

**SOIL MINERALOGY, SLOPE AND SOIL AND WATER
CONSERVATION EFFECTS ON INFILTRATION, SEAL
FORMATION, EROSION AND CROP YIELD UNDER
SEMI-ARID CONDITIONS**

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This thesis is my original work and has not been presented for a degree in any other university.



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Table of Contents

Abbreviations and Symbols.....	v
List of Tables	vi
List of Figures	vii
List of Appendices	viii
Abstract.....	ix
CHAPTER 1	1
1 Introduction	1
1.1 General.....	1
1.2 Study hypotheses.....	3
1.3 Objectives.....	4
CHAPTER 2	5
2 Literature Review	5
2.1 Soil Mineralogy and Texture Effects on Crust Characteristics, Infiltration and Erosion.....	5
2.2 Soil Mineralogy and Texture Effects on Interrill Slope Factor.....	7
2.3.1 Indigenous Soil and Water Conservation Techniques Effects on Runoff, Erosion and Crop Yields.....	11
CHAPTER 3	14
3 Materials and Methods	14
3.1 Laboratory studies	14
3.2 Field study.....	20
CHAPTER 4	24
4 Results and Discussions	24
4.1 Soil Mineralogy Effects on Crust Micromorphology, Infiltration and Erosion	24
4.2. Soil Mineralogy and Texture Effects on Interrill Slope Factor.....	37
4.3 Indigenous Soil and Water Conservation Techniques Effects on Runoff and Erosion and Crop Yields	45
CHAPTER 5	58
5 Conclusions and Recommendations.....	58
References	62

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Abbreviations and Symbols

BTL	Big Trash Lines
CEC	Cation Exchange Capacity
EC	Electrolyte Conductivity
ESP	Exchangeable Sodium Percentage
Fig.	Figure
Figs.	Figures
IR	Infiltration Rate
ISWC	Indigenous Soil and Water Conservation
MWD	Mean Weight Diameter
RMWD	Relative Mean Weight Diameter
S_f	Slope factor
SL	Stone Lines
STL	Small Trash Lines

List of Tables

Table	Page
1 Some physical, chemical and mineralogical properties of the studied soils.....	16
2 Some physical and chemical properties of the soil profile at Tunyai.....	21
3 Total soil loss and mean weight diameter values of the studied soils.....	28
4 Total soil loss for the entire rainstorm at various slope gradients and soils.....	43
5 Seasonal rainfall and runoff in five rainy seasons and various treatments.....	56
6 Seasonal soil loss (Mg ha^{-1}) for the various rainy seasons and treatments.....	57
7 Seasonal yields (Mg ha^{-1}) of maize and cowpea in the five rainy seasons and under the various treatments.....	58

List of Figures

Figure	Page
1 The rainfall simulator with a rotating disk.....	19
2 Schematic layout of the runoff plots in the field.....	27
3 Particle size distribution in the various soils before the rainstorms.....	30
4 Photographs of the crust surface in various soils.....	31
5 Infiltration rate as a function of cummulative rainfall for various soils.....	32
6 Scanning electron micrographs of the crusts and the soil underneath for Tunyai, Neve Ya'ar and Molo soils.....	34
7 Scanning electron micrographs of the crusts and the soil underneath for Netanya soil.....	35
8 Particle size distribution of the sediments in the runoff for various soils.....	40
9 Infiltration rate as a function of cummulative rainfall for various slope gradients and soils.....	42
10 Slope factor as a function of the slope angle for various soils.....	44
11 Amounts of the different particle sizes in runoff and their mean weight diameter for various slope gradients and soils....	46
12 Relative mean weight diameter values as a function of the sine of the slope factor.....	48
13 Distribution of daily rainfall for the five rainy seasons.....	50
14 Daily runoff as a percentage of daily rainfall during the five rainy seasons and for the various treatments.....	52
15 Seasonal biomass yield as functions of the seasonal infiltrated water.....	61

List of Appendices

Appendix		Page
1	Infiltration rates (mm h^{-1}) as functions of cummulative rainfall for the various soils at 9% slope gradient.....	79
2	Aggregate size distribution (g) before rainstorm for the various soils at 9% slope gradient	81
3	Particle size distribution (g) in the runoff for the various soils at 9% slope gradient before rainstorm.....	81
4	Soil loss for the various soils at the various slopes.....	82

Abstract

Soil erosion and runoff are serious and widespread land degradation problems in many parts of the world especially in arid and semi-arid regions, where water is the main limiting factor for crop production. This thesis presents the results of three studies conducted to investigate the effects of soil mineralogy, texture and slope gradient on seal formation and its properties and their effects on infiltration, runoff and erosion. Water and soil conservation effects on infiltration, erosion and crop yield under seal formation conditions in semi arid conditions was also investigated.

In the 1st laboratory experiment, soils with different mineralogy and texture were subjected to 80 mm of simulated rainfall at 9% slope gradient. The mean weight diameter (MWD) values were 2.8 mm in the kaolinitic soil, 0.25 and 0.31 mm in the montmorillonitic soils, and 0.84 and 0.87 mm in the non-phyllosilicate soils. The final infiltration rate (IR) was 20.5 mm h⁻¹ in the kaolinitic soil and ≤ 9.3 mm h⁻¹ in the montmorillonitic soils. The kaolinitic soil had a thin crust (~ 0.1 mm) containing large particles (~ 0.1 mm), while the montmorillonitic soils had thicker crusts (> 0.2 mm) comprising either small (~ 0.02 mm) particles with a very developed "washed in" zone underneath, or large (~ 0.2 mm) ones with fine material between them. Crust layer in the non-phyllosilicate soils was ~ 0.2 mm and composed of fine particles ~ 0.01 mm. The high aggregate stability and the low dispersivity of the kaolinitic soil, which decreased the soil detachment; and its low runoff, which decreased the transport capacity, limited the soil loss to 0.33 kg m⁻². The low aggregate stability and high runoff of the montmorillonitic soils contributed to their soil losses of 1.24 and 1.14 kg m⁻². The intermediate aggregate stability and the high runoff of the non-phyllosilicate soils accounted for their intermediate soil losses of 0.75 and 0.8 kg m⁻².

In the 2nd laboratory study kaolinitic and montmorillonitic soils were subjected to 80 mm of simulated rainfall at 9%, 15%, 20%, and 25% slope gradient. The slope factor (S_f) values of the kaolinitic soil at slope gradient $> 9\%$ were lower than the corresponding values of the montmorillonitic soils. A positive linear regression significantly fitted the relation between the relative MWD (the ratio of the MWD values at any slope gradient to that at 9% slope) values and the corresponding S_f values at 99% confidence level ($r^2 = 0.78$). It was concluded that the higher S_f values in the montmorillonitic soils than in the kaolinitic soil was a result of the high runoff rate in the former soils than in the latter soil.

In the field study big trash line (BTL), small trash line (STL), and stone line (SL) techniques, and control were evaluated. These indigenous soil and water conservation techniques (ISWC) were assigned to 12 runoff plots (2 by 6 m each) with 10% slope in the semi-arid Tunyai area in Kenya, during five consecutive rainy seasons. The ISWC techniques significantly decreased the runoff and the soil loss, and increased the maize and cowpea yields compared with the control treatment in most of the rainy seasons. The BTL was the most effective technique, but no consistent differences were found between the STL and SL techniques. In BTL, STL, SL and control, the seasonal average runoff for each treatment was 25, 31, 29 and 51 mm, respectively, and the seasonal average soil loss was 0.23, 0.33, 0.3, and 0.67 Mg ha⁻¹, respectively. The seasonal average biomass was 4.8, 4.0, 4.0 and 2.5 Mg ha⁻¹, respectively. The seasonal biomass increased linearly and significantly ($\alpha = 0.01$) with increasing water infiltration. Therefore as more water infiltrated, more water was available for crop production, and this resulted in higher crop yields.

CHAPTER 1

1 Introduction

1.1 General

Soil erosion is a major environmental problem in the world. An estimated 6 - 7 million hectares of agricultural land worldwide is made unproductive each year because of soil erosion, leading to loss of production worth US\$ 42 billion in semi-arid areas alone (IUCN/UNEP/WWF, 1991). Eighty five percent of Kenya is arid or semi arid and at least 9.4 million people and half of the country's livestock live there (Vaetozold and Schmidt, 1983).

Soil erosion reduces the soil's depth and its capacity to store water and nutrients, which plants require for growth (Hudson, 1992; Gachene, 1995; Gachene *et al.*, 1997). In east Africa, soil erosion rates of 2 to 7.5 m³ ha⁻¹ y⁻¹ (0.2 to 0.75 mm y⁻¹) have been measured on catchments up to 20 km² (Rapp, 1975; Christiansson, 1989). Staples (1934) measured extreme rates of 50 - 100 m³ ha⁻¹ y⁻¹ (5 - 10 mm y⁻¹) from 50 m² plots. Despite this huge loss of hitherto productive agricultural land each year, the high rate of population growth in many countries in Africa calls for increased and sustained food and fiber production. In Kenya, for example, the rate of population growth is about 4% per annum (World Bank, 1990). Consequently, there is urgent need to reduce soil erosion and runoff.

In the semi-arid regions, where water is the main limiting factor for crop production, rainwater runoff from arable lands is a serious problem. Runoff occurs when the rainfall intensity exceeds the soil's infiltration rate (IR). Depending on the field characteristics (slope and surface roughness), the runoff may flow out of the field and/or accumulate in small depressions within the field. Runoff out of a cultivated field is usually lost for crop production, and it contributes to soil erosion and fertilizer depletion. Local

runoff within the field leads to non-uniform water distribution, which, in turn, significantly reduces crop yields (Warrick and Gardner, 1983). Therefore, it is essential to study the interrelationships among rainfall parameters, soil properties, and infiltration and erosion process in order to control runoff and erosion.

Several factors are responsible for the reduction of IR with time during a rainstorm. In soils with stable structure that does not deteriorate during rainfall, the initial IR is high because of the combined gravitational and matric potential gradients that draw water into the soil (Shainberg and Levy, 1996). As the wetting front moves deeper, the matric potential gradient decreases and the hydraulic gradient tends to unity. At this time, the IR approaches a steady state, which is approximately equal to the saturated hydraulic conductivity of the soil profile. The soil structure, however, is seldom completely stable. Impact energy from water drops can cause the soil surface structure to break down, and form a surface seal with very low hydraulic conductivity. Consequently, a sharp decrease of the IR occurs. Furthermore, chemical dispersion of the soil clays enhances the aggregate breakdown at the soil surface. The dispersed clay particles move with the infiltrating water and lodge in the pores near the soil surface decreasing the hydraulic conductivity of the seal and the IR of the soil. This makes soil mineralogy important with respect to runoff because of the differences in the dispersivity of the various clay types (Stern *et al.*, 1991).

Soil erosion during rainfall is an outcome of two main processes: (i) detachment of soil particles from the soil surface and (ii) transportation of the detached particles from the impacted soil surface. Slope affects soil erosion rate through its morphological characteristics and aspect. Gradient and length are the two main morphological slope characteristics that affect soil erosion. Gradient is the more important slope characteristic in interrill erosion. An increase of the slope gradient increases the runoff velocity,

which, in turn, enhances the runoff transport capacity. Runoff is the primary carrier of soil particles from cropland during the erosion process and can cause significant detachment. The ability of runoff to transport and/detach soil particles can be reduced using appropriate soil and water conservation measures. Soil and water conservation practices can be divided into three approaches: (i) reducing runoff - practices that are designed to prevent initiation of runoff; (ii) retaining runoff - practices that accept initiation of runoff but reduce the distance of runoff flow and retain it in the field and (iii) controlling runoff - practices that accept initiation of runoff and flow out of the field but with minimum erosion hazard.

Reduced sediment transport from cultivated fields and increased water conservation could be achieved by reducing the amount and velocity of runoff. Reducing the amount lessens the quantity of water available for sediment transport, whereas reducing the velocity provides time for sediments to settle from water before they are transported from the field. It also provides more time for water to infiltrate the soil, thus improving water conservation.

1.2 Study hypotheses

1. Soil mineralogy and texture have substantial effects on aggregate stability and, therefore, may influence the size and density of the detached particles at the impacted soil surface, which in turn affect the crust characteristics, infiltration rate (IR) and soil loss under rainfall conditions
2. Soil mineralogy and texture have substantial effects on aggregate stability and, therefore, may influence the size and density of the detached particles at the impacted soil surface, which probably influences differently the capacity of the rain-impact flow to transport the detached particles in various slope gradients.

3. Decreasing the spacing between the trash and stone lines to 2 m would increase the efficiency of indigenous soil and water conservation (ISWC) techniques to reduce runoff and erosion and increase crop yield under seal formation conditions.

1.3 Objectives

The general objective of this study was to investigate the effects of soil properties, such as soil mineralogy and texture and topography, on seal formation and its properties, and their effects on infiltration, runoff, erosion and water and soil conservation techniques in semi arid conditions.

1.3.1 Specific objectives

1. To examine the effects of soil mineralogy and texture on crust micromorphology, infiltration, runoff and soil loss.
2. To determine the interaction effect between soil mineralogy, texture and slope factor on erosion.
3. To determine the effects of close spaced (2 m) trash and stone lines and of the size of the trash lines on the runoff, erosion and crop yield during some five consecutive rainy seasons under semi-arid conditions.

CHAPTER 2

2 Literature Review

2.1 Soil Mineralogy and Texture Effects on Crust Characteristics, Infiltration and Erosion

Surface crusting is a common occurrence in many cultivated soils in arid and semi-arid regions (Kemper and Miller, 1974). Important effects of soil crust on soil surface phenomena include: reduction of IR, enhancement of runoff and erosion, impairment of aeration, and interference with seed germination. These effects have led many investigators to study soil crust characteristics (Duley, 1939; Evans and Buol, 1968; Sharma *et al.*, 1981; Tarchitzky *et al.*, 1984; Norton, 1987; Bresson and Bioffin, 1990).

McIntyre (1958) described the general sequence of events that leads to crust formation under rainfall conditions as follows: (1) breakdown of soil aggregates caused by raindrop impact or slaking; (2) movement of fine particles into the upper few millimeters of the soil, and deposition in the voids, and (3) compaction of the soil surface to form a thin film, which restricts further entry of water and movement of soil particles. In coarse textured soils there is vertical segregation, with coarse particles accumulating near the surface and formation of a clay "skin" a few millimeters below the soil surface. A "washed-in" layer may exist below the clay "skin" (Biielders and Baveye, 1995). After initiation of runoff there is redistribution of material (Valentin and Bresson, 1992).

Luk *et al.* (1990) subjected some loess soils that were dominated by illite and kaolinite minerals, to rainfall of a range of durations. Scanning electron microscope observations of the crusts in these soils revealed a rearrangement of the micro-fabric at the soil surface. Gal *et al.* (1984) and McIntyre (1958) reported that in the final stage of crust formation, the crust comprises a 0.1-mm-thick "skin", composed almost solely of fine particles,

and a 2-mm-thick “washed in” layer. Moreover, Chen *et al.* (1980) observed a crust comprising coarse particles stripped of the fine ones in a sandy loam soil.

The tendency of a soil to form a crust depends on aggregate stability (Le Bissonnais, 1996). Goldenberg *et al.* (1988) classified the factors that affect aggregate stability as solution factors and soil factors. Many studies have addressed only solution factors, such as: electrolyte conductivity (EC) (Shainberg and Letey, 1984), pH (Suarez *et al.*, 1984) and soluble silica (Shanmuganathan and Oades, 1983). Soil factors that have received some attention include exchangeable sodium percentage (ESP) (Levy and van der Watt, 1988), organic matter content (Le Bissonnais and Arrouays, 1997), and texture and carbonate content (Ben-Hur *et al.*, 1985).

Aggregate stability has been found to increase with increasing clay content (Kemper and Koch, 1966). Conversely, Moldenhauer and Kemper (1969) found that increasing clay content promoted crust formation. Ben-Hur *et al.* (1985) explained this paradox by suggesting that in soils containing $> 20\%$ clay, the clay fraction acts as a cementing material, stabilizing soil aggregates against the beating action of raindrops, and so preventing crust formation. On the other hand, in soils containing $\leq 20\%$ clay, the clay acts as a substrate for crust formation, decreasing the steady-state hydraulic conductivity of the crust.

Soil mineralogy has a substantial effect on aggregate stability and dispersion. Singer (1994) reviewed the effects of clay mineralogy on soil dispersivity and concluded that montmorillonitic soils are the most dispersive and kaolinitic soils the least dispersive. The dispersivity of illitic soils is intermediate, but may sometimes exceed that of montmorillonitic soils. In soils dominated by 2:1 clays, the aggregate stability is affected mainly by polyvalent metal-organic matter complexes that form bridges between the negatively charged clay platelets (Six *et al.*, 2000). However,

the stability in 1:1 clay-dominated soils is mainly induced by the binding capacity of the minerals themselves (Oades and Waters, 1991). Soils that are dominated by clay-sized minerals, such as quartz and feldspar, disaggregate preferentially over soils containing kaolinite and smectite when these soils are shaken in distilled water (Neaman *et al.*, 1999; Böhmann *et al.*, 1996).

However, in spite of the dominant effect of soil mineralogy and texture on soil dispersivity and aggregate stability, little is known about their effects on seal formation and micromorphology, runoff and soil loss. The effects of soil mineralogy on crust formation, IR, and erosion were studied for some soils from South Africa and Israel by Stern *et al.* (1991), who used a laboratory rainfall simulator; they suggested that soils in which either kaolinite or illite predominated, but which contained small amounts of smectite, were as susceptible to crust formation as montmorillonitic soils. However, montmorillonitic soils were much more erodible than soils that contained only small amounts of smectite, and the soils that did not contain smectite were the least erodible. Other investigators have reported similar findings on erosion and final IR (Ben-Hur *et al.*, 1992; Levy and van der Watt, 1988), for a range of soil with various texture and organic matter contents.

2.2 Soil Mineralogy and Texture Effects on Interrill Slope Factor

Soil erosion by water involves two major processes: (i) detachment of soil material from the surface soil by raindrop impact and runoff shear and (ii) transport of the resulting sediment by raindrop splash and overland flow (Baver *et al.*, 1972). A widely used equation for prediction of soil loss is the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978).

Recent erosion models have divided the erosion process into two components: rill and interrill erosion (Foster, 1982). Rill erosion is due mainly to detachment and transport of soil particles by flowing water, whereas in interrill erosion, detachment of soil particles is controlled by the raindrop impact, and transport of soil particles is facilitated by splash and runoff flow (Watson and Laflen, 1986). Foster (1982), Singer and Blackard (1982), Rubio-Montoya and Brown (1984), and McCool *et al.* (1987) observed that the erosion obtained from slope with length < 4 m is mainly interrill erosion.

In the original Water Erosion Prediction Project (WEPP) proposal, Lane *et al.* (1987) related interrill erosion (D_i) with rainfall intensity (I) and interrill slope factor (S_f) by Eq. [1]

$$D_i = K_i I^2 S_f \quad [1]$$

where, K_i is the interrill erodibility factor, which expresses the inherent susceptibility of the soil to interrill erosion.

Kinnell (1993) suggested that the hydrology of interrill areas should be taken into account in the determination of interrill erodibility; this is done by means of Eq. [2]

$$D_i = K_i I Q S_f \quad [2]$$

where Q is the runoff rate and K_i is an estimate of the interrill erodibility factor. In this equation the factors influencing the erosive stress (I and Q) are separated from the factor K_i that accounts for the response of the affected surface to the erosive stress.

Numerous studies have attempted to establish the relationship between the interrill erosion and the K_i , I , Q and S_f factors in disturbed soil

samples using laboratory rainfall simulators (Römkens *et al.*, 1977; Trott and Singer, 1983; Ben-Hur *et al.*, 1992). This is because laboratory rainfall simulators have several advantages, such as savings in cost and time and offering better control of the test environment compared to field measurements (Agassi and Bradford, 1999).

Important factor governing interrill erosion is slope gradient (Fox and Bryan, 1999). The contribution of slope gradient to erosion is expressed as a slope factor (S_f), which is defined as the ratio of soil loss per unit area at any slope to that from a standard slope when all other conditions are the same.

The USLE slope factor increased with slope angle (θ), in degrees, as described in Eq. [3] (Wischmeier and Smith, 1978)

$$S_f = 64.51 \sin^2 \theta + 4.56 \sin \theta + 0.065 \quad [3]$$

where the standard slope is 9%.

The WEPP model for interrill erosion (Elliot *et al.*, 1989) found that

$$S_f = 1.05 - 0.85 \exp(-4 \sin \theta) \quad [4]$$

where $S_f = 0.2$ for a flat slope and 1.0 for a 45° slope. Extension of Eq. [4] to be comparable with the USLE slope factor (Eq. [3]) led to Eq. [5]

$$S_f = 2.17 [1.05 - 0.85 \exp(-4 \sin \theta)] \quad [5]$$

where $S_f = 1.0$ for a 9% slope (Ben-Hur *et al.*, 1992).

The exponential increase of the S_f with an increase of the slope gradient is because that at low slope gradients, the soil loss is limited by the transport capacity of the runoff despite the availability of raindrop-detached

sediments. In contrast, at steep slopes, the runoff flow velocity is high, which, in turn, increases the runoff transport capacity and the soil loss.

The slope factor should be isolated, in general, as a unique surface property regardless of soil type because the slope gradient affects the erosivity of rainfall and overland flow but not soil erodibility. However, Ben-Hur *et al.* (1992) found different S_f values for soils with different mineralogy at a given θ value when they were subjected to distilled water rainfall. Ben-Hur *et al.* (1992) concluded that Eq. [5] could be used to estimate the slope factor for soils lacking smectite (nondispersive soils). In contrast, for soils, containing kaolinite or illite as the predominant clay and a low percentage of smectite (dispersive soil), Eq. [6] defines the slope factor.

$$S_f = \exp(-0.58 + 6.67 \sin \theta) \quad [6]$$

Ben-Hur and Agassi (1997) in measuring the slope factor for soils with different properties found that the soils could be divided into three main groups regarding their mineralogy; two groups were as found by Ben-Hur *et al.* (1992) and a third group, soils containing smectite as a dominant clay (montmorillonitic soil). For the montmorillonitic soil, Eq. [7] defines the slope factor

$$S_f = \exp(-0.68 + 8.28 \sin \theta) \quad [7]$$

Furthermore, Singer and Blackard (1982) reported results of an experiment on interrill erosion using loam and silty-clay loam soils. The results of that study showed that the loam soil had greater S_f values at slope gradients $> 9\%$ than the silty-clay loam soil. They concluded that soil texture influences the relationship between soil loss and slope gradient.

Meyer and Harmon (1989), and Bradford and Foster (1996) performed similar experiments and made similar conclusions.

These differences between the S_f functions in the several soil groups suggested that there is an interaction between the slope gradient and soil properties in their effect on D_i . It is hypothesized that soil mineralogy and texture have effects on the size and density of the detached particles at the impacted soil surface, which probably in turn influences differently the capacity of the rain-impact flow to transport the detached particles in various slope gradients: a hypothesis that the present study sets out to confirm.

2.3.1 Indigenous Soil and Water Conservation Techniques Effects on Runoff, Erosion and Crop Yields

To combat the massive problems of runoff and erosion, resource poor smallholder farmers in arid and semi-arid regions often use inexpensive, indigenous soil and water conservation (ISWC) techniques (Hallsworth, 1987). Sanders (1988) and Hudson (1992) reported that these ISWC techniques are found in many regions where lack of moisture limits crop production. Critchley *et al.* (1994) observed that ISWC techniques aim to conserve soil and water *in situ* and allocated them to six categories, based on the type of technology: grass strips, trash lines, pits, earth bunds, stone lines, and protection ditches.

Inventories of ISWC techniques abound in the literature (Hallsworth, 1987; Roose, 1992; International Fund for Agricultural Development, 1992; Kerr and Sanghi, 1992; Reij *et al.*, 1996). Many of these studies recognised the usefulness of ISWC techniques to the resource poor smallholder farmers and lamented the scarcity of quantitative investigations (Chambers, 1983; Richards, 1985; Willcocks and Twomlow, 1993). A few isolated studies that focused on soil moisture conservation by the pitting technique indicated

that crop yields increased in treated plots compared with the controls. For example, in a semi-arid region in Kenya, Gichangi *et al.* (1992) harvested 0.81 Mg ha⁻¹ of cowpea grains in treated plots and 0.31 Mg ha⁻¹ in untreated plots, under seasonal rainfall of 330 mm; in Niger, Hassan (1996) obtained 0.4 Mg ha⁻¹ of millet grains from untreated plots and 1 Mg ha⁻¹ from treated plots; and in Mali, where the seasonal rainfall of 538 mm fell in 35 days, Wedum *et al.* (1996) obtained 1.49 Mg ha⁻¹ of sorghum grains from treated land compared with 0.39 Mg ha⁻¹ from untreated land.

In comprehensive reviews of ISWC technologies, Critchley *et al.* (1994) and Stocking (1985) noted that although trash and stone lines were the most commonly used techniques in arid and semi-arid regions since time immemorial, detailed studies about them were rare and scattered. The trash line technique uses lines made of crop material that remains after harvesting the grains or pulses. The material is formed into ridges across the slope, and is sometimes modified by the inclusion of logs or pegs (Gichuki, 1992; Silotoe, 1993). The stone line technique, in which stones are arranged in lines across the slope, is used where stones are abundant on the soil surface.

The trash and stone line techniques differ in some respects. For example, in contrast to stone lines, trash lines allow water to infiltrate into the soil in the area directly beneath them, and the trash rots after a few seasons thus adding organic matter to the soil. The trash line technique requires less labour to construct but frequent maintenance, whereas the stone line technique requires more labour to construct but little maintenance (Wakindiki *et al.*, 1998).

The trash and stone line techniques both form semipermeable barriers across the slope that decrease the surface runoff velocity and increase the infiltration duration of the impounded water, but allow passage of excess runoff. As a result, the amount of infiltrated water increases and the runoff

volume and its erosive power decrease. Likewise, retention of sediment in the trash and stone lines results in reduced soil and nutrient losses (Gachene et al., 1997).

In a study of ISWC techniques used by farmers in Kenya, Gichuki (1992) observed that the farmers placed the trash or stone lines about 15 m apart in the field. However, in semi-arid regions, seal formation is a common occurrence (Kemper and Miller, 1974) that decreases the infiltration rate and increases runoff and soil erosion (Ben-Hur *et al.*, 1985). The raindrop impact energy causes the soil surface structure to break down and consequently a seal is formed. Hence, under seal-formation conditions, the 15 m spacing between the trash or stone lines is probably too large to prevent surface runoff and soil erosion out of the cultivated field during rainstorms. In a semi-arid region in eastern Kenya, Okoba *et al.* (1998) observed significant ($\alpha = 0.05$) reductions in runoff and soil erosion in Luvisols protected by trash and stone line techniques when the spacing between the lines was reduced from 15 to 7.5 m.

Furthermore, when the trash line technique was applied under seal-formation conditions, the trash, that covered the soil surface limited seal formation on the area beneath it. Hence, the surface runoff that flowed across the area between the trash lines could infiltrate in the area beneath the trash, thus decreasing the total runoff. Consequently, the width of the trash line affects the area of the soil surface with no seal, which, in turn can affect the amount of infiltrated water and the runoff in the field.

CHAPTER 3

3 Materials and Methods

The work in this thesis was divided into two main parts: (i) laboratory studies conducted at the Insitute of Soil, Water and Environmental Sciences, Volcani Center, Israel and (ii) a field experiment conducted at Tunyai, in Tharaka District, Kenya.

3.1 Laboratory studies

3.1.1 Soil samples

Soil samples from Molo, Njoro and Tunyai in Kenya, and from Netanya and Neve Ya'ar in Israel were used in these studies. All the samples were collected from 0 to 0.2-m depths in cultivated fields. Sampling was done during the dry season in Kenya and during summer in Israel. They were air dried, crushed to pass through a 4-mm sieve and mixed thoroughly. The < 2-mm fraction of each soil was characterized by standard analytical procedures as described by Rowell (1994) (Table 1). Cation exchange capacity (CEC) was determined by treating the sample with ammonium acetate buffered at pH 7.0. Sodium was determined using a flame photometer. The ratio of Sodium to CEC was expressed as a percentage to give the Exchangeable Sodium Percentage (ESP). Hydrometer method was used to determine the soil texture. Organic matter content was determined by the loss-on-ignition procedure. Soil mineralogy was determined in the laboratory of A.P. Gonzalez at the Faculty of Sciences, University of La Coruna, Spain, by X-ray diffraction method, with a Co-K α source for X-rays (Whittig, 1965). Estimates of the amounts of the various clay minerals were derived from the relative peak areas on the diffractograms.

The mineralogy of the soils (Table 1) indicated that the studied soils could be divided into two main groups (Neaman et al., 2000): (i) phyllosilicate soils, which included the Tunyai, Neve Ya'ar and Netanya soils; (ii) non-phyllosilicate soils, which included the Molo and Njoro soils.

3.1.2 Experimental layout

The laboratory study included two experiments, (i) Soil mineralogy and texture effects on crust micromorphology, infiltration and erosion; (ii) Soil mineralogy and texture effects on slope factor. In the 1st experiment, the Molo, Njoro, Tunyai, Netanya and Neve Ya'ar soils were tested by fast-wetting aggregate stability, rainfall simulator, and scanning electron microscope methods. For the rainfall simulator study, the soils were tested at 9% slope gradient, and the particle-size distribution of the eroded sediment was determined by pouring the runoff through a nested set of 2-, 1-, 0.5-, 0.25-, 0.1-, and 0.05-mm sieves. The runoff that contained sediment < 0.05 mm was gently put into 1-litre cylinders and the clay concentration was determined with a hydrometer. In order to determine the particle-size distribution in the bulk soil samples before the rainstorm, a separate 40-g sample of each soil was subjected to dry sieving through a set of sieves with 2-, 1-, 0.5-, 0.25-, 0.1- and 0.05-mm openings.

In the 2nd experiment, the Tunyai, Netanya, and Neve Ya'ar soils were run in the rainfall simulator at 9, 15, 20 and 25% slope gradients. The particle-size distribution of the eroded sediment was determined by pouring the runoff through a nested set of 2-, 1-, 0.5-, 0.25-, and 0.1-mm sieves.

All the studies were conducted in three replicates, and the data were subjected to analysis of variance as a Complete Randomized Design (CRD). Separation of means was done using Turkey's Honestly Significant Difference, with a 0.05 significance level (SAS Institute, 1990).

Table 1: Some physical, chemical and mineralogical properties of the studied soils

Location	Soil Taxonomy	Mechanical composition,			Organic			Soil mineralogy#					
		Sand	Silt	Clay	CEC cmol _c kg ⁻¹	Matter g kg ⁻¹	ESP	Mic.	Mon.	Kao.	Qua.	Fel.	Gib.
Tunyai	Rhodic Eutrustox	121	239	640	17.0	27.1	0.88	0	0	5	0	0	1
Neve Ya'ar	Typic Chromoxerert	108	262	630	56.0	21.6	0.59	3	5	3	1	0	0
Netanya	Typic Rhodoxeralf	850	50	100	15.0	11.1	0.73	2	5	3	1	0	0
Molo	Inceptic Haplustalf	312	304	384	24.6	61.7	0.86	1	0	0	5	3	0
Njoro	Typic Haplustepts	319	340	341	25.6	58.8	0.89	1	0	0	5	3	0

Mic. = mica, Mon. = montmorillonite, Kao. = kaolinite, Qua. = quartz, Fel. = feldspar, Gib. = gibbsite, 1 = 0 – 3, 2 = 3 – 10, 3 = 10 – 30, 5 = >50 percent of the total clay fraction.

3.1.3 Methods

3.1.3.1 Aggregate stability

The soil aggregate stability was determined by the fast-wetting method proposed by Le Bissonnais (1996). Soil samples with aggregates of 3 to 4 mm were put in an oven at 40°C for 24 h, and 5 g of the oven-dry aggregates were gently immersed in a beaker containing 50 cm³ of deionised water for 10 min. The water was then sucked off with a pipette. The soil material was transferred to a 50-μm sieve that had previously been immersed in ethanol and gently moved up and down in ethanol five times to separate the <50-μm fragments from the >50-μm ones. The >50-μm fraction was oven dried and then gently dry sieved by hand on a column of sieves of mesh sizes 2, 1, 0.5, 0.25, 0.1 and 0.05 mm. The weight of each fraction was then calculated; that of the <50-μm fraction was the difference between the initial weight and the sum of the weights of the other six fractions. The aggregate stability for each soil sample was expressed by calculating the (mean weight diameter) MWD of the seven classes:

$$MWD = \sum_{i=1}^7 \bar{x}_i w_i \quad [8]$$

where, w_i is the weight fraction of aggregates in the size class i with a diameter $\bar{x}_i$.

3.1.3.2 Rainfall simulation

The soil samples were packed in 0.5 by 0.3 m perforated trays, in triplicate, in an 0.02 m thick layer, to a mean bulk density of 1.29 (±0.03) Mg m⁻³. The trays were then placed over a 0.08-m-thick layer of coarse sand on the desired slope gradient at the rainfall simulator (Fig. 1) (Morin et al., 1967). The samples were first prewetted from below with tap water (EC = 0.7 dS m⁻¹) and then subjected to an 80-mm rainstorm of deionised

water (simulated rainwater quality). The mean diameter of the raindrops was 1.9 mm, median drop velocity 6.02 m s^{-1} , kinetic energy $18.1 \text{ J mm}^{-1} \text{ m}^{-2}$, and rain intensity 40 mm h^{-1} .

During the rainstorm, the volume of the rainfall percolating through the soil was measured, and the IR was calculated. As soon as runoff was observed to commence, it was collected until the end of the rainstorm. The runoff sample from each replicate were analyzed by a wet sieving procedure similar to that described by Gabriels and Moldenhauer (1978), to determine the particle-size distribution of the eroded sediments. Each sample was gently poured in bulk through a nested set of sieves. Extreme care was taken to ensure a high degree of uniformity in sieving operations and to avoid creating artifacts.

3.1.3.3 Scanning Electron Microscopy

The trays with the soils that were crusted after the rainstorm were left to dry for a week. A piece of crust was carefully broken along its natural planes of weakness into approximately 15-mm fragments. The top of the crust was mechanically stabilized by coating it with a gold layer. The sample was glued onto the scanning electron microscope stub with conductive carbon glue and the fracture was covered by sputtering with a thin layer of gold, approximately 40 nm in thickness. The samples were then placed in the scanning electron microscope and micrographs were taken.



Fig. 1: The rainfall simulator with a rotating disc.

3.2 Field study

3.2.1 Site characteristics

The field experiment was conducted at Tunyai in Tharaka District, Kenya. The site is located approximately 37° 50' E and 0° 2' S. The long-term average annual rainfall in this region is 600 mm, which is distributed almost equally between two rainy seasons: the first from March to May and the second from October to December, referred to below as the 1st and 2nd season, respectively. The annual average precipitation in this region is between 40 and 50% of the potential evaporation. Rain-fed smallholder subsistence agriculture is the dominant land use in this region.

A soil profile was opened in the experimental site, and was described according to soil taxonomy guidelines (Food and Agricultural Organization, 1977) and soil colour charts (Munsell Color Company, 1971). Soil samples were collected from each master horizon and their physical and chemical properties (Table 2) were determined.

The soils at the site are classified as Rhodic Ferralsols (Food and Agricultural Organization, 1990) or Rhodic Eutrutox (Soil Survey Staff, 1998). The soil profile was deep and well drained. Soil texture was determined by the hydrometer method (Day, 1965) after pretreating the samples with 30% hydrogen peroxide and shaking them in calgon solution overnight. The soil chemical properties were determined according to Hinga *et al.* (1980).

3.2.2 Experimental layout

The land at the experimental site had previously lain fallow for about 5 years, being used for cattle grazing. In February 1997, this land was cleared and cultivated with hand tools. A cutoff drain was dug above the experimental site to prevent surface runoff from higher ground from entering the experimental area. Twelve runoff plots measuring 2 m by 6 m each were constructed along a contour on a ~ 10% slope. The plots they

Table 2: Some physical and chemical properties of the soil profile in the field experimental site.

Horizon	Depth (m)	Boundary	Colour	Texture	Cutans	Structure	Pores	Consistency	Others
Ap	0 - 0.25	Clear wavy Gradual smooth	2.5 YR 3/4 Reddish brown	Clay	Nil	Moderate fine crumbly	Many very fine, fine, medium and coarse	Slightly hard; Very friable; Slightly sticky, slightly plastic	Many roots
B1	0.25 - 0.55		2.5 YR 3/4 Dark reddish brown	Clay	Nil	Moderate medium sub- angular blocky	Many very fine and fine, few medium and coarse	Hard; friable; Slightly sticky, slightly plastic	Slightly compact
B2	0.55 - 1.2		10 YR 3/4 Dusky red	Clay	Very fine patchy and thin clay	Weak medium sub-angular blocky	Many very fine, fine and medium, few coarse	Slightly hard; Very friable; Slightly sticky, slightly plastic	None

Depth (m)	Sand	Silt	Clay	CEC	pH	OC	N	P	K	Ca	Mg	Na
	g kg ⁻¹			cmol _c kg ⁻¹	(H ₂ O)	g kg ⁻¹		mg kg ⁻¹	cmol _c kg ⁻¹			
0 - 0.25	160	240	600	18	5.7	9.0	0.9	0.8	0.19	2.62	1.52	0.05
0.25 - 0.55	100	220	680	20	6.1	8.5	0.5	0.9	0.28	3.00	1.88	0.09
0.55 - 1.2	120	180	700	15	5.9	5.9	0.4	0.9	0.22	2.90	2.08	0.10

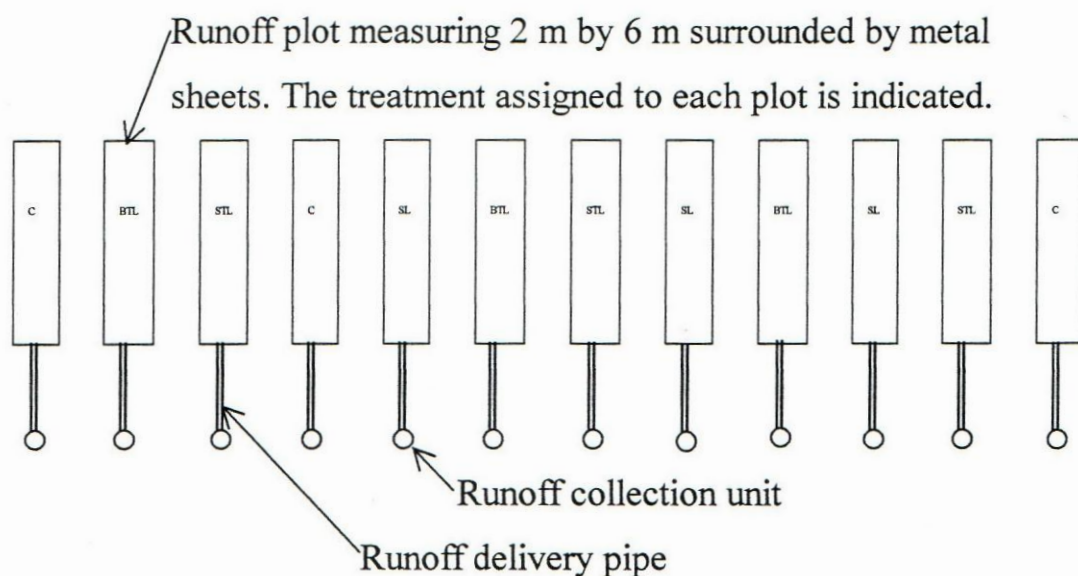
CEC - cation exchange capacity; OC - organic carbon. The pH was measured at a soil: water ratio of 1:2.5

were separated from each other by buffer zones ~ 2 m wide (Fig. 2). Each plot was enclosed by galvanized iron sheets embedded 0.2 m into the ground and projecting 0.2 m above it, and an end plate was installed at the end of each plot to block the runoff and direct it into a trough. Each trough was covered with a lid to prevent direct entry of rainfall. The trough delivered the runoff into a 1-m^3 tank via a conveyor pipe. This design was similar to that used by Gachene *et al.* (1997). The tanks containing runoff were emptied each morning preceding a daily rainstorm. The runoff in each tank was mixed thoroughly and three sub-samples were taken to determine the amount of soil loss by weighing the sediment after oven drying at 105°C . The daily rainfall was taken from rainfall recording station: 09037184, Tunyai, located 500 m south east of the experimental site.

Four treatments, each with three replicates, were randomly assigned to the runoff plots (Fig. 2). The treatments were: (1) big trash lines (BTL) - trash lines 0.6 m wide and 0.3 m high, with total trash content of 2.5 Mg ha^{-1} of the crop residues; (2) small trash lines (STL) - trash lines 0.3 m wide and 0.15 m high, with total trash content of 1.5 Mg ha^{-1} of crop residues; (3) stone lines (SL) - stone lines 0.3 m wide and 0.15 m high. Stones ~ 10 cm that were abundant on the soil surface were used; and (4) control - no ISWC technique applied. All the trash and stone lines constructed in the respective runoff plots in these treatments were aligned across the slope at a 2-m spacing.

Agronomic aspects (e.g., time of planting, plant population, seed varieties, etc.) at the experimental site were in accordance with the local practices and conditions. No inorganic fertilizers were added, but 5 Mg ha^{-1} of farmyard manure was added at the beginning of each season. Seeds were planted just before or after the first daily rainstorm in each rainy season. Katumani composite, a drought-escaping maize (*Zea mays* L.) variety was planted as a sole crop during the 1st season of each year of the study. The

spacing between the maize plants was 0.25 m within the rows and 0.75 m between the rows. Two rows were planted between the trash or stone lines, in the plots where these techniques were applied. In the 2nd season in each year of the study, maize was intercropped with cowpea (*Vigna unguiculata*) variety M66 in all the treatment plots. A single row of this crop was planted between the two rows of maize at spacing within the row of 0.25 m. The plant rows and spacing between the plants in the control treatment were the same as in the trash and stone line treatments. All plots were kept free of weeds by hand hoeing during the rainy seasons. At the end of each season, the crop was harvested by hand and the dry weights of crop grains and stover from each plot were determined.



BTL = Big Trash Lines, STL = Small Trash Lines, SL = Stone Lines, C = Control

Fig. 2: Schematic layout of the runoff plots in the field.

CHAPTER 4

4 Results and Discussions

4.1 Soil Mineralogy Effects on Crust Micromorphology, Infiltration and Erosion

The MWD values as determined by the fast-wetting method for the studied soil samples are presented in Table 3.

Table 3: Total soil loss and mean weight diameter values for the various studied soils.

Soil	Total soil loss kg m ⁻²	Mean Weight Diameter, mm	
		In fast-wetting test	In runoff
Tunyai	0.33 ^{a*}	2.8 ^a	0.12 ^a
Neve Ya'ar	1.24 ^b	0.25 ^b	0.03 ^b
Netanya	1.14 ^b	0.31 ^b	0.20 ^c
Molo	0.75 ^c	0.84 ^c	0.18 ^c
Njoro	0.80 ^c	0.87 ^c	0.21 ^c

* Different letter superscripts within a column indicate significant difference among the soils at $\alpha = 0.05$.

The higher the MWD, the higher was the aggregate stability of the tested soil (Le Bissonnais, 1996). Hence, it can be concluded from these results that the kaolinitic soil (Tunyai) had the greatest aggregate stability, montmorillonitic soils (Neve Ya'ar and Netanya) had the least, while the non-phyllosilicate soils (Molo and Njoro) had intermediate levels of aggregate stability. These differences in the aggregate stability of the soils are probably a result of differences in their mineralogy and organic matter contents (Table 1). The higher dispersivity of montmorillonite than of kaolinite (Singer, 1994) decreased the aggregate stability of the montmorillonitic soils compared with the kaolinitic soil (Table 3). In contrast, the higher organic matter content of the non-phyllosilicate soils

(Molo and Njoro) raised their aggregate stability (Le Bissonnais, 1996) above those of the montmorillonitic soils, but not as high as that of the kaolinitic soil (Table 3).

The particle-size distributions of the various soils before the rainstorms (Fig. 3) indicate that the clayey, kaolinitic (Tunyai) and montmorillonitic (Neve Ya'ar) soils had an appreciable proportion of large aggregates, the non-phyllosilicate soils had quite uniform aggregate size distribution, and in the sandy loam, montmorillonitic soil (Netanya), the 0.1- to 0.25-mm aggregate size had the highest frequency. In contrast, the photographs of the surface of the various soils after the rainstorm run (Fig. 4) indicate that most of the aggregates at the soil surface were broken down by the raindrop impact. The photograph of the Njoro soil is not presented in Fig. 4 because it was similar to that of the Molo soil. In the montmorillonitic soils, all the aggregates at the soil surface had been dispersed and smooth crusts developed (Fig. 4). In contrast, the other soil surface were partly covered with aggregates, with more aggregates on the kaolinitic soil surface than on that of the non-phyllosilicate soils (Fig. 4). These photographs are consistent with the MWD results (Table 3), which showed that the kaolinitic soils had the most stable aggregates and the montmorillonitic soils the least stable ones.

The IR of the studied soils as functions of cumulative rainfall are presented in Fig. 5. The IR decreased with increasing cumulative rainfall until a final IR was reached. The rate of decrease in IR and the final IR values differed among the various soils (Fig. 5). Based on their final IR values and the total runoff obtained during the entire rainstorm, the five studied soils were separated into two groups: the first group, comprising only the Tunyai soil, the IR decreased gradually and the final IR was significantly high (20.5 mm h^{-1}); in the second group, comprising the rest

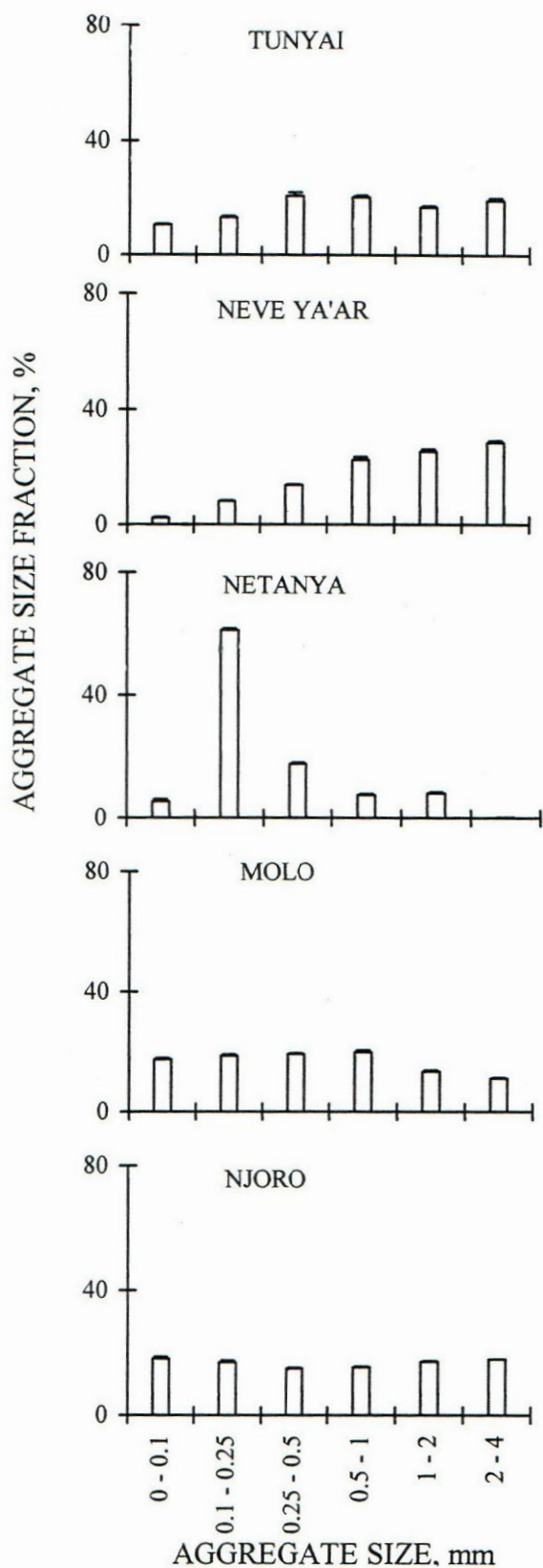


Fig. 3: Particle size distribution in the various soils before the rainstorms.
Bars indicate standard deviation.

TUNYAI (KAOLINITIC, 64% CLAY)



NEVE YA'AR (MONTMORILLONITIC, 63% CLAY)



NETANYA (MONTMORILLONITIC, 10% CLAY)



MOLO (NON-PHYLLOSILICATE, 34.4% CLAY)

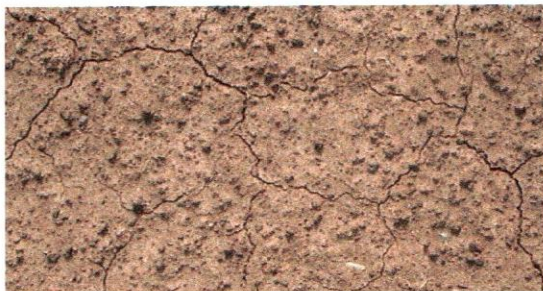


Fig. 4: Photographs of the crust surface in various soils. The scale is 1: 2.

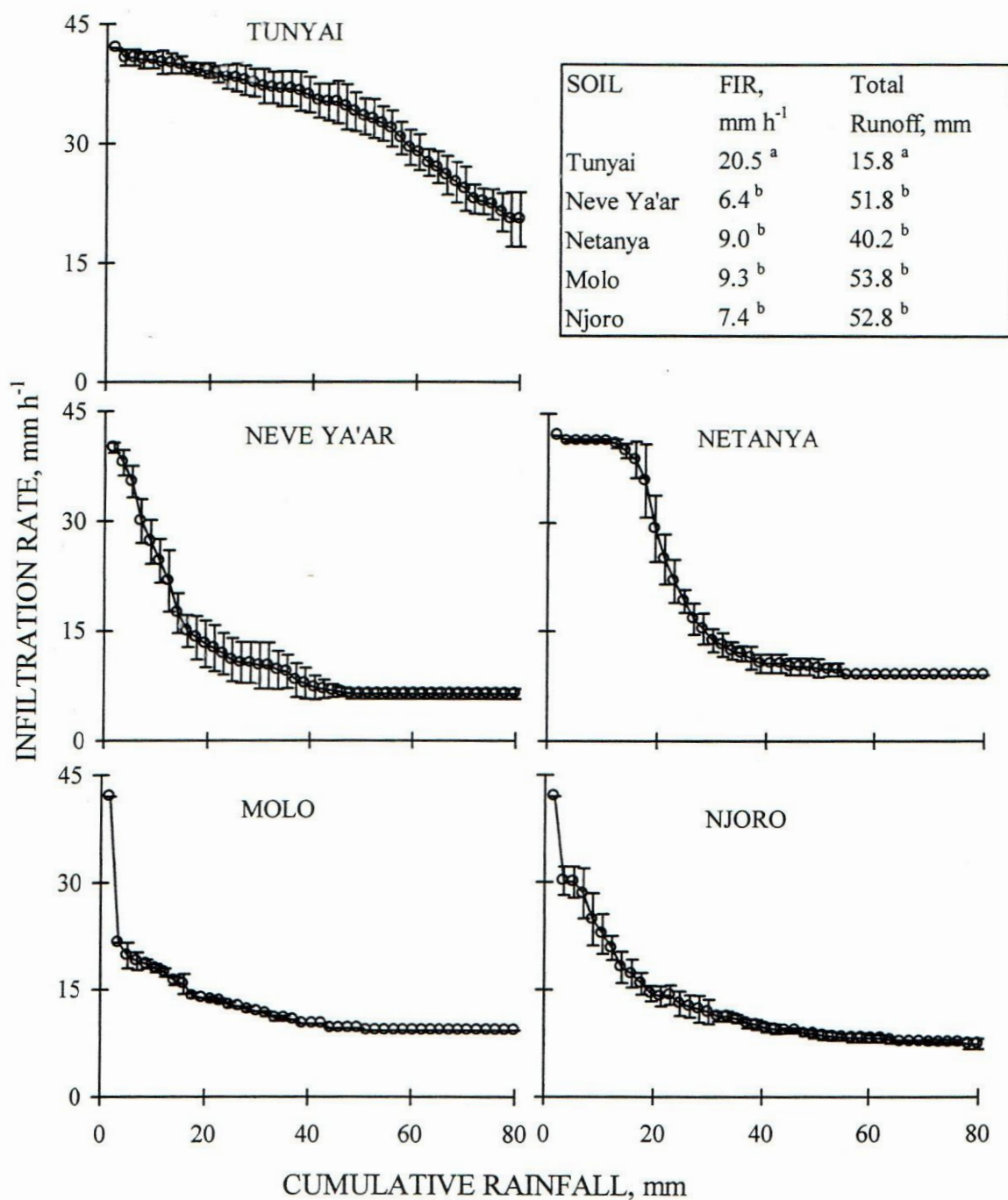


Fig. 5: Infiltration rate as a function of cumulative rainfall for the various studied soil. Bars indicate standard deviation and the different letter superscripts following the final infiltration rate values indicate significant differences between soils for each parameter.

of the soils, the IR decreased sharply and the final IR was significantly low ($\leq 9.3 \text{ mm h}^{-1}$). The final IR values shown in Fig. 5 are not consistent with the MWD values (Table 3), which divided the soils into three groups, according to their aggregate stability. This indicates that the aggregate stability of the soil is not the only factor that affects crust formation and soil loss. The rearrangement of particles in the crust, and its thickness also affect the IR of the soil under seal conditions.

The crust micromorphology of Tunyai, Neve Ya'ar and Molo soils is shown in Fig. 6 and that of Netanya in Fig 7. The crust micromorphology of Njoro soil is not presented because it was similar to that of the Molo soil. These scanning electron microscope observations reveal that the crust on the kaolinitic soil (Tunyai) was made up of a thin layer ($\sim 0.1 \text{ mm}$) of slightly compacted aggregates $\sim 0.1 \text{ mm}$ in size. In contrast, beneath this 0.1-mm uppermost layer, thick aggregates, $> 0.3 \text{ mm}$ in size, were observed. The structure of the layer immediately under the uppermost crust layer (Fig. 6A) was similar to that of the bulk soil at $\sim 0.5 \text{ cm}$ depth, which was not affected by the rainfall (Fig. 6B). This suggests that the soil layer immediately below the crust layer (Fig. 6A) was not disturbed by raindrop impact and that no accumulation of dispersed material occurred in this layer (no "washed in" zone). This crust characteristic limited the sharp reduction of the hydraulic conductivity of the seal and the soil IR (Fig. 5).

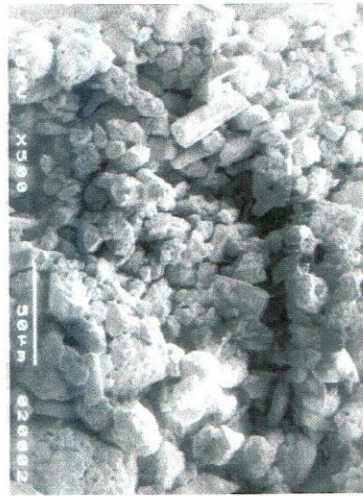
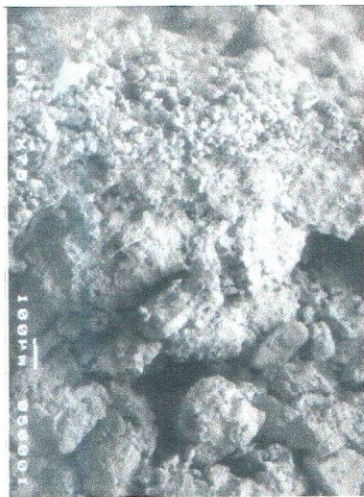
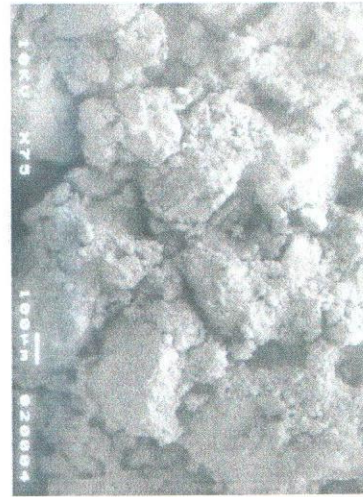
TUNYAI**NEVE YA'AR****MOLO****A****B**

Fig. 6: Scanning electron micrographs of the crusts and the soil underneath (A), and of the bulk soil at 5 mm depth that was not affected by rainfall (B), for the Tunyai, Neve Ya'ar and Molo soils. The micrograph in (B) for Neve Ya'ar soil shows the “washed-in” zone.



Fig. 7: Scanning electron micrographs of the crusts and the bulk soil underneath for Netanya soil.

In the Neve Ya'ar soil, an uppermost layer made of micro-aggregates (~ 0.02 mm) and ~ 0.2 mm thick ("skin" layer) was observed (Fig. 6A). Under this layer a dense and compacted layer ~ 0.5 mm thick was formed; this was a "washed in" zone, in which dispersed clay particles, transferred from the upper layer with the infiltrated water accumulated (Fig. 6B). The high clay content in Neve Ya'ar soil, and the high dispersivity of montmorillonite, which is the dominant clay in this soil, allowed the high accumulation of the clay particles in this "washed in" zone.

In Molo soil, an upper layer, ~ 0.2 mm thick, comprising well-compacted particles ~ 0.01 mm in size, was observed (Fig. 6A). This upper layer was the crust, and its structure was significantly different from that of the bulk soil at ~ 0.5 -cm depth (Fig. 6B). In the lower soil layer (Fig. 6B), relatively large aggregates, measuring ~ 0.3 mm with small micro-aggregates between them were observed.

In the Netanya soil, the structure of the upper 3-mm layer, which is the crust layer, was different from that of the bulk soil (Fig. 7). In the crust layer, fairly naked sand particles, ~ 0.2 mm in size and fine material between them were observed. In contrast, in the bulk soil, the sand particles were coated with fine materials, and almost no fine material was in the pores between the sand grains. The crust layer showed two zones: a uppermost compacted 0.5 mm layer, and a lesser compacted 2.5 mm layer underneath. The compacted structure of the uppermost layer of the crust was a result of the raindrop impact during the rainstorm. In contrast, the impact of the raindrops and the dispersion of the montmorillonite in the upper layer of the soil had stripped the fine material from the sand particles. However, because of the low clay content in Netanya soil, the amount of dispersed material was low, therefore, the sealing of the pores between the sand grains in the crust layer was limited.

The low final IR values ($\leq 9.3 \text{ mm h}^{-1}$) of Neve Ya'ar, Netanya, Molo and Njoro soils (Fig. 5) can be explained by the compacted structure and relatively thick ($> 0.2 \text{ mm}$) crusts that developed in these soils (Fig. 6A and Fig. 7). These crusts comprised either only small particles ($\sim 0.01 \text{ mm}$), or an uppermost layer of particles measuring $\sim 0.02 \text{ mm}$ with a highly developed "washed in" zone beneath it, or relatively large particles ($\sim 0.2 \text{ mm}$) with fine material between them. In contrast, the Tunyai soil characterized by a high final IR (20.5 mm h^{-1}) (Fig. 5), the crust thickness was small ($\sim 0.1 \text{ mm}$) and it contained relatively large particles ($\sim 0.1 \text{ mm}$ in size) (Fig. 6A).

Total soil loss values from the entire rainstorm for the various soils are presented in Table 3. The soil loss was lowest in the kaolinitic soil (Tunyai), highest in the montmorillonitic soils (Neve Ya'ar and Netanya) and intermediate in the non-phyllsilicate soils (Molo and Njoro). These soil loss values were not consistent with the IR values of the soils (Fig. 5), since the soils were divided into only two groups according to their final IR. A similar observation was made by Stern et al. (1991), who found that soils with different mineralogy could be divided into two groups based on their final IR and into three groups based on their soil loss rates.

Interrill erosion involves two major processes: (i) detachment of soil material from the soil surface by raindrop impact; and (ii) transport of the resulting sediment by runoff flow. Soil detachment depends mainly on rainfall characteristics and the aggregate stability of the soil. In the present study, all the soils were subjected to rainfall with the same characteristics. Therefore, the soil detachment depended mainly on the aggregate stability of the soil. The transport of the sediments depends on the runoff characteristics and the particle-size distribution on the impacted soil surface. Because in the present study the slope of all the soils was kept at

9%, runoff rate was the main runoff characteristic, which determined transport capacity.

Under these conditions, the soil loss values of the various soils can be explained as follows. The soil loss in the kaolinitic soil was the lowest (Table 3) because the aggregate stability of this soil was high (Table 3), the runoff rate was low (Fig. 5) which, combined with the big aggregates decreased the runoff transport capacity. In the montmorillonitic soils, the low aggregate stability (Table 3) combined with high runoff rate (Fig. 5) led to the highest soil loss (Table 3). In the case of the non-phyllosilicate soils, the intermediate aggregate stability (Table 3) combined with high runoff rates (Fig. 5) resulted in intermediate soil loss values (Table 3).

The particle-size distributions of the sediments in the runoff and their MWD values for each soil are presented in Fig. 8 and Table 3, respectively. The particle-size distribution in the runoff was controlled mainly by that at the impacted soil surface and the runoff transport capacity during the rainstorm. The high clay content in the montmorillonitic Neve Ya'ar soil and the high dispersivity of montmorillonite probably led to the high frequency of very small particles at the impacted soil surface. This led to the high frequency (~ 80%) of clay-size particles (Fig. 8) and the very low MWD value (0.03 mm) in the runoff in this soil (Table 3). In contrast, in the montmorillonitic Netanya soil, which contained 85% sand and 10% clay (Table 1), the sand particles apparently had the highest frequency at the impacted soil surface. In this case, the sand particles measuring 0.1 to 0.25 mm in size had the highest frequency (~ 50%) in the sediments (Fig. 8) and the MWD in the runoff was high (0.2 mm) (Table 3). The clay contents in the kaolinitic Tunyai soil and the montmorillonitic Neve Ya'ar soil were similar. However, the MWD value in the runoff in the former soil was significantly higher than in the latter (Table 3). The low dispersivity of the kaolinite in Tunyai soil probably led to a high frequency of relatively

large particles at the impacted soil surface and in the runoff (Fig. 8) and to high MWD value (0.12 mm) of the sediments (Table 3). The clay contents of the non-phyllosilicate soils were relatively high (Table 1). Likewise, the particles at the crust in these soils were very small (~ 0.01 mm) (Fig. 6A), indicating that the aggregates at the surfaces of these soils were broken down into small particles. However, the MWD values in the runoff from these soils were relatively high, similar to that from the Netanya soil (Table 3). This suggests that in these soils, some of the aggregates at the soil surface were not broken down and/or were broken down to relatively large particles that were eroded with the runoff during the rainstorm.

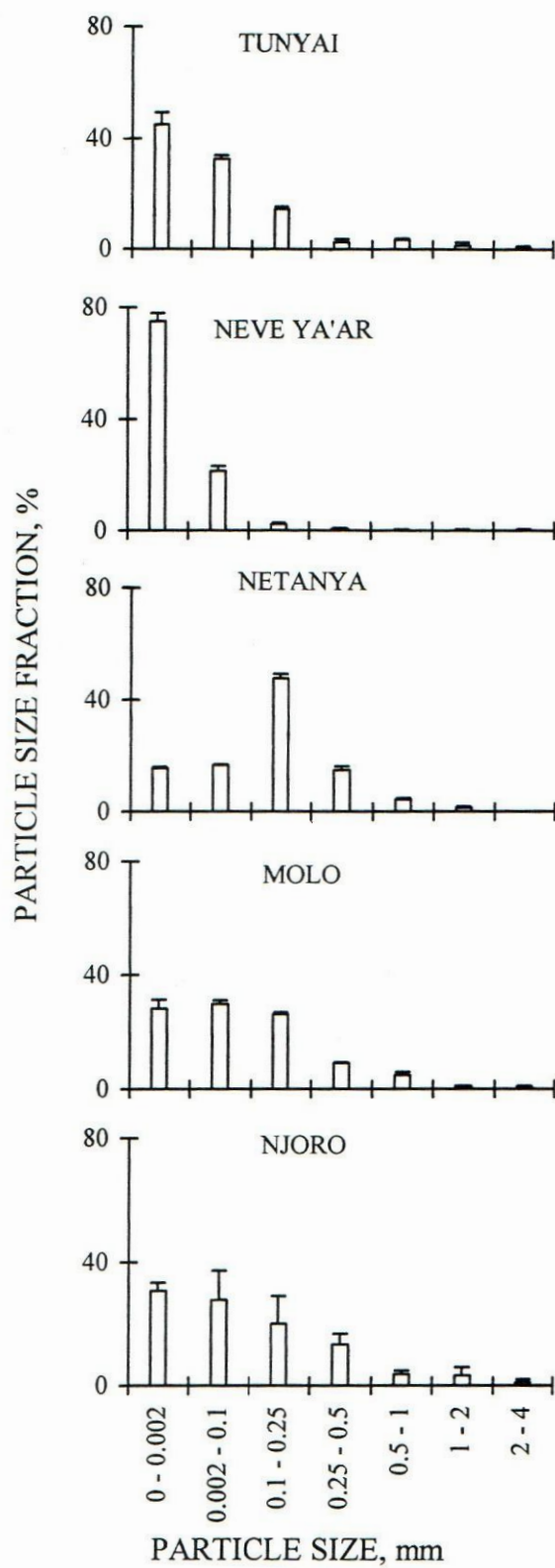


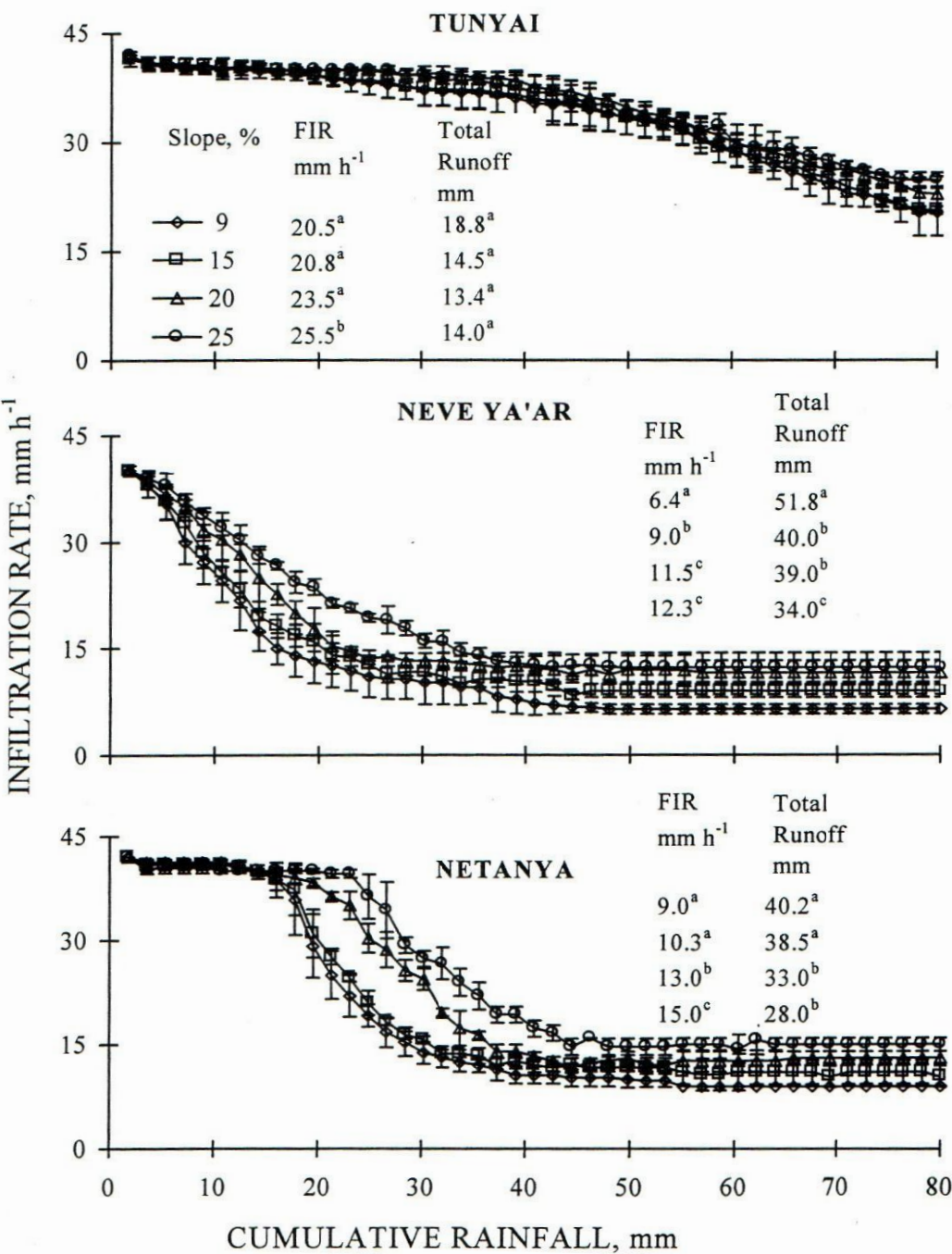
Fig.8: Particle size distribution of the sediments in the runoff for the various soils. Bars indicate standard deviation.

4.2. Soil Mineralogy and Texture Effects on Interrill Slope Factor

The IR values of Tunyai, Netanya and Neve Ya'ar soils at various slope gradients are presented in Fig. 9 as functions of cumulative rainfall. In these soils, the IR decreased with an increase of cumulative rainfall until a final IR was reached. This IR decrease was due to a seal formation at the soil surface as described in section 4.1. The studied soils were divided into two groups based on their mineralogy (section 4.1): (i) kaolinitic soil comprising the Tunyai soil; (ii) montmorillonitic soils comprising the Netanya and Neve Ya'ar soils.

In these two soil groups, the IR value, at certain cumulative rainfall depth, increased, in general, with an increase of the slope gradients (Fig. 9). Statistical analysis of the final IR values at the various slope gradient (Fig. 9) indicated that the soil with steeper slope gradient developed, in general, a seal with significantly ($\alpha = 0.05$) higher final IR. These differences in the final IR values were more pronounced in the montmorillonitic soils than in the kaolinitic soil (Fig. 9). The perpendicular component of the force of the raindrop impact on a soil surface decreases only slightly with an increase in slope gradient (from 1.0 at 5% slope to 0.96 at 30% slope) (Warrington *et al.*, 1989). Thus, the increase of the slope gradient should have minor effects on soil detachment, on aggregate breakdown at the soil surface and on seal formation. Poesen (1986) and Warrington *et al.* (1989) suggested that the increase in the final IR with an increase in slope gradient is associated with higher erosion of the soil seal during the rainstorm in the steeper slopes, which, in turn, decreases the seal thickness and increases the soil IR as the slope gradient increases. The higher increase of the soil loss rate with the increase of the slope gradient in Netanya and Neve Ya'ar soils than in Tunyai soil (Table 4) probably enhanced the erosion of the seals at the two former soils. This observation can also explain the higher increase

of their final IR in Netanya and Neve Ya'ar with an increase of the slope gradient



(Fig. 9).

Fig. 9. Infiltration rate as a function of cumulative rainfall for various slope gradients and soils. Bars indicate standard deviation and the different letter superscripts following the final infiltration rate

Table 4: Total soil loss for the entire rainstorm at various slope gradients and soils.

Slope gradient	Tunyai	Netanya	Neve Ya'ar
%	----- kg m ⁻² -----		
9	0.33 ^{a1*}	1.14 ^{b1}	1.24 ^{c1}
15	0.35 ^{a1}	1.52 ^{b2}	1.63 ^{b2}
20	0.42 ^{a2}	2.93 ^{b3}	2.53 ^{c3}
25	0.45 ^{a2}	3.46 ^{b4}	3.93 ^{c4}

*Different superscripts following the values indicate significant differences at $\alpha = 0.05$ among the soil loss values. The letter superscripts indicate significant differences between the soils for each slope gradient, and the digit superscript indicate significant differences between the slopes for each soil.

Slope factor values of kaolinitic (Tunyai) and montmorillonitic (Netanya and Neve Ya'ar) soils as a function of the sine of the slope angle (θ), assuming slope factor 1 for a 9% slope, are presented in Fig. 10. The slope factor values of the kaolinitic soil at slope gradient $> 9\%$ were lower than the corresponding values of the montmorillonitic soils (Fig. 10).

For the kaolinitic soil, the modified WEPP, Eq. [5] defines the slope factor, with significance at the 95% confidence level ($r^2 = 0.94$). In contrast, for Netanya and Neve Ya'ar soils, despite the considerable differences between their texture (Table 1), no significant differences were found between their slope factor values, and Eq. [6] defines their slope factor, with significance at the 95% confidence level ($r^2 = 0.96$). It can be concluded from these results that the slope factor was affected mainly by the soil mineralogy, and an increase in the soil dispersivity (presence of a smectite clay in the soil) increased the slope factor value. This conclusion is in agreement with the findings of Ben-Hur *et al.* (1992) and Ben-Hur and Aggassi (1997) who found different slope factor functions for various soils with different soil mineralogy.

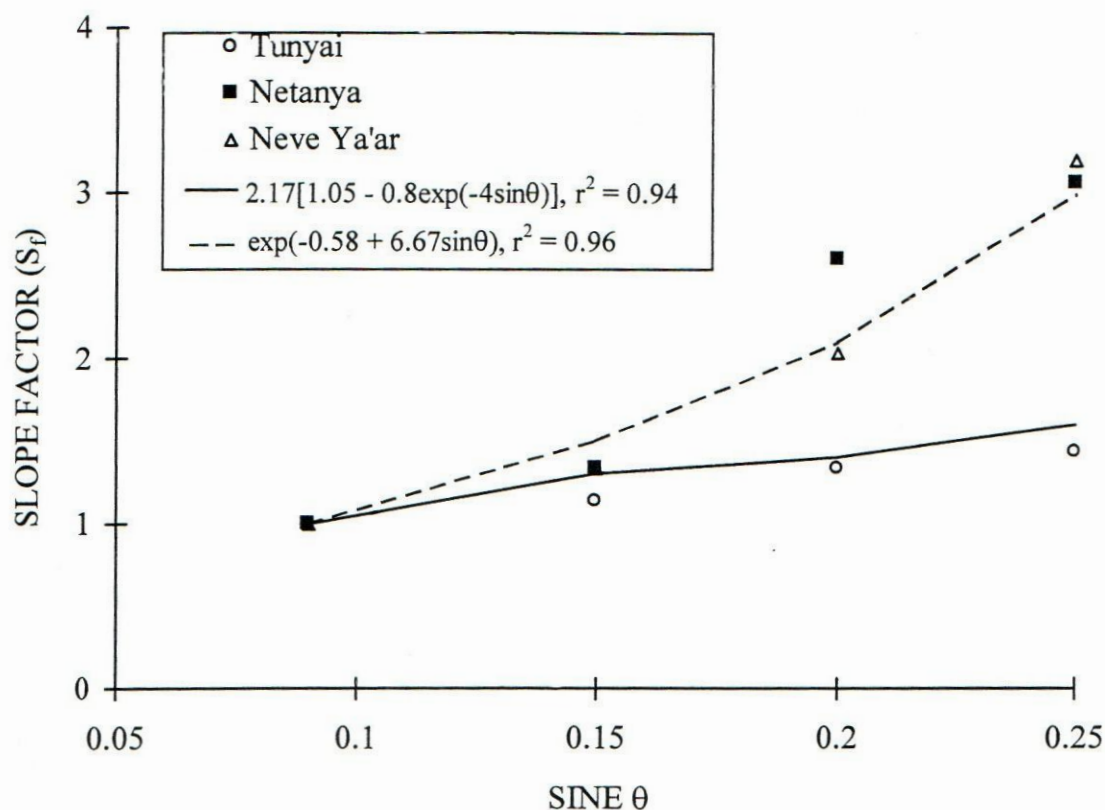


Fig. 10. Slope factor (S_f) as a function of the slope angle (Sine θ) for the various soils.

In the present study, the soil loss was determined in the runoff water only. Under these conditions, the transportation of the sediments was dependent mainly on the runoff characteristics and on the particle-size distribution at the impacted soil surface. Because the slope gradient has a minor effect on the raindrop impact, the soil detachment and the particle-size distributions on the impacted soil surface at the various slope gradients for each soil should be similar. In addition, the two main runoff characteristics that would affect the runoff transport capacity are (i) runoff rate and (ii) runoff velocity. Although an increase in slope gradient increases the runoff velocity, a small decrease of runoff rate was observed with the increase of the slope gradient in the three soils (Fig. 9). Moreover, the total runoff was relatively low (< 15.8 mm) in the kaolinitic soil, and

high in the montmorillonitic soils; > 28.0 mm in Netanya and > 34.0 mm in Neve Ya'ar (Fig. 9). It is suggested that the difference in the slope factor between the kaolinitic and montmorillonitic soils (Fig. 10) was because of the differences in the runoff transport capacity of these two soil groups as described below.

Small size particles (< 0.1 mm) are light and very transportable, and therefore, relatively large amount of these particles at the impacted soil surface would be transported with the runoff even at low (9%) slope gradient. In contrast, the coarse particles (> 0.1 mm) are heavier and less transportable. Consequently, it is expected that for a certain amount of runoff, the amount of increase of coarse particles in the runoff will be higher than for the small particles as the slope gradient increases.

The amount of the different particle sizes in the runoff and their MWD values for the various slope gradients and soils are presented in Fig. 11. At 9% slope, the < 0.1 mm eroded particle size was the dominant size in the clayey, Tunnyai and Neve Ya'ar soils, and the $0.1 - 0.25$ mm particle size in the sandy loam, Netanya soil (Fig. 11). In these three soils, an increase of the slope gradient increased more the amount of coarse particles in the runoff than that of the small particles (Fig. 11). This was observed from the higher MWD values at slope gradient $\geq 15\%$ than at 9% (Fig. 11). These results indicated that the increase of the slope gradient increases mainly the erosion of the coarse particles.

The increase in the amount of coarse particles in the runoff relative to the small particles with an increase of the slope gradient was significantly higher in the montmorillonitic soils but not in the kaolinitic soil. Within the smectitic group, the increase in the amount of coarse particles in the runoff relative to the small particles was significantly higher in the clayey soil (Neve Ya'ar) than in the sandy loam soil (Netanya) with an increase of the slope gradient (Fig. 11). For example,

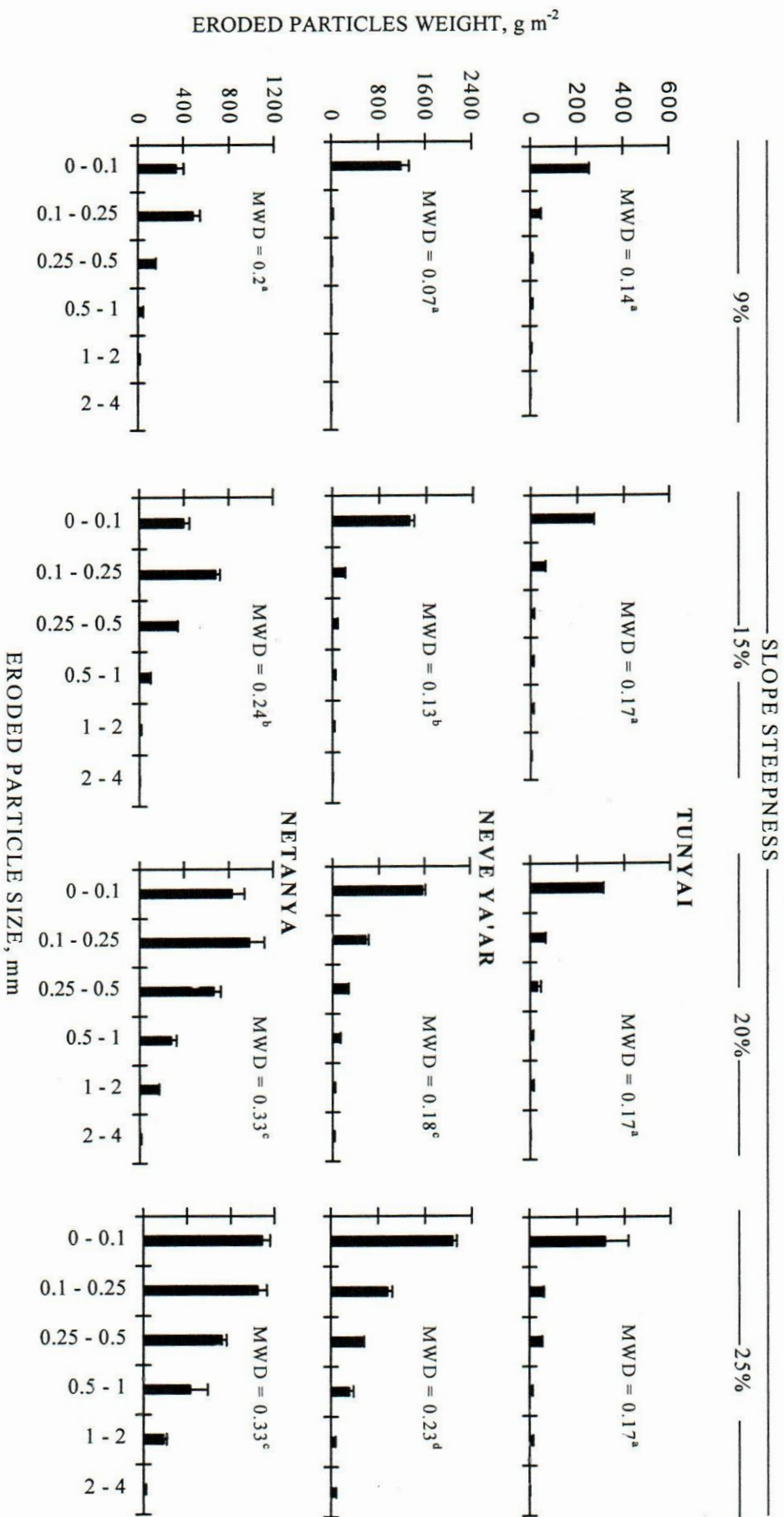


Fig. 11. The amounts of the different particles sizes in the runoff and their mean weight diameter (MWD) values for the various slope gradients and soils. The different letter superscript following the MWD values indicate a significant difference at $\alpha = 0.05$ among the slope gradients in each soil.

an increase of the slope gradient to 25% increased, on average, the amount of small particles for Tunyai, Netanya and Neve Ya'ar soils by 1.3, 3.2 and 1.7 times of that at 9% slope, respectively, and the coarse particles by 2.3, 9 and 43 times, respectively.

In the kaolinitic soil, the increase of the runoff velocity with the increase of the slope gradient, had probably limited affect on the runoff transport capacity because of the low total amount of the runoff (<15.8 mm, Fig. 9) obtained in this soil. Consequently, erosion of the coarse particles in this soil was also low even at steep slope gradients. In contrast, the total amount of runoff was relatively high in the montmorillonitic soils (>28.0 mm in Netanya and > 34.0 mm in Neve Ya'ar (Fig. 9)). In this case, the combination of high runoff rate and an increase of the runoff velocity increased sharply the erosion of the coarse particles with the increase of the slope gradient.

In order to determine the relationships between the particle size distribution in the runoff and the slope factor, a relative MWD (RMWD) value, which is the ratio of MWD value at any slope gradient to that at 9% slope, was calculated for the various slope gradients and soils. These RMWD values as a function of the corresponding slope factor values are presented in Fig. 12. A positive, linear regression significantly fitted these data points at the 99% confidence level ($r^2 = 0.78$). This positive regression indicated that an increase of slope factor was associated with higher increase of coarse particles erosion than of small particles.

It can be concluded from the results in Figs. 9, 11 and 12 that the higher slope factor values in the montmorillonitic soils than in the kaolinitic soil (Fig. 10) were a result of the higher runoff rate in the former soils than in the latter soil. The high runoff rate in the montmorillonitic soils increased significantly the transportation of the coarse particles from the impacted soil surface with the increase of the slope gradient. In

contrast, the low runoff rate in the kaolinitic soil limited this transportation of the coarse particles. Consequently, an increase of the slope gradient increased more sharply the slope factor in the montmorillonitic soils than in kaolinitic soil (Fig. 10).

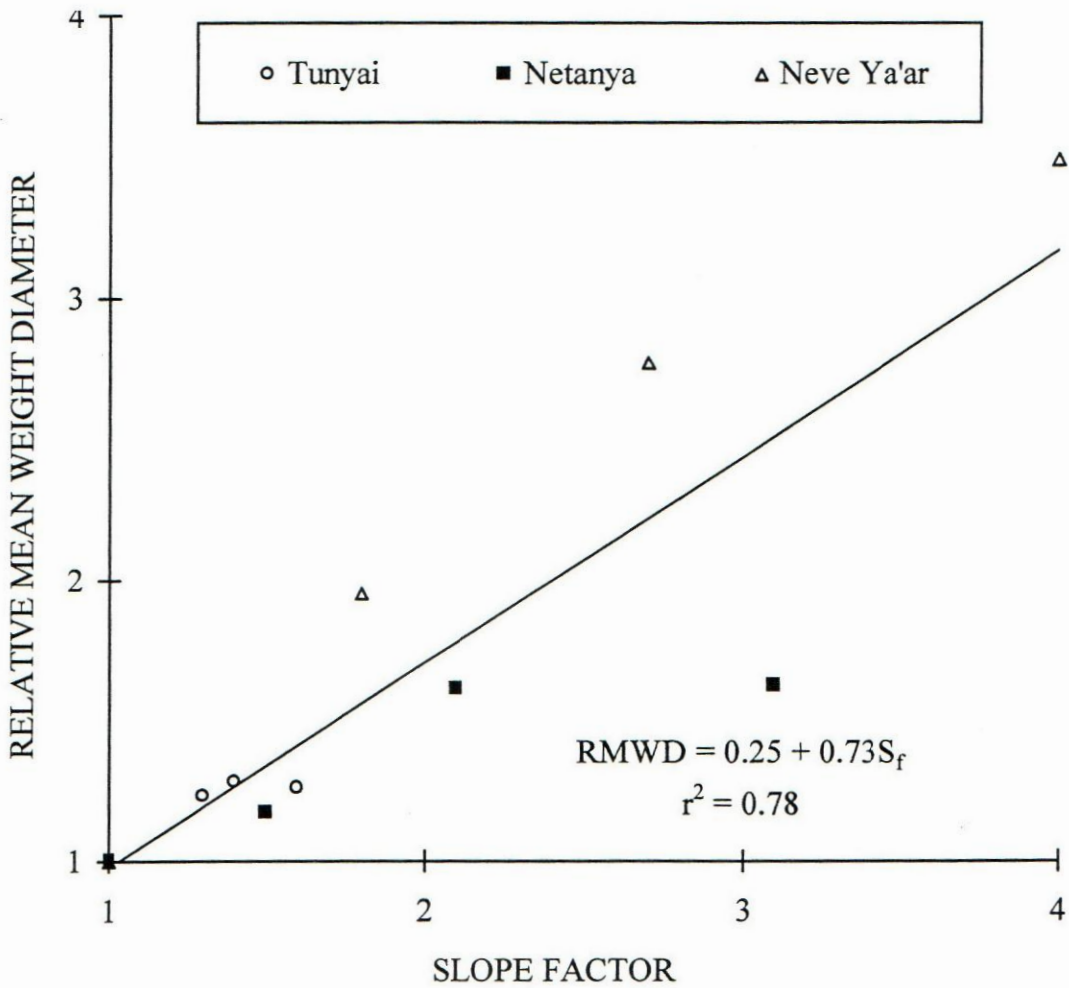


Fig. 12: Relative mean weight diameter (RMWD) values as a function of the sine of the slope factor (S_f).

4.3 Indigenous Soil and Water Conservation Techniques Effects on Runoff and Erosion and Crop Yields

The distribution of daily rainfall for the five consecutive rainy seasons at Tunyai is presented in Fig. 13. The pattern of rainfall distributions over the five seasons showed marked variations in both frequency of storms and amount of rainfall. There were 22, 60, 28, 18 and 16 rainy days, respectively, during the five consecutive rainy seasons. The two rainy seasons in 1997 showed a normal distribution pattern of daily rainfall. In the 1st season, a peak of 78-mm rainfall was reached on 12th April; the total rainfall in this season was 507 mm, which was 44% higher than the long-term average. In the 2nd season of 1997, daily rainstorms increased in magnitude as the season progressed and a peak of 91-mm rainfall was reached on 13th November. Daily rainstorms in this season were more frequent and many of them were heavier than in the preceding season. The total rainfall in this season was 1334 mm, which was 4.3 times more than the long-term average.

The daily rainfall distribution in the 1st season of 1998 exhibited an “M” pattern (Fig. 13). The two daily rainfall peaks were 94 mm on 20th March and 80 mm on 9th May. The total rainfall in this season was 611 mm, which was 73% higher than the long-term average. The total rainfall in the 2nd season of 1998 was 253 mm, which was similar to the long-term average value. In this rainy season, 79% of the rainfall fell in 14 out of the 18 rainy days in November, and two daily rainstorms occurred in December. The rainfall distribution in this season did not show a clear peak.

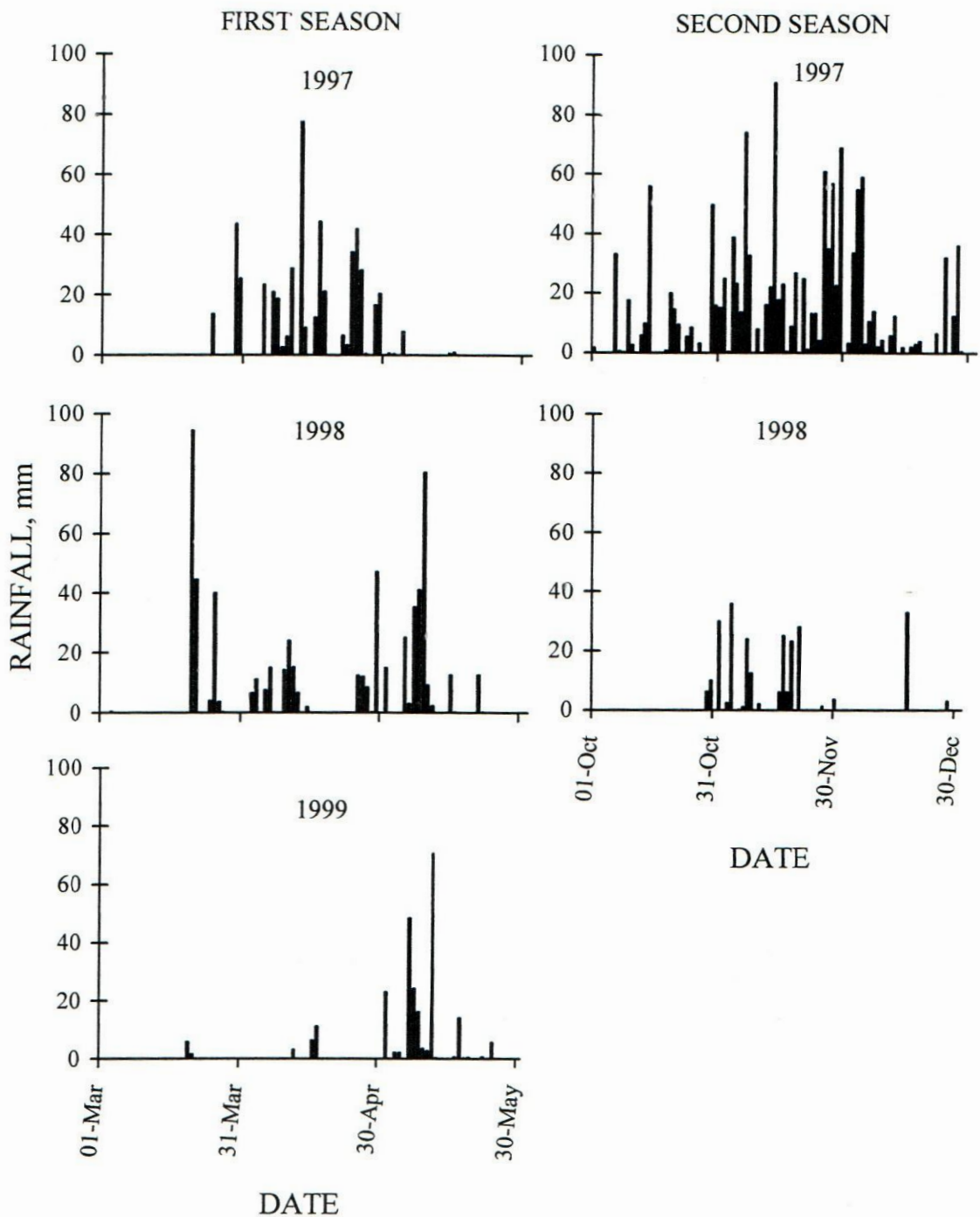


Fig. 13: Distribution of daily rainfall for five consecutive rainy seasons.

Rainfall distribution during the 1st season of 1999 was skewed towards the end of the season. There were two rainy days in March, three in April, and seven in May. Of the total seasonal rainfall 0.3% fell in March, 8.5% in April, and 88.2% in May. The total rainfall in this season

was 243 mm, which was similar to the long-term average. These significant variations in rainfall distribution among the various rainy seasons are typical of a semi-arid region.

Daily runoff for the various treatments during the five rainy seasons is presented in Fig. 14 as percentage of daily rainfall. In general, the changes in runoff percentage with time showed similar patterns in all the treatments. In most cases the runoff percentage in the control treatment was higher than those in the ISWC treatments (Fig. 14). These differences between the control and the ISWC treatments are discussed below.

Runoff was generated by 5, 6, 5, 2 and 2 storms, respectively, during the five consecutive rainy seasons, as shown in Fig. 14. Generally, daily runoff was associated with daily rainfall > 30 mm (Figs. 13 and 14). However in some days, rainfall > 30 mm did not generate runoff. For example, during the 2nd season in 1997, rainfall generated runoff in only six of the sixteen days in which it exceeded 30 mm. Subjecting the soil from the experimental site to simulated rainfall revealed that the infiltration rate of this soil decreased as cumulative rainfall increased, until a final infiltration rate of 20.5 mm h^{-1} was reached (Fig. 5). This decrease in the infiltration rate was because of the breakdown of the aggregates at the soil surface, and consequent seal formation (Duley, 1939). For the rainstorms > 30 mm that did not generate runoff, it is likely that the rainfall intensity of these rainstorms was lower than the infiltration rate and/or that the water storage capacity of the soil surface accommodated the water quickly to prevent runoff.

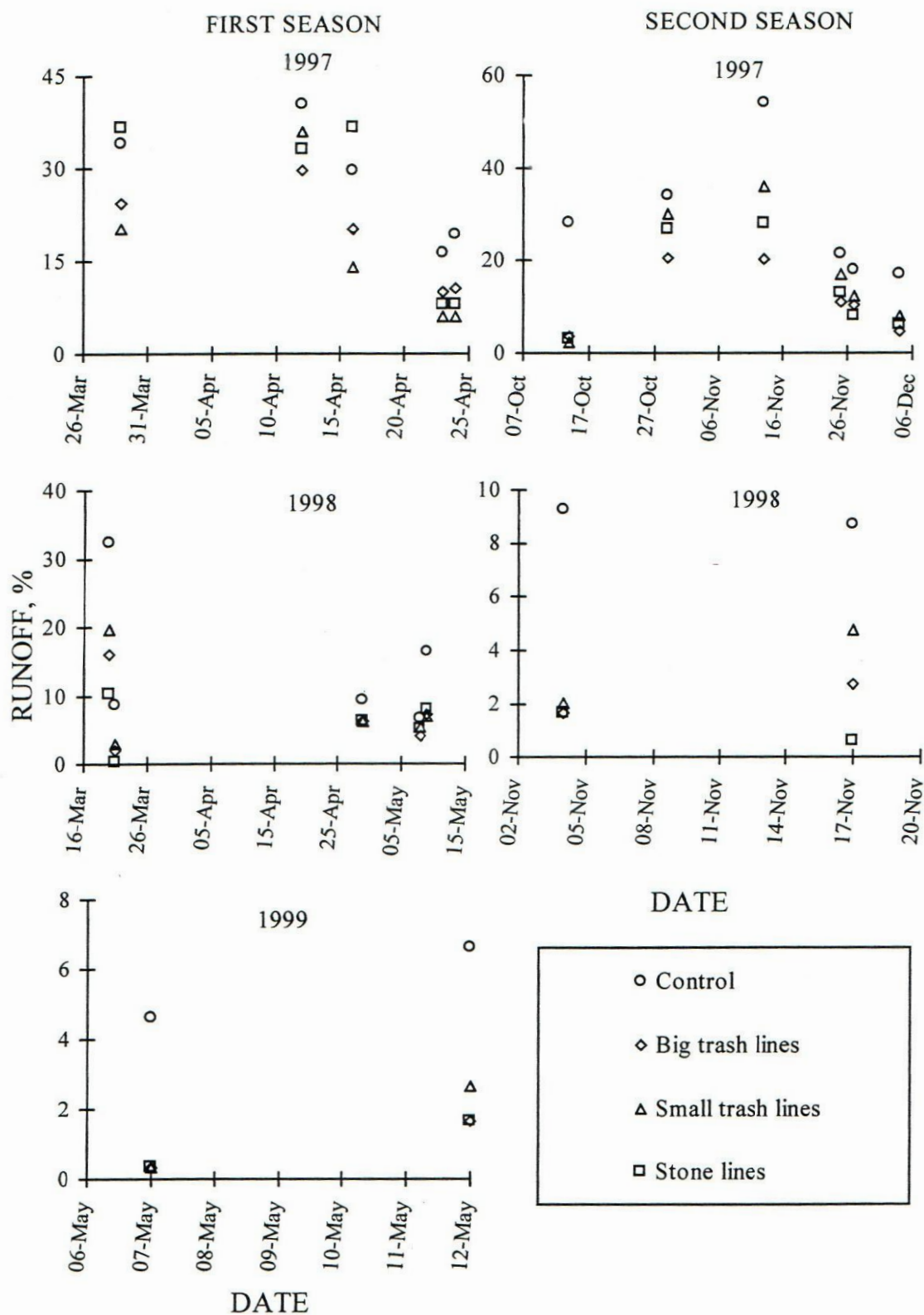


Fig. 14: Daily runoff as percentages of daily rainfall during the five rainy seasons and for the various treatments.

In the 1st season of 1997, the 1st rainstorm precipitated 13 mm of water, and the runoff occurred in the 2nd rainstorm of 43 mm (Figs. 13 and 14). The next rainstorm that generated runoff was on 4th April; the amount of rainfall of this rainstorm was 78 mm, which was the greatest in this season (Fig. 13). After that date the runoff percentage decreased, in general, with time. The rainstorms that generated runoff after 4th April precipitated 44, 34, and 42 mm and the runoff percentages that were obtained from these rainstorms in the control treatment were 30, 16 and 19%, respectively.

In the 2nd season of 1997, the first runoff was recorded on 14th October. On this day rainfall was 55 mm (Figs. 13 and 14). Before this rainstorm, a total of 77 mm of rainfall had fallen within 8 days without generating any runoff. The runoff percentage increased with time into the season. The highest runoff (54% in the control treatment) was obtained when a rainfall of 91 mm was received. This was the highest amount of rainfall during the season. Later in the season the runoff that was generated from the control treatment decreased gradually to 22, 18 and 17%, from rainstorms of 61, 57 and 59 mm, respectively.

In the 1st season of 1998, the highest runoff percentage (32% in the control treatment) was obtained from a day's rainfall of 94 mm. This was the 2nd rainstorm of this season (Figs. 13 and 14). A day later, a 45 mm rainstorm generated 9% runoff in the control treatment. After this rainstorm, no runoff was obtained for a long period although a total of 184 mm of rainfall fell within 17 days (Figs. 13 and 14). Only three rainstorms of 47, 36 and 80 mm that fell on 29th April and 7th and 9th May, respectively generated runoff in the remaining part of the rainstorms of that season. During these rainstorms runoff percentages in the control treatment were 9.3, 6.6 and 16.4%, respectively.

During the last two rainy seasons, runoff was generated by rainfall only 2 days (Fig. 14). In the 2nd season of 1998, in which the 1st rainstorm was on 29th October, these rainstorms occurred at the beginning of the crop-growing season (4th and 17th November) (Fig. 13). In contrast, the two rainstorms that generated runoff in the 1st season of 1999 fell towards the end of the crop-growing seasons, on 7th and 12th May.

In the 1st and 2nd seasons of 1997 and the 1st season of 1998, in which runoff was generated both at the beginning and at the end of the growing season, the runoff percentages in the control treatment early in the growing seasons were significantly higher than those generated towards the end of each season (Fig. 14). This occurred despite the fact that the rainfall amounts late in the growing season were similar to or greater than those at the beginning (Fig. 13). These differences in runoff percentages, between the beginning and the end of the growing season could be due to the effect of the crop canopy on seal formation. At the beginning of the growing season, the crop canopy was sparse and most of the soil surface was exposed. Under these conditions, the raindrop impact probably broke down the aggregates at the soil surface, thus forming a seal, which, in turn, decreased the infiltration rate and increased the runoff (Fig. 14). However, the drying of the seal between consecutive rainstorms broke down the crust, resulting in an increase in the soil infiltration rate (Ben-Hur *et al.*, 1985). In contrast, towards the end of the growing season, the crop canopy was extensive and most of the soil surface was covered and thus protected from the raindrop impact. In this case, the renewal of the seal and the resulting decrease in the infiltration rate were probably limited. This would explain the relatively low runoff percentages towards the end of the growing season (Fig. 14).

The seasonal rainfall depths, and the cumulative depths and percentages of the runoff in the various treatments during the five rainy

seasons are presented in Table 5. The runoff depth in the control treatment ranged from 6 mm in the 2nd season of 1998 to 115 mm in the 2nd season of 1997, and the runoff percentage in this treatment was highest (14.5%) in the 1st season of 1997 and lowest (2.5%) in the 2nd season of 1998. This wide variation of the runoff percentages among rainy seasons was most likely caused by the wide variation in the rainfall characteristics, such as rainstorm amount, intensity and frequency.

The BTL, STL and SL techniques significantly decreased the runoff compared with the control treatment in all the rainy seasons (Table 5). In most of the seasons the plots treated with the BTL technique had significantly ($\alpha < 0.05$) less seasonal runoff than the rest of the ISWC techniques that were studied. Likewise, the SL technique was, in general more efficient in decreasing the runoff than the STL technique (Table 5).

The mechanism that could account for the reduction of the runoff by the studied ISWC techniques is that both the trash and stone lines decreased the runoff velocity along the slope, thus, in turn, increasing the duration for infiltration and the amount of infiltrated water. Also, with the BTL and STL techniques, the trash that covered the soil surface reduced seal formation and increased the infiltration rate in the area beneath the trash; in these cases, the higher infiltration rate in the area beneath the trash decreased the total runoff from the treated plot. The lower runoff that was obtained with the SL technique than with the STL technique (Table 5) indicated that the STL were not efficient in decreasing the runoff velocity or in increasing the infiltration rate in the area below the trash. However, the larger size of the trash line in the BTL technique increased these efficiencies.

Table 5: Seasonal rainfall and runoff from various treatments in the five rainy seasons at Tunyai.

Season	Rainfall	Control		Big trash lines		Small trash lines		Stone lines	
	(mm)	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)
1 st 1997	507	73 ^{a*}	14.5	51 ^b	10	48 ^b	9.4	64 ^c	12.6
2 nd 1997	1334	115 ^a	8.6	46 ^b	3.7	71 ^c	5.3	57 ^d	4.2
1 st 1998	611	54 ^a	8.9	27 ^b	4.3	31 ^c	5.0	21 ^d	3.5
2 nd 1998	253	6 ^a	2.5	2 ^b	0.6	2 ^b	0.9	1 ^c	0.3
1 st 1999	243	7 ^a	2.9	1 ^b	0.5	2 ^b	0.8	1 ^b	0.5

* Different letter superscripts in each row indicate significant difference among treatments at $\alpha \leq 0.05$.

Seasonal soil losses in the various rainy seasons and under the various treatments are presented in Table 6. Soil loss in the control treatment was relatively high, ranging from 0.47 Mg ha⁻¹ in the 1st season of 1999 to 0.84 Mg ha⁻¹ in the 2nd season of 1997. All the ISWC techniques significantly decreased the soil loss compared with the control treatment during all the rainy seasons. The lowest soil loss in all the rainy seasons occurred with the BTL technique. However significant difference in soil loss were found between the STL and SL techniques except during the 2nd season of 1997 (Table 6). The average soil loss over the five rainy seasons was greater in the control treatment than in the BTL, STL and SL treatments by factors of 2.8, 2.1 and 2.2, respectively (Table 6). On the other hand, the average runoff over the five rainy seasons was greater in the control treatment than in the BTL, STL and SL treatments by factors of 2.0, 1.7 and 1.8, respectively (Table 5). These results indicate that the effect of the ISWC techniques in decreasing soil loss was not only by reduction of the surface runoff. Trapping of the sediments as the excess runoff passed through the trash and stone lines used in the ISWC techniques was probably another mechanism that decreased the soil loss.

Table 6: Seasonal soil loss (Mg ha⁻¹) for the various treatments in five rainy seasons at Tunyai.

Season	Control	Big trash lines	Small trash lines	Stone lines
1 st 1997	0.69 ^{a*}	0.26 ^b	0.44 ^c	0.42 ^c
2 nd 1997	0.84 ^a	0.43 ^b	0.53 ^c	0.36 ^d
1 st 1998	0.56 ^a	0.15 ^b	0.21 ^c	0.22 ^c
2 nd 1998	0.79 ^a	0.24 ^b	0.35 ^c	0.35 ^c
1 st 1999	0.47 ^a	0.09 ^b	0.10 ^b	0.14 ^c

*Different letter superscripts in each row indicate significant difference among treatments at $\alpha = 0.05$.

The yields of maize and cowpea grain and stover for the four treatments in five rainy seasons are presented in Table 7. Cowpea was grown as an intercrop only in the 2nd seasons of 1997 and 1998; therefore, Table 7 presents the cowpea yields only for these two seasons. The grain yield of maize in the control treatment ranged from 0.16 Mg ha⁻¹ in the 1st season of 1999, with seasonal rainfall of 243 mm, to 0.56 Mg ha⁻¹ in the 2nd season of 1997, when seasonal rainfall was 1334 mm (Tables 5 and 7). A similar trend was found in the stover yield of the maize in this treatment. The grain yields of cowpea in the control treatment were 0.44 and 0.56 Mg ha⁻¹ in the 2nd seasons of 1997 and 1998, respectively, and its stover yields in these seasons were 2.09 and 1.94 Mg ha⁻¹, respectively (Table 7).

Table 7. Seasonal yields (Mg ha⁻¹) of maize and cowpea under the various treatments in the five rainy seasons at Tunyai.

Season	Control		Big trash lines		Small trash lines		Stone lines	
	Grain	Stover	Grain	Stover	Grain	Stover	Grain	Stover
-----Maize-----								
1 st 1997	0.42 ^{a*}	1.25 ^a	0.74 ^b	2.10 ^b	0.54 ^a	2.02 ^b	0.48 ^a	1.92 ^b
2 nd 1997	0.56 ^a	1.42 ^a	1.22 ^b	4.20 ^b	0.84 ^c	3.82 ^c	0.89 ^c	3.65 ^c
1 st 1998	0.54 ^a	1.49 ^a	1.47 ^b	3.20 ^b	0.86 ^c	2.52 ^c	1.28 ^b	2.63 ^c
2 nd 1998	0.25 ^a	0.65 ^a	1.11 ^b	2.84 ^b	0.66 ^c	1.51 ^c	1.0 ^d	1.65 ^c
1 st 1999	0.16 ^a	0.67 ^a	0.42 ^b	0.86 ^b	0.46 ^b	0.84 ^b	0.41 ^b	0.9 ^b
-----Cowpea-----								
2 nd 1997	0.44 ^a	2.09 ^a	0.56 ^b	2.05 ^a	0.41 ^a	2.16 ^a	0.42 ^a	2.0 ^a
2 nd 1998	0.56 ^a	1.94 ^a	0.94 ^b	2.39 ^b	0.84 ^c	2.55 ^c	0.84 ^c	2.2 ^d

*Different letter superscripts in each row indicate significant difference among treatments at $\alpha \leq 0.05$ for grain or stover respectively.

The total crop biomass (grain plus stover of maize and cowpea) in the consecutive rainy seasons was 1.67, 4.51, 2.03, 3.43, and 0.83 Mg ha⁻¹, respectively, in the control treatment (Table 7). The rainfall efficiency, with

respect to water use, could be defined as the ratio between the crop biomass and the rainfall that was received during the growing season. In the control treatment, the rainfall efficiencies in the consecutive rainy seasons for the control treatment were 3.3, 3.4, 3.3, 13.5 and 3.4 Kg mm⁻¹, respectively. These results indicate that the rainfall efficiencies in the various rainy seasons were similar, except that in the 2nd season of 1998, which was much higher. This high rainfall efficiency in the 2nd season of 1998 despite the low amount of seasonal rainfall in this season (253 mm) was probably due to highly uniform distribution of the rainstorms, particularly in the early part of the growing season (Fig. 13). Apparently this ensured availability of enough water for the establishment and growth of plants in the critical stages.

All the ISWC techniques significantly increased the maize yield in all the rainy seasons except for the STL and SL techniques in the 1st season of 1997. The highest yield in all the rainy seasons, except the 1st season of 1999, was obtained with the BTL technique. However, no consistent differences in maize yield between STL and SL techniques were found. In contrast, the BTL treatment significantly increased the grain yield of cowpea in the two growing seasons. However its stover yield increased significantly only in the 2nd season of 1998. Likewise, the STL and SL techniques significantly increased the grain and stover yields of the cowpea in the 2nd season of 1998, but had no significant effect on the cowpea yield in the 2nd season of 1997.

The total biomass yields with the BTL technique in the consecutive rainy seasons were 1.7, 1.8, 2.3, 2.1 and 1.5 times, respectively, higher than those in the control treatment (Table 7). The same trend in the increase of the biomass yield relative to the control was found in the STL and SL treatments. These results indicate that the ISWC techniques were most effective in increasing yields in the 1st and 2nd rainy seasons of 1998. This

high effectiveness of the ISWC techniques was probably a result of the amount of the rainfall distribution, i.e, rainfall amount and intervals between the rainstorms, especially in the 1st and the 2nd rainy seasons of 1998.

A possible reason for the increased crop yields in the ISWC treatments would be the lower runoff in the plots where the ISWC techniques were applied, which in turn, increased the water infiltration in these plots (Table 5). Seasonal biomass yields as functions of the seasonal infiltrated water in the various treatments and rainy seasons, and the regression line between these variables are presented in Fig. 15. This figure indicates that the seasonal biomass increased linearly and significantly ($\alpha = 0.01$) with increasing water infiltration. The more the water infiltration, the more the water available for crop production, and the higher the yield. However, the scatter of the points around the regression line, especially for the low values of water infiltration, was relatively high (Fig. 15). This wide scatter of the points was a result of the effect of the rainfall distribution on the rainfall efficiency and of the effectiveness of the ISWC techniques in increasing the yield.

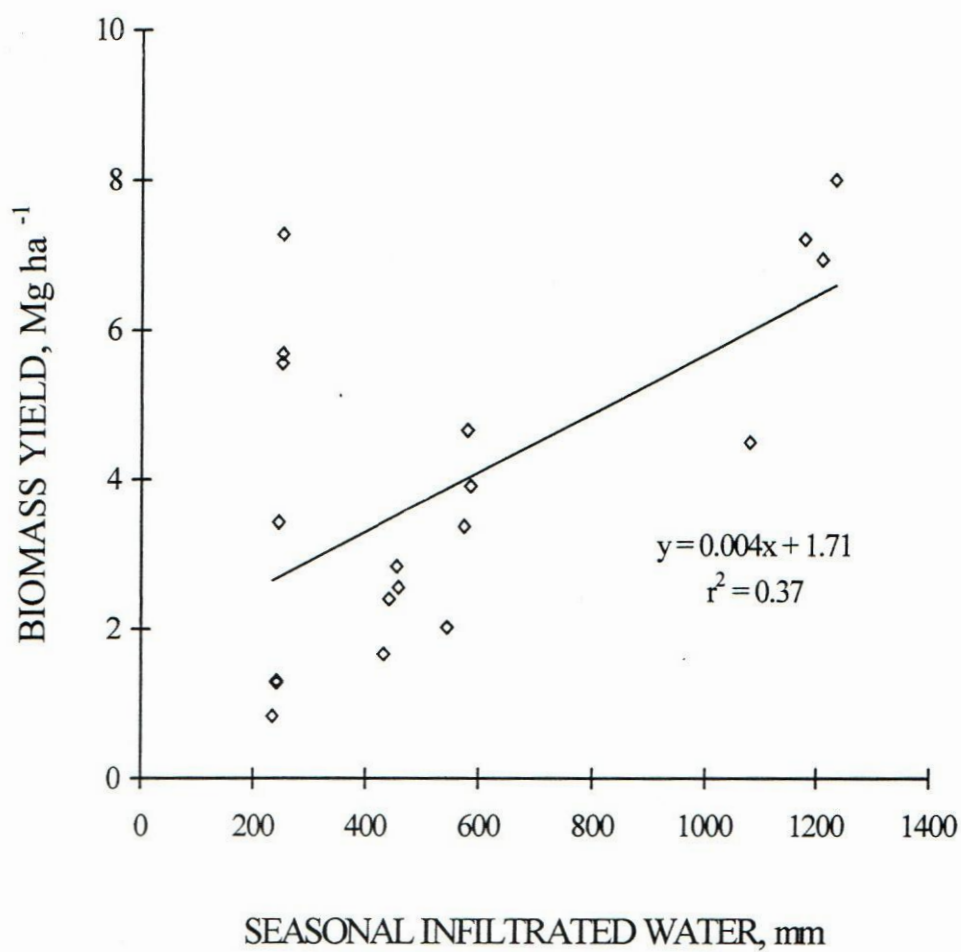


Fig. 15: Seasonal biomass yield as a function of the seasonal infiltrated water and the regression line for the various treatments and rainy seasons.

CHAPTER 5

5 Conclusions and Recommendations

The studied soils could be divided into three groups based on their aggregate stability, which are consistent with the measured soil loss rates. In contrast, the soils could be divided into two groups according to their IR values. The 1st group comprised only the kaolinitic soil, and its final IR was 20.5 mm h⁻¹. The 2nd group comprised the rest of the soils and their final IR values were < 9.3 mm h⁻¹. Scanning electron microscope observations indicated that the kaolinitic soil had a thin crust (~ 0.1 mm) containing large particles (~ 0.1 mm), while the montmorillonitic soils had thicker crusts (> 0.2 mm) comprising either small (~ 0.02 mm) particles with a well developed “washed in” zone underneath, or large (~ 0.2 mm) ones with fine material between them. Crust layer in the non-phyllosilicate soils was ~ 0.2 mm and composed of fine particles ~ 0.01 mm. The high aggregate stability and the low dispersivity of the kaolinitic soil, which decreased the soil detachment, and its low runoff, which decreased the transport capacity, limited the soil loss to 0.33 kg m⁻². The low aggregate stability and high runoff of the montmorillonitic soils contributed to their soil losses of 1.24 and 1.14 kg m⁻². The intermediate aggregate stability and the high runoff of the non-phyllosilicate soils accounted for their intermediate soil losses of 0.75 and 0.8 kg m⁻².

The slope factor values of the kaolinitic soil at slope gradient > 9% were lower than the corresponding values of the montmorillonitic soils. The S_f values could significantly be predicted for the kaolinitic soil using the equation:

$$S_f = 2.17[1.05 - 0.85\exp(-4\sin\theta)]$$

where θ is slope angle in degrees, and for the montmorillonitic soils using the equation:

$$S_f = \exp(-0.58 + 6.67\sin\theta).$$

This was despite the considerable differences in the texture of the two montmorillonitic soils. The above results indicated that the slope factor was affected mainly by the soil mineralogy, and an increase in the soil dispersivity (presence of a smectite clay in the soil) increased the slope factor value.

A positive linear regression significantly fitted the relation between the RMWD values and the corresponding slope factor values at 99% confidence level ($r^2 = 0.78$). This indicated that an increase of slope factor was associated with higher increase in erosion of coarse particles than of small ones. It was concluded that the higher slope factor values in the montmorillonitic soils than in the kaolinitic soil was a result of the high runoff rate in the former soils than in the latter soil. The high runoff rate in the montmorillonitic soils increased significantly the transportation of the coarse particles from the impacted soil surface with the increase of the slope gradient. In contrast, the low runoff rate in the kaolinitic soil limited this transportation of the coarse particles. Consequently, an increase of the slope gradient increased more sharply the slope factor in the montmorillonitic soils than in kaolinitic soil.

In the field experiment, runoff was generally associated with daily rainstorms >30 mm. The impact energy of the raindrops probably broke down the aggregates at the soil surface and consequently formed a seal that decreased the infiltration rate of the soil and increased the runoff. In the rainstorms >30 mm that did not generate runoff, it is likely that the rainfall intensity of these rainstorms was low and below the infiltration rate and/or that the water storage capacity of the soil surface was able to absorb water sufficiently quickly to prevent runoff.

In this study, the amount of runoff in the control treatment were significantly higher in the early part of the growing seasons than towards

the end. This was apparently because early in the growing season, the crop canopy was sparse and most of the soil surface was bare and exposed to the impact of the raindrops that formed a seal and led to a low infiltration rate. In contrast, towards the end of the growing season, the crop canopy was dense, and so protected the soil surface from impacts and limited the renewal of the seal and the consequent decrease in infiltration rate and increase of the runoff.

The BTL, STL and SL techniques, with 2-m space between the trash or stone lines, significantly decreased the runoff compared with the control treatment in all the five rainy seasons. The seasonal average runoff amount for the five successive rainy seasons, was 25, 31, 29 and 51 mm, for BTL, STL, SL and Control respectively. These treatments probably decreased the runoff velocity along the slope, which in turn, increased the duration of infiltration and the amount of infiltrated water. Also, the trash used in the BTL and STL techniques limited the seal formation in the area beneath the trash, which led to increased infiltration and decreased runoff. The BTL, STL and SL techniques significantly decreased the soil loss. The seasonal average soil loss, was 0.23, 0.33, 0.3, and 0.67 Mg ha⁻¹ for BTL, STL, SL and Control respectively. Therefore the trash and stone lines were effective in reducing runoff and in trapping the sediments.

All the ISWC techniques increased the crop yield significantly. The seasonal average biomass yield for each treatment was 4.8, 4.0, 4.0 and 2.5 Mg ha⁻¹, for BTL, STL, SL and Control respectively, in the successive seasons. The seasonal biomass yield increased linearly and significantly ($\alpha = 0.01$) with increasing water infiltration. This indicated that the greater the amount of infiltrated water, the greater the amount of water available for crop production and, hence, the greater the yield.

It is recommended that more work should be done to quantify the relationship between particle rearrangement, crust thickness, infiltration and

erosion at the impacted soil surface. The role of non-phyllosilicate clays in seal formation and their effects on the slope factor should also be investigated further. Practical quantitative functions relating seal formation and indigenous soil and water conservation techniques should be developed.

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Appendices

Appendix 1. Infiltration rate (mm h^{-1}) as a function of cumulative rainfall for the various studied at 9% slope gradient

Cumulative Molo 9%					Njoro 9%			Tunyai 9%				Natanya 9%				Neve-Ya'ar, 9%		
Rain, mm	REP 1	REP 2	REP 3		REP 1	REP 2	REP 3	REP 1	REP 2	REP 3	REP 4	REP 1	REP 2	REP 3	REP 1	REP 2	REP 3	
1.78	42	42	42	42	42	42	42	42	42	42	42	42	42	42	39.6	39.6	40.8	
3.56	21.6	21.6	21.6	29.4	28.8	32.4	40.8	40.8	39.6	42	41.4	41	41.4	36	39	39		
5.33	18	19.8	21.6	29.4	28.2	32.4	40.8	40.8	39.6	42	41.4	41	41.4	33	37.2	36		
7.11	18	18.6	20.4	27	25.8	32.4	40.2	40.2	39.6	42	41.4	41	41.4	27	30	33		
8.89	18	18.6	19.2	24	21.6	28.8	40.2	40.2	39.6	42	41.4	41	41.4	24	27.6	30		
10.67	17.4	18	18.6	22.2	20.4	25.8	40.2	40.2	38.4	42	41.4	41	41.4	21.6	24.6	27.6		
12.44	16.8	17.4	18	19.8	19.8	22.8	40.2	40.2	38.4	41.4	40.2	41	41.4	18	21	26.4		
14.22	15.6	16.2	16.8	19.5	15.6	19.2	40.2	40.2	38.4	40.8	39	41	39.6	15	16.8	20.4		
16.00	15	15	17.4	18.6	15	18	39.6	40.2	38.4	39.6	36	41	39	13	14.4	17.4		
17.78	13.8	14.4	14.4	17.4	14.4	15.6	39.6	40.2	38.4	39	30	39	38.4	12	12.6	17.4		
19.56	13.8	13.8	13.8	13.8	13.8	15.6	39.6	40.2	38.4	38.4	24	32.4	31.2	10.8	12	16.8		
21.33	13.2	13.8	13.8	13.2	13.2	15.6	39.6	39.6	37.8	37.8	21	27	27	10.2	11.4	16.2		
23.11	13.2	13.2	13.8	15	12.6	15	39.6	39.6	37.8	36.6	18.6	23.4	24	9.6	10.8	15		
24.89	12.6	13.2	12.6	12	12	15	39.6	39.6	37.8	36	17.4	19.8	20.4	9	9.6	14.4		
26.67	12.6	12.6	12.6	12	11.4	14.4	39	39.6	37.8	35.4	14.4	17.4	18.6	9	9	13.8		
28.44	12.6	12	12	11.4	10.8	14.4	39	39	37.2	35.4	13.2	15.6	17.4	9	9	13.8		
30.22	12	12	12	10.8	10.8	13.8	39	39	36	34.8	12	14.4	15	8.4	8.4	13.8		
32.00	12	11.4	11.4	10.8	10.8	12	39	38.4	36	34.8	12	12.6	15	8.4	8.4	13.8		
33.78	11.4	10.8	10.8	10.8	10.8	12	39	38.4	36	34.2	11.4	12	13.8	8.4	7.8	12.6		
35.56	11.4	10.8	10.8	10.2	10.8	11.4	39	38.4	36	34.2	11.4	11.4	13.2	8.4	7.8	12		
37.33	10.8	10.8	10.8	9.6	10.2	10.8	39	38.4	34.8	34.2	10.2	10.8	13.2	6.6	7.2	10.8		
39.11	10.2	10.2	10.2	9.6	9.6	10.8	37.8	38.4	34.2	34.2	9.6	10.2	12	6.6	6.6	10.2		
40.89	10.2	10.2	10.2	9.6	9	10.2	37.8	36.6	33.6	33.6	9.6	10.2	12	6.6	6	9		
42.67	10.2	10.2	10.2	9	9	10.2	37.8	36.6	33	33.6	9.6	10.2	12	6.6	6	8.4		
44.44	9.6	9.6	9.6	9	9	9.6	37.8	37.2	32.4	33.6	9	10.2	11.4	6.6	6	7.8		
46.22	9.6	9.6	9.6	9	9	9.6	37.8	36	31.2	33.6	9	10.2	11.4	6.6	6	7.2		
48.00	9.6	9.6	9.6	9	8.4	9.3	36.6	35.4	31.2	33	9	10.2	11.4	6	6	7.2		
49.78	9.6	9.6	9.6	8.4	8.4	9.3	36	34.2	30.6	33	9	9.6	11.4	6	6	7.2		
51.56	9.3	9.3	9.3	8.7	7.8	9	36	33.6	30	33	9	9.6	10.8	6	6	7.2		
53.33	9.3	9.3	9.3	8.4	7.8	9	34.2	33.6	29.4	33	9	9.6	10.8	6	6	7.2		
55.11	9.3	9.3	9.3	8.4	7.8	8.7	34.2	32.4	28.8	32.4	9	9	9	6	6	7.2		
56.89	9.3	9.3	9.3	8.4	7.5	8.7	33	30	28.2	31.8	9	9	9	6	6	7.2		
58.67	9.3	9.3	9.3	8.4	7.5	8.7	31.8	27.6	27.6	31.2	9	9	9	6	6	7.2		
60.44	9.3	9.3	9.3	8.4	7.5	8.4	31.2	27	27	30.6	9	9	9	6	6	7.2		
62.22	9.3	9.3	9.3	8.4	7.5	8.4	27.6	26	27	30	9	9	9	6	6	7.2		

64.00	9.3	9.3	9.3	8.4	7.5	7.8	27.6	24.6	26.7	29.4	9	9	9	6	6	7.2
65.78	9.3	9.3	9.3	7.8	7.5	7.8	27.6	22.8	25.8	28.2	9	9	9	6	6	7.2
67.56	9.3	9.3	9.3	7.8	7.5	7.8	27	21.6	25.2	27	9	9	9	6	6	7.2
69.33	9.3	9.3	9.3	7.8	7.5	7.8	26.7	20.4	24.6	25.8	9	9	9	6	6	7.2
71.11	9.3	9.3	9.3	7.8	7.2	7.8	23.4	20.4	24.6	24	9	9	9	6	6	7.2
72.89	9.3	9.3	9.3	7.8	7.2	7.8	23.1	20.4	23.7	24	9	9	9	6	6	7.2
74.67	9.3	9.3	9.3	7.8	7.2	7.8	22.2	19.8	23.7	24	9	9	9	6	6	7.2
76.44	9.3	9.3	9.3	7.8	7.2	7.8	20.4	18.6	22.8	24	9	9	9	6	6	7.2
78.22	9.3	9.3	9.3	7.8	6.6	7.8	18.6	16.8	22.8	24	9	9	9	6	6	7.2
80.00	9.3	9.3	9.3	7.8	6.6	7.8	18.6	16.8	22.8	24	9	9	9	6	6	7.2

Appendix 2. Aggregate size distribution (g) of the various soils before the rainstorm at 9% slope gradient.

Soil		Size, mm						Sample g
		0 - 0.1	0.1 - 0.25	0.25 - 0.5	0.5 - 1	1 - 2	2 - 4	
Tunyai	Rep 1	4.1	5	8.7	8.3	6.5	7.4	40
	Rep 2	4.35	5.38	8.3	7.73	6.75	7.49	40
	Rep 3	4.1	5.32	7.73	8.07	6.79	7.99	40
Molo	Rep 1	6.98	7.57	7.79	7.82	5.33	4.51	40
	Rep 2	7.15	7.24	7.64	8.17	5.5	4.3	40
	Rep 3	6.9	7.51	7.78	8	5.3	4.51	40
Njoro	Rep 1	7.45	6.64	5.85	6.15	6.82	7.09	40
	Rep 2	7.31	6.7	6.09	6.09	6.7	7.11	40
	Rep 3	6.98	6.98	5.87	6.17	6.9	7.1	40
Netanya	Rep 1	2.54	24.24	6.81	2.9	3.4	0.11	40
	Rep 2	2.03	24.43	7.12	3.05	3.26	0.11	40
	Rep 3	1.83	24.57	7.31	3.15	3.04	0.1	40
Neve Ya'ar	Rep 1	1.01	3.29	5.47	8.89	9.74	11.6	40
	Rep 2	1.02	3.26	5.51	8.57	10.2	11.44	40
	Rep 3	0.88	3.05	5.29	9.36	10.38	11.04	40

Appendix 3. Distribution of particles (g) in the runoff for the various soils at 9% slope gradient.

Size, mm		0 - 0.002	0.002 - 0.1	0.1 - 0.25	0.25 - 0.5	0.5 - 1	1 - 2	2 - 4
Tunyai	Rep 1	22.22	16	7	1	1.86	1.02	0.5
	Rep 2	23.71	15	6.72	1.01	1.5	0.06	0
	Rep 3	18.7	15.78	7.17	1.73	1.64	0.92	0.46
Molo	Rep 1	32.97	30.82	28.08	10	5.6	1.24	1.09
	Rep 2	33.43	34.35	29.47	10	4.28	1.14	1.13
	Rep 3	29.08	36	31.51	11	7	1.21	1
Njoro	Rep 1	35.92	44.12	13	10.69	5.84	3.45	1.37
	Rep 2	32.78	28.73	34.73	18.54	3.23	1.07	0.13
	Rep 3	40.8	25.88	24.73	18.89	3.73	7.43	2.54
Natanya	Rep 1	28.44	29.3	88.22	23.78	8.56	1.64	0.05
	Rep 2	26.41	28.1	78.96	27.73	6.22	2.94	0.05
	Rep 3	24.44	27.01	76.54	23.77	6.76	2.13	0.04
Neve Ya'ar	Rep 1	127.92	31.83	2.8	1	0.3	0.1	0.05
	Rep 2	139.8	40	4.5	1	0.5	0.1	0.5
	Rep 3	150.34	48	5.46	2	1	1	1

Appendix 4. Soil loss (g) from the various soils at various slope gradients.

Particle Size, mm	Soil								
	Tunyai			Netanya			NeveYa'ar		
	Rep1	Rep2	Rep3	Rep1	Rep2	Rep3	Rep1	Rep2	Rep3
0 - 0.1	38.22	37.11	35.48	59.24	51.71	38.95	159.75	179.8	198.34
0.1 - 0.25	7	6.72	7.38	83.72	69.32	66.54	2.8	4.5	5
0.25 - 0.5	1	1.01	1.93	21.04	24.53	20.97	1	1	2
0.5 - 1	1.86	1.5	1.64	7.33	6.22	5.96	0.3	0.5	1
1 - 2	1.02	0.06	0.92	1.64	2.94	1.33	0.1	0.1	1
2 - 4	0.5	0	0.46	0.05	0.05	0.04	0.5	0	0.46
Total	49.6	46.4	47.81	173.02	154.77	133.79	164.45	185.9	207.8
15%									
0 - 0.1	39.8	40.5	37.7	50.94	62.64	65.8	196.2	209.35	184.53
0.1 - 0.25	8.7	9.5	7.2	97.5	109.72	99.67	20.89	32.5	27.1
0.25 - 0.5	1.56	1.76	2.28	51.5	52	51.79	13.8	6.6	10.4
0.5 - 1	1.73	1.68	2.13	11.31	15.41	12.81	4.5	5	8.73
1 - 2	1.78	1.64	1.13	3	2	1.14	2.5	3.5	4.8
2 - 4	0.5	0	0.5	0.5	0	0.5	1	1	1.5
Total	54.07	55.08	50.94	214.75	241.77	231.71	238.89	257.95	237.06
20%-									
0 - 0.1	47.1	45	43.8	105.8	135.7	133.33	225.6	239.1	240.7
0.1 - 0.25	8.6	10.2	8.7	129.58	145.9	169.2	84.44	74.74	94
0.25 - 0.5	2.24	6.6	5.3	101.16	108.79	89.59	33.1	41.66	36.2
0.5 - 1	1.97	1.71	1.97	35.34	50.4	39.8	15.7	17.4	21.2
1 - 2	2.3	1.59	1.91	25.55	23.61	26.07	2	4.3	7
2 - 4	0.5	0.1	0.46	1	2	1	4.3	3.6	2
Total	62.71	65.2	62.14	398.43	466.4	458.99	365.14	380.8	401.1
25%									
0 - 0.1	31.2	53.4	58.9	168.88	150.2	169.01	319.6	313.26	300.26
0.1 - 0.25	8.2	9.2	8.4	170.48	155.01	146.02	130.9	155.3	143.2
0.25 - 0.5	5.6	6.9	8.4	110.1	112.19	100.2	74.9	72.2	84.9
0.5 - 1	1.91	1.88	1.98	37.8	76.3	79.65	57.8	37.59	45.2
1 - 2	1.64	2.21	2	26.1	23.28	32.6	11.5	11	9.1
2 - 4	0.1	0.1	0.2	2	0.6	3.8	2	2	15
Total	48.65	73.69	79.88	515.36	517.58	531.28	596.7	591.35	597.66