.6. Rainfall intensity during a storm of 27.4 mm on the 25th of August 2000.

The last erosive storm of the season was on the 16th of September 2000, which was 21.8 mm. This storm was the longest storm of the season with duration of about 10 hours, but with an interruption of about four hours after the first hour of the storm. The intensities for this storm were low for most of the duration, except for a few minutes when it reached about 100 mm/hr. The I_{30} and the erosivity index were 16.8 mm/hr and 6200.88 J mm/m^2/hr, respectively. The intensities are presented in Figure 4.7.

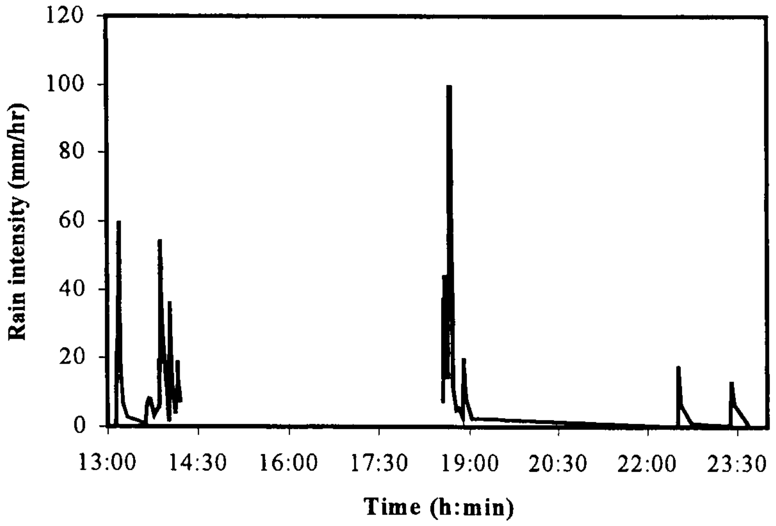


Figure 4.7. Rainfall intensity during a storm of 21.8 mm on the 16th of Sept. 2000.

The summary of the rainfall characteristics during the rainfall season of 2000 is presented in Table 4.2.

Table 4.2. Summary of rainfall characteristics for 2000 rainfall season

Date	Rain (mm)	I_{30} (mm/hr)	Total Kinetic Energy (E) (J/m^2)	EI_{30} (J mm/m^2/hr)
8-July	19.6	28.8	380.2	10949.76
12-July	18.6	32.4	418.6	13561.99
12-Aug	35.6	40.8	791.2	32280.9
13-Aug	9.6	8.4	104.7	879.48
25-Aug	27.4	9.6	212.2	2037.1
16-Sept	21.8	16.8	369.1	6200.9

During the main rainfall season of 2001, there were four storms that generated runoff. The amounts of rainfall received during three of the four storms were quite high (>30 mm). The rainfall intensities for these storms are presented in Figures 4.8 to 4.11.

The rainfall intensities for the storm of the 1st of August 2001 are given in Figure 4.8. Despite the high amount of rainfall (40 mm) during this storm, little runoff was obtained from a few plots probably due to the dry soil condition, because this being the first storm of the main rainy season. The I_{30} and the erosion index (EI_{30}) index were calculated to be 19.2 mm/hr and 7050.8 J mm/m^2/hr, respectively. The storm of the 5th of August 2001 was 33.8 mm. The intensities for this storm are given in Figure 4.9. The storm lasted for about five hours but most of the rain was received during the first hour of the storm, after which the storm continued at a lower intensity (<10 mm/hr). Generally the intensities were lower with a peak intensity of only 52 mm/hr. The I_{30} and EI_{30} index were 19.6 mm/hr and 7614.21 J mm/m^2/hr, respectively.

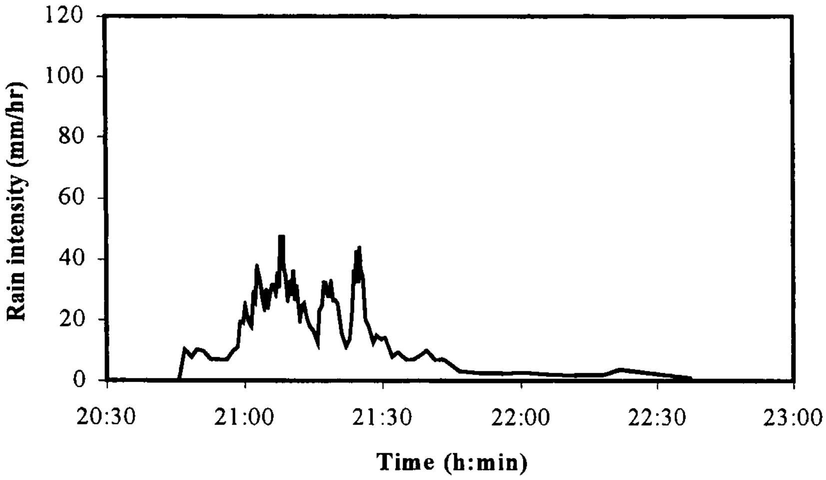


Figure 4.8. Rainfall intensity during a storm of 40 mm on the 1st of August 2001.

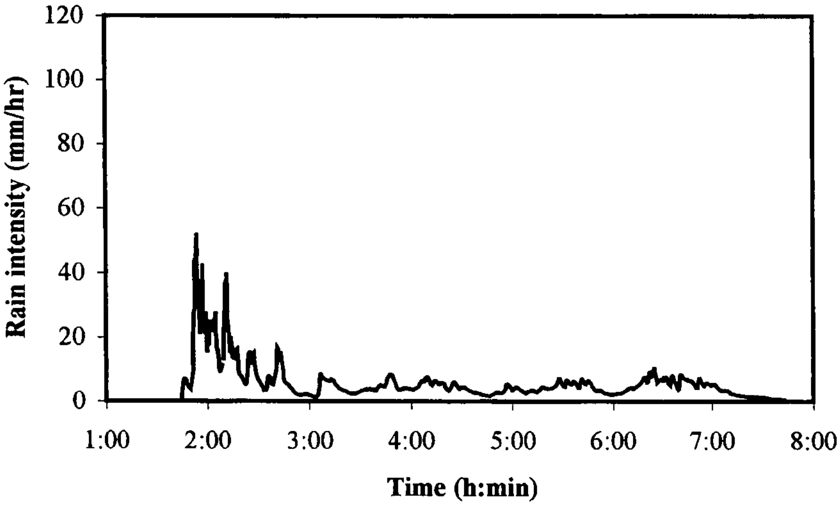


Figure 4.9. Rainfall intensity during a storm of 33.8 mm on the 5th of August 2001.

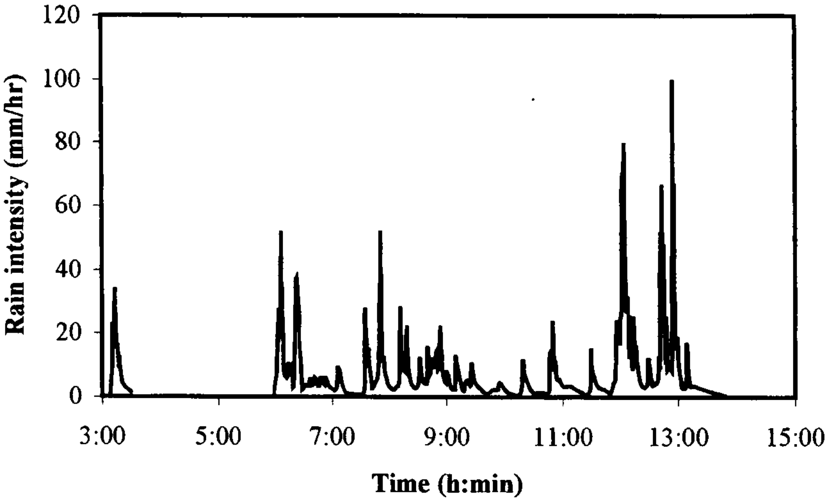


Figure 4.10. Rainfall intensity during a storm of 53.8 mm on the 8th of August 2001.

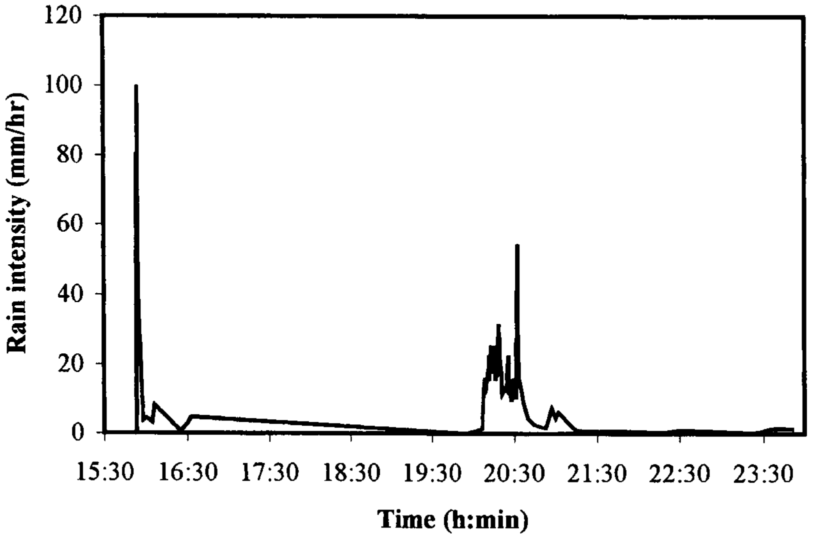


Figure 4.11. Rainfall intensity during a storm of 15.2 mm on the 16th of Sept. 2001.

The storm on the 8th of August, which caused runoff from all the plots, including the ones with a residue rate of 8t/ha, was 53.8 mm. The intensities are given in Figure 4.10. The reason for the higher runoff during this storm (discussed in a later section) could probably be due to the wet soil condition from the two previous heavy storms. Furthermore, the duration of this storm was quite long, well over seven hours. The I_{30} was, however, low compared to the other storms of the season, which was 18.4 mm/hr. The storm of the 14th of September was 15.2 mm, which caused runoff from only a few plots. Although, the amount of rain during this storm was low, the I_{30} was relatively high, i.e. 16 mm/hr. The intensities for this storm are given in Figure 4.11. A summary of the rainfall characteristics for the 2001 season is given in Table 4.3.

Table 4.3. Summary of rainfall characteristics for 2001 rainfall season

Date	Rain (mm)	I_{30} (mm/hr)	Total Kinetic Energy (E) (J/m^2)	EI_{30} (J mm/m^2/hr)
1-Aug	40	19.2	367.23	7050.82
5-Aug	33.8	19.6	388.48	7614.21
8-Aug	53.8	18.4	879.00	16173.60
14-Sep	15.2	16.0	223.57	3577.12

The main characteristics of rainfall, such as rainfall amount and intensity, total kinetic energy of a storm, and erosivity index are positively related to one another. The rainfall erosivity factor has been found to correlate well to a power function of the rainfall amount (Renard & Freimund, 1994). Ten years of monthly data on erosivity and rainfall amount from the Ethiopian highlands (SCRP, 1996) have been fitted to a power function and the result shows a good correlation between the two parameters (Figure 4.12).

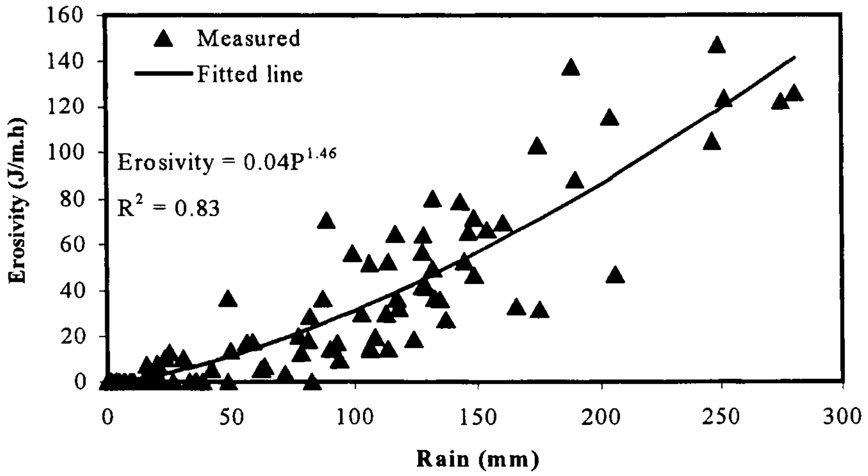


Figure 4.12. Erosivity as a function of rainfall amount fitted to a power function.

The data from this study, for the two seasons, have also been analysed using regression statistics to determine the relationship between some of the parameters. The rainfall amount was found to correlate better with the total kinetic energy of the storm than with the erosion index. The data on the rainfall amount and the total kinetic energy fitted both linear and non-linear functions well and the result is presented in Figure 4.13.

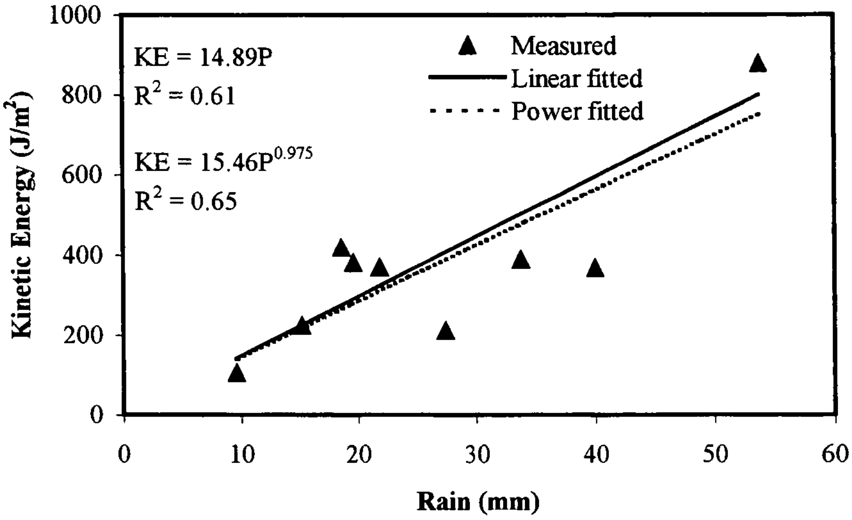


Figure 4.13. Total kinetic energy of the storm as a function of rainfall amount fitted to linear and power functions based on the combined data from two main rainfall seasons at Alemaya University experimental site.

4.2.3 Runoff

4.2.3.1 Runoff from erosive rainstorms

Runoff from each of the erosive rainstorms during the two years of study (2000 and 2001) was measured during the main rainfall season, which is during July, August and September. The results for the two years are summarized in Tables 4.4 and 4.5.

As indicated in Table 4.4, all the tillage treatments with a residue rate of 8t/ha have not generated any runoff during the first year of the experiment. During all the rainstorms of the 2000 rainfall season (Table 4.4), the runoff amount was higher from no-tillage than from the traditional and conventional tillage treatments at all levels of residue cover. The residue rates of 4t/ha have restricted runoff to a very minimum or zero level and 8t/ha have totally eliminated runoff and controlled erosion during both years.

However, the runoff reduction relative to the bare plots, at a rate of 2t/ha varied depending on the type of storm and tillage practice. For instance, there was 89% less runoff from the no-tillage treatment covered with a residue rate of 2t/ha compared with the bare plot of the same tillage, during the fifth storm. Generally it varied from 7% (on the 12th of August) to 89% (on the 25th of August) on the no-tillage treatment.

On all the tillage treatments the highest runoff at 2t/ha residue cover was observed during a high intensity storm on the 12th of August of the first year. As discussed in the preceding Section 4.2.2, and shown in Figure 4.4, this storm had the highest maximum 30-minute intensity (40.8 mm/hr) and correspondingly the highest erosion index (32280.9 J mm/m^2/hr) of all the storms. Other rainfall characteristics, such as drop size and velocity, which are difficult to measure due to lack of routine methods (Agassi & Bradford, 1999), might have also contributed to the fact that a residue cover of 2t/ha was insufficient to reduce runoff during this specific storm.

On the traditional tillage treatment the highest reduction in runoff (97%) by a residue rate of 2t/ha, was observed during the second storm on the 12th of July. The runoff from the conventional tillage has generally been lower compared with the other two tillage treatments. Subsequently, the runoff reduction on conventional tillage due to residue rate of 2t/ha has been lower, ranging from 53% for the fourth erosive storm to 11% for the third storm, compared to the bare plot.

Table 4.4. Summary of runoff from erosive storms on different dates from three tillage treatments and four levels of residue cover at the AU Experimental site during the 2000 main rainfall season

Tillage	Residue rate (t/ha)	Dates of rain						**Total**
		08/07/00	12/07/00	12/08/00	13/08/00	25/08/00	16/09/00	
		Rain (mm)						
		19.6	18.6	35.6	9.6	27.4	21.8	**216.2$^{\#}$**
		Runoff (mm)						
No-tillage	0	2.37	4.57	8.80	2.13	4.16	6.76	**28.79**
(NT)	2	0.62	0.75	8.20	0.64	0.46	2.08	**12.75**
	4	0.07	0.05	2.50	0.00	0.00	0.37	**2.99**
	8	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Average	**NT**	**0.76**	**1.34**	**4.88**	**0.69**	**1.15**	**2.30**	**11.13**
Traditional	0	0.33	1.17	8.65	1.52	4.05	5.54	**21.26**
(TT)	2	0.19	0.03	7.00	0.39	1.07	3.72	**12.4**
	4	0.00	0.00	0.90	0.00	0.00	0.00	**0.90**
	8	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Average	**TT**	**0.13**	**0.30**	**4.14**	**0.48**	**1.28**	**2.32**	**8.64**
Conventional	0	0.15	0.16	7.20	0.51	4.24	5.32	**17.58**
(CT)	2	0.46	0.00	6.40	0.24	2.39	4.47	**13.96**
	4	0.00	0.00	0.40	0.00	0.00	0.37	**0.77**
	8	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Average	**CT**	**0.15**	**0.04**	**3.50**	**0.19**	**1.66**	**2.54**	**8.08**
Average	0	0.95a*	1.97a	8.22a	1.38a	4.15a	5.87a	**22.54a**
	2	0.43b	0.26b	7.20b	0.42ab	1.31b	3.42b	**13.04b**
	4	0.02c	0.02b	1.27c	0.00b	0.00c	0.25c	**1.56c**
	8	0.00c	0.00b	0.00d	0.00b	0.00c	0.00c	**0.00c**
LSD (Prob.)		**0.280 (0.05)**	**0.971 (0.01)**	**0.839 (0.01)**	**1.112 (0.01)**	**1.257 (0.01)**	**0.848 (0.01)**	**3.365 (0.01)**

(*): Numbers in the same column followed by the same letter(s) are not significantly different at a probability level given in bracket in the same column,

($^{\#}$): Total rainfall of the season.

Table 4.5. Summary of runoff from erosive storms on different dates from three tillage treatments and four levels of residue cover at the AU Experimental site during the 2001 main rainfall season

Tillage	Residue rate (t/ha)	Dates of rain				**Total**
		01/08/01	05/08/01	08/08/01	14/09/01	
		Rain (mm)				
		40.0	33.8	53.8	15.2	**269.2**$^{\#}$
		Runoff (mm)				
No-tillage	0	6.70	6.91	8.99	2.90	**25.50**
	2	0.43	1.39	1.86	0.00	**3.68**
	4	0.11	0.41	0.27	0.00	**0.79**
	8	0.00	0.32	0.16	0.00	**0.48**
Average	**NT**	**1.81**	**2.26**	**2.82**	**0.73**	**7.61**
Traditional	0	2.18	7.76	8.29	0.72	**18.95**
	2	0.92	0.51	2.98	0.19	**4.60**
	4	0.76	0.53	0.96	0.00	**2.25**
	8	0.00	0.08	0.32	0.00	**0.40**
Average	**TT**	**1.46**	**2.22**	**3.14**	**0.23**	**6.55**
Conventional	0	3.67	6.54	8.06	0.32	**18.59**
	2	0.27	1.25	2.77	0.00	**4.29**
	4	0.00	0.00	1.36	0.00	**1.36**
	8	0.00	0.14	0.19	0.00	**0.19**
Average	**CT**	**0.98**	**1.98**	**3.09**	**0.08**	**6.14**
Average	0	4.10a*	7.07a	8.44a	1.31a	**20.92a**
	2	0.96b	1.05b	2.53b	0.06b	**4.60b**
	4	0.62b	0.31b	0.86c	0.00b	**1.79bc**
	8	0.00b	0.18b	0.22c	0.00b	**0.40c**
LSD **(Prob.)**		**1.635** **(0.01)**	**1.252** **(0.01)**	**1.590** **(0.01)**	**0.394** **(0.01)**	**3.787** **(0.01)**

(*): Numbers in the same column followed by the same letter(s) are not significantly at a probability level given in bracket in the same column.

($^{\#}$): Total rainfall of the season

During the first year of the study, the relationship between runoff and the percentage residue cover was non-linear during all the erosive storms on traditional and no-tillage, except for the third storm (12th of August 2000), which was linear. On the conventional tillage, however, the relationship was mainly linear, indicating that the application of residue for runoff reduction was much less effective compared with other tillage practices, because of the already low runoff from the uncovered plots.

The results from the UFS study (Section 3.2.3) with a constant intensity simulated rainfall of 60 mm/hr also showed similar linear relationships between runoff and percentage residue cover for all three tillage treatments (see Figure 3.14).

An analysis of variance indicated that the effect of tillage on runoff was significant at a 5% probability level during the first few storms. Afterwards the tillage effect was not significant, probably due to the stabilisation of the soil, the smoothening of the tillage by raindrop impact, disappearance of the roughness and reduction of the surface depression storage created by tillage. The significant differences during the first three storms were between the no-tillage and the traditional and conventional tillage treatments. Bradford & Huang (1994) reported that differences in runoff between conservation and conventional tillage systems are more pronounced on freshly tilled soil before the impact from raindrop forms surface sealing and crusting.

Regarding the effect of residue, the analysis of variance showed that the differences due to residue effects have been significant during all of the storms. The highly significant differences (at 1% probability level) were mainly between the bare plots and the plots with residue rates higher than 2t/ha. There were no significant differences between the 4 and 8t/ha during any of the erosive storms.

During the second year of the experiment (2001) runoff from the three tillage treatments, at the four rates of residue cover from the four erosive storms decreased sharply with an increase in residue amount. The decrease in runoff from the addition of residue varied depending on the type of tillage and the storm, like during the previous year. For the residue rate of 2t/ha it ranged from 79 to 100% for no-tillage, 52 to 93% for traditional and 66 to 100% for conventional tillage. Generally, the degree of runoff reduction at a residue rate of 2t/ha was much more pronounced for all the erosive storms in the second compared to the previous year. As discussed in Section 4.2.2, despite the higher amounts, the rainfall intensities during the second year were generally lower than of the previous year. For instance, the storm with an amount of 53.8 mm had the maximum 30-minute intensity of only 18.4 mm/hr.

The analysis of variance showed that, during the second year, the effect of tillage on runoff was not significant for all the erosive storms, except during the last storm, where runoff from no-tillage was significantly higher at a 5% probability level. Conversely, residue cover had a highly significant effect ($P<0.0001$) on runoff during all the erosive storms.

For most of the storms the significant differences were between the bare and the residue covered plots. There were no significant differences in runoff from the different rates of residue cover, except for the third storm (8-August) where runoff from a residue rate of 2t/ha was significantly higher than from the higher residue rates (4 and 8t/ha).

From the results of both years of the experiment it appears that the minimum amount of residue cover required to significantly reduce runoff, depends on the rainfall characteristics. In almost all the cases a residue cover of 2t/ha effectively reduced runoff with the exception of two storms (12/08/2000 and 8/08/2001) where at least a residue rate of 4t/ha was required. The storm on the 12th of August 2000 represented a typical runoff producing storm lasting approximately two hours that started with half an hour very high intensity of up to 240 mm/hr which declined to around 40 mm/hr later. The storm of the 8th of August 2001 represents a larger duration, 10 hours, storm with sporadic short high intensity pulses reaching rates of up to 100 mm/hr.

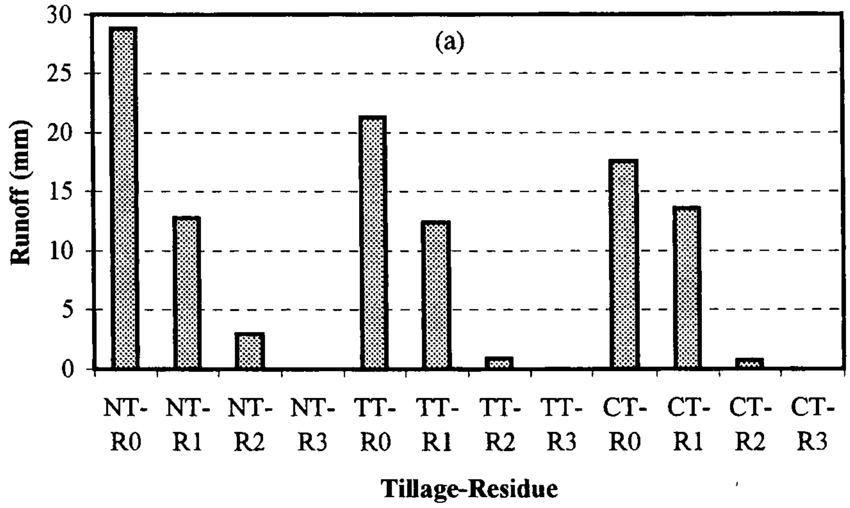
However, reports indicate that the role of intensity is not always so obvious because storms with a long duration and low intensity can also produce runoff. So, it appears that runoff and erosion are related to two types of rainfall events, the short-lived intense storm where the infiltration capacity of the soil is exceeded, and the prolonged storm of low intensity that saturates the soil after which runoff begins. In many instances it is difficult to separate the effects of these two types of events (Morgan, 1995). The response of the soil to rainfall also depends on the preceding rainfall and the initial soil wetness conditions, as demonstrated by the light storm event of the 13th of August 2000 (9.6 mm) that produced runoff following the intense storm of the 12th of August 2000 (35.6 mm).

Apart from the rainfall characteristics the loosening of the soil by the different tillage methods also affected the reduction in runoff by residue cover. The study under simulated rainfall also revealed that mean runoff, over the four rates of residue cover, from conventional tillage was lower than from stubble mulch and no-tillage (see Section 3.2.4). Conventional tillage with mouldboard ploughing is generally reported to increase infiltration through increased soil porosity and the establishment of channels or voids in the surface layer that conduct water more readily into the soil profile (Edwards, 1982; Lidstrom & Onstad, 1984). Tillage can also increase infiltration by disruption of surface crusts and dense layers, or by creating surface depressions for temporary storage of water (Unger, 1992). Tillage also alters topsoil physical properties such as bulk density, pore size distribution, infiltrability and soil water retention properties (Cassel, 1982; Xu & Mermoud, 2001), which could affect the runoff and erosion processes.

4.2.3.2 Total runoff

In order to better illustrate the effect of tillage and residue cover on runoff and establish some relationships, the total runoff during the two seasons is presented here.

The average total runoff for the three tillage and four rates of residue treatments during the main rainfall seasons of both experimental years (2000 and 2001), are given in Tables 4.4 and 4.5, and is illustrated using a bar graph in Figure 4.14. Figure 4.14 illustrates that residue rates of 4t/ha and 8t/ha had essentially eliminated runoff from all three tillage treatments for both years. The decrease in total runoff with an increase in percentage residue cover was linear during the first year and non-linear (polynomial) during the second year.



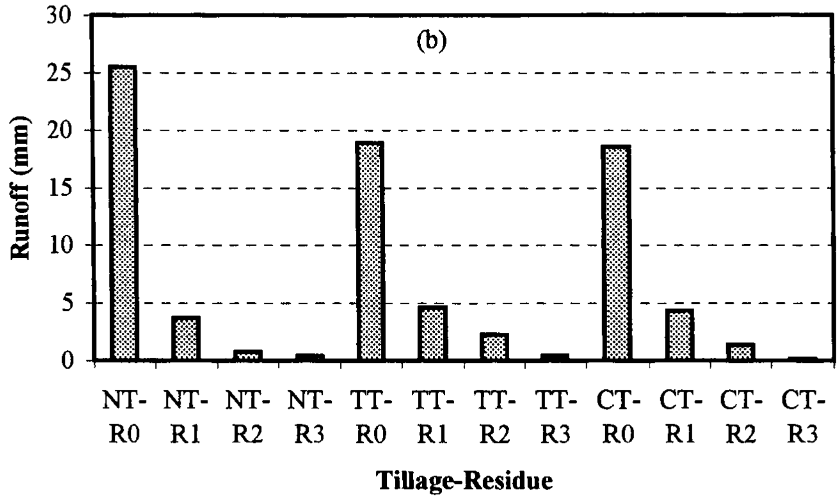


Figure 4.14. Average total runoff during the main rainfall seasons of year (a) 2000 and (b) 2001, from three tillage treatments and four rates of residue cover. *Note*: R0, R1, R2 and R3 are residue rates of 0, 2, 4, and 8t/ha, respectively.

An analysis of variance, conducted on the total runoff over the season, revealed that for 2000 there have been significant differences between mean runoff over the three tillage practices due to the effect of residue at 1% probability level. However, the effect of tillage on total runoff has not been significant at 5% probability level. It was, however, significant at 10% level.

For 2001 the total runoff data also revealed that there was a significant effect of residue as well as residue – tillage interaction at 1% and 5% probability level, respectively. The effect of tillage, however, has not been significant. Although the effect of tillage on total runoff has not been statistically significant, the average total runoff from the three tillage practices was in the order of *no-tillage>traditional >conventional tillage.*

The average total runoff from the three tillage treatments was related to the tillage depth at each of the residue treatments and for the combined means (Figures 4.15 and 4.16). The Figures for the two seasons show that the mean total runoff decreased with an increase in tillage depth on the bare soil. Tillage depth had little effect in the presence of a residue cover. When residue cover is not available, it might be advisable to use conventional tillage on this soil, which could increase infiltration and decrease runoff compared to no-tillage and traditional tillage practices.

Generally, the combined mean total runoff, over the four rates of residue cover, as a function of tillage depth for both seasons (Figure 4.15b and 4.16b) shows a decrease in runoff with an increase in tillage depth. This result is also confirmed by the simulation study on a sandy soil (see Chapter 3), where conventional tillage was found to conserve soil and water better than the stubble mulch and the no-tillage.

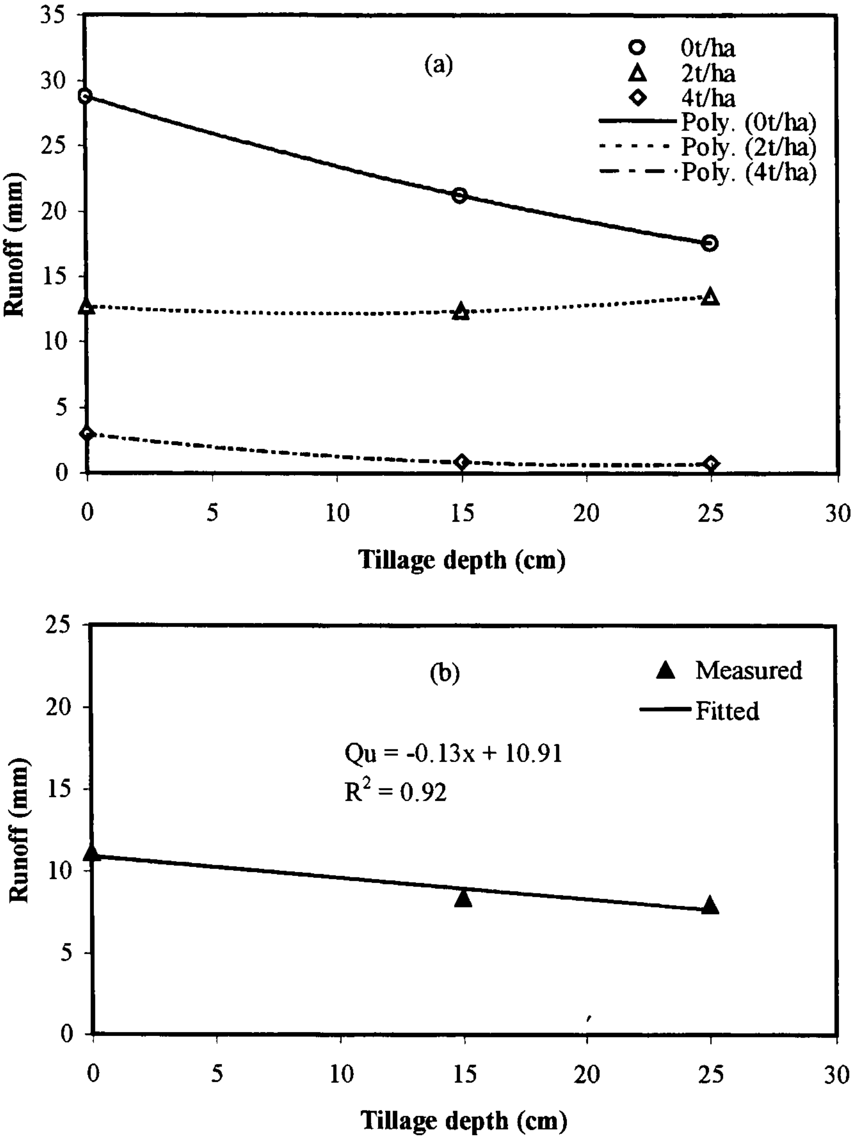
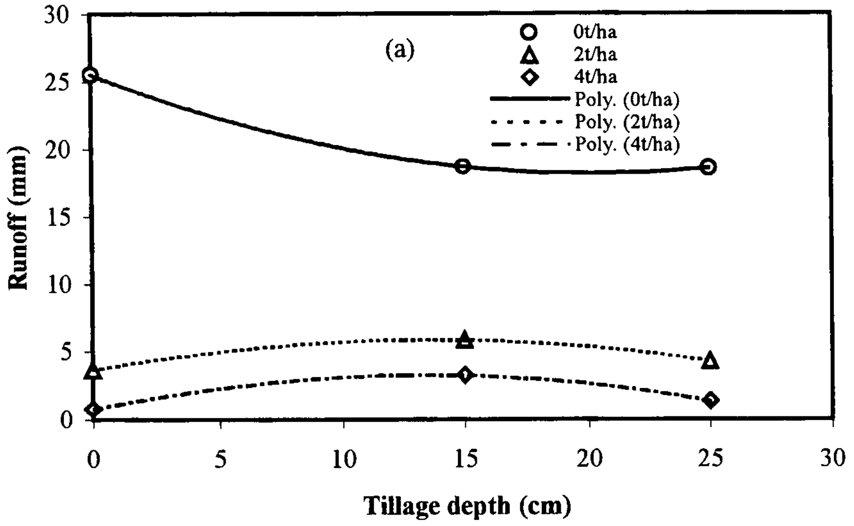


Figure 4.15. Total runoff as a function of tillage depth for (a) three rates of residue cover and (b) the combined mean runoff for four rates of residue cover, year 2000.



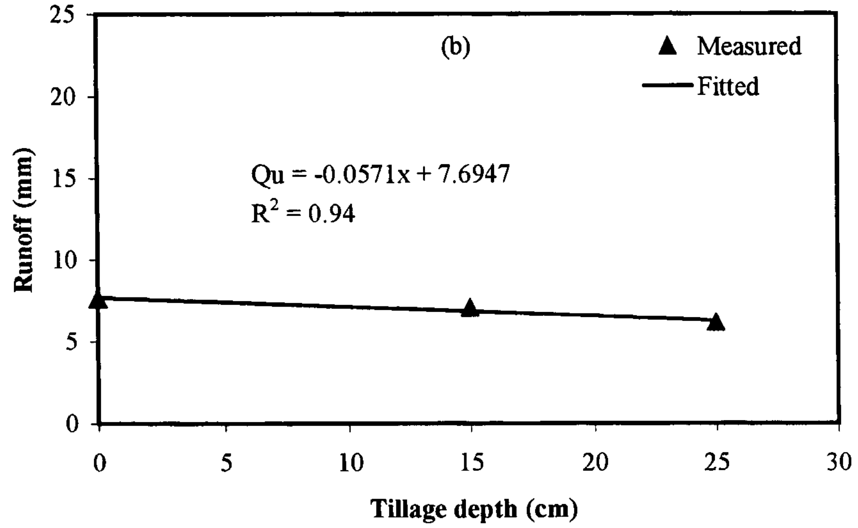


Figure 4.16. Total runoff as a function of tillage depth for (a) three rates of residue cover and (b) the combined mean runoff from the four rates of residue cover, year 2001.

The total runoff from the three tillage practices and the mean total runoff (Table 4.4 and 4.5) were related to residue cover (Figures 4.17 and 4.18). The Figures illustrate the decrease in runoff with an increase of residue cover. The linear decline in total runoff with increasing residue cover (Figure 4.17) was thought to have resulted mainly from the high runoff measured at the 2t/ha or 62% residue cover during the high intensity storm of the 12th of August 2000. When the runoff from the 12th of August storm is omitted from the data, the function changes to an exponential form.

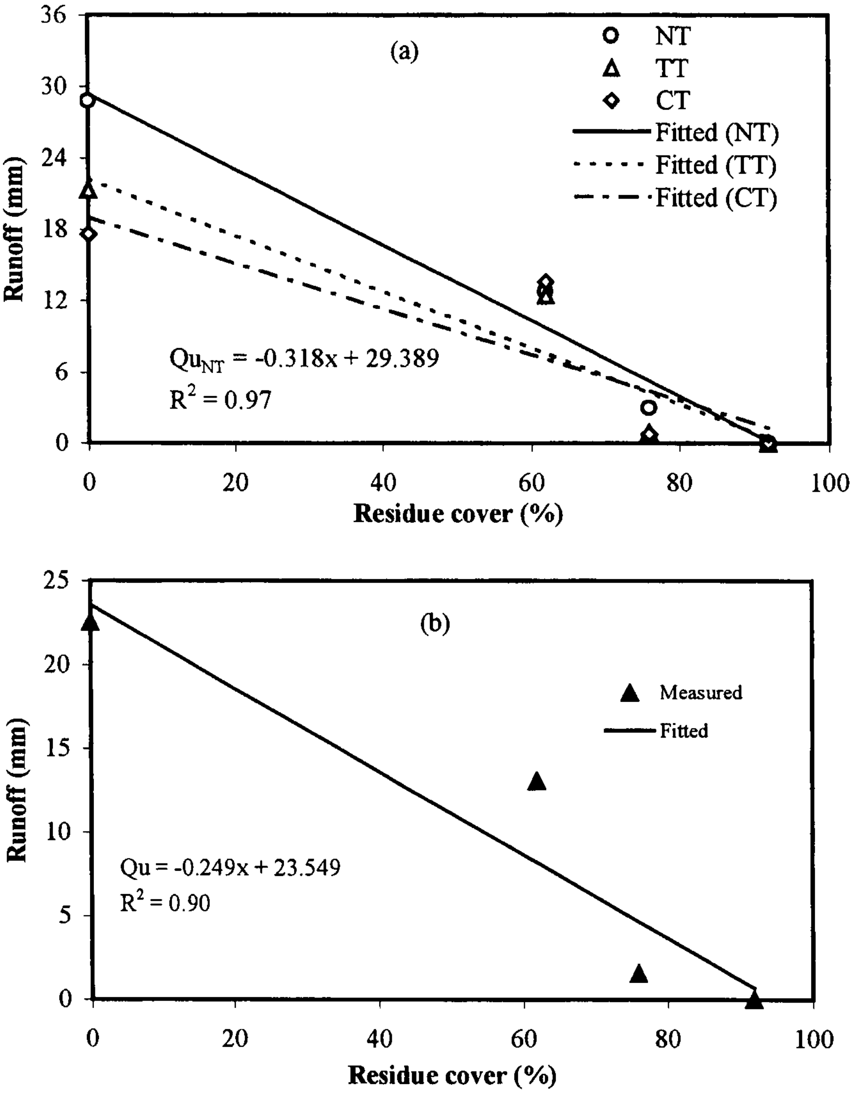


Figure 4.17. Mean total runoff (Qu) as a function of percentage residue cover during the main rainfall season of 2000 for (a) three tillage treatments and (b) the combined mean runoff.

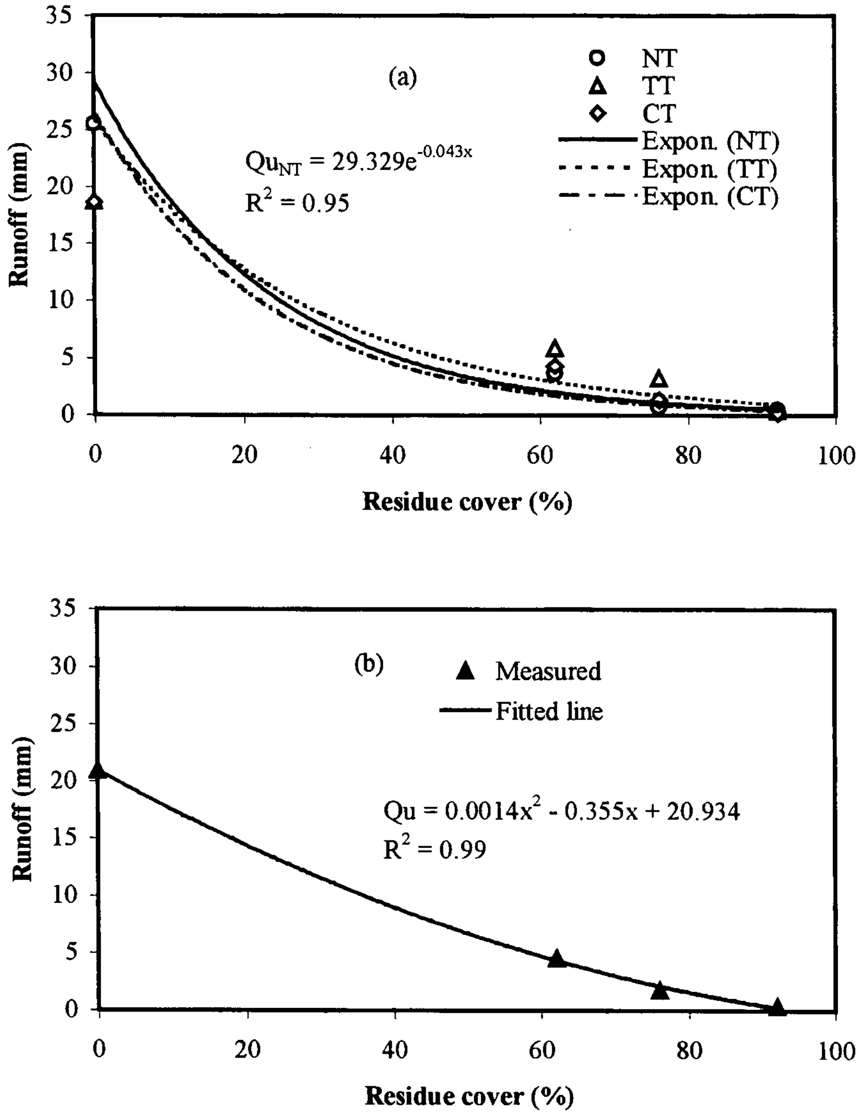


Figure 4.18. Mean total runoff (Qu) as a function of percentage residue cover during the main rainfall season of 2001 for (a) three tillage treatments and (b) the combined mean runoff from the four rates of residue cover.

4.2.3.3 Runoff coefficients

The runoff coefficients were calculated as the ratio of runoff to the rainfall amount and are expressed in percentage. The results are presented in Tables 4.6 and 4.7 and Figure 4.19 for both seasons, respectively. Because all the treatments received the same amounts of rain the treatment effects for the runoff coefficient will be similar to those discussed for runoff in Section 4.2.3.

The relationship between residue cover and the mean runoff coefficient of all the tillage treatments is presented in Figure 4.20, showing a substantial decrease in the runoff coefficient with an increase in residue cover. As shown in Figure 4.20, there was a negative linear relationship between runoff coefficient and the percentage residue cover for the first year data, while it was non-linear for the second year data that was fitted to a second-degree polynomial function. Freebrain *et al.* (1993) reported a linear relationship between the runoff coefficient and percentage residue cover. The result of the rainfall simulation study (see Section 3.2.4.2) also showed that the relationship between these two parameters was linear. The combined data from the two seasons was related to the percentage residue cover in a second-degree polynomial form with strong coefficient of determination (Figure 4.20c).

Table 4.6. Runoff coefficients for three tillage and four rates of residue cover during the main rainfall season of 2000

Tillage	Residue (t/ha)	Dates of rain						
		08-Jul	12-Jul	12-Aug	13-Aug	25-Aug	16-Sep	**Total**
		Rain (mm)						
		19.6	18.6	35.6	9.6	27.4	21.8	**216.2***
		Runoff coefficient (%)						
No-tillage	0	12.09	24.57	24.72	22.19	15.18	31.01	**13.32**
	2	3.16	4.03	23.03	6.67	1.68	9.54	**5.90**
	4	0.36	0.32	7.02	0.00	0.00	1.70	**1.38**
	8	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Traditional	0	1.68	6.29	24.30	15.83	14.78	25.41	**9.83**
	2	1.02	0.16	19.66	4.06	3.91	17.06	**5.74**
	4	0.00	0.00	2.53	0.00	0.00	0.00	**0.42**
	8	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Conventional	0	0.82	0.86	20.22	5.31	15.47	24.40	**8.04**
	2	2.40	0.00	17.98	2.50	8.72	20.50	**6.46**
	4	0.00	0.00	1.12	0.00	0.00	1.70	**0.36**
	8	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Average	0	4.86	10.57	23.08	14.44	15.15	26.94	**10.43**
	2	2.19	1.40	20.22	4.41	4.77	15.70	**6.03**
	4	0.12	0.11	3.56	0.00	0.00	1.13	**0.72**
	8	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**

*The total rainfall of the season.

Table 4.7. Runoff coefficients for three tillage and four rates of residue cover during the main rainfall season of 2001

Tillage	Residue (t/ha)	Dates of rain				
		1-Aug	5-Aug	8-Aug	14-Sep	**Total**
		Rain (mm)				
		40	33.8	53.8	15.2	**269.2**[*]
		Runoff coefficient (%)				
No-tillage	0	16.75	20.44	16.71	19.08	**9.47**
	2	1.08	4.11	3.46	0.00	**1.37**
	4	0.28	1.21	0.50	0.00	**0.29**
	8	0.00	0.95	0.30	0.00	**0.18**
Traditional	0	4.80	22.96	15.41	4.74	**7.04**
	2	5.45	1.51	5.54	1.25	**1.71**
	4	4.40	1.57	1.78	0.00	**0.84**
	8	0.00	0.24	0.59	0.00	**0.15**
Conventional	0	9.18	19.35	14.98	2.11	**6.91**
	2	0.68	3.70	5.15	0.00	**1.59**
	4	0.00	0.00	2.53	0.00	**0.51**
	8	0.00	0.41	0.35	0.00	**0.07**
Average	0	10.25	20.92	15.69	8.62	**7.77**
	2	2.40	3.11	4.70	0.39	**1.71**
	4	1.55	0.92	1.60	0.00	**0.66**
	8	0.00	0.53	0.41	0.00	**0.15**

[*] The total rainfall of the season.

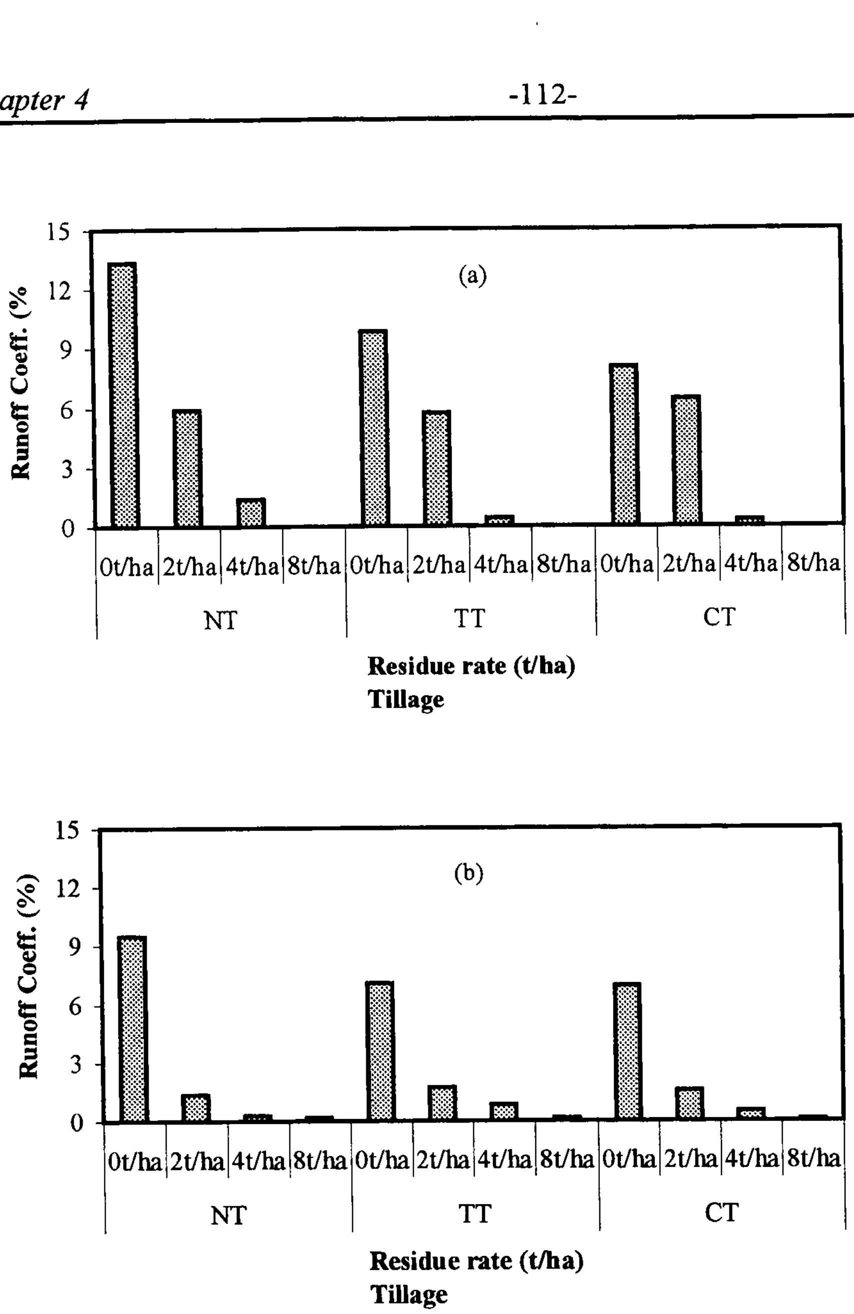


Figure 4.19. Runoff coefficients for three tillage practices at four residue rates during the main rainfall seasons of (a) 2000 and (b) 2001, based on the total rainfall and total runoff.

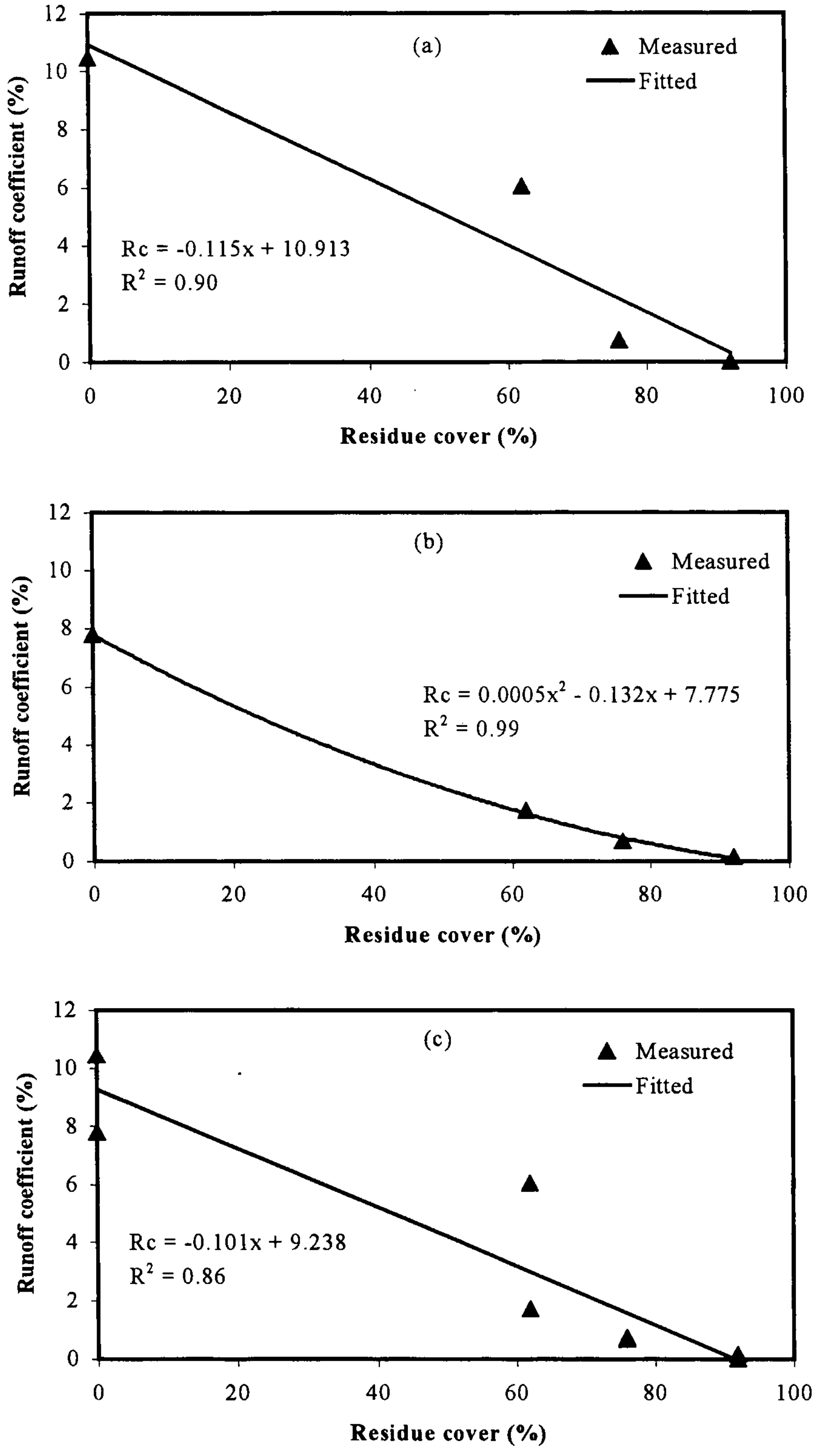


Figure 4.20. Runoff coefficients as a function of percentage residue cover for the main season of (a) 2000, (b) 2001, and (c) combined data from the two seasons.

4.2.3.4 Runoff mulch factor

The relationship between residue cover and the runoff mulch factor, which is expressed as the ratio between the total runoff from residue-covered plots and the total runoff from plots without residue, are given in Figure 4.21. It shows the relative effectiveness of residue in reducing runoff.

The 2001 data fitted a non-linear decline better (Figure 4.21b). The combined data of the runoff mulch factor for the two seasons were also related to the percentage residue cover in a linear as well as non-linear form (Equations 4.1 and 4.2) with strong coefficient of determination (Figure 4.21c). The result of the simulated rainfall study (see Section 3.2.1.4) showed a non-linear inverse exponential function relationship between the runoff mulch factor and the percentage residue cover. The 2001 data was also fitted to an inverse exponential function (not shown in Figure 4.21c), but with a lower coefficient of determination. The differences between the fitted equations for the runoff mulch factor at the same residue rate, i.e. Equations 4.1 and 4.2 and those obtained for the simulated rainfall (Figure 3.19), is believed to be due to the difference in soil type, slope and rainfall characteristics. Gilley *et al.*, (1986) reported an inverse exponential relationship between these two parameters for sorghum and soybean residues.

$$RMF = 3 * 10^{-5} x^{2} - 0.014 + 1,\ R^{2} = 0.97 \ \ldots\ldots\ldots\ldots\ [4.1]$$

$$RMF = -0.011x + 1,\ R^{2} = 0.96 \ \ldots\ldots\ldots\ldots\ [4.2]$$

Where RMF = Runoff Mulch Factor

x = Percentage residue cover

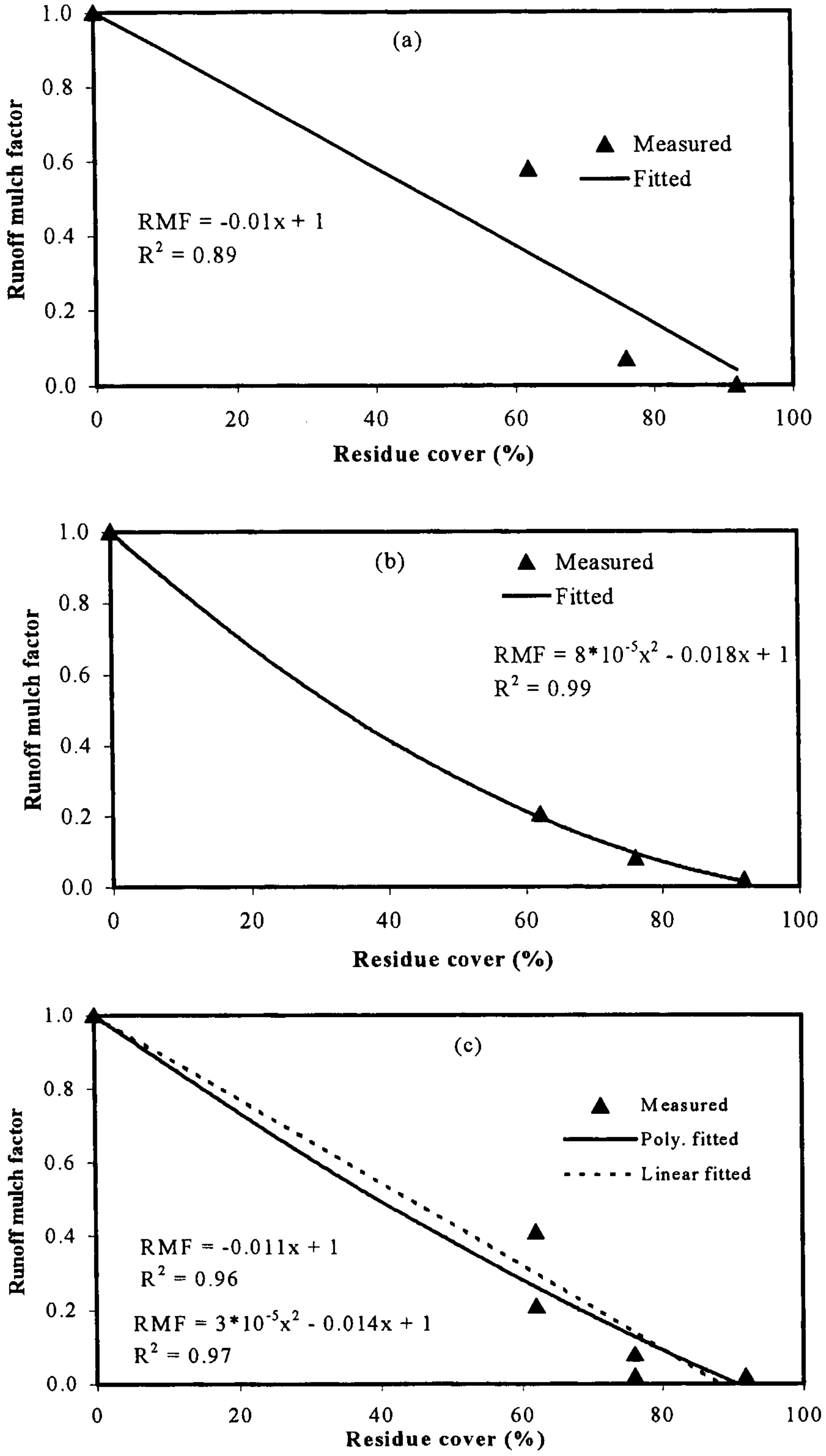


Figure 4.21. Runoff mulch factor (RMF) as a function of percentage residue cover for three tillage practices during the main rainfall season of (a) 2000, (b) 2001, and (c) combined data from the two years.

4.3 Empirical Relationships Between Total Runoff and Rainfall Characteristics

Erosion is closely related to rainfall through the detaching power of raindrops striking the soil surface and through the contribution of rainfall to runoff. The response of soil to rainfall also depends on the antecedent rainfall conditions. When rain fall on a dry soil most of the water will infiltrate generating little runoff (Morgan, 1995). The amount of runoff generated from a given area depends mainly on the rainfall characteristics, such as rainfall amount, intensity and kinetic energy. The relationships between rainfall characteristics and runoff amounts are presented here.

4.3.1 Total Rainfall

Empirical relationships between the normalized runoff and rainfall for the different events of the two rainfall seasons (2000 and 2001) and for the combined data of the two years are presented in Figure 4.22. Runoff from the different rates of residue cover was normalized by dividing the runoff from a given rate of residue cover with the mean runoff mulch factor for that rate. By doing this all data is converted to their bare condition equivalents. Figures 4.22(a) to (c) show that runoff increased non-linearly as the rainfall amount increased. The combined data from the two seasons was also fitted to linear equation. On an annual basis, runoff depth is reported to be linearly related to rainfall depth (Boers *et al.*, 1986). Boers *et al.* (1986) suggested that this relationship could also be adapted for a single storm event on a daily basis. However, Karnieli & Ben-Asher (1993) reported that the relationship between runoff and rainfall was non-linear, quadratic form.

Figure 4.23 shows relationships between mean runoff from bare plots, averaged over the three tillage practices, and rainfall for two cases where runoff was related to all rainfall events (Figure 4.23a) and in Figure 4.23b to the rainfall amount from erosive storms only. The threshold rainfall value of 5.3 mm can be determined from the linear equation in

Figure 4.23(b) as the intercept of the x-axis when the runoff amount is zero. Figure 4.23(a) shows that the data fitted a quadratic equation well.

4.3.2 Kinetic Energy

The total kinetic energy of the storms was related to the normalized runoff for the events during the two seasons as well as the combined data of the two years. The results are given in Figure 4.24. The type of relationship between these two parameters, however, varied. The first year's data was fitted to a polynomial function, whereas the data for the second year and the combined data fitted a linear equation better.

4.3.3 Erosivity

The relationships between the erosivity index, which is the product of the total kinetic energy and the maximum 30-minute intensity, and the normalized runoff are presented in Figure 4.25. The first year's data was fitted to a polynomial function, whereas the data for the second year and the combined data were fitted to linear equations.

4.3.4 Application of the Empirical Equations

Depending on the type of rainfall characteristics available, either the total rainfall, kinetic energy or erosivity index can be used to estimate runoff under bare conditions from soils similar to the one used in this experiment, using the appropriate equations. When a residue cover is present the calculated expected runoff can be corrected by multiplying it with the appropriate runoff mulch factor, calculated using Equations 4.1 or 4.2.

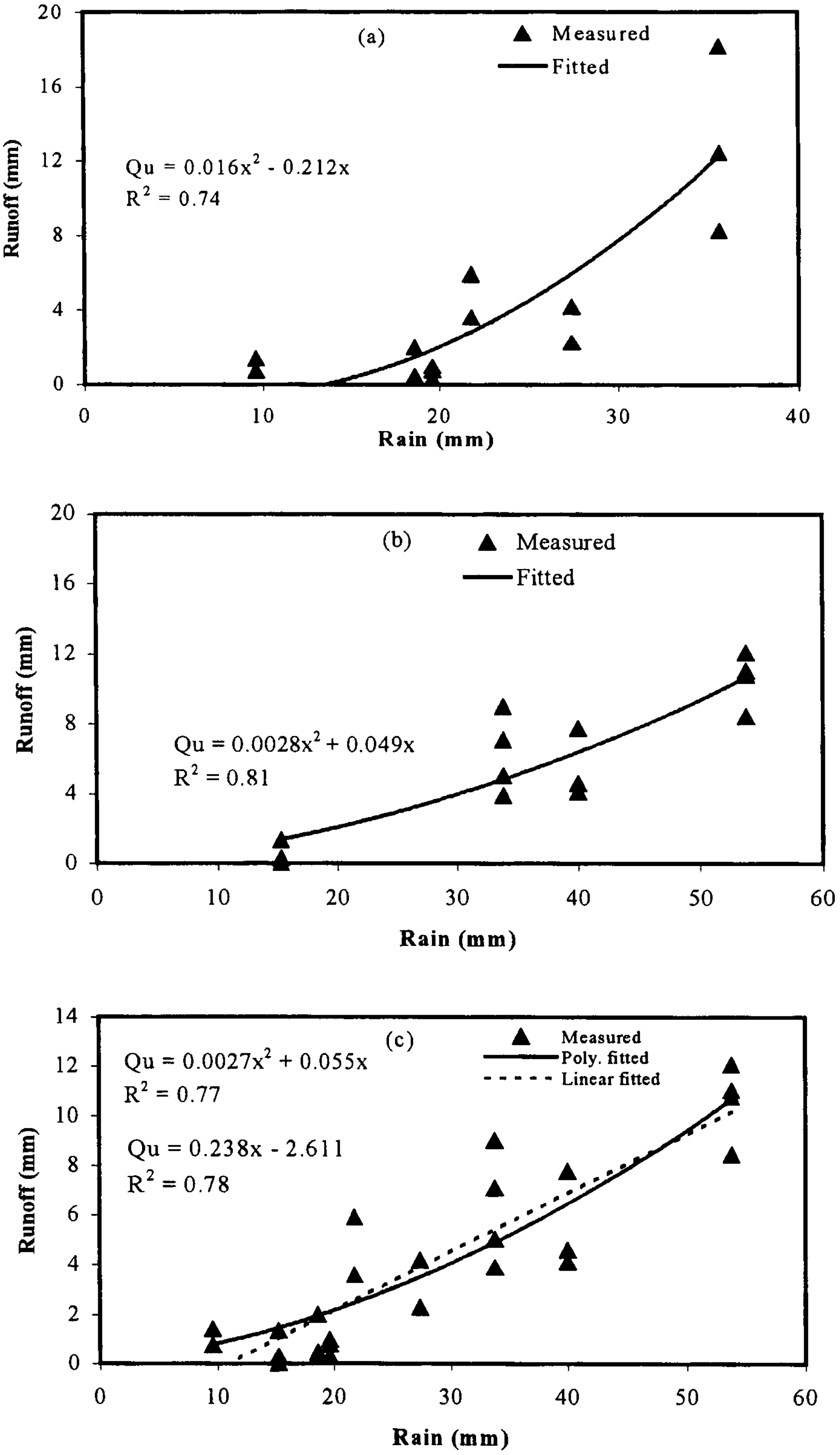
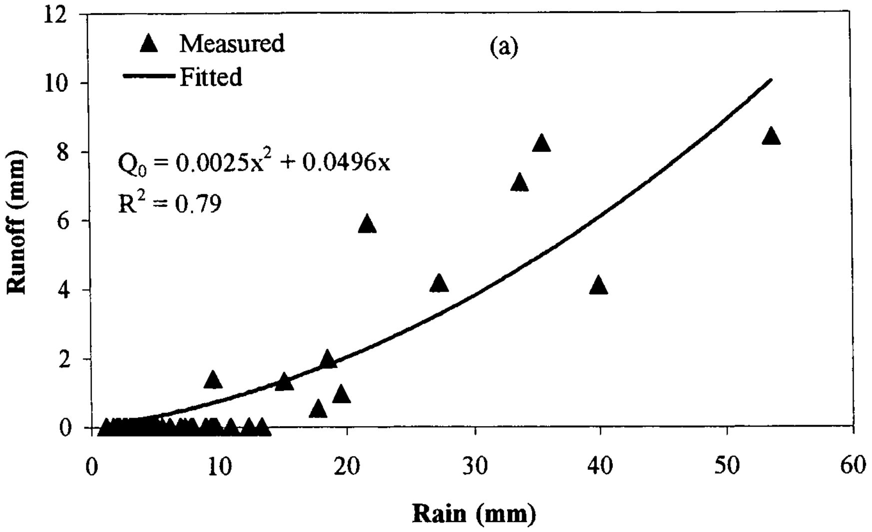


Figure 4.22. Relationships between the normalized runoff and rainfall for (a) 2000, (b) 2001 and (c) combined data for both seasons.



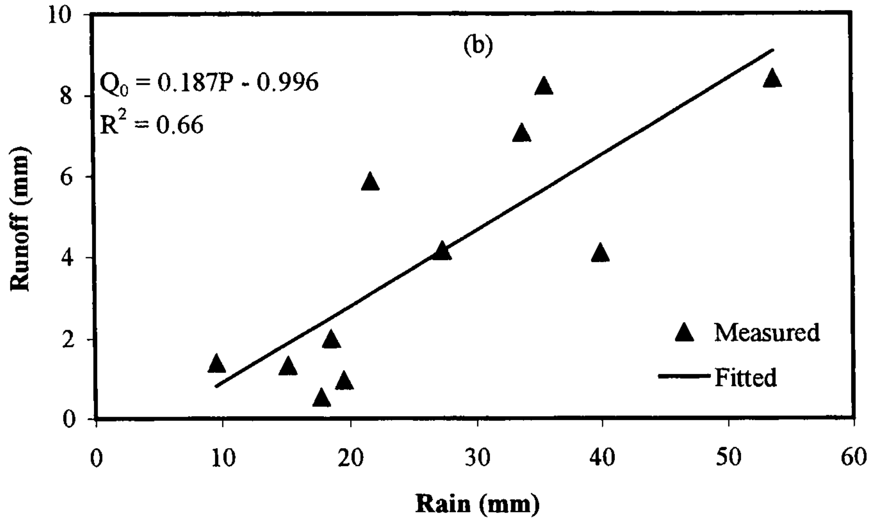


Figure 4.23. Runoff from bare plots as a function of rainfall for (a) all rainfall events and (b) for rainfall from erosive storms, for the combined data of both seasons.

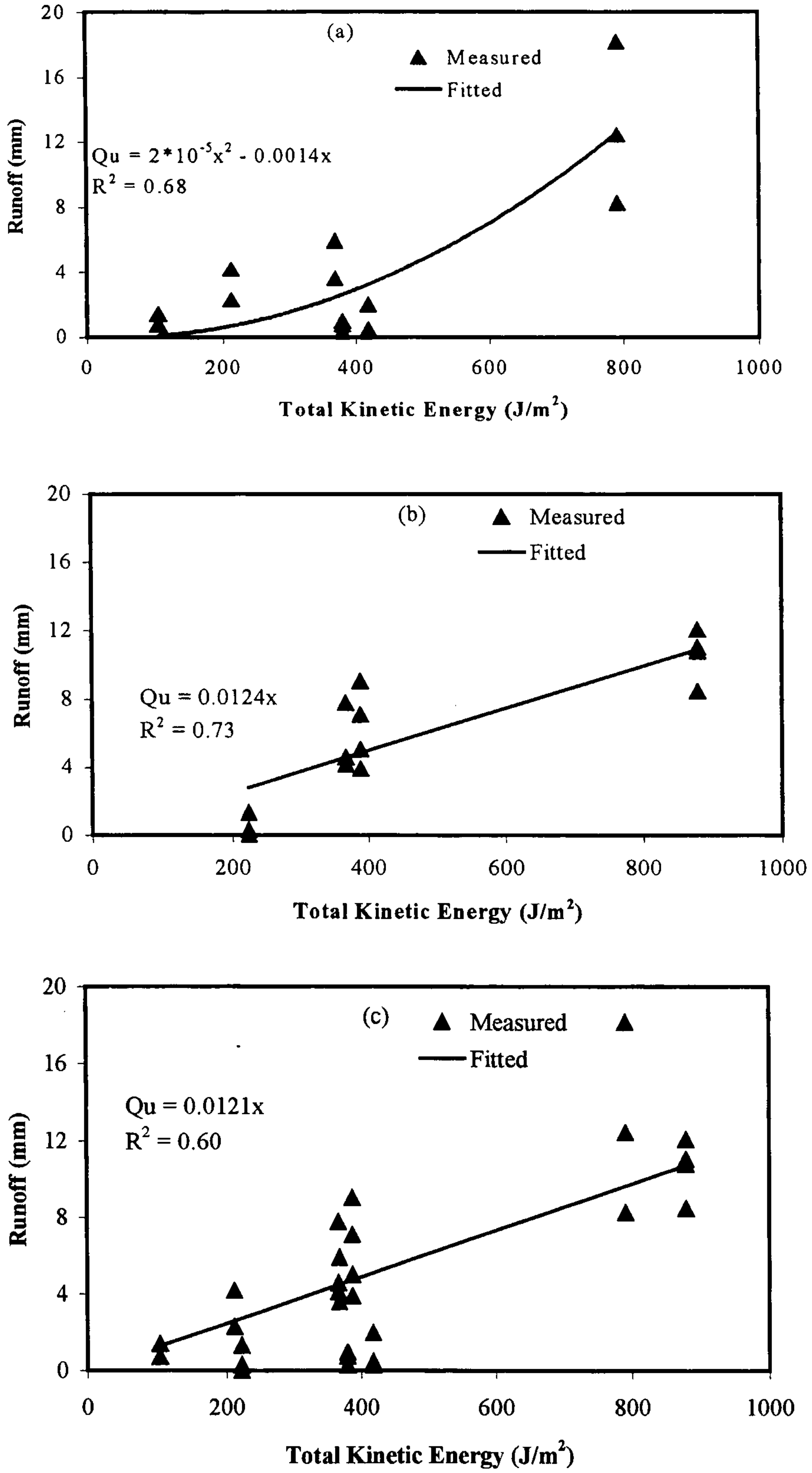


Figure 4.24. Relationships between normalized runoff and kinetic energy for (a) 2000, (b) 2001 and (c) combined data for both seasons.

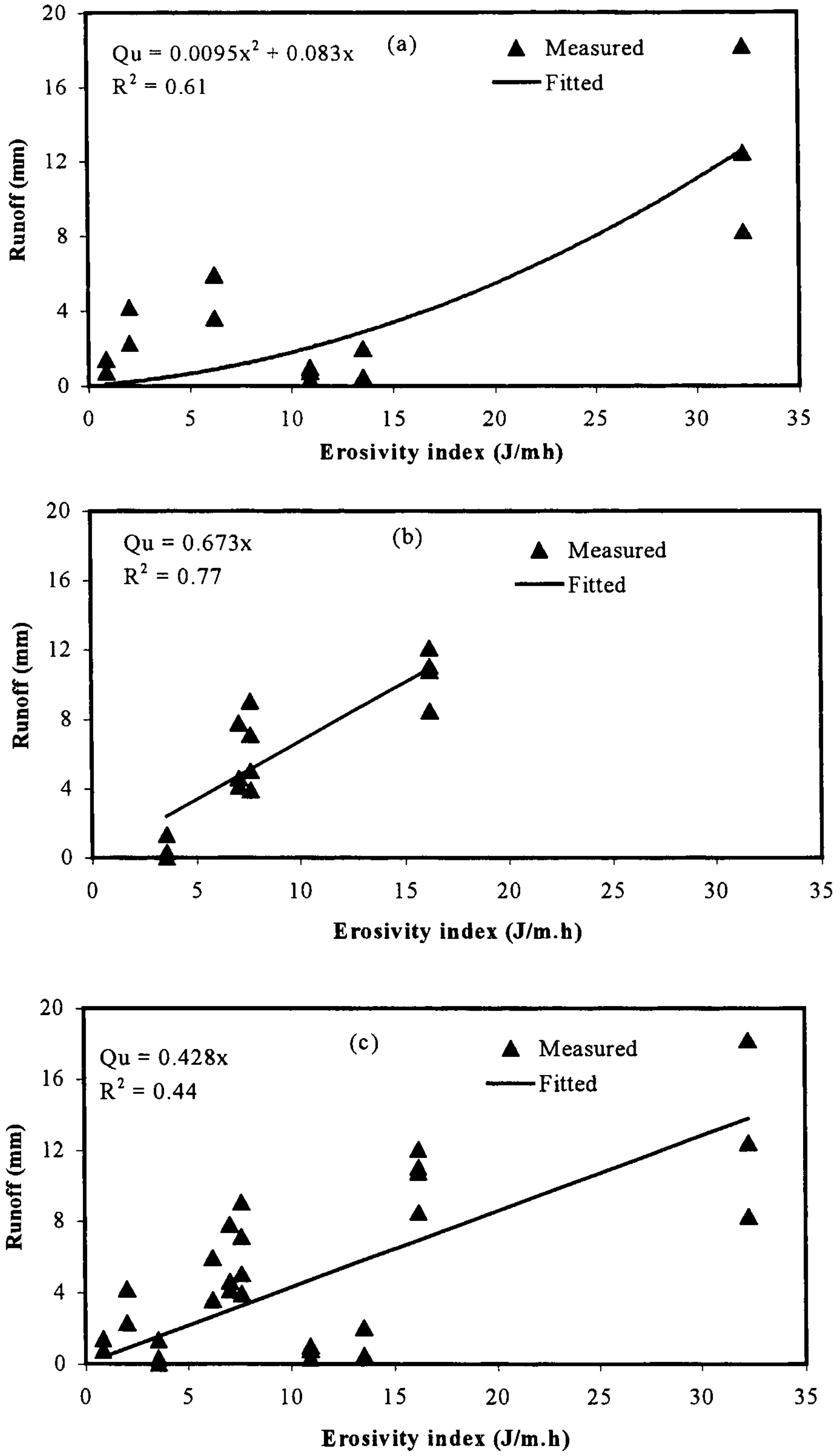


Figure 4.25. Relationships between normalized runoff and erosivity index for (a) 2000, (b) 2001 and (c) combined data for both seasons.

4.4 Conclusions

The effect of tillage practices and rates of residue cover on runoff was investigated in a field experiment at the Alemaya University, Ethiopia, which consisted of three tillage treatments, namely no-tillage, traditional and conventional tillage, combined with four levels of wheat residue cover (0, 2, 4, and 8t/ha). The objective of this experiment was to evaluate the effects of the different treatments on runoff. The experiment ran for two consecutive seasons, 2000 and 2001, during the main rainfall season, which covered the months of July, August and September.

Apart from the total rainfall, the intensity characteristics of the storms affected the amounts of runoff. The intensity characteristics included parameters like the peak intensity or intensities, the duration of the high intensity peak(s) and where it occurred during the storm. Unfortunately there were only ten storms during the two seasons that produced runoff. This small number of storms made it impossible to do a proper analysis on the effect of rainstorm characteristics on runoff. Apart from the total rainfall the 30-minute intensity, total kinetic energy and erosivity index of each event were used as indicators of the rainstorm characteristics.

The amount of residue cover required for reducing runoff was closely related to the intensity of the storm. The combined runoff data for the two seasons showed that runoff decreased non-linearly with an increase in the percentage residue cover. It was observed that for most of the storms a residue rate of 2t/ha reduced runoff significantly compared with the bare plots. For these storms, the decrease in runoff at higher residue rates of 4 and 8t/ha were non-significant. At higher intensity storms, such as the one on the 12th of August 2000, which reached intensities of more than 200 mm/hr, a residue rate of 2t/ha was insufficient to reduce runoff and residue rate of 4t/ha was required to sufficiently reduce runoff for these soil and rainfall conditions. Roth *et al.* (1988) recommended that at least 4 – 6t/ha of mulch is needed to reduce runoff and erosion effectively. However, other reports by Lattanzi *et al.* (1974) and Unger *et al.* (1991) indicated that much lower residue amounts could greatly reduce erosion because surface residue reduces soil loss much more than it reduces runoff. In another report, Freebrain *et al.* (1993) suggested that a cover level of 30% appears to be a critical for erosion control. In this experiment a rate of 2t/ha was equal to 60% cover.

There was a significant effect of tillage on runoff at a 5% probability level during the first few storms of the first season, where runoff from no-tillage was significantly higher than from the traditional and conventional tillage. It appears that absence of roughness associated with no-tillage practices may have resulted in higher runoff compared with tilled conditions. Freebrain *et al.* (1993) reported that the roughness created by a chisel plough was able to reduce annual runoff from 34 mm on a smooth no-tillage to 16 mm on a tilled soil. Bradford & Huang (1994) reported that differences in runoff between conservation and conventional tillage systems was more pronounced on freshly tilled soil before the impact from the raindrops created surface sealing and crusting.

Generally, the effect of tillage on runoff is reported to take a long time to influence certain physical and hydraulic properties of the soil. For instance, Dickey *et al.* (1989) reported that between 5 to 6 years is required for changes in soil physical properties to become measurable, resulting in higher infiltration rates and lower runoff. In another study, Voorhees & Lindstrom (1984) have reported that 3 to 4 years are required before conservation tillage has a more favourable porosity in the upper 0 to 15 cm depth of soil.

The runoff generated from a given area is a function of the rainfall characteristics. Relationships between runoff and rainfall characteristics, such the as amount, erosivity and kinetic energy were established from the two year data set. The total runoff from the residue-covered plots was normalized by dividing the runoff amount from each of the residue-covered plots by its respective mean runoff mulch factor. This conversion of the runoff data would assume as if all the runoff data were obtained from the uncovered plots and would allow establishment of unique equations through regression analysis. The relationships between runoff and total rainfall was non-linear, which was fitted to a second-degree polynomial function. Conversely, the relationship between total runoff and total kinetic energy was linear, as well as that of the runoff – erosivity index relationship.

The results from this study indicate that residue cover is more important in reducing runoff than the effect of tillage for this particular soil and climate condition. It has been established by several natural and simulated rainfall studies that surface cover reduces soil erosion more than any other factor in tillage management (Freebrain & Wockner, 1986; Gilley *et al.*, 1986a; Sallaway *et al.*, 1988). Allowing the residue to remain on the soil surface could significantly reduce the amount of surface crusting thereby increasing infiltration (Hillel, 1980). Soil surface characteristics usually govern water entry into the soil during rainfall events. The surface cover reduces erosion by reducing the runoff volume through stubble protecting the soil surface, thus reducing aggregate breakdown and compaction of the soil surface by raindrop impact (Edwards, 1982; Freebrain *et al.*, 1993).

CHAPTER 5

EFFECT OF TILLAGE AND RESIDUE COVER ON EROSION UNDER SIMULATED RAINFALL (UFS EXPERIMENTAL SITE)

5.1 Introduction

Tillage alters the porosity, pore size distribution and pore continuity of the soil profile near the surface (Hillel, 1980; Klute, 1982) and thus has a major effect upon the infiltrability of the soil. When the rate of water application to a soil surface exceeds the infiltration rate, water ponding occurs and runoff begins, resulting in erosion. A reduction in runoff and erosion will result from practices that increase the infiltration capacity of the soil, increase the contact time and/or reduce surface sealing (Bennie & Hensley 2001). It is commonly accepted that covering the soil with crop residue will help reduce runoff and erosion (Hillel, 1980; Papendick *et al.*, 1990; Sallaway *et al.*, 1988; Unger *et al.*, 1991). Primary tillage operations can also increase infiltration thereby reducing the danger of erosion by increasing soil porosity and establishing channels or voids in the surface layer that conduct water into the soil profile (Lindstrom & Onstad, 1984).

Crop residue management is one of the most effective means of controlling runoff and erosion on cultivated land (Mannering & Meyer, 1963; Lattanzi *et al.*, 1974). The importance of protecting the soil surface from rainfall with a crop residue to preserve beneficial soil properties and thereby reduce erosion has long been recognized.

Tillage is often considered to encourage erosion through degradation of soil physical properties, leading to an increase in runoff and sediment concentration. A lack of tillage decreases both runoff and sediment concentration through an increase in aggregate stability and infiltration capacity resulting from biotic activity (Kinnel, 1996). However, contradictory results have been reported from various runoff studies, many of which may be explained due to regional differences in soil physical properties (Myer & Wagger, 1996).

An erosion experiment was conducted under simulated rainfall at the University of the Free State Experimental Site on a sandy soil with the objective of evaluating the effect of tillage and residue cover on erosion. The experiment consisted of three tillage practices and four rates of residue cover (see Section 2.2.2). This chapter, therefore, presents the results of the soil loss under simulated rainfall for the three tillage practices and four rates of residue cover.

5.2 Results and Discussion

5.2.1 Erosion under Simulated Rainfall With a Constant Intensity

Soil loss from a given area depends principally on the energy of the rainfall (erosivity) and the vulnerability of the soil to erosion (soil erodibility). There are also other factors that influence the erosion rate of a soil, such as topographical factors (slope and slope length) and soil management factors. Tillage is one of the soil management factors that influence the susceptibility of a soil to erosion. The soil lost from an area is the quantity discharged across a boundary by surface water flow (Kinnel, 1997; Kinnel & Risse, 1998). As a result, soil loss for a rainfall event (A_e) is given by the product of the runoff amount for that event (Q_e) and the sediment concentration for that event (C_e).

$$A_e = Q_e C_e \qquad \text{[5.1]}$$

5.2.1.1 Sediment concentration

The sediment concentration, which is expressed in gram of suspended sediment in a liter of runoff, is shown in Figure 5.1 for three tillage treatments at four rates of residue cover.

To illustrate the effect of tillage practices, the results are presented at the same rate of residue cover. For the bare no-tillage treatment the sediment concentration was as high as 11.9g/l whereas, at a residue rate of 8t/ha, it dropped to 0.13g/l. The intensity of the simulated rainfall was kept constant at 60 mm/hr.

The sediment concentration per liter of runoff from the bare no-tillage treatment was higher than for stubble mulch and conventional tillage and started to stabilize at 10g/l after about 70 mm of cumulative rain (Figure 5.1a). The sediment concentration from the freshly ploughed conventional tillage started to increase after two hours or 120 mm of rainfall, showing a sharp increase thereafter. The stubble mulch tillage was in between these two tillage treatments.

The results of sediment concentration at different rates of residue cover are presented in Figures 5.1 (b), (c) and (d). At all three levels of residue cover, namely 2t/ha, 4t/ha and 8t/ha the sediment concentration from the no-tillage treatment was lower than that from stubble mulch and conventional tillage, with the residue applied on the surface. This indicates that the presence of residue has been much more effective in reducing the soil loss from no-tillage. At a residue cover of 2t/ha the sediment concentration from stubble mulch increased until a cumulative rainfall of 100 mm was reached, where after it declined very sharply to the same level as the other treatments. However, at the rate of 2t/ha residue cover the sediment concentration from conventional tillage continued to increase and did not stabilize as the other treatments with an increase in cumulative rainfall. At higher residue covers (4t/ha and 8t/ha) the sediment concentration started to decrease after a cumulative rainfall of between 90 mm to 120 mm on all three tillage treatments.

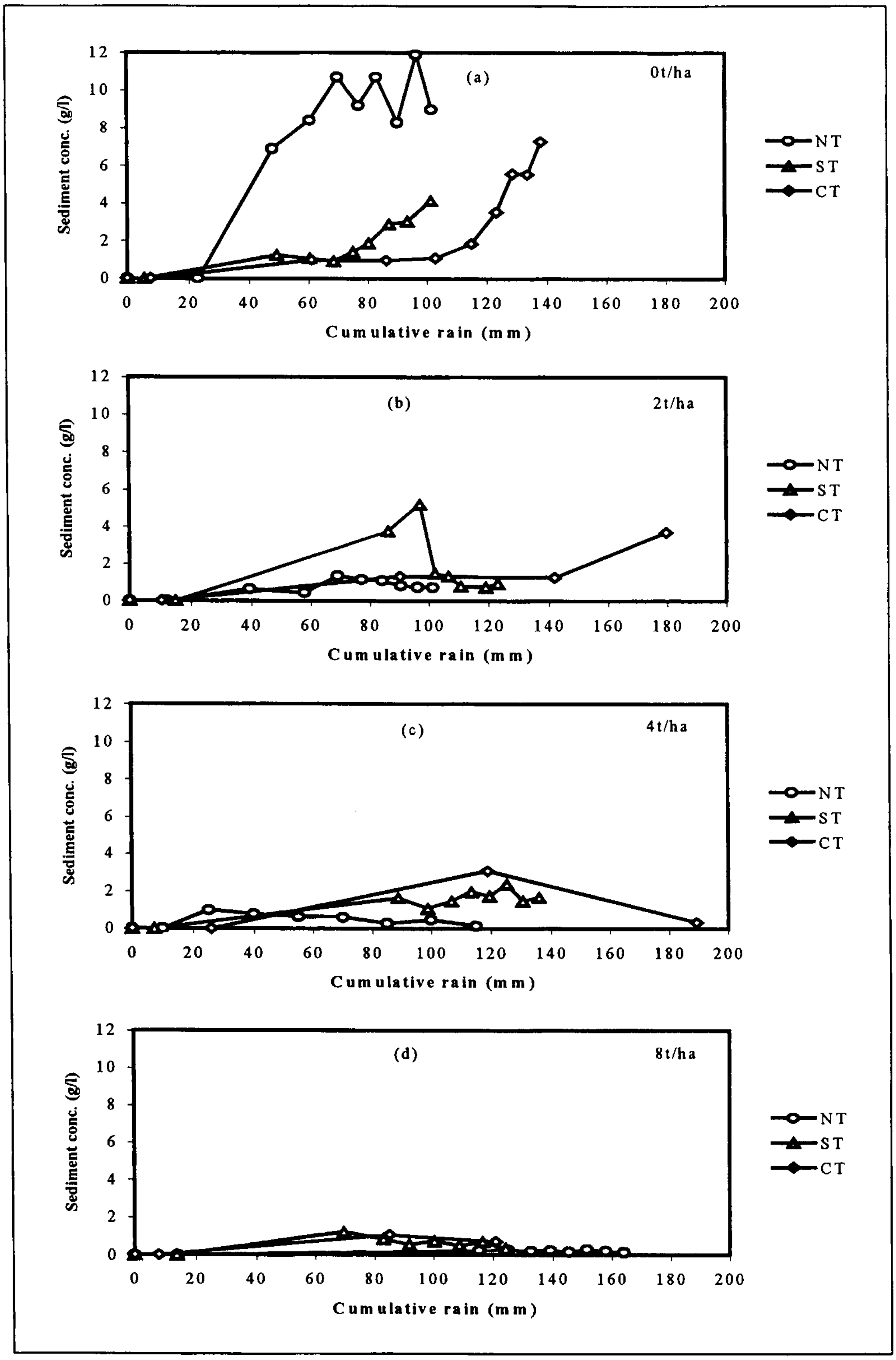


Figure 5.1. Sediment concentration as function of cumulative rainfall for three tillage practices at residue rates of (a) 0t/ha, (b) 2t/ha, (c) 4t/ha, and (d) 8t/ha.

Gilley *et al.* (1986a) reported a reduction in sediment losses with increased corn residue application. Choudhary *et al.* (1997) examined the long-term effect of tillage on soil loss from a silt loam soil and reported that the conventional method of mouldboard plowing had the highest soil loss compared to chisel plowing and no-tillage. In their case the conventional tillage was not covered with residue after mouldboard ploughing. In another report, Bradford & Huang (1994) indicated that the surface residue effect was greater than soil tillage in maintaining high infiltration rate and reducing soil loss.

The sediment concentration mulch factor (SCMF), which is the ratio between the sediment concentration from plots with residue and the sediment concentration from plots without residue (Gilley *et al.*, 1986, 1986a), is an indicator of the relative effectiveness of residue cover in reducing sediment loss. The SCMF for the three tillage treatments has been calculated and the results are presented in Figure 5.2. The results showed that the SCMF decreased linearly with an increase in percentage residue cover, with small differences in the slopes of the fitted equations. It can be observed from Figure 5.2a that addition of residue has been much more effective in reducing sediment concentration on no-tillage than on the other two tillage treatments. Figure 5.2b shows that the average SCMF of the three tillage practices as a function of percentage residue cover.

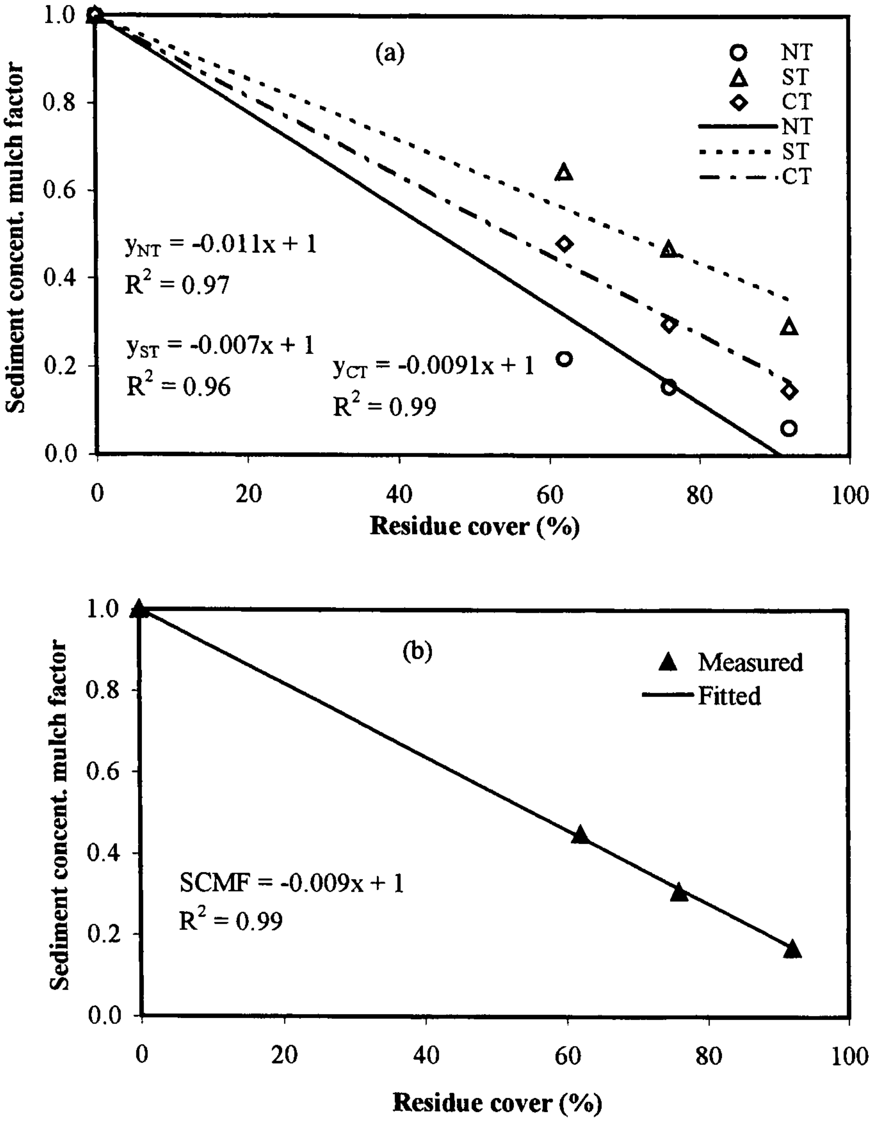


Figure 5.2. Sediment concentration mulch factor (SCMF) as a function of percentage residue cover fitted to linear equations for (a) three tillage treatments and (b) for the mean of the three tillage treatments.

5.2.1.2 Soil loss

The soil losses from the different treatments are given in Figure 5.3. For comparative purposes, the mean soil loss from the tillage treatments at a cumulative rainfall of 100 mm was compared. It can be observed from Figure 5.3 that the highest soil loss of

0.925t/ha came from the bare no-tillage with a densely sealed surface and a high runoff. This was followed by the bare stubble mulch tillage (0.20t/ha) without residue. The no-tillage treatments covered with residue rates of 2t/ha, 4t/ha and 8t/ha had soil losses of 0.10t/ha, 0.057t/ha and 0.008t/ha, respectively. Conventional tillage had the lowest soil loss of 0.044, 0.027, 0.022 and 0.021t/ha for plots covered with 0, 2, 4, and 8t/ha of residue, respectively. The loose surface conditions of the freshly ploughed soil reduced runoff, which resulted in lower soil loss.

When comparing the soil loss from the three tillage practices under bare soil conditions, the soil loss from stubble mulch tillage and conventional tillage was 21.6% and 4.7% of the loss from the no-tillage practice, respectively. The mean soil loss of the residue cover treatments for each of the three tillage treatments is presented in Figure 5.4. It shows that the no-tillage treatment had significantly higher (5% probability level) soil loss (0.272t/ha) than stubble mulch tillage (0.085t/ha) and conventional tillage (0.028t/ha), which did not differ significantly.

Foley *et al.* (1991) examined the effect of conventional, stubble mulch, and no-tillage on the infiltration of an Oxisol and Alfisol and reported that tillage treatments did not affect infiltration rates but the dominant factor affecting infiltration was surface protection. Once a crust has formed on exposed soil, infiltration remained low under subsequent rainfall unless the seal had been mechanically disturbed, especially for no-tillage. Overall, they concluded that surface protection by stubble is the most effective approach to improve water storage during fallow periods.

Moreover, Rao *et al.* (1998a, 1998b) argued that effectiveness of soil management practices in reducing runoff on Alfisols depend on the ability to reduce the formation of crusts. Mechanical rupture of crusts by tillage methods has little long-term impact on increasing infiltration rate, as the effect of tillage is soon lost by the formation of new surface crusts after a few rainstorms. They emphasized the need for developing alternative methods to improve the organic matter content of the soil and the structural stability of the soil that are required to maintain high infiltration rates, and thereby reducing runoff and soil loss.

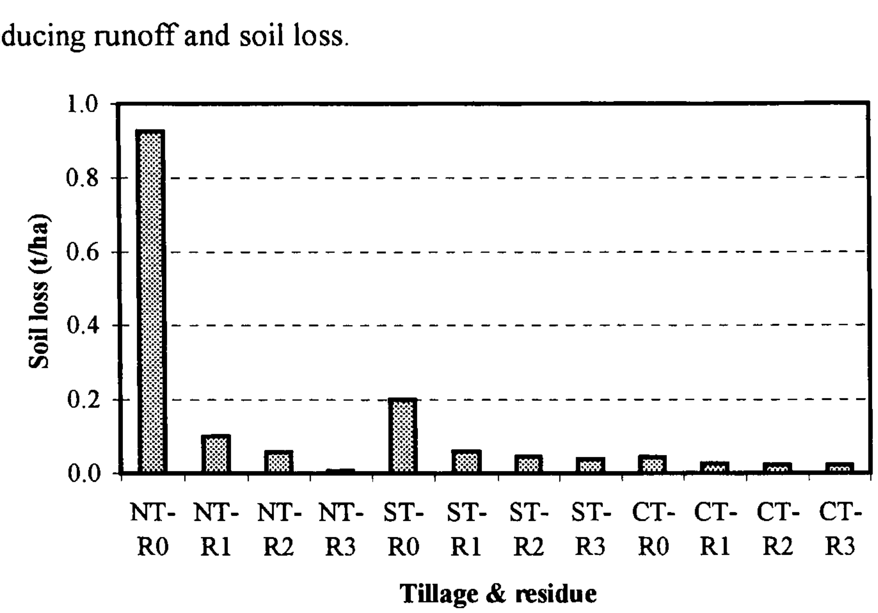


Figure 5.3. Mean soil loss from three tillage practices and four levels of residue cover at a cumulative rainfall of 100 mm. *Note:* NT = No-tillage, ST = Stubble mulch tillage, CT = Conventional tillage. R0 = No residue, R1 = 2t/ha, R2 = 4t/ha and R3 = 8t/ha residue

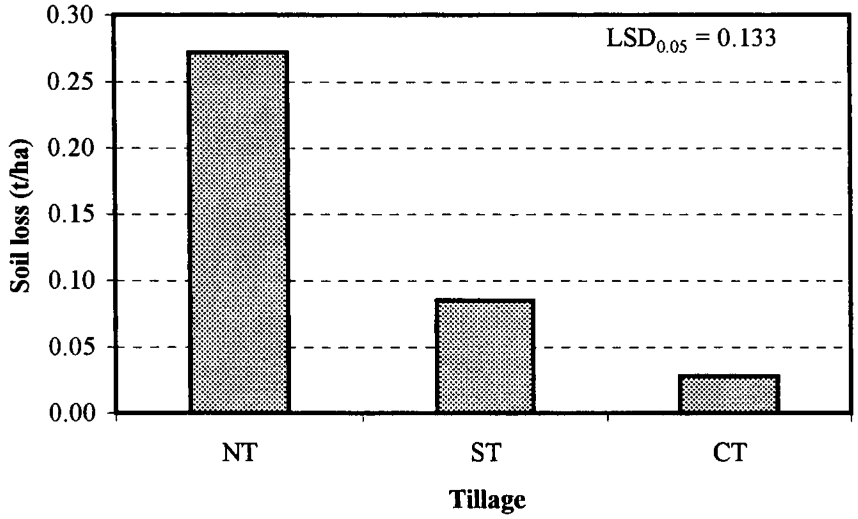


Figure 5.4. Mean soil loss from the three tillage practices at a cumulative rainfall of 100 mm.

An analysis of variance on the residue rates indicated that a rate of 2t/ha reduced the soil losses significantly compared to the bare soil. The differences among the different rates of residue cover were non-significant. The means of the different tillage practices for each of the residue rates are given in Table 5.1.

Table 5.1. Mean soil loss (t/ha), over the three tillage practices, from four levels of residue cover at a cumulative rainfall of 100 mm

Residue cover (t/ha)	Soil loss (t/ha)
0	0.389^{a*}
2	0.061^{b}
4	0.041^{b}
8	0.022^{b}
LSD	0.168

(*): Numbers in the same column followed by the same letter(s) are not significantly different at 1% probability level.

The equations for the relationships between the mean soil loss from the tillage treatments and the percentage residue cover are summarized in Table 5.2 for the three tillage treatments.

Table 5.2. Relationship of soil loss (SL, t/ha)) and percentage residue cover (Pc)

Tillage	Equation	R^2
No-tillage	$SL = 1*10^{-4}*Pc^2 - 0.0198*Pc + 0.924$	0.99
Stubble mulch	$SL = -1.9*10^{-3}*Pc + 0.193$	0.96
Conventional	$SL = -2.6*10^{-4}*Pc + 0.043$	0.98

Mean soil loss from the three tillage treatments was related to different rates of residue (t/ha) (Figure 5.5) and percentage residue cover (Figure 5.6). From close observation of both graphs and the practicality of the relationships, the soil loss – percentage residue cover relationships makes more sense and has more practical applicability than the soil loss – residue rate relationships. The type of relationship, however, varies from one tillage type to the other. The soil loss – percentage residue cover relationship on the no-tillage treatment was fitted to a second-degree polynomial equation with strong coefficient of determination (R^2 = 0.99). The relationships on the conventional and stubble mulch treatments were, however, linear.

The curves in Figure 5.6 illustrate the interaction between residue rates and the tillage treatments. The amount of soil loss reduction by the different rates of residue cover from the three tillage treatments were 89% reduction in soil loss by 2t/ha compared to the bare no-tillage treatment with corresponding values of 72% and 39%, for stubble mulching and conventional tillage, respectively. It is obvious that a residue rate of 2t/ha drastically reduced soil loss irrespective of the type of tillage.

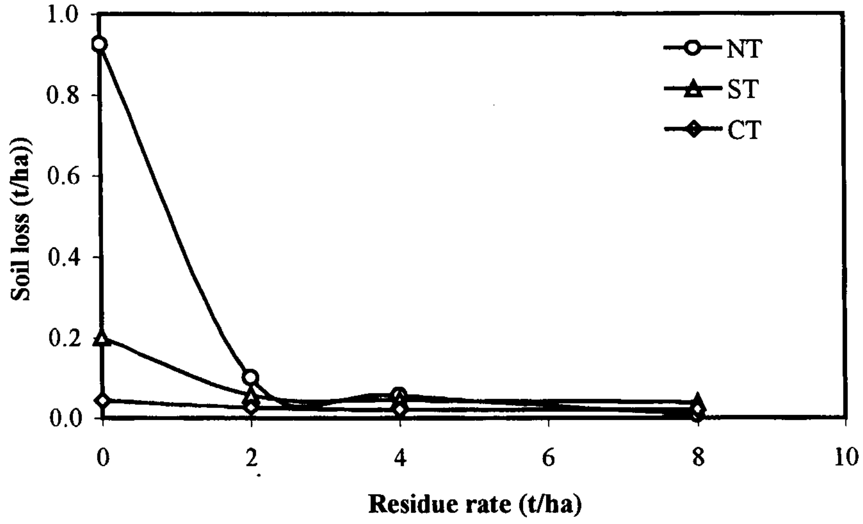


Figure 5.5. Mean soil loss as function of residue rate from three tillage practices at a cumulative rainfall of 100 mm. Note: NT = No-tillage, ST = Stubble mulch tillage, CT = Conventional tillage.

The relationship between the combined mean soil loss from the tillage treatments and percentage residue cover is presented in Figure 5.7. The data was fitted to two different equations, quadratic (second-degree polynomial) and exponential functions. In both cases the data fitted the equations well with strong coefficients of determination (R^2 = 0.99).

The polynomial equation has more physical meaning in that it gives a definite intercept, which corresponds to an amount of soil loss at zero cover.

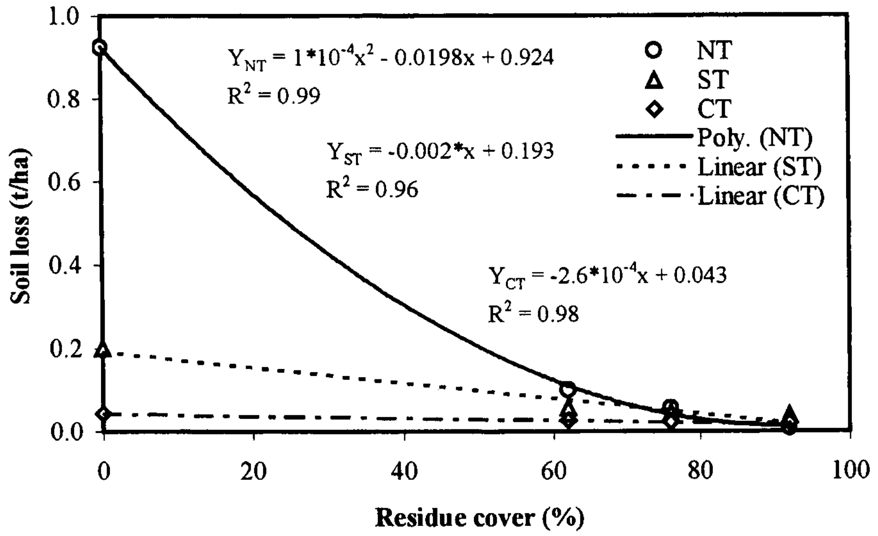


Figure 5.6. Mean soil loss as a function of percentage residue cover for three tillage practices at a cumulative rainfall of 100 mm.

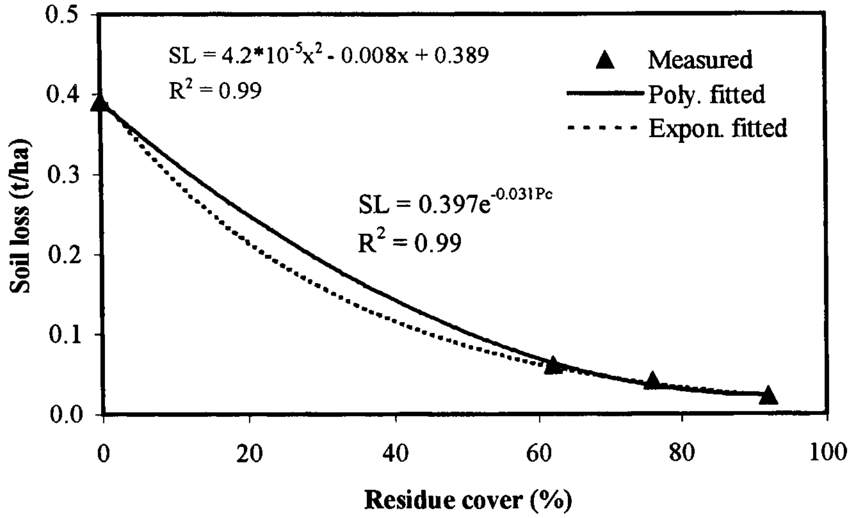


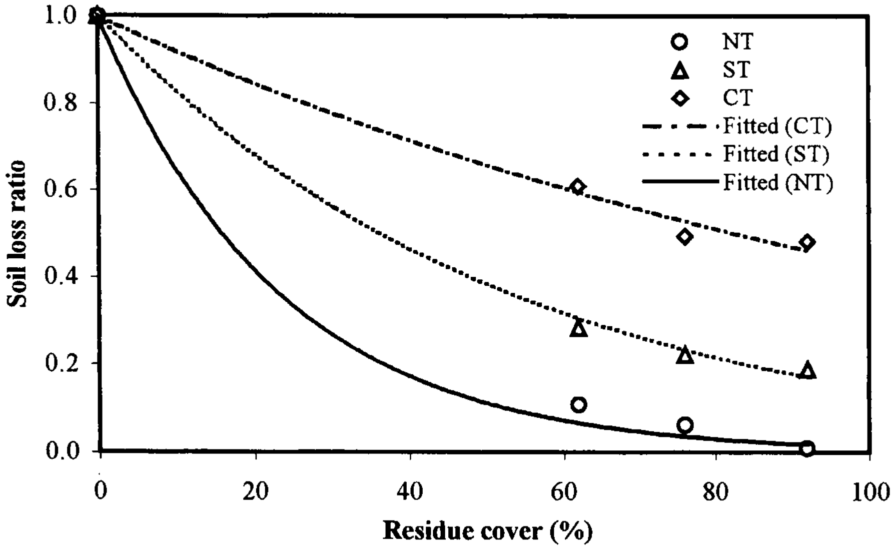
Figure 5.7. Mean soil loss (SL) as a function of percentage residue cover fitted to polynomial and inverse exponential equations.

Lattanzi *et al.* (1974) reported that soil loss decreased in an inverse exponential form to essentially zero as the wheat residue rate increased to 8t/ha (equivalent to 95% cover in their case). Singer *et al.* (1981), however, reported that soil loss decreased significantly as residue rates increased in a linear rather than an inverse exponential form. In another report, Zuzel & Pikul (1993) indicated that soil loss was related to residue cover in a non-linear second-degree polynomial function which have more physical meaning, i.e. it has the advantage of a determinate intercept at zero cover that represents the data more realistically.

5.2.1.3 Soil loss ratio

The relative effectiveness of residue in reducing soil loss on the tillage treatments can be described better using a soil loss ratio concept, which is also called the soil loss mulch factor (Gilley *et al.*, 1986a; Gilley *et al.*, 1986; Freebrain *et al.*, 1993). The soil loss ratio is obtained by dividing the amount of soil loss from plots with residue cover by the amount of soil loss from plots without residue cover on the same tillage experiment. This method of analysis shows how effective a given residue amount is in reducing soil loss on a given tillage.

Soil loss ratios as a function of percentage residue cover, for the three tillage treatments, are given in Figure 5.8. It can be seen that additions of residue cover at different rates were more effective on no-tillage compared to stubble mulch and conventional tillage. The no-tillage treatment with a residue rate of 2t/ha reduced the soil loss to only 11% of the soil loss from the bare no-tillage, where as the stubble mulch and conventional tillages at the same residue rate had, respectively, 29% and 61% of the soil loss from their respective bare plots. Therefore, for this particular experiment and soil condition the addition of residue was more effective in reducing runoff and hence soil loss under the no-tillage practice with its dense sealed surface conditions.



$SLR_{NT} = e^{-0.044Pc}$
$R^2 = 0.90$

$SLR_{ST} = e^{-0.019Pc}$
$R^2 = 0.99$

$SLR_{CT} = e^{-0.0084Pc}$
$R^2 = 0.98$

Figure 5.8. Soil loss ratio (SLR) as a function of percentage residue cover (Pc) for three tillage practices. *Note*: NT = No-tillage, ST = Stubble mulch tillage, CT = Conventional tillage.

The relationship between the mean of soil loss ratio from the tillage treatments, and the percentage residue cover is presented in Figure 5.9. The data fitted both the second-degree polynomial (quadratic) and inverse exponential functions well with strong coefficients of determination in both cases as described in Equations 5.2 and 5.3. The intercept in the polynomial equation gives the soil loss ratio at zero percentage surface cover, which equals one.

$$SLR = 0.0001*Pc^2-0.02*Pc+1, \qquad R^2 = 0.99 \quad [5.2]$$

$$SLR = e^{-0.03*Pc}, \qquad R^2 = 0.99 \quad [5.3]$$

Where, *SLR* is the soil loss ratio and *Pc* is the percentage residue cover.

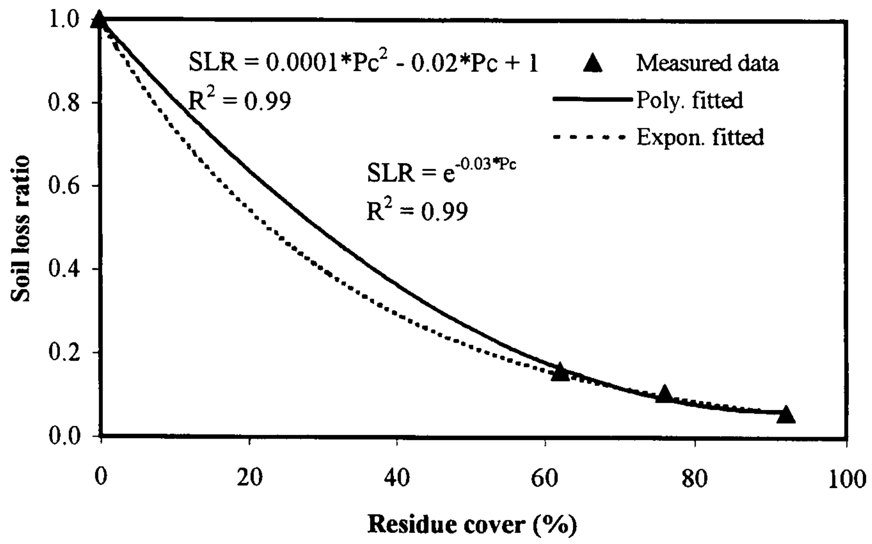


Figure 5.9. Soil loss ratio as a function of percentage residue cover.

Gilley *et al.* (1986) also reported similar inverse exponential relationships for sorghum and soybean residue, which are given in Equations 5.4 and 5.5.

Sorghum $SLR = e^{-0.073*Pc}$, $R^2 = 0.99$ ....[5.4]

Soybean $SLR = e^{-0.045*Pc}$, $R^2 = 0.95$..........................[5.5]

The application of the soil loss ratio concept is that it can be used to estimate the potential soil loss from covered areas if the soil loss from uncovered fields and the percentage residue cover are known from the following Equation 5.6.

$$SL_C = SL_U * e^{-0.03*Pc} \quad \text{[5.6]}$$

Where, SL_C is the soil loss from a covered field, SL_U is the soil loss from uncovered field and Pc is the percentage residue cover.

5.2.2 Erosion Under Simulated Rainfall with Varying Intensity

Generally erosion rate is found to correlate very well with rainfall intensity. This was discussed in detail in Section 1.5. The relationship between erosion rate and rainfall intensity was established for stubble mulch and conventional tillage and the result is presented in Figure 5.10. It shows that the data from the two tillage practices fitted the power equation very well. Le Bissonnais *et al.* (1998) showed that there was a close relationship between sediment concentration and rainfall intensity.

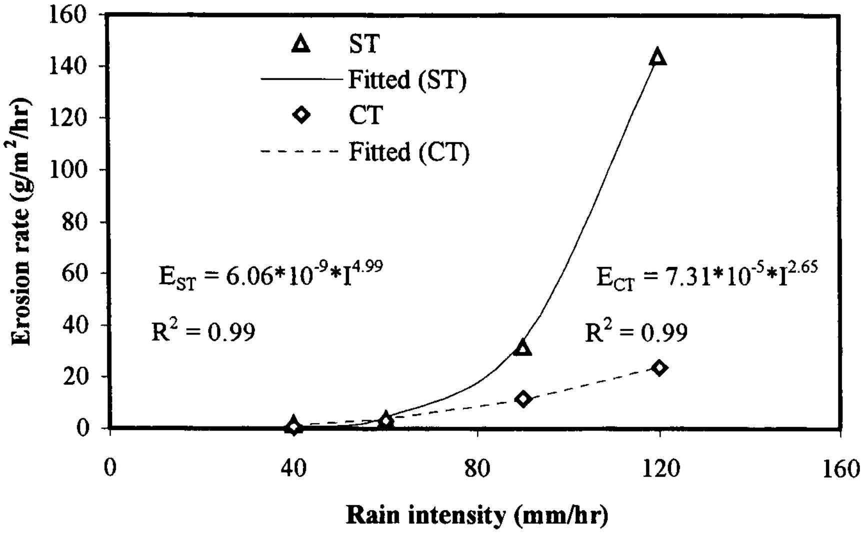


Figure 5.10. Erosion rate as a function of rainfall intensity on bare soil of the stubble mulch and conventional tillage practices.

Meyer (1981) gives an equation for erosion rate as a power function of the rainfall intensity, which is described as $E = K_i I^a$, where E is the erosion rate, K_i is a coefficient for the relative erodibility of the soil, a is an exponent of the best-fit line, and I the rainfall intensity. He suggested that for different types of soils the values of the exponent, a, is close to *2* except for clay soil. In this study the data fitted the power equation well with exponent values varying between 2.65 and 4.99, depending on the degree of soil loosening by tillage. The erodibility coefficient of the freshly ploughed conventional tillage was lower than for stubble mulch tillage (Figure 5.10).

5.3 Empirical Relationships Between Soil Loss, Runoff and Rainfall

The relationships between soil loss rate (erosion rate, $g/m^2/hr$) and runoff rate (mm/hr) for all the tillage and residue treatments are given in Figure 5.11. In the case of lower residue rates (0t/ha and 2t/ha) the relationships were non-linear, i.e. power function and polynomial form. However, at higher residue rates (4t/ha and 8t/ha) the relationships were linear except in the case of no-tillage where the 4t/ha fitted a non-linear equation.

As would be expected, Figure 5.11 shows that for a given tillage treatment the plots without residue cover had a higher erosion rate compared to the ones covered with residue at the same runoff rate. Generally all three tillage treatments at higher residue rates had only a small amount of soil loss compared to the ones without residue.

Several studies have shown non-linear relationships between erosion rate and runoff rate. Bradford & Huang (1994) and Huang (1995) reported that the relationship between soil loss rate and runoff rate was non-linear, a polynomial form.

The cumulative soil losses were related to cumulative rainfall for all tillage and residue treatments and are presented in Figure 5.12. On the no-tillage treatments it can be seen that the cumulative soil losses were very high for the bare plot compared to plots covered with different amounts of residue, which remained very low throughout the rainy period.

On the stubble mulch treatments, however, there were not pronounced differences between the uncovered and covered plots, although the bare plot had a slightly higher soil loss compared to the covered ones. Generally the amount of soil loss decreased with an increase in residue rate in the order of *0t/ha > 2t/ha > 4t > 8t/ha.*

The soil losses from the conventional tillage treatment were quite small compared to the other two tillage practices. Despite the higher runoff from the bare plots it had a very low amount of soil loss. The treatments with residue cover rates of 2t/ha and higher almost eliminated runoff and reduced the soil loss to nearly zero on conventional tillage.

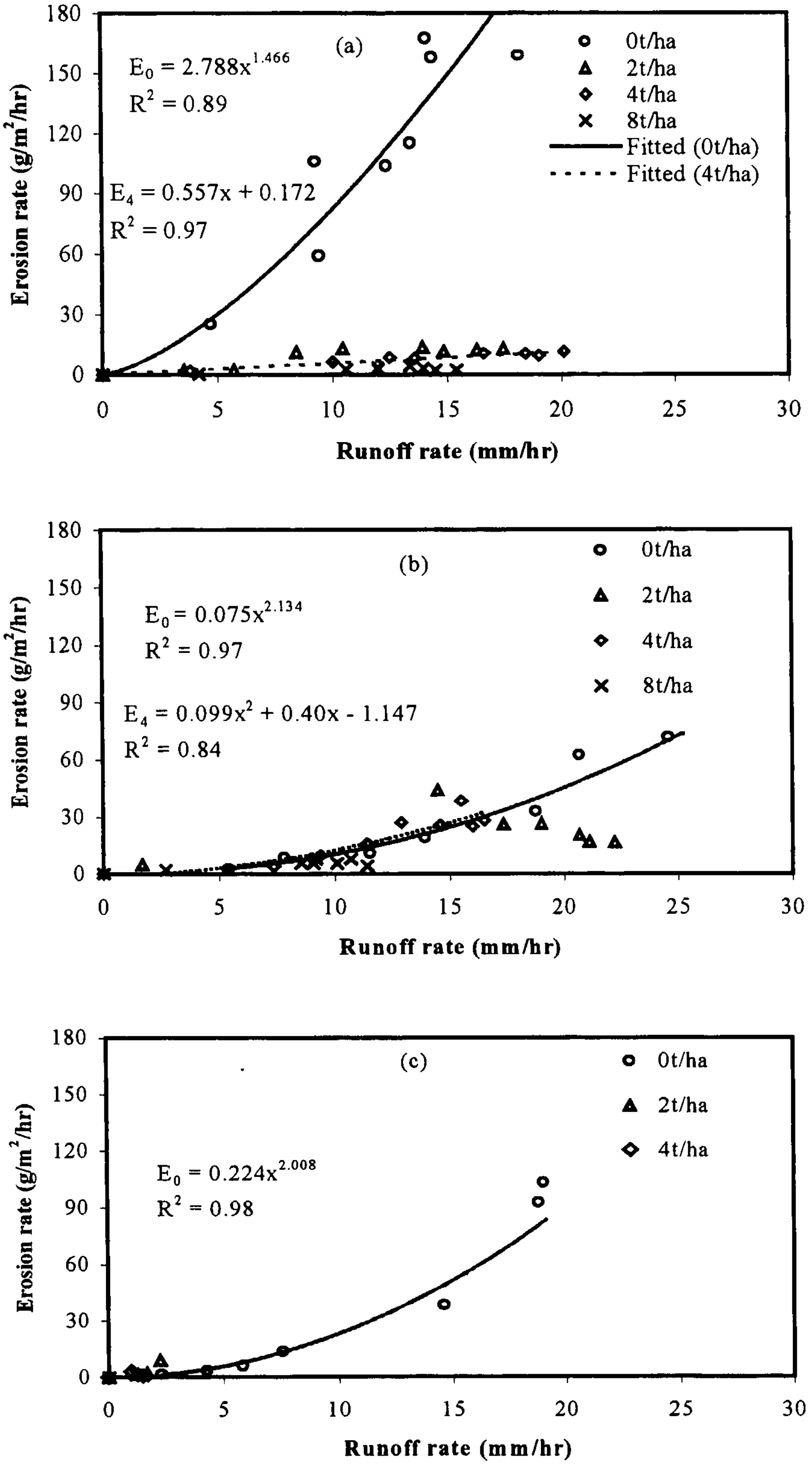


Figure 5.11. Erosion rate as a function of runoff rate for three tillage practices at four rates of residue cover for (a) No-tillage, (b) Stubble mulch and (c) Conventional tillage.

The relationships between soil loss and cumulative rainfall on all three tillage treatments at all residue levels are non-linear. The data from the three tillage treatments without residue cover were fitted to a second-degree polynomial equation by fixing the intercept at zero. The equations and the coefficients of determination are given in Table 5.3. Gilley *et al.* (1986a) also reported similar polynomial relationship between soil loss and cumulative rainfall.

Table 5.3. Relationship between cumulative soil loss (SL, t/ha) and cumulative rainfall (P, mm) fitted to quadratic functions for three tillage treatments without residue cover

Tillage types	Equation	Coefficient, R^2
No-tillage	$SL = 1.7*10^{-4}*P^2 - 0.0057*P$	0.99
Stubble mulch	$SL = 8*10^{-5}*P^2 - 0.0043*P$	0.93
Conventional	$SL = 4*10^{-5}*P^2 - 0.0034*P$	0.84

Soil loss correlated positively with both the amount of runoff and rainfall depth. These two variables were analyzed to determine their combined effect on soil loss. A multiple linear regression analysis was performed to describe the relationship between soil loss as a dependent variable and runoff and rainfall amounts as independent variables. Regression analysis was then performed on each of the tillage - residue treatment combinations. The fitted regression equations together with the coefficients of determination for each of the treatments are given in Table 5.4. The results showed that there were a strong relationship between the cumulative soil loss on one hand and the runoff and rainfall amount on the other hand.

From the previous analysis it was clear that the soil loss was positively correlated to both runoff rate and amount, as well as to rainfall depth. The erosion rate data from this experiment was fitted to the square of the rainfall amount but it was found that the data didn't fit well, i.e. the coefficient of determination was very low. Thus the data from the three tillage treatments, at different rates of residue cover, was fitted to the power function of the form of $E = aP^b$, where E is the erosion rate, P is the rainfall amount and a

and *b* are the coefficient and exponent of best fit, respectively. The results are presented in Figure 5.13.

Table 5.4. Regression equations and coefficients of determination for the soil loss (SL, t/ha) as a function of rainfall (P, mm) and runoff (Q, mm) amounts for three tillage practices and four rates of residue cover

Tillage type	Residue rate (t/ha)	Regression equations	Coefficient, R^2
No-tillage	0	$SL = -0.0046*P+0.064*Q$	0.99
	2	$SL = -0.00013*P+0.01*Q$	0.99
	4	$SL = 0.00093*P-0.001*Q$	0.98
	8	$SL = 0.00001*P+0.002*Q$	0.99
Stubble mulch	0	$SL = -0.0013*P+0.023*Q$	0.97
	2	$SL = 0.00091*P+0.01*Q$	0.96
	4	$SL = -0.0015*P+0.018*Q$	0.99
	8	$SL = 0.00018*P+0.005*Q$	0.99
Conventional	0	$SL = -0.0017*P+0.049*Q$	0.96
	2	$SL = -0.00051*P+0.04*Q$	0.97
	4	$SL = 0.00035*P-0.004*Q$	0.92
	8	$SL = 0.00011*P+0.004*Q$	0.99

The systematic decrease in the coefficients of the fitted power equation, given in Figure 5.13a, from no-tillage to conventional tillage suggest that the erosion rate decreases as it goes from no-tillage to conventional tillage. In other words, the erosion rate decreased with an increase in the depth of tillage. This condition was also true on the residue-covered plots (Figures 5.13b and 5.13c). However, the data for some tillage did not fit well to any of the equations and were, therefore, excluded from the graphical presentations (stubble mulch tillage in Figure 5.13b and conventional tillage in Figure 5.13c. Thus the coefficient of the power equation could be used as an indicator of the relative erodibility of the soil, as Meyer, (1981) suggested for erosion-rain intensity relationships. On the other hand the exponent of the equation increased with an increase in the depth of tillage as shown in Figure 5.13a.

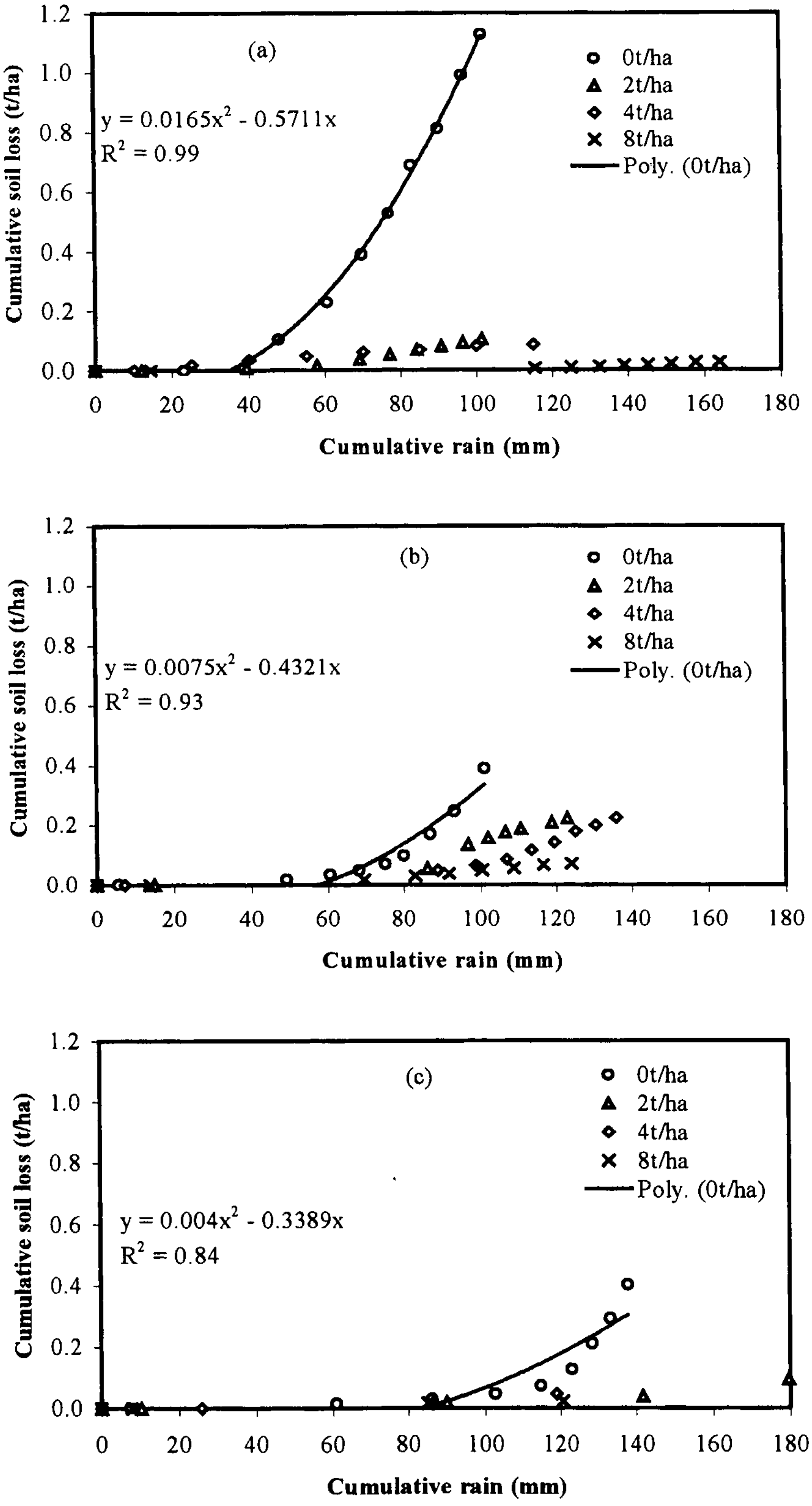


Figure 5.12. Cumulative soil loss as a function of cumulative rainfall for (a) No-tillage, (b) Stubble mulch, and (c) Conventional tillage, at four levels of residue cover.

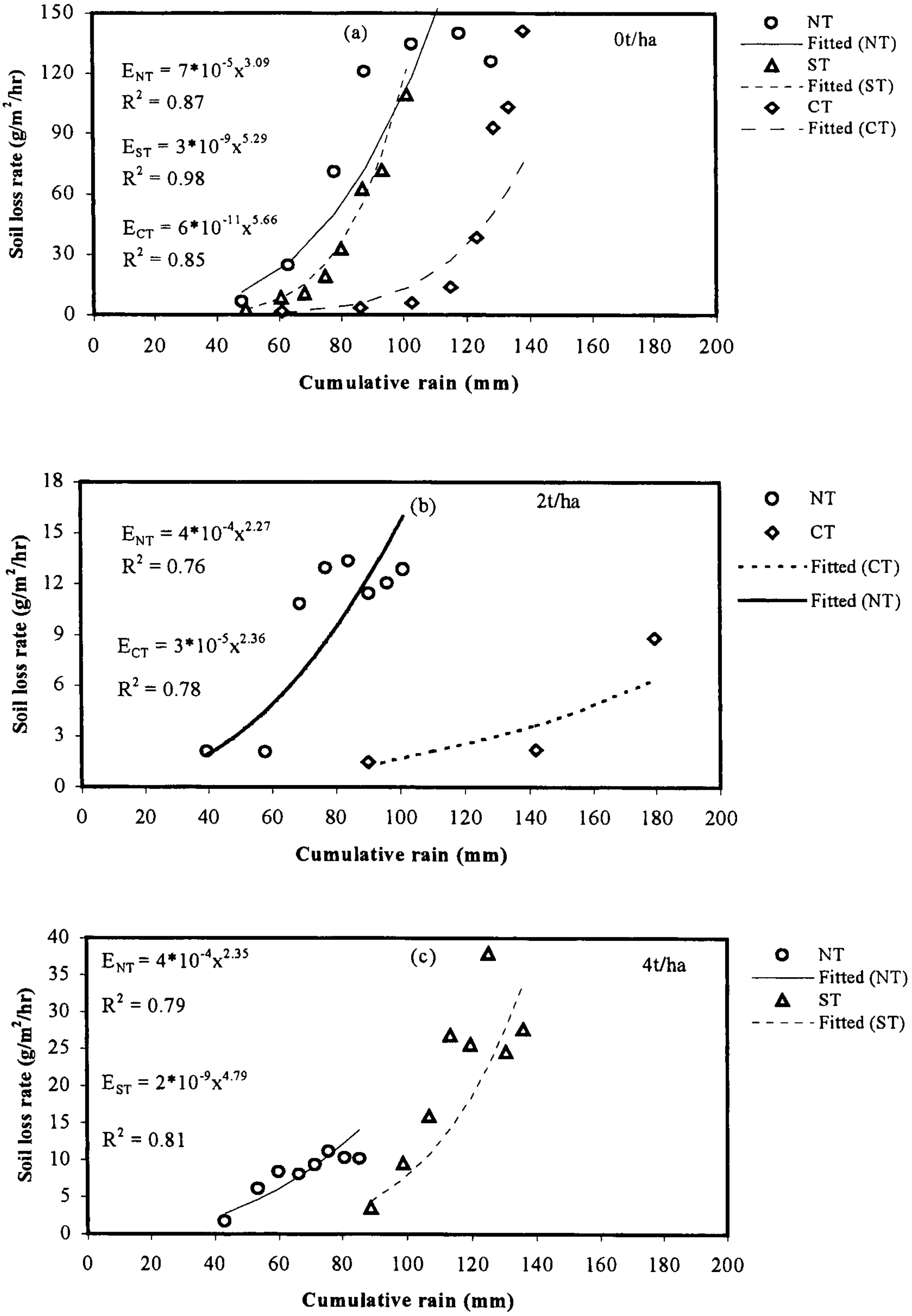


Figure 5.13. Soil loss rate as a function of cumulative rainfall for three tillage treatments at residue levels of (a) 0t/ha, (b) 2t/ha and (c) 4t/ha.

5.4 Conclusions

An experiment was carried out to investigate the effects of tillage and residue cover on soil loss under simulated rainfall conditions. The results of the experiment on three tillage practices and four rates of residue cover revealed that the no-tillage treatment had a significantly higher mean soil loss per unit area than stubble mulch and conventional tillage, when averaged over the four residue rates. However, the sediment concentration (gram of suspended sediment in a liter of runoff) at different rates of residue cover has been lower for no-tillage compared to the stubble mulch and conventional tillage. The sediment concentration mulch factor for the three tillage practices showed that the application of residue cover was much more effective on no-tillage followed by conventional and stubble mulch tillage.

The effect of residue cover on soil loss was highly significant at a 1% probability level. The soil loss per unit area decreased exponentially with an increase in the amount of residue cover. For instance, the treatments with a residue rate of 2t/ha reduced the soil loss substantially to about 15.7% of the soil loss from the bare plot treatment. The soil loss ratio indicated that the use of residue to reduce soil loss reduction was much more effective on a no-tillage treatment followed by stubble mulch and conventional tillage.

Empirical relationships between soil loss, runoff and rainfall has been established with different combinations of variables. Erosion rate related well to both runoff rate and cumulative rainfall with a power function, especially on the bare plots. Likewise, there was a strong relationship between soil loss per unit area and cumulative rainfall, which is a second-degree polynomial function.

Conservation tillage systems, such as reduced tillage and no-tillage are reported to be effective in reducing soil erosion because of the greater crop residue cover, greater soil resistance to soil detachment and transport, or reduced soil erodibility and often reduced runoff (Lindstorm & Onstad, 1984). Differences in runoff and erosion due to tillage have not been as consistent, because of the effect of other factors, such as residue cover, rainfall intensity, rainfall amount and timing, soil texture, and surface roughness (Unger, 1992). For instance, Kinnel (1996) reported that differences in tillage practices had no major impact on either sediment concentration or runoff amount. The reason being the high capacity of the soil to maintain its tillage-induced surface roughness under rain after cultivation.

However, as a general rule, tillage is considered to encourage erosion through degradation of soil physical properties, leading to an increase in runoff and sediment concentration. Lack of tillage decreases both runoff and sediment concentration through an increase in aggregate stability and infiltration capacity resulting from biotic activity (Kinnel, 1996). Myers & Wagger, (1996) argued that regional differences in soil physical properties explain many of the contradictory results from various runoff studies.

This study has shown that under bare soil conditions conventional tillage is more effective in decreasing both runoff and soil loss than stubble mulch and no-tillage for this particular type of soil and climate condition. More rain was required to produce the same amount of soil loss from conventional than from no-tillage. Residue rates higher than 2t/ha or 62% ground cover decreased soil losses by more than 85% on all the tillage practices.

The conservation tillage practices of stubble mulching and no-tillage can only be recommended on sandy to sandy loam topsoil under semi-arid climatic conditions, when it is possible to maintain a residue cover of at least 2t/ha all the time. Loosening of the soil below the surface mulch will further decrease soil loss through decreasing the runoff.

CHAPTER 6

EFFECT OF TILLAGE AND RESIDUE COVER ON EROSION UNDER NATURAL RAINFALL (AU EXPERIMENTAL SITE)

6.1 Introduction

The method of tillage and the corresponding amount of residue left on the soil surface influence the volume and rate of runoff and therefore soil erosion during rainfall events. Infiltration, surface water storage and erosion have been shown to be all directly affected by tillage and residue cover (Mohamoud *et al.*, 1990b; Unger *et al.*, 1991; Unger, 1992). Tillage is sometimes a detachment mechanism that creates a steady supply of detached aggregates, thus increasing soil erosion. Cover such as plant residue that is in direct contact with the soil surface has a greater impact on retarding soil erosion than any other single factor, because it intercepts raindrop impact energy, reduce flow velocity of runoff water, and minimize detachment and transport processes (Foster, 1982; Cruse *et al.*, 2001).

Adoption of soil resource management and agricultural practices that seek to conserve soil and water resources and minimize environmental degradation is attracting the overwhelming interest among researchers and the general public in many countries (Choudhary *et al.*, 1997). Tillage is an operation over which the farmer has considerable control, and it should therefore be a target when developing improved management practices for soil and water conservation (Freebrain *et al.*, 1993).

Soil erosion is a serious problem on the Ethiopian highland soils. Most of the productive topsoil in the highlands of Ethiopia has been degraded, resulting in chronic food shortages and persistent poverty. It is estimated that serious erosion have affected some 25% of the area, and some estimates found that 4% of the highland is so seriously eroded that it will not be economically productive again in the foreseeable future (SCRP, 1996).

Tillage practices and cultivation of crops with animal drawn implements is a centuries old practice in the highlands of Ethiopia. In Ethiopia, 90% of the land preparation for crop production is done by smallholder farmers with a traditional 'maresha' plough pulled by a pair of local zebu oxen (Appendix 1.2). The traditional tillage system involves multiple, up to five, passes for all types of soils before a field is ready for planting, during which intensive rainfall occurs. Each cultivation pass is perpendicular to the previous one. The first pass reaches 8 cm soil depth while with the last pass depth of up to 20 cm can be attained (Astatke *et al.*, 2002).

In Ethiopia land is usually prepared before the main rainy season of June, July and August, but some crops are sown during the rainy season, leaving the tilled soil exposed to heavy rain for most of the time, resulting in high erosion. Tractor powered tillage implements are to a limited extent used for tillage operations, mainly on larger state and private commercial farms, but also sometimes for initial and primary tillage of small plots through rental agreements.

Effective water management and reduction of soil erosion are essential to sustain soil productivity. Thus, there is a need to develop tillage techniques, which maximize infiltration while minimizing erosion. In response to these and other problems related to land degradation some efforts have been under way to develop land preparation farm implements that are appropriate for small-scale farmers. An animal drawn implement called the broad bed maker (BBM) has been developed by a research consortium in order to solve the waterlogging problem on vertisols in the Ethiopian highlands, by modifying the local maresha. The BBM creates 80 cm wide beds separated by 40 cm wide furrows that allow excess water during heavy rains to be expelled allowing for early planting to take advantage of a longer growing period, and resulting in higher yields and less erosion (Astake *et al.*, 2002). However, the use of this technology has not been adopted on a broader scale.

Of several options available to control soil erosion, minimizing the degree of soil disturbance and covering the soil surface with crop residue could effectively limit soil erosion and enhance crop productivity. However, the use of minimum or reduced tillage for crop production in Ethiopia is at its very early stage, even at a research level. This is an entirely new concept, which has not yet taken its base well. Nonetheless, it is worth mentioning the research done on development of implements for minimum tillage jointly by the International Livestock Research Institute (ILRI) and the Ethiopian Agricultural Research Organization (EARO) are showing promising results, both at the research station and on-farm trials (Astatke *et al.*, 2002).

The soil and water conservation research project of the Ethiopian Ministry of Agriculture have been collecting data on runoff and soil loss from several research sites distributed across different agro-ecological zones from runoff plots established on traditional tillage practices. On the other hand, there has been a growing mechanization of crop production in the private sector using conventional tillage methods. Research institutes are also starting to focus on the possible use of minimum tillage for crop production. An evaluation and a comparative study on the effectiveness of the different tillage practices combined with crop residue management practices in relation to soil and water conservation has not been done so far.

A field experiment was carried out using no-tillage, traditional and conventional tillage practices, each with four rates of wheat residue cover (0, 2, 4, and 8t/ha) under natural rainfall conditions at the Alemaya University experimental site during the main rainfall seasons of 2000 and 2001. The objective was the evaluation its effects on runoff and erosion. The results from this experiment are reported here.

6.2 Results and Discussion

6.2.1 Soil Loss

Soil loss that occurred during four rainstorms was measured for each of the experimental years, 2000 and 2001. The total soil loss for a rainy event was calculated from the sediment concentration of the runoff sample, which was taken from the runoff collector after every erosive storm.

6.2.1.1 Sediment concentration

The soil loss from a given field in suspension with runoff water, known as sediment concentration, is expressed in gram per liter. The sediment concentrations for the storms of the 12th of August and the 16th of September 2000, which had the highest and the lowest erosivity index respectively, are presented in Figure 6.1 for comparative purposes. The average sediment concentrations from the three tillage and four rates of residue treatments are also presented for both experimental years (2000 and 2001) in Figure 6.1 and 6.2, respectively. It can be seen from Figure 6.1 that conventional tillage had the highest sediment concentration during the two storms for the first three levels of residue cover, compared with the traditional and no-tillage treatments. From the treatments with 8t/ha residue cover there were no runoff.

During the storm of 35.6 mm on the 12th of August 2000 the sediment concentration for the bare conventional tillage was 41% and 37% higher than no-tillage and traditional tillage without residue cover, respectively. Likewise, during the fourth storm of 21.8 mm on the 16th of September 2000 the sediment concentration from the bare conventional tillage treatment was 25% and 43% higher than from the bare no-tillage and traditional tillage, respectively. During this storm the sediment concentration from conventional tillage with a residue rate of 2t/ha was even higher than from the bare traditional and no-tillage treatments.

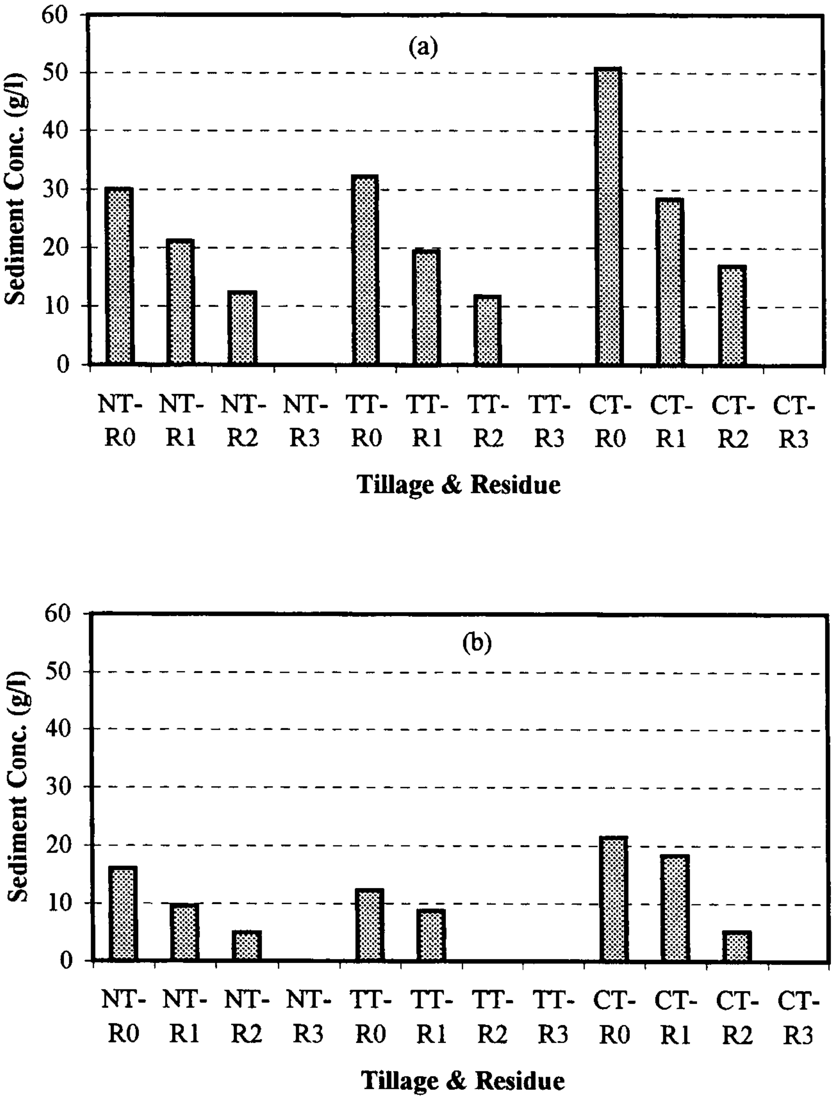


Figure 6.1. Average sediment concentration for three tillage and four rates of residue treatments during a storm of (a) 35.6 mm on the 12th of August, and (b) 21.8 mm on the 16th of September 2000.

Figure 6.1 also shows the enormous difference between the sediment concentrations during both storms, although the difference in the amount of rainfall was quite small. As discussed previously (Section 4.2.1), the rainfall intensities were much higher for the storm of the 12th of August compared to the one on the 16th of September. Correspondingly the maximum 30-minute intensity and the erosion index were also higher for the 12th of August storm.

The sediment concentration during the second year (Figure 6.2) was quite low compared to the first year. The sediment concentration during a storm of 53.8 mm (the largest storm of the season) was the highest on bare traditional tillage followed by bare conventional tillage. No-tillage had the lowest sediment concentration (Figure 6.2a). The average sediment concentration was slightly higher on no-tillage compared to the other two tillage practices (Figure 6.2b).

It should be emphasized that the soil loss from a treatment is the product of sediment concentration and total runoff. Thus, the treatments with the highest sediment concentrations did not necessary have the highest soil losses.

The sediment concentration mulch factor (SCMF), which is the ratio between the sediment concentration from residue – covered plots and the sediment concentration from plots without residue, was used to illustrate the relative effectiveness of residue to lower the sediment load of runoff (Gilley *et al.*, 1986a). The average sediment concentration over the four erosive rainfall events for each of the three tillage practices was used to calculate the SCMF for both years. The results are presented in Figure 6.3. The intercepts of the fitted equations were fixed at 1 because the SCMF is a ratio, with a maximum value of 1.

For the first year, the separate relationships for the three tillage practices were found to be the same. Likewise, the fitted equation for the second year was also found to be similar to the previous year when rounded to two decimal points, apparently showing a similar effect of residue on sediment concentration during both years, irrespective of the tillage practice used. Unlike the result of the simulated rainfall study (Section 5.2.1.1), which was fitted to an inverse exponential function, the data from this natural rainfall was fitted to a linear equation. Gilley *et al.* (1986a; 1986) also reported an inverse exponential relationship between SCMF and the percentage residue cover.

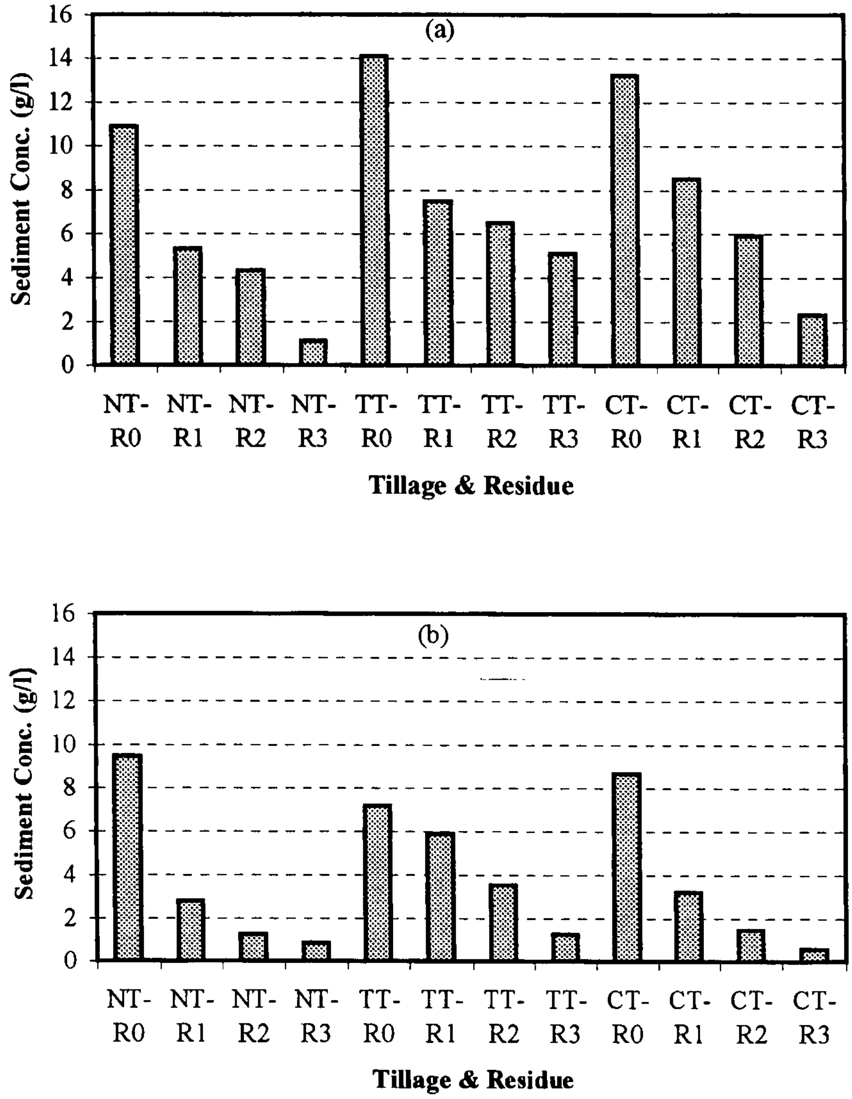


Figure 6.2. Sediment concentration (a) during the storm of 53.8 mm on the 8th of August and (b) average of the four storms, 2001 main rainfall season.

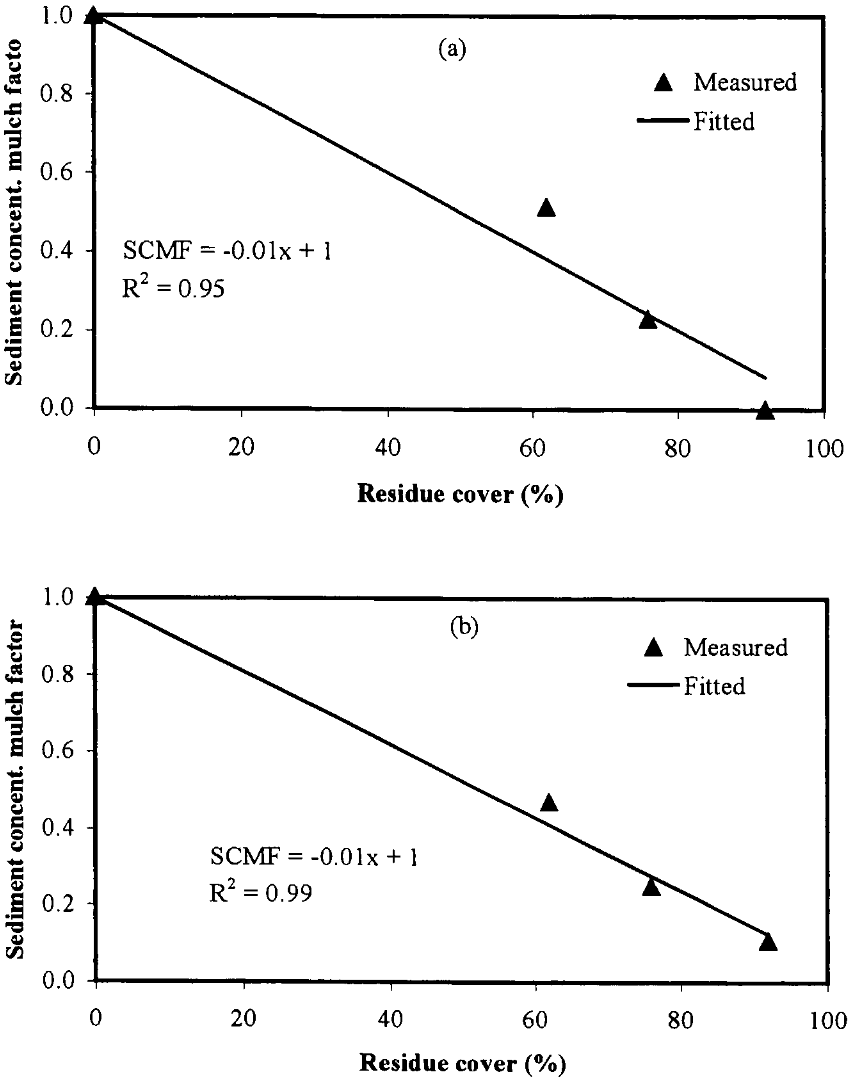


Figure 6.3. Sediment concentration mulch factor (SCMF) as a function of percentage residue cover for (a) 2000 and (b) 2001, based on average sediment concentrations of the three tillage practices for the four rates of residue cover.

6.2.1.2 Effect of residue cover

The soil losses from the three tillage practices and four rates of residue cover for both experimental years are presented in Tables 6.1 and 6.2, respectively. The total soil loss for the season is also given for all the tillage treatment and residue rate combinations.

During the first year of the experiment, soil losses occurred mainly from the bare plots of the three tillage practices. There was little soil loss from plots with a residue rate of 2t/ha for all the erosive storms, with the exception of the intense storm of the 12th of August 2000, when a residue rate of 2t/ha was insufficient to control soil losses. Plots with a residue rate of 4t/ha had little soil loss except during the last two storms. The ones with 8t/ha had no soil loss during any of the storms. As shown in Table 6.1, the intense storm of the 12th of August caused the highest soil loss from the bare plots of the three tillage treatments. When compared to the total soil loss for the main rainfall season of the first year, the single storm of the 12th of August was responsible for 48.7%, 73.7%, and 76.2% of the total soil loss from bare plots of no-tillage, traditional and conventional tillage respectively.

As mentioned in the previous chapter, rainfall intensity is an important factor in soil erosion since interrill soil erosion varies with the square of rainfall intensity (Meyer, 1981). The kinetic energy of a raindrop is also related to the rainfall intensity. For example, the infiltration rate of a soil was reported to decrease sharply with time, as the kinetic energy and intensity of a storm increased, thus increasing runoff and erosion (Karen, 1990).

The effect of different residue rates in general, and the 2t/ha rate in particular, varied depending on the type of tillage practices and the storm characteristics. For example, the reduction in soil loss from no-tillage during 2000 at a residue rate of 2t/ha was 93, 88, 35 and 83% for the four consecutive erosive storms, respectively. These reductions were significant except the value of 35% for the very intense erosive third storm. For traditional tillage these values were 83, 98, 52 and 55% for the four erosive storms, respectively. From the conventional tillage there was no soil loss during the first two storms. This could probably be due to the effect of ploughing that increased infiltrability due to increased porosity of the topsoil, creation of surface roughness and small depressions immediately after tillage.

A study by Freebrain *et al.* (1993) suggested that roughness associated with tilled soils could result in lesser runoff and erosion compared with no-tillage under certain circumstances. Lindstrom & Onstad (1984) reported that primary tillage operations, such as mouldboard ploughing, increased infiltration thereby reducing the danger of erosion by increasing soil porosity and establishing channels or voids in the surface soil layer that conduct water into the soil profile. Kinnel (1996) indicated that differences in tillage practices had no major impact on either sediment concentration or runoff amount, on soils that maintain its tillage-induced surface roughness under rain after cultivation.

As shown in Table 6.1, the soil loss from conventional tillage at residue rates of 0t/ha and 2t/ha was higher than from traditional and no-tillage at the same residue rates during the last two storms of 2000. This may be the result of tillage induced roughness and depression storage being destroyed by the impact of raindrops of the previous storms, especially the intense storm of the 12th of August that might have formed a surface crust on the bare plots.

Rao *et al.* (1998a, 1998b) reported that the effectiveness of soil management practices in reducing runoff and erosion on Alfisols was dependent on the resistance to the formation of crusts. The mechanical breakup of crusts by tillage is soon lost with the formation of another surface crust after a few rainstorms.

During the second year (2001), the soil loss has generally been very low from all the tillage and residue treatments compared with the first year (Table 6.2). The highest soil loss from a single storm was from the bare plot of conventional tillage, which was 1.064t/ha compared to 3.67t/ha during the previous year. As described in Section 4.2.2, the rainfall amounts per single storm event during the second year were higher than the previous year but the rainfall intensities were lower. This was the reason for the lower soil loss per storm during the second year, as illustrated by the relationship between soil loss and storm erosivity index (Figure 6.14b).

Table 6.1. Soil loss from erosive storms on different dates from three tillage practices and four levels of residue treatments at the AU Experimental site during the main rainfall season of 2000

Tillage	Residue rate (t/ha)	Date of rain				**Total**
		08/07/00	12/07/00	12/08/00	16/09/00	
		Rain (mm)				
		19.6	18.6	35.6	21.8	**95.6(216.2)**[#]
		Soil loss (t/ha)				
No-tillage	0	1.322	0.381	2.647	1.084	**5.434**
(NT)	2	0.087	0.047	1.734	0.190	**2.058**
	4	0.000	0.013	0.310	0.037	**0.360**
	8	0.000	0.000	0.000	0.000	**0.000**
Average	**NT**	**0.352**	**0.110**	**1.173**	**0.328**	**1.963**
Traditional	0	0.159	0.129	2.809	0.716	**3.813**
(TT)	2	0.028	0.002	1.351	0.324	**1.705**
	4	0.000	0.000	0.211	0.000	**0.211**
	8	0.000	0.000	0.000	0.000	**0.00**
Average	**TT**	**0.047**	**0.035**	**1.093**	**0.260**	**1.972**
Conventional	0	0.000	0.012	3.670	1.137	**4.819**
(CT)	2	0.000	0.000	1.812	0.814	**2.626**
	4	0.000	0.000	0.072	0.039	**0.111**
	8	0.000	0.000	0.000	0.000	**0.000**
Average	**CT**	**0.000**	**0.003**	**1.388**	**0.497**	**1.889**
Average	0	0.494a*	0.174a	3.042a	0.979a	**4.689a**
	2	0.038b	0.016b	1.632b	0.443b	**2.130b**
	4	0.000b	0.004b	0.198c	0.025c	**0.227c**
	8	0.000b	0.000b	0.000c	0.000c	**0.000c**
LSD **(Prob.)**		**0.299** **(0.05)**	**0.118** **(0.01)**	**1.228** **(0.01)**	**0.367** **(0.01)**	**1.506** **(0.01)**

(*): Numbers in the same column followed by the same letter(s) are not significantly different at a probability level given in bracket in the same column.

(#): Number in the bracket referrers to the total rainfall for the season.

Table 6.2. Soil loss from erosive storms on different dates from three tillage practices and four levels of residue treatments at the AU Experimental site during the main rainfall season of 2001

Tillage	Residue rate (t/ha)	Date of rain				**Total**
		01/08/01	05/08/01	08/08/01	14/09/01	
		Rain (mm)				
		40	33.8	53.8	15.2	**142.8(269.2)**$^{\#}$
		Soil loss (t/ha)				
No-tillage	0	0.563	0.608	0.978	0.249	**2.398**
(NT)	2	0.034	0.034	0.094	0.000	**0.162**
	4	0.000	0.003	0.008	0.000	**0.012**
	8	0.000	0.007	0.006	0.000	**0.013**
Average	**NT**	**0.149**	**0.163**	**0.272**	**0.062a**	**0.646**
Traditional	0	0.069	0.373	0.630	0.035	**1.106**
(TT)	2	0.064	0.105	0.159	0.006	**0.334**
	4	0.068	0.039	0.063	0.000	**0.169**
	8	0.000	0.000	0.044	0.000	**0.044**
Average	**TT**	**0.050**	**0.129**	**0.224**	**0.010b**	**0.413**
Conventional	0	0.178	0.425	1.064	0.036	**1.703**
(CT)	2	0.019	0.043	0.137	0.000	**0.198**
	4	0.000	0.000	0.071	0.000	**0.071**
	8	0.000	0.000	0.016	0.000	**0.016**
Average	**CT**	**0.049**	**0.117**	**0.322**	**0.009b**	**0.497**
Average	0	0.279a*	0.469a	0.891a	0.107a	**1.745a**
	2	0.039b	0.061b	0.130b	0.002b	**0.231b**
	4	0.026b	0.014b	0.047b	0.000b	**0.088bc**
	8	0.000b	0.003b	0.022b	0.000b	**0.025c**
LSD (Prob.)		**0.158 (0.01)**	**0.093 (0.01)**	**0.185 (0.01)**	**0.038 (0.01)**	**0.181 (0.01)**

(*): Numbers in the same column followed by the same letter(s) are not significantly different at a probability level given in bracket in the same column.

($^{\#}$): Number in the bracket referrers to the total rainfall for the season.

The main rainfall season started late (August) in the second year of the experiment compared to July in normal years. This allowed time for the tilled plots to stabilize before the first erosive rain. After the plot preparations, there were light showers of 13 mm that wetted the soil to a shallow depth over three days, before the first erosive storm of 40 mm. The storm of the 8th of August 2001, with 53.8 mm of rainfall, caused soil loss from all of the tillage treatments at all levels of residue cover including 8t/ha. The last storm caused soil losses from only the bare plots of the three tillage treatments, except for the traditional tillage which had a little soil loss at 2t/ha residue rate. Overall, there was a significant reduction in soil loss by a residue rate of 2t/ha from all of the tillage treatments, with little variation between tillage practices and storm events.

For six of the eight storms that caused erosion during 2000 and 2001, there were significant differences in soil loss only between the bare and 2t/ha residue rates. Among the different residue rates there were no significant differences. For the other two storms there were significant differences between 0 and 2t/ha and 2 and 4t/ha residue rates. From this it can be concluded that a residue rate of 2t/ha will be sufficient to control erosion from this soil, except for the occasional high intensity storms where a higher residue rate of 4 to 6t/ha will be preferred.

The mean total soil loss from the three tillage practices and four rates of residue cover for the separate and combined seasons are given in Figure 6.4. The soil loss during the second year was lower compared to the previous year. The highest total soil losses during both seasons were from bare no-tillage plots, followed by the bare conventional tillage. It can be observed that on all the tillage and residue combinations the amount of soil loss decreased significantly with an increase in the amount of residue. The amount of reduction in soil loss due to the presence of residue varied depending on the type of tillage. During the first year, the no-tillage treatment with a residue rate of 2t/ha lost 62% less soil compared to the bare plot. The comparative values were 55% and 45% for traditional and conventional tillage treatments, respectively.

Figure 6.5 illustrates the decline in the mean soil loss per storm with an increase in the percentage residue cover. As shown in Figure 6.5, the declines were linear for the first season (Figure 6.5a) and non-linear (Figure 6.5b) for the second season. The slopes of the fitted lines increased with higher amounts of rainfall, which shows that the amounts of soil loss were larger when the amount of rain per storm increased. The non-linear relationship between soil loss and percentage residue cover for the second season, at different amount of rainfall (Figure 6.5b), also illustrates the interaction between rainfall amount and percentage residue cover, especially at lower residue rates. The decrease in the total soil loss per season, representing the mean of the tillage treatments, with increasing percentage residue cover, are presented in Figure 6.6 for both seasons. The decrease in soil loss was linear for the first year, with a 0.053t/ha reduction for every 1% increase in the percentage residue cover. The decline was non-linear for the second year with a more rapid decline with an increase of residue cover from 0 to 60%. Linear relationships between soil loss and the percentage residue cover have also been reported by some authors (Singer *et al.*, 1981; Kinnel, 1996; Cruse *et al.*, 2001), while others have reported non-linear (inverse exponential or polynomial functions) relationships between the two parameters (Gilley *et al.*, 1986a; Papendick *et al.*, 1990; Freebrain *et al.*, 1993).

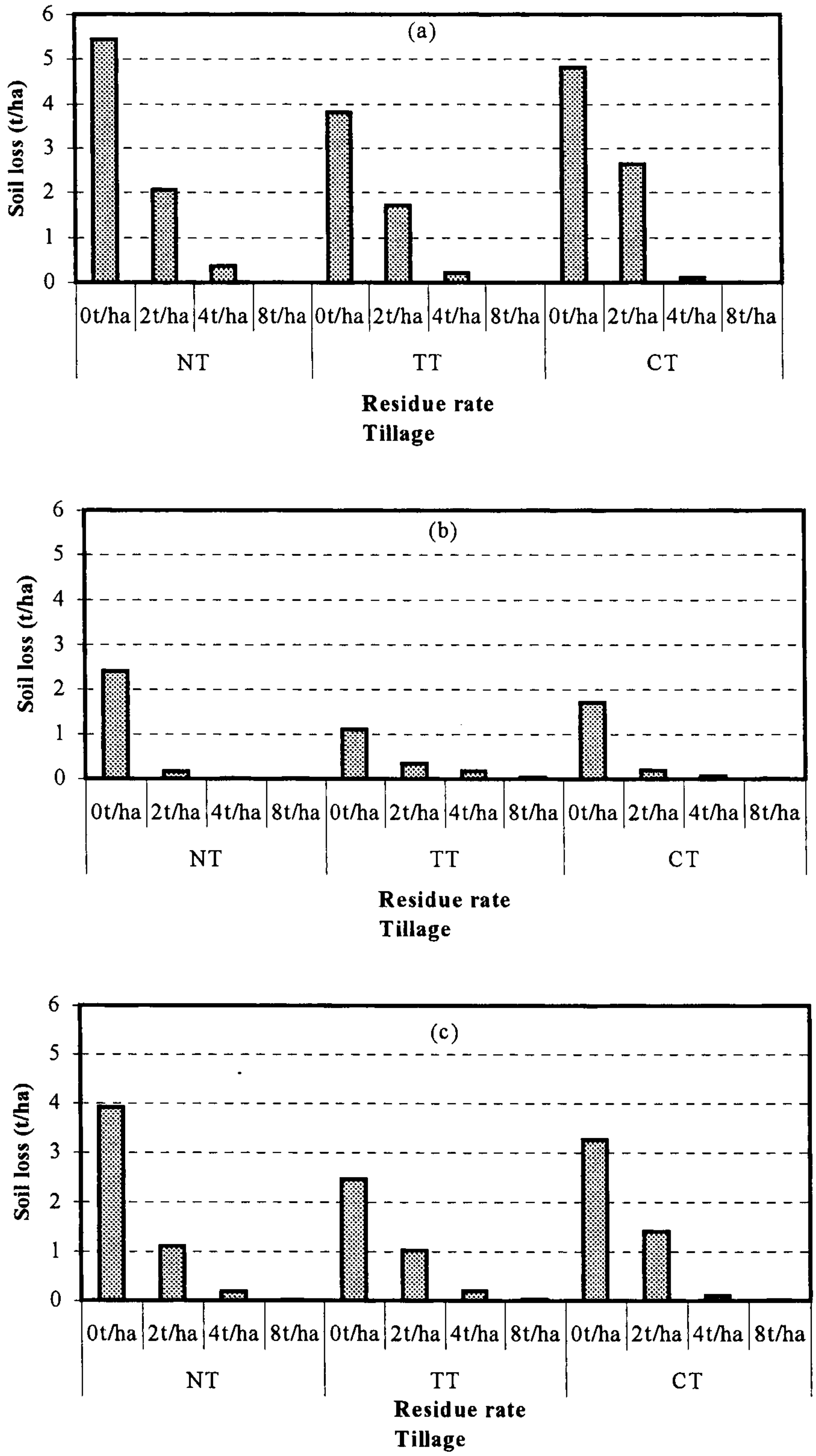


Figure 6.4. Mean total soil loss from three tillage practices at four rates of residue cover during the main season of (a) 2000, (b) 2001, and (c) the average for the two seasons.

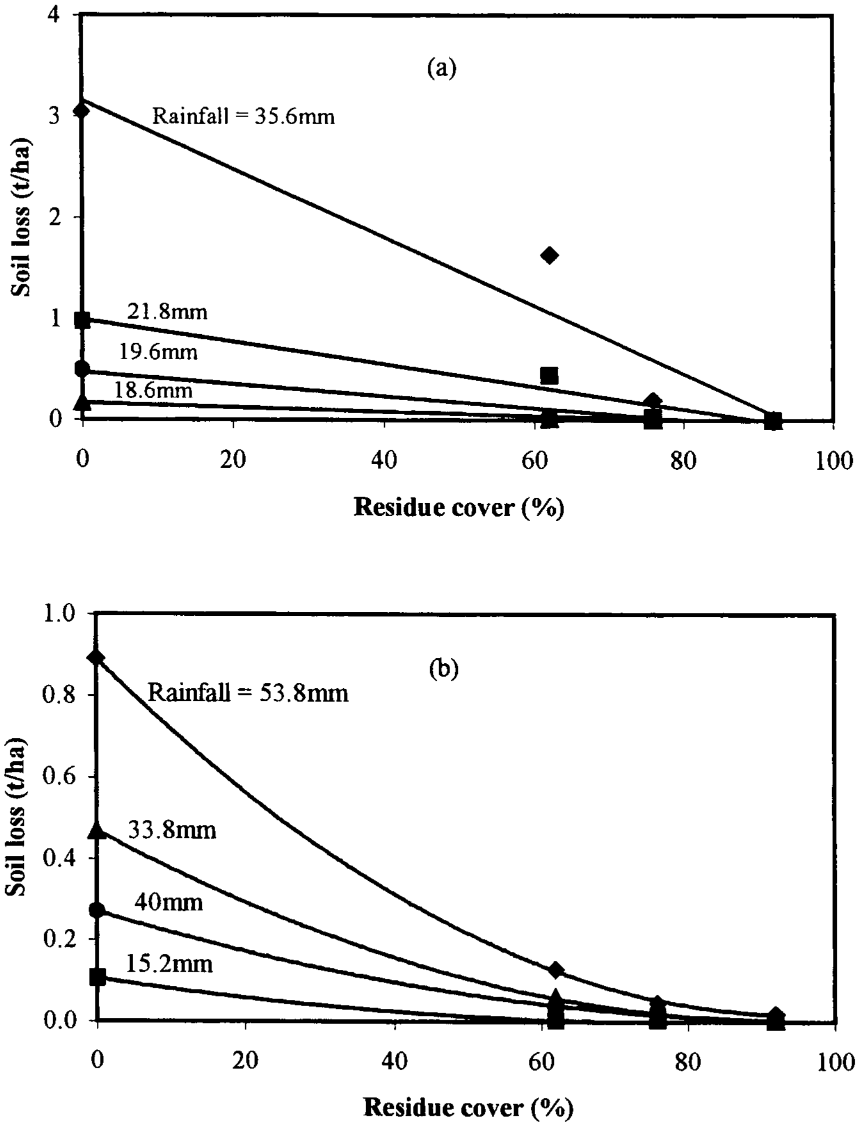


Figure 6.5. Mean soil loss from three tillage practices as a function of percentage residue cover for the different erosive storms during the rainfall season of (a) 2000, and (b) 2001.

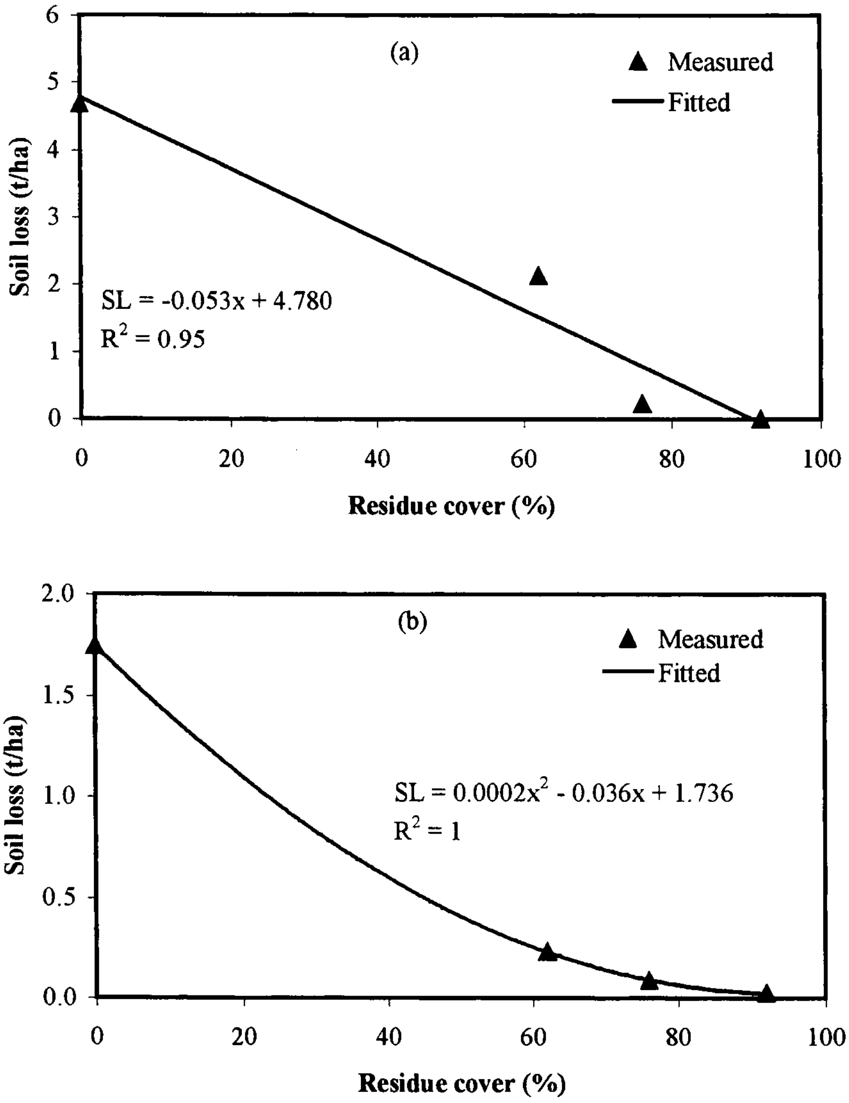


Figure 6.6. Mean total soil loss from three tillage practices as a function of percentage residue cover for the main rainfall season of (a) 2000, and (b) 2001.

In order to illustrate the interaction between the tillage practices and residue cover, the relationships between soil loss and percentage residue cover for each of the three tillage treatments are presented in Figure 6.7. The data from the first year fitted linear equations while the second year's data fitted non-linear equations.

The differences in the slopes of the lines are primarily as a result of the differences in soil loss from the bare treatments. From this it can be concluded that the relative decline in soil loss with increasing percentage residue cover is independent of the type of tillage practice, as will be illustrated later in Figure 6.10.

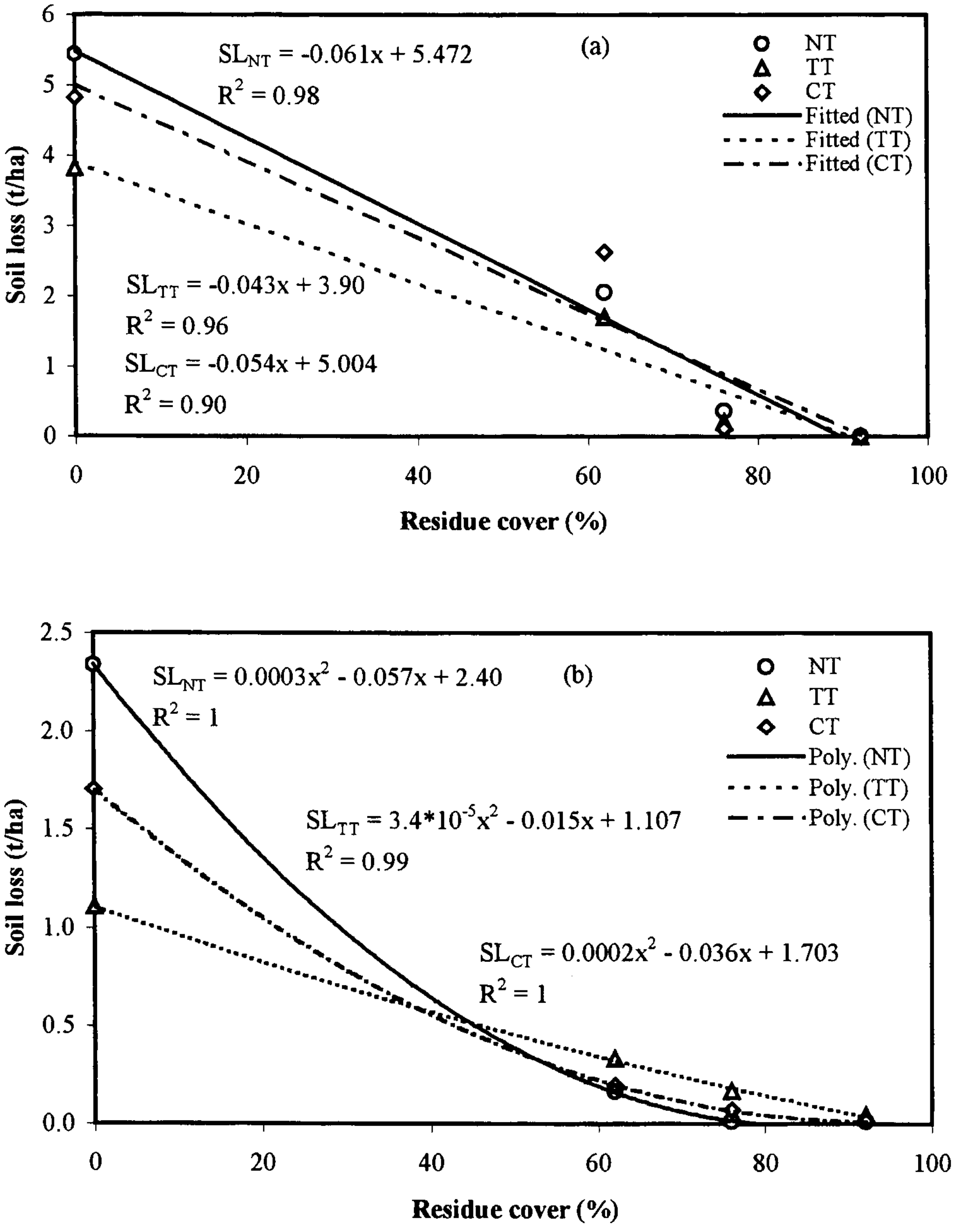


Figure 6.7. Mean soil loss from three tillage practices as a function of percentage residue cover for the main season of (a) 2000, and (b) 2001.

The most frequently reported relationships between these two variables were second-degree polynomial and inverse exponential functions (Latanzi *et al.*, 1974; Gilley *et al.*, 1986a; Gilley *et al.*, 1986; Papendick *et al.*, 1990; Zuzel & Pikul, 1993), although linear relationships were also reported in some literature (Singer *et al.*, 1981; Kinnel, 1996; Cruse *et al.*, 2001). The reason for the difference in the relationships for the two years of the same experiment could be due to the difference in the rainfall characteristics.

6.2.1.3 Effect of tillage

The mean total soil losses from the three tillage treatments for both years are given in Figure 6.8. It shows that the mean total soil loss from all the storm events is the highest for no-tillage, followed by conventional tillage. Traditional tillage had the lowest soil loss for both seasons. These differences, however, were not statistically significant. Despite the higher sediment concentration from conventional tillage compared with the other two tillage practices, the soil loss from conventional tillage was lower than from no-tillage. The soil loss from a given area is the product of the sediment concentration and runoff amount. Thus, the higher runoff generated from no-tillage resulted in a higher soil loss than from conventional tillage. Similar results were found under simulated rainfall (Section 5.2.1.1).

Lindstrom & Onstad (1984) warned that soil erosion could be a serious problem on no-tillage when insufficient residue is present to reduce the runoff flow velocity. In another study, Myers & Wagger (1996) reported that residue cover did not substantially reduce runoff from no-tillage treatments but consistently decreased soil loss.

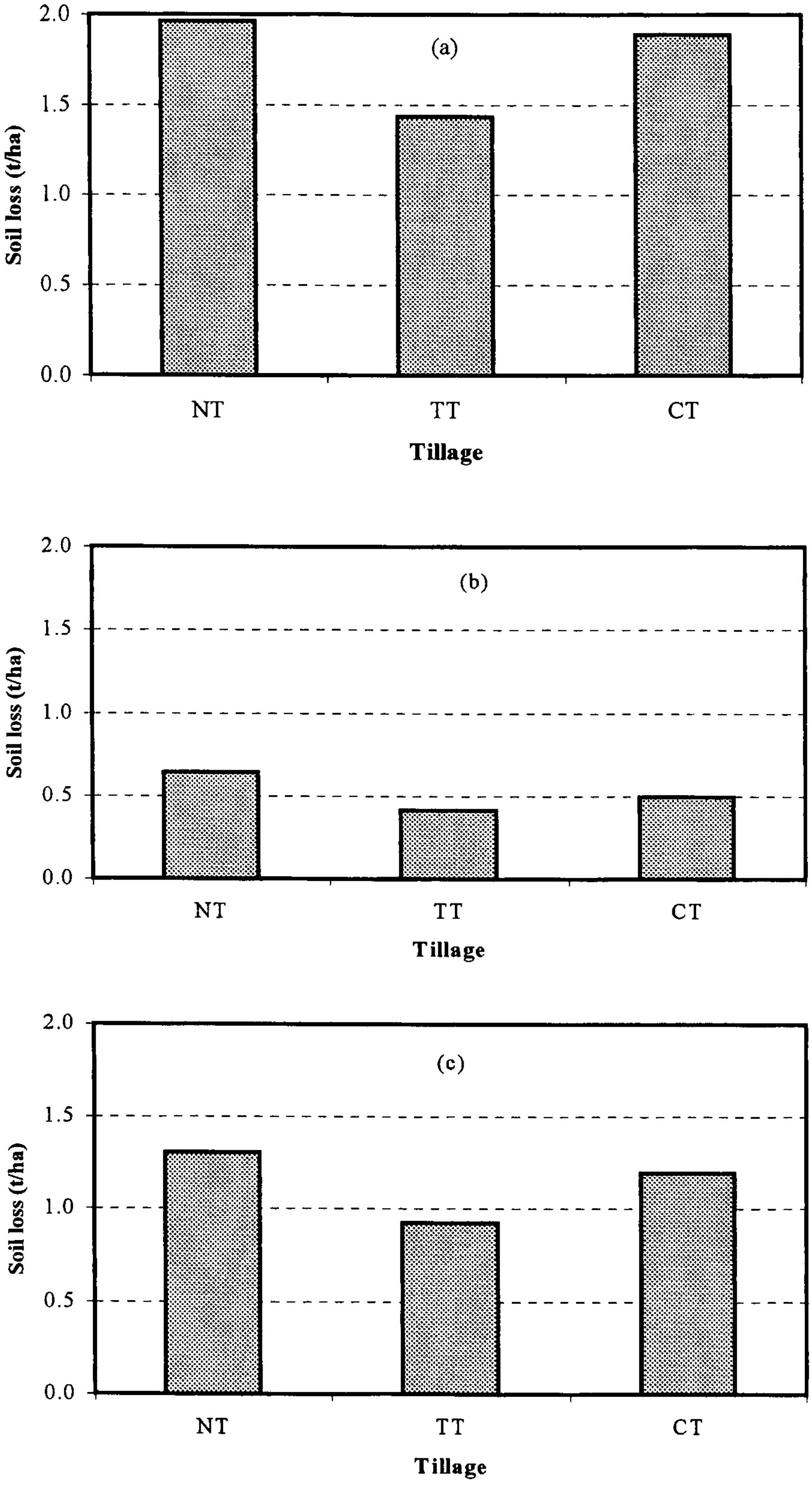


Figure 6.8. Mean total soil loss, over rates of residue cover, from three tillage treatments during the main rainfall season of (a) 2000, (b) 2001, and (c) average of the two years.

Overall, the type of tillage practice had little effect on the total soil loss except on the bare no-tillage plots that had the highest erosion for all the storms. When no-tillage is practiced on this type of soil, care should be taken that a wheat residue cover of at least 2t/ha or 60% ground cover should be maintained at all times.

The effect of tillage was generally limited to the first few erosive storms until the tillage induced roughness and depression storage disappeared. It is possible that two years were not long enough to detect the differences due to tillage practices. The effect of a tillage practice is reported to take several years to change certain physical and hydraulic properties of the soil. For instance, Dickey *et al.* (1989) reported that between 5 and 6 years is required for changes in soil physical properties, resulting in higher water intake, to become measurable. Voorhees & Lindstrom (1984) reported that 3 to 4 years were required before conservation tillage had a more favourable porosity in the upper 0 to 15 cm depth of the soil.

6.2.1.4 Soil loss ratio

The soil loss ratio, also called soil loss mulch factor, is the ratio between the soil loss from the plots covered with residue and the soil loss from bare plots without residue cover. The relationships between soil loss ratio and percentage residue cover are given in Figure 6.9. Figure 6.9a shows a linear relationship between the soil loss ratio and the percentage residue cover for the first year's data. This differs from the exponential relationship found for the second year and under the simulated rainfall for this study and several many others (Gilley *et al.*, 1986a; Gilley *et al.*, 1986; Freebrain *et al.*, 1993; Papendick *et al.*, 1990). The main contribution to the linear relationship in 2000 came from the high runoff from the 2t/ha residue rate during the 12th of August storm. The relationship between the soil loss ratio for the combined data from both years and the percentage residue cover was also linear, similar to the first year's data. The fitted equation was also identical to that of the first year.

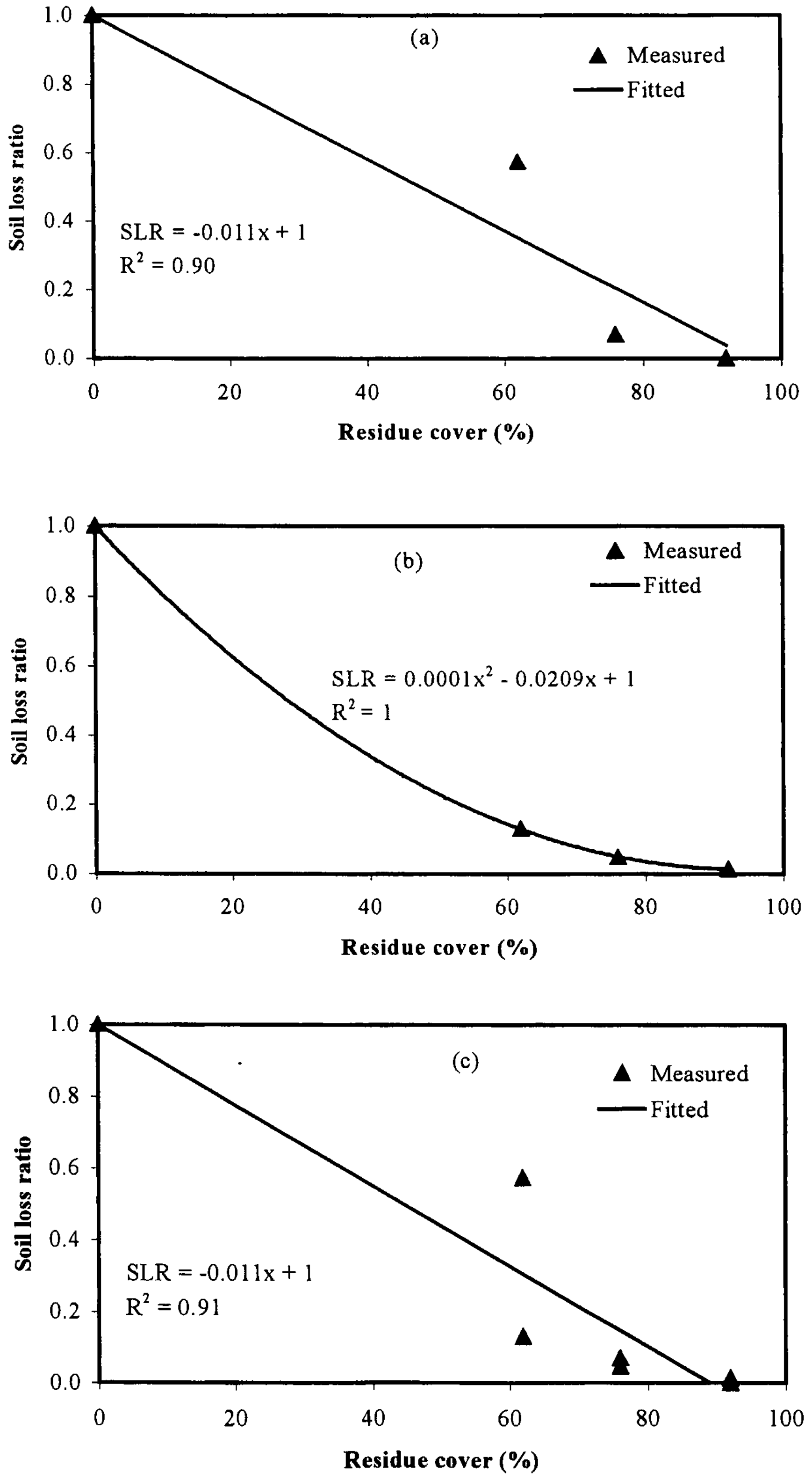


Figure 6.9. Soil loss ratios as a function of percentage residue cover for (a) 2000, (b) 2001, and (c) the combined data for both seasons.

Figure 6.10 illustrates the effect of the three tillage treatments on the soil loss ratios. For the first year, there were no differences among the three tillage practices. During the second year the residue cover seemed to be more effective in reducing soil loss on no-tillage than on conventional and on traditional tillage. This was probably due to the fact that the soil loss from the bare no-tillage was the highest which made the addition of residue more effective on the no-tillage.

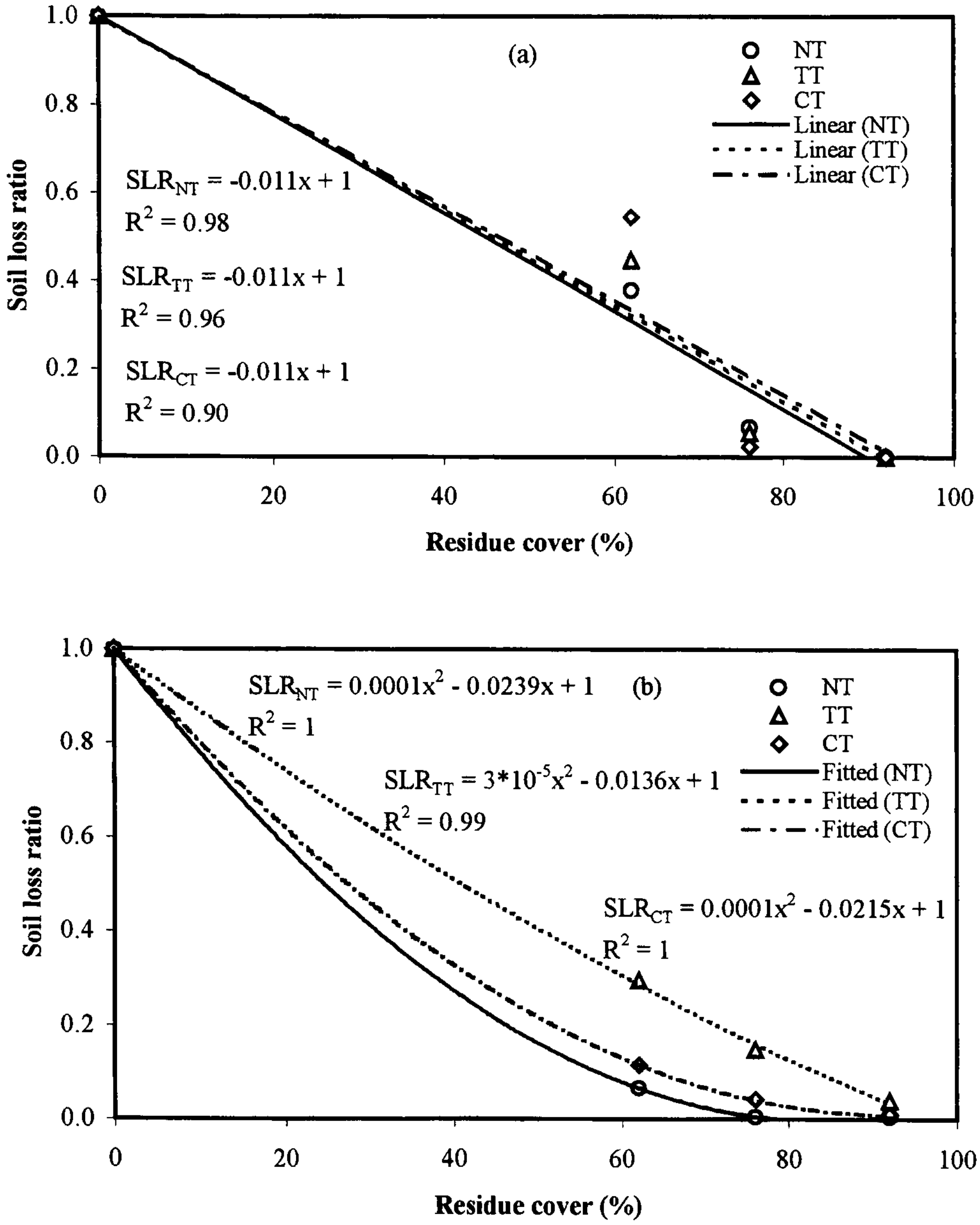


Figure 6.10. Soil loss ratios as a function of percentage residue cover for three tillage practices during the main season of (a) 2000, and (b) 2001.

6.2.2 Empirical Relationships Between Soil Loss, Runoff and Rainfall Characteristics

Soil loss depends on the runoff amount and the sediment concentration, which in turn depends on the rainfall amount and intensity and the erodibility of the soil. Erosion rate (g/m^2/hr) is a function of rainfall intensity (Meyer 1981; Foster *et al.*, 1982). The rainfall erosivity factor was found to correlate well with a power function of the rainfall amount (Renard & Freimund, 1994). Ten years' monthly data on erosivity and rainfall amounts from the Ethiopian highlands (SCRP, 1996) have also been fitted to a power function and the result shows a good correlation between these two parameters (Section 4.2.2, Figure 4.12).

The data from this study was used to obtain empirical relationships between soil loss, runoff, rainfall amount and erosivity index. The soil loss – runoff relationship for both years' data are presented in Figures 6.11 and 6.12. The relationships between the combined data of rainfall and runoff from event storms, for separate and combined seasons, were found to be non-linear (Figure 6.11). Figure 6.12 also shows non-linear relationships between the mean total soil loss and runoff with a strong coefficient of determination.

Regression analyses were conducted between soil loss and rainfall amount for residue rates of 0, 2, and 4t/ha. The results of both years are presented in Figure 6.13. The type of relationships between soil loss and rainfall amount, however, varied depending on the rate of residue on the surface. Generally, the relationships between soil loss and rainfall amounts, for the three rates of residue cover, showed consistent increase in soil loss with higher amounts of rain but the effect of rainfall amount decreased with higher rates of residue cover.

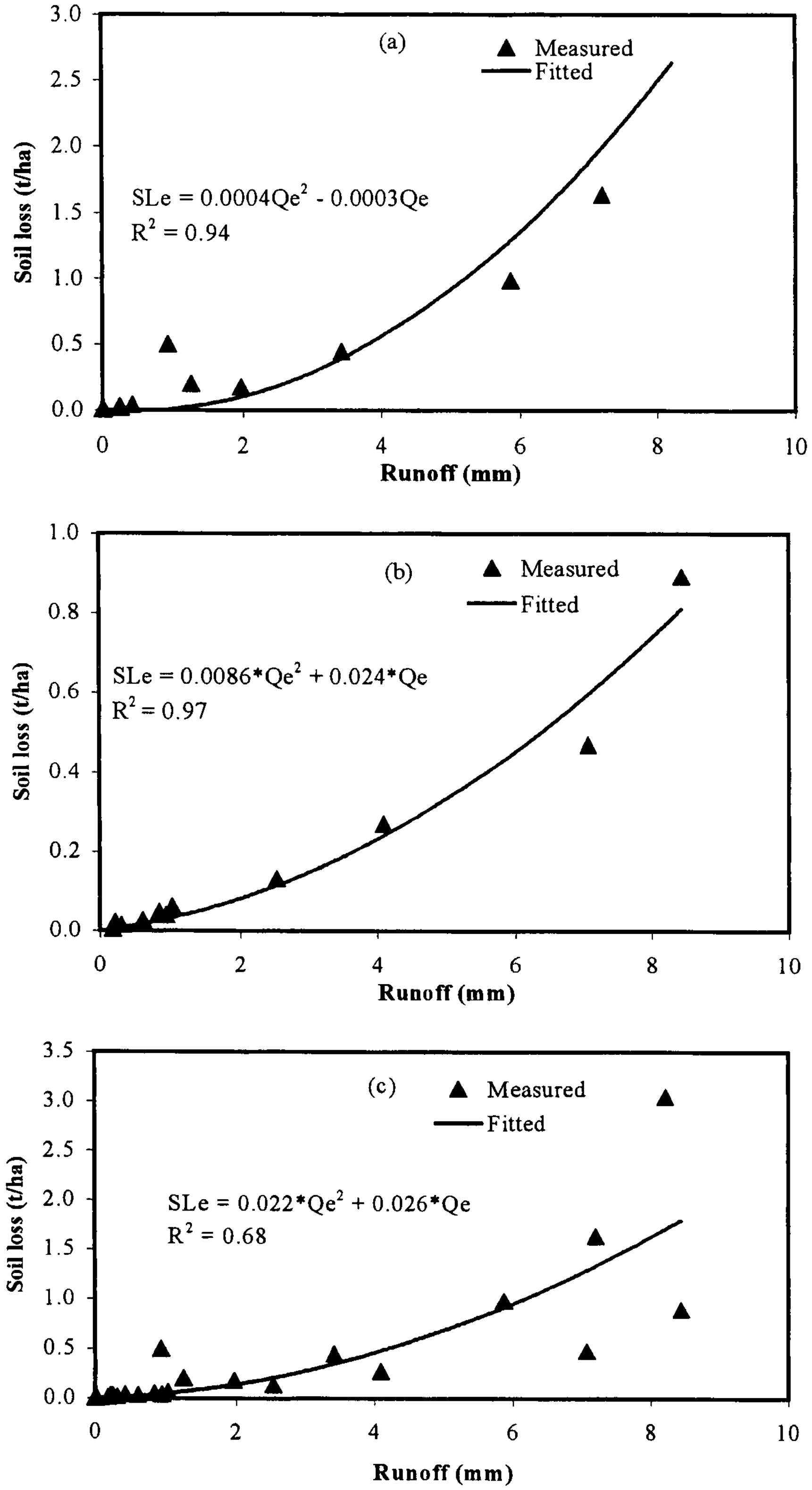
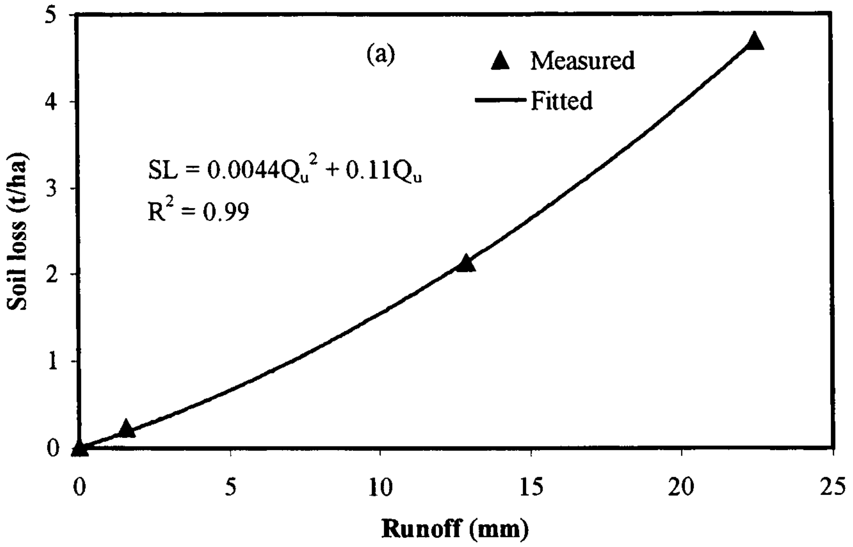


Figure 6.11. Mean event soil loss (SLe) as a function of event runoff (Qe) for the rainfall seasons of (a) 2000, (b) 2001, and (c) the combined data for both seasons.



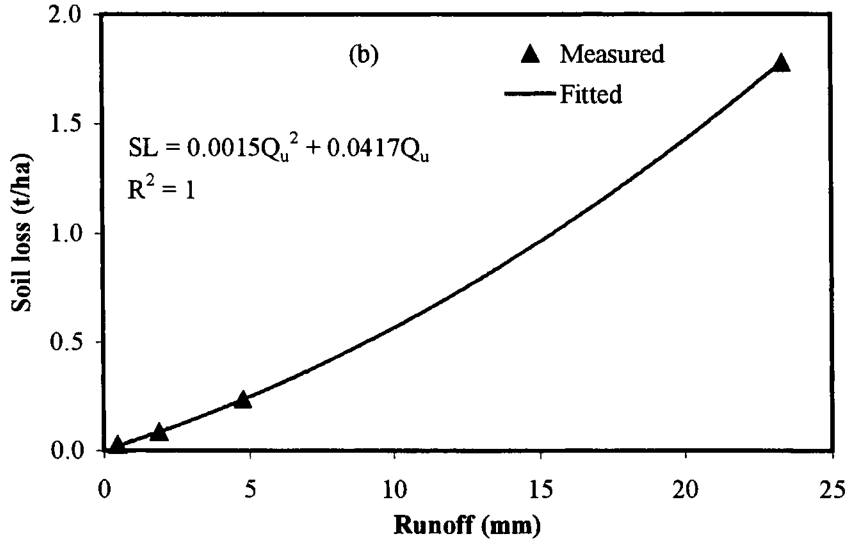


Figure 6.12. Mean total soil loss (SL) as a function mean total runoff (Q_u) for the main rainfall season of (a) 2000, and (b) 2001.

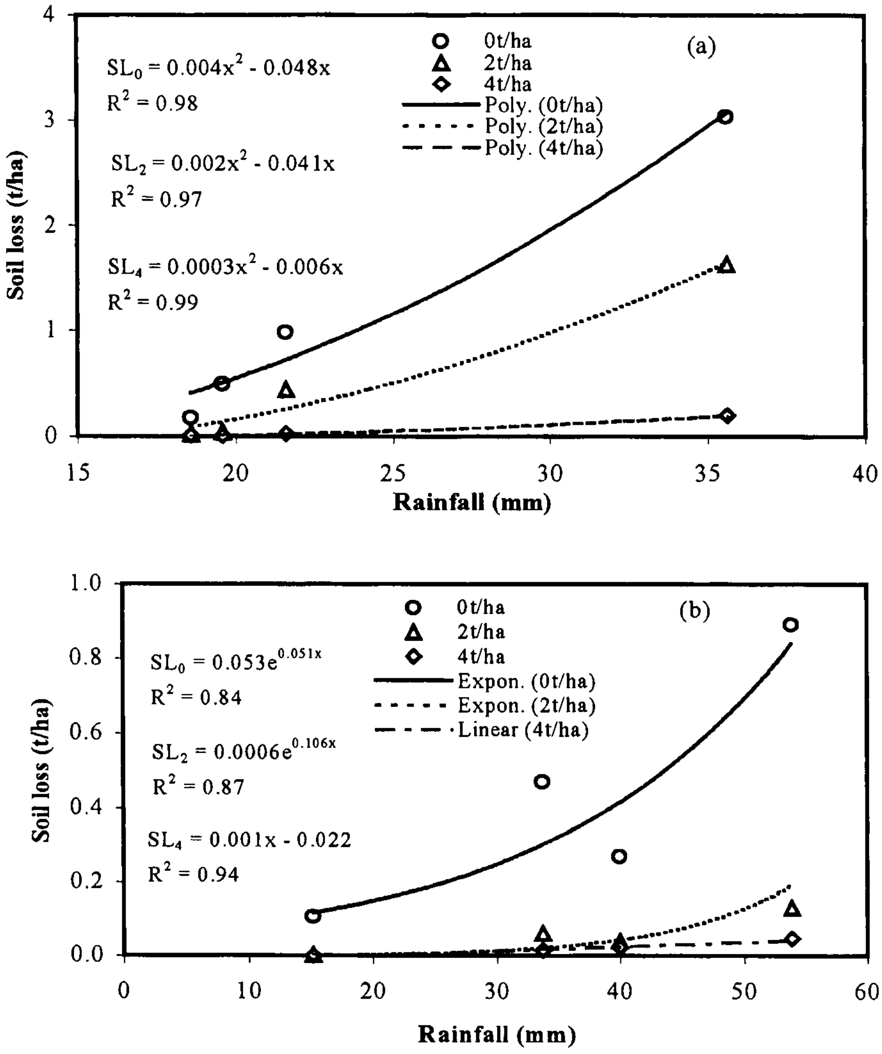


Figure 6.13. Mean event soil loss (SLe) as a function of event rainfall amount for three residue rates during the main rainfall season of (a) 2000, and (b) 2001.

Among the factors involved in the erosion process, the energy of rainfall to cause erosion and its intensity are said to be the main ones. The product of the maximum 30-minute intensity and the total kinetic energy of a storm is used as an index of the erosivity of a storm (EI_{30}). This index together with the soil erodibility factor forms the basis for the Universal Soil Loss Equation, which is based on the multiplication-of-factors type. The relationships between soil loss from bare plots of the three tillage practices and the erosivity index of the storms for separate and both seasons were non-linear, as illustrated in Figure 6.14.

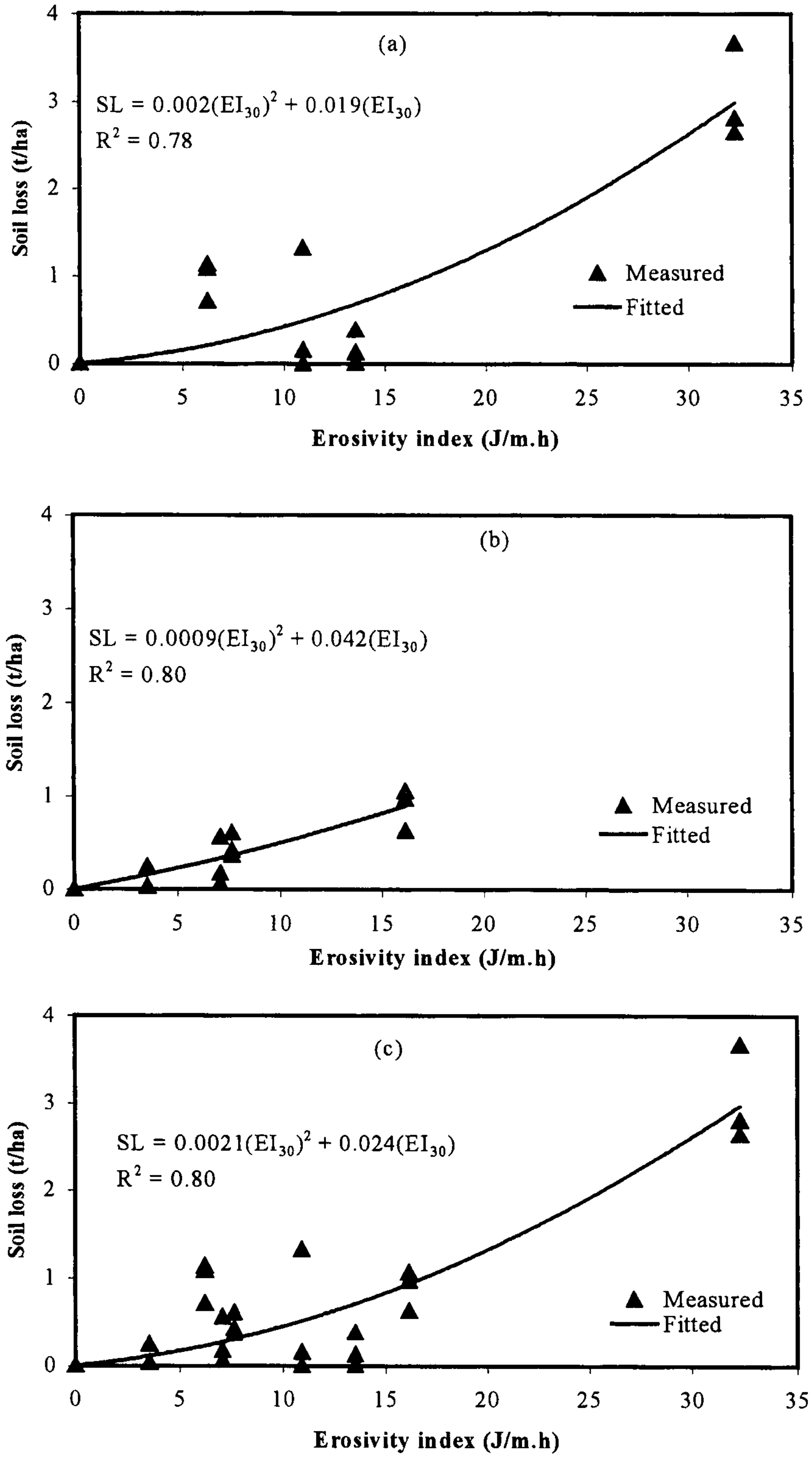


Figure 6.14. Mean soil loss (SL) from bare plots of the three tillage practices as a function of erosivity index (EI_{30}) for the main season of (a) 2000, (b) 2001 and (c) the combined data for both seasons.

6.3 Conclusions

A field experiment was carried out at the Alemaya University experimental site, Ethiopia, to determine the effects of tillage practices and residue cover on soil loss under natural rainfall conditions for two consecutive rainfall seasons. The results showed that soil loss was the highest from no-tillage with no residue cover followed by the bare conventional tillage. Traditional tillage had the lowest soil loss of the bare treatments during both seasons. The mean total soil losses from the bare plots varied between 5.4 and 3.8t/ha for the first year with higher intensity storms, to 2.4 and 1.4 t/ha for the second year. These values are not exceptionally higher. The differences between the tillage practices were not statistically significant.

Residue rates of 2 to 4t/ha decreased the soil losses significantly. The mean total soil loss from all the bare tillage treatments was reduced from 4.7 to 2.1 and 0.2t/ha by 2 and 4t/ha residue cover respectively for the first rainfall season. No soil loss was measured from a 8t/ha residue cover. For the second season the relative reduction was even more impressive when the mean soil loss of 1.7t/ha from the bare plots was reduced to 0.2 and 0.09t/ha by residue rates of 2 and 4t/ha respectively. Roth *et al.* (1988) recommended that at least 4 - 6t/ha of mulch is needed to reduce runoff and erosion effectively. However, Unger *et al.* (1991) argued that much lower residue amounts could greatly reduce erosion because surface residue reduces soil loss much more than it reduces runoff. Freebrain *et al.* (1993) indicated that residue cover levels of about 30% appear to be critical for erosion control. For this study residue cover levels of 60% were effective in controlling soil loss.

From the first year's rainfall and soil loss data it was observed that the effectiveness of residue cover for reducing runoff and erosion depends on the rainfall characteristics in general and rainfall intensity in particular. The reduction in soil loss at a residue rate of 2t/ha varied from as high as 98% on traditional tillage during the second low intensity storm of the first season to as low as 35% on no-tillage during the high intensity third storm of the first rainfall season. It is important to note that rainfall intensity has a greater effect on soil loss than the rainfall amount. Soil loss from two comparable rainfall amounts of 35.6 and 33.8 mm during the first and the second year respectively, can be taken as an example. The average soil loss from the bare plots of the tillage practices was 3.04t/ha for the high intensity storm of 35.6 mm and 0.47t/ha for the low intensity storm of 33.6 mm.

It is evident from the data that as a general recommendation, maintaining a wheat residue rate of 2t/ha or providing 60% ground cover should be efficient to reduce soil loss over the long term. To effectively reduce soil loss during high intensity storms a higher residue rate of at least 4t/ha is required.

A good correlation between soil loss and the erosivity index of a storm was found. The following erosivity index classes can be defined:

< 15 J/m.h – low: soil loss less than 1t/ha
15 – 30 J/m.h – medium: soil loss between 1-3t/ha
>30 J/m.h – high: soil loss greater than 3t/ha

Soil loss is the product of sediment concentration and runoff. Sediment concentration alone does not seem to be a good indicator of the erosion that occurs. For example conventional tillage had the highest suspension concentrations in this study but because of the lower runoff amount the soil losses were less than from no-tillage.

Soil loss ratio, expressed as a function of percentage residue cover, is an indication of the relative effectiveness of residue cover on the three tillage practices. The relationship between these two variables was linear for the first year's data and non-linear for the second year. The reason for the different types of relationship can be attributed to the difference in rainfall characteristics over the two seasons in general and the one very high intensity storm of the first year in particular.

Empirical relationships have been established between soil loss, runoff and rainfall. From the soil loss – runoff per event relationships it can be concluded that 6 mm of runoff per storm will be required to produce erosion of 1t/ha or less. When the runoff per storm exceeds 8 to 10 mm high soil losses, in the order of 2-3t/ha can be expected. The annual soil loss – runoff relationships differed between the seasons because of the difference in the number of higher intensity storms per season. For the first season a total of 20 mm runoff produced 4t/ha soil loss against 1.5 t/ha for the second season.

Although good relationships between soil loss and rainfall were found for the different seasons, its value as a tool for estimating soil loss is poor. The reason being that the number of high intensity storms is more important than the total seasonal rainfall.

The erosivity index, which was related to soil loss in a non-linear equation, seems to be the best indicator of expected soil loss from bare soil. This value can then be multiplied by the appropriate soil loss mulch factor or soil loss ratio in order to estimate soil loss from residue covered plots.

In order to understand and measure the effect of tillage and residue cover better, an experiment of this kind should continue over a longer period of time. This study constitutes a step forward in comparing the effectiveness of different tillage practices in relation to soil and water conservation and the relative importance of conservation and traditional tillage practices in relation to the rapidly expanding conventional tillage on the emerging commercial farms in the Ethiopian agriculture.

CHAPTER 7

COMPARISON OF RESULTS FROM THE TWO LAND UNITS AND IMPLICATIONS FOR THE PREDICTION OF RUNOFF

7.1 Introduction

The results of the experiments at Bloemfontein and Alemaya have been discussed separately in previous chapters covering the effects of tillage and residue cover on infiltration, runoff and soil loss. At both sites increasing the residue rate and tillage depth significantly decreased runoff and soil loss. Relationships were established between the different factors involved in the erosion process and the different tillage and residue treatments. The results from both experimental sites will be compared in this chapter and applied for the estimation of runoff from rainfall data.

7.2 Comparison of Factors Affecting Runoff

The factors affecting the amount of runoff from a given storm is a function of mainly the rainfall characteristics and soil management aspects. Tillage practices and the amount of residue remaining on the soil surface are among the important factors affecting runoff and erosion. Three tillage practices and four levels of wheat residue cover were investigated at the University of the Free State (UFS) and Alemaya University (AU) experimental sites, under simulated and natural rainfall conditions, respectively, in relation to their effect on runoff and erosion. The effect of no-tillage, stubble mulch or traditional tillage and conventional tillage, each combined with 0, 2, 4 and 8t/ha wheat residue cover at the two sites, on runoff and soil loss will be compared in the following discussions.

Simulated rainfall was used on a sandy soil with 8.4% clay in the topsoil at the Bloemfontein site. At the Alemaya site the soil was more clayey namely a clayey topsoil with 45.1% clay.

7.2.1 Residue Cover and Tillage Practices

Total runoff

An increase in the amount of residue cover decreased the amount of runoff at both experimental sites. A residue rate of 2t/ha decreased runoff significantly at both sites. The relationships between total runoff and percentage residue cover at both sites are given in Figure 7.1. The mean total runoff at AU site is the average of the two rainfall seasons (2000 and 2001). It can be seen from Figure 7.1 that runoff decreased linearly in both cases.

The differences in runoff between the two sites can be ascribed to the more clayey soil at the AU site and the application differences between simulated rainfall with a constant intensity and natural rainfall with variable intensities. The soil of the UFS experimental site was a sandy soil with less than 10% clay content whereas that of the AU site was a clayey type with more than 40% clay content. With the infiltration rate believed to be decreasing with an increase in silt plus clay content, it can be expected that higher runoff would occur from a clayey soil of the AU site. The cumulative rainfall amount for the UFS site was uninterrupted simulated application of 100 mm and that of the AU site was the average of several natural rainstorms totaling 137.7 mm (average of the total runoff producing storms of both seasons). The initial soil wetness before a storm is an important factor that determines runoff during a storm. The rainfall between erosive storms at the AU site wetted the soil, which was favorable for runoff generation.

The runoff from the bare AU soil was higher than from the UFS soil. This resulted in a steeper decrease in runoff at the AU site with an increase in the amount of residue cover. The slopes of the fitted straight lines give the rates of decrease in runoff. These rates were a decrease of 0.242 mm and 0.067 mm of runoff for the AU and the UFS sites, respectively, for every 1% increase in percentage residue cover. Moreover, a residue rate of 8t/ha did not produce any runoff at AU site while there was 2.27 mm of runoff at the UFS site.

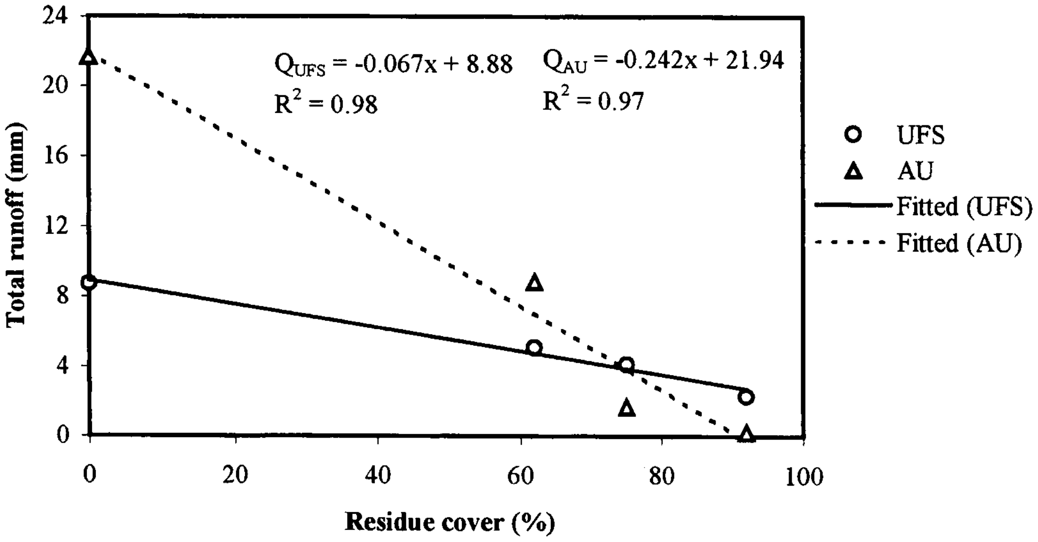


Figure 7.1. Relationships between mean total runoff, averaged over the three tillage practices, and percentage residue cover for the UFS and AU experimental sites.

Runoff coefficient

The runoff coefficients, which is the ratio between the total runoff and total rainfall over the same period, for both sites are given as a function of percentage residue cover in Figure 7.2. The runoff coefficients decreased linearly with an increase in the percentage residue cover at both sites. On bare plots without residue cover the runoff coefficients were about the same for both sites. However, on residue-covered plots higher runoff coefficients were obtained at Bloemfontein compared with Alemaya, which indicate that residue mulches were more effective at Alemaya.

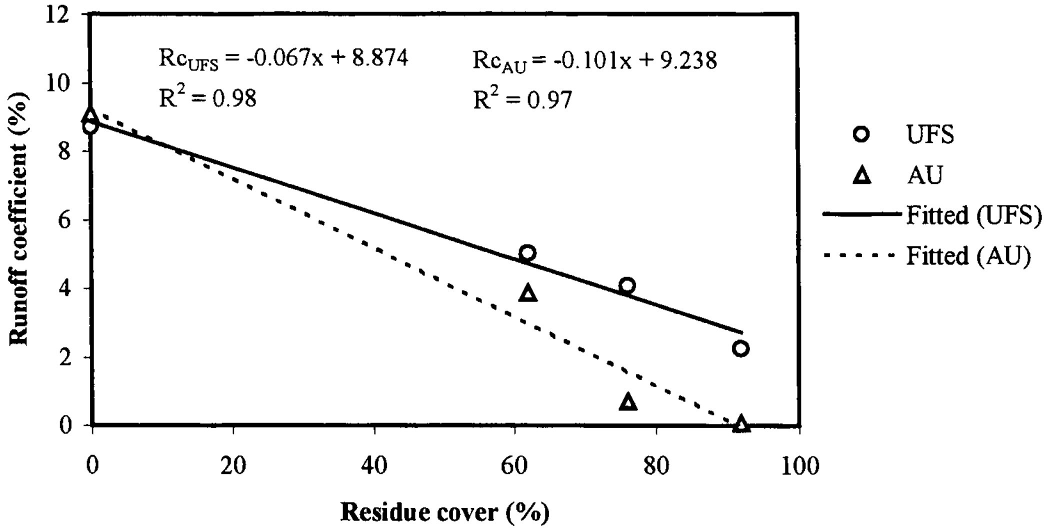


Figure 7.2. Runoff coefficients as a function of percentage residue cover for the UFS and AU experimental sites.

Runoff mulch factor

The runoff mulch factor, which is the ratio between runoff from residue-covered plots and runoff from bare plots without residue, is an indicator of the effectiveness of residue cover in reducing runoff relative to the bare condition. The results for both sites are given in Figure 7.3. The runoff mulch factor decreased exponentially with an increase in the percentage residue cover for both sites (Figure 7.3a). The data was also fitted to a linear equation with higher coefficients of determination (Figure 7.3b). However, exponential relationships between the runoff mulch factor and percentage residue cover is the most acceptable in literature. Figure 7.3 also illustrates that applying residue as a surface mulch was much more effective on the Alemaya than on the Bloemfontein soil. For example, at the UFS site, a residue cover of 62% reduced runoff by 50% compared with the bare plots, whereas the corresponding value was less than 20% for the AU site, according to the fitted curve. According to the linear relationships between the runoff mulch factors and percentage residue cover (Figure 7.3b) the differences in the runoff mulch factors between the two sites were smaller.

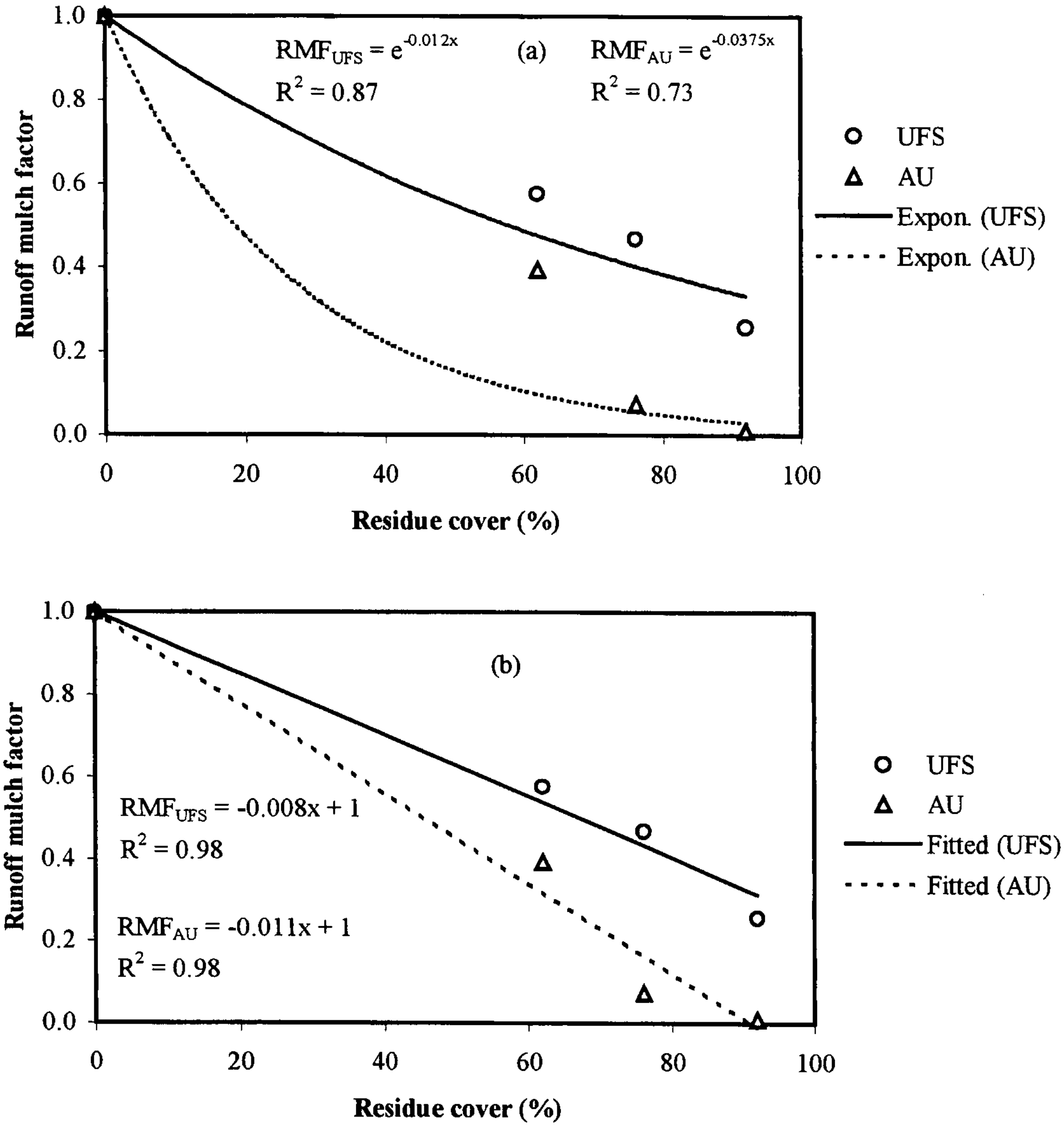


Figure 7.3. Runoff mulch factors as a function of percentage residue cover fitted to (a) exponential and (b) linear functions for the UFS and AU sites.

7.2.2 Tillage Depth

Selection of the appropriate tillage practice for a particular soil type can decrease runoff and soil erosion. A conservation tillage practice such as no-tillage is generally credited for reducing soil losses when compared with conventional tillage practices. However, the reported results are not consistent due to differences in soil properties and other factors affecting runoff. A long-term tillage experiment at the UFS site revealed that runoff from no-tillage plots were higher than from conventionally tilled plots (Bennie, 2000; Bennie & Hensley, 2001). The results from the simulated rainfall experiment on the same soil of this study were also in agreement with the findings reported by these authors. Although the tillage experiment at the AU site was launched only recently, the results regarding the effect of tillage practices on runoff were similar to that of the simulated rainfall experiment at the UFS site.

The relationships between runoff and tillage depth for the bare plots at both sites are compared in Figure 7.4. The depth of tillage for the traditionally tilled plots at the AU site was similar to that of stubble mulch tillage at the UFS site.

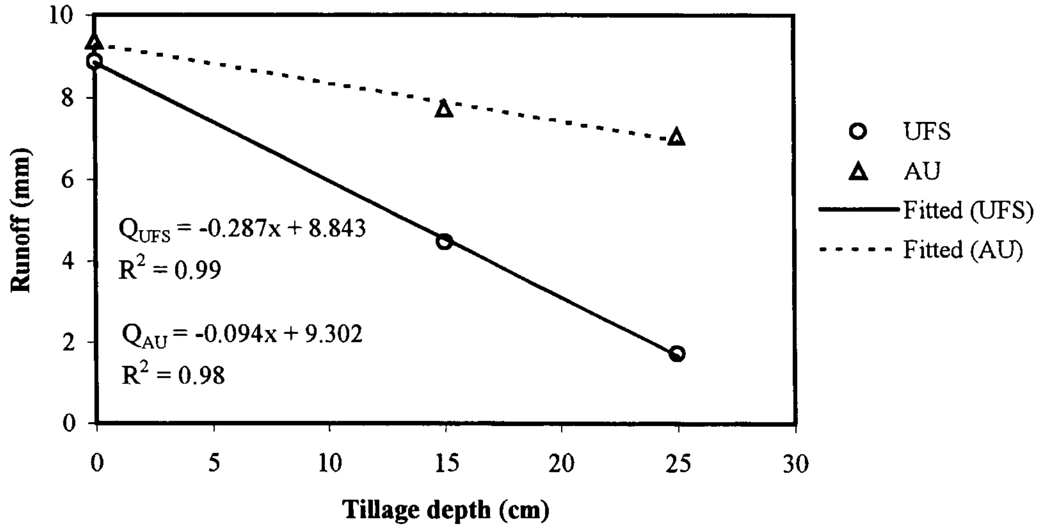


Figure 7.4. Relationships between runoff and tillage depth for the UFS and AU experimental sites.

Runoff decreased linearly with an increase in depth of tillage at both sites. However, the rate of decrease in runoff was higher for the Bloemfontein than for the Alemaya soil. The reason is probably the difference in soil structure. As described earlier, the Bloemfontein soil was sandy with no structure. Conventional tillage, using mouldboard ploughing, created small aggregates and improved the structure of the soil temporarily, until such time that excessive raindrop impact destroyed the aggregates and a surface crust was formed. The soil of the AU-site was more clayey with good structure. Consequently, the differences in runoff due to tillage were smaller. Unfortunately, the duration of the tillage experiment at the AU-site was too short to observe any changes in tillage-induced physical and hydraulic soil properties affecting runoff.

A runoff tillage factor (RTF) was derived, similar to the runoff mulch factor. The RTF was defined here as the ratio between runoff from tilled plots and the runoff from no-tillage plots. Figure 7.5 shows the relationships between the runoff tillage factors as a function of tillage depth. The runoff tillage factor can be used as an indicator of the effectiveness of tillage operations in reducing runoff on a particular type of soil. The RTF values were 0.5 and 0.2 for the stubble mulch and conventional tillage practices respectively. It can be seen from Figure 7.5 that stubble mulch tillage reduced runoff to 50% of that from no-tillage and for conventional tillage it was only 20%.

Nevertheless, it can be concluded from the two years of runoff data at AU that increasing the depth of tillage using mouldboard ploughing reduced runoff compared with traditional and no-tillage practices, as indicated by a reduction in the runoff tillage factor (Figure 7.5).

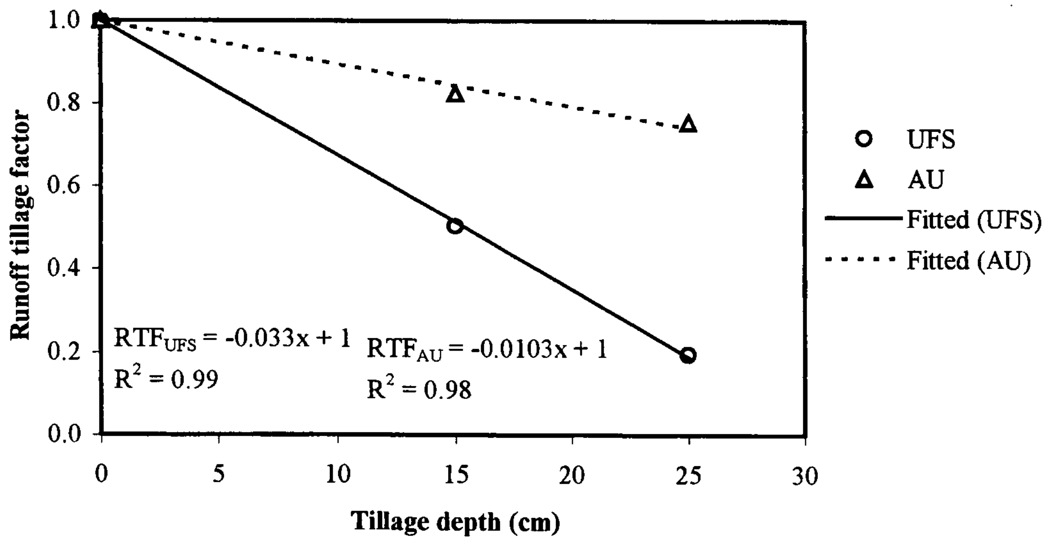


Figure 7.5. Runoff tillage factor as a function of tillage depth for the UFS and AU sites.

7.2.3 Rainfall Intensity

The rainfall characteristics in general and rainfall intensities in particular, represent the energy of a storm that is available to detach soil particles from a given field. These together with runoff are responsible for the transport of the detached soil particles. The infiltration rate of a soil is also reported to be dependent on the rainfall intensity. It has been established by several researchers, as well as by this study, that the infiltration rate of the soil increases with an increase in rainfall intensity. For example, Moldenhauer *et al.* (1960), cited by Flanagan *et al.* (1988), reported a positive relationship between infiltration rates and rainfall intensities in their analysis of runoff from natural storms. Hawkins (1982), cited by Flanagan *et al.* (1988), also found similar increases in infiltration rates with rainfall intensity for several field data sets.

The final infiltration rate of the soil at the AU experimental site, measured with a double ring infiltrometer, was found to be very high, more than 150 mm/hr. The applicability of this value can be questioned since the clay content is more than 40%. The infiltration rate for the soil of the AU-site was therefore estimated from the rainfall intensity and runoff amount using the procedure that will be described in Section 7.3.2.2.

At the UFS experimental site infiltration rates were measured using various simulated rainfall intensities on bare plots of stubble mulch and conventional tillage. The average infiltration rates of these measurements on both tillage practices are compared with the infiltration rates on bare plots calculated for the AU-site. The results are presented in Figure 7.6. It can be seen that the infiltration rate of the soils increased non-linearly and linearly with an increase in the rainfall intensity at the UFS and AU sites, respectively, both with high coefficients of determination. The infiltration rate at the UFS-site increased at a decreasing rate and appeared to decline beyond a rainfall intensity of 100 mm/hr.

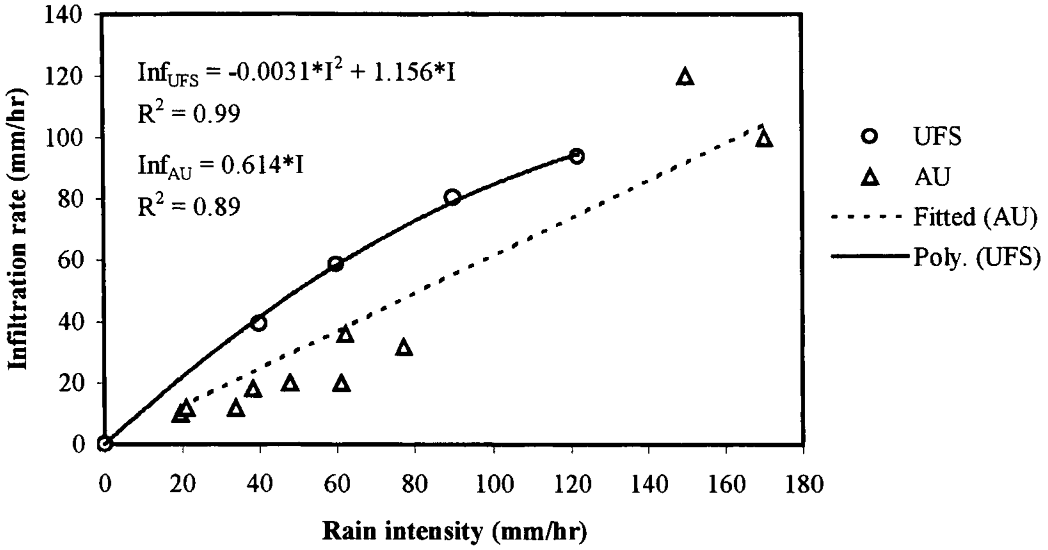


Figure 7.6. Relationships between infiltration rates and rainfall intensities for the UFS and AU experimental sites.

7.3 Comparison of Factors Affecting Erosion

Soil erosion is affected by several factors, such as rainfall amount and intensity, topography, soil management practices and surface cover conditions. Tillage and residue management practices are among important factors affecting erosion. Three tillage practices combined with four levels of residue cover were compared to determine their effect on erosion under natural and simulated rainfall conditions at the Alemaya University (AU) and University of the Free State (UFS) experimental sites, respectively. The main results from both sites will be compared here.

7.3.1 Residue Cover

Total soil loss

Increasing the amount of residue mulch on the surface resulted in a decrease in soil loss at both experimental sites. Figure 7.7 shows the linear decrease in the mean total soil loss from the different tillage practices as functions of residue cover for both sites. It is known that erosion is also directly related to the rainfall intensity. Meyer (1981) reported that erosion rate is related to the square of the rainfall intensity, i.e. $E = K_i I^2$, where E is the erosion rate (kg/m^2/hr), K_i is the relative erodibility and I is the rainfall intensity (mm/hr). This suggests that comparison of the absolute soil loss values from simulated rainfall of a constant intensity to that from natural rainstorms with variable intensity may not be of any value, because the total amounts of rainfall and the intensities differed. Conversely, the general trend between soil loss and percentage residue cover under both conditions may be compared. At both sites, residue covers of 4 and 8t/ha or values greater than 76% ground cover restricted erosion to a nearly zero soil loss level.

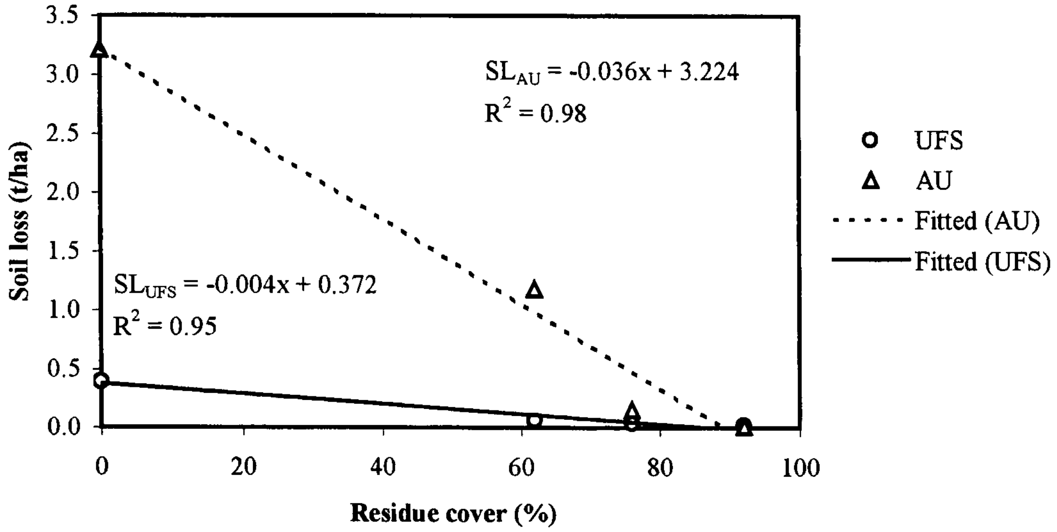


Figure 7.7. Relationships between soil loss and percentage residue cover for the UFS and AU experimental sites.

Soil loss ratio

The soil loss ratio, also called soil loss mulch factor, is a ratio between the soil loss from residue-covered plots and soil loss from the bare plot without residue cover. It gives an indication of the effectiveness of residue cover in reducing soil loss relative to the bare conditions. This is a better criterion for comparing the results from the two land units.

The soil loss ratios presented as functions of percentage residue cover, for the two sites, are given in Figure 7.8. The data from the UFS-site as well as the average data for the two seasons at the AU-site were fitted to inverse exponential functions. The data from the AU-site actually fitted to a linear equation better, with a higher coefficient of determination. The soil loss from all tillage treatments at a residue rate of 2t/ha (62% surface cover) was quite high at the AU-site because of the exceptionally high soil loss recorded from a single high intensity storm during the first season (2000) of the experiment, which contributed to the high soil loss ratio at this residue rate. This in turn resulted in a lower coefficient of determination when the data was fitted to an inverse exponential function.

The soil loss ratio – residue cover functions for the two land types are similar and almost identical. This implies that the effectiveness of residue cover in reducing soil loss from both land types were the same. If the soil loss from bare conditions (SL_{bare}, t/ha) is known the reduced soil loss (SL_{cover}, t/ha) at a specified level of percentage residue cover (Pc, %) can be predicted by using equation (7.1).

$$SL_{cover} = SL_{bare} * e^{-0.0357*Pc} \qquad [7.1]$$

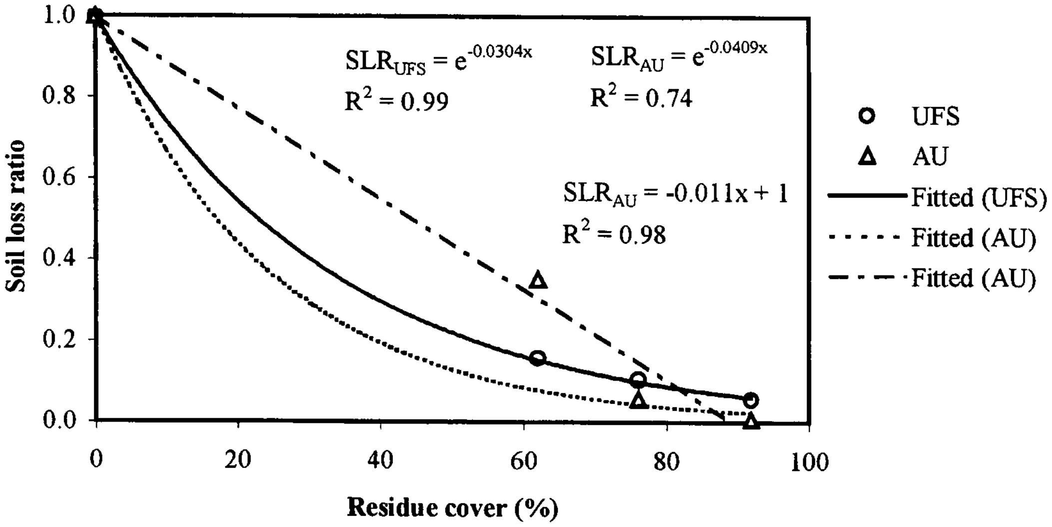


Figure 7.8. Soil loss ratio as a function of percentage residue cover for the UFS and AU sites.

7.3.2 Tillage Practices

Tillage is one of the soil management practices that modify the physical soil properties affecting soil erosion. Tillage sometimes enhances the detachment mechanisms that create a steady supply of detached aggregates, thus increasing soil erosion. Tillage also alters the pore size distribution of the topsoil affecting the infiltration process, which in turn affects erosion. The type of tillage also affects the rate of residue cover maintained at the surface.

The effects of different tillage practices on soil loss, at the UFS- and the AU-sites varied, as illustrated in Figure 7.9. At both sites no-tillage (NT) resulted in the highest mean soil loss of the four rates of residue cover mainly due to the high soil losses from the bare plots. It is evident from Figure 7.8 that when no-tillage or stubble mulch (traditional) tillage is practiced on these soils a residue cover of at least 30-40% should be maintained at all times. This is also in agreement with the recommendation of Unger *et al.* (1991). The decrease in soil losses by conventional tillage (CT) at the UFS and traditional tillage (TT) at the AU-sites, were a function of the depth of tillage. Deeper tillage increased the infiltration the infiltration rate and reduced runoff thus decreasing soil loss.

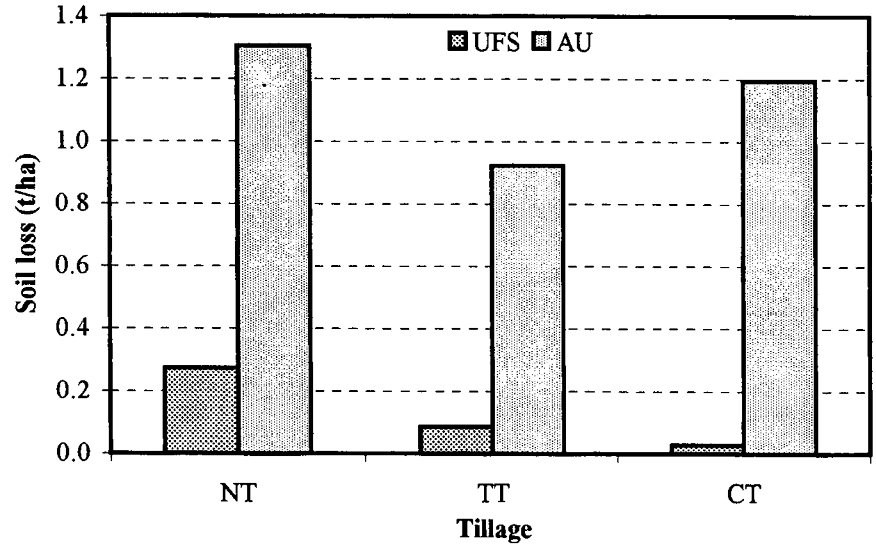


Figure 7.9. Soil loss from three tillage practices at the UFS and AU sites.

7.4 Prediction of Runoff from Rainfall Characteristics

7.4.1 Theory

The amount of runoff that results from a given rainfall event or storm depends on many factors, such as the storm characteristics, properties of the soil, slope and the degree of surface cover. For runoff to be generated from a given area, the rainfall intensity should exceed the final steady state infiltration rate of a soil. This implies that the topsoil layer should be at or near saturation.

Rainfall intensities and amounts are among the main factors affecting runoff. In addition to these, the initial soil water content in the upper soil layer just before a rainstorm is among the most important factors affecting the rainfall – runoff relationship (Karnieli & Ben-Asher, 1993). Karnieli & Ben-Asher (1993) proposed a model based on a mass balance in which runoff was assumed to begin when the amount of rainfall is equal to the initial soil water deficit. In many parts of arid and semi-arid regions, a considerable part of annual rainfall is stored in the soil to fill up the deficit. Therefore, under such conditions it is logical to assume that the difference between the initial soil water content and saturation (sorptivity) plays an important role in controlling runoff.

Several rainfall – runoff models, such as the Kinematic Runoff and Erosion Model (Whoolhiser, 1990, cited by Karnieli & Ben-Asher, 1993) use initial soil water content as one of the model's initial conditions where the soil water content is actually measured or estimated. Thus, a water balance model can be used to estimate runoff by considering the soil as a reservoir that overflows when full.

The water balance equation can be described as:

$$Q = P - ET - D - Z\Delta\theta \quad \text{[7.2]}$$

Where Q is runoff, P is precipitation, ET is evapotranspiration, D is deep percolation through the lower boundary of the soil profile, which is assumed to be negative in arid and semi-arid regions in the absence of shallow water tables, and $Z\Delta\theta$ is the change of soil water storage to a depth of Z from the upper soil surface, in a vertical system. The term $Z\Delta\theta$ is the product of the depth (Z) from the soil surface to the lower boundary of the transmission zone and its change in volumetric water content ($\Delta\theta$).

During a rainstorm without runoff, the entire amount of water infiltrates into the soil, and the soil water stored increases by the same amount. This can be described by Equation 7.3, assuming that evaporation and deep percolation during a rainfall event are negligible. However, for the period between two rainy events without runoff, the water balance equation should take into account the amounts of evapotranspiration and deep percolation as given in Equation 7.4.

$$P = Z\Delta\theta = Z(\theta_f - \theta_i) \quad [7.3]$$

$$ET + D = Z(\theta_f - \theta_t) \quad [7.4]$$

Where θ_i and θ_f are the initial and final soil water content values, respectively and θ_t is the soil water content t days after the rain event.

When evapotranspiration and deep percolation are the dominant water loss factors, the increase in sorptivity can be described by a dynamic decay of the soil water content (Karnieli & Ben-Asher, 1993), which is given in Equation 7.5.

$$Z\theta_t = (Z\theta_i + P)e^{-K\Delta t} \quad [7.5]$$

Where K is a recession factor (dimensionless, $0 < K < 1$) related to the actual evapotranspiration and deep percolation.

When rainfall intensity exceeds the infiltration rate of the soil, water starts to accumulate in the depressions and runoff begins. The runoff amount that is produced from a given storm is also closely related to the rainfall amount for that event. It had been reported that the annual runoff amount (Q, mm) is linearly related to the annual rainfall amount (P, mm) (Boers *et al.*, 1986). Boers *et al.* (1986) suggested that this relationship could also be adapted to fit single storms on a daily basis.

$$Q = \begin{cases} aP - b & if\ aP > b \\ 0 & if\ ap \le b \end{cases} \qquad [7.6]$$

Where a and b are constants. From Equation 7.6, the threshold precipitation (P_T) where runoff starts is given by $P_T = b/a$. The model proposed by Karnieli & Ben-Asher (1993) assumed that at the threshold value (P_T) the water content of the soil profile to some depth (Z) is at saturation. When P is less than P_T no runoff occurs, whereas when P exceeds P_T the amount of runoff equals a portion of the rain, given by the runoff coefficient a in Equation 7.6.

7.4.2 Prediction of Runoff from Natural Rainfall

7.4.2.1 Prediction of runoff from rainfall amounts

The relationship between rainfall and runoff from bare plots were established for the first year's (2000) data of the AU-site for two cases. The first case is where all storm events, including those that produced no runoff, were included. The second case is where only erosive storms, that produced runoff, were included in the equation. In both cases runoff increased linearly with the amount of rainfall. The fitted equations are given in Figure 7.10 where Q_A represents runoff, where all storms are included in the equation, and Q_E where only storms that produced runoff were included.

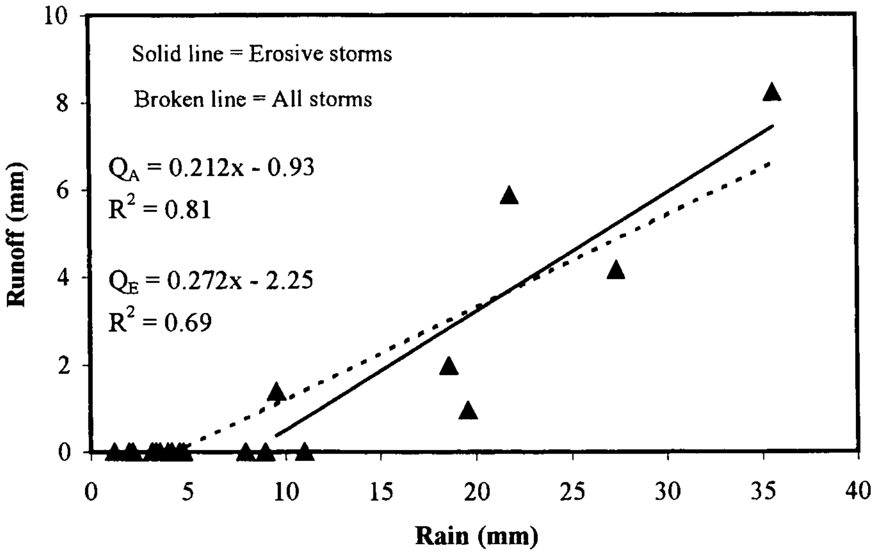


Figure 7.10. Relationships between runoff and rainfall for the 2000 season at the AU site.

The linear equations for both cases, presented in Figure 7.10 can only be applied to bare soils. To make provisions for the effect of residue cover on runoff the equation can be rewritten in the form of Equations 7.7 and 7.8.

$$Q_A = [0.212(p - 4.39)] * RMF, \qquad R^2 = 0.81 \ldots\ldots [7.7]$$

$$Q_E = [0.272(p - 8.27)] * RMF, \qquad R^2 = 0.69 \ldots\ldots [7.8]$$

In Equations 7.7 and 7.8, Q_A and Q_E are runoff related to all rainstorms and erosive storms respectively, P is the rainfall amount, and *RMF* is runoff mulch factor. The RMF can be calculated using either of the following equations.

In Equations 7.7 and 7.8 the slopes of the straight line represent the runoff coefficient, which is the ratio between runoff and rainfall. As described by Boers *et al.* (1986), the threshold value of rainfall that marks the beginning of runoff is 4.39 mm for all storms and 8.27 mm for the erosive storms only. Thus, the given relationships assume that all storm events with less than the rainfall threshold value will not produce runoff. This assumption, however, doesn't take into account the effect of rainfall intensity (Boers *et al.*, 1986) and the wetness status of the soil prior to rainfall, on runoff production.

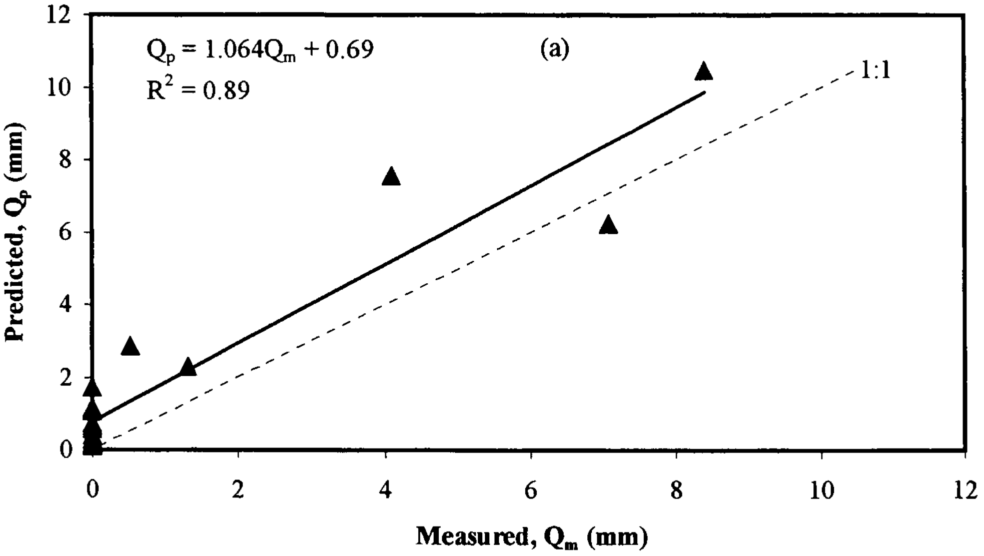
Equations 7.9 and 7.10 were used to predict the expected runoff from bare plots using the rainfall events of the 2001 experiment at the AU site. The actual runoff was also measured. The relationships between the predicted and measured runoff for the 2001 season using both equations are given in Figure 7.11. It can be seen that the equations developed from the 2000 data overestimated runoff for the second year. However, the prediction of runoff using all the rainfall events appeared to be more reliable than only the storms that produced runoff.

$$RMF = e^{-0.0375*Pc} \quad \text{[7.9]}$$

$$RMF = -0.011*Pc+1 \quad \text{[7.10]}$$

The errors of prediction using both equations are presented in Table 7.1. The error is defined here as the difference between the predicted and measured runoff. It can be seen from Table 7.1 that the linear equation developed only from the erosive storms overestimated runoff by about 50% at higher erosive storms.

The model performance was evaluated following the procedure as described by Willmott (1982). Several performance parameters were used, such as different forms of error measures and an index of agreement. Quantitative measures of the performance of the two linear models are summarized in Table 7.2.



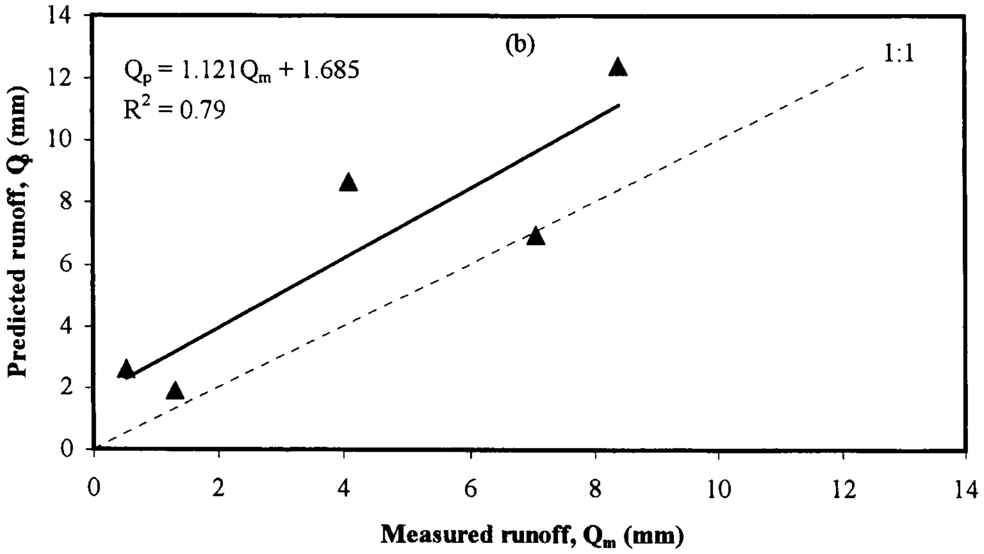


Figure 7.11. Relationships between predicted and measured runoff using (a) all storms and (b) only erosive storms, for the 2001 season at the AU-site.

Table 7.1. Measured and predicted runoff using Equations 7.7 and 7.8 for the bare plots of the AU-site during the 2001 rainfall season

Rain (mm)	Measured runoff, Q_m (mm)	Predicted, Q_p (mm)		Error* (Erosive storms)	Error* (All storms)
		Erosive storms	All storms		
15.2	1.13	1.88	2.29	0.75	1.16
17.8	0.53	2.59	2.84	2.06	2.31
33.8	7.07	6.94	6.24	-0.13	-0.83
40	4.10	8.63	7.55	4.53	3.45
53.8	8.40	12.38	10.48	3.98	2.08

* Error is defined as Q_p-Q_m

Table 7.2. Quantitative measures of model performance* for prediction of runoff from rainfall amounts

Performance parameters	Model based on erosive storms only	Model based on all storms
Measured mean	4.28	4.28
Predicted mean	6.49	5.88
MAE	2.25	1.93
RMSE	2.86	2.15
RMSEs	2.66	0.98
RMSEu	1.85	1.64
D-index	0.82	0.87
R^2	0.79	0.89

*The terms in the Table are: MAE = Mean absolute error, RMSE = Root mean square error, with subscript *s* and *u* for systematic and unsystematic errors respectively, and D-index is an index of agreement.

As indicated in Table 7.2, the model performance parameters showed that the equation based on all storms is a better predictor of runoff than the one based on erosive storms only. This was shown by the relatively lower error values and higher index of agreement for the all storm equation.

7.4.2.2 Prediction of runoff from rainfall Intensity: Area under the curve method

In order to estimate runoff from rainfall intensity the infiltration rate of the soil is required. The rainfall intensities for the AU-site were measured. Unfortunately the final infiltration rate of the soil, measured with a double ring infiltrometer, was found to be very high (>150 mm/hr). It was decided that this data couldn't be used as a representative value for the final infiltration rate of a soil that has 45% clay content.

Alternatively, the final infiltration rate of the soil was estimated using the peak rainfall intensities and total runoff amount for each of the storm events of the 2000-season. It has been established by several researchers that the infiltration rate of a soil increases with an increase in rainfall intensity. For example, Moldenhauer *et al.* (1960), cited by Flanagan *et al.* (1988), reported a positive relationship between infiltration rates and rainfall intensities in their analysis of runoff from natural storms. Hawkins (1982), cited by Flanagan *et al.* (1988), also found similar increases in infiltration rates with rainfall intensity for several field data sets.

From theory we know that runoff amount is the difference between rainfall and infiltration depth when the rainfall intensity exceeds the infiltration rate of the soil. This can be illustrated using Equation 7.11.

$$R = \begin{cases} 0, & if\ f > I \\ I - f, & if\ f < I \end{cases} \qquad \text{[7.11]}$$

Where R is the excess rainfall rate (mm/hr), I is the rainfall intensity (mm/hr) and f is the infiltration rate of the soil (mm/hr),

From Equation 7.11 it follows that for a storm event during which the rainfall intensity exceeds the infiltration rate of the soil, the total runoff for that event is the sum of the product of the differences between the rainfall intensity and the infiltration rate and the time interval considered. This can be represented using Equation 7.15.

$$Q = \sum_{i=1}^{n} t_i (I_i - f) \quad [7.12]$$

Where Q is runoff amount (mm), t_i is the time interval over which the calculation was performed (hr) and n is the number of intervals.

Thus, it was assumed that the area under the rainfall intensity curve and above an arbitrary final infiltration rate value represents the excess amount of rain that can be considered as runoff. Runoff was calculated with Equation 7.12 starting with an arbitrary value for f and through iteration the infiltration rate was obtained that yielded exactly the same calculated as measured runoff values. An example of the estimation procedure is given in Figure 7.12.

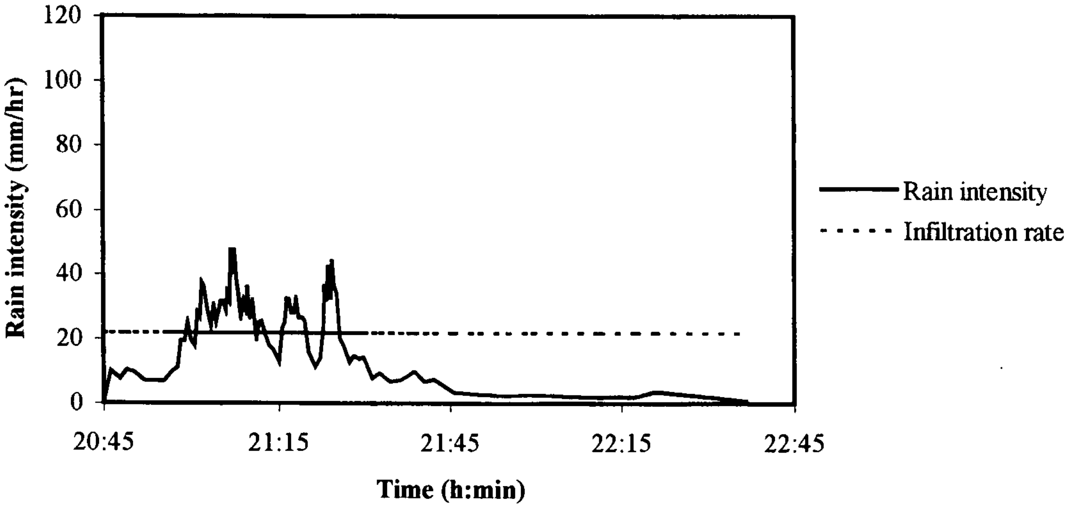


Figure 7.12. An example of the estimation of infiltration rate from rainfall intensity curve.

This procedure was used to derive the infiltration rates of the bare plots for the rainfall events that produced runoff. The bare plots were chosen because it was easier to establish a relationship for bare plots and then convert it to runoff from the residue-covered plots using the appropriate runoff mulch factor.

The relationship between the calculated infiltration rates of the soil and average peak rainfall intensities, is presented in Figure 7.13. A linear increase was found between these two variables. The equation in Figure 7.13 was used to estimate the infiltration rates for the individual storms of the second year's data from the mean peak rainfall intensities. The runoff amounts from bare plots were then estimated using Equation 7.12. The estimated runoff amounts were compared with the actual average runoff measured during the storm. The results are presented in Table 7.3 and Figure 7.14.

The predicted runoff agreed very well with the actual values. The model performance was evaluated following the procedure as described by Willmott (1982). The summary of performance parameters is shown in Table 7.4. As indicated in Table 7.4, the performance test showed low error values and a high index of agreement. This procedure appears to be relatively easy to apply under conditions where the rainfall intensities during the storms are recorded.

Table 7.3. Predicted infiltration rate and runoff amount for the 2001 rainfall season

Average peak intensity (mm/hr)	Measured runoff (mm)	Predicted infiltration rate (mm/hr)	Predicted runoff (mm)
33.79	7.07	22.0	4.8
38.34	4.1	24.9	5.5
47.82	8.04	31.1	9.6
77.25	1.31	50.2	1.6

Table 7.4. Summary of model performance parameters for area under the curve method

Model performance indicators	Performance parameter values
Measured mean	5.13
Predicted mean	5.38
Root mean square error (RMSE)	1.55
Mean absolute error (MAE)	1.38
Index of agreement (D-index)	0.92

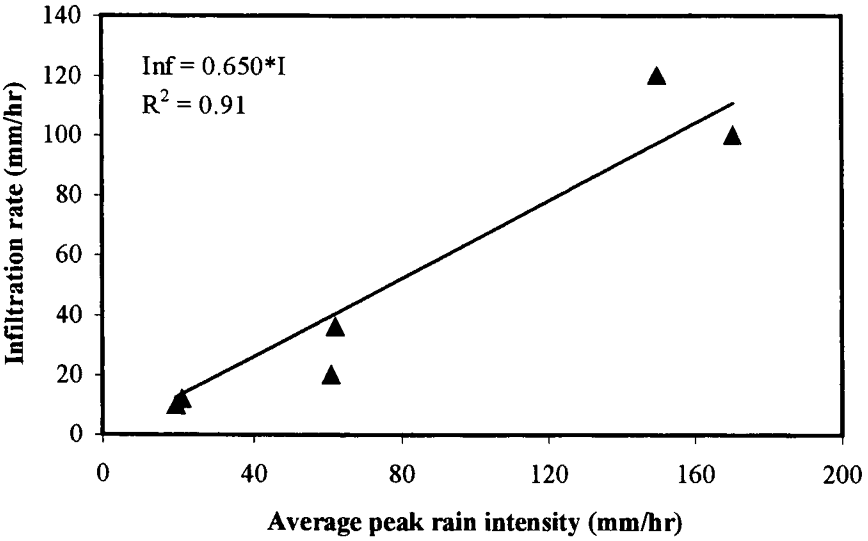


Figure 7.13. Estimated infiltration rate as a function of average peak rainfall intensity for 2000 rainfall season.

To obtain a more representative equation relating soil infiltration rate to the mean peak rainfall intensity during storms, for future application on similar soils, the combined data of both seasons are presented in Figure 7.15. It can be observed from Figure 7.15 that the slope of the line is identical to the rainfall intensity – infiltration rate relationship of the first year's data (Figure 7.14).

Predicted runoff from bare soil using this procedure can also be corrected for residue cover by multiplication with the corresponding runoff mulch factor.

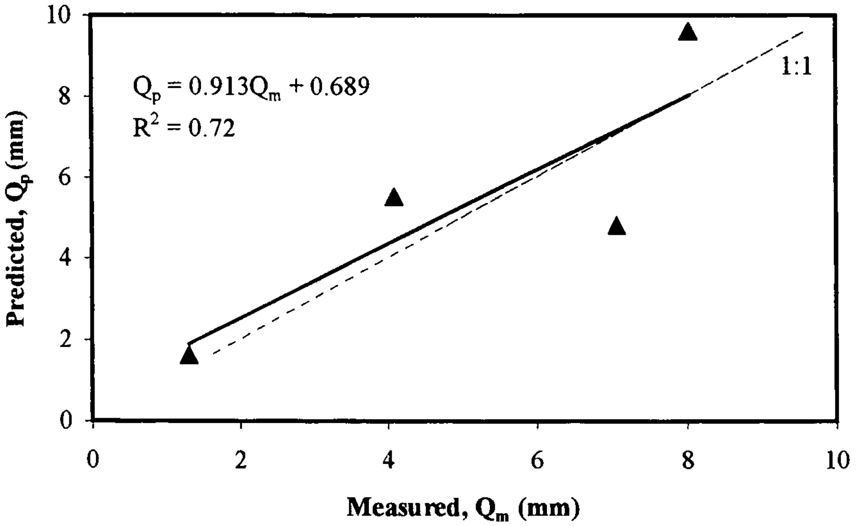


Figure 7.14. Relationships between measured and predicted runoff from infiltration – rainfall intensity relationship for 2001 rainfall season.

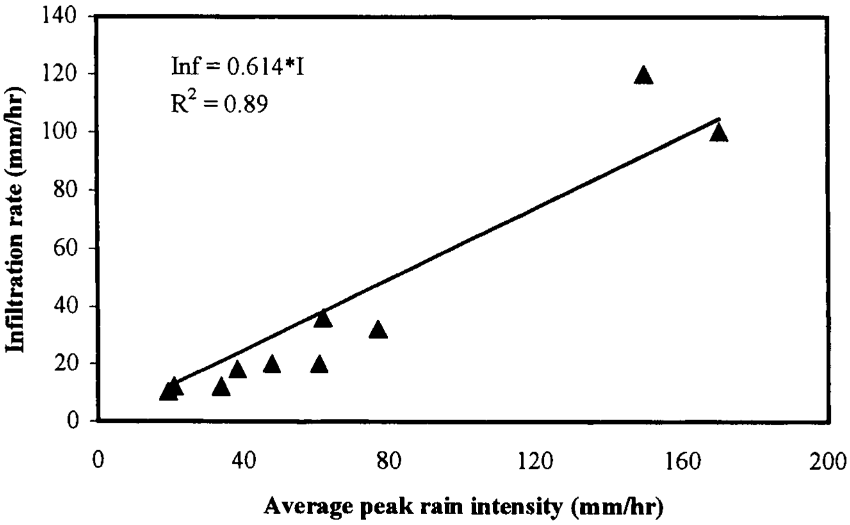
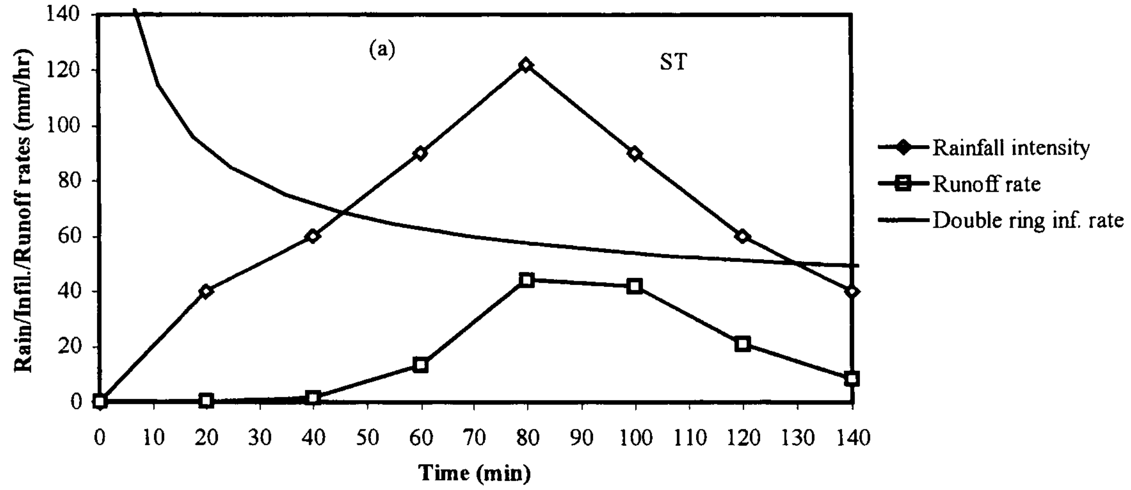


Figure 7.15. Infiltration rates as a function of average peak rainfall intensity based on the combined data of the two seasons.

7.4.3 Prediction of Runoff from Simulated Rainfall

A simulated rainstorm was generated on the UFS site, using the rainfall simulator. The changes in rainfall intensities are given in Figure 7.16. The simulation storm was applied to stubble mulch and conventional tillage plots. The runoff rates were measured and the infiltration rates were calculated. An infiltration curve was also determined for each plot using a double ring infiltrometer. More information on this experiment can be obtained from Section 3.2.3. The possibility of using rainfall intensity and infiltration rate curves to estimate or predict runoff will be investigated in this section.

Figure 7.16 shows the variation in rainfall intensity, infiltration rates (double ring infiltrometer) and runoff rates for the bare plots of the stubble mulch and conventional tillage practices, during a simulated rainfall event, as a function of time. The amount of rainfall with intensities higher than the infiltration rates, presented by the areas between the rainfall intensity and infiltration rate curves in Figure 7.16a and 7.16b, was calculated for each tillage practices. Values of 40 mm for stubble mulch tillage (Figure 7.16a) and 55 mm for conventional tillage (Figure 7.16b) were obtained. The value of 40 mm for stubble mulch tillage compares well with measured runoff of 43.7 mm during the storm. However, for conventional tillage the estimated amount of 55 mm, compared poorly with the actual measured runoff value of 11.83 mm. The conventional tillage plot was freshly ploughed to a depth of 250 mm. It had been shown and discussed in Section 7.2.2 that runoff is affected by the depth of tillage and that the runoff tillage factor can be used to correct runoff. For this case a factor of 0.2 is applicable (Figure 7.5). When the estimated runoff of 55 mm was corrected for the effect of depth of tillage by multiplying it by the runoff tillage factor for the conventional tillage (0.2) a value of 11 mm runoff was obtained, which is almost equal to the actual measured value of 11.83 mm.



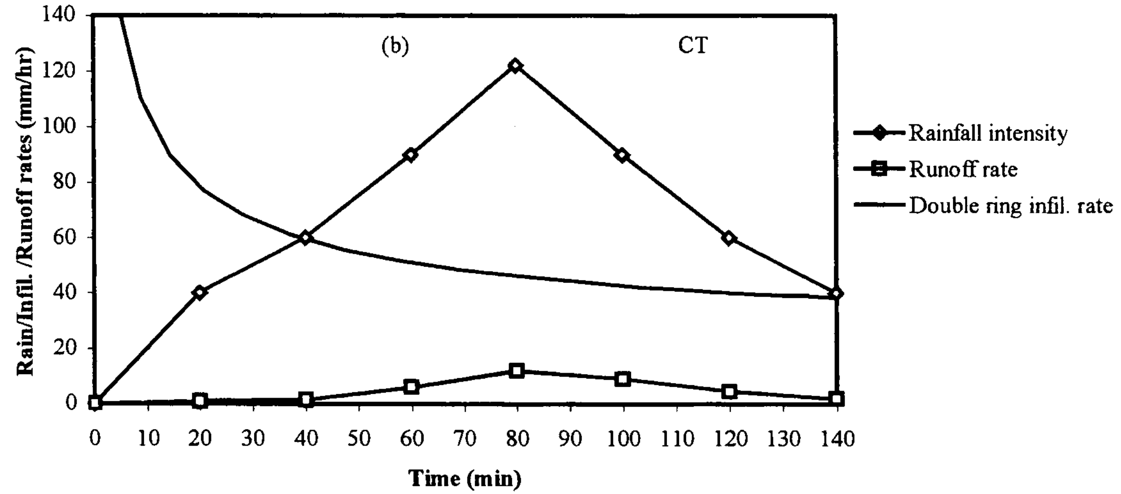


Figure 7.16. Rainfall intensity, infiltration and runoff rates as a function of time for (a) stubble mulch tillage and (b) conventional tillage practices.

The rainfall intensity and infiltration rates can also be plotted as a function of cumulative rainfall or infiltration, as illustrated in Figure 7.17. These graphs are also very suited for the calculation of potential runoff. It also indicates the cumulative rainfall required to produce or to start runoff.

This exercise showed that, as was demonstrated in Section 7.4.2.2, that the area between the rainfall intensity and infiltration rate curves, when plotted as a function of time or cumulative rainfall, represents the potential runoff from a bare soil. This value then needs to be corrected for residue cover or tillage depth by multiplication with the applicable factor. It must be noted that only the effects of mulching and tillage were considered and the inclusion of factors like slope, etc. will also require appropriate correction factors.

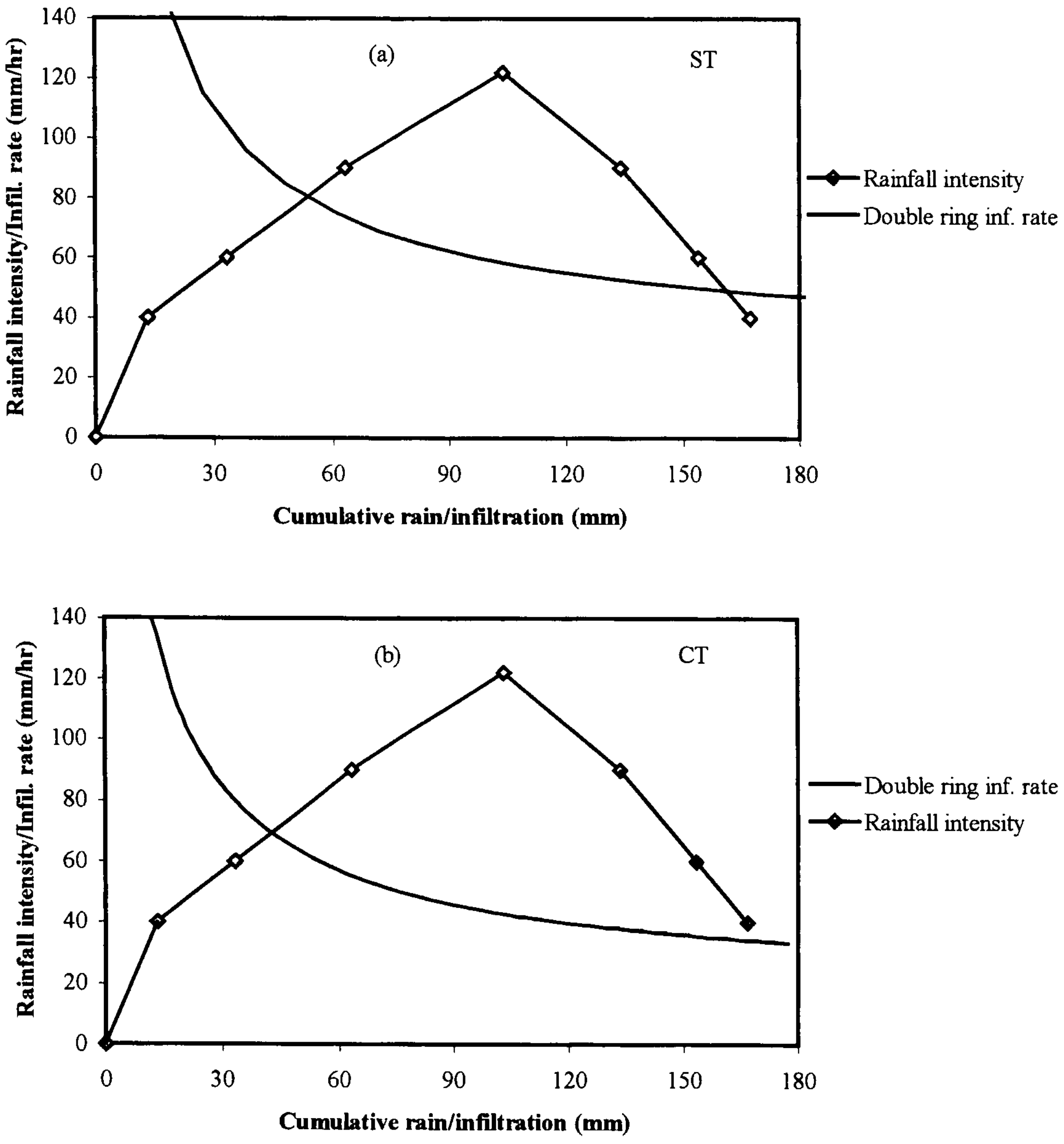


Figure 7.17. Rainfall intensity and infiltration rate as a function of cumulative rainfall and infiltration for (a) stubble mulch tillage and (b) conventional tillage.

7.5 Estimation of Soil Loss from Sediment Concentration and Runoff

The total soil loss from a given area is the product of sediment concentration and runoff amount. The sediment concentration of runoff depends on several factors, such as the energy (the detaching ability) of the raindrop impact and the degree of looseness (the detachability) of the soil surface. Tillage operations can modify the topsoil physical properties, such as bulk density and aggregate stability of the soil. The effect of raindrop impact on soil detachment processes depends on the degree of soil disturbance and the amount of residue cover on the soil surface.

The procedure for runoff prediction from rainfall amount for bare as well as residue-covered plots has been discussed in Section 7.4. A gross estimation of total soil loss can be obtained as the product of sediment concentration and runoff amount, given in Equation 7.13.

$$SL = (SC * Q_u) \quad \text{[7.13]}$$

Where SL (kg/ha) is the total soil loss, SC (kg/m^3) is the sediment concentration and Q_u (m^3/ha) is the total runoff.

Results of the experiments at the UFS- and AU-sites have shown that sediment concentration depends on the type of tillage practice and the amount of residue cover. The relationships between the mean relative sediment concentration of the tillage practices and percentage residue cover for the UFS- and AU-sites are given in Figure 7.18. It can be seen that the linear decrease in relative sediment concentration or sediment concentration mulch factor with an increase in percentage residue cover, were similar for both sites. A sediment concentration mulch factor of 1 represents sediment concentrations of 2.5 kg/m^3 for the UFS-site soil and 16.2 kg/m^3 for the AU-site soil. When the sediment concentration from a bare soil (SC_{bare}) is known, the sediment concentration at a given percentage residue cover (Pc, %) (SC_{cover}) can be calculated with Equation 7.14. The term in the parenthesis in Equation 7.14 represents the runoff mulch factor from Figure 7.14 rounded to two decimal points. The soil loss can then be estimated with Equation 7.13 using the estimated or measured runoff and sediment concentration.

$$SC_{cover} = (1 - 0.01 * Pc) * SC_{bare} \quad [7.14]$$

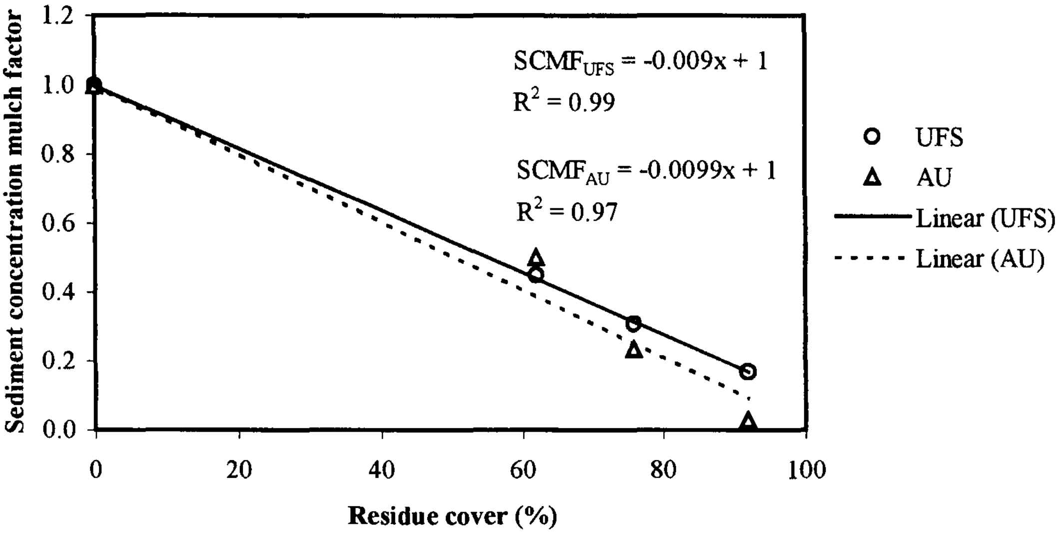


Figure 7.18. Mean sediment concentration mulch factors, averaged over the three tillage practices, as a function of percentage residue cover for the UFS and AU sites.

The sediment concentration at a specific residue cover is expected to vary depending on the rainfall intensity and storm duration. Although these factors can limit the accuracy of estimating soil loss, the estimated value can be used as a gross approximation of the total soil loss when runoff was predicted from rainfall intensity – infiltration rate relationships.

Multiple linear and non-linear regression analyses were also performed between the soil loss from bare plots and rainfall amount of the three tillage practices. The equations are given in Table 7.5. These empirical relationships can be used as possible additional prediction tools for a first estimation of soil loss from bare soil conditions. To correct the calculated soil loss for residue cover it can be multiplied by the appropriate soil ratio (Figure 7.8).

Table 7.5. Result of regression analysis between soil loss (SL, t/ha), runoff (Q, mm) and rainfall (P, mm) amounts on bare plots at the UFS and AU sites

Site	Tillage type	Regression equations	Coefficient, R^2
UFS	No-tillage (NT)	$SL = 1.7*10^{-4}*P^2 - 0.006*P$	0.99
		$SL = 0.064*Q - 0.0046*P$	0.99
	Stubble mulch (ST)	$SL = 8*10^{-5}*P^2 - 0.004*P$	0.93
		$SL = 0.023*Q - 0.0013*P$	0.97
	Conventional (CT)	$SL = 4*10^{-5}*P^2 - 0.003*P$	0.84
		$SL = 0.049*Q - 0.0017*P$	0.96
	Combined data	$SL = 9.6*10^{-5}*P^2 - 0.0043*P$	0.92
		$SL = 0.045*Q - 0.0025*P$	0.97
AU		$SL = 0.2001*Q - 0.0032*P$	0.65
		$SL = 0.022*Q^2 + 0.026*Q$	0.68

7.6 Conclusions

Experiments relating runoff and soil loss to different tillage practices and levels of residue cover were conducted at two sites with different climatic, soil and topographic conditions, namely at the University of the Free State, South Africa and Alemaya University, Ethiopia. The experiments consisted of three tillage practices, namely no-tillage, stubble mulch (traditional in Ethiopia) tillage and conventional tillage, each combined with four levels of wheat residue cover with the aim of evaluating its effect on runoff and soil loss. The experiments at the UFS-site were conducted with simulated rainfall of a constant intensity on a sandy soil and at the AU-site it was conducted under natural rainfall on a well-structured clay soil. The results from both sites, which have been discussed in detail in the previous chapters, were compared in this chapter for the two land units, in terms of the factors that affected runoff and soil loss and possible procedures for predicting runoff and soil loss were discussed.

The effects of residue cover and tillage practices on runoff have been quite similar at both sites despite the difference in the soil type and rainfall conditions. The relative values of runoff, as represented by the runoff mulch factor, were slightly higher for the UFS-site as compared with the AU-site. The lower decrease in relative runoff due to the application of residue at UFS site can probably be due to the high infiltration rate of the sandy soil even under bare soil conditions, smaller slope (<1%) of the field and the use of simulated rainfall with a constant intensity. The effect of depth of tillage on runoff, however, was much more pronounced at the UFS-site, where runoff decreased sharply with an increase in tillage depth.

The effects of residue cover on soil loss can be described in terms of the soil loss ratio. At both sites, the soil loss ratio showed a significant exponential decrease in soil loss due to the application of residue. The relationships indicated that a percentage residue cover of 30%, derived from the deflection of the curve, appears to be the critical level. Freebrain *et al.* (1993) also suggested 30% to be the critical residue cover level for erosion control. Tillage depth had a significant effect on soil loss at the UFS-site, where soil loss decreased linearly with an increase in tillage depth due to an increase in infiltrability of the soil. At the AU-site, however, there was no systematic decrease in soil loss with an increase in tillage depth.

Generally, both tillage and residue cover affected runoff and soil loss on the two land units in a similar way, but to a different degree. The general tendency reported in literature towards the superiority of no-tillage compared with conventional tillage could not be found in this study. At the UFS-site, conventional tillage was found to be more effective than no-tillage in reducing runoff and soil loss under bare conditions. Although results for more seasons are required to draw a final conclusion for the AU-site regarding the effectiveness of tillage, it was found that no-tillage was less effective in conserving water and soil compared with traditional and conventional tillage.

Regarding runoff prediction, it was attempted to estimate runoff from the rainfall characteristics. A linear equation between rainfall and runoff was developed from the first year's rainfall – runoff data of the AU-site. This equation was used to estimate runoff for the second year at the same site. It gave an acceptable but slight overestimation of runoff.

Linear relationships between rainfall intensity and the infiltration rate of the soil, that were derived from the experimental data, were also used to estimate runoff from the rainfall intensity curve at both sites. At the AU-site the linear equation, based on the first year's data, was used to estimate runoff for the second year. The result gave a good correlation between the measured and estimated runoff. For the UFS-site the infiltration rate curve, determined with a double ring infiltrometer, was used to estimate runoff from the simulated rainfall intensity. It gave good comparable values on bare stubble mulch tillage but overestimated runoff for conventional tillage. This was attributed to the greater depth of tillage for conventional mouldboard ploughing, which resulted in lower measured runoff values. When the predicted runoff from conventional tillage was corrected for tillage depth, making use of the runoff tillage factor, the corrected runoff value agreed well with the measured value.

Prediction of soil loss depends on factors affecting the sediment concentration and amount of runoff. Sediment concentration is affected by the degree of soil looseness and surface cover conditions. Most importantly the presence of adequate surface residue cover provides protection against raindrop impact, thus affecting the detachment rate of soil particles.

Both experimental sites showed a similar relationship between the mean sediment concentration mulch factor and percentage residue cover. This relationship can be used to estimate the sediment concentration at a specific percentage residue cover when the sediment concentrations from bare soil conditions are known. Therefore, if runoff can be predicted from rainfall amount or rainfall intensity and the infiltration rate of the soil, soil loss can be predicted by multiplying the runoff with the sediment concentration. Empirical equations, relating soil loss to runoff and rainfall amount, were derived that can also be used for this purpose.

CHAPTER 8

GENERAL DISCUSSION AND CONCLUSIONS

The general objective of the study was to investigate the effect of different tillage practices and levels of residue cover on runoff and soil loss and to determine the relationships between the different factors involved in runoff and erosion processes on two different land units. To accomplish these objectives two field studies were conducted. The first field study was conducted at the University of the Free State experimental site, South Africa, where long-term experimental plots were used to determine the effect of three tillage practices, namely no-tillage, stubble mulch and conventional tillage, each combined with four rates of wheat residue cover (0, 2, 4, and 8t/ha) on runoff and soil loss. A rainfall simulator was used on this sandy soil to obtain different rainfall intensities and durations. The second field experiment was conducted at the Alemaya University experimental site under natural rainfall for two consecutive seasons. Three tillage practices, namely no-tillage, traditional and conventional tillage, each combined with residue rates of 0, 2, 4 and 8t/ha were used as treatments which were replicated twice. The effect of these treatments on infiltration, runoff and soil loss were determined at both experimental sites.

Infiltration from Simulated Rainfall

The infiltration results obtained with simulated rainfall on the bare plots, without any residue cover, of the three tillage practices showed that the type of tillage practice had a substantial effect on the initial infiltration rate of the soil. Conventional tillage had the highest initial infiltration rate whereas no-tillage had the lowest rate. The higher infiltration rate on the conventional tillage practice was ascribed to be due to the increased porosity of the topsoil created by the mouldboard ploughing tillage operation. Mouldboard ploughing was reported to increase infiltration by increasing soil porosity and the establishment of channels in the surface layer of soil that conduct water more readily into the soil profile (Edwards, 1982; Lindstrom & Onstad, 1984). Tillage also loosens surface crusts, disrupts dense layers, and provides surface depressions for temporary storage of water (Unger, 1992), thus providing more time for infiltration. The final infiltration rates under these bare soil surface conditions were, however, nearly the same for all three tillage practices.

Application of residue cover on the tilled surfaces at different rates significantly increased the final infiltration rate of the soil. It was found that the final infiltration rate of soil increased linearly with an increase in the percentage residue cover for all the tillage practices. Tillage practice also had a significant effect on the final infiltration rate of the soil in the presence of residue cover. Conventional tillage had a higher final infiltration rate compared to stubble mulch and no-tillage, which were the same at similar residue rates. It should be noted that the different amounts of wheat residue were applied on the surface of freshly ploughed (25 cm depth) soil on the conventional tillage treatments. On the stubble mulch treatments the soil was tilled to a depth of 15 cm with sweeps after which the old crop residue was removed and replaced with the required amounts of fresh residue. On the no-till plots the old crop residue was removed and replaced with the different amounts of fresh residue cover.

The result of this study is in agreement with other findings, such as Morin & Benyamini (1977) who reported that the final infiltration rate of a mulched sandy soil was seven times higher than the bare soil. Yuxia Li *et al.* (2001) also reported a higher final infiltration rate for a residue covered black clay soil than the bare soil. Generally, crop residues retained on or near the soil surface enhance infiltration by dissipating raindrop energy, thus minimizing aggregate dispersion and surface sealing, and by retarding surface water flow, thus providing more time for infiltration (Unger, 1992).

Runoff from simulated rainfall

Runoff from the three tillage practices and four rates of residue cover at a cumulative rainfall of 100 mm, applied at 60 mm/hr, was used to compare the different treatments. Runoff decreased linearly as the amount of residue cover increased from a rate of 0t/ha to 8t/ha. Conventional tillage practice had the lowest amount of runoff at all residue levels compared with the other two tillage practices. For stubble mulch and no-tillage residue rates of 2 and 8t/ha were required, respectively, to produce the same runoff as from bare conventionally ploughed conditions. This implicates that residue cover rates of at least 2 and 8t/ha should be maintained on this sandy topsoil to achieve conservation tillage benefits from stubble mulch and no-tillage practices, respectively. The long-term studies reported by Bennie (2000), and Bennie & Hensley (2001) also suggested that no-tillage practice was not beneficial in terms of both soil and water conservation and crop yield compared to conventional and stubble mulch tillage, on soils similar to the one used in this study. The reason being insufficient levels of residue cover with dryland cropping under low rainfall climatic conditions.

The presence of residue mulch delayed the commencement of runoff on all three tillage treatments. Even under bare soil conditions, the runoff initiation time was delayed significantly by conventional tillage compared to mulched no-tillage and stubble mulch tillage treatments. This could probably be due to the surface roughness created by mouldboard ploughing. Mohamoud *et al.* (1990b) also reported, while comparing no-tillage with other tillage practices, with the surface residue removed, that runoff occurred sooner on no-till because of the rapid filling of surface pores and clogging of pores by raindrop splash. Runoff occurred later under tilled conditions because of greater surface roughness and depression storage. No-tillage systems generally have smooth surfaces and therefore, less depression storage than conventional tillage systems.

Although in many cases conservation tillage practices, such as no-tillage were reported to enhance water conservation and increase crop yields compared to conventional tillage, opposite results, or no differences, were also reported. For example, Myers & Wagger (1996) reported that conventional tillage had 73% less runoff than no-tillage treatments in a simulation study on a sandy clay loam soil. The results of this study also suggest, under this particular experimental and soil conditions, that conventional tillage with mouldboard ploughing is more appropriate in improving the soil structure, which would increase the infiltration of rainwater until such time that too much rain causes the formation of a surface crust. Moreover, the primary tillage with moldboard ploughing creates roughness and depression storage, which can store more rainwater and increase the infiltration opportunity time.

The presence of a surface cover on conventionally tilled soils will protect the soil from raindrop impact and maintain a higher infiltration rate during the rainy period. The mulching of conventionally deep tilled soil is usually impractical under commercial large scale farming conditions. For small scale subsistence food production the addition of crop residue mulch on soil that has been loosened to a depth of 15 cm or more would be beneficial in reducing runoff. Under commercial farms conditions the non-inverting deep ripping of especially sandy soils combined with a crop residue mulch on the surface will also generate less runoff.

Runoff from natural rainfall

A field experiment, conducted at the Alemaya University (AU), Ethiopia, consisted of three tillage treatments, namely no-tillage, traditional and conventional tillage, combined with 0, 2, 4 and 8t/ha wheat residue mulches. The experiment was conducted for two consecutive rainfall seasons, 2000 and 2001, which covered the months of July, August and September.

At the AU-site, apart from the treatment effects, the varying rainfall characteristics in general and the rainfall intensity in particular affected the amounts of runoff. The rainfall characteristics included parameters like the peak intensity or intensities, the duration of the high intensity peak(s) and where it occurred during the storm. Apart from the total rainfall, the 30-minute intensity, total kinetic energy and erosivity index of each event were used as indicators of the rainstorm characteristics and these indices were related to the runoff amount.

The amount of residue cover required to reduce runoff was found to be closely related to the intensity of the storm. It was observed that for most of the storms a residue rate of 2t/ha reduced runoff significantly compared with the bare plots. However, at higher intensity storms, a residue rate of 2t/ha was insufficient to reduce runoff and a higher, 4t/ha residue rate, was required to sufficiently reduce runoff for these soil and rainfall conditions. The minimum residue cover required to significantly reduce runoff also depends on other factors, such as topography. Roth *et al.* (1988) recommended that at least 4 to 6t/ha of residue is needed to reduce runoff and erosion effectively while other reports (Lattanzi *et al.*, 1974; Unger *et al.*, 1991) indicated that much lower residue amounts could greatly reduce erosion because surface residue reduces soil loss much more than it reduces runoff. Others suggested that a 30% cover of the surface by residue appears to be a critical level for erosion control (Freebrain *et al.*, 1993). In this experiment a rate of 2t/ha was equal to 62% cover.

Tillage affected runoff only during the first few storms where runoff from no-tillage was significantly higher than from the traditional and conventional tillage treatments. It appeared that the absence of roughness associated with no-tillage practices may have resulted in higher runoff compared with tilled conditions. Freebrain *et al.*, (1993) reported that the roughness created by a chisel plough was able to reduce annual runoff significantly. Bradford & Huang (1994) also reported that differences in runoff between conservation and conventional tillage systems were more pronounced immediately after the soil was freshly tilled and before the impact from the raindrops created surface sealing and crusting.

Tillage practices are reported to take a long time to have a measurable effect on some of the physical and hydraulic properties of the soil. For example, Dickey *et al.* (1989) reported that between 5 to 6 years is required for changes in soil physical properties to take place due to tillage, resulting in higher infiltration rates and lower runoff. In another study, Voorhees & Lindstrom (1984) have reported that 3 to 4 years are required before conservation tillage creates a more favourable porosity in the upper 0 to 15 cm depth of soil.

The results from this study indicate that the amount of residue cover had a greater effect on reducing runoff than the effect of tillage for this particular soil and climate condition. It has been established by several natural and simulated rainfall studies that surface cover reduces soil erosion more than any other factor in tillage management (Freebrain & Wockner, 1986; Gilley *et al.*, 1986a; Sallaway *et al.*, 1988). Allowing the residue to remain on the soil surface could significantly reduce the amount of surface crusting thereby increasing infiltration (Hillel, 1980) and reducing the runoff volume through stubble protecting the soil surface, thus reducing aggregate breakdown and compaction of the soil surface by raindrop impact (Edwards, 1982; Freebrain *et al.*, 1993).

Soil loss from simulated rainfall

The results of the rainfall simulation study at the UFS-site on the three tillage practices and four rates of residue cover revealed that the no-tillage treatment had a significantly higher mean soil loss per unit area than the stubble mulch and conventional tillage treatments at comparable levels of residue cover. However, the sediment concentration (gram of suspended sediment in a liter of runoff) at the different rates of residue cover was lower for no-tillage compared with stubble mulch and conventional tillage, but the mean runoff was higher resulting in a higher sediment yield. The sediment concentration mulch factor for the three tillage practices showed that the presence of residue cover was much more effective on no-tillage followed by conventional and stubble mulch tillage.

The soil loss per unit area decreased exponentially with an increase in the amount of residue cover. For instance, the treatments with a residue rate of 2t/ha reduced the soil loss substantially to about 15.7% of the soil loss from the bare plot treatments. The soil loss ratio indicated that the use of residue to reduce soil loss was much more effective on no-tillage, followed by stubble mulch and conventional tillage treatments.

Conservation tillage systems, such as reduced tillage and no-tillage are reported to be effective in reducing soil erosion because of the higher crop residue cover that can be maintained, greater soil resistance to soil detachment and transport, or reduced soil erodibility and often reduced runoff (Lindstorm & Onstad, 1984). Differences in runoff and erosion due to tillage have not been as consistent, because of the effect of other factors, such as the amount of residue cover, rainfall intensity, rainfall amount and timing, soil texture, and surface roughness (Unger, 1992). For instance, Kinnel (1996) reported that differences in tillage practices had no major impact on either sediment concentration or runoff amount because of the high capacity of the soil to maintain its tillage-induced surface roughness during rain following cultivation.

However, as a general rule, tillage is considered to encourage erosion through degradation of soil physical properties, leading to an increase in runoff and sediment concentration. Lack of tillage decreases both runoff and sediment concentration through an increase in aggregate stability and infiltration capacity resulting from biotic activity (Kinnel, 1996). In this study bare soil conditions created by conventional tillage were more effective in decreasing both runoff and soil loss than stubble mulch and no-tillage for this particular sandy type of soil and dry climatic condition. More rain was required to produce the same amount of soil loss from conventional than from no-tillage at the same levels of residue cover. Residue rates higher than 2t/ha or 62% ground cover decreased soil losses by more than 85% on all the tillage practices.

The conservation tillage practices of stubble mulching and no-tillage can only be recommended on sandy and sandy loam topsoils, under semi-arid climatic conditions, when it is possible to maintain at least a wheat residue amount of 2t/ha or residue cover of 60% all the time.

Soil loss under natural rainfall

The experiment at AU was conducted to quantify the impact of tillage and residue cover on soil loss under natural rainfall conditions. Results over the two seasons showed that the average total soil loss was the highest for the no-tillage treatment, followed by conventional tillage. The traditional ox-plough practice had the lowest soil loss. During the first year of the experiment conventional tillage had the highest average sediment concentration, of which the high intensity of a single storm, which formed a surface crust and disintegrated the soil aggregates, made the highest contribution. During the second year the rainfall intensities were generally lower which caused lower amounts of soil loss compared with the previous year.

During the first year, soil losses occurred mainly from the bare plots of the three tillage practices. There were little soil loss from the no-tillage and traditional tillage treatments at a residue rate of 2t/ha during the first two storms and none from the conventional tillage. The treatments with a residue rate of 4t/ha effectively controlled erosion with the exception of the third storm with a very high erosivity index. This single high intensity erosive rain event of the first year that resulted in high soil losses from the bare plots emphasized the importance of maintaining an effective residue mulch of more than 2t/ha on the soil surface.

From the first year's rainfall and soil loss data it was observed that the effectiveness of residue cover in reducing runoff and erosion depends on the rainfall characteristics in general and rainfall intensity in particular. The reduction in soil loss at a residue rate of

2t/ha varied from as high as 98% with traditional tillage during the second low intensity storm of the first season, to as low as 35% from no-tillage during the third high intensity storm of the first rainfall season. It is important to note that rainfall intensity has a greater effect on soil loss than the rainfall amount. Soil loss from two comparable rainfall amounts of 35.6 and 33.8 mm, during the first and the second years respectively, can be taken as an example. The average soil loss from the bare plots of the tillage practices was 3.04t/ha for a high intensity storm of 35.6 mm and 0.47t/ha for a low intensity storm of 33.6 mm.

It is evident from the data that as a general recommendation maintaining a wheat residue rate of 2t/ha, providing 60% cover, should be efficient in reducing soil loss over the long term. To effectively reduce soil loss during high intensity storms a higher residue rate of at least 4t/ha or 76% residue cover is required.

Comparisons of the results from the two land units

A comparison of the results obtained from the UFS and AU experimentation were made in terms of different factors affecting runoff and soil loss, such as residue cover and tillage practice. Moreover, the rainfall intensity – infiltration rate relationships at both sites were compared. Although, the soil and rainfall conditions differed at both sites, the general trend regarding the effects of residue and tillage on runoff and soil loss were very similar. The slopes of the fitted curves for the relationships between runoff, runoff coefficient and runoff mulch factor and the percentage residue cover were higher at the AU-site compared to the UFS-site, indicating a higher effectiveness of the mulch. This is probably due to higher runoff from bare plots, which might have resulted from a steeper slope (5%) and more clayey soil at the AU-site. The effect of tillage, however, was more pronounced at the UFS-site compared to the AU-site. This was attributed to the type of soil at the UFS, which is sandy and without structure. Therefore, the type of tillage practice and depth of tillage that may be suitable for a given area, might not produce the same beneficial effect on another type of soil.

Prediction of runoff from rainfall characteristics

The amount of runoff from a given rainfall event or storm depends on many factors, such as the storm characteristics, properties of the soil and the degree of surface cover. For runoff to be generated from a given area, the rainfall intensity should exceed the infiltration rate of a soil. A relationship between rainfall amount and runoff was established for the first year's data at the AU-site using two approaches; the first was where all the rainfall events, including those without runoff, were considered, and the second where only runoff producing storms were considered. Linear equations were derived for the two approaches and tested on the second year's data. Both equations predicted runoff for the second year data reasonably well, with a slight overestimation at higher rainfall amounts. The indices of agreement were 0.87 and 0.82 for the equations based on all rainstorms and erosive storms, respectively.

Prediction of runoff from the mean peak rainfall intensity and infiltration rate of the soil was also conducted using the area under the curve method. A procedure was developed for estimating the soil infiltration rate from the runoff amount and mean peak rainfall intensity from the first year's data at the AU-site. A linear relationship was found between average peak rainfall intensities and infiltration rates of the soil. This equation was used to calculate the infiltration rates of the soil for each of the second year's rainfall events, which was then applied to predict the runoff with the area under the curve method. The predicted runoff agreed reasonably well with the measured values. Model performance tests, based on the parameters proposed by Willmott (1982), gave a high index of agreement (D-index = 0.92) and low error values (RMSE = 1.55).

The possibility of runoff prediction from simulated rainfall intensity and infiltration rate (from double ring infiltrometer) on the Bloemfontein soil showed that the area under the curve method can also be used to estimate potential runoff, taking into account the effect of depth of tillage on runoff by applying the derived runoff tillage factors.

The total soil loss from a given area is the product of sediment concentration and runoff amount. If the runoff amount from a given area is known or can be predicted, the total soil loss could then be estimated by multiplying the runoff with the average sediment concentration. Relative sediment concentration was derived for both the UFS and AU land units as a function of percentage residue cover. The sediment concentration at a specific residue cover is expected to vary depending on the rainfall intensity and storm duration. Although these factors can limit the accuracy of estimating soil loss, the estimated values can be used as a gross approximation of the total soil loss from runoff which can be estimated the from rainfall amount or from the rainfall intensity – infiltration rate relationships.

To conclude it can be stated that the following objectives of the study were achieved:

- The differences among the tillage practices in runoff generation and soil loss could be explained in terms of the depth of tillage and the amount of residue mulch on the surface. The deeper the depth of tillage and the higher the amount of residue, the less will the runoff and soil loss be.
- The amount of residue required to effectively reduce runoff and soil loss depends on the rainfall characteristics in general and rainfall intensity in particular.
- Empirical relationships were obtained between the different factors involved in runoff generation and erosion processes. These were, between runoff and depth of tillage; runoff and percentage residue cover; runoff and rainfall amount and intensity. Similarly, relationships were also established between

soil loss and percentage residue cover; soil loss and tillage depth; soil loss and runoff; soil loss and rainfall characteristics (amount, intensity, erosivity index).

- Some of the empirical relationships, such as the relationships between runoff and rainfall amount and average peak rainfall intensities and infiltration rates of the soil, established on the first year's data at the AU-site, were used to predict runoff based on the second year's data with reasonable accuracy. The procedure of rainfall intensity – infiltration rate relationship, termed as the area under the curve method, was also applied for the UFS-site to predict runoff.

It should be noted that the tillage experiment at the AU-site was just started, with only two years of data. Viable conclusions on the influence of tillage on the physical and hydraulic properties of soil, that may affect runoff and soil loss, should be based on a long-term data. Therefore, the tillage experiment at the AU-site should continue for a longer time in order to obtain more information on the different factors affecting runoff and erosion and to refine the empirical relationships established between the different factors in this study.

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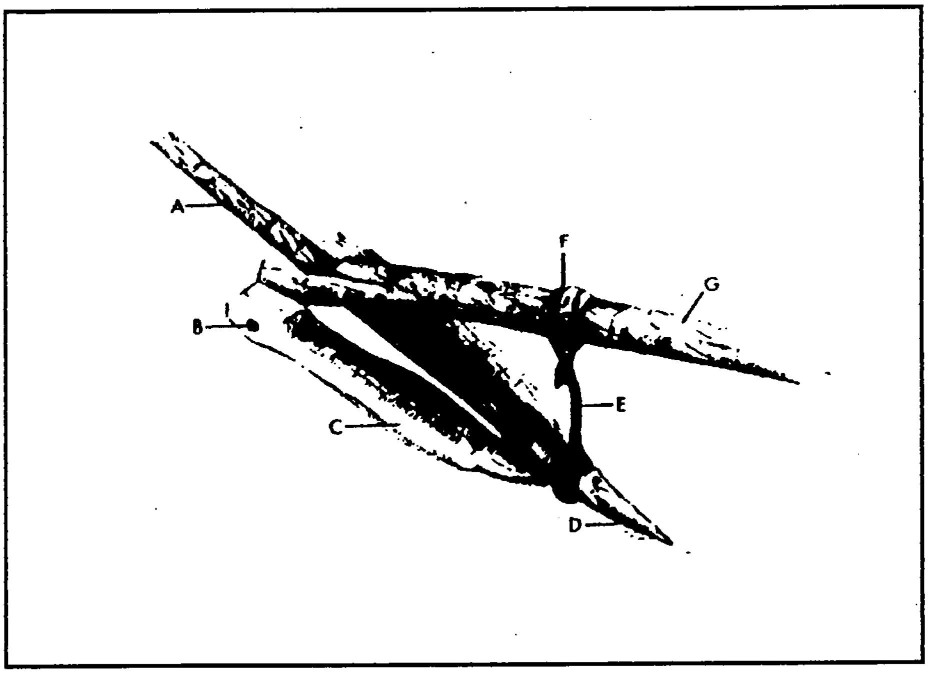
APPENDIX 1

APPENDIX 1.1: The Ethiopian maresha and its parts: (A) stilt; (B) crosspeg for ears; (C) ears; (D) share; (E) sheath; (F) leather strap; (G) beam. *Source*: Goe, (1989).



APPENDIX 1.2: A farmer ploughing a field with maresha pulled by a pair of local zebu oxen.

APPENDIX 1.3: The blade harrow (A) and funnel planter (B) attachments to the broad bed maker for minimum tillage. *Source*: Astatke *et al.*, (2002).