MANAGEMENT FINAL

Covering Period: June, 1992 - July, 1995

Submitted to the Office of the Science Advisor
US Agency for International Development

Title: **INFILTRATION, RUNOFF AND EROSION IN SEMI-ARID SOILS**

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Project Number: C11-255

Grant Number:

A.I.D. Grant Project Officer: Dr. John Daly

Project Duration: November, 91 - October, 95

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Executive Summary

In arid and semiarid lands (ASAL) of Kenya, unreliable rainfall and problem soils constitute major constraints to crop and fodder production. The rainfall is often low and poorly distributed, occurs in high intensities of short duration and is highly erosive. The problems associated with the dominant soils of the area include structural instability, strong soil crusting and hard setting and high erodibility. When exposed to erosive rainstorms, the soils generate high amounts of runoff and soil loss and have low infiltrability.

The effectiveness of any land management option in runoff control was studied in relation to how such a practice alters, or maintains, the infiltration characteristics of the soils and/or the factors influencing the infiltration process. The information thus gained then becomes valuable input into water balance/crop yield prediction models.

In field experiments in Katumani, Kenya, the effect of surface cover, tillage and organic manuring on rain infiltration, runoff yields and soil loss were measured. Runoff yield and soil loss decreased with increase in surface cover. Mulch (with surface contacts) cover was more effective than canopy cover provided by growing crops. The effects of low rate of cover was more dramatic in soil loss reduction than in runoff reduction. Soil tillage and farmyard manure application also had a significant effect on soil macrostructure (cloddiness), soil aggregation, crusting, infiltration and soil losses.

Much work has been done in ASAL of Kenya and throughout the world on soil and water conservation for crop and fodder production without enough proper understanding of the basic soil processes influencing seal formation runoff and erosion. These properties were often considered to depend on basic soil properties such as soil texture, clay mineralogy, composition of exchangeable cations (e.g. ESP), organic matter and sesqioxides content etc., and this approach is reflected in manuscripts 1-4 of this report. However, the limited success in predicting infiltration runoff and erosion under natural conditions from laboratory and simulated rain experiments led to the realization

that these properties depended also on time dependent variables, such as antecedent water content, the rate of soil wetting and duration of aging (manuscript #5). Slow wetting by low intensity rain (<1-5 mm h^{-1}) reduced aggregate slaking and soils' susceptibility to seal formation under high intensity (30 $mm.h^{-1}$) rain. Aging (increasing the time, in hours, between prewetting and the high intensity rain) increased the cohesive forces between soil particles and reduced runoff and erosion. Similarly, different tillage operations lead to different aggregate sizes and aggregate size affects the rate of seal formation, but not the equilibrium infiltration (manuscript #6).

The realization of the importance of time-dependent variables in seal formation, runoff and erosion should be further studied and will lead to better infiltration models and soil treatments leading to water conservation.

4) Research Objectives

The general objectives of this research project was the improvement of water management in ASAL of Kenya in order to stabilize and increase crop production and to avoid soil erosion by water.

Specific objectives were:

1) To measure infiltration, runoff and erosion from few dominant soils in ASAL of Kenya. To evaluate the role of soil crusting (sealing) in determining runoff and erosion and to relate these parameters to soil properties.
2) To study the effect of plant cover (crops canopy, mulch) and organic residues on crust formation, runoff and erosion.
3) To study the effect of cultivation methods (conventional, no-till, tied ridges, microbasins) on runoff and yield
4) To develop a model which predicts seal formation runoff and erosion from soil properties.

Many water conservation and soil erosion prediction projects are being carried out in Kenya and throughout the world (including the WEPP project in USA). The ability to predict runoff and erosion in field experiments exposed to natural rain

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has been limited. Many of the contradictory results on the effect of soil and rain properties, cultivation plant cover and soil treatments on runoff, erosion and crop yield stem from our limited understanding of the processes involved in rain infiltration runoff and erosion. In this project we realized the importance of time-dependent variables, such as prewetting rate antecedent moisture content, aging, etc. in stabilizing aggregates and controlling runoff and erosion. The effect of time-dependent parameters on runoff and erosion is difficult to control and measure in field experiments and therefore these variables were not considered. It should be emphasized that the role of time-dependent variables in controlling runoff and erosion is often more important than the effect of the basic soil properties (such as texture, clay mineralogy, ESP, etc.)

5) Methods and Results

A. KENYA

The Kenyan collaborators summarized their 3-years results in the following two reports:

1) E.K. Biamah. July, 1995. Infiltration, runoff and erosion of semiarid soils in Kenya - Report of Microplot experimental research at the National Dryland Research Center, Katumani, Machakos, Kenya (62 pages + appendices).
2) G.E. Okwach. 1995. Infiltration, runoff and soil erosion in semiarid soils in Kenya - Report of the Katumani Macro-Plots Component of USAID-CDR Research Program (61 pages).

The Methods and Results section of these reports follows. the full reports are included in the Appendices (Report Nos. 1 and 2).

1) E.K. Biamah - Microplots experiments (Report No. 1)

Experimental Methodology

1. Experimental Procedure

This experiment was based on a completely randomized design. Each block was representative of the soil type and consisted of four treatments: conventional tillage (CT) using a forked hoe, zero tillage (ZT) with no manure, conventional tillage with 5

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tonnes/ha of farmyard manure (5 FYM), conventional tillage with 10 tonnes/ha of farmyard manure (10 FYM). Each treatment was replicated three times resulting in a total of 12 runoff plots for the experiment. In each plot, infiltration and hydraulic conductivity, profile soil moisture, penetration resistance, shear strength measurements were taken using a disc permeameter, neutron probe, cone penetrometer and shear vane apparatus, respectively. Profile soil moisture was monitored in each plot through two access tubes installed 30 cm from each plot end and to a maximum depth of 120 cm or lower depending on where the stone line was located. A runoff and sediment collection assembly consisted of a collecting trough, a PVC pipe, a 200-liter metallic drum and a 20-liter plastic container.

The neutron probe that was used at the site was calibrated for the 25-80 cm and 80-120 cm depth ranges. The two calibrations were necessary because of the prevalence of iron concretions in lower soil horizons.

Collection of data involved soil moisture which was determined down the profile on a weekly basis in every plot using a neutron probe. Rainfall was recorded on a storm basis using two rain gauges (manual and recording) installed at the site. Rainfall intensity and distribution was obtained from the recording rain gauge. Runoff and soil loss were monitored on a storm basis. Bulk density was determined for two depth ranges of 0-15 cm and 15-30 cm at the beginning and at the end of every season. Penetration resistance was measured at selected time intervals within a rain season. Soil shear strength was measured on a weekly basis using a shear vane apparatus. Soil aggregate stability was determined using the wet sieving method. Infiltration after each rainstorm was taken as the different between rainfall and runoff. The saturated hydraulic conductivity at the site was determined in situ using a disc permeameter. During each rainstorm, there was minimal evaporation since the relative humidity was high. After the onset of the rains, and subsequent breakdown in soil macrostructure, surface storage on the plots became negligible.

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The analysis of collected data was conducted using two statistical methods, analysis of variance (ANOVA) and regression analysis. All these analyses were based on a 5% level of significance. The variables analyzed included; treatment, runoff, soil loss infiltration and rainfall amount. The least significant difference (LSD) at 5% level of significance was used to determine the differences between the treatments.

Experimental treatments

Farmyard Manure. The farmyard manure used was a mixture of cow dung and grass straws obtained form the Dairy Farm at the Research Station. Respective quantities of 5 and 10 tonnes per hectare of air dry manure were weighed, spread evenly and then incorporated in the soil in the appropriate plots at the beginning of each season.

Conventional Tillage. This was achieved using a forked hoe. It involved one tillage operation that was carried out at the beginning of each season. Thereafter, no more tillage was done. Weed control was achieved by manually uprooting the weeds.

Zero Tillage. Zero tillage was achieved by leaving the soil weed free and undisturbed. As was the case with the other three treatments, the soil was left bare to eliminate the effect of crop cover on soil loss and runoff. Hence, it served as a control representing extremes in runoff and soil loss.

Results

Soil Properties

The infiltrability of the soil improved with the application of farmyard manure which increased the stability of aggregates. Besides, the maintenance of a cloddy soil macrostructure through tillage, helped to impound runoff in depression storage and hence enhanced infiltration. Some seasonal decrease in infiltration was attributed to surface sealing and crusting of the top soil which resulted in high volumes of surface runoff.

Seasonal soil moisture variations were more pronounced in the 0-10 cm depth than the 0-100 cm depth. The differences in soil moisture between treatments (0-10 cm) were not significant

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at the onset when infiltrability was enhanced by depressional storage and the end of the season when treatment effects were negligible. The highest soil moisture was observed under 10 FYM followed by 5 FYM, CT and ZT. This did prove that FYM application was effective in enhancing soil moisture storage. Under all treatments, field capacity moisture conditions were never reached during the experimental period.

Soil bulk density was highest under ZT and CT but least under the farmyard manure treatments. Bulk density was low when soil moisture was high and high under low soil moisture conditions.

Penetration resistance and soil shear strength were highest at the beginning of the season when the soil profile was still dry. The highest values were recorded under ZT indicting a need for soil tillage soon after harvest when there is still some residual soil moisture. Penetration resistance was least under the farmyard manure treatments.

Soil aggregation improved with the application of farmyard manure. At the end of the rains, there was a reduction in soil aggregation for all treatments. The highest decrease was in CRT and ZRT. This was attributed to the decrease in soil organic matter content due to top soil losses and organic matter oxidation as a result of high temperatures at the experimental site.

Seasonal Rainfall

In the two rain seasons, there was a strong correlation between storm kinetic energy, runoff and soil loss. Rainfall of low amount spread over long duration never caused runoff while high rainfall over short durations was highly erosive. High erositivity led to increased soil erosion.

The short rains of 1992/93 were longer than usual and peaked in January 1993 with 35% of the seasonal rainfall. The long-term peak month of the short rains in November. The seasonal rainfall of 767 mm for the short rains period was much higher than the long-term average of 378 mm. Runoff during the month of January was 43% (ZT), 37% (CT), 28% (10 FTM) and 31% (5 FYM) of the month's total rainfall.

During the short rains period, the most erosive storm of 84 mm resulted in a soil loss of 3.3 kg/m^2 (CT), 1.7 kg/m^2 (ZT), 1.5 kg/m^2 (5 FYM), 1.4 kg/m^2 (10 FYM) and runoff of 75% (ZT), 64% (CT), 40% (5 FTM) and 37% (10 FYM).

During the long rains period, April, which is usually the peak of the long rains, received only 39 mm of rainfall far below the monthly mean of 147 mm. the most erosive storm of 46 mm was received at the onset of the long rains and resulted in soil loss of 2.7 kg/m^2 (CT), 2.2 kg/m^2 (ZT), 1.5 kg/m^2 (5 FYM) 1.5 kg/m^2 (10 FYM) and runoff of 87% (ZT), 68% (CT), 56% (5 FYM) and 49% (10 FYM).

Generally in the two rain seasons, the first storms were small in magnitude, spread over long time durations and of low intensities and consequently could not cause runoff and soil loss. In the short rains period, which received 64 storms, 20 erosive and 25 above 9 mm and well and evenly distributed, the farmers had a bumper harvest. Over the long rains period, in which eleven storms were received, eight of them below 9 mm, there was poor crop performance and this resulted in a complete crop failure.

Surface Runoff

Storm runoff was influenced by rainfall intensity, rainfall amount, antecedent moisture content and storm duration. Surface runoff was strongly influenced by rainfall amount under all treatments. Under high soil moisture conditions, storms of less than 5 mm caused runoff while under initial dry conditions (onset of rains), storms greater than 15 mm never caused runoff. There was no significant difference in runoff between CT and ZT but the two treatments resulted in much higher runoff than farmyard manure treatments. Treatment differences in runoff were negligible for small storms.

At the beginning of the season, the initial cloddy surfaces due to soil tillage enhanced depression storage and hence the absence of runoff and soil loss. With time, there was an increase in soil sealing, crusting, and compaction (due to raindrop impact coupled with the inherent low organic matter content) which

contributed to the high runoff volume observed in Zero tillage. Farmyard manure application was able to significantly reduce runoff when compared to conventional tillage with no manure and zero tillage. The farmyard manure in the soil led to an increase in water holding capacity and a reduction in soil surface sealing and crusting. Runoff expressed as a percentage of seasonal rainfall was 43%, 48% (ZT), 37%, 37% (CT), 29%, 31% (5 FYM) and 27%, 28% (10 FYM) during the short rains and long rains period, respectively.

Soil Loss

Soil loss was influenced by rainfall characteristics, degree of soil aggregation and antecedent soil moisture conditions. High runoff volumes often resulted in increased soil loss while low runoff volumes gave little soil loss at the onset of the season. However, later in the season soil loss tended to decrease even when runoff increased. Soil loss decreased in the order of ZT, CT, 5 FYM and 10 FYM over the experimental period. More soil was lost during the short rains 9518 gm^{-2} (ZT), 14770 gm^{-2} (CT), 10038 gm^{-2} (5 FYM) and 9346 gm^{-2} (10 FYM) than the long rains period 4478 gm^{-2} (ZT), 3974 gm^{-2} (CT), 2373 gm^{-2} (5 FYM) and 2162 gm^{-2} (10 FYM).

At low bulk density and low soil shear strength, storms of low intensity and low magnitude caused little soil loss as a result of their low erositivity. However, high intensity storms resulted in high of runoff and soil loss due to their high erosivity. Under low bulk density, soil particles were easily detached while under high bulk density and high rainfall intensity, the increased runoff led to more soil loss and runoff at the onset of the season. Later in the season after the soil had crusted and compacted due to raindrop impact, high rainfall intensities led to increased runoff but reduced soil loss.

Farmyard manure application significantly reduced soil loss through improved soil aggregation and a reduction in bulk density and soil shear strength.

2. G.E. Okwach - Macroplots experiments (Report number 2)

A. Methodology

The experimental plots

The site of this study is the middle of three terraces that had been constructed some fifteen years ago on a gently-sloping hillslope. The soil is a strongly weathered, well-drained, deep (0.80-1.20 m), dark reddish-brown (2.52YR2.5/4, moist) to dark brown (10 YR2/2, moist) Chromic Luvisol, derived from undifferentiated quartzo-feldsphatic gneisses. The texture is sandy clay loam, tending to sandy clay at lower horizons. These soils are low in organic matter (0.52 to 1.0%) and nitrogen (0.07 to 0.09%). The A horizon averages 0.19 m in depth. It has a weak to moderate, medium, sub-angular blocky structure, with a tendency to harden when dry and become friable and easily erodible when wet. It has a CEC-soil of 12.1 to 23.9 me/100g and a slightly acidic pH-water (5.7 - 6.9), a base saturation of 45 - 59% and electrical conductivity of 0.04 - 0.11 dS m^{-1}. The B-horizon consists of a weak to moderate, fine, medium to coarse, sub-angular blocky structure, with a CEC-soil ranging between 11.1 and 21.7 me/100g, a pH-water of 5.7 -6.5, and a base saturation of 50- 55%.

Four plots were selected for this study. Each plot measures 7 m wide by 15 m long, with the long axis oriented down the slope. The plots are bounded at the top and the two sides by 0.3 m. high galvanized iron sheets of 18 gauge thickness. These sheets are inserted into the soil to a depth of 0.15 m, so that the above-ground portion is also 0.15 m high.

Runoff is collected at the lower end of each plot by means of large V-shaped tipping buckets of approximately 7 liter capacity, connected to electronic data loggers. Following installation, these runoff measuring tipping buckets had been calibrated to obtain bucket tipping capacity and how this varied with flow rates. The loggers were logged to 1 minute time intervals, and were, therefore, capable of yielding estimates of 1 minute variations in runoff rates, as well as giving the total runoff amount yielded from each plot during each storm.

At the bottom end of each plot is a collecting trough, which measures 0.25 m, wide and 7 m long and captures all runoff leaving the plot. The trough is made of the same galvanized iron sheet as the side boundaries. Each trough is placed some 0.15 m below the plot surface, re-enforced by sand and concrete. The trough is installed at a slope of 1%, with the lower end draining into a collecting pit. The other end of the trough is sealed, to prevent runoff and sediment loss, by a metallic place welded and glued to the trough body. The pit measured 1.25 m by 1.15 m and is 0.80 m deep. A 0.26 m opening at the lower end of the pit enables the draining of runoff water into the lower terrace bank for safe discharge. The walls, floor and draining channel of the collecting pit are all reenforced with concrete.

In the collecting pit, receiving water and sediment from the collecting trough, is a sediment settling drum. This settling facility is an ordinary 200 liter oil drum (0.56 m diameter and 0.88 m height), cut and remodeled to allow runoff inflow and outflow. The inflow opening is cut at 0.55 m from the base, while the outflow opening is at 0.45 m from the base. Runoff, therefore, collects in the drum to a height of 0.45 m and then drains out without the possibility of interfering with the inflow. To minimize the time lag of flow measurement compared with actual plot runoff the drum is filled with water before each event. The drum is placed on a concrete platform, which lifts it off the 0.80 m-deep pit floor in such a way that some 0.15 - 0.20 m of the top of the settling drum remains protruding above the surrounding soil level. The purpose of this protrusion is to prevent runoff from outside the experimental area (plot) from flowing in and mixing with the collected plot runoff.

Attached and sealed to the outflow opening on the drum is a short rectangular basin, known as the runoff guide, which channels water from the drum to the tipping bucket.

This structure is 0.54 m long and 0.28 m wide, with the length running at right angles to the direction in which the collecting bucket tips. In the center of the runoff guide is the inlet manifold. This is an opening, measuring approximately 0.04 m wide and 0.24 m long, through which runoff from the drum passes

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to the tipping bucket flow rate measuring device directly below it.

Treatments

The original intention of the macro-plots component of this study at Katumani was to evaluate the effects of slope steepness, slope lengths and methods of cultivation on runoff, infiltration, and soil erosion. However, my absence from Katumani during much of the early part of the project duration (while completing my Ph.D degree program in Australia) prevented the establishment of the necessary macro-plots with the specifications required, such as varying slope steepness and lengths. Modifications were then made to enable the use of some of the already established large runoff plots at Katumani. The selected runoff plots were subjected to different soil management systems, giving four unreplicated treatments. These treatments were as follows:

A. Conventionally Cultivated Bare Fallow. Cultivation and weeding were done conventionally using a traditional hand-hoe. No crop was planted. Neither mulch nor fertilizer was added. The soil surface was kept weed-free throughout the season.

B. Traditional Maize Monocrop. Conventional tillage system by means of a traditional hand-hoe. A low maize population density of 22,000 plants per hectare was grown at a spacing of 0.90 m (between rows) by 0.50 m (between plants). Neither surface mulch, nor fertilizers were added.

C. Maize-Bean Intercropping. Conventional tillage system, with a low maize plant population (22,000 plants per hectare at 0.90 m by 0.50 m spacing), planted in alternate single rows with 74,000 bean plants per hectare (0.90 m by 0.15 m). The planting arrangement was such that maize to bean rows were 0.45 m from each other. Neither surface mulch, nor fertilizer was applied.

D. Traditional Maize Monocrop with Mulch. Conventional tillage system, with the traditional low maize plant density as in Treatment **B** (traditional maize monocrop). No fertilizer was applied. Maize stover mulch was applied at the rate of half of that produced in this treatment in the previous season.

Measurements showed that such an amount of mulch provided approximately 10% cover to the soil surface.

The experimentation ran for six seasons, commencing with SR1992 (October, 1992) and ending with the LR1995 (July, 1995).

Measurements

A number of measurements were made during the six seasons of this study. However, due to my absence from Kenya during much of this period, only the basic data were collected in most seasons. these measurements included:

- Daily rainfall
- Daily runoff
- Soil loss

In addition, soil surface hydraulic conductivity wa measured by means of the disc permeameter. There was no direct measurements of infiltration. However, from the rainfall and runoff data obtained by the electronic loggers, an analytical theory enabled some modest determination of infiltration characteristics.

Results

Surface runoff

The runoff losses from the four treatments are shown in Table 1 for the SR1992 to LR1995 seasons, respectively. As expected, runoff decreased with increase in ground cover provided by vegetation. In all the five seasons, the effects of vegetation on runoff control is readily visible from the reduction observed between the bare fallow and the maize monocrop. Increasing the level of vegetation cover, by adding beans to the maize in the intercrop treatment, resulted in further reduction of runoff. The reduction of runoff by the intercrop treatment beyond that due to maize monocrop was, however, less dramatic than that between the bare fallow and the maize monocrop.

When small amounts of mulch were added to the traditional maize monocrop system, in the maize with mulch treatment,the reduction in runoff loss beyond that of the traditional system was more dramatic in all seasons than under intercropping. Although the level of cover afforded under the various treatments

was not measured, it is clear that mulch had a greater effect on runoff than growing vegetation.

The amount of runoff lost by all treatments in any season was found to be related to the prevailing rainfall characteristics. Of particular significance were the rainfall amount and the seasonal average rainfall intensity. Thus, the highest seasonal rainfall obtained in the SR1992 season (776 mm) resulted in corresponding highest runoff loss in each treatment. The converse was, however, not true. In other words, the lowest seasonal rainfall (200 mm in the LR1994 season) did not yield the lowest runoff amount for each treatment. The least seasonal runoff lost in each treatment was obtained in the LR1995 (with the rainfall amounting to 254 mm). Analysis showed that the differences in runoff lost in these two seasons were correlated more with the corresponding seasonal average rainfall rate that with rainfall amount. The seasonal mean average rainfall intensity for the LR1994 was 10.2 mm/h, while that of the LR1995 was 6.7 mm/h. Thus, the more intense LR1994 storms yielded higher runoff than the less intense LR1995 storms, despite the higher amount of rainfall realized in the latter season, compared to the former season.

Table 1: Percentage reduction, with respect to the bare fallow plot, in surface runoff loss (mm) under different treatments

Treatment	Surface Runoff (mm)	Percentage reduction in soil loss with respect to the bare fallow plot (%)
Bare Fallow	444	0.0
Maize Monocrop	421	5.2
Maize - Bean Intercrop	391	11.9
Maize with Mulch	303	31.8

Table 2: Percentage reduction, with respect to the bare fallow plot, in total soil loss (t/ha) under different treatments

Treatment	Soil Loss (t/ha)	Percentage reduction in soil loss with respect to the bare fallow plot (%)
Bare Fallow	238.0	0.0
Maize Monocrop	190.2	20.1
Maize - Bean Intercrop	159.0	33.2
Maize with Mulch	96.4	59.5

Table 3: Hydraulic conductivity of the experimental plots as measured by the disc permeameter in December 1994, during the SR1994 season - Mean of three measurements per plot.

Treatment	Saturated Hydraulic Conductivity (mm/h)		Hydraulic Conductivity at - 30 mm suction (mm/h)	
	Mean	Std.Dev.	Mean	Std.Dev.
Bare Fallow	22.15	6.71	5.62	3.24
Maize Mono-crop	55.46	17.97	22.80	11.40
Maize-Bean Intercrop	35.77	21.03	12.06	6.96
Maize with Mulch	49.41	12.55	7.92	4.57

Soil Erosion

The soil loss from the four treatments are shown in Table 2. Soil erosion seemed to follow much of the trend initiated by runoff loss, albeit, more dramatically. This dramatic decline of soil loss at higher cover is shown clearly in Table 2, in which

the percentage reduction of soil loss by the various treatments with respect to the bare surface are much higher than those for runoff (Table 1).

Three treatments showed significant differences in soil loss, at $P \leq 0.05$, when all the soil-yielding events were combined over the five seasons of study. The soil loss in both the maize-bean intercrop and the maize with mulch treatments were significantly ($P \leq 0.05$) less than the bare fallow system. The maize with mulch was also significantly ($P \leq 0.05$) less than the maize monocrop without mulch.

Soil Hydraulic Conductivity

The disc permeameter of Perroux and White (1988) was used to determine the hydraulic conductivity of the four runoff plots only during the SR1994 season. All measurements were taken in December 1994 at two water potentials, namely, 0 mm (saturated flow) and at -30 mm suction. four readings were made on each plot for each measurement potential. The results are shown in Table 8.

The hydraulic conductivity values obtained by the disc permeameter at both water potentials did not show any particular trend with respect to treatment. Moreover, there were wide within-plot variations of estimates, as indicated by the large standard deviations. It is possible that the value obtained during these measurements were more reflective of sit specificity than treatment effects. These measurements were, therefore, inconclusive.

Methods and Results - ISRAEL

The work done in Israel is summarized in 5 publications. Three of these have already been published and two publications were sent to the journals. These publications are:

1) Levy, G.J., J. Levin and I. Shainberg. 1994. Seal formation and interrill soil erosion. Soil Sci. Soc. Am. J. 58: 203-209.

2) Shainberg, I., and G.J Levy. 1994. Organic polymers and soil sealing in cultivated soils. Soil Sci. 158: 267-272.

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3) Bezalel, I., J. Morin, Y. Benyamini, M. Agassi and I. Shainberg. 1995. Water drop energy and soil seal properties. Soil Sci. 159: 13-

4) Levy, G.J., J. Levin and I. Shainberg. 1995. Prewetting rate and aging effects on seal formation and interrill soil erosion. Soil Sci. Soc. Am. J. (sent for publication).

5) Shainberg, I., G.J. Levy, J.Levin and D. Goldstein. 1996. Aggregate size and seal properties. Soil Sci. Soc.Ama. J. (sent for publication).

Abstracts of these manuscripts, which include methods and results follow. The full manuscripts are in the appendix (manuscript numbers 1-5)

Seal formation and Interrill Soil Erosion

G.J. Levy, J. Levin and I. Shainberg

Abstract

Interrill soil erosion depends primarily on soil detachment by raindrop impact (splash) and the transport capacity of thin sheet flow. Both splash and sheet flow erosion depend on soil surface properties. The purpose of this study was to investigate the effect of seal formation on interrill soil loss. samples of three soils types - a Typic Chromoxerert, a Calcic Haploxeralf and a Typic Rhodoxeralf - with various naturally occurring exchangeable sodium percentage (ESP) levels were used. The soils were exposed to simulated rain using three different waters: distilled (DW), tap (TW), and saline (SW). the electrical conductivity (EC) of the TW and SW was 0.;8 and 5.09 dS m^{-1}, respectively. Seal formation was characterized by the final infiltration rate (FIR) and amount of runoff. Seal formation was enhanced with an increase in soil sodicity and a decrease in water salinity for each soil type. Nearly 70% of the variation in FIR (and seal formation) was explained by water salinity and soil ESP. Most of the variation in soil loss was explained by clay content, soil ESP, and water salinity. with the exception of samples with ESP <5 rained on with DW, soil loss increased linearly with an increase in soil clay content. Seal strength,

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as inferred from surface pitting by impacting raindrops, decreased with an increase in clay content, and was inversely related to soil erosion.

Organic Polymers and Soil Sealing in Cultivated Soils

I. Shainberg and G.J. Levy

Abstract

The beating action of rain or sprinkler drops causes the breakdown of aggregates and clay dispersion, which subsequently leads to seal formation. Seal formation reduces infiltration rate and generates high levels of runoff. Chemical soil amendments (e.g., phosphogypsum, organic polymers) can improve aggregate stability and limit clay dispersion and thus prevent seal formation. This review discusses the effects of organic polymers on controlling seal formation as characterized by change in soil infiltration rate and dependence on soil properties. Soil susceptibility to sealing depends on a number of soil properties, including soil texture and mineralogy, composition of the exchangeable cations, and water quality. Addition of small amounts of polymers (10-20 kg ha^{-1}), either sprayed directly onto the soil surface or added to the applied water, stabilizes and cements together aggregates at the soil surface, thereby increasing their resistance to seal formation. The infiltration rate of a polymer-treated soil subjected to distilled water rain is two to three times that of a non-treated soil. The efficacy of anionic polymers in preventing seal formation is enhanced when the soil clay is maintained in a flocculated state. The latter is achieved by addition of electrolytes (either in the "rain" water or phosphogypsum addition) in the soil solution at the soil surface. Combined application of anionic polymers with electrolytes results in final infiltration value of ~25 mm h^{-1}, which are 10 times higher than the control. Polymer effectiveness in controlling seal formation depends also on charge type and density and on the molecular weight of the polymer. The effect of polymers and water quality on seal formation is in good agreement with the effect of the polymers on the flocculation patterns of soil

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clays. Of the polymers currently available and under study, anionic polyacrylamide has been found to be the most effective in controlling seal formation, and soil erosion and has the longest residual effect.

Water Drop Energy and Soil Seal Properties

I. Bezalel, J. Morin, Y. Benyamini, M. Agassi and I. Shainberg

Abstract

Rain properties (depth, drop size, and impact velocity) affect the infiltration rate (IR) curve and final IR (FIR) of soils. Because the IR is not a unique function of rain depth or rain energy, the objective of this study was to find a unique function of rain properties that determines the IR of the soil. Simulated rain of constant intensity (40 mm h^{-1}), with 2.53- and 3.37-mm-diameter drops, was applied from heights of 0.4, 1.0, 2.0, 6.0, and 10.0 m on two soil samples: Ruppin hamra (sandy loam, mixed, Typic Rhodoxeralf), and Ruhama loess (silty loam, mixed, Calcic Halopxeralf). The FIR of the two soils decreased with increasing kinetic energy (KE) of the drops. The sandy loam was less stable than the silty loam, and seal formation in it was more susceptible to the KE of the drops. The infiltration decay process was better correlated with rain momentum than with rain depth or KE. Thus, prediction of infiltration rate decay for a given soil exposed to rains of various drop sizes and velocities is best based on drop momentum and the soil stability constant.

Prewetting Rate and Aging Effects on Seal Formation and Interrill Soil Erosion

G.J. Levy, J. Levin and I. Shainberg

Abstract

Slaking of surface aggregates may affect seal formation and interrill soil erosion. An investigation was conducted of the effects of time-dependent variables, such as prewetting rate and aging duration, on seal formation and interrill soil loss in two soils exposed to simulated rain. Aggregates (4-9.5 mm) from a Calcic Haploxeralf and a Typic Chromoxerert were packed in pans, placed in a rainfall simulator, and prewetted by either (a) a

water table 20 mm below the soil surface or (b) 5 mm of rain at rates of 1, 6 or 30 mm h^{-1}. After presetting the soil pans were left to age for 15 min or 18 h, and then subjected to 60 mm of distilled water simulated rainfall. The final infiltration rate increased from 5.0 to 26.6 mm h^{-1}, percent runoff decreased from 59.1 to 2.5, and soil loss decreased from 302 to 5.4 g m^{-2} with a decrease in prewetting rate from 30 to 1 mm h^{-1} in the Typic Chromoxerert; similar effects were observed in the Calcic Haploxeralf. For both soils, aging was effective in increasing the infiltration parameters (infiltration rate and runoff) only when partial slaking was achieved by slow and moderate prewetting rates. Conversely, 18 h of aging effectively decreased soil loss also in the fast prewetting rates in both soils. Aggregate slaking, which occurred during prewetting by compression of entrapped air, enhanced aggregate breakdown by the impact of the raindrops, and both factors played an important role in surface crusting. Slaking was significantly reduced by slow prewetting of the surface aggregates. Aging increased the cohesion forces between soil particle and reduced the latter's erodibility.

Aggregate Size and Seal Properties

I. Shainberg, G.J. Levy, J. Levin and D. Goldstein

Abstract

The formation of a disrupted layer and a seal at soil surfaces exposed to the impact of raindrops is a common feature of many cultivated soils. A distinction was made in this study between a disrupted layer and a seal. The effect of aggregate size on seal permeability, the thickness of the disrupted layer, and on aggregate stability in two soils exposed to simulated rain was studied. Aggregates with sizes of <4, 2-4, 4-9.5 and 9.5-12.0 from a Typic Chromoxerert and a Calcic Haploxeralf were used for the study. Seal formation was determined in samples exposed to distilled water (DW) rain with a kinetic energy of 12.4 J mm^{-1} m^{-2}. The thickness of the disrupted layer was estimated from petrographic microscope observations of air-dried samples exposed to rain. Aggregate stability was determined by bombarding 3-7 g of dried aggregates, placed on a sieve with a size opening of

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0.3 or 0.8 mn, with drops of 3.1 J mm^{-1} m^{-2} kinetic energy. Aggregate stability, the thickness of the disrupted layer and cumulative infiltration increased with aggregate size. these observations suggest that the rate of seal formation increased with a decrease in aggregate size. Conversely, the final infiltration rate (IR) of the fully-developed seal in both soils was low (<4 mm h^{-1}) and was not affected by aggregate size. The results indicate that in soils exposed to rain aggregate disintegration is the first process in seal formation and clay dispersion determine seal permeability. The permeability of the seal rather than that of the disrupted layer determines the equilibrium IR of the soil.

6) Impact, Relevance and Technology Transfer

The principal investigators from Israel and Kenya visited each other several times and discussed, in person, scientific concepts, methodologies and the experimental results. The principal investigators benefitted very much form these discussions.

It is hoped that the "new" concept that infiltration runoff and erosion are not only soil and rain-dependent variables, but also time-dependent variables, is absorbed by all collaborators in both countries. It is hoped that these ideas will influence the design of new field experiments and the analysis of the results.

Scientifically, the success of a project is measured by the number and quality of the publications. Based on this criteria, it seems to the principal investigators that the project was indeed successful.

7) Project Activities/Outputs

The following meetings took place within the project:

A. Dr. M. Agassi, from Israel, visited in Kenya in December, 1991. He visited potential project sites and discussed the experimental methodology with the Kenyan collaborators.

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B. Dr. H. Frenkel, from Israel, visited Kenya in August, 1993, and reviewed the research findings with the Kenyan collaborators.

C. Mr. E.K. Biamah visited Israel in November, 1992, for very fruitful discussions and visits in research sites.

Dr. I. Shainberg visited Kenya in 1990. During his visit the original research proposal was written and cooperation between the Kenyan and Israeli collaborators was established.

The following publications summarize the output of the project:

1) E.K. Biamah. July, 1995. Infiltration, Runoff and Erosion of Semi-Arid Soils in Kenya. Report of Microplot Experimental Research at the National Dryland Research Center, Katumani, Machakos, Kenya (62 pages + appendices).

2) G.E. Okwach. 1995. Infiltration, Runoff and Soil Erosion in Semi-Arid Soils in Kenya. Report of the Katumani Macro-Plots Component of USAID-CDR Research Program (61 pages).

3) G.J. Levy, J. Levin and I. Shainberg. 1994. Soil Formation and Interrill Soil Erosion. Soil Sci.Soc. am. J. 58: 203-209.

4) I. Shainberg and G.J. Levy. 1994. Organic Polymers and Soil Sealing in Cultivated Soils. Soil Sci. 158: 267-171.

5) I. Bezalel, J. Morin, Y. Benyamini, M. Agassi and I. Shainberg. 1995. Water Drop Energy and Soil Seal Properties. Soil Sci. 159: 143-

6) G.J. Levy, J. Levin and I. Shainberg. 1995. Presetting Rate and Aging Effects on Seal Formation and Interrill Soil Erosion. Soil Sci. Soc.Am. J. (sent for publication).

7) I. Shainberg, G.J.Levy, J.Levin and D. Goldstein. 1996. Aggregate Size and Seal Properties. Soil Sci. Soc. Am. J. (sent for publication.

The publications are enclosed in the appendix.

8) **Project Productivity**

The project made a contribution towards its goals and objectives. It is believed that soil management in rainfed farming in the semi-arid regions of Kenya could be improved by applying the concepts developed in this project.

9) Future Work

No future work is being planned at present.

10) Literature Cited

Literature citation is available in the reports and the manuscripts.

INFILTRATION, RUNOFF AND EROSION OF SEMI ARID SOILS IN KENYA

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JUNE, 1992 - FEBRUARY, 1994

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GENERAL OVERVIEW ON EXCHANGE VISITS AND FUNDING

Dr. Menachem Agassi from Israel visited Kenya towards the end of 1991 and held discussions with me on our collaborative research project. We did visit several potential USAID-CDR project sites and collected soil samples for characterization in Israel. Unfortunately, these samples could not be sent to Israel due to unforeseen reasons.
I have now arranged to carry out rainfall simulation studies in our soil and water laboratory using the same soil samples.

Before coming back to Kenya, I visited Israel in November, 1992 and had very fruitful discussions with Professor I. Shainberg, Dr. Guy Levy and Dr. Haim Frenkel about our collaborative research. We visited some USAID-CDR research sites in Israel with Professor Shainberg and Dr. Guy Levy and also was exposed to the facilities available for laboratory analyses of soil samples. The equipment at the Institute of Soils and Water were fairly sophisticated and hence most appropriate for the intended study. Before my departure from Israel, I reaffirmed my commitment to the success of our collaborative research and promised to do a good job as soon as the funds were released to Kenya.

In early 1993 and mid 1994, I received the disbursements for the period June,1992 to December, 1993. I am pleased to report that these funds have been properly utilized for the intended purpose as reflected in this report. Within the month of August, 1993, Dr. Haim Frenkel, Scientific Director, ARO had a three weeks visit to Kenya and I did take him around the country to see an ongoing USAID-CDR Research at Katumani, Machakos and also visited the other proposed USAID-CDR research sites in Baringo and West Pokot.

USAID-CDR COLLABORATIVE RESEARCH IN KENYA

During the period June, 1992 to February, 1994, field and laboratory experimental studies were conducted on the following pertinent hydrological and soil properties: rainfall, infiltration, runoff and soil loss; soil bulk density, topsoil moisture (0 - 10cm), profile soil moisture, soil aggregate stability, penetration resistance, soil organic matter content and soil shear strength (see appendices, tables and figures).

Over the period, the short rains began in late October, 1992 and that is when the field data collection started. Fortunately we had some unusually long short rains period that continued upto March, 1993. However the long rains which were due in March, 1993 became erratic and unreliable to the extent that it virtually stopped raining in early May, 1993 and there were no rains in the season. During the short rains period (1993-94), the rains were sufficient to cause runoff. The data presented here covers the period October, 1992 to February, 1994.

SCIENTIFIC SUMMARY

In semi arid environments of Kenya, dominant soil types are structurally unstable, have crusting properties and frequent soil moisture deficits. Under these conditions, there is a need to understand how soil macrostructure (cloddiness), soil aggregation, soil compaction and surface soil crusting when affected by tillage and organic manuring would influence infiltration of rain water and available soil moisture. In this experiment, seasonal effects of tillage and farmyard manure applications on infiltration, runoff and soil loss of a crusting sandy clay loam soil (orthic luvisol, FAO/UNESCO Classification, 1974) were investigated on microplots of size $2m^2$ under marginal rainfall conditions. The plots were left bare (no test crop) to eliminate any influence of vegetative cover on pertinent hydrologic and soil properties.

The results obtained showed some significant changes in soil macrostructure (cloddiness) and soil aggregation with rainfall events and soil treatments. Soil crusting and subsequent compaction of the top soil layer increased with time and significantly reduced infiltration, profile soil moisture and soil loss but increased runoff within the experimental period. Soil shear strength and bulk density variations within the rainy season influenced soil erodibility and the moisture retention characteristics of the top soil. This study did prove the significant role of tillage and farmyard manure application in facilitating better infiltration rates, improving soil moisture, and reducing soil loss during the initial stages of the rainy season when there is no vegetative cover, the rainstorms are highly erosive and soil erosion is severe.

1. INTRODUCTION

1.1 General Background

In arid and semi arid lands (ASAL) environments of Kenya, where the Katumani Experimental Site is located, unreliable rainfall and problem soils constitute major constraints to crop and fodder production. The rainfall is often low and poorly distributed, occurs in high intensities of short duration and is highly erosive. The problems associated with the dominant soils of the area include structural instability, strong soil crusting and hardsetting and high erodibility. When exposed to erosive rainstorms, the soils generate high amounts of runoff and soil loss and have low infiltrability.

The development of rainfed agriculture for ASAL areas requires tillage and residue/manure management practices that protect these fragile and easily degraded lands from soil erosion. Tillage research conducted at Katumani (Marimi, 1978; Njihia, 1979; Muchiri and Gichuki, 1982; Kilewe and Ulsaker, 1983) found that conventional tillage, tied ridges, bench terraces, residue mulch and farmyard manure were sufficiently effective in controlling runoff through increased surface water storage, breakdown of soil surface crust, improved infiltrability and moisture retention characteristics of the soils. According to Njihia (1979), tied ridges effectively controlled runoff even from a maximum storm of 70 mm/day (with a return period of 3 years). In this experiment, a grain yield of maize was realized from tied ridged and stover mulch plots for a seasonal rainfall of 171 mm. Marimi(1978), observed that runoff occurred from conventional tillage treatments when rainfall exceeded 15 mm.

Traditional tillage and residue/manure management methods that are widely practised in Katumani, include residue mulching, tied ridging, conventional tillage (hand hoeing and Ox-ploughing), with and without farmyard manure and bench

terracing. Additionally, conservation tillage methods like zero tillage (no till), terracing, cover cropping, intercropping, contour buffer stripping, have been used to optimize soil conditions for improved crop performance and yield. Most of these tillage operations involve high energy inputs (labour intensive, use of hand tools) both in construction and maintenance.

The applicability of these tillage practices depends on soil properties, climatic conditions, types of crops to be grown and socio economic conditions of the beneficiaries (smallholder farmers). For instance, contour bunds and ridges have proved to be very effective in areas where rainfall intensities and runoff rates are high. These structures are recommended for stable soils with surface sealing and crusting properties and low water intake rates. Contour bunds and ridges are expected to impound the runoff and increase the infiltration opportunity time of the soil. In conventional tillage, farmers use oxen or hand hoes to break the land upto a maximum depth of 20 cm - often leaving large soil clods at the surface. Often conventional tillage involves primary tillage operation with no secondary tillage until weed control. Minimum tillage operations often involve strip tillage (narrow strips of 20 cm width cut along the planting rows) or spot tillage (where planting holes of size 10 x 10 cm are made using hand hoes). Minimum tillage is also practised using the traditional slash and burn techniques. Contour buffer strips of widths of 1 to 2 m are often combined with contour ridges to check runoff and soil loss. Tied ridging at 2 to 3 m spacing along the furrows is usually done before the onset of the rains to avoid any breakages of ridges due to concentrated runoff flows. Crop residues are either placed on the soil surface (to dissipate rain energy and reduce surface sealing effects) or incorporated into the soil (ridges and furrows) as a means of supplementing organic matter deficiencies and improving the water holding capacities of soils. Farmyard manure (mixture of cowdung and grass/crop straw) is often applied in appropriate quantities along furrows (in which seedlings are planted) to conserve soil moisture and enhance seedling emergence. At times the manure is applied in planting holes to create some favourable soil conditions for plant emergence and growth.

1.2 Tillage and Moisture Conservation

The primary objective of any tillage operation should be to optimize soil conditions such as bulk density, pore size distribution, temperature, consistency, soil water intake rate and moisture retention capacity for increased crop and fodder production through appropriate and timely seedbed preparation.

Smallholder farmers in dryland farming areas of Kenya use traditional methods of seedbed preparation and cultivation (e.g hand hoeing and ox-ploughing). In practice, timely seedbed preparation using these methods is difficult to achieve especially where ground breaking operations require high energy inputs. The occurrence of soil surface hardpans has often delayed tillage operations up to the onset of the rains when soil moisture conditions would be favourable. High labour demands during this peak period have delayed seedbed preparation operations and consequently affected soil productivity. Furthermore, soil productivity is threatened by shallow digging (causing subsurface hardpans) and soil erosion hazards (due to tillage operations on steep slopes and highly erodible soils) that are quite evident on fragmented smallholder farms.

In these marginal rainfall areas, recurrent low soil moisture conditions have been attributed to low infiltration of rainwater (due to hardsetting, soil surface sealing and crusting properties) and low organic matter content of the soils. Rainfall impact causes surface sealing and crusting of bare soils resulting in very high runoff water losses. It is this runoff water that must be harnessed and conserved in the soil to sustain crop growth. This calls for appropriate tillage and residue management practices that improve rain penetration and hence conserving adequate soil moisture for plant growth. Tillage techniques used to control runoff include maintenance of ground cover (e.g cover cropping and mulching), modification of soil surface macro conditions (e.g zero, minimum, conventional and conservation tillage) and increasing surface water storage by runoff impounding structures (e.g tied ridges, U and V shaped micro basins). Another soil management practice that is widely used by farmers in arid and semi arid lands (ASAL) is the incorporation of organic manure

into the soil. This practice has significantly increased rainwater infiltration rates and moisture conservation and hence improved seedling emergence and crop development in ASAL.

Tillage research studies conducted in ASAL areas have focused on the effects of some tillage practices on soil and moisture conservation for increased crop production. The studies have attempted to develop appropriate and sustainable tillage and residue management methods that would maintain favourable soil conditions for good plant growth on small scale farms. To be successfully adopted by smallholder farmers, these tillage methods must offer tangible benefits through increased crop yields, fuelwood and fodder production. These tillage methods whilst adapted to area specific soil conditions, should also be well designed to cope with the high rainfall intensities, high erodibility of soils and high temperatures prevailing in the areas.

1.3 Tillage Research in ASAL

Tillage research conducted in dryland farming areas of Kenya, has focused on tillage methods such as mulching, farmyard manuring, tied ridging, zero tillage, conventional tillage and contour furrows. These studies were conducted in marginal rainfall areas where the soils were characterized as having inherent low organic matter content and surface sealing and crusting properties. Rainfall in these areas is quite intense, of short duration and highly erosive.

Within the semi arid area of Makaveti, Machakos, Pereira et al. (1952), conducted a pasture improvement study and found that the infiltration rate of a Luvisol (FAO/UNESCO classification) improved when its soil surface crust was broken through contour ploughing, ridging and ripping. The best pastures were obtained by contour ploughing and ridging with some incorporation of a small dressing of cattle manure. Ploughing and ridging conserved moisture but deep ripping did not assist in grass establishment under the low rainfall conditions of the experimental site.

In the same area, Pereira et al. (1954) conducted a crop rotation study in which infiltration rates were comparatively low after one year of uniform cropping. The rotation of grasses, cover crops and cultivated crops over a three year period had some short term improvements on soil structure.

In an experiment done in a dry area of Kenya, Pereira et al. (1954) found that 10 cm mulch of elephant grass in a coffee plantation produced after two years an infiltration rate equal to that of five years under elephant grass.

Pereira et al. (1958) in a water conservation study in a semi arid area, established that tied ridges do not improve the resistance of soil to surface sealing, but may impede surface flow of water within the furrow, thus allowing more time for water to infiltrate.

Pereira et al. (1964) found that clean weeding caused an average of 15% reduction in infiltration during very heavy storms compared with minimum weeding or the incorporation of grass mulch into the soil during cultivation.

Pereira et al. (1967) studied soil and water conservation systems for high rainfall areas of Kenya. The study established that contour ploughing (using Nichols terraces) and tied ridging of a Kikuyu red loam soil (Nitisol, FAO/UNESCO Classification) on slopes of 10%, effectively controlled soil and runoff water losses. Runoff was heaviest from well established grass leys (Cynodon dactylion) immediately after intensive grazing and subsequent trampling by livestock and when exposed to rainfall intensities exceeding 50 mm/hr. The trampling effects at the site were transient with variable runoff rates. Soil surface profiles at the experimental site showed remarkable slope stability under intensive tillage.

Furthermore, some benching effect was noted on fields under contour cultivation. High soil loss and runoff rates were observed where ridging and tying operations were undertaken at different times. Where both operations were done at the same time, the tied ridges effectively controlled runoff and reduced soil loss. At the same site, soil moisture measurements (using gypsum blocks) were taken at 0.6, 1.2, 1.8, 2.4 and 3 m depths for two terrace spacings (1.5 and 6 m VIs) on 10% slopes. There were no significant differences in the availability of soil moisture between the two treatments. Soil moisture extraction patterns of star grass (Cynodon dactylion) showed extensive root development to 3 m depths nine months after planting. Over the two year period of soil moisture measurements, moisture deficits occurred when rainfall was less than the consumptive use of Cynodon dactylion.

In a tillage study at Katumani, Machakos, Marimi (1978) found that zero tillage, conventional tillage and tied ridging operations on a sandy clay soil (chromic Luvisol, FAO/UNESCO Classification) broke the soil surface crust and improved infiltrability and moisture storage of the soil. Higher soil moisture contents were obtained under tied ridges when compared with the other tillage storage methods. Minimum tillage stored the least amount of soil moisture. Significantly higher dry matter and grain yields of maize and beans were obtained in tied ridged plots as opposed to low yields in the other plots. Minimum tillage gave the lowest crop yields.

During this study period, runoff occurred on two occasions from zero and conventional tillage when rainfall exceeded 15 mm. This confirmed that soil surface sealing occurred rapidly even with light rains.

Onchere (1977), in an infiltration study at Kitale, found that bare fallow, minimum tillage and conventional tillage operations on an orthic Luvisol (FAO/UNESCO Classification) at a slope of 3%, significantly improved infiltration and other soil properties. It was observed that the method of seedbed preparation significantly influenced the pore size distribution and density, moisture holding capacity, bulk density and surface sealing and crusting properties of the soil. Whereas the coarse seedbed had no crusted soil surface, the other seedbeds showed some

crusting. Bare fallow had the least crusted soil surface. From the moisture characteristic curves, a coarse seedbed absorbed more water than the other treatments and hence had the highest moisture holding capacity (9.1% by volume).

Njihia (1979) at Katumani, Machakos monitored the effects of tied ridges, conventional tillage, crop residue mulch and farmyard manure on soil and moisture conservation. These tillage practices were tested on red sandy clay soil (chromic Luvisol, FAO/UNESCO Classification) at a slope of 12%. The soils had strong surface sealing and crusting properties and an average bulk density of 1.25 g/cm^3. Maize stover mulch was sufficiently effective in controlling runoff through increased surface water storage. The storage increased the time available for infiltration. Maize stover also helped minimize evaporation and surface sealing and crusting. Tied ridges effectively controlled runoff even from a maximum storm of 70 mm/day (with a return period of 3 years). Conventional tillage with or without farmyard manure lost about 40 percent of the storm rainfall. A grain yield of maize was realized from the tied ridged and stover mulch plots for a seasonal rainfall of 171 mm. No grain was harvested from conventional tillage with or without farm yard manure.

Muchiri and Gichuki (1982) at Katumani found that contour furrows were effective in controlling surface runoff and subsequently conserving soil moisture in a semi arid area. The desi plough used in making contour furrows was reported to produce a much rougher seedbed and a draft requirement, depth of tillage and rate of work comparable to the mouldboard plough.

Kilewe and Ulsaker (1983) at Katumani, found that contour furrowing, bench terracing and conventional tillage operations on a sandy clay loam (ferral - chromic Luvisols, FAO/UNESCO Classification) effectively controlled runoff and conserved soil moisture. The study showed that conventional furrows, wide furrows and mini benches retained all the runoff within the furrows and increased infiltration opportunity time after the rainfall. Wide furrows (1 m wide) had the highest soil moisture content followed by conventional tillage during both the short and long rains. These furrows had significantly higher maize grain yield than all the other tillage methods.

In a tillage study at Embu, Ngugi et al. (1986) monitored the effects of conventional tillage and two minimum tillage operations (strip and spot tillage) on brown clays (eutric Nitisols, FAO/UNESCO Classification). The soils had a low organic matter content (1.66%) and were located in a medium rainfall area (1081 mm). The study showed that conventional tillage had the best crop performance and yield when compared with the other tillage methods during both rainy seasons (short and long rains).

Liniger (1989) observed that the reduction of runoff and evaporation loss was a significant factor in mulched plots. Consequently the maximum storage of plant available water was between 45 and 110% higher in the mulched plots than under conventional tillage. Mulching was also reported to have increased maize yields by 4.5 times when compared to similar yields under conventional tillage.

In Kalalu, Laikipia, Gicheru (1990) monitored the effect of conventional tillage, tied ridging and crop residue mulching on soil moisture conservation under marginal rainfall (750 mm) conditions. The experiment was carried on a clay soil (ferric Acrisols, FAO/UNESCO Classification) at a slope of 2%. This study showed that crop residue mulching (despite lagging behind in seedling emergence) did conserve more moisture and had the best crop (maize and beans) performance and yield when compared with the other two tillage practices. The tied ridged plots had the lowest amount of soil moisture and hence the poorest crop performance and yield (due to no runoff to impound and high evaporation water losses from increased soil surface area).

1.4 Rationale, Objectives and Scope of Study

1.4.1 Rationale of the Study

Low, unreliable and erratic rainfall coupled with problem soils constitute major constraints to crop and fodder production in arid and semi arid lands (ASAL) of Kenya. The physico-chemical properties of ASAL soils limit their use for agricultural

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purposes. In order to develop rainfed agriculture for these areas, there is need for farming practices that protect these fragile and easily degraded lands.

In ASAL, a lot has been done in the areas of soil and water conservation, waterharvesting and conservation for crop and fodder production without some proper understanding of the hydrologic and soil properties influencing the effectiveness of erosion control and moisture conservation structures. An understanding of these systems and also the inherent soil properties is inevitable for there to be meaningful and scientific strides in the design of appropriate soil and water management practices for specific areas.

In order to design effective soil and water (moisture) conservation systems for semi arid conditions, an essential prerequisite is the measurement of infiltration, soil loss and runoff from the dominant soil in the study area. Of significant importance is an understanding of inherent soil characteristics in relation to the effects of raindrop impact on crust formation and aggregate stability.

In marginal rainfall areas such as Katumani, structural instability, crusting, hardsetting, high runoff and soil loss are typical to the dominant soils of the area. The measurement, understanding and ability to predict infiltration, runoff and soil loss from these soils which are highly susceptible to crusting are essential for their proper management.

1.4.2 Objectives of Study

The objectives of this study were: to study the effects of zero tillage, conventional tillage and farmyard manure application on infiltration, runoff and soil loss of an unstable Luvisol under natural rainfall; to monitor soil properties (moisture content, aggregation, organic matter content, soil crust strength, soil shear strength and bulk density) and rainfall properties (rainfall intensity, amount and kinetic energy) influencing infiltration and runoff and to determine the effects of changing soil shear

strength and bulk density (due to raindrop impact and different manure application rates) on infiltration, runoff and soil loss of the Luvisol.

1.4.3 Scope of Study

This study was aimed at evaluating the effects of different tillage practices such as zero tillage, conventional tillage (using forked hoe) and farmyard manure application rates (5 and 10 tonnes/ha) on infiltration, runoff and soil loss of an unstable and crusting luvisol at Katumani, Machakos, Kenya. The study looked at rainfall properties (intensity, amount and kinetic energy) and soil properties (soil moisture, soil shear strength, soil bulk density, soil crust strength, organic matter content and aggregation) with a view to relating them to infiltration, runoff and soil loss.

2. THE DRYLAND RESEARCH STUDY AREA

2.1 The Physical Environment

2.1.1 Climate

The seasonal rainfall patterns in Kenya are governed by the seasonal shifts and intensity of the low pressure Inter Tropical Convergence Zone (ITCZ). In ASAL areas, the mean annual rainfall ranges from 200 mm (ACZ VII) to 900 mm (ACZ IV). Rainfall occurrence is primarily bimodal with two distinct rainy seasons (short and long rains). The short rains account for about 65 % of the total annual rainfall. ASAL rainfall though low and erratic, occurs in high intensities of short duration and is highly erosive. High amounts of runoff are often generated from these storms due to inherent low infiltration rates of the soils. Surface runoff is mainly the result of soil surface sealing during rainstorms. Concentrated runoff flows are responsible for the severe erosion that occurs in these marginal rainfall areas. Potential evaporation ranges from 1450 to 2200 mm.

2.1.2 Soils

The most dominant soils of ASAL (Luvisols/Acrisols and Vertisols) are considered to be problematic because their physico-chemical properties limit their uses for agricultural purposes. The problems associated with these soils and that which limit agricultural production are salinity, sodicity, poor drainage, soil erosion and low soil fertility. Except for the vertisols, the other two soils have unstable structures and are characterized as having a fairly low organic matter content, low water retention capacity, very strong surface sealing and crusting properties and high erodibility. Surface sealing and crusting properties are enhanced by the high intensity, short duration rainfall. The formation of surface sealing and crusting is caused by the breakdown in soil aggregates and the dispersion of soil clays after getting exposed to the beating action of falling raindrops.

The effects of clay and silt content on aggregate stability and crust formation have been studied. Soils with more than 20% clay were found to be the most sensitive to crust formation and had the lowest infiltration rate (Ben-Hur et al., 1985). With increasing percentage of clay, the soil structure was more stable and had a low formation of crusts. In soils with low clay content (<20%), the stability of aggregates diminished. When exposed to rainfall, soils with unstable structure (due to low clay content, moderate ESP, low sesquioxides content) will form a crust when rained upon with rain of low impact energy. Conversely, soils with stable structure may form a crust only under rain with high intensity.

The soils of ASAL have clay content range of 10 - 20% (Luvisols and Acrisols) to 50% (Vertisols). The sesquioxides and organic matter contents and ESP vary with soil types. From the foregoing properties, it is clear that the luvisols and acrisols have soil crusting problems. The thick soil crusts that develop significantly reduce rain infiltration. Depending on the soil type, up to 70% of rainfall may be lost as surface runoff. Soil crusting also inhibits the emergence of small seeds (e.g sorghum and millet).

The dominant clays of Luvisols/Acrisols are usually of the 1:1 ratio (Kaolinite). Water infiltration in the soils is rather low especially in the B horizons where the textures are heavy. The management of these soils requires deep ploughing (to break the crust and subsoil hardpan) and addition of organic matter content from residue mulch or organic manure. Luvisols/Acrisols are often cropped during the rainy season. Vertisols are characterized as deep soils having moderate to high salt and sodium content, montmorillonitic (2:1) clay mineralogy, and low infiltration rates (due to swelling when wet). Structural tillage practices are not feasible on Vertisols due to their unstable structure (2:1 clays). Vertisols are usually cropped after the rainy season.

Overall, tillage management requirements of these three soils would depend on clay mineralogy, workability, moisture holding capacity and other soil characteristics.

Luvisols/Acrisols have a compact subsoil layer (argillic horizon) due to an increase in clay content from A to B. These soil problems (especially the sealing and crusting) are known to affect seedling emergence, decrease rain infiltration and consequently result in high surface runoff rates (with minimal soil loss unless the soils are disturbed and have a cloddy top soil structure).

Vertisols, due to their swelling and shrinking properties, affect crop root development when dry and infiltration when wet. These soils are workable immediately after the rainy season (under optimum soil moisture conditions) when the soils are loose and crumbly and hence requiring low draught per unit area.

2.1.3 Cropping Systems

The major crops grown in ASAL areas include maize, beans, sorghum, millet, cassava, pigeon peas, sweet potatoes, cowpeas, groundnuts and cotton. Crop performance and yield are significantly influenced by the amount of rainfall and distribution throughout the rainy season. Due to inherent soil moisture deficits, the period of cropping is limited to the rainy season. The potential length of growing

season as determined by the long and short rains influences the choice of crops in these areas. Most crops are grown during the short rains since more rainfall occurs within this period. Intercropping is a very common farming practice as it minimizes the risks of crop failure due to unexpected soil moisture deficits. Usually combinations of two or three crops are evident in most of these areas.

2.1.4 Land Productivity

During the past two to three decades, human and livestock population in arid and semi arid areas of Kenya has significantly increased and consequently led to an over exploitation of the limited land resources. Soil and vegetative degradation have become widespread due to overgrazing, deforestation, burning and over cultivation. Accompanying this unprecedented population increase, is the fragmentation of landholdings and sedentarization of pastoralists who have destabilized the very fragile ecology of the areas. This has adversely affected food and fodder production and left the entire population vulnerable to food and fibre shortages. Unpredictable weather conditions have exacerbated the problems and further eroded the production potential of the resource base.

2.2 Available Tillage Technologies

Traditional tillage and residue management methods that are widely practised in this region, include slash and burn, residue mulching, ridging, mixed cropping, conventional tillage (hand hoeing), crop rotation and shifting cultivation. Additionally, new conservation tillage methods like zero tillage (no till), terracing, cover cropping, intercropping, contour buffer stripping, tied ridging, contour bunding and ploughing have been introduced to optimize soil conditions for improved crop performance and yield. Most of these tillage operations involve high energy inputs (labour intensive; use of hand tools) both in construction and maintenance.

The applicability of these tillage practices depends on soil properties, climatic conditions, types of crops to be grown and socio economic conditions of the beneficiaries (smallholder farmers). For instance, contour bunds and ridges have proved to be very effective in marginal rainfall areas where rainfall intensities and runoff rates are high. These structures are recommended for stable soils with surface sealing and crusting properties and low water intake rates. Contour bunds and ridges are expected to impound the runoff and increase the infiltration opportunity time of the soil.

In conventional tillage, farmers use hand hoes to break the land upto a depth of 20 cm often leaving large soil clods at the surface. Where the clods are too large and the weeds have grown, harrowing to break the clods and remove the weeds is recommended. Often conventional tillage involves primary tillage operation with no secondary tillage until weed control.

Minimum tillage operations often involve strip tillage (narrow strips of 20 cm width cut along the planting rows) or spot tillage (where planting holes of size 10 x 10 cm are made using hand hoes). Minimum tillage is also practised using the traditional slash and burn techniques.

Contour buffer strips of widths of 1 to 2 m are often combined with contour ridges to check runoff and soil loss. Tied ridging at 2 to 3 m spacing along the furrows is usually done before the onset of the rains to avoid any breakages of ridges due to concentrated runoff flows.

Crop residues are either placed on the soil surface (to dissipate rain energy and reduce surface sealing effects) or incorporated into the soil (ridges and furrows) as a means of supplementing organic matter deficiencies and improving the water holding capacities of soils.

2.3 Available Land Potential

Despite the many inherent physico-chemical problems, ASAL soils are of high agricultural potential. The major limiting factor to optimum crop production is soil moisture. The low soil moisture conditions in these areas are attributed to low infiltrability (due to surface sealing and crusting; and low organic matter content) and subsequent high runoff rates. Relatively low, erratic and poorly distributed rainfall and high evaporation water losses in these areas have also significantly contributed to this soil moisture deficit.

There is scope for improving soil moisture management through tillage and residue management techniques that would harness runoff water losses and conserve in the soil in situ to sustain crop growth. These techniques should be adapted to area specific crop and fodder production conditions. Considerably better crop and fodder yields can be obtained through simple improvements in the management of available rainfall and soils. Tillage practices recommended should focus on the improvement of physical soil properties to reduce surface runoff and conserve more soil moisture.

2.4 Available Research Data

For purposes of selecting appropriate tillage and residue management techniques, sufficient hydrological and soils data are available on some ASAL areas. Rainfall and temperature are measured at many locations. These data are available from responsible government departments/research centres and other organizations. The Ministry of Water Development and the Department of Meteorology have good reports on climatic data taken within the research project area. Other sources of information include the Farm Management Handbook of Kenya. Kenya Soil Survey (KSS) and the Department of Remote Sensing and Mapping (former KREMU) have reports on the soils; vegetation and land use. When choosing appropriate tillage and residue management techniques, site specific data have to be measured especially on infiltration, runoff, rainfall intensities and duration, and physical and chemical soil properties.

3. MATERIALS, EQUIPMENT AND METHODOLOGY

3.1 Materials and Equipment

3.1.1 Characterization of Soils

Augerings were made randomly at the site and composite samples taken to a maximum depth of 150cm. The following properties were examined from the soil samples taken: colour, structure, pH, consistency, depth and texture. A profile pit was dug at the site and soil samples were taken for laboratory analysis. Infiltration and hydraulic conductivity tests at the site were conducted using a disc permeameter.

The soil type at the experimental site was then classified as a *sandy clay loam orthic Luvisol.* This soil was structurally unstable as depicted by a rapid breakdown in soil aggregation when exposed to intense rainstorm events. This instability was attributed to the inherent low organic matter content of the soil.

3.1.2 Farmyard Manure

Farmyard manure application rates of 5 and 10 tonnes per hectare were used as soil amendments on the soil type. This farmyard manure was a mixture of cow dung and grass straws with distinct chemical properties.

3.1.3 Disc Permeameter

The disc permeameter is a three dimensional flow equipment used for in situ measurement of infiltration and hydraulic conductivity. This equipment involves minimum soil disturbance during flow, is relatively rapid, robust, easy to use and is relatively cheap. The disc geometry minimizes the effect of capillarity and hence is biased towards flow in the vertical direction as is the case with infiltration and hydraulic conductivity. The permeameter is designed for accurate control of pressure

at the supply surface. This permits macropores of various sizes to be included in or excluded from the flow process. The disc is often placed against the soil surface (with suitable contact material where necessary) and three dimensional flow commences. Sorptivity is determined from the early stages of flow.

For steady state flow (final infiltration rate), at least ten measurements should be taken to ensure that an accurate value is obtained. To calculate the hydraulic conductivity, the sorptivity, steady state flow rate, the initial volumetric moisture content and volumetric moisture content at the supply potential are required.

3.1.4 Neutron Moisture Probe

The neutron moisture probe consists of a shield, a detector tube, a preamplification circuit to send a signal from the detector and a counting device. The neutron source is often a Radium/Americum-Beryllium mixture. The count rate gives the water content on a volume basis through the use of a calibration curve provided by the manufacture or plotted from wet and dry calibration measurements taken in the field.

The Americum Beryllium mixture (radioactive source) emits fast moving neutrons which are slowed down by water in the immediate surrounding (often about 15 - 10 cm from the probe). The neutron moisture probe can be used for frequent moisture determinations in the field without disturbing the soil as in gravimetric sampling. The neutron scatter method of measuring soil water content gives the amount of water on a volume basis. It also allows repeated measurements to be taken at a given place with minimum disturbance of the soil profile.

For the most precise measurements, the neutron probe should be calibrated for areas that are exceptionally high in clay, organic matter or any material containing high concentrations of hydrogen or other light weight elements.

3.1.5 Cone Penetrometer

A hand held cone penetrometer for top soil layers (type 1B, Eijkelkamp Equipment) was used in this study. This instrument measures the penetration resistance by means of a compression spring.

There are two cone types (0.25 cm^2 and 0.5 cm^2) and three kinds of compression springs (50 N, 100 N and 150 N). A particular combination of a cone and a compression spring can be selected depending on the penetration resistance to be expected.

The spring within the penetrometer is compressed when the cone encounters a resistance as it is driven into the soil. A slip ring on a graduated scale is taken along as the spring is compressed and so it indicates the maximum compression measured. Using spring constants and cone areas, the compression can be translated into penetration resistance.

3.1.6 Runoff and Sediment Collection Equipment

The runoff collection equipment used in this experiment, consisted of sheet metal borders around the 2 m^2 plot size, a collecting trough, a PVC pipe to convey the runoff and suspended sediment into the collector. The collector used in each experiment plot comprised of a 200 litre metallic drum and a 20 litre plastic container.

3.1.7 Neutron Probe Access Tubes

In each plot, two access tubes 30 cm from each end were installed to a maximum depth of 120 cm or lower depending on where the stone line was located. The stone line was so variable that it was impossible to reach a depth of 120 cm in some of the plots. The inner and outer diameters of the tube were 48 mm and 50 mm respectively.

3.2 Experimental Methodology

3.2.1 Experimental Procedure

This experiment was based on a completely randomized design. Each block was representative of the soil type and consisted of four treatments: conventional tillage using a forked hoe, zero tillage with no manure, conventional tillage with 5 tonnes/ha of farmyard manure, conventional tillage with 10 tonnes/ha of farmyard manure. Each treatment was replicated three times

This experiment was based on a completely randomized design. Each block was representative of the soil type and consisted of four treatments: conventional tillage(CT) using a forked hoe, zero tillage(ZT) with no manure, conventional tillage with 5 tonnes/ha of farmyard manure(5 FYM), conventional tillage with 10 tonnes/ha of farmyard manure(10 FYM). Each treatment was replicated three times resulting in a total of 12 runoff plots for the experiment. In each plot, infiltration and hydraulic conductivity, profile soil moisture, penetration resistance, shear strength measurements were taken using a disc permeameter, neutron probe, cone penetrometer and shear vane apparatus respectively. Profile soil moisture was monitored in each plot through two access tubes installed 30 cm from each plot end and to a maximum depth of 120 cm or lower depending on where the stone line was located. A runoff and sediment collection assembly consisted of a collecting trough, a PVC pipe, a 200 litre metallic drum and a 20 litre plastic container.

The neutron probe that was used at the site was calibrated for the 25-80 cm and 80-120 cm depth ranges (see Figure 1). The two calibrations were necessary because of the prevalence of iron concretions in lower soil horizons.

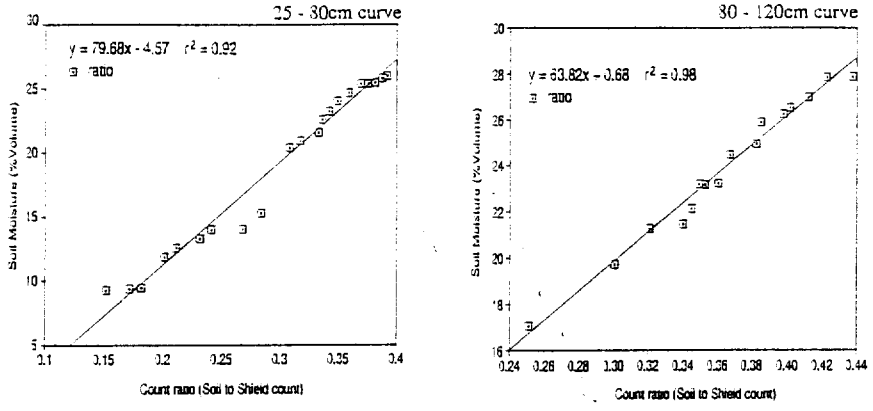

Fig. 1. Neutron probe calibration curves (25 - 80 cm; 80 - 120 cm).

Collection of data involved soil moisture which was determined down the profile on a weekly basis in every plot using a neutron probe. Rainfall was recorded on a storm basis using two rain gauges (manual and recording) installed at the site. Rainfall intensity and distribution was obtained from the recording rain gauge. Runoff and soil loss were monitored on a storm basis. Bulk density was determined for two depth ranges of 0-15 cm and 15-30 cm at the beginning and at the end of every season. Penetration resistance was measured at selected time intervals within a rain season. Soil shear strength was measured on a weekly basis using a shear vane apparatus. Soil aggregate stability was determined using the wet sieving method. Infiltration after each rainstorm was taken as the difference between rainfall and runoff. The saturated hydraulic conductivity at the site was determined in situ using a disc permeameter. During each rainstorm, there was minimal evaporation since the relative humidity was high. After the onset of the rains, and subsequent breakdown in soil macrostructure, surface storage on the plots became negligible.

The analysis of collected data was conducted using two statistical methods, analysis of variance (ANOVA) and regression analysis. All these analyses were based on a 5% level of significance. The variables analyzed included; treatment, runoff, soil loss, infiltration and rainfall amount. The least significant difference (LSD) at 5% level of significance was used to determine the differences between the treatments.

3.2.1.1 Experimental Treatments

Farmyard Manure .The farmyard manure used was a mixture of cow dung and grass straws obtained from the Dairy Farm at the Research Station. Respective quantities of 5 and 10 tonnes per hectare of air dry manure were weighed, spread evenly and then incorporated in the soil in the appropriate plots at the beginning of each season.

Conventional Tillage. This was achieved using a forked hoe. It involved one tillage operation that was carried out at the beginning of each season. Thereafter no more tillage was done. Weed control was achieved by manually uprooting the weeds.

Zero Tillage. Zero tillage was achieved by leaving the soil weed free and undisturbed. As was the case with the other three treatments, the soil was left bare to eliminate the effect of crop cover on soil loss and runoff. Hence it served as a control representing extremes in runoff and soil loss.

3.2.1.2 Installation of Access Tubes

Two aluminium access tubes were installed so that they could be used for dipping the neutron probe. The aluminium access tubes were installed at the centre of every plot to a maximum depth range of 90 to 120 cm. Before the installation of these tubes, a special auger, slightly undersized with a diameter slightly less than that of the access tubes was used to prepare the auger hole. This was done to ensure that the interface between the soil and tube was air tight and hence there would be no possibility of downward water movement along the tube.

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3.2.1.3 Calibration of Neutron Moisture Probe

This was done for both wet and dry runs. The access tubes used for the calibration were installed outside the experimental plots. The tubes were left in the ground for three weeks to ensure that the soil around the access tube settled. For either of the two calibrations, three access tubes were used.

For the wet calibration, a drum was opened on both sides and then cut into two equal parts transversely. One half of the drum was put around the access tube and driven into the soil to a depth of about 20 cm. The diameter of the drum was 1 m. Water was then poured in the installed drum and allowed to pond around the access tube for three consecutive days after which ponding was stopped and soil moisture allowed to redistribute within the profile. An area equal to the cross sectional area of the drum was covered by polythene to avoid evaporation.

Probe readings were then taken at various depths after which core samples were taken at the same depth for gravimetric moisture determination. At each depth, three samples were taken. The gravimetric soil moisture of the three samples was averaged and the mean was taken to correspond to the mean probe reading at that depth.

The percentage soil moisture on weight basis was converted to percentage soil moisture on volume basis by multiplying it with the soil bulk density at the given depth. The dry calibration was done at the peak of the dry season using the same procedure as above.

3.2.1.4 Installation of Runoff and Sediment Collection Equipment

The 20 litre capacity bucket was directly placed inside the 200 litre drum below the inflow spout of the drum so as to reduce the time and labour requirements to sample and clean up after rain storms and to improve on the accuracy of volume measurements. The drum had a tight fitting cover to reduce evaporation of water collected in the drum after a rainfall event and was emptied after every rainstorm.

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3.2.1.5 Installation of Disc Permeameter

The disc permeameter was placed on the soil surface with the edge of the steel ring coming into contact with the soil. Any large stones that would interfere with the disc were removed. The ring was inserted about 10 mm into the soil surface making sure that the depth of insertion was constant as this affects the supply potential. In order to ensure that the permeameter was as level as possible on the ring, a spirit level was used. The permeameter was then placed into a bucket of clean water after which the side tube was filled with water to the desired volume. The reservoir tube was also filled with water and ensuring that the one way valve had been wetted to an air tight seal. The permeameter was then carefully placed in the ring. To begin infiltration measurements, the stop cock on the side tube was opened. The stop watch was used to monitor the time taken to empty the water reservoir after all the water in the side tube is drained into the ponded surface.

3.2.1.6 Collection of Data

Soil Moisture. Soil moisture was determined down the profile on a weekly basis in every plot using a neutron probe. The probe was placed on top of the access tube which was about 5 cm from the ground surface. The probe was then switched on and the shield count was read before lowering the detector into the tube. The probe was then switched off, and the detector lowered to the desired depth and the probe switched on again. The soil count readings appearing on the screen were equivalent to the number of thermalized neutrons that had collided with the hydrogen atoms in water. The soil count readings were taken at 30 second intervals. The count ratio was given as the ratio of the soil count to that of the shield count.

Runoff Data and Soil Loss. Rainfall was recorded on a storm basis using two manual rain gauges installed at the site. Runoff after every downpour was collected and the volume measured using a calibrated bucket and a measuring cylinder of capacity 2000 ml. For small rainfall events,the bucket was sufficient for all the runoff. In such a case, water with suspended sediment was decanted from the bucket, its

volume determined, agitated and a sample was taken using sampling bottles of 500 ml capacity. The sludge was weighed, thoroughly mixed and a sample was taken for laboratory analysis. Weighing was achieved using a spring balance. When the sludge was little, it was all taken for laboratory analysis. In each storm, three samples per plot were collected for analysis.

For big runoff events where there was overflow into the drum, the calibrated bucket was used to get out the water. The little water that remained was removed using a rimless plastic bottle. In each bucket of 20 litres, three samples were taken. The samples were then thoroughly agitated and one composite sample taken for laboratory analysis. Where the water in the bucket was less than 20 litres, it was thoroughly mixed and one sample was taken for laboratory analysis.

In the laboratory, the samples were dried at 105°C for 24 hours until there was no more water. The sediment left in the drying dish was then weighed. Suspended sediment was calculated as follows:

$$SS = \left(\frac{Wt_{ds}}{V_{sb}}\right) V_r \qquad [1]$$

Where;

SS = Suspended sediment (g)

V_{sb} = Volume of sample taken in the bottle (litres).

V_r = Total volume of runoff from which the sample was obtained (litres).

Wt_{ds} = Weight of dry sample (g)

The weight of soil in the sludge was calculated as shown below;

$$W_s = \left(\frac{Wt_{ds}}{Wt_{ws}}\right) Wt_{sc} \qquad [2]$$

Where:

W_s = Weight of soil in the sludge
Wt_{ds} = Weight of oven dried sediment
Wt_{ws} = Weight of sample of sludge before oven drying
Wt_{sc} = Total weight of sludge collected in the bucket or drum

The volume of water in the sludge, V_s, was calculated as shown below:

$$V_s = \frac{Wt_b - Wt_a}{Wt_b} Wt_a \qquad [3]$$

Where:

V_s = Volume of water in the sludge (litre)
Wt_{ws} = Weight of wet sludge
Wt_{ds} = Weight of oven dried sludge

Runoff was expressed in mm while soil loss was in g/m^2

Soil Bulk Density. This was determined using undisturbed soil cores of volume 100 cm^3 from the top soil depth. Two cores per plot were taken at each of the two depth ranges of 0-15 and 15-30 cm. Soil samples were taken at the beginning and at the end of every season.

Penetration Resistance. It was not possible to take cone penetrometer readings at the beginning of the season due to lack of equipment. However, later in the season, penetrometer readings were taken. The maximum compression of the spring was in mm from the scale of the penetrometer. Using the spring constant and cone area the compression was translated into cone resistance using the equation:

$$\text{Cone resistance } (N/cm^2) = \frac{\text{total force } (N)}{\text{cone area } (cm^2)} \qquad [4]$$

The cone area was 0.25 cm^2 while the spring constant was 20 N/cm.

Soil Shear Strength. Soil shear strength was measured on a weekly basis using a shear vane and it was expressed in kPa.

Soil Aggregate Stability. Aggregate stability was determined using wet sieving to determine the water stability of the aggregates. A representative sample of air dry aggregates were passed through a 2 mm sieve which was placed on the uppermost level of a set of graduated sieves (1.00 mm, 0.5 mm, 0.212 mm and 0.063 mm). A spray of water was applied and the sieves were shaken for ten minutes after which they were oven dried. The oven dry weight of the soil left on each sieve was determined. The results obtained were correlated with the coarse primary particles retained on each sieve to avoid designating them falsely as aggregates. This was done by dispersing the material collected from each sieve using a mechanical stirrer and a dispersing agent (Calgon). The soil sample and the dispersing agent were stirred for 10 minutes. The material was passed through the same sieve and washed until only sand was retained or clear water was coming out of the sieve. The sample was then dried and weighed. The weight of sand retained after the second sieving was subtracted from the total weight of the undispersed material retained after the first sieving. The percentage of water stable aggregates, %SA was calculated as follows:

$$\%SA = 100 \times \frac{(wt.\ retained) - (wt.\ sand)}{(Total\ Sample\ wt.) - (wt.\ sand)} \quad [5]$$

Infiltration. The amount of rainwater that had infiltrated into the soil after each rain storm was taken as the difference between rainfall and runoff. During each rainstorm, there was minimal evaporation since the relative humidity was high. Surface storage on the plots was negligible because the soil surface was almost smooth.

Using a disc permeameter, the infiltration rate at predetermined scale increments on the reservoir tube were recorded. Recording continued until flow became steady (i.e. the time when scale increments did not change). At least ten measurements were taken to ensure that an accurate value for steady state flow rate was obtained. Several reservoir volumes were required before steady state flow was reached.

At the end of the infiltration measurements, the stop cock was closed and the permeameter removed. The water level in the ring was observed and a soil sample taken off the surface with a spatula. The samples were then placed in an air tight container for the determination of saturated hydraulic conductivity.

Cumulative infiltration at any time, t, is the total amount of water, Q, that has gone into the soil at time, t, divided by the cross sectional area, πr^2 (area of the ring). Cumulative infiltration was calculated by:

$$\frac{Q}{\pi r^2} = (SR - SR_i)\frac{RC}{\pi r^2} \quad [6]$$

Where SR is scale reading at the time of measurement; SR_i is the initial scale reading and RC is the reservoir calibration.

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Sorptivity, S_o was calculated from the initial time data. $Q/\pi r^2$ on the Y axis was plotted against the square root of time $t^{0.5}$ on the X axis. The slope of the straight line was the sorptivity and had the units of length/time.

The steady state flow rate, $q/\pi r^2$, was found by plotting the cumulative infiltration during the last part of the experiment as a function of time.

Soil Hydraulic Conductivity. The saturated hydraulic conductivity at the site was determined in situ using a CSIRO disc permeameter which had been calibrated to give the volume of water per scale reading. The initial soil water content and bulk density were needed to calculate the hydraulic conductivity and were obtained from soil samples taken prior to the beginning of the experiment. Three samples were taken for each infiltration measurement.

The hydraulic conductivity was given by:

$$K_o = \frac{Q}{\pi r_o^2} - \frac{4bS_o^2}{\pi r_o(\theta_o - \theta_n)} \qquad [7]$$

Where r_o is the radius of the ring, θ_n is the volumetric moisture content at the measurement potential, θ_o is the volumetric moisture content at the initial potential and b is approximately 0.55.

Macroscopic capillary length was calculated as shown below:

$$\lambda_c = \frac{bS_o^2}{(\theta_o - \theta_n)K_o} \qquad [8]$$

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The mean pore size was given by:

$$\lambda_m = 7.4/(\lambda c) \quad [9]$$

Both the pore size and the capillary length were expressed in mm.

3.2.1.7 Analysis of Data

Two methods of data analysis used in this study included analysis of variance (ANOVA) and regression analysis. All these analyses were based on a 5% level of significance. The variables analyzed included; treatment, runoff, soil loss, infiltration and rainfall amount.

The least significant difference (LSD) at 5% level of significance was used to determine the differences between the treatments.

4. RESULTS AND DISCUSSION

4.1 Bulk Soil Properties at Site

Soil physical and chemical properties at the Experimental Site are given in Table 1. The soil properties considered included soil bulk density, soil textural composition and organic matter at various depths. An increase in clay down the profile was observed leading to textural changes from sandy clay loam to clay. The soil had a low organic matter content, decreasing with depth. The percentage of stable aggregates also decreased with depth possibly as a result of the decrease in soil organic matter. Soil bulk density decreased with depth and hence resulting in an increase in soil porosity down the profile. Bulk density of the soil ranged from 1420

kg m^{-3} in the top 15 cm to 1340 kg m^{-3} in the 60-100 cm horizon. The high bulk density in the top horizons was attributed to physical degradation (compaction) due raindrop impact. Changes in percent organic matter, bulk density and texture with depth were consistent with the changes in moisture characteristics for the different soil horizons.

Table 1. Soil properties at the experimental site.

Soil Profile Depth (cm)	Bulk Density kg m^{-3}	Soil Textural Composition			Organic Matter Content (%)	Textural Class
		Sand 2-0.05mm	Silt 0.05-0.002mm	Clay <0.002mm		
0-15	1420	67	5	28	1.6	SCL
15-35	1400	64	7	29	1.4	SCL
35-60	1370	57	8	35	0.7	SCL
60-100	1340	51	8	41	0.6	SC

Field capacity moisture varied from a maximum of 26% at the 0-10 cm depth to a minimum of 22% at the 30-60 cm depth (see Table 2). Maximum field capacity moisture was observed at the 10-30 cm depth (27%). The high field capacity moisture at the 0-30 cm depth was attributed to the high organic matter content relative to the other horizons.

Available soil moisture decreased with depth as a result of an increase in clay content down the profile. Thus the highest available water was in the 0-10 cm depth while the lowest was in the 60-100 cm depth.

Table 2. Soil Moisture Status in the Profile

Depth (cm)	Field Capacity (%)	Wilting Point (%)	Available Water (%)
0-10	26	9	17
10-30	27	13	14
30-60	22	11	11
60-100	24	15	9

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4.1.1 Infiltration and Moisture Retention Characteristics

After the onset of the rains, rainwater from the first eight storms infiltrated into the soil since there was no runoff. Under all treatments, infiltration was observed to decrease with time. The highest infiltration amount was observed under 10 FYM followed by 5 FYM, CT and ZT. The high volumes of surface runoff were attributed to the inherent low aggregate stability and subsequent surface sealing and crusting properties of the soil. No significant differences in infiltration between ZT and CT were observed.

Hydraulic conductivity varied from moderate to moderately rapid. The highest hydraulic conductivity values were observed under 10 FYM (70 mm/hr) while the least hydraulic conductivity was under CT (58 mm/hr). 5 FYM and ZT had hydraulic conductivities of 66 mm/hr and 57 mm/hr respectively. ZT had the least hydraulic conductivity followed by CT. More water was retained at saturation under CT (44%) than under ZT (41%). 5 FYM and 10 FYM retained 47% soil moisture at saturation.

Soil moisture held in the profile increased with depth at all suctions (see Table 3). This was consistent with the soil texture and bulk density changes with depth. Clay content was highest at lower horizons while sand content was highest in the top 0-15 cm. The high water holding capacity of clay did explain the high water content held at lower soil horizons (40.6% clay and 51.4% sand) as compared to the 0-10 cm soil depth (27.9% clay and 67.2% sand).

Table 3. Profile soil moisture release characteristics of a luvisol.

Depth	% Volumetric Moisture Content						
	Suction (bars)						
	0.00	0.10	0.50	1	5	10	15
10	40	33	26	15	12	11	9
30	43	29	22	16	13	12	11
60	45	34	27	17	15	14	13
100	47	38	24	20	16	16	15

At low suctions (0.1 bars), there was more water held in the FYM treatments than the other treatments. At high suction (15 bars), the treatment differences in soil moisture became negligible. Thus the effect of farmyard manure on soil moisture release characteristics decreased at high suctions (see Table 4).

Table 4. Treatment soil moisture release characteristics.

Treatment	% Volumetric Moisture Content						
	Suction in Bars						
	0.00	0.10	0.50	1	5	10	15
10 FYM	46	35	22	22	20	18	13
5 FYM	44	34	21	20	18	17	14
CT	41	32	20	20	17	15	14
ZT	41	31	18	17	16	15	14

4.1.2 Soil Moisture and Bulk Density

The trend of soil moisture in the top soil depth (0-10 cm) was more or less similar under all treatments (see Figure 2), though the seasonal soil moisture kept on fluctuating as a result of wetting due to rainfall and drying during the dry spells. Variation of soil moisture with time was more pronounced in the 0-10 cm range as

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compared to the 0-100 cm range. In both depth ranges, the highest soil moisture content was observed under 10 FYM followed by 5 FYM, CT and ZT. The soil moisture down the profile was low at the onset of the rains possibly as a result of the previous dry season. Under all treatments , the peak profile soil moisture was observed in January and November coinciding with the period of maximum rainfall.

Down the profile (0 - 100 cm), maximum soil moisture was observed under 10 FYM, followed by 5 FYM, CT and ZT. As the short rains season continued, the differences in soil moisture between CT, ZT and 5 FYM became negligible (see Figure 3). Soil moisture down the profile was lowest at the onset of the rains. This was attributed to the past dry season (April to October). Field capacity moisture conditions (248 mm in the first metre depth) were never reached even in January when 270 mm of rainfall were received. This was attributed to the high runoff generated from the bare runoff plots. Evaporation from the surface could also have contributed to the soil moisture deficit. Despite the low profile soil moisture within the study period, crop performance in the area was very good and farmers had bumper maize/bean harvests.

The observations in profile soil moisture were consistent with the observed trends in treatment runoff. The high soil moisture content under 10 FYM and 5 FYM can be attributed to the addition of farm yard manure. Farmyard manure improved soil aggregation and hence increased the water retention capacity of the soil.

During the study period, the highest bulk densities were observed under ZT followed by CT, 5 FYM and 10 FYM (see Figure 4). The high bulk density observed under ZT can be attributed to soil compaction as a result of rain drop impact. The relatively low bulk density under 5 FYM and 10 FYM can be attributed to the incorporation of farmyard manure into the soil.

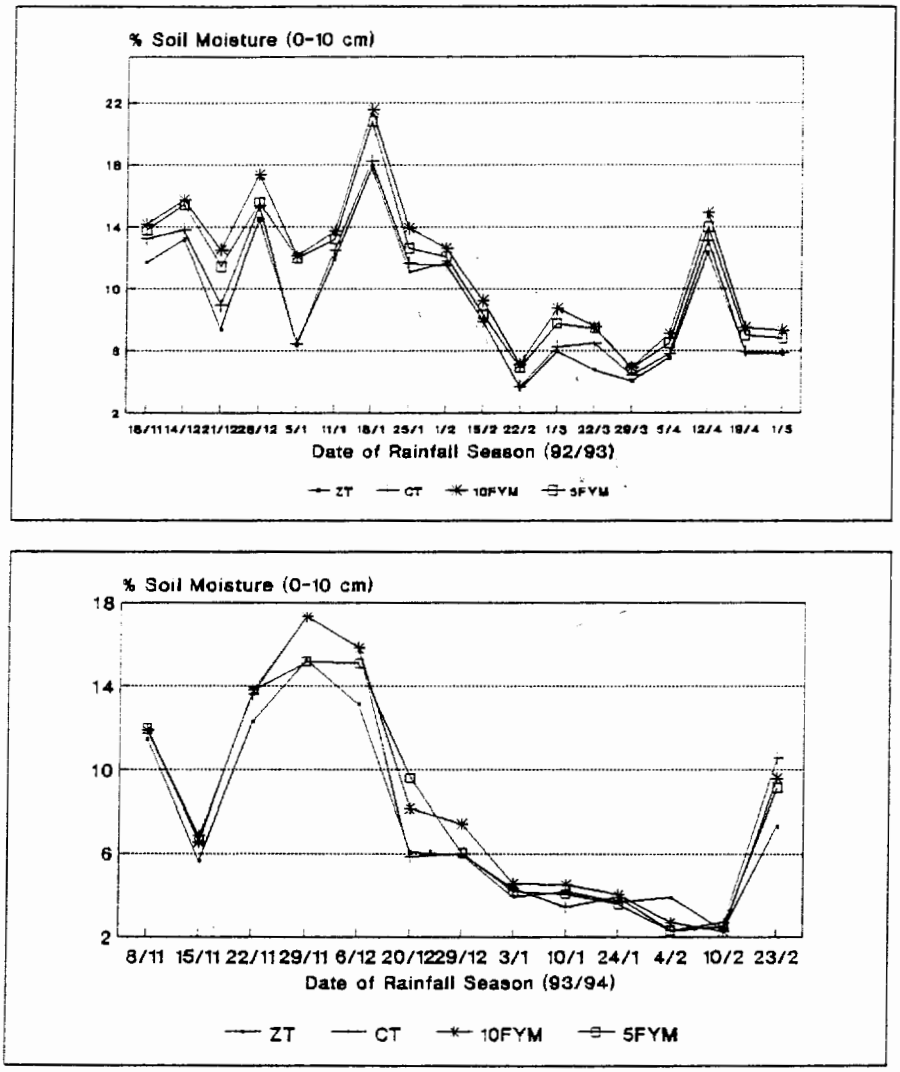
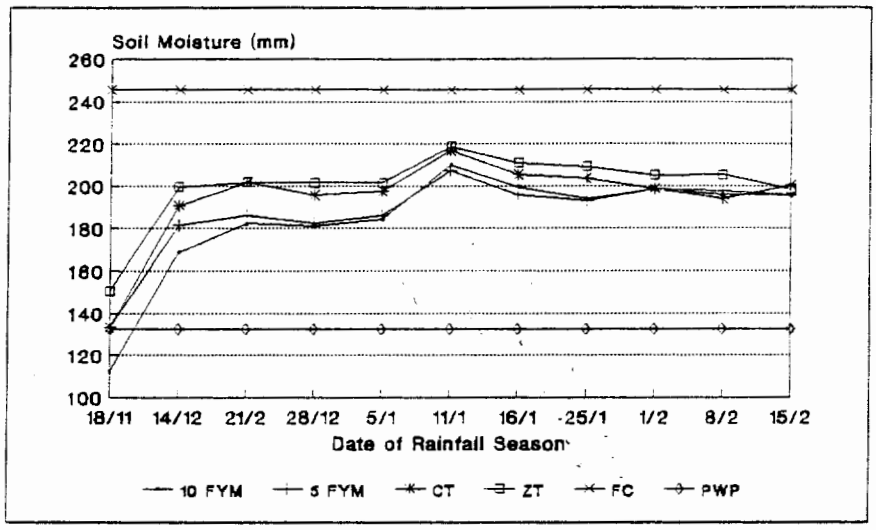


Fig. 2. Seasonal variation in soil moisture (0-10 cm), 1992-94.



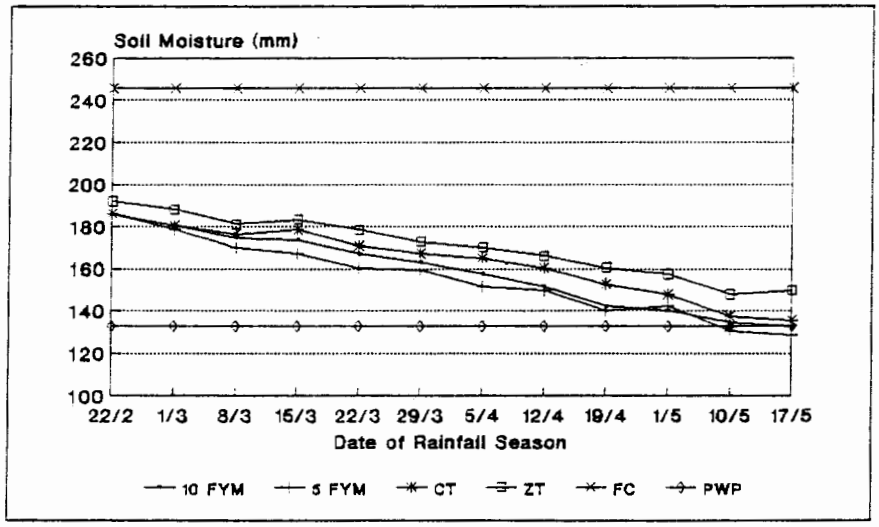
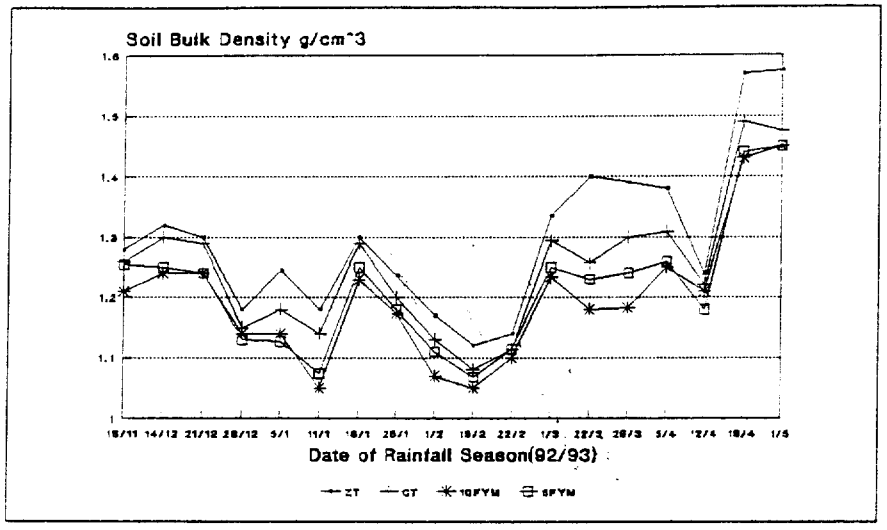


Fig. 3. Treatment effects on profile soil moisture (0-100 cm), 1992-93.



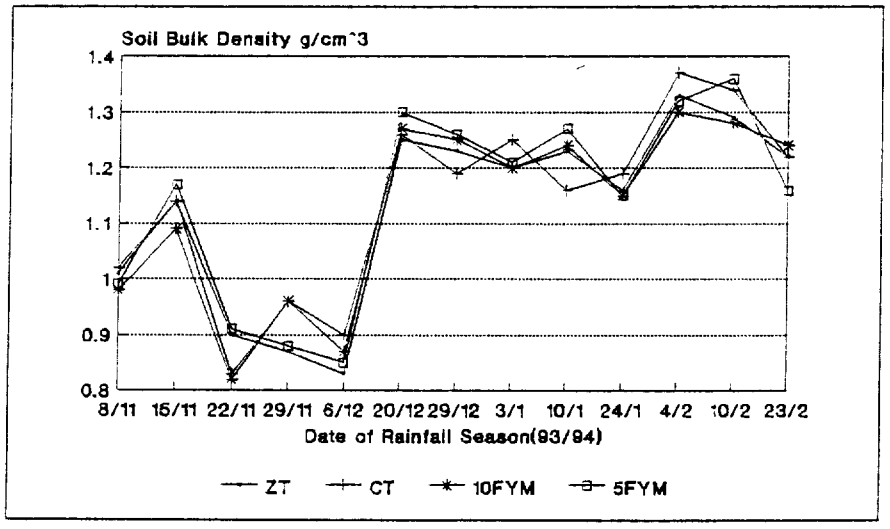


Fig. 4. Seasonal variation in bulk density, 1992-94.

For all treatments, the least bulk density was observed on 22/11/93 and 6/12/93 after some dry spell. High bulk densities were observed at the end of each rainfall season. During the long rains period of 1993, the soil moisture was fairly low because the rainfall was sparsely distributed and of low amounts.

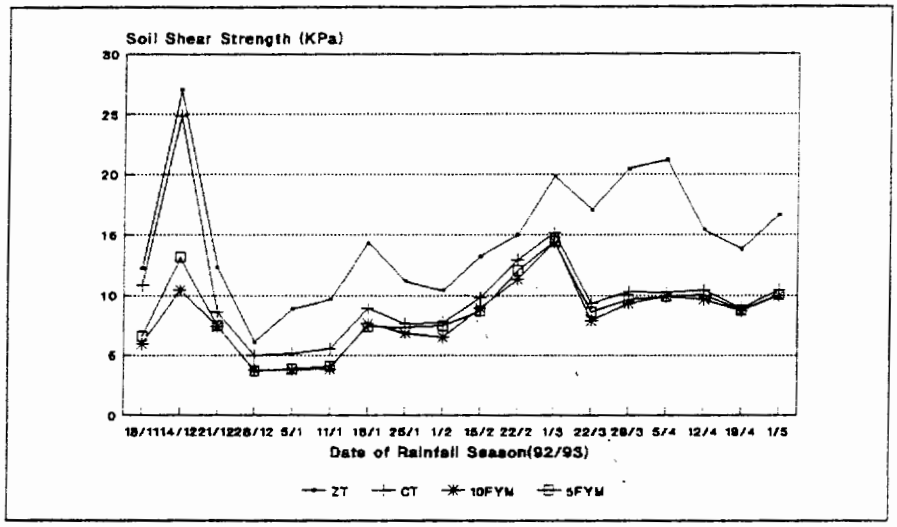
Generally, soil bulk density tended to increase under low moisture conditions (end of season) and to decrease under high soil moisture (after a rainstorm). High bulk density is known to impede root growth leading to poor water and nutrient extraction from deep soil horizons. It also leads to inadequate aeration and subsequently to poor crop performance.

4.1.3 Soil Shear and Crust Strengths

The highest values for soil shear strength of the zero tillage treatment were recorded at the beginning of the season (see Figure 5). During the experimental period, soil shear strength under ZT remained relatively higher than under the other three treatments.

Though seasonal variations in soil shear strengths were observed, they were less pronounced when compared to variations in bulk density and soil moisture content. Bulk density and soil shear strength tended to follow a similar trend with bulk density increasing when soil shear strength was increasing and vice versa.

Given the low aggregate stability of the soils, surface sealing and subsequent crusting did occur especially after high energy storms. A storm of 46 mm received on 13/3/93 nearly destroyed all the clods in the treatments. The breakdown in soil macro structure resulted in surface sealing and crusting and hence the increase in soil shear strength.



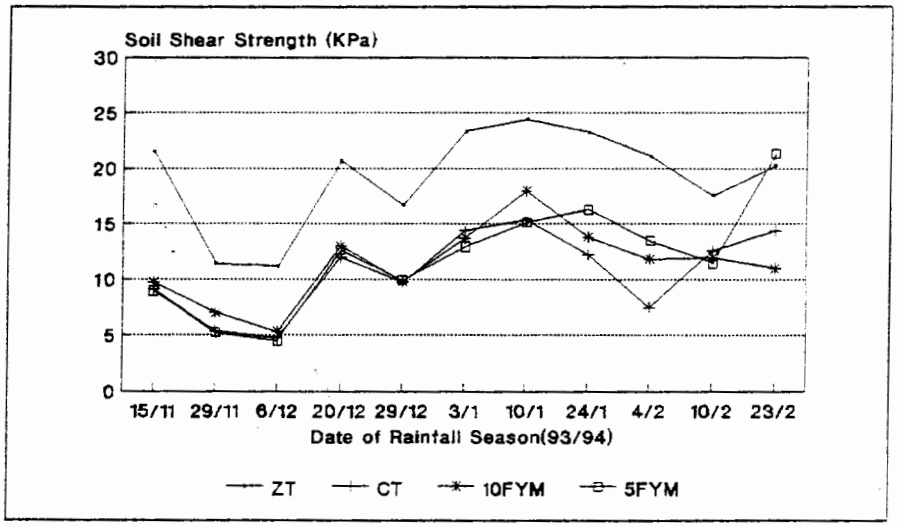


Fig. 5. Treatment variation in soil shear strength, 1992/93.

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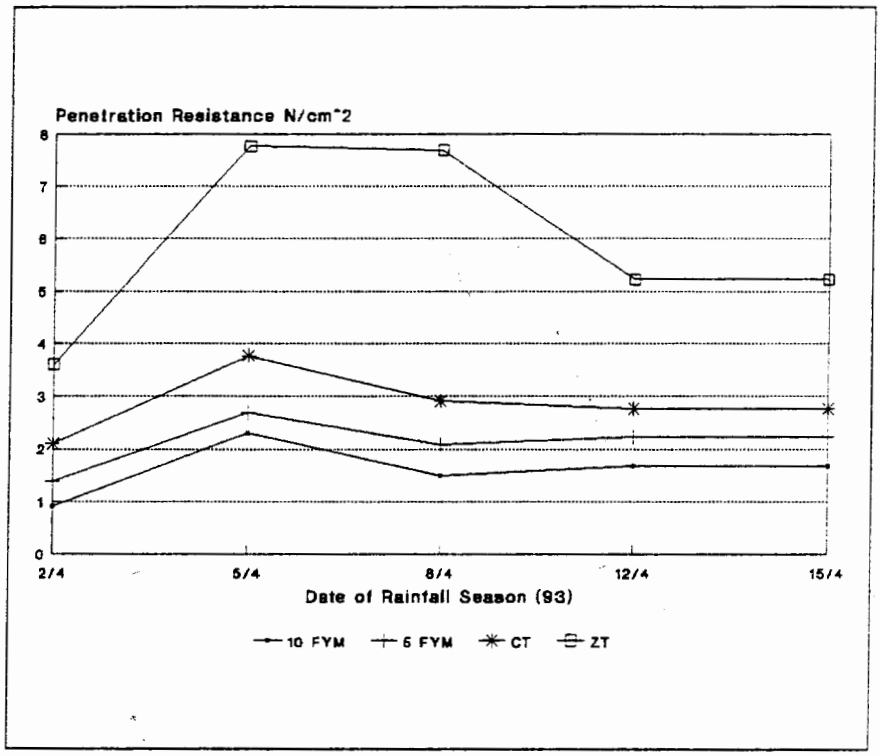

Fig. 6. Treatment differences in penetration resistance, 1992/93.

Resistance to penetration was found to be highest under zero tillage followed by conventional tillage, 5 FYM and least under 10 FYM. Penetration resistance was influenced by soil moisture. The first penetrometer readings were taken on 2/4/93 after a storm of 12 mm on 1/4/93. It was at this time that the lowest resistance to penetration was recorded. Penetration resistance increased steadily and peaked on 12/4/93 for all treatments. On 18/4/93, a decline in resistance to penetration was

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observed for all treatments. This could have been as a consequence of the 3 mm and 20 mm of rainfall received on 16/4 and 17/4/93 respectively (see Figure 6).

4.1.4 Soil Organic Matter Content and Aggregate Stability

Soil organic matter under all treatments was very low (see Table 5). This could have been the cause of the low stability of aggregates observed. As expected, the highest amount of organic matter (1.7%) was found in the soil where 10 tonnes of farmyard manure had been applied followed by 5 FYM (1.6%), CT (1.6%) and ZT (1.5%).

By the end of the season, organic matter under all treatments had decreased, the highest decrease being under conventional tillage treatment. The decline in organic matter under was largely attributed to the high quantities of top soil that were lost through runoff. The high temperatures at the study area could have also contributed to loss of organic matter through oxidation.

The percentage of stable aggregates ranged from 26% (10 FYM) to 11% (CT). The percentage of stable aggregates under 5 FYM was 20% while that under ZT was 12%.

Table 5. Seasonal treatment differences in soil organic matter content, 1992/93

Treatment	Initial Organic Matter(%)	Final Organic Matter(%)	% Reduction in Organic Matter
10 FYM	1.7	1.6	0.1
5 FYM	1.6	1.5	0.1
CT	1.6	1.4	0.2
ZT	1.5	1.4	0.1

The low stability of aggregates was attributed to the low organic matter content of the soil observed at the site. The relatively high aggregate stability under 10 FYM and 5 FYM was attributed to the addition of farmyard manure which led to increased soil organic matter content. If soil aggregation is improved, the breakdown of soil

clods can be reduced. In this way a rough surface can be maintained especially during the initial stages of the season. This would then facilitate depressional storage and hence increase the infiltrability of the soil and decrease runoff and soil loss.

4.2 Seasonal Rainfall

Recorded storm rainfall varied between 0.5 mm and 70 mm with a mean of 12 mm and standard deviation of 17 mm. The highest amount of monthly rainfall was received in January (269 mm). This rainfall was five times as much as the long term mean of 50 mm for that month (see Figure 7). Over the experimental period, the maximum storm duration recorded was 10 hours and 48 minutes with a rainfall amount of 24 mm while the minimum storm duration was 6 minutes and a rainfall amount of 1 mm. The mean storm duration was 2 hours and 30 minutes.

From October to December, a total rainfall amount of 404 mm was received and this was much higher than the seasonal average of 286 mm (27 years record). The total rainfall received in the short rains period of October 1992 - February 1993 was 767 mm compared to the 27 years mean of 379 mm (see Figure 7). During the study period, the short rains peaked in January 1993 and not in November as expected. The month of April, which is often the peak of the long rains received only 38 mm of rainfall, far below the monthly average of 144 mm (27 years record).

During the short rains period, the rainstorms were well distributed. It was raining continuously for several days after an interval of two to seven days during the first 35 days (see Table 6). Towards the end of the crop growing season (February), the rains that fell were not utilized by the crop which had dried and was being harvested. Nevertheless, the farmers reported having had the highest maize/bean yields in a period of ten years.

Table 6. Distribution of seasonal rainfall, 1992/93

Date	Days of consecutive rainfall	Rainfall (mm)
28/10 - 1/11	4	10
3/11 - 6/11	4	38
11/11 - 15/11	5	41
17/11	1	1
23/11 - 25/11	3	10
28/11 - 1/12	4	84
7/12	1	4
9/12	1	7
11/12 - 12/12	2	75
14/12	1	7
17/12 - 19/12	3	81
28/12 - 2/01	6	38
6/01 - 10/02	5	49
13/1 - 21/01	9	143
23/1	1	10
26/1 - 1/02	7	78
8/2 - 12/2	5	84
14/2 - 15/2	2	7
13/3	1	46
15/3	1	2
19/3	1	2
23/3 - 24/3	2	7
1/4	1	12
16/4 - 17/4	2	22
19/4	1	4
6/5	1	9
12/5	1	4

At the onset of the long rains period, a storm of 46 mm received on 13/3/93 completely destroyed the soil clods of freshly tilled plots. This was the first rainstorm of the season and it contributed 60% of the erosive rainfall for that period. This was the most intense and erosive rainstorm observed during the entire experimental period.

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Over the long rains season. the rainfall received was not adequate and hence all the crops planted wilted and dried up. Soon after planting on 15/3/93 upto 31/3/93 (18 days), only 12 mm of rainfall was received, giving the crops a poor establishment. From March to May, only 103 mm of rainfall were recorded as compared with a mean of 297 mm (27 years record). Rainfall kept on reducing progressively from January to May. In May, 13 mm were received whereas the mean monthly value is 65 mm. There were no rains recorded after the month of May.

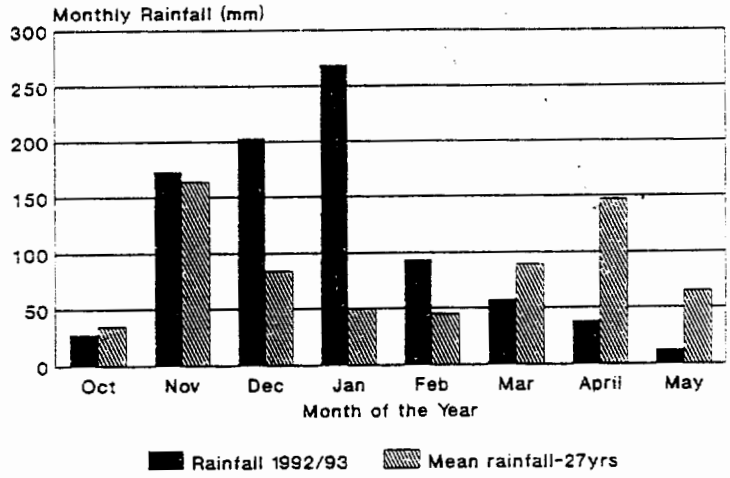

Fig. 7. Comparison of seasonal (1992/93) with long term (27 years record) rainfall distribution.

4.2.1 Rainfall Events and Distribution

The highest number of rainfall events in any one month was recorded in January (23 events) while the least was recorded in May (2 events). For the other months, the number of rainfall events was as follows: October (3), November (17), December (23), February (8), March (5), April (4) and May (2). From October 1992 to March 1993, there were 69 rainy days over a 151 days period while from October to May there were 75 rainy days over a 200 days period. The period of March to May had only 11 rainy days stretched over a 61 days period.

During the first 40 days of crop establishment, which is a vegetative growth stage, most crops are sensitive to soil moisture deficits. In this long rains period, a total rainfall amount of 95 mm had been received. Except for an initial storm of 46 mm, the rest of the rainfall was low and thinly distributed. Hence the maize crop planted in the adjacent area experienced a very serious soil moisture shortage, and hence dried up. Consequently, no maize/bean crop was realized in the area during the long rains period.

Total rainfall in the short rains season of as little as 155 mm (1981) and as much as 925 mm (1961) has been recorded. On the other hand, total rainfall in the long rains season of as little as 133 mm (1973) and as much as 660 mm (1979) has been observed (Stewart and Faught, 1984).

4.2.2 Storm Intensity, Energy and Erosivity

The product EI_{30} (Wischmeier's erosivity index) was used as an index of storm erosivity in this study. Where E is the total storm kinetic energy and I_{30} is the maximum 30 minute intensity.

I_{30} varied from 46 mm/hr to 0.5 mm/hr with a mean of 8 mm/hr while storm kinetic energy varied from zero to 1360 J/m^2. Coefficients of correlation varied from 0.76 between I_{30} and rainfall and 0.40 between I_{30} and storm duration. The correlation coefficient obtained between kinetic energy (KE) and rainfall amounts was 0.94. Correlation coefficients between KE and runoff (0.92) and KE and soil loss (0.89) were also high. Other correlation coefficients of 0.71 and 0.80 were obtained between I_{30} and runoff and I_{30} and soil loss respectively. These coefficients increased to 0.79 and 0.84 respectively when I_{30} was multiplied by the total storm energy, E. These observations confirmed that EI_{30} is a better index of erosivity than either E or I_{30}.

Coefficients of determination were higher between I_{30} and soil loss than between I_{30} and runoff. The coefficient of determination (r^2) between I_{30} and runoff for the various treatments were 0.55 (CT), 0.48 (10 FYM), 0.49 (5 FYM) and 0.57 (ZT).

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For I_{30} and soil loss r^2 values were 0.72 (CT), 0.66 (10 FYM), 0.65 (5 FYM) and 0.64 (ZT) while for EI_{30} and soil loss, they were 0.86 (CT), 0.67 (10 FYM), 0.68 (5 FYM) and 0.71 (ZT).

4.2.3 Rainfall and Runoff Response

There was a strong positive correlation between rainfall and runoff ($r = 0.94$) implying that rainfall amounts strongly influenced runoff. The best predictors of runoff were rainfall amounts and total storm kinetic energy with regression coefficients ranging between 0.94 and 0.84 for the four treatments. From initially dry soil conditions, rainfall amounts less than 6 mm never caused runoff. There was a storm of less than 5 mm that caused runoff just as there were storms of more than 5 mm that never caused runoff indicating the significance of antecedent moisture content, soil surface conditions and rainfall characteristics in influencing the occurrence of runoff.

The influence of rainfall amount on runoff was greatest under CT ($r^2 = 0.93$) followed by ZT (0.92), 10 FYM and 5 FYM (0.89). The influence of kinetic energy on runoff was also highest under CT (0.90) and least under 10FYM (0.84).

I_{30} coefficients of determination (r^2) with runoff were 0.72 (ZT), 0.66 (CT), 0.59 (5 FYM) and 0.57 (10 FYM). Therefore rainfall amount influenced runoff more than I_{30}. This was attributed to the many rainfall events of low intensity, high amounts and long duration that caused runoff. Many rainfall events occurred intermittently over several hours. During prolonged storms, rainfall intensity might be low but because of the duration, soil saturation results leading to runoff. In such a case rainfall amount would be a better estimator of runoff as compared to rainfall intensity. I_{30} would therefore be a good runoff indicator for intense rainfall events of short duration and high amounts.

Table 7. Runoff expressed as a percentage of erosive rainfall, 1992/93.

Date	Rainfall (mm)	Treatment (% Runoff)			
		CT	10FYM	5FYM	ZT
12/11	16	33	4	6	46
15/11	17	35	11	15	45
28-1/12	84	64	37	40	75
9/12	7	14	6	8	15
11/12	67	70	62	64	75
12/12	7	17	13	14	20
17-18/12	75	64	47	49	67
19/12	5	58	46	47	64
31/12	17	25	15	18	31
7/1	24	3	2	2	3
10/1	11	37	13	15	65
14/1	17	18	14	15	32
16/1	37	49	32	35	58
17/1	3	18	10	12	21
18/1	11	16	11	11	26
20/1	38	60	53	55	67
28/1	10	41	24	26	49
30/1	52	65	56	63	73
8-9/2	50	28	19	21	32
11/2	30	47	39	38	52
13/3	46	68	49	56	87
1/4	12	26	24	23	41
17/4	20	31	28	28	34
Mean runoff (%)		39	27	29	47
Total runoff (mm)		326	238	255	379

There were no significant differences in runoff between the two tillage treatments. However the two treatments had much higher runoff when compared to the farmyard manure treatments. The differences in amounts of runoff between the four treatments were negligible for small storms but significant for large storms.

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The occurrence of runoff was influenced by the interval between storms. The shorter the interval, the more the runoff. When there had been a large storm the previous day (above 37 mm), even a small storm of 3.5 mm caused runoff. Whereas when there had been a dry spell of two days, rainfall of 13 mm never caused runoff.

There was a noticeable trend between runoff and rainfall during the experimental period. When rainfall amounts were high, the amount of runoff and soil loss was also high. While low runoff and low soil loss were observed under small storms. When Kilewe and Ulsaker (1984) related total kinetic energy to rainfall amounts for the storms in Katumani, the resulting relationship had an r^2 of 0.97 indicating that nearly all variations in total kinetic energy can be accounted for by rainfall amount. Total runoff expressed as a percentage of erosive rainfall during the duration of the study was 47 (ZT), 39 (CT), 29 (5FYM) and 27 (10FYM) (see Table 7).

The short rains of 1992 were quite extra ordinary in that they went on longer than usual. The peak of the rainy season was experienced in January 1993 though long term data indicate that peak rainfall is often expected in the month of November.

From October to December, the normal short rains period, 404 mm of rainfall had been received and this was much higher than the seasonal average of 286 mm (27 years record). The monthly rainfall received from November to February was much higher than the long term average. The month of April, which is often the peak of the long rains received only 38 mm of rainfall, far below the monthly average of 144 mm (27 years record). The comparison of the mean (27 years record) and seasonal monthly rainfall distribution for 1992/93 are shown in Figure 7.

4.3 Storm Runoff

Though the first storm was received on 28/10/1992 it was not until 12/11/1992 that runoff was observed. Throughout the season, 75 rainfall events of various magnitudes were received but only twenty five caused runoff. The first nine storms never caused any runoff or soil loss and they totalled upto 70 mm. This can be attributed to the fact that they were small in magnitude, spread over long time durations and occurred at the time when the soil was dry following the dry season.

The initial results did not reflect significant treatment differences in runoff between 5 FYM and 10 FYM though there tended to be less runoff under the latter treatment (see Figure 8 and Table 8).

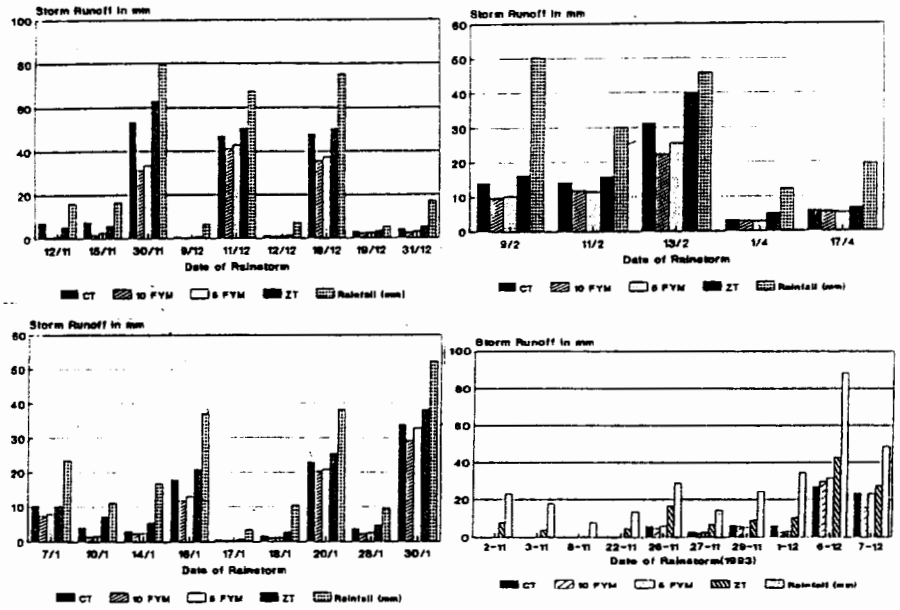

Fig. 8. Seasonal treatment differences in storm runoff, 1992/93.

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Table 8. Treatment differences in seasonal runoff, 1992/93.

	Rainfall (mm)	Runoff (mm)			
Year and Season		ZT	CT	5FYM	10FYM
1992 Short rains	767	327(a)	286(a)	221(b)	207(b)
1993 Long rains	108	52(a)	40(b)	34(c)	31(c)
Total	875	379(a)	326(b)	255(c)	238(c)

Values with the same letter in parenthesis were not significantly different at P (0.05).

4.4 Storm Soil Loss

The highest amount of soil loss was observed under conventional tillage followed by zero tillage, 5 FYM and 10 FYM (see Figure 9 and Table 9). The amount of soil loss during the study period was 18.6, 14, 12.4 and 11.5 kg/m^2 under conventional tillage, zero tillage, 5 FYM and 10 FYM respectively. More soil was lost during the short rains as compared to the long rains due to the many rainfall events that occurred in the short rains period. The initial storms never caused runoff and soil loss. This was attributed to the low initial soil moisture conditions and high infiltrability of the soil. Light rainfall facilitated erosion by loosening the soil surface such that the loosened soil particles were then easily washed away by the next runoff event.

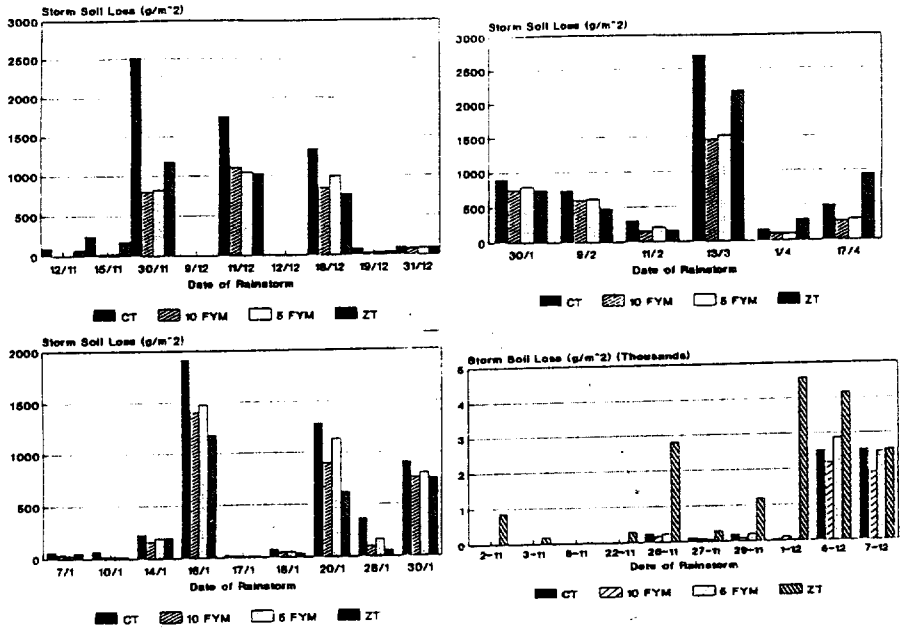

Fig. 9. Seasonal treatment differences in storm soil loss, 1992/93.

On a storm basis, the lowest and highest amounts of soil loss in the two rain periods were experienced on 9/12/93 (6.5 mm) and 13/3/93 (46 mm) respectively. The soil loss on 13/3/93 was as follows: 2.7 kg/m^2 (CT), 2.2 kg/m^2 (ZT), 1.5 kg/m^2 (10 FYM) and 1.5 kg/m^2 (5 FYM). The duration of the storm was one hour and the total kinetic energy was 1236 J/m^2. The high amount of soil loss was attributed to the fact that the land had just been tilled and the storm was very erosive (56540 Jm^{-2} mm hr^{-1}).

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There was good correlation between soil loss and storm kinetic energy (r^2 = 0.9). Therefore kinetic energy did significantly influence soil loss. Soil loss was also influenced by runoff (r^2=0.74) and rainfall amount (r^2=0.71).

Table 9. Treatment differences in seasonal soil loss, 1992/93.

	(Soil loss g/m^2)			
Year and Season	ZT	CT	5FYM	10FYM
1992 Short rains	9518	14770	10038	9346
1993 Long rains	4478	3874	2373	2162
Total	13996	18644	12411	11508

For small storms, the differences in soil loss were small and hence negligible. On the whole, the amount of soil loss was high (for heavy storms) irrespective of treatments and time. As the season progressed, soil loss under zero tillage became markedly reduced to the extent that it was at times less than that lost under 10 FYM or 5 FYM. Soil loss under conventional tillage remained consistently higher than that under ZT, 10 FYM and 5 FYM throughout the season. Variations in soil erosion can be attributed to compaction of the soil surface and surface sealing and crusting (due to intense rainstorms). Although tillage can facilitate the breakdown of soil crusts and enhance infiltration, it can also lead to high soil loss as was observed in this study.

Table 10. Storm rainfall and treatment soil loss, 1992/93

Date	Rainfall (mm)	Soil loss (gm/m²)			
		CT	10FYM	5FYM	ZT
12/11	16	106.3	1.8	4.0	79.9
15/11	17	251.6	21.6	25.0	177.5
28/11-1/12	84	3335.8	1368.4	1448.3	1732.0
9/12	7	4.5	0.5	0.9	2.1
11/12	67	1980.1	1469.3	1502.6	1512.4
12/12	7	17.1	5.3	5.5	4.2
17-18/12	75	1514.3	814.6	1152.1	910.0
19/12	5	149.6	49.4	58.7	78.6
31/12	17	106.1	85.8	89.6	103.5
7/1	24	120.0	9.8	17.5	112.4
10/1	11	81.0	10.4	19.5	13.6
14/1	17	257.0	160.3	192.5	196.8
16/1	37	2130.8	1802.1	1898.0	1695.7
17/1	3	19.9	12.2	12.8	12.9
18/1	11	101.4	83.8	84.6	65.6
20/1	38	1834.7	1635.2	1636.7	70.3
28/1	10	475.6	108.3	136.6	62.2
30/1	52	1128.0	931.7	932.1	940.4
8-9/2	50	720.3	583.3	633.9	651.2
11/2	30	436.6	192.0	187.1	196.6
13/3	46	2697.1	1460.2	1521.3	2174.6
1/4	12	261.8	86.7	213.1	610.6
17/4	20	914.8	615.1	638.5	1693.3
Total soil loss (g/m²)		18644.4	11507.8	12410.9	13096.4

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5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

5.1.1 Soil Properties

The infiltrabilty of the soil improved with the application of farmyard manure which increased the stability of aggregates. Besides, the maintenance of a cloddy soil macrostructure through tillage, helped to impound runoff in depression storage and hence enhanced infiltration. Some seasonal decrease in infiltration was attributed to surface sealing and crusting of the top soil which resulted in high volumes of surface runoff.

Seasonal soil moisture variations were more pronounced in the 0-10 cm depth than the 0-100 cm depth. The differences in soil moisture between treatments (0-10 cm) were not significant at the onset when infiltrability was enhanced by depressional storage and the end of the season when treatment effects were negligible. The highest soil moisture was observed under 10 FYM followed by 5 FYM, CT and ZT. This did prove that FYM application was effective in enhancing soil moisture storage. Under all treatments, field capacity moisture conditions were never reached during the experimental period.

Soil bulk density was highest under ZT and CT but least under the farmyard manure treatments. Bulk density was low when soil moisture was high and high under low soil moisture conditions.

Penetration resistance and soil shear strength were highest at the beginning of the season when the soil profile was still dry. The highest values were recorded under ZT indicating a need for soil tillage soon after harvest when there is still some residual soil moisture. Penetration resistance was least under the farmyard manure treatments.

Soil aggregation improved with the application of farmyard manure. At the end of the rains, there was a reduction in soil aggregation for all treatments. The highest decrease was in CT and ZT. This was attributed to the decrease in soil organic matter content due to top soil losses and organic matter oxidation as a result of high temperatures at the experimental site.

5.1.2 Seasonal Rainfall

In the two rain seasons, there was a strong correlation between storm kinetic energy, runoff and soil loss. Rainfall of low amount spread over long duration never caused runoff while high rainfall over short durations was highly erosive. High erosivity led to increased soil erosion.

The short rains of 1992/93 were longer than usual and peaked in January 1993 with 35% of the seasonal rainfall. The longterm peak month of the short rains is November. The seasonal rainfall of 767 mm for the short rains period was much higher than the longterm average of 378 mm. Runoff during the month of January was 43% (ZT), 37% (CT), 28% (10 FYM) and 31% (5 FYM) of the month's total rainfall.

During the short rains period, the most erosive storm of 84 mm resulted in a soil loss of 3.3 kg/m^2 (CT), 1.7 kg/m^2 (ZT), 1.5 kg/m^2 (5 FYM), 1.4 kg/m^2 (10 FYM) and runoff of 75% (ZT), 64% (CT), 40% (5 FYM) and 37% (10 FYM).

During the long rains period, April, which is usually the peak of the long rains, received only 38 mm of rainfall far below the monthly mean of 147 mm. The most erosive storm of 46 mm was received at the onset of the long rains and resulted in soil loss of 2.7 kg/m^2 (CT), 2.2 kg/m^2 (ZT), 1.5 kg/m^2 (5 FYM) 1.5 kg/m^2 (10 FYM) and runoff of 87% (ZT), 68% (CT), 56%(5 FYM) and 49% (10 FYM).

Generally in the two rain seasons, the first storms were small in magnitude, spread over long time durations and of low intensities and consequently could not cause runoff and soil loss. In the short rains period, which received 64 storms, 20 erosive and 25 above 9 mm and well and evenly distributed, the farmers had a bumper harvest. Over the long rains period, in which eleven storms were received, eight of them below 9 mm, there was poor crop performance and this resulted in a complete crop failure.

5.1.3 Surface Runoff

Storm runoff was influenced by rainfall intensity, rainfall amount, antecedent moisture content and storm duration. Surface runoff was strongly influenced by rainfall amount under all treatments. Under high soil moisture conditions, storms of less than 5 mm caused runoff while under initial dry conditions (onset of rains), storms greater than 15 mm never caused runoff. There was no significant difference in runoff between CT and ZT but the two treatments resulted in much higher runoff than farmyard manure treatments. Treatment differences in runoff were negligible for small storms.

At the beginning of the season, the initial cloddy surfaces due to soil tillage enhanced depression storage and hence the absence of runoff and soil loss. With time, there was an increase in soil sealing, crusting, and compaction (due to raindrop impact coupled with the inherent low organic matter content) which contributed to the high runoff volume observed in zero tillage. Farmyard manure application was able to significantly reduce runoff when compared to conventional tillage with no manure and zero tillage. The farmyard manure in the soil led to an increase in water holding capacity and a reduction in soil surface sealing and crusting. Runoff expressed as a percentage of seasonal rainfall was 43%, 48% (ZT), 37%, 37% (CT), 29%, 31% (5 FYM) and 27%, 28% (10 FYM) during the short rains and long rains period respectively.

5.1.4 Soil Loss

Soil loss was influenced by rainfall characteristics, degree of soil aggregation and antecedent soil moisture conditions. High runoff volumes often resulted in increased soil loss while low runoff volumes gave little soil loss at the onset of the season. However later in the season soil loss tended to decrease even when runoff increased. Soil loss decreased in the order of ZT, CT, 5 FYM and 10 FYM over the experimental period. More soil was lost during the short rains 9518 gm^{-2} (ZT), 14770 gm^{-2} (CT), 10038 gm^{-2} (5 FYM) and 9346 gm^{-2} (10 FYM) than the long rains period 4478 gm^{-2} (ZT), 3974 gm^{-2} (CT), 2373 gm^{-2} (5 FYM) and 2162 gm^{-2} (10 FYM).

At low bulk density and low soil shear strength, storms of low intensity and low magnitude caused little soil loss as a result of their low erosivity. However, high intensity storms resulted in high of runoff and soil loss due to their high erosivity. Under low bulk density, soil particles were easily detached while under high bulk density and high rainfall intensity, the increased runoff led to more soil loss and runoff at the onset of the season. Later in the season after the soil had crusted and compacted due to raindrop impact, high rainfall intensities led to increased runoff but reduced soil loss.

Farmyard manure application significantly reduced soil loss through improved soil aggregation and a reduction in bulk density and soil shear strength.

5.2 Recommendations

Soil aggregation due to improved organic matter content of the soil is practically feasible in a farmer's setting only through periodic application of farmyard manure as a farm management practice .The combined effects of improved crop growth and soil conditions as a result of farmyard manure application can be expected to lead to some significant reductions in soil and water losses.

Zero tillage is recommended on medium textured soils with high biological activity and on self structuring, cracking clay soils. Zero tillage is also favourable where the top soil is shallow, stable, of high organic matter content and underlain by structurally unstable soils such as plinthite. Hence zero tillage is not appropriate for the soil conditions at Katumani. Zero tillage is not suitable for this soil because it leads to alot of runoff due to soil sealing and crusting. Furthermore the high bulk density observed under zero tillage may impede root development and subsequently lead to poor crop performance.

Conventional tillage without any farmyard manure leads to a lot of soil loss for this structurally unstable soil which has an inherent low aggregate stability. In the absence of farmyard manure and crop residues, mechanical measures such as ridging are recommended in order to conserve as much runoff as possible in situ.

ACKNOWLEDGEMENTS

The authors would like to express his sincere appreciation for the financial and material support received from the USAID-CDR collaborative research program. Other thanks go to the National Dryland Farming Research Centre (KARI), Katumani for availing their facilities for this study.

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APPENDICES

APPENDIX 1

Infiltration, Runoff and Sediment Data for 1992/93 Period, Katumani, Machakos, Kenya.

Date	Day No.	Storm No.	Rainfall (mm)	Treatment	Runoff (mm)	Runoff (%)	Infiltration (mm)	Sediment Loss (g/m2)
28/10/92	1	1	10.90		0.00	0.00	10.90	0.00
29/10/92	2	2	8.40		0.00	0.00	8.40	0.00
30/10/92	3	3	8.95		0.00	0.00	8.95	0.00
1/11/92	4	4	1.60		0.00	0.00	1.60	0.00
3/11/92	7	5	15.20		0.00	0.00	15.20	0.00
4/11/92	8	6	5.70		0.00	0.00	5.70	0.00
5/11/92	9	7	6.30		0.00	0.00	6.30	0.00
6/11/92	10	8	10.40		0.00	0.00	10.40	0.00
11/11/92	15	9	2.90		0.00	0.00	2.90	0.00
12/11/92	16	10	16.00	ZT	7.30	45.63	8.70	106.33
			16.00	10FYM	0.56	3.52	15.44	1.83
			16.00	5FYM	0.93	5.81	15.07	4.06
			16.00	CT	5.34	33.38	10.66	79.86
13/11/92	17	11	1.50		0.00	0.00	1.50	0.00
14/11/92	18	12	7.20		0.00	0.00	7.20	0.00
15/11/92	19	13	16.60	ZT	7.52	45.32	9.08	251.64
			16.60	10FYM	1.78	10.74	14.82	21.62
			16.60	5FYM	2.56	15.41	14.04	25.01
			16.60	CT	5.84	35.18	10.76	177.52
17/11/92	21	14	0.75		0.00	0.00	0.75	0.00
23/11/92	27	15	2.55		0.00	0.00	2.55	0.00
24/11/92	28	16	4.80		0.00	0.00	4.80	0.00
25/11/92	29	17	2.40		0.00	0.00	2.40	0.00
28/11/92	32	18	70.00					
29/11/92	33	19	3.55					
30/11/92	34	20	5.75					
01/12/92	35	21	4.35					
28/11-1/12/92	35	18-21	83.65	CT	53.40	63.83	30.25	3335.79
			83.65	10FYM	31.00	37.05	52.66	1368.44
			83.65	5FYM	33.42	39.95	50.23	1448.31
			83.65	ZT	62.76	75.02	20.90	1731.96
07/12/92	41	22	3.50		0.00	0.00	3.50	0.00
9/12/92	43	23	6.50	CT	0.89	13.64	5.61	4.50
			6.50	10FYM	0.40	6.21	6.10	0.45
			6.50	5FYM	0.50	7.69	6.00	0.94
			6.50	ZT	0.97	14.85	5.54	2.10
11/12/92	45	24	67.25	CT	47.08	70.01	20.17	1980.12

			67.25	10FYM	41.35	61.48	25.90	1469.32
			67.25	5FYM	42.93	63.83	24.32	1512.41
			67.25	ZT	50.56	75.18	16.69	1502.57
12/12/92	46	25	7.40	CT	1.23	16.58	6.17	17.13
			7.40	10FYM	0.96	13.02	6.44	5.32
			7.40	5FYM	1.02	13.83	6.38	5.49
			7.40	ZT	1.50	20.23	5.90	2.24
14/12/92	48	26	7.20		0.00	0.00	0.00	0.00
17-18/12/92	52	27	75.35	CT	47.90	63.57	27.45	1514.25
			75.35	10FYM	35.37	46.94	39.98	910.00
			75.35	5FYM	37.21	49.38	38.14	1152.14
			75.35	ZT	50.14	66.55	25.21	814.58
19/12/92	53	28	5.25	CT	3.04	57.97	2.21	149.63
			5.25	10FYM	2.42	46.03	2.83	49.42
			5.25	5FYM	2.45	46.67	2.80	58.68
			5.25	ZT	3.34	63.56	1.91	78.59
28/12/92	62	29	3.95		0.00	0.00	3.95	0.00
29/12/92	63	30	1.35		0.00	0.00	1.35	0.00
30/12/92	64	31	3.90		0.00	0.00	3.90	0.00
31/12/92	65	32	16.90	CT	4.25	25.17	12.65	106.12
			16.90	10FYM	2.58	15.29	14.32	85.81
			16.90	5FYM	2.97	17.55	13.93	89.63
			16.90	ZT	5.25	31.07	11.65	103.48
1/1/93	66	33	6.40		0.00	0.00	6.40	0.00
2/1/93	67	34	5.05		0.00	0.00	6.40	0.00
6/1/93	71	35	2.40		0.00	0.00	2.40	0.00
7/1/93	72	36	23.50	CT	10.40	44.26	13.10	119.96
			23.50	10FYM	7.38	31.42	16.12	9.78
			23.50	5FYM	8.03	34.18	15.47	17.50
			23.50	ZT	10.28	43.76	13.22	112.37
8/1/93	73	37	10.60		0.00	0.00	10.60	0.00
9/1/93	74	38	0.75		0.00	0.00	0.75	0.00
10/1/93	75	39	11.25	CT	4.11	36.53	7.14	81.01
			11.25	10FYM	1.43	12.68	9.82	19.48
			11.25	5FYM	1.67	14.87	9.58	13.57
			11.25	ZT	7.26	64.50	3.99	10.40
13/1/93	78	40	13.10		0.00	0.00	13.10	0.00
14/1/93	79	41	16.80	CT	3.09	18.39	13.71	257.02
			16.80	10FYM	2.36	14.07	14.44	160.27
			16.80	5FYM	2.48	14.76	14.32	192.50
			16.80	ZT	5.43	32.30	11.37	196.81
15/1/93	80	42	0.50		0.00	0.00	11.25	0.00

16/1/93	81	43	36.95	CT	17.95	48.58	19.00	2130.78
			36.95	10FYM	11.75	31.81	25.20	1802.12
			36.95	5FYM	13.02	35.25	23.93	1898.04
			36.95	ZT	20.87	56.48	16.08	1695.68
17/1/93	82	44	3.45	CT	0.62	17.87	2.83	19.87
			3.45	10FYM	0.36	10.53	3.09	12.23
			3.45	5FYM	0.41	11.88	3.04	12.77
			3.45	ZT	0.71	20.48	2.74	12.85
18/1/93	83	45	10.50	CT	1.71	16.29	8.79	101.37
			10.50	10FYM	1.20	11.43	9.30	83.76
			10.50	5FYM	1.18	11.27	9.32	84.57
			10.50	ZT	2.74	26.10	7.76	65.55
19/1/93	84	46	2.30		0.00	0.00	2.30	0.00
20/1/93	85	47	38.10	CT	22.99	60.35	15.11	1834.73
			38.10	10FYM	20.28	53.24	17.82	1635.22
			38.10	5FYM	20.84	54.71	17.26	1636.67
			38.10	ZT	25.45	66.81	12.65	970.27
21/1/93	86	48	11.35		0.00	0.00	11.35	0.00
23/1/93	88	49	10.40		0.00	0.00	10.40	0.00
26/1/93	91	50	4.20		0.00	0.00	4.20	0.00
27/1/93	92	51	5.00		0.00	0.00	5.00	0.00
28/1/93	93	52	9.50	CT	3.85	40.56	5.65	475.56
			9.50	10FYM	2.31	24.32	7.19	108.25
			9.50	5FYM	2.44	25.72	7.06	136.62
			9.50	ZT	4.64	48.81	4.86	62.18
29/1/93	94	53	3.40		0.00	0.00	3.40	0.00
30/1/93	95	54	52.25	CT	33.98	65.04	18.27	1127.97
			52.25	10FYM	29.23	55.94	23.02	931.73
			52.25	5FYM	32.91	62.98	19.34	932.12
			52.25	ZT	38.11	72.94	14.14	940.42
31/1/93	96	55	1.50		0.00	0.00	1.50	0.00
1/2/93	97	56	2.00		0.00	0.00	2.00	0.00
8-9/2/93	105	57	50.20	CT	14.01	27.92	36.19	720.25
			50.20	10FYM	9.65	19.23	40.55	583.32
			50.20	5FYM	10.31	20.53	39.89	633.92
			50.20	ZT	16.19	32.24	34.01	651.24
10/12/93	106	58	1.40		0.00	0.00	1.40	0.00
11/2/93	107	59	30.10	CT	14.18	47.11	15.92	436.64
			30.10	10FYM	11.82	39.28	18.28	191.95
			30.10	5FYM	11.49	38.17	18.61	187.12
			30.10	ZT	15.78	52.44	14.32	196.56
12/2/93	108	60	2.50		0.00	0.00	2.50	0.00

14/2/93	110	61	1.20		0.00	0.00	1.20	0.00
15/2/93	111	62	5.90		0.00	0.00	5.90	0.00
13/3/93	140	63	45.75	CT	31.20	68.20	14.55	2697.07
			45.75	10FYM	22.28	48.69	23.47	1460.23
			45.75	5FYM	25.55	55.85	20.20	1521.30
			45.75	ZT	39.95	87.32	5.80	2174.61
15/3/93	142	64	2.30		0.00	0.00	2.30	0.00
19/3/93	146	65	2.00		0.00	0.00	2.00	0.00
23/3/93	150	66	3.70		0.00	0.00	3.70	0.00
24/3/93	151	67	3.60		0.00	0.00	3.60	0.00
1/4/93	159	68	12.30	CT	3.16	25.69	9.14	261.76
			12.30	10FYM	2.92	23.77	9.38	86.68
			12.30	5FYM	2.82	22.89	9.49	213.09
			12.30	ZT	5.08	41.30	7.22	610.59
16/4/93	174	69	2.50		0.00	0.00	2.50	0.00
17/4/93	175	70	19.50	CT	5.98	30.68	13.52	914.84
			19.50	10FYM	5.54	28.43	13.96	615.07
			19.50	5FYM	5.40	27.68	14.10	638.51
			19.50	ZT	6.68	34.27	12.82	1693.26
19/4/93	177	71	3.80		0.00	0.00	3.80	0.00
6/5/93	194	72	8.75		0.00	0.00	8.75	0.00
12/5/93	200	73	3.90		0.00	0.00	3.90	0.00
2/11/93	1	1	23.50	ZT	7.67	32.64	15.83	844.97
			23.50	CT	0.00	0.00	23.50	0.00
			23.50	10FYM	0.00	0.00	23.50	0.00
			23.50	5FYM	0.00	0.00	23.50	0.00
3/11/93	2	2	18.00	ZT	3.79	21.06	14.21	174.58
			18.00	CT	0.00	0.00	18.00	0.00
			18.00	10FYM	0.00	0.00	18.00	0.00
			18.00	5FYM	0.00	0.00	18.00	0.00
8/11/93	7	3	8.00	ZT	0.51	6.38	7.49	6.12
			8.00	CT	0.00	0.00	8.00	0.00
			8.00	10FYM	0.00	0.00	8.00	0.00
			8.00	5FYM	0.00	0.00	8.00	0.00
22/11/93	21	4	13.50	ZT	4.55	33.70	8.95	302.58
			13.50	CT	0.37	2.74	13.13	5.81
			13.50	10FYM	0.00	0.00	13.50	0.00
			13.50	5FYM	0.00	0.00	13.50	0.00
26/11/93	25	5	29.00	ZT	16.77	57.83	12.23	2804.20
			29.00	CT	6.14	21.17	22.86	251.41
			29.00	10FYM	4.94	17.03	24.06	154.98
			29.00	5FYM	6.09	21.00	22.91	227.59

27/11/93	26	6	14.50	ZT	6.82	47.03	7.68	297.89
			14.50	CT	2.98	20.55	11.52	107.85
			14.50	10FYM	2.20	15.17	12.30	59.18
			14.50	5FYM	2.31	15.93	12.19	32.63
29/11/93	28	7	24.50	ZT	9.30	37.96	15.20	1178.15
			24.50	CT	6.59	26.90	17.91	198.19
			24.50	10FYM	5.72	23.35	18.78	92.54
			24.50	5FYM	5.14	20.98	19.36	204.78
1/12/93	30	8	35.00	ZT	10.49	29.97	24.51	4584.96
			35.00	CT	6.11	17.46	28.89	33.80
			35.00	10FYM	2.68	7.66	32.32	98.50
			35.00	5FYM	2.86	8.17	32.14	15.42
6/12/93	35	9	88.50	ZT	42.83	48.40	45.67	4176.59
			88.50	CT	27.40	30.96	61.10	2499.53
			88.50	10FYM	30.08	33.99	58.42	2150.07
			88.50	5FYM	31.69	35.81	56.81	2850.11
7/12/93	36	10	48.50	ZT	27.64	56.99	20.86	2538.34
			48.50	CT	23.78	32.45	32.76	2527.40
			48.50	10FYM	15.74	48.08	25.18	1880.69
			48.50	5FYM	23.32	0.00	48.50	2459.40

APPENDIX 2

Seasonal Soil Shear Strength (kPa). 1992-94

Date	ZT	CT	10FYM	5FYM
18/11	12.26	10.82	5.95	6.62
14/12	27.06	24.90	10.45	13.17
21/12	12.33	8.62	7.38	7.50
28/12	6.10	4.98	3.80	3.71
5/1	8.87	5.18	3.79	3.86
11/1	9.68	5.55	3.88	4.13
18/1	14.35	8.96	7.63	7.36
25/1	11.20	7.61	6.85	7.30
1/2	10.40	7.73	6.48	7.48
15/2	13.23	9.80	8.90	8.65
22/2	15.01	12.93	11.36	12.06
1/3	19.85	15.17	14.38	14.43
22/3	17.07	9.32	7.90	8.57
29/3	20.43	10.28	9.35	9.67
5/4	21.18	10.20	9.90	9.85
12/4	15.45	10.45	9.62	10.05
19/4	13.82	8.94	8.65	8.75
1/5	16.67	10.48	9.95	10.05
15/11	21.50	9.13	9.72	8.94
29/11	11.42	5.38	7.00	5.25
6/12	11.17	4.75	5.33	4.50
20/12	20.67	12.00	13.00	12.63
29/12	16.68	9.70	9.78	9.93
3/1	23.33	14.38	13.75	12.94
10/1	24.42	15.38	18.00	15.13
24/1	23.25	12.25	13.83	16.31
4/2	21.08	7.50	11.83	13.50
10/2	17.58	12.63	12.00	11.44
23/2	20.25	14.38	11.00	21.31

APPENDIX 3

Seasonal Soil Bulk Densities, 1992-94

Date	ZT	CT	10FYM	5FYM
18/11	1.28	1.26	1.21	1.25
14/12	1.32	1.30	1.24	1.25
21/12	1.30	1.29	1.24	1.24
28/12	1.18	1.15	1.14	1.13
5/1	1.25	1.18	1.14	1.13
11/1	1.18	1.14	1.05	1.07
18/1	1.30	1.29	1.23	1.25
25/1	1.24	1.20	1.17	1.18
1/2	1.17	1.13	1.07	1.11
15/2	1.12	1.08	1.05	1.07
22/2	1.14	1.11	1.10	1.11
1/3	1.34	1.29	1.23	1.25
22/3	1.40	1.26	1.18	1.23
29/3	1.39	1.30	1.18	1.24
5/4	1.38	1.31	1.25	1.26
12/4	1.24	1.22	1.21	1.18
19/4	1.57	1.49	1.43	1.44
1/5	1.58	1.48	1.45	1.45
8/11	1.01	1.02	0.98	0.99
15/11	1.14	1.14	1.09	1.17
22/11	0.90	0.83	0.82	0.91
29/11	0.87	0.96	0.96	0.88
6/12	0.83	0.90	0.87	0.85
20/12	1.25	1.26	1.27	1.30
29/12	1.23	1.19	1.25	1.26
3/1	1.20	1.25	1.20	1.21
10/1	1.23	1.16	1.24	1.27
24/1	1.16	1.19	1.15	1.15
4/2	1.33	1.37	1.30	1.32
10/2	1.29	1.34	1.28	1.36
23/2	1.22	1.22	1.24	1.16

APPENDIX 4

Top Soil (0-10 cm) Moisture in Percent Volume, 1992-94

Date	ZT	CT	10FYM	5FYM
18/11	11.71	13.23	14.17	13.82
14/12	13.18	13.82	15.75	15.40
21/12	7.36	8.93	12.53	11.43
28/12	14.50	15.37	17.38	15.56
5/1	6.39	6.46	12.10	12.00
11/1	11.94	12.51	13.77	13.20
18/1	17.80	18.26	21.54	20.80
25/1	11.09	11.64	13.91	12.61
1/2	11.69	11.48	12.61	12.09
15/2	7.94	7.87	9.24	8.36
22/2	3.54	3.71	5.12	4.91
1/3	5.97	6.27	8.74	7.78
22/3	4.79	6.53	7.56	7.47
29/3	4.06	4.44	4.93	4.87
5/4	5.57	5.80	7.12	6.49
12/4	12.31	13.15	14.91	14.01
19/4	5.81	5.94	7.49	7.00
1/5	5.80	5.90	7.35	6.80
8/11	11.45	11.91	11.87	11.96
15/11	5.63	6.86	6.52	6.65
22/11	12.29	13.63	13.79	13.78
29/11	15.24	17.35	17.32	15.18
6/12	13.12	15.86	15.80	15.11
20/12	6.08	5.85	8.15	9.63
29/12	5.94	5.98	7.42	6.03
3/1	3.91	4.31	4.56	4.17
10/1	4.17	3.42	4.52	4.05
24/1	3.67	3.88	4.02	3.57
4/2	3.88	2.33	2.68	2.28
10/2	2.32	2.70	2.27	2.53
23/2	7.32	10.59	9.62	9.15

APPENDIX 5

Penetration Resistance (N/cm²), 1992-93

Date	10FYM	5FYM	CT	ZT
2/4	0.9	1.4	2.1	3.6
5/4	2.31	2.7	3.8	7.8
8/4	1.5	2.08	2.9	7.69
12/4	1.69	2.23	2.8	5.23
15/4	1.69	2.23	2.8	5.23

APPENDIX 6

Profile Soil (0-100 cm) Moisture in mm, 1992-93

Date	10FYM	5FYM	CT	ZT	FC	PWP
18/11	112.46	133.53	133.53	150.78	245.6	132.6
14/12	168.98	181.44	191	199.64	245.6	132.6
21/2	182.4	186.2	202	202	245.6	132.6
28/12	181.4	182.4	195.8	201.6	245.6	132.6
5/1	184.3	186.2	197.7	201.6	245.6	132.6
11/1	210.2	207.3	216.9	218.8	245.6	132.6
16/1	199.6	195.8	205.4	211.1	245.6	132.6
25/1	193.9	192.9	203.5	209.2	245.6	132.6
1/2	198.7	198.7	198.7	205.2	245.6	132.6
8/2	195.8	197.7	193.9	205.4	245.6	132.6
15/2	195.8	195.8	200.6	198.7	245.6	132.6
22/2	186.2	186.2	186.2	192	245.6	132.6
1/3	180.5	178.6	180.5	188.1	245.6	132.6
8/3	174.7	169.9	176.6	181.4	245.6	132.6
15/3	173.8	167.1	178.6	183.4	245.6	132.6
22/3	167.1	160.4	170.9	178.6	245.6	132.6
29/3	163.2	159.4	167.1	172.8	245.6	132.6
5/4	157.5	151.7	165.1	170	245.6	132.6
12/4	151.7	149.8	160.4	166.1	245.6	132.6
19/4	142.2	140.2	152.7	160.4	245.6	132.6
1/5	140.2	142.2	147.9	157.5	245.6	132.6
10/5	134.5	130.7	137.4	147.9	245.6	132.6
17/5	132.6	128.7	135.4	149.8	245.6	132.6

APPENDIX 5

Penetration Resistance (N/cm²), 1992-93

Date	10FYM	5FYM	CT	ZT
2/4	0.9	1.4	2.1	3.6
5/4	2.31	2.7	3.8	7.8
8/4	1.5	2.08	2.9	7.69
12/4	1.69	2.23	2.8	5.23
15/4	1.69	2.23	2.8	5.23

APPENDIX 6

Profile Soil (0-100 cm) Moisture in mm, 1992-93

Date	10FYM	5FYM	CT	ZT	FC	PWP
18/11	112.46	133.53	133.53	150.78	245.6	132.6
14/12	168.98	181.44	191	199.64	245.6	132.6
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28/12	181.4	182.4	195.8	201.6	245.6	132.6
5/1	184.3	186.2	197.7	201.6	245.6	132.6
11/1	210.2	207.3	216.9	218.8	245.6	132.6
16/1	199.6	195.8	205.4	211.1	245.6	132.6
25/1	193.9	192.9	203.5	209.2	245.6	132.6
1/2	198.7	198.7	198.7	205.2	245.6	132.6
8/2	195.8	197.7	193.9	205.4	245.6	132.6
15/2	195.8	195.8	200.6	198.7	245.6	132.6
22/2	186.2	186.2	186.2	192	245.6	132.6
1/3	180.5	178.6	180.5	188.1	245.6	132.6
8/3	174.7	169.9	176.6	181.4	245.6	132.6
15/3	173.8	167.1	178.6	183.4	245.6	132.6
22/3	167.1	160.4	170.9	178.6	245.6	132.6
29/3	163.2	159.4	167.1	172.8	245.6	132.6
5/4	157.5	151.7	165.1	170	245.6	132.6
12/4	151.7	149.8	160.4	166.1	245.6	132.6
19/4	142.2	140.2	152.7	160.4	245.6	132.6
1/5	140.2	142.2	147.9	157.5	245.6	132.6
10/5	134.5	130.7	137.4	147.9	245.6	132.6
17/5	132.6	128.7	135.4	149.8	245.6	132.6

INFILTRATION, RUNOFF AND SOIL EROSION IN SEMI-ARID SOILS IN KENYA

REPORT OF THE KATUMANI MACRO-PLOTS COMPONENT
OF THE USAID-CDR RESEARCH PROGRAM FOR
JUNE 1992 - JUNE 1995

BY
GEORGE E. OKWACH

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1. INTRODUCTION

1.1 Study Background

Only 15% of the land area of Kenya is agriculturally productive. The remainder of the country is classified as arid and semi-arid land (ASAL) (Braun, 1982). In the ASAL areas agriculture is limited both by low rainfall and soil quality (fertility and physical properties). The little rain that falls in the ASAL of Kenya is both variable in onset and unpredictable in amount and distribution. Agriculture in this region is mainly for subsistence, and seasonal crop failure is a common feature.

This study was conducted at the National Dryland Farming Research Centre, Katumani as part of the USAID-CDR funded research program.

1.2 Description of the Study Area

1.2.1 *Location*

The National Dryland Farming Research Centre, Katumani (which will now be referred to in this report simply as **"Katumani"**) lies at longitude 37°14'E and latitude 01°35'S. The centre is located about 80 km south east of Nairobi, and some 9 km south of Machakos town, the administrative and commercial headquarters of Machakos District of Eastern Province in Kenya. Katumani is situated at an altitude of 1600 metres above sea level, and occupies a total area of 489 hectares.

1.2.2 *Climate*

Katumani experiences a semi-arid tropical climate, with a bimodal pattern of rainfall. It is on the boundary between agro-ecological zones 4 and 5 (Jaetzold and Schmidt, 1983). The Katumani rains are mainly monsoonal in character. The first rains of the year are often of southern monsoon origin, and come in the months of March to May, with the peak in April. This season is traditionally known as the *Long Rains*. [The term *Season* will be used in this report to refer primarily to the crop growing period between planting (the onset of rains) and harvesting of the crop.] Following the Long Rains is an extended dry period that reaches to mid-October when the second season (known as the *Short Rains*) is expected to commence. The Short Rains season,

brought about by the northern monsoon winds, has its peak in November, and begins to taper off towards mid December. At the end of the monsoon rains in December, some convective influences may occur, although this is not often. Whenever they occur, the convective effects often appear to extend the short rains into the months of January or February of the succeeding year.

The annual rainfall received at Katumani varies between 500 mm and 800 mm (Siderius and Muchena, 1977), with a mean of 711 mm. This is shown in Table 1. The average seasonal rainfall for the long rains (March - May) is 301 mm (42.3% of mean annual total) , while that for the short rains (October - December) is 283 mm (39.8% of mean annual total). Both the seasonal and the annual rainfall totals exhibit wide variations (Stewart and Faught, 1984; Stewart and Kashasha, 1984).

Table 1

Monthly and annual rainfall of Katumani Research Centre (1958-1980)

Month	Mean (mm)	Highest (mm)	Lowest (mm)	Max. 24 Hour Fall (mm)	Average No. of Days of Rain ≥ 1 mm
January	50	190	0	67.0	4
February	45	117	0	40.3	4
March	89	216	0	64.1	7
April	147	315	20	82.5	12
May	65	151	11	58.2	7
June	11	35	0	19.3	2
July	7	37	0	20.5	1
August	5	20	0	12.5	2
September	9	43	0	25.8	1
October	35	136	0	86.9	3
November	164	463	34	186.9	14
December	84	262	12	46.7	8
Year	**711**	**1263**	**450**	**186.9**	**65**

Source : Kenya Meteorological Department (1984): "Climatological Statistics for Kenya".

Katumani experiences a mean annual temperature of 19.2°C. The 34 years mean maximum and minimum temperatures are 24.7°C and 13.7° C, respectively (Table 2). The hottest months are often those preceding the rainy seasons.

Table 2

Monthly and annual temperatures of Katumani Research Centre (1956-1980)

Month	Means (°C)			Extremes (°C)		Dry Bulb (°C)		Dew Point (°C)	
	Max.	Min.	Range	Highest	Lowest	0600 GMT	1200 GMT	0600 GMT	1200 GMT
January	25.8	13.8	12.0	32.2	8.1	18.8	24.2	14.6	12.8
February	27.1	14.3	12.8	31.1	5.6	18.9	25.3	14.8	13.5
March	26.4	15.3	11.1	31.1	8.6	19.1	25.1	15.5	14.1
April	25.1	15.7	9.4	29.1	10.0	18.6	23.6	16.2	16.0
May	24.2	14.3	9.9	30.3	7.8	18.0	22.6	14.9	15.0
June	23.0	12.0	11.0	28.9	6.7	16.4	21.5	12.6	12.3
July	22.1	11.6	10.5	27.8	6.1	15.5	20.6	12.1	11.7
August	22.6	11.6	11.0	30.0	5.4	15.6	21.2	12.0	12.4
September	25.1	12.2	12.9	30.6	6.1	17.1	23.7	12.5	11.5
October	26.3	13.8	12.5	31.1	6.7	18.6	24.9	13.0	11.0
November	24.1	15.1	9.0	28.9	8.5	18.0	22.7	15.0	14.2
December	24.2	14.3	9.9	29.4	9.5	18.5	23.0	15.1	14.2
Year	24.7	13.7	11.0	32.2	5.4	17.8	23.2	14.0	13.2

Source : Kenya Meteorological Department (1984): "Climatological Statistics for Kenya".

Table 3

Monthly and annual sunshine (1974 - 1980), radiation (1974 - 1980), evaporation (1965 - 1980) and wind (1965 - 1980) data for Katumani Research Centre.

Month	Daily Sunshine			Daily Radiation# (Instrument GB)			Monthly Evaporation (Pan Type A)			Daily Wind Run
	Mean (h)	Max. Mean (h)	Min. Mean (h)	Mean (MJ/m^2)	Max. Mean (MJ/m^2)	Min. Mean (MJ/m^2)	Mean (mm)	Highest (mm)	Lowest (mm)	Km
Jan.	9.2	10.4	6.7	22.2	24.6	17.3	170	211	133	190.8
Feb.	9.6	10.7	8.6	23.0	25.6	18.7	183	216	146	190.0
Mar.	8.9	10.3	6.2	22.6	25.3	15.6	200	254	140	185.7
April	7.5	8.5	5.5	19.2	22.9	14.0	162	178	147	114.2
May	7.0	8.3	6.1	17.5	20.8	13.4	121	144	108	116.7
June	5.0	6.6	4.0	15.4	19.4	13.1	102	130	90	112.6
July	4.1	5.7	3.0	13.6	16.4	10.5	99	120	84	116.2
Aug.	4.3	5.8	2.4	14.1	16.8	8.8	115	140	99	134.2
Sept.	6.5	7.7	5.1	19.6	23.8	16.8	160	173	140	166.5
Oct.	8.6	9.5	7.2	21.5	23.6	18.5	199	225	180	198.4
Nov.	7.5	9.0	5.8	19.2	21.7	14.9	149	179	127	182.5
Dec.	8.4	9.8	7.0	21.0	23.7	17.7	147	173	125	171.0
Year	7.2	8.2	6.5	19.1	20.9	16.3	1807	2099	1606	159.1

From: Kenya Meteorological Department (1984): "Climatological Statistics for Kenya".

Values converted to MJ m^{-2} from original units of Langleys.

For example, January, February and March have higher mean temperatures, and precede the Long Rains rainy season. Similarly, September and October, just before the Short Rains season, are hot months. June, July and August are colder months (Table 2). The hotter months tend to be associated with longer daily sunshine hours and higher radiation values (Table 3).

The shorter daily sunshine hours experienced during the colder months (June - August) is basically a result of the extensive cloudiness associated with these months, rather than changes in day-length (defined as time from sunrise to sunset). Both radiation and evaporation (Table 3) seem to follow the monthly pattern set by sunshine hours and temperature. Daily wind runs also appear to be longer in hotter and wetter months, than in the cold and dry months of the mid-year period. Relative humidity, however, tends to exhibit no definite pattern of variation with time of year (Table 4).

Table 4

Relative Humidity of Katumani Research Centre (1956 - 1980)

MONTH	0600 GMT (%)	1200 GMT (%)
January	77	51
February	78	49
March	80	52
April	85	65
May	82	63
June	78	56
July	80	57
August	79	57
September	75	47
October	71	43
November	83	59
December	81	58
Year	79	55

Source : Kenya Meteorological Department (1984): "Climatological Statistics for Kenya".

Designation of rainy seasons as used in this report

The naming of rainy seasons, as described above, will be used extensively in this report, and will be referred to by a "Season-Year" format in an abbreviated form. For example, the long rains of 1993 season, and the short rains that followed it, will be abbreviated throughout this work as *LR1993* and *SR1993*, respectively. All other rainy (growing) seasons will be similarly designated. It is to be noted, however, that in this report, a January and / or February rainfall is designated as being part of the short rains season of the previous year, and analysed as such. Similarly, any rains falling in the months of June and / or July will be reckoned as part of that year's long rains. This is a minor deviation from the traditional concept of restricting the seasonal rains to the three months described above. There are two reasons for this inclusion. Firstly, the rains falling during the two-month extension beyond the traditional three-month seasonal designation often result in appreciable hydrologic and soil erosion processes that are relevant to this study. Secondly, such extensions often occur before the harvesting of the previous season's crops, and may strictly be considered part of the season. Thus such data will be analysed and presented as part of the preceding season.

1.2.3 *Soils and Topography*

A detailed survey of Katumani soils was carried out in 1986 and reported by Gicheru and Ita (1987) using the nomenclature of FAO-UNESCO (1974). This is the soil classification that will be employed in this report. The following description is based on the soil survey report of Gicheru and Ita (1987).

Five major soil classes were identified in Katumani. The parent material underlying all these soils is undifferentiated quartzo-feldsphatic gneisses of the Basement Systems Complex (Baker, 1954, cited in Gicheru and Ita (1987)). The predominant soils are *Luvisols,* covering a total of 384 hectares (or 78.5% of total area of Katumani). These are deep to very deep, well drained, dark red to reddish brown, weakly structured, friable soils whose clay content increases with depth. Other soil types are the shallow *Cambisols* and the very shallow *Lithosols.* The above three soil types are slightly acidic, have a base saturation averaging 50%, and a top soil organic matter content of <1%.

Other soil types include *Vertisols* and *Fluvisols.* The *Vertisols*, cover 4 hectares of land, and are poorly drained, cracking calcareous clayey soils of black colour with an

organic matter content of approximately 0.8%. The cracks are characteristically 1-2 cm wide. The *Fluvisols* have higher organic matter contents (averaging 1.2%), probably due to their location in river valleys where the vegetation tends to be more productive. They are moderately well drained, dark to reddish brown clayey soils.

Topographically, Katumani consists of flat to hilly landscapes, with a relief variation of 10 - 20 m. The slopes are straight, with gradient range of between 2% and 20% (Gicheru and Ita, 1987).

2 TECHNICAL JUSTIFICATION OF THE STUDY

2.1 Conceptual Framework

The semi-arid regions of eastern Kenya are characterised by climatic and land conditions that limit crop productivity to levels below the optimum required for subsistence. These conditions include low and erratic rainfall, higher temperatures, fragile and highly erodible soils and, in many places, hilly and sloping landscapes. Moreover, the rainfall is often intensive, leading to high surface runoff losses, thus aggravating the moisture deficit situation. Runoff on the sloppy arable landscapes result in soil erosion and nutrient decline, particularly where vegetal cover is low or non-existent. However, not only does runoff cause erosion, but there is a positive feedback through the effect of erosion increasing subsequent runoff. The removal of the well aggregated topsoil leaves a poorly structured sub-soil which tends to crust readily under rainfall impact, thus shedding even larger proportions of rainfall as runoff.

Positive feedback is similarly important in the relationships between erosion, soil fertility, soil cover, and infiltration/runoff. Loss of soil and nutrients through erosion leads to reduced fertility. Reduced fertility results in less biomass production and, consequently, less surface cover and less soil macrofaunal activity. These result in reduced infiltration, higher runoff, increased soil and nutrient erosion, and further reduction in soil fertility. The complexity of these interactions has important implications for improved soil surface management strategies and the research and development activities that pursue them.

The productivity of a crop in a particular climatic setting is determined largely by the physical, chemical and biological conditions of the soil. The physical conditions of the soil drive the hydrology (infiltration, runoff and soil water storage), while the chemical and biological conditions determine soil nutrient availability. These soil properties are neither static nor uniform, but vary with time, space and land management practices.

The hydrologic characteristics of the soil determines both the productivity of the cropping system (through the amount of water useable by the crops) and the erosion hazard caused by runoff of water in excess of that which infiltrates. Thus the understanding of surface hydrology is the key that permits the modelling and

simulation of hydrologic, crop growth, and soil erosion processes, thereby enabling an analysis of the long term effects of various cropping practices.

The infiltration process is a central component of the water balance, and depends on soil surface conditions such as roughness and presence, or absence, of seals and crusts, tillage, and surface cover (Chow *et. al.*, 1988; Freebairn *et. al.*, 1989; Mohamoud, *et. al.*, 1990). Improved predictions of crop growth depend upon better simulation of the hydrological components of the soil-plant system (McCown and Jones, 1992; Okwach *et. al.*, 1992a).

There is a dearth of scientific work and information on the infiltration process on the soils of Katumani in particular, and Machakos district in general. There is need to relate the surface runoff process to changing infiltration characteristics of the soil. The effectiveness of any land management option in runoff control can best be studied in relation to how such a practice alters, or maintains, the infiltration characteristics of the soil, and / or the factors influencing the infiltration process. The information thus gained then becomes valuable input into water balance/crop yield prediction models.

Soil erosion due to surface runoff is the single most important cause of land degradation and loss of productivity in much of the semi-arid eastern Kenya (Barber *et. al.*, 1981; Rukandema *et. al.*, 1981; Rukandema, 1984). The rate and amount of runoff losses can directly be related to the rate and amount of soil lost through erosion. But the problem of rain water lost as runoff in a semi-arid environment is more immediate than the long term effects of depleted fertility. The proportion of rainfall that is lost as runoff from a single event in lowland Machakos district may be as high as 60% (data from Kilewe (1987) study). Such high losses occur in a situation in which total seasonal rainfall is, itself, inadequate for optimal crop production. Runoff reduces the amount of water that can infiltrate to replenish the soil moisture for crop use, and thus contributes to the problem of low crop yields (Marimi, 1975). It is important, therefore, that runoff losses be reduced, and infiltration enhanced, through water-conserving surface management techniques. Equally important is the need for suitable predictive tools that enable simulation and prediction of the effects of appropriate soil surface management strategies on runoff, infiltration and soil erosion. This study sought to document the possible relationship between runoff, infiltration, and soil erosion under different land management strategies, with a view to obtaining parameters needed for modelling seal formation, runoff, infiltration, and soil erosion.

2.2 Objectives

The objectives of this study were;

1. to measure the relationship between runoff, infiltration and soil erosion under the Katumani *Luvisol*, which is a dominant soil type in much of semi-arid eastern Kenya, under different soil surface management systems relevant to agriculture in the region.

2. to evaluate the role of crusting in determining infiltration and runoff in these soils.

3. to develop a model which relates crusting, runoff, and infiltration to soil properties.

3 METHODOLOGY

3.1 Description of the Experimental Area

The site of this study is the middle of three terraces that had been constructed some fifteen years ago on a gently-sloping hillslope. The area selected is demarcated by 1 meter high bunds on either side (top and bottom). The selected terrace consists of undulating to rolling slopes of 5 - 16 degrees gradient. The soil is a strongly weathered, well drained, deep (0.80-1.20 m), dark reddish-brown (2.5YR2.5/4, moist) to dark brown (10YR2/2, moist) *Chromic Luvisol*, derived from undifferentiated quartzo-feldsphatic gneisses (Gicheru and Ita, 1987). The texture is sandy clay loam, tending to sandy clay at lower horizons. These soils are low in organic matter (0.52 to 1.0%) and nitrogen (0.07 to 0.09%). The A horizon averages 0.19 m. in depth. It has a weak to moderate, medium, sub-angular blocky structure, with a tendency to harden when dry and become friable and easily erodible when wet. It has a CEC-soil of 12.1 to 23.9 me/100g and a slightly acidic pH-water (5.7 - 6.9), a base saturation of 45 - 59% and electrical conductivity of 0.04 - 0.11 dS m^{-1} (Gicheru and Ita, 1987). The B-horizon consists of a weak to moderate, fine, medium to coarse, sub-angular blocky structure, with a CEC-soil ranging between 11.1 and 21.7 me/100g, a pH-water of 5.7 - 6.5, and a base saturation of 50 - 55%.

3.2 Experimental Plots

The instrumented runoff plots used in this study were part of the twelve that had been installed in 1989, and used in the study by Okwach (1994) which ran from LR1990 to LR1992. Thus the facilities became available for the duration of this USAID-CDR funded study (SR1992 to LR1995). However, because the study of Okwach (1994) had imposed heavy fertilizer treatments on eight of the twelve experimental sites, only the four previously non-mulched runoff plots were selected for this study, so as to avoid any cumulative or residual effects of fertility.

Each plot had been individually surveyed for slope in 1989, following their installation. The four plots selected for this study had been designated in the previous study (Okwach, 1994) as Plots 1 (11.0% slope), 6 (8.7% slope), 7 (8.7% slope), and 12 (8.3% slope). The cross slope is negligible, or non-existent. Each plot measures 7 m wide by 15 m long, with the long axis oriented down the slope. The plots are bounded at the top and the two sides by 0.3 m. high galvanised iron sheets of 18 gauge

thickness. These sheets are inserted into the soil to a depth of 0.15 m, so that the above-ground portion is also 0.15 m high.

Runoff is collected at the lower end of each plot by means of large V-shaped tipping buckets, of approximately 7 litre capacity, connected to electronic data loggers. Following installation, these runoff measuring tipping buckets had been calibrated to obtain bucket tipping capacity and how this varied with flow rates. The loggers were logged to 1 minute time intervals, and were, therefore, capable of yielding estimates of 1 minute variations in runoff rates, as well as giving the total runoff amount yielded from each plot during each storm.

At the bottom end of each plot is a collecting trough, which measures 0.25 m. wide and 7 m. long, and captures all runoff leaving the plot. The trough is made of the same galvanised iron sheet as the side boundaries. Each trough is placed some 0.15 m. below the plot surface, re-enforced by sand and concrete. The trough is installed at a slope of 1%, with the lower end draining into a collecting pit. The other end of the trough is sealed, to prevent runoff and sediment loss, by a metallic plate welded and glued to the trough body. The pit measures 1.25 m by 1.15 m and is 0.80 m deep. A 0.26 m opening at the lower end of the pit enables the draining of runoff water into the lower terrace bank for safe discharge. The walls, floor and draining channel of the collecting pit are all re-enforced with concrete.

In the collecting pit, receiving water and sediment from the collecting trough, is a sediment settling drum. This settling facility is an ordinary 200 litre oil drum (0.56 m diameter and 0.88 m height), cut and re-modelled to allow runoff inflow and outflow. The inflow opening is cut at 0.55 m from the base, while the outflow opening is at 0.45 m from the base. Runoff, therefore, collects in the drum to a height of 0.45 m and then drains out without the possibility of interfering with the inflow. To minimise the time lag of flow measurement compared with actual plot runoff the drum is filled with water before each event. The drum is placed on a concrete platform, which lifts it off the 0.80 m -deep pit floor in such a way that some 0.15 - 0.20 m of the top of the settling drum remains protruding above the surrounding soil level. The purpose of this protrusion is to prevent runoff from outside the experimental area (plot) from flowing in and mixing with the collected plot runoff.

Attached and sealed to the outflow opening on the drum is a short rectangular basin, known as the runoff guide, which channels water from the drum to the tipping bucket.

This structure is 0.54 m long and 0.28 m wide, with the length running at right angles to the direction in which the collecting bucket tips. In the centre of the runoff guide is the inlet manifold. This is an opening, measuring approximately 0.04 m wide and 0.24 m long, through which runoff from the drum passes to the tipping bucket flow rate measuring device directly below it.

Between Plots 6 and 7 is a 10 - 12 m space in which two tipping bucket electronic raingauges are installed. Between these two gauges is a manual, daily recording rain gauge. These raingauges provided estimates of both the total and the instantaneous intensity of each rainfall event. Like for the runoff measurements, the rainfall loggers were also logged to 1 minute time intervals.

3.3 Treatments

The original intention of the macro-plots component of this study at Katumani was to evaluate the effects of slope steepness, slope lengths, and methods of cultivation on runoff, infiltration, and soil erosion. However, my absence from Katumani during much of the early part of the project duration (while completing my Ph.D. degree programme in Australia) prevented the establishment of the necessary macro-plots with the specifications required, such as varying slope steepness and lengths. Modifications were then made to enable the use of some of the already established large runoff plots at Katumani, as pointed out in Section 3.2. The selected runoff plots were subjected to different soil management systems, giving four unreplicated treatments. These treatments were as follows:

A ***Conventionally Cultivated Bare Fallow*** **(Plot 12):**

Cultivation and weeding were done conventionally using a traditional hand-hoe. No crop was planted. Neither mulch nor fertilizer was added. The soil surface was kept weed-free throughout the season.

B ***Traditional Maize Monocrop*** **(Plot 1):**

Conventional tillage system by means of a traditional hand-hoe. A low maize population density of 22, 000 plants per hectare was grown at a spacing of 0.90 m (between rows) by 0.50 m (between plants) . Neither surface mulch, nor fertilizers were added.

C. ***Maize-Bean Intercropping*** **(Plot 7):**

Conventional tillage system, with a low maize plant population (22,000 plants per hectare at 0.90 m by 0.50 m spacing), planted in alternate single rows with 74,000 bean plants per hectare (0.90 m by 0.15 m). The planting arrangement was such that maize to bean rows were 0.45 m from each other. Neither surface mulch, nor fertilizer was applied.

D ***Traditional Maize Monocrop with Mulch*** **(Plot 6):**

Conventional tillage system, with the traditional low maize plant density as in Treatment **B** (traditional maize monocrop). No fertilizer was applied. Maize stover mulch was applied at the rate of half of that produced in this treatment in the previous season. Measurements showed that such an amount of mulch provided approximately 10% cover to the soil surface.

The experimentation ran for six seasons, commencing with SR1992 (October of 1992) and ending with the LR1995 (July of 1995).

3.4 Measurements

A number of measurements were made during the six seasons of this study. However, due to my absence from Kenya during much of this period, only the basic data were collected in most seasons. These measurements included;

- Daily rainfall
- Daily runoff
- Soil loss

In addition, soil surface hydraulic conductivity was measured by means of the disc permeameter (Perroux and White, 1988) only in December of 1994, during the SR1994 season. There was no direct measurements of infiltration. However, from the rainfall and runoff data obtained by the electronic loggers, an analytical theory will be presented that enables some modest determination of infiltration characteristics. Also not measured was the effects of treatments on crust formation.

4. RESULTS

The seasonal results of runoff, soil loss, and hydraulic conductivity will be presented and discussed from measurements made during the study period. In addition, infiltration characteristics will be derived from rainfall and runoff data, using appropriate theory. It should be pointed out, however, that the LR1993 was a complete failure. The total rainfall received was a meagre 55mm, which did not yield any runoff in any of the four treatments investigated. Crop germination was poor, and the few germinated seedlings soon died of water stress. There was a total crop failure. For this reason, the results to be presented in this section will be limited to the remaining five seasons: SR1992, SR1993, LR1994, SR1994, and LR1995.

4.1 Surface Runoff

The runoff losses from the four treatments are shown in Figures 1 to 5 for the SR1992 to LR1995 seasons, respectively. As expected, runoff decreased with increase in ground cover provided by vegetation. In all the five seasons, the effects of vegetation on runoff control is readily visible from the reduction observed between the bare fallow and the maize monocrop. Increasing the level of vegetation cover, by adding beans to the maize in the intercrop treatment, resulted in further reduction of runoff. The reduction of runoff by the intercrop treatment beyond that due to maize monocrop was, however, less dramatic than that between the bare fallow and the maize monocrop (Figures 1, 3, 4, and 5). In the SR1993 season, the intercrop yielded more runoff (64mm) than the maize monocrop (63mm).

When small amounts of mulch was added to the traditional maize monocrop system, in the maize with mulch treatment, the reduction in runoff loss beyond that of the traditional system was more dramatic in all seasons than under intercropping. Although the level of cover afforded under the various treatments was not measured, it is clear that mulch had a greater effect on runoff than growing vegetation.

Figure 6 shows the comparison between treatment runoff loss over all the runoff-producing rainfall events obtained in all the five seasons. Of the four treatments, only the maize with mulch (mean event runoff loss of 13mm) was significantly different ($P \leq 0.05$) from the bare fallow treatment (mean event runoff loss of 19mm). There were no other treatment differences. Table 5 shows the level of

reduction in runoff obtained by each cropped treatment with respect to the bare fallow system.

Table 5

Percentage reduction, with respect to the bare fallow plot, in surface runoff loss (mm) under different treatments

Treatment	Surface Runoff# (mm)	Percentage reduction in soil loss with respect to the bare fallow plot (%)
Bare Fallow	444	0.0
Maize Monocrop	421	5.2
Maize - Bean Intercrop	391	11.9
Maize with Mulch	303	31.8

The greater effect provided by adding small amounts of mulch to the traditional maize monocrop system (31.8%), than by increased canopy cover (11.9%), is evident.

The amount of runoff lost by all treatments in any season was found to be related to the prevailing rainfall characteristics. Of particular significance were the rainfall amount and the seasonal average rainfall intensity. Thus the highest seasonal rainfall obtained in the SR1992 season (776mm) resulted in corresponding highest runoff loss in each treatment. The converse was, however, not true. In other words, the lowest seasonal rainfall (200mm in the LR1994 season) did not yield the lowest runoff amount for each treatment. The least seasonal runoff lost in each treatment was obtained in the LR1995 (with the rainfall amounting to 254mm). Analysis showed that the differences in runoff lost in these two seasons were correlated more with the corresponding seasonal average rainfall rate than with rainfall amount. The seasonal mean average rainfall intensity for the LR1994 was 10.2 mm/h, while that of the LR1995 was 6.7 mm/h. Thus the more intense LR1994 storms yielded higher runoff than the less intense LR1995 storms, despite the higher amount of rainfall realised in the latter season, compared to the former season.

Total of five seasons (SR1992 to LR1995, but excluding the failed LR1993 season)

4.2 Infiltration Characteristics

4.2.1 *Theory of Analysis - The Mass Balance Procedure*

The Katumani macro-plots component of this study did not attempt to measure infiltration characteristics by such common field methods as the use of infiltrometers (Bouwer, 1986). Infiltration characteristics were derived from the measured rainfall and runoff data using a method that will be referred to simply as the *Mass Balance*, because it involves simple subtraction of runoff parameters from the corresponding rainfall parameters, under appropriate theory and assumptions.

In simple description, the mass balance method of calculating infiltration involves subtraction of runoff from rainfall parameters, ignoring depression storage, flow depth storage, and evaporation losses. Surface depression storage has been defined as the water temporarily stored on the soil surface in depressions that must be filled before runoff commences, or during downslope movement of overland flow (Horton, 1933; Linsley *et. a.*, 1949). The concept of the flow-depth storage has been defined by Rose *et. al.* (1983b) as the surface storage due to spatial and temporal variation of flow depth, evidenced by an increase in depth of overland flow with distance, or length of the plane.

During an unsteady water supply, as in natural storms, a time lag exists between the rainfall commencement and runoff initiation. During this pre-ponded stage, the soil absorbs water at a rate equal to the storm intensity, which is less than the soil's infiltration capacity (Chu, 1978). Because of the structural (crust formation) and / or the hydraulic (matric potential-water content relationship) changes that take place on the soil surface during a storm, the initially high infiltration rate declines with time, as the soil becomes saturated and ponded, and approximates the infiltration capacity. This state of ponded infiltration is maintained so long as the rainfall intensity remains high enough, above the soil's capacity to absorb the water as fast as it arrives on the surface.

4.2.1.1 *Infiltration Rate as a Function of Time ($I(t)$)*

The water balance during any time period in an area receiving rainfall of intensity P and sum $\sum P$, may be represented as

$$\sum P = \sum Q + \sum I + \sum DS + \sum T + \sum E + \sum F \qquad [1]$$

where Q, I, DS, T, E, and F are, respectively, the rates of runoff, infiltration, depression storage, interception by vegetal cover, and evapotraspiration, and flow-depth storage, and the summation implies the sum (or amount) of these components during the time period of interest. For small time intervals, such as the 1 minute logging time step used in this study, the effects of DS and T are small compared to P, Q, and I, and may be ignored (Williams and Bonell, 1988) once ponded condition is realised. Similarly, E and F may be assumed to be insignificantly small components of P, during a storm. Solving for $\sum I$ in the resulting equation gives

$$\sum I = \sum P - \sum Q \qquad [2]$$

during ponded conditions. As a further approximation, it can be assumed that, at any instant during excess-rainfall state,

$$I(t) = P(t) - Q(t) \qquad [3]$$

when the variation in DS is small (Williams and Bonell, 1988) and the interception capacity is satisfied (Linsley *et. al.*, 1988). A number of workers, among them Dunne and Dietrich (1980a), Lindstrom and Voorhees (1980), Bonell and Williams (1986), Williams and Bonell (1987; 1988), and Dunne *et. al.* (1991) have used such a "simplistic" view of infiltration.

4.2.1.2 *Determination of Infiltration Rate During Excess-Rainfall State*

The analysis of the logger runoff data yielded, for each experimental plot, the parameters Q and $\sum Q$, as function of time. In addition, the analysis of the rainfall logger data provides P and $\sum P$. With the assumptions made above, the time dependent $\sum I$ is then obtained by Equation [2]. Plotting both $\sum P$ and $\sum I$ together against time, t, yields twin curves which overlap at small t, prior to attainment of excess-rainfall state, but diverge at incipient ponding as excess rainfall is realised, and runoff appears under sufficiently high P. The slopes of the linear, diverging portions of the two curves represent the average rates at which the respective processes occur, for the duration corresponding with the high rainfall intensity for which ponded condition is sustained (Bonell and Williams, 1986). Evidence for "ponding" (excess-rainfall state) is then obtainable by examining and comparing the rainfall intensity, P, and the infiltration rate, I. Infiltration during

excess rainfall occurs at a rate I_R when $P > I$ (Dunne *et. al.*, 1991), such that $R > 0$ (Rose, 1985), where R is the excess rainfall rate. Graphically, this is evidenced by a steeper slope of $\sum P$ versus t curve compared to that of $\sum I$ versus t. The method of subtracting Q from P to obtain I that is less than P implies that the condition $P > I$ occurs only when Q is non-zero, that is, when runoff is progressing, since $I = P$ when $Q = 0$ (Rose, 1985). When $P > I$, Q derives from the resulting R, which also feeds the surface depressional storage and determines I_R, the infiltration rate during excess rainfall conditions.

It is pointed out that the occasional use of the terms *Ponding* or *Ponded* in these discussions is meant to achieve brevity of what may more correctly be described as *Excess Rainfall Condition*, when $P > I$. These terms (*Ponded, Ponding, Non-ponded*, etc) are not intended to imply a condition of uniform coverage of the entire soil surface by water, as may be obtained under ring infiltrometer measurements, since such conditions are not easily realised under natural rain storms on rough arable surfaces. Symbolically, I_R will be used to describe the infiltration rate during the state of excess rainfall, when the soil surface depressions are filling (or filled) and overland flow is realised.

The analysis described in this section should not lead to the assumption that non-ponded infiltration is a feature only of small t, prior to initial saturation. Only under constant surface water supply rate (steady rate simulated rain) or variable but high rates does an early non-ponded infiltration give way to one ponded stage that lasts for the rest of the rain event (Chu, 1978). During a natural storm, rainfall intensity continuously changes. This leads to corresponding changes in both the infiltration rate and the surface water storage, and hence ponding. Ponding ceases, and I again becomes equal to P, whenever P falls below the infiltration capacity, I_c (Dunne *et. al.*, 1991), and hydraulic conductivity, K (Hawkins, 1982). Thus the ponded condition is only maintained as long as P is sufficiently greater than I to maintain a constant supply of excess rainfall on the soil surface. These relational variations between P, I and Q raise two implications for the analysis suggested by the use of Equation [2] and / or Equation [3]. Firstly, that P must be greater than I for the entire duration over which the analysis is done, and that any variations in P, within the period of interest, must be small enough not to significantly affect change in depressional storage, DS. Equation [3] holds only when the rate of change of DS over the duration of interest is minimal. Secondly, the greater the difference between P and I ($P > I$) the higher the proportion of land generating Q, and hence the better the estimate of I as an overall catchment parameter. Hawkins (1982) showed that the proportion of land producing

runoff increases with rainfall intensity. Okwach (1994) reported visual observations of partial runoff generation, during some few day-time storms received on these runoff plots, and that the proportion of the runoff-generating areas increased with rainfall intensity.

The analysis described in this section was adopted in this study, to obtain the ponded infiltration rate during some 42 runoff-yielding rainfall events obtained in the five seasons under analysis. The results are now presented.

4.2.2 *Results of the Procedure Described in Section 4.2.1*

In describing the results obtained by the mass balance method of deriving infiltration from rainfall and runoff, the rainfall event of 26th. November 1992 (in the SR1992) has been arbitrarily selected to illustrate the procedure, before the combined results are presented. This was a 72 minute storm of 20.2mm.

Figure 7 shows the variation of storm intensity and runoff rate for the illustrative storm for the bare fallow treatment. Subtracting the instantaneous runoff rate from rainfall intensity yielded the corresponding infiltration rate, shown in Figure 8 for the bare fallow treatment.

Cumulating the storm intensity, runoff rate and infiltration rate, and plotting these against time, yields the relative amounts of the three parameters, as shown in Figures 9 to 12 for the four treatments. The relative magnitude of runoff and infiltration, in relation to rainfall, seem to be influenced by the amount of cover. Runoff exceeded infiltration in the bare fallow treatment (Figure 9), and matched infiltration in the maize monocrop (Figure 10), while infiltration exceeded runoff by amounts which seem to increase with cover levels in the remaining two treatments (Figures 11, and 12). This observation illustrates the reason for the lower runoff under increased cover. Again, there is observed greater increase in infiltration in moving from the intercrop to maize with mulch, than from bare fallow to intercrop, thus re-emphasising the significant role mulch plays in influencing surface hydrology.

Figures 9 to 12 are necessary for the visual determination of possible sections of the storm in which excess rainfall conditions prevailed. As pointed out in Section 4.2.1, the slopes of the linear, diverging portions of the cumulative rainfall and cumulative

infiltration curves represent the average rates at which the respective processes occur. Separating the rate data corresponding to the relevant portion of the two curves, and plotting these against time yielded two short curves for rainfall and infiltration, whose slopes represented the respective rates. These are illustrated for the four treatments in Figures 13 to 16. The difference between the treatments is seen in both the distance between the rainfall and the infiltration curves, and the relative magnitude of the gradients of the two lines. As pointed out earlier, ponded conditions existed when rainfall intensity exceeded infiltration rate, and a time when runoff was in progress. The magnitude of the gradient of the infiltration curve at such condition was then taken as the parameter I_R, which, for the illustrative storm, was 12.6 mm/h for the bare fallow (Figure 13), 14.6 mm/h for the maize monocrop (Figure 14), 16.0 mm/h for the intercrop (Figure 15), and 24.7 mm/h for the maize with mulch (Figure 16). Thus is observed the effects of cover in maintaining higher infiltration rates, compared to no cover situations.

The procedure illustrated for the storm of 26/11/92 was applied for the 42 identified storms from the five seasons under investigation. The I_R values obtained for each treatment under each storm were plotted against the respective rainfall intensity during excess rainfall, P_R. The results are shown in Figure 17 for all treatments. In all treatments, infiltration appears to increase with rainfall intensity. However, the rates at which I_R increased with P_R at rates differed with treatment. These rates are shown as coefficient a in Table 6.

Both Figure 17 and Table 6 show that the rate at which ponded infiltration rate (I_R) responds to changes in rainfall intensity (P_R) increases with cover, and with a bigger increase above the traditional maize monocrop system realised by use of mulch, than by intercropping.

Table 6

Effects of treatments on the rate of change of I_R with P_R during rainfall events received in the five seasons by regression analysis of the form: $I_R = aP_R + b$

Treatment	Coefficient a	Coefficient b
Bare Fallow	0.342	0.730
Maize Monocrop	0.461	0.812
Maize - Bean Intercrop	0.477	0.861
Maize with Mulch	0.621	0.905

4.3 Soil Erosion

The soil loss from the four treatments are shown in Figures 18 to 22 for the SR1992 to LR1995, respectively. Soil erosion seemed to follow much of the trend initiated by runoff loss, albeit, more dramatically. This dramatic decline of soil loss at higher cover is shown more clearly in Table 7, in which the percentage reduction of soil loss by the various treatments with respect to the bare surface are much higher those for runoff (Table 5).

Table 7

Percentage reduction, with respect to the bare fallow plot, in total soil loss (t/ha) under different treatments

Treatment	Soil Loss# (t/ha)	Percentage reduction in soil loss with respect to the bare fallow plot (%)
Bare Fallow	238.0	0.0
Maize Monocrop	190.2	20.1
Maize - Bean Intercrop	159.0	33.2
Maize with Mulch	96.4	59.5

Three treatments showed significant differences in soil loss, at $P \leq 0.05$, when all the soil-yielding events were combined over the five seasons of study (Figure 23). The soil loss in both the maize-bean intercrop and the maize with mulch treatments were significantly ($P \leq 0.05$) less than the bare fallow system. The maize with mulch was also significantly ($P \leq 0.05$) less than the maize monocrop without mulch.

Total of five seasons (SR1992 to LR1995, but excluding the failed LR1993 season)

4.4 Soil Hydraulic Conductivity

The disc permeameter of Perroux and White (1988) was used to determine the hydraulic conductivity of the four runoff plots only during the SR1994 season. All measurements were taken in December 1994 at two water potentials, namely, 0 mm (saturated flow) and at -30 mm suction. Four readings were made on each plot for each measurement potential. The results are shown in Table 8.

Table 8

Hydraulic conductivity of the experimental plots as measured by the disc permeameter in December 1994, during the SR1994 season - Mean of three measurements per plot

Treatment	Saturated Hydraulic Conductivity (mm/h)		Hydraulic Conductivity at - 30mm suction (mm/h)	
	Mean	Std. Dev.	Mean	Std. Dev.
Bare Fallow	22.15	6.71	5.62	3.24
Maize Monocrop	55.46	17.97	22.80	11.40
Maize - Bean Intercrop	35.77	21.03	12.06	6.96
Maize with Mulch	49.41	12.55	7.92	4.57

The hydraulic conductivity values obtained by the disc permeameter at both water potentials did not show any particular trend with respect to treatment. Moreover, there were wide within-plot variations of estimates, as indicated by the large standard deviations. It is possible that the values obtained during these measurements were more reflective of site specificity than treatment effects. These measurements were, therefore, inconclusive.

5. DISCUSSION

The effects of cover in reducing surface runoff and soil erosion is well documented in literature. These effects may be summarised, at least in the short run, during a storm, in terms of three broad roles, namely (Morgan, 1979; Cogo *et. al.*, 1984);

1. The protection of soil against destructive kinetic energy due to direct raindrop impact
2. Reduction of flow velocity
3. Increase in flow depth

These three broad roles offer means of examining and discussing the observed differences between treatment performance in runoff production and soil erosion.

High raindrop impact on bare soil surface results in soil detachment, aggregate disruption, surface crusting, and reduced infiltration rates (Hudson, 1957; McIntyre, 1958a; Rose, 1960; Ghadiri and Payne, 1977, 1979; Morgan, 1979). The protection of the soil surface against the destructive raindrop impact (role number (1) above) implies reduction of both the rate of, and the proportion of the surface under crust formation (Lindstrom and Onstad, 1984; Folorunso *et. al.*, 1992), and the reduction of the rate of surface roughness decay under raindrop impact (Okwach, 1994). The overall effect is the maintenance of high infiltration capacity in relation to rainfall intensity (Lal, 1975a,b; Collinet and Valentine, 1979; Suwardjo and Abujamin, 1985), and the reduction of runoff amount (Lal, 1975 a,b; Mensa-Bonsu and Obeng, 1979; Cogo *et. al.*, 1984; Kilewe, 1987; Kilewe and Mbuvi, 1988).

Role number (2), the reduction of runoff velocity, is due to both the physical obstruction, by cover, on the pathway of flow, leading to longer tortuous paths, and the increased hydraulic roughness on which the flow operates (Foster *et. al.*, 1984). The resulting reduction in flow velocity implies an increase in residence time for surface water to infiltrate, hence allowing post-storm infiltration to reduce runoff volume (Dunne *et. al.*, 1991).

Under increase in flow depth (role (3)) may be listed additional cover (from the resulting deeper surface water) of the soil against raindrop impact (Cogo *et. at.*, 1984), with the corresponding reduction in crust formation. The significance of a cover-induced higher depth of flow may be more noticeable on soils with greater surface roughness, such as those under regular cultivation. As the flow depth increases

(under high cover), a greater proportion of the irregular surface comes under water, thus providing more area available for the infiltration process (Dunne and Dietrich, 1980a,b), as overland water is raised to the higher parts of the micro-topography characterised by greater permeability (Dunne *et. al.*, 1991).

Protection of soil surface against raindrop impact (role (1)) is effected by both the canopy and the mulch, provided the latter type of cover is not buried in the soil. Clearly, however, the second role (reduction in flow velocity) and the third (increase in flow depth) can only be effected by a cover that is in contact with the soil surface. Only the cover that has physical contact with runoff can alter the flow hydraulic characteristics.

The progressive decline in runoff loss under increasing cover (either as vegetation alone or as vegetation plus mulch) observed in Section 4 can be attributed to the increased protection offered by the cover factor in such management practices. While the bare fallow treatment lies exposed to the full destructive forces of both the rainfall and overland flow, the cropped and mulched systems provide some measure of protection to the soil at degrees that depend on the plant density (population), the cropping system - whether monocrop or intercrop, the stage of growth, and, where applicable, the rate of mulch. The most effective continuity of canopy cover is provided under intercropping (Greenland, 1975; Aina *et. al.*, 1979). Thus the difference, and the progressive decline in runoff amount, observed between the bare fallow practice and the cropped but unmulched systems (maize monocrop and intercrop) must be explained solely on the basis of the increased level of soil surface protection inherent in the latter two systems, as opposed to the bare surface.

From the consideration of the three roles of cover given above, it is clear that the canopy effects in the cropped but unmulched treatments do not affect to the hydraulics of overland flow. The lack of significance in the difference in runoff amount between the maize monocrop with no mulch, and the maize-beans intercrop with no mulch (Figure 6) has also been reported for the Katumani environment by Kilewe and Mbuvi (1988). This observation may suggest a need for a much greater proportion of canopy cover than that provided by the maize-bean intercrop level in this study. Alternatively, it may call for a new choice of cover type to handle the hydraulic processes taking place on the soil surface, under the canopy. This need introduces the maize with mulch treatment into the traditional production system.

The maize with mulch system comes in as a possible alternative to the intercrop treatment in terms of the provision of ground cover for the reduction of runoff and soil loss. The soils of the semi-arid eastern Kenya have low fertility status. Traditionally, crops are grown at low densities to avoid heavy competition between the individual plants for soil moisture and plant nutrients - the two most limiting production resources. Higher crop densities must, of necessity, be accompanied by an effective soil moisture conserving strategies and supplementary nutrient supply. In the absence of the financial resources to support such supplemental nutrient supply (in terms of chemical fertilisers), the introduction of a low rate of mulch to the traditional low population maize monocrop system may be necessary to make the traditional maize production level capable of reducing runoff loss, and hence reduce the soil water deficit that typically limits maize yields. In this respect, the significant reduction in runoff loss under mulch, above the bare fallow treatment, is important testimony to the role played by even a small amount of cover in contact with the soil. Significant reduction in runoff amount by such small level of cover have been reported. On the *Nitosols* of the University of Nairobi Agricultural Research Farm, in Kenya, Bekele and Thomas (1992) reported a 40% reduction in runoff loss from plots covered by maize stover mulch at a rate of 13% (0.50 t/ha). Work done under simulated conditions (Okwach, 1988), and natural rainfall and field conditions (Okwach, 1994) have shown that runoff reduction increases beyond some basic amount of mulch cover, but at diminishing rates.

The infiltration rate realised during excess rainfall, I_R, may be described as the flux across the soil surface when such surface is subjected to excess water. It is the highest infiltration rate possible under the prevailing conditions of soil properties (texture and structure), moisture content, surface roughness, surface seal condition, rainfall intensity, and the attendant ponded area and water depth (Free *et. al*, 1940; Morin and Benjamini, 1977; Skaggs and Khaleel, 1982). The variation of I_R with P_R may be explained in terms of the spatial variation of infiltration characteristics of the soil. The interaction of rainfall intensity and the effects of microtopography in the distribution of effective macropores necessary for infiltration result in different amount of surface depression storage and preferred flow paths. The troughs of the micro-depressions associated with rough soil surfaces tend to have lower infiltration capacities, and hydraulic conductivity, than the crests due to the greater density of macropores are at the higher parts of the microtopography, resulting in greater hydraulic conductivities than in the intervening micro-depressions (Dunne *et. al.*, 1991). Dunne *et. al.* (1991) explains the dependence of infiltration rate on rainfall intensity as due to the increase in the depth of ponding which raises the water to more permeable higher parts of the

micro-relief regions. Secondly, a higher P, in itself, will exceed the saturated hydraulic conductivity, K_s, of larger proportion of the land surface. Both factors raise the spatially averaged K_s of the soil, and result in greater I. It is clear the explanation for the often observed variation of I to changes in P given by Dunne *et. al.*(1991) holds more fully under a non-crusting soil.

Causes of the variation between I and P are not easy to determine, since a number of factors play a part (Dunne *et. al.*, 1991). Another factor that has widely been held responsible for this spatial and temporal variation of the relationship between I and P is the formation of crusts on the soil surface under raindrop impact (Duley, 1939; McIntyre, 1958a, b; Morin and Benjamini, 1977; Farres, 1978; De Ploey and Poesen, 1985; Freebairn and Gupta, 1990; Roth and Helming, 1992). Surface crusts may cause negative correlation between I and P (McIntyre, 1958a, b; Farres, 1978). While raindrop impact on the bare soil surface causes crusts, which then result in decreased I, and a negative correlation between I and P, further rainfall, and the resulting overland flow, may also cause the detachment, and entrainment, of the already formed seals, thus increasing infiltration (McIntyre, 1958a; Dunne and Dietrich, 1980a; Roth and Helming, 1992; Hairsine and Hook, 1994). Thus the complexity imposed by the crust factor in the relation and / or variation between I and P may be in whether, at any given time, a storm is favouring the formation or removal of crusts at soil surface, or the mix between the two opposing processes.

Within the context of the results obtained in this study, it is likely that the low I_R associated with the bare fallow and the maize monocrop treatments were due to high rates of crust formation during the current, and / or previous, storms. The lack of protection of the soil surface in the bare fallow system, and the minimal amount of such protection under the cropped but unmulched treatments, could have resulted in higher rates of crust formation than removal. Barber *et. al.* (1979) investigated runoff generation in, and erodibility of, two dominant Kenyan soils, of which the Katumani *Luvisol* was one, and observed that crust formation and runoff generation, under simulated rainfall, were faster on the Katumani soil.

Increasing the cover level by providing mulch in addition to that supplied by the crop canopy resulted in increased protection against raindrop impact, reduced rate and amount of crust formation, and improved infiltration characteristics, including I_R. The relative rates at which I_R (Table 6 and Figure 17) responds to changes in P_R under different treatments may reflect the relative proportion of the soil surface with a crust

in such treatments. The low rate of response of I_R to P_R observed for the bare fallow system could imply an extensive crust formation, such that only smaller proportion of the soil surface retained K_s at a rate greater than P (Hawkins, 1982). In such situations, the increased overland flow resulting from increments in P can only reach and inundate relatively smaller proportions of the land area in which $K_s > P$, so that the increase in the resulting spatially averaged I_R is modest, and less than for better covered and less crusted treatments (Dunne *et. al.*, 1991). As cover level increases, firstly by the introduction of the unmulched crops, and more so under mulch, the proportion of the land area under protection is increased, progressively less area receives direct raindrop impact, and the rate and magnitude of crust formation is progressively reduced. This progressive protection (under increased cover) means that greater proportion of the soil surface retains K_s at a rate greater than P over a wider range of P. The increased ponding and flow depth resulting from increased P then inundates a greater proportion of highly permeable areas of the land surface.

If it is assumed that the bare fallow system offers the maximum possible proportion of crusted surface under the prevailing soil surface conditions and P, and that crust formation directly under cover is nil, then the proportion of crusted surface must be determined by the relative proportion of the land surface left unprotected by cover. For example, if we take Table 6, and look at the relative rates of response of I_R to changes in P for each treatment, it is noted that the bare fallow treatment showed a rate of I_R response of 0.342 (approximately, 0.3) to changes in P_R. This means that, at any given P, approximately 70% of the land surface of the bare fallow system will be under crust, and 30% will still retain a condition of $K_s > P$. Similarly, approximately 50% of the land surface in the maize monocrop, and 60% in the maize with mulch treatments will still have, at that same P, $K_s > P$. Thus, the effects of cover in increasing the I_R may be understood, including their responsiveness to an increase in P. This information may become important in hydrologic modelling. Okwach (1994) has shown that I_R may be used with Darcy's law, with appropriate assumptions and measurements, to yield acceptable estimates of the saturated hydraulic conductivity across the crusted soil layer.

The role of cover, both canopy and mulch, in reducing soil erosion is well documented. This role is directly linked with the effects that cover has on overland flow in particular, and surface hydrology in general. For example, in the *Alfisols* of western Nigeria, Lal (1975a) reports total elimination of runoff and soil loss under rice straw mulch applied at the rate of 4 to 6 tons/ha, on slopes ranging from 1 to 15%. Lattanzi *et. al.* (1974) obtained a 40% reduction in soil loss from a 5% (approximately 0.5 t/ha

of mulch) surface mulch cover. In the Lattanzi *et. al.* (1974) study, soil loss was further reduced to 80%, compared to bare surface when mulch was increased to 20% cover level. The results obtained in this study show a 59.5% reduction in soil loss from an approximate mulch cover of 10% in the mulched treatment (although the reduction here includes the effects of the low population canopy cover).

The important conclusion, however, is the substantial reduction in soil loss from a minimal amount of crop residue mulch. This has important bearing on management decision, especially where crop residues have important alternative used, as in semi-arid eastern Kenya where it is used to supplement farm animal feed. In terms of soil erosion control alone, it appears that the practice of adding small amounts of mulch to the traditional monocrop maize (or possibly even under intercrop) may be an important management treatment.

The ability of mulch to effect a high level of soil loss reduction at low rates is a common feature of the protective role of mulch cover (Bekele and Thomas, 1992; Okwach *et. al.*, 1992b). This ability may open the opportunity for mulching to be easily adoptable even in communities in which crop residues have alternative uses, such as the semi-arid eastern Kenya.

6. CONCLUSION

Runoff yield and soil loss decreased with increase in surface cover. Mulch (surface contact) cover was more effective than canopy cover provided by growing crops. The effects of low rate of cover was more dramatic in soil loss reduction than in runoff reduction.

The infiltration rate under any treatment during excess rainfall condition was defined and determined. Equations were developed, by simple linear regression, that relates infiltration rate during excess rainfall with average rainfall intensity. Infiltration rates increased with cover. It is suggested that the differences between treatments observed in infiltration rates during excess rainfall conditions are reflective of the extent to which such treatments relate to crust formation. There was, however, no direct measurements of crusting on the experimental plots, an omission that greatly limits the usefulness of this study with respect to objectives 2 and 3, described in Section 2.2.

The disc permeameter measurements failed to yield accurate estimates of hydraulic conductivity. There was no particular treatment-related trend in hydraulic conductivity.

7. SUGGESTIONS FOR FURTHER STUDY

It is suggested that the argument posed in Section 5 (page 28) regarding the rate of response of I_R to P_R under different treatments be further investigated, along with actual measurements of surface seals and crusts with a view to obtaining the exact relation between them. Measurements should include estimation of the potential difference across crusted surfaces, and the thickness of such crusts, under different treatments. The effects of changing slope steepness and length, which were not investigated in the macro-plot scale, should be studied as per the original intentions.

It may be relevant and important, for modelling purposes, to investigate the relationship between soil surface roughness, crust formation, runoff, and infiltration, and how tillage influences such relationships.

8. FINANCIAL REPORT

I returned home from Australia on 20th November, 1994 to find a cheque of US$5000 waiting for me at the USAID office in Nairobi. Although I took the cheque to the bank immediately, it was not until mid February of 1995 that ~~the~~ it was cleared, and the money became available for withdrawal. The bank calculated the amount in Kenya Shillings at Kshs. 43.63 per US dollar, which was the mean exchange rate prevailing in February 1995. Thus the total amount available for the Katumani component of this study was Kshs. 218,150.

It should be noted that some expenditure had been incurred by my field assistance in connection with this study prior to my arrival from Australia. Most of these expenses were paid for before I arrived, partly by Mr. Biamah's component of the study, and partly by miscellaneous funds available at the Katumani Research Centre.

The following is the account of how the Kshs. 218,150 from the US$5000 I received was used.

EXPENDITURE (Photocopies of all supportive documents are given in Appendix B)	**COST (KShs)**
Upgrade of a three year old Computer and Purchase of a new Printer: (Computer Upgraded from a 286, 105 MB Hard Disk, 2 MB RAM To a 386 DX, 365 MB Hard Disk, 8 MB RAM) + Labour Charges	124,300.00
Purchase of a 24 Pin Dot Matrix Printer	40,000.00
18% tax (VAT) on computer upgrade and purchase of printer	29,574.00
Payment of Casual Labour	13,571.00
Cost of Fax Transmissions	6,606.05
Purchase of soldering iron and wire for field equipment maintenance	2,352.00
New lock for office door	613.60
Petrol	800.00
Stationery	517.00
TOTAL EXPENDITURE	**218,333.65**

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APPENDIX A - FIGURES

Figure 1 : Total Runoff Losses From Four Treatments During the SR1992 Season

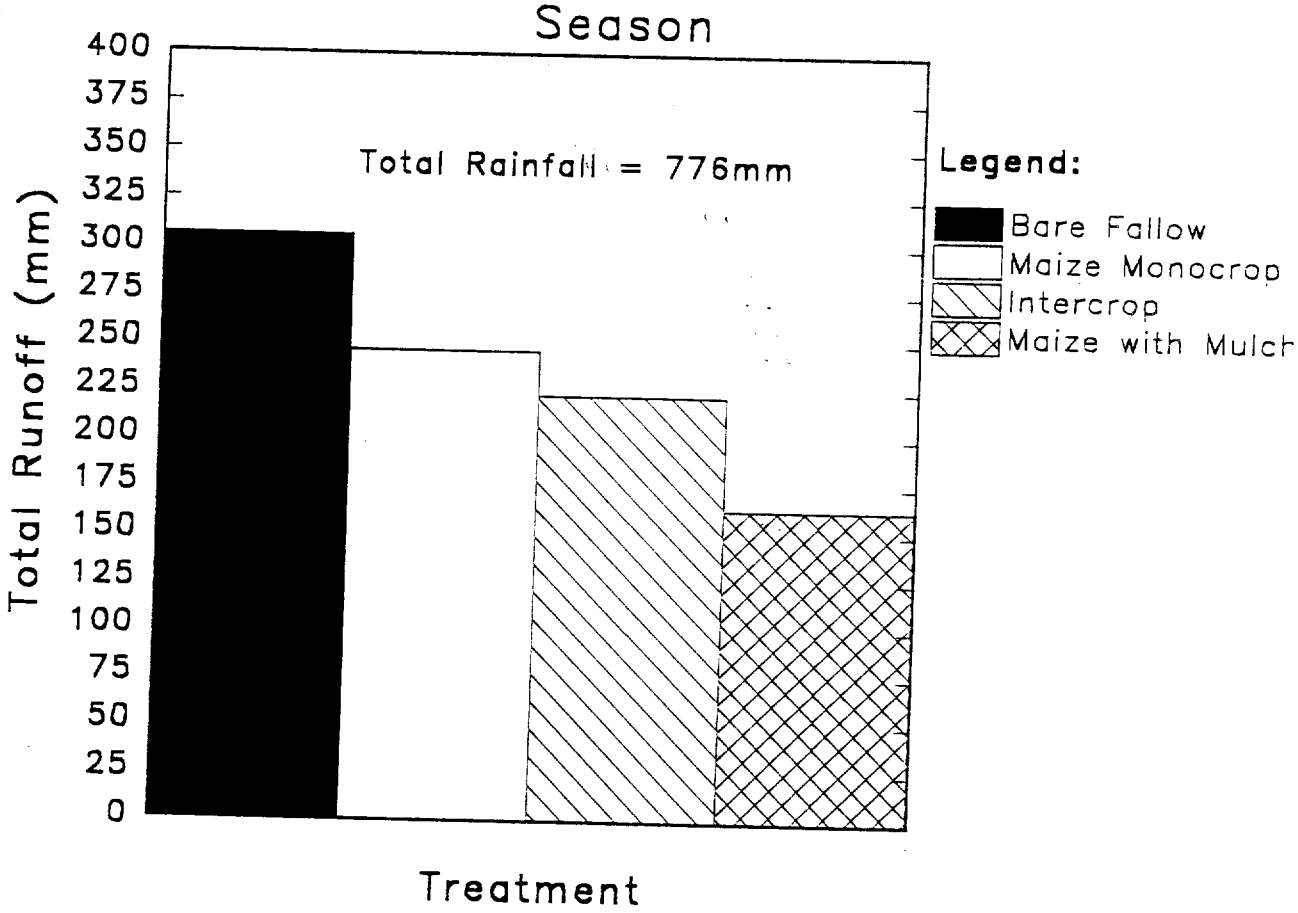


Figure 2 : Total Runoff Losses From Four Treatments During the SR1993 Season

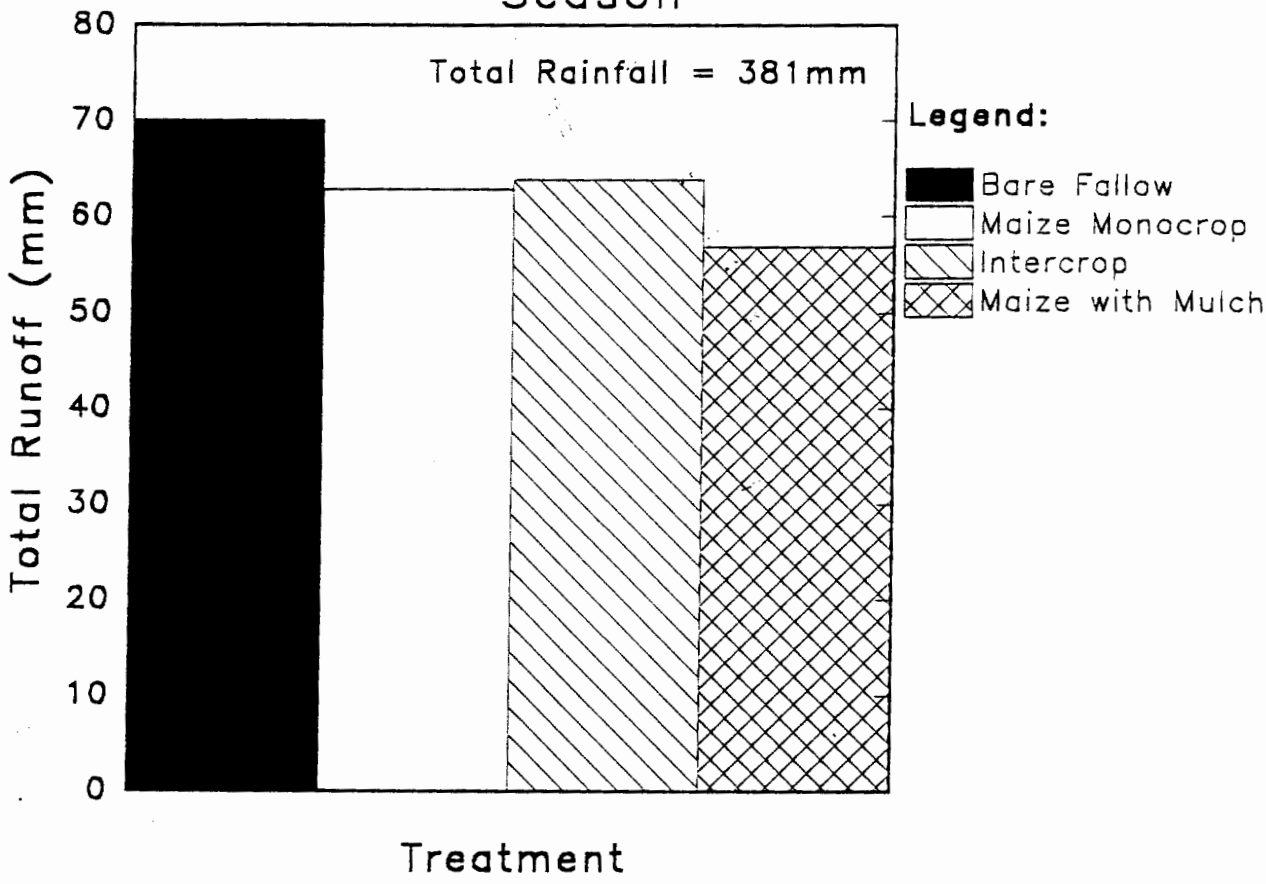


Figure 3 : Total Runoff Losses From Four Treatments During the LR1994 Season

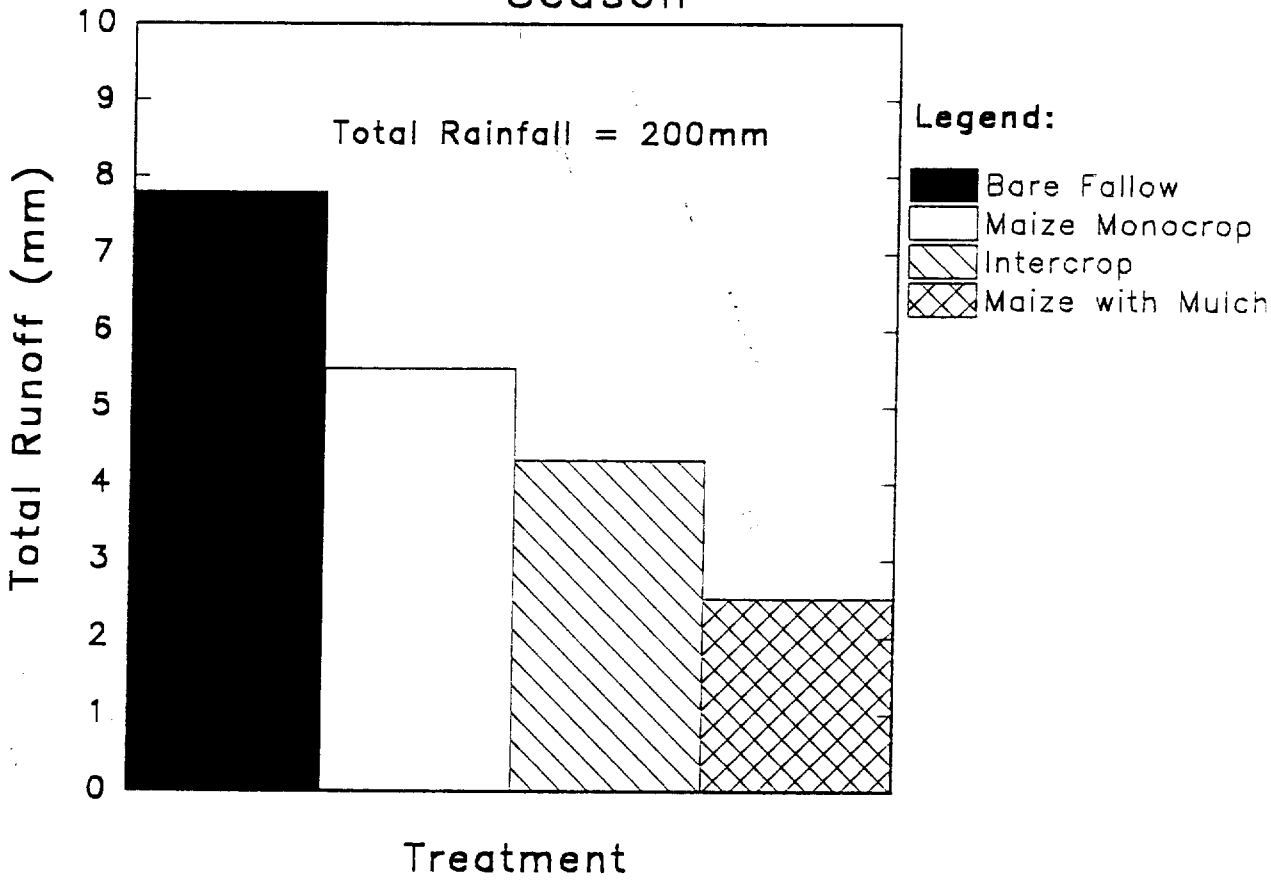


Figure 4 : Total Runoff Losses From Four Treatments During the SR1994 Season

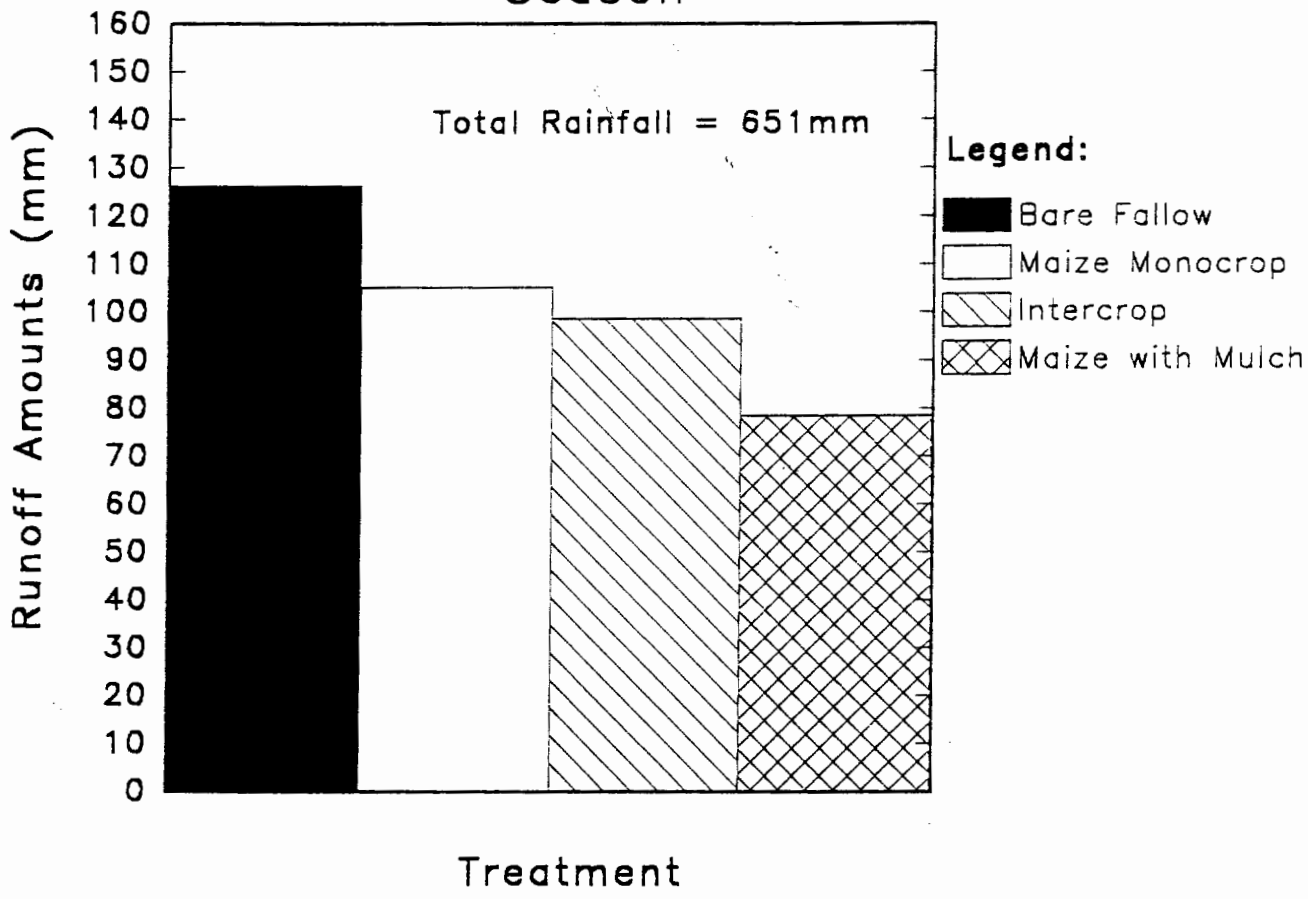


Figure 5 : Total Runoff Losses From Four Treatments During the LR1995 Season

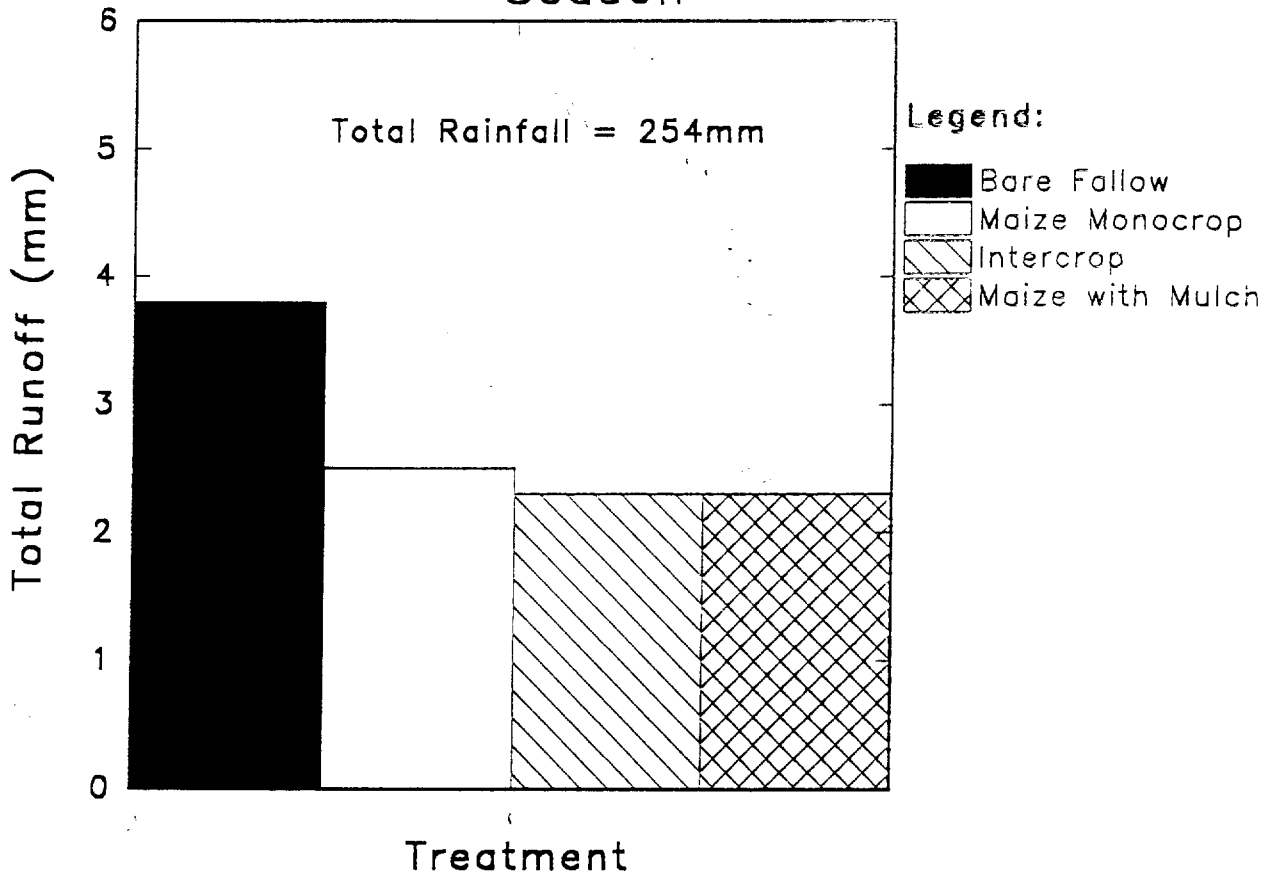


Figure 6: Comparison of Treatment Runoff Loss From SR1992 to LR1995

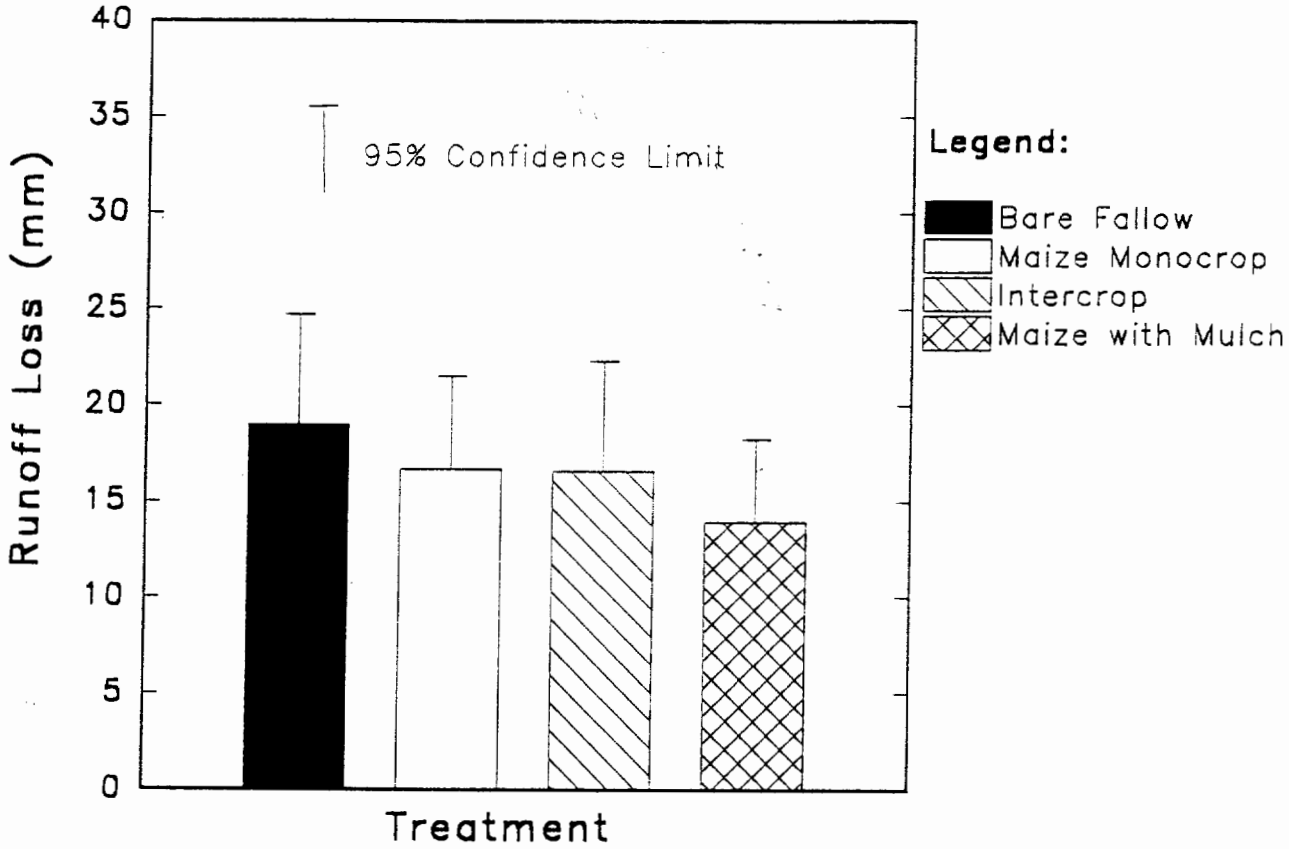


Figure 7 : Variation of Runoff Rate with Rainfall Intensity During a Rainfall Event on 26/11/92 on the Bare Fallow Treatment

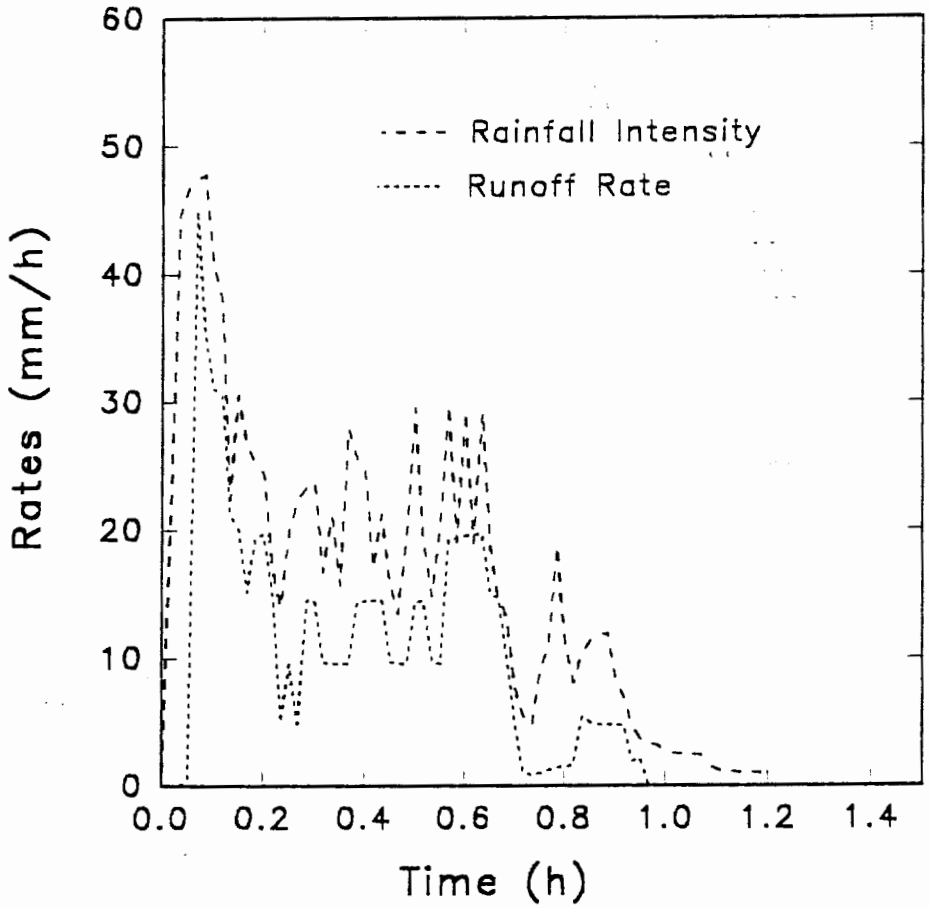


Figure 8 : Relationship Between Rainfall Intensity and Mass Balance Determined Infiltration Rate on the Bare Fallow During a Rainfall Event on 26/11/92

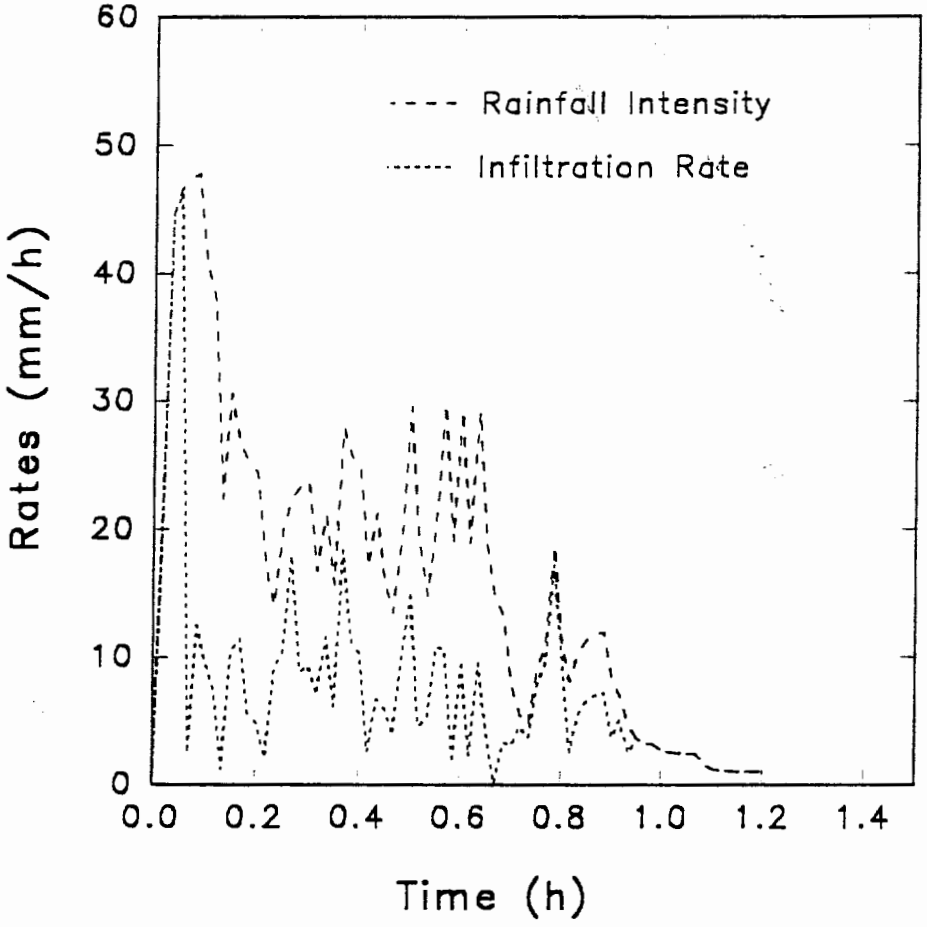


Figure 9 : Mass Balance Determination of Infiltration from Rainfall and Runoff for a Rainfall Event on 26/11/92 on the Bare Fallow Treatment

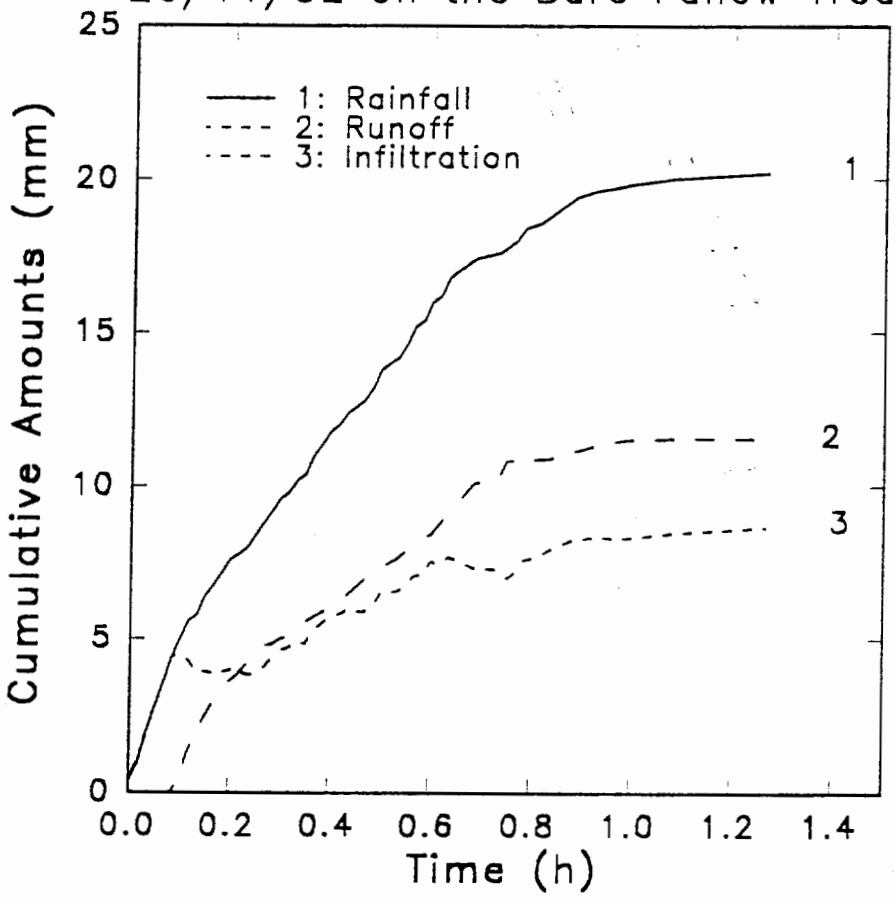


Figure 10: Mass Balance Determination of Infiltration from Rainfall and Runoff for a Rainfall Event on 26/11/92 on the Maize Monocrop Treatment

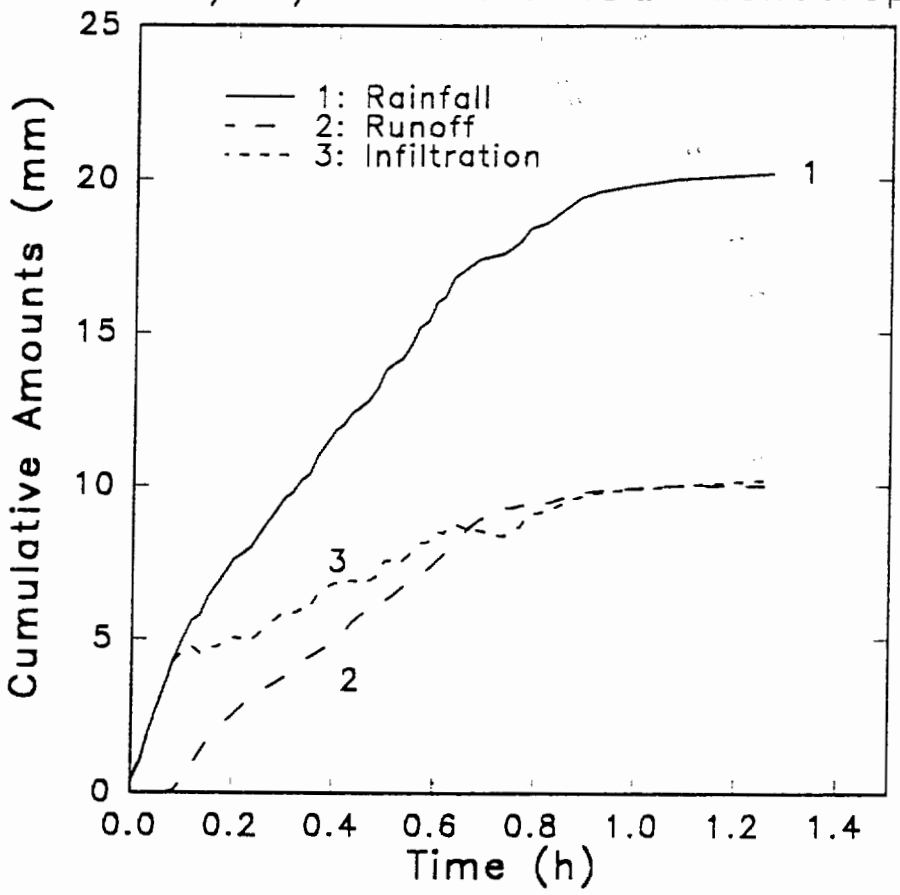


Figure 11: Mass Balance Determination of Infiltration from Rainfall and Runoff for a Rainfall Event on 26/11/92 on the Intercrop Treatment

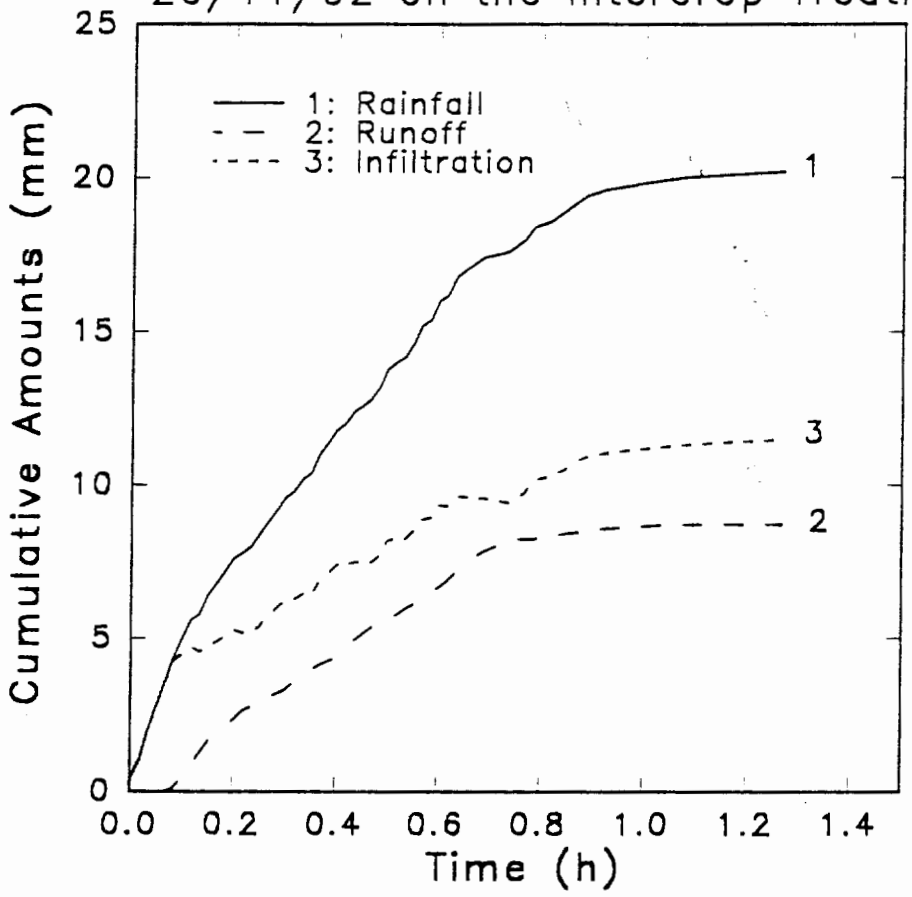


Figure 12: Mass Balance Determination of Infiltration from Rainfall and Runoff for a Rainfall Event on 26/11/92 on the Maize with Mulch Treatment

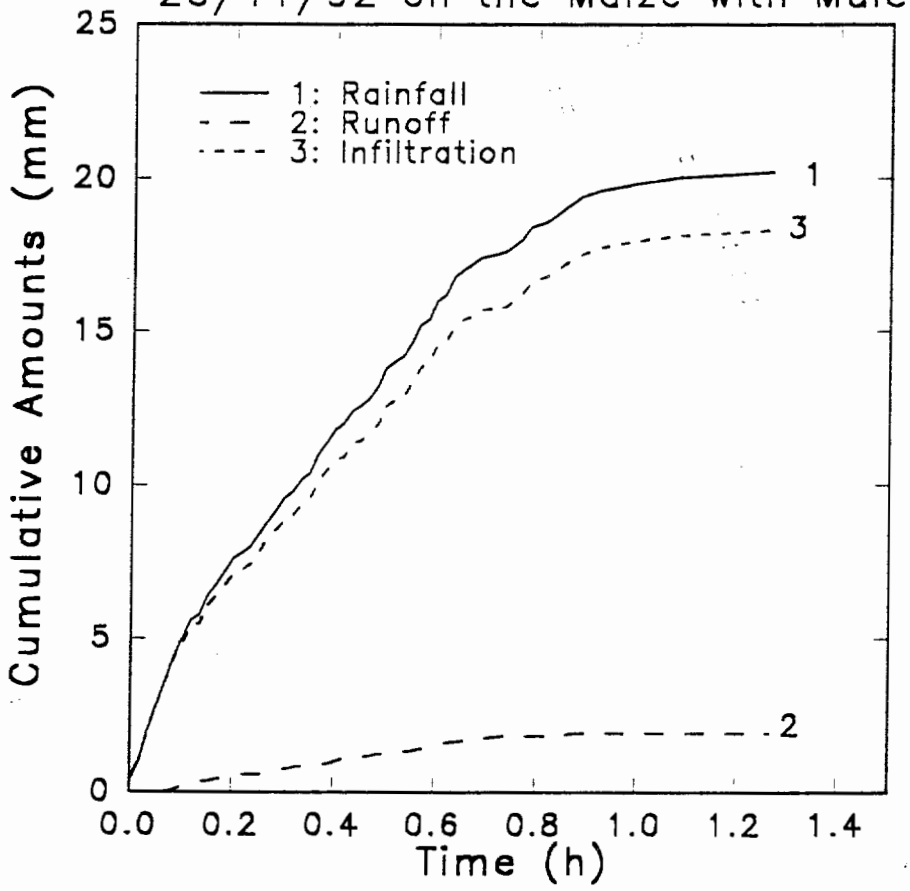


Figure 13: Determination of Rainfall Intensity and Infiltration Rate During Rainfall Excess for a Rainfall Event on 26/11/92 on the Bare Fallow Treatment

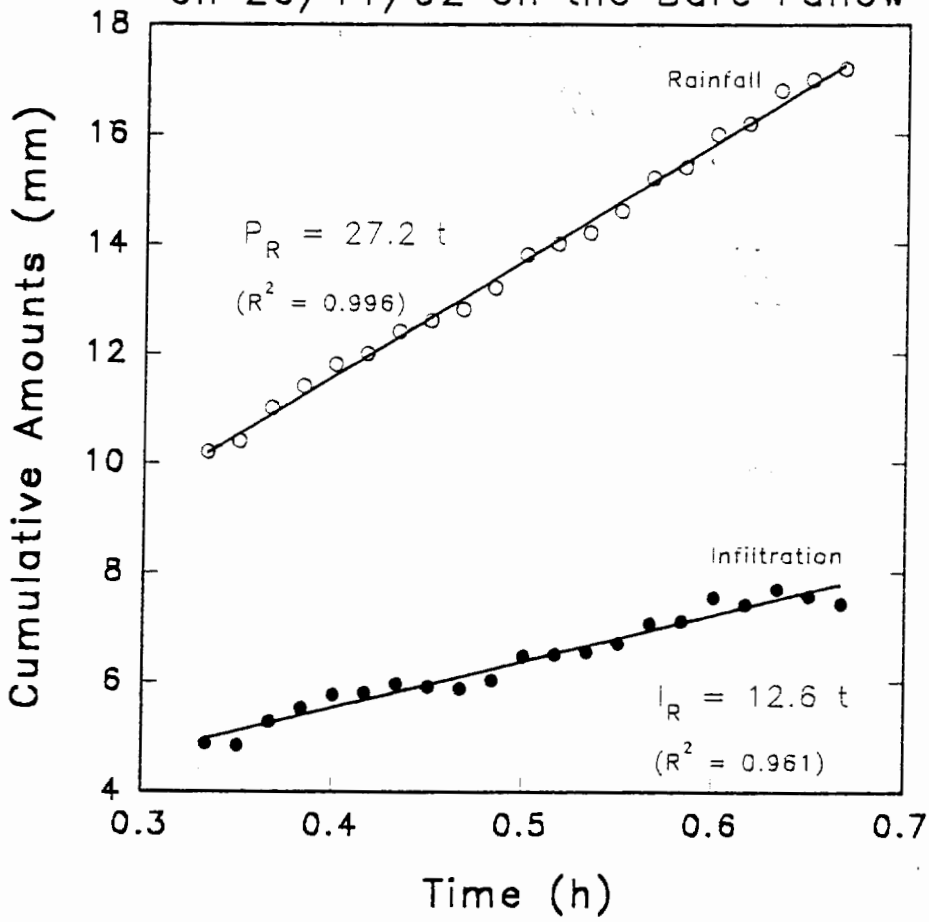


Figure 14 : Determination of Rainfall Intensity and Infiltration Rate During Rainfall Excess for a Rainfall Event on 26/11/92 on the Maize Monocrop Treatment

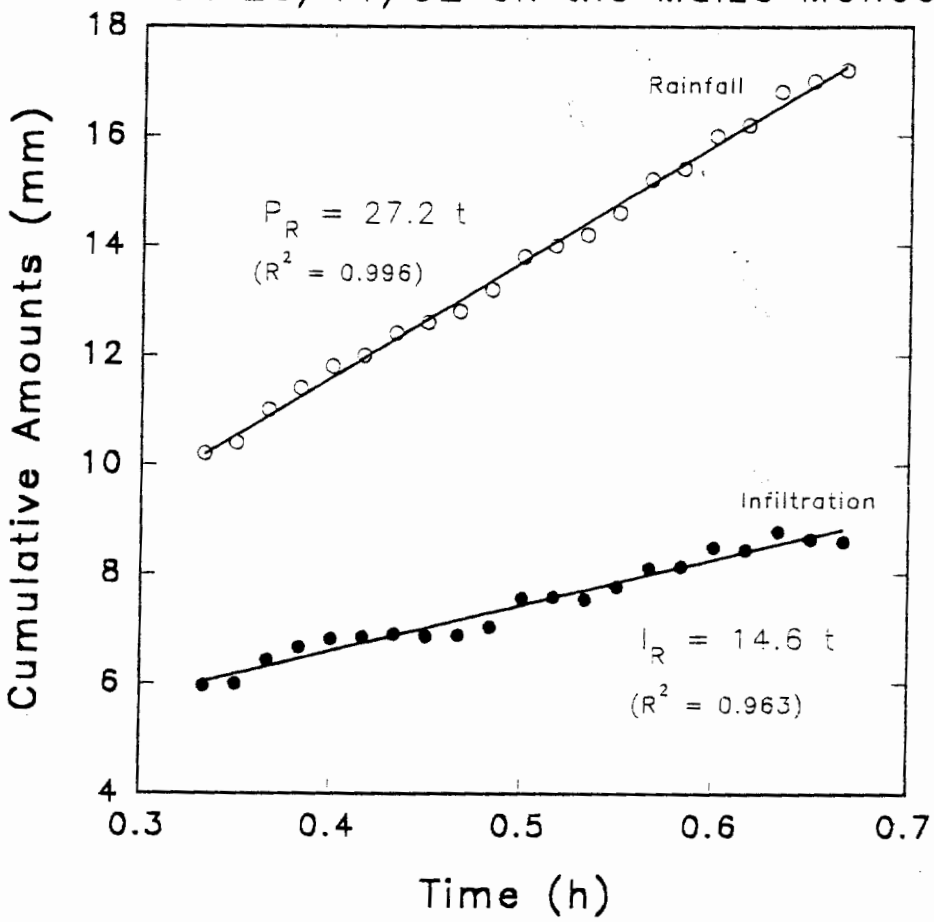


Figure 15: Determination of Rainfall Intensity and Infiltration Rate During Rainfall Excess for a Rainfall Event on 26/11/92 on the Intercrop Treatment

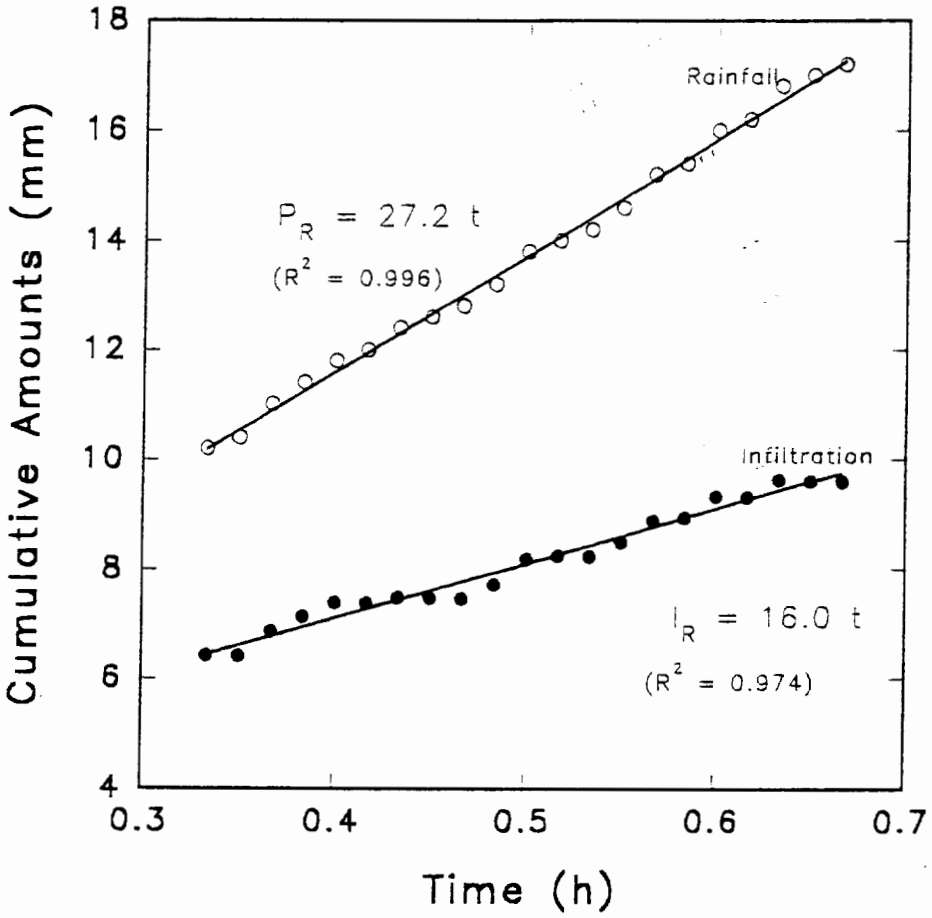


Figure 16: Determination of Rainfall Intensity and Infiltration Rate During Rainfall Excess for a Rainfall Event on 26/11/92 on the Maize with Mulch Treatment

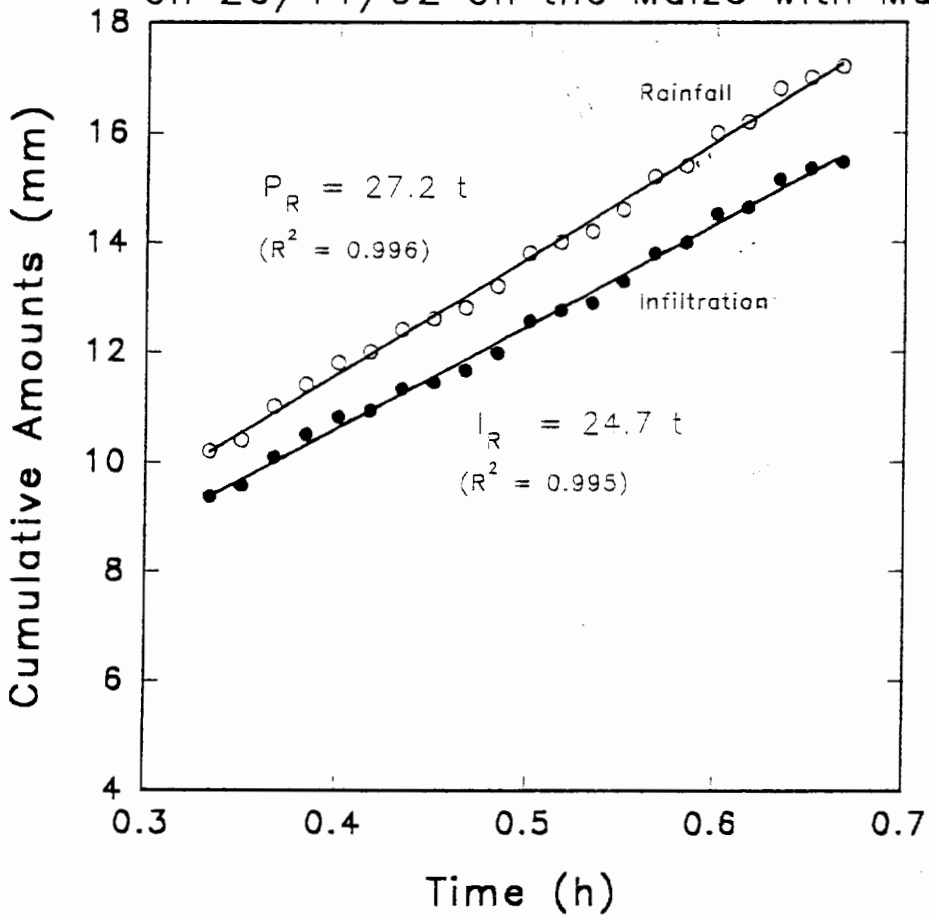


Figure 17: The Influence of Treatment on the Relationship Between Infiltration Rate (I_R) and Rainfall Intensity (P_R) During Rainfall Excess Over all Seasons

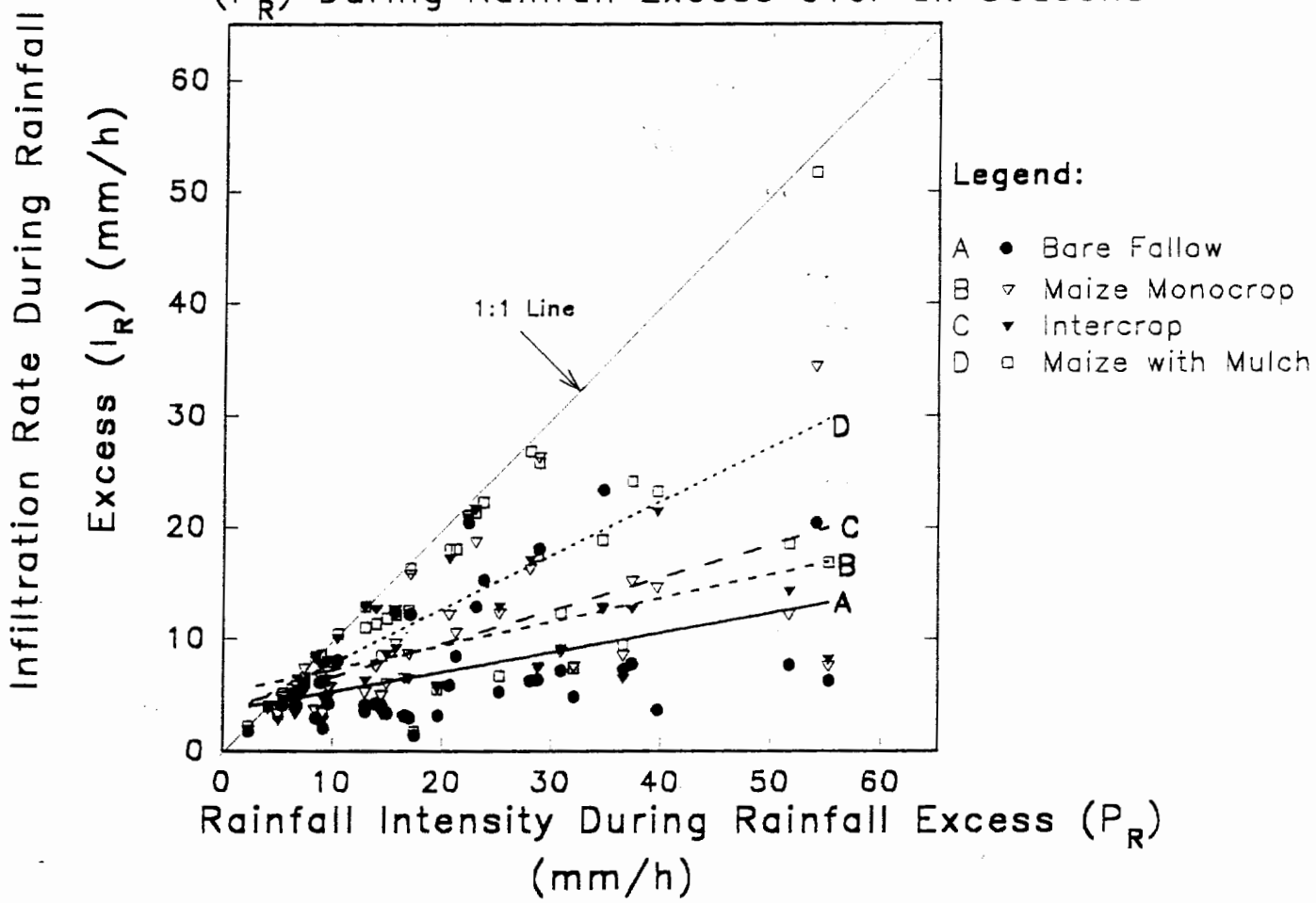


Figure 18: Soil Loss From Four Treatments During the SR1992 Season

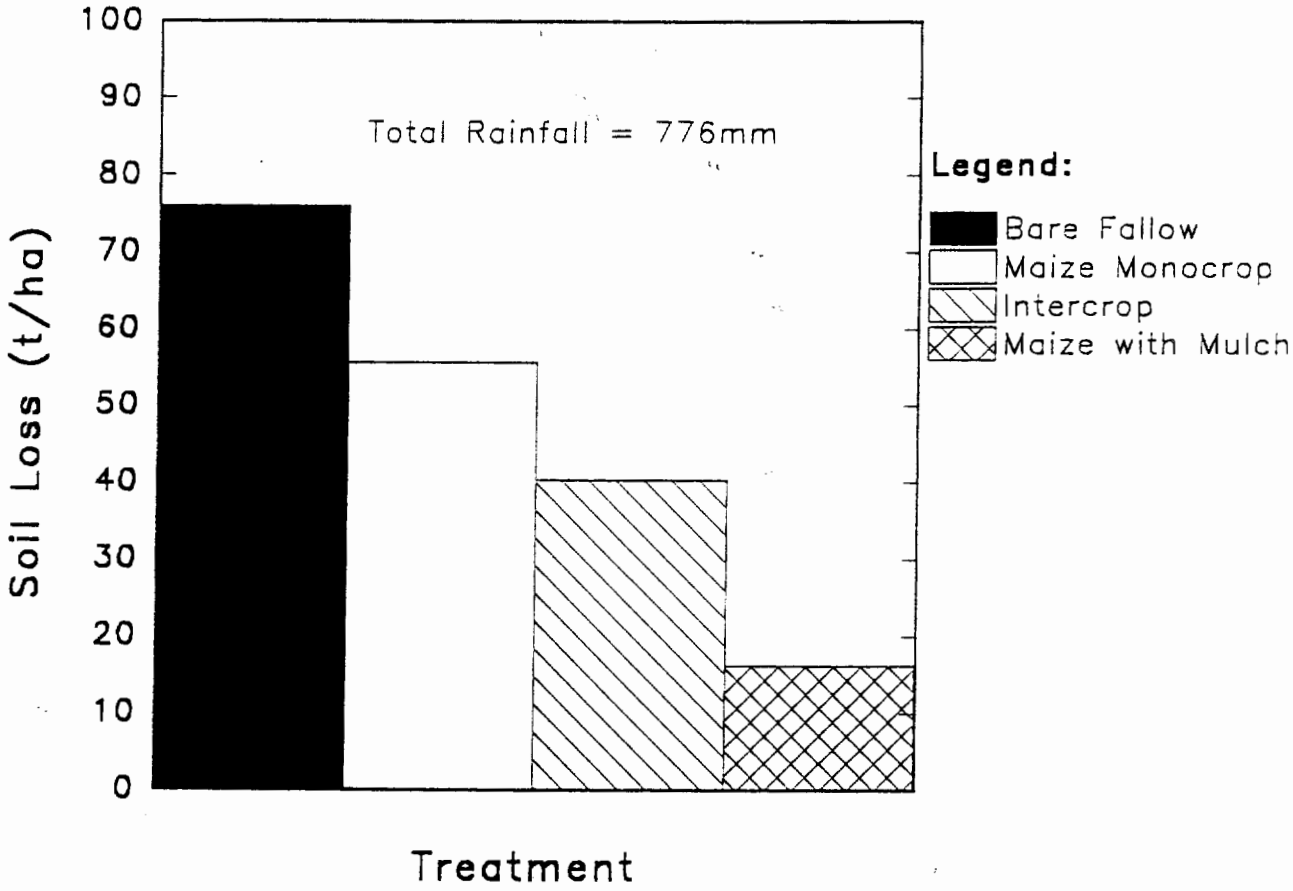


Figure 19: Soil Loss From Four Treatments During the SR1993 Season

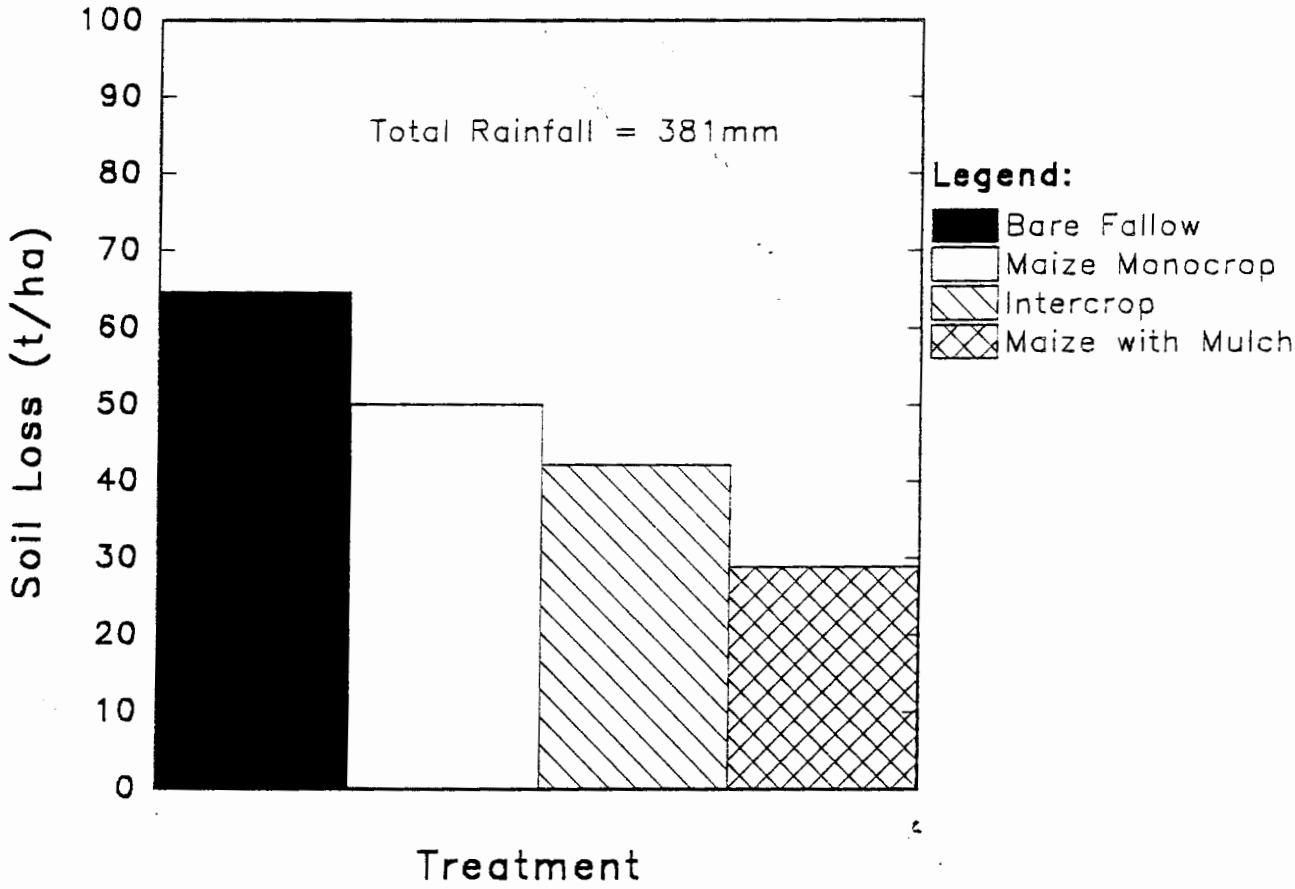


Figure 21: Soil Loss From Four Treatments During the SR1994 Season

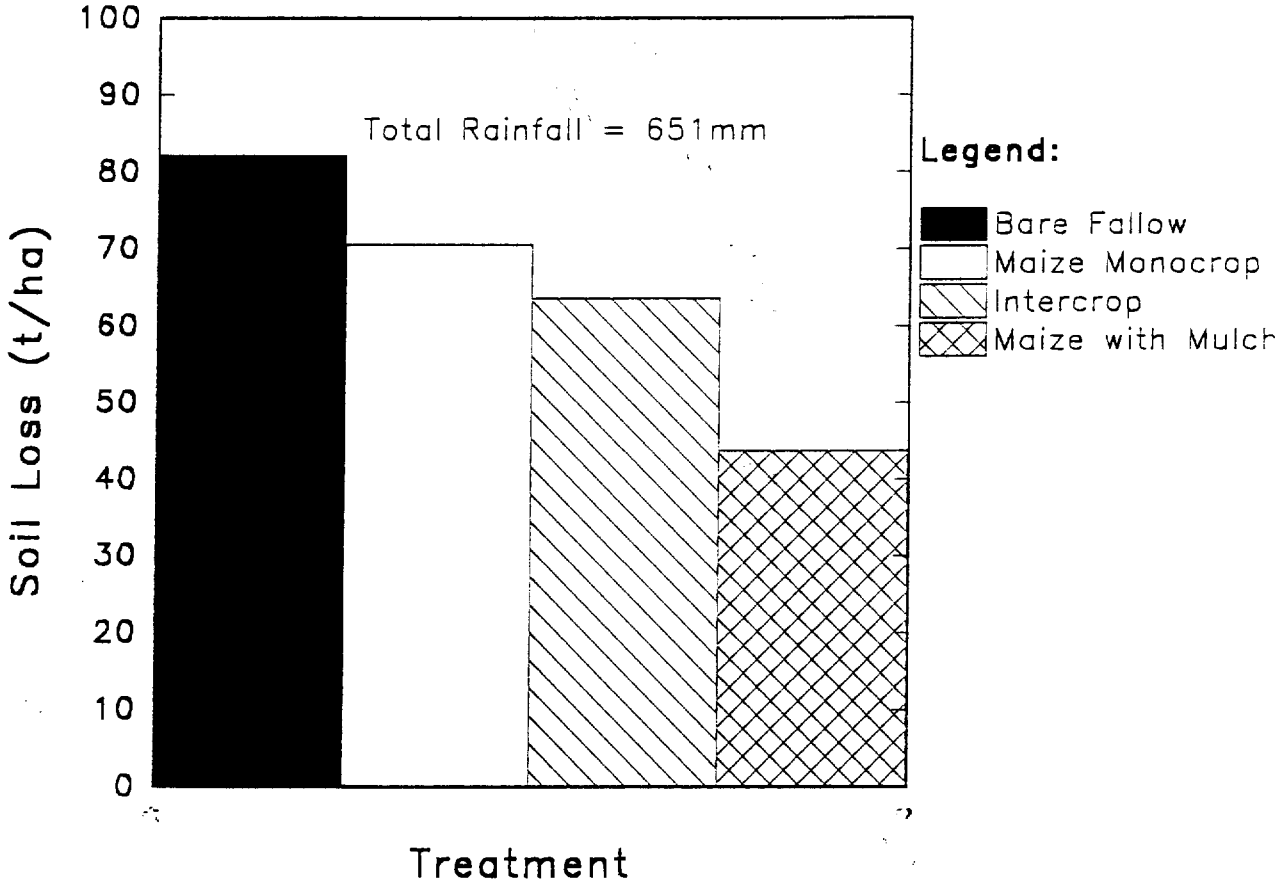


Figure 22: Soil Loss From Four Treatments During the LR1995 Season

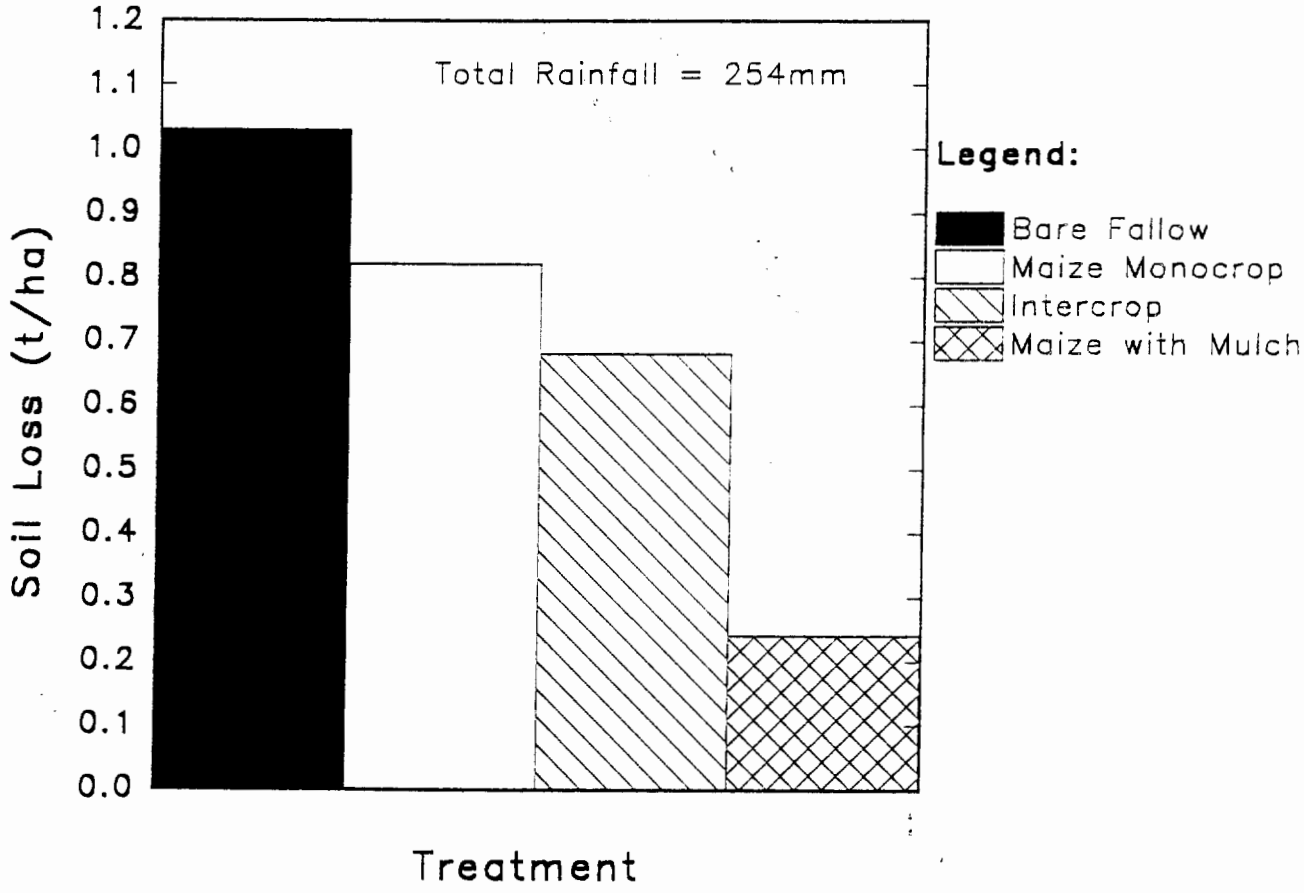
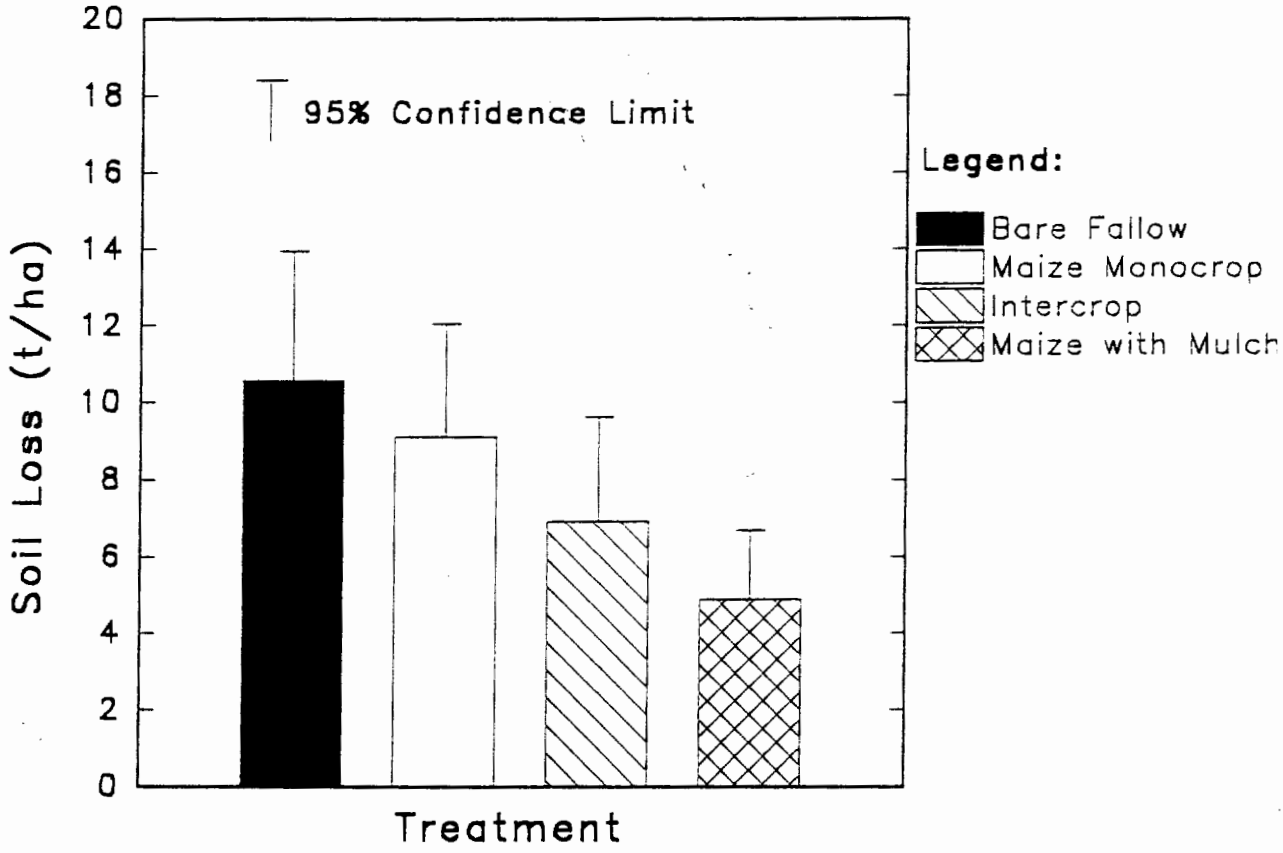


Figure 23: Comparison of Treatment Soil Loss From SR1992 to LR1995



Reprinted from the *Soil Science Society of America Journal*
Volume 58, no. 1, January–February 1994
677 South Segoe Rd., Madison, WI 53711 USA

Paper #1

Seal Formation and Interrill Soil Erosion

G. J. Levy,* J. Levin, and I. Shainberg

ABSTRACT

Interrill soil erosion depends primarily on soil detachment by raindrop impact (splash) and the transport capacity of thin sheet flow. Both splash and sheet flow erosion depend on soil surface properties. The purpose of this study was to investigate the effect of seal formation on interrill soil loss. Samples of three soil types — a Typic Chromoxerert, a Calcic Haploxeralf and a Typic Rhodoxeralf — with various naturally occurring exchangeable sodium percentage (ESP) levels were used. The soils were exposed to simulated rain using three different waters: distilled (DW), tap (TW), and saline (SW). The electrical conductivity (EC) of the TW and SW was 0.8 and 5.0 dS m^{-1}, respectively. Seal formation was characterized by the final infiltration rate (FIR) and amount of runoff . Seal formation was enhanced with an increase in soil sodicity and a decrease in water salinity for each soil type. Nearly 70% of the variation in FIR (and seal formation) was explained by water salinity and soil ESP. Most of the variation in soil loss was explained by clay content, soil ESP, and water salinity. With the exception of samples with ESP <5 rained on with DW, soil loss increased linearly with an increase in soil clay content. Seal strength, as inferred from surface pitting by impacting raindrops, decreased with an increase in clay content, and was inversely related to soil erosion.

PROCESS-BASED SOIL EROSION MODELS commonly divide erosion into rill and interrill components. Interrill soil erosion involves (i) detachment of soil material from the soil surface by raindrop impact and runoff shear, and (ii) transport of the resulting sediment by raindrop splash and flowing runoff. The detachment capacity of interrill flow is small because of its low velocity (Young and Wiersma, 1973). Raindrop detachment is high because the kinetic energy of raindrops has been estimated to be 260 times that of surface flow (Hudson, 1971). However, most of the sediment removed from the interrill area is transported by runoff flow (Young and Wiersma, 1973).

In addition to soil detachment, the beating action of raindrops causes the development of a seal at the soil surface. Seal formation in soils exposed to drop impact is due to two mechanisms (Agassi et al., 1981; McIntyre, 1958): (i) physical disintegration of soil aggregates and their compaction; and (ii) a physicochemical dispersion and movement of clay particles into a region of 0.1- to 0.5-mm depth, where they lodge and clog the conducting pores. The two mechanisms act simultaneously as the first enhances the latter. The seals formed are thin (<2–3-mm) layers that have a greater density, higher shear strength, and lower saturated conductivity than the underlying soil. Surface sealing, usually characterized by low IR and high runoff levels, is significantly affected by the electrolyte concentration of the soil solution at the soil surface (i.e., that of the applied water) and the ESP of the soil. Low electrolyte concentration in the soil solution and high ESP enhance clay swelling and dispersion, leading to an easier breakdown of the soil aggregates and to the formation of a less permeable seal (Agassi et al., 1981; Kazman et al., 1983).

Seal formation may affect interrill soil erosion in

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Published in Soil Sci. Soc. Am. J. 58:203–209 (1994).

Abbreviations: ESP, exchangeable sodium percentage; DW, distilled water; TW, tap water; SW, saline water; EC, electrical conductivity; IR, infiltration rate; FIR, final infiltration rate; SAR, sodium adsorption ratio; R^2, coefficient of determination; CEC, cation-exchange capacity.

Table 1. Some physical and chemical properties of the soils used.

Soil	Classification	Exchangeable sodium percentage	Particle-size distribution			Cation-exchange capacity	$CaCO_3$	OM†
			sand	silt	clay			
		%	%			$cmol_c\ kg^{-1}$	%	
Grumusol	Typic Chromoxerert	3.1	36.0	24.0	40.0	43.6	14.0	2.32
		13.3	31.0	22.5	46.5	38.7	15.1	2.07
		24.6	25.0	21.0	54.0	36.8	16.7	1.24
Loess	Calcic Haploxeralf	3.7	50.0	31.0	19.0	17.6	25.1	1.49
		4.7	70.0	12.5	17.5	12.8	17.3	1.50
		5.4	60.0	17.5	22.5	19.1	24.4	1.57
		12.6	62.5	15.0	22.5	17.5	18.2	1.83
		29.8	62.5	20.0	17.5	10.0	22.9	1.15
Hamra	Typic Rhodoxeralf	1.9	85.6	3.0	11.4	16.1	tr‡	1.78
		4.7	70.6	3.8	25.7	17.9	tr	1.20
		10.0	81.8	3.1	15.0	11.8	tr	0.81
		20.2	92.5	1.2	6.3	7.1	0.0	0.41

† OM = Organic material determined by the loss-on-ignition method (Ben-Dor and Banin, 1989).
‡ tr = traces.

the following opposite ways: (i) seal development increases the shear strength of the soil surface (Bradford et al., 1987) and thus reduces soil detachment (Moore and Singer, 1990); and (ii) seal formation increases runoff, which in turn increases the transport capacity for entrained material (Moore and Singer, 1990). Furthermore, once runoff starts, the presence of an overland flow increases the erosive power of the raindrops and hence soil detachment (Ferreira and Singer, 1985). The relative contribution of each of the two opposing tendencies to interrill soil erosion is not known, and was the subject of this study. To attain our objective we investigated the effect of soil texture, soil ESP, and the electrolyte concentration of the applied water on seal formation and interrill soil erosion.

MATERIALS AND METHODS

Three different soil types were chosen for this study: a sandy loam hamra (Typic Rhodoxeralf) from the coastal plain; a typic loamy loess (Calcic Haploxeralf) from the northern and central Negev; and a dark brown clayey grumusol (Typic Chromoxerert) from the Pleshet plain, Israel. Soil samples from the 0- to 250-mm depth with different naturally occurring ESP levels were brought to the laboratory and analyzed. Some physical and chemical properties of the soils are given in Table 1. In the grumusol, the sample with the intermediate ESP level was obtained by mixing equal amounts of soil samples with low and high ESPs.

Infiltration, runoff, and erosion were studied using a drip-type rainfall simulator. The simulator consisted of a 750 by 600 by 80 mm closed water chamber that generated rainfall of a known constant drop size through a set of hypodermic needles (approximately 1000) arranged at spacings of 20 by 20 mm. The average droplet diameter was 2.97 ± 0.05 mm. A drop fall of 1.6-m height was used to obtain drops with an impact velocity of 4.98 m s^{-1} and a kinetic energy of 12.4 J mm^{-1} m^{-2} (Epema and Riezebos, 1983). Application intensity was maintained at 31 mm h^{-1} using a peristaltic pump.

Air-dried aggregates, crushed to pass through a 4.0-mm sieve, were packed in 200 by 400 mm trays, 20 mm deep, over a 5-mm-thick layer of coarse sand. The trays were placed in the simulator at a slope of 15%, saturated from underneath with TW, and exposed to 60 mm of rain. During each rainstorm, the volume of water percolating through the soil was collected and recorded as a function of time. Runoff water was collected in buckets continuously throughout the storm. At the end of the storm the runoff water and suspended material in the buckets were thoroughly mixed and a 0.25-L subsample was taken. The subsample was dried, the weight of the eroded material was determined, and total soil loss from the entire storm was calculated. Splash from the soil trays was not measured. It was found that soil carried by splash is positively correlated with the soil removed by runoff water (Young and Wiersma, 1973). Hence, soil loss from runoff water can serve as an indication of soil detachment.

Three water qualities were studied: (i) DW; (ii) TW with electrolyte concentration of 8 $mmol_c$ L^{-1} and a SAR of 2; and (iii) SW with an electrolyte concentration of 50 $mmol_c$ L^{-1}. In the case of the SW, a $NaCl$–$CaCl_2$ solution was prepared with a SAR comparable to the ESP of each of the soils used. Three replicates were used for each treatment concurrently.

The infiltration data obtained from the rainfall simulator were analyzed using a nonlinear equation proposed by Morin and Benyamini (1977). A nonlinear regression program calculated the parameters of the equation that gave the best R^2 between paired calculated and measured infiltration rate values. The total depth of runoff water from each single rainstorm was calculated using the instantaneous infiltration rate derived from the equation of Morin and Benyamini (1977). Calculated runoff values were preferred over measured values because of water splash from the boxes, which could reach 15% of the applied rain (Agassi and Levy, 1991). Significance of difference among treatments for the infiltration and erosion parameters studied was determined using Tukey's procedure for a multiple range test (Steel and Torrie, 1960).

RESULTS AND DISCUSSION

Seal formation is commonly characterized by changes in the infiltration rate with time or cumulative rain (Fig.

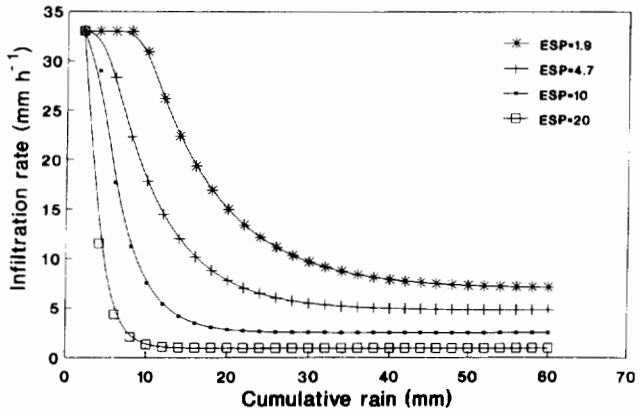

Fig. 1. Infiltration rate of the hamra soil samples with different exchangeable sodium percentage (ESP) levels as a function of cumulative rain of distilled water.

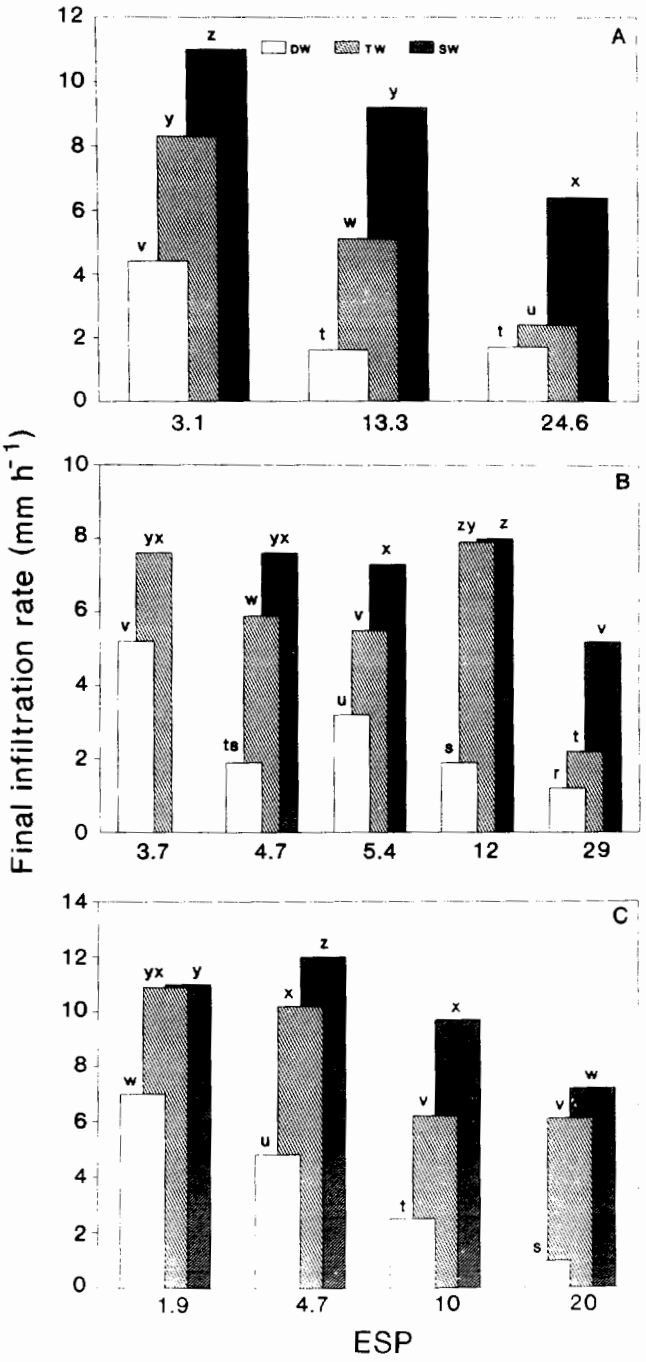

Fig. 2. Final infiltration rate (FIR) as a function of water quality and exchangeable sodium percentage (ESP) for the (A) grumusol, (B) loess, and (C) hamra soils. Bars labeled with the same letter do not differ significantly at the 0.05 level.

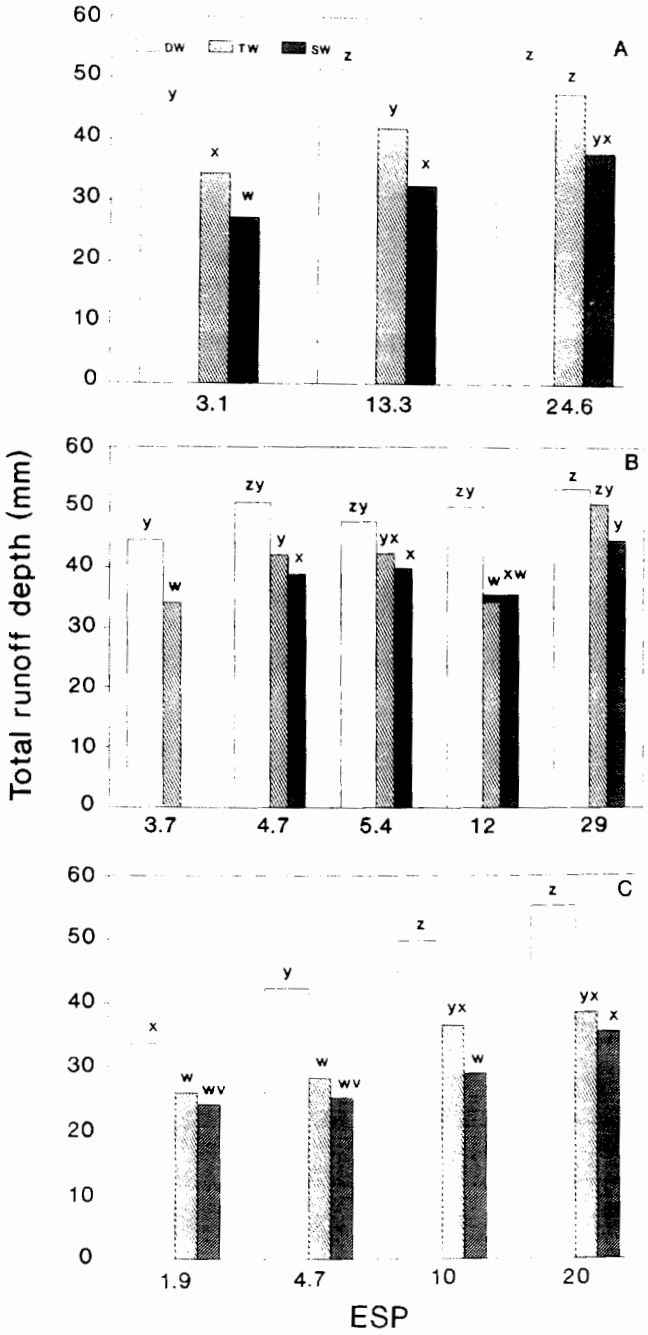

Fig. 3. Total runoff depth as a function of water quality and exchangeable sodium percentage (ESP) for the (A) grumusol, (B) loess, and (C) hamra soils. Bars labeled with the same letter do not differ significantly at the 0.05 level.

1). However, infiltration rate curves are not suitable for quantitative comparison between treatments. Thus, two parameters were used to represent the infiltration curves, (i) the steady-state infiltration rate at the end of the storm (FIR), and (ii) total amount of runoff from the entire rain event. Total runoff is an integrated value that depends mainly on the rate at which the seal is formed.

The FIR values of the different treatments for the three soils are presented in Fig. 2. Similar to previous studies (Agassi et al., 1981; Kazman et al., 1983), changes in FIR followed the trend where, for each soil type, FIR decreased (i) with a decrease in the electrolyte concentration of the applied water, and (ii) with an increase in soil ESP. When DW was used, the detrimental effect of ESP on the FIR was evident at low ESP values (<5). As the electrolyte concentration in the applied water increased, the effect of ESP became evident only at ESP >10 (Fig. 2). The effect of electrolyte concentration on the FIR was pronounced at the lower range of the ESP (Fig. 2), which suggests that TW should not be used in rain simulation studies.

Calculated total runoff values for the various treatments are presented in Fig. 3. For each soil type, total runoff increased with a decrease in the electrolyte con-

Table 2. Correlation coefficients between soil loss and final infiltration rate (FIR), and total amount of runoff (Roff).

Soil	Variable	Linear	Logarithmic	Power
Grumusol	FIR	−0.77*	−0.80**	−0.79**
	Roff	0.77*	0.81**	0.80**
Loess	FIR	−0.71**	−0.70**	−0.71**
	Roff	0.73**	0.75**	0.74**
Hamra	FIR	−0.58	−0.56*	−0.58*
	Roff	0.59	0.58*	0.59*
Total†	FIR	−0.65	−0.67***	−0.69***
	Roff	0.66	0.75***	0.73***

*,**,*** Significant at the 0.05, 0.01, and 0.001 levels of confidence, respectively.
† Results of the correlation analysis of all data from the three soils pooled together.

centration of the applied water and an increase in soil ESP. The effect of ESP and electrolyte concentration on runoff was, however, not as pronounced as on the FIR. The effects of water salinity and soil ESP on total runoff were the greatest in the hamra and the smallest in the loess (Fig. 3).

Correlating total soil loss from the 60-mm storms with FIR and with runoff percentage using various functions gave, in most cases, significant but low ($R < 0.8$) correlation coefficients (Table 2). The sign of the coefficients, negative for FIR and positive for runoff, indicates that soil loss increased with a decrease in FIR and an increase in total runoff. The seal formed at the soil surface during rain increases the shear strength of the soil surface compared with an unsealed surface (Bradford et al., 1987), and hence decreases the soil's susceptibility to detachment (Moore and Singer, 1990). The negative correlation between FIR and soil loss indicates either that the increase in surface shear strength following the beating of the raindrops is not big enough to affect soil loss, or that the FIR is not a sensitive criterion for surface shear strength.

The soil samples used had different naturally occurring ESP levels, different clay contents, CEC values, etc. (Table 1). In order to obtain a quantitative estimation of the relative contribution of all soil properties and water quality to the experimental FIR and soil loss, a stepwise linear regression technique was used. Several soil properties were omitted from the regression analysis because of their high degree of intercorrelation with other properties. Thus, the following properties were used in the analysis: silt, clay, $CaCO_3$, and organic matter contents; the ratio of clay to silt; CEC of the clay fraction; and ESP. The regression results for FIR at different water qualities and for all data pooled together are presented in Table 3 (only variables with a significance level of $P < 0.05$ are reported). For the case where all the data were pooled together, electrolyte concentration was also used as a variable in the regression.

Results of the regression for FIR indicated that, for each water quality, ESP explained >50% of the variation in FIR. When all the data were pooled together, water quality explained a larger portion of the variation in FIR than did soil ESP (Table 3). The contribution of lime to the variation in FIR was small but significant (Table 3). The size of $CaCO_3$ particles is in the silt size range, and silt-size particles are commonly associated with low structural stability (Cary and Evans, 1974). It is suggested, therefore, that the observed decrease in FIR with an increase in $CaCO_3$ is related to the physical weakening of soil stability induced by lime. This hypothesis was further verified when silt content replaced $CaCO_3$ in the regression output after the latter was omitted from the regression analysis (Table 3). The effect of lime was especially pronounced when SW was used. Under conditions where the clay dispersion and swelling mechanisms are limited, due to the high electrolyte concentration, the negative effect of lime content and positive effect of organic matter on cementing soil aggregates is significant (Table 3).

Soil erosion as a function of soil ESP and water quality for each of the three soils is presented in Fig. 4. Two general observations can be made:

1. For each soil type, soil loss was not a monotonic function of soil ESP or water salinity (as observed for FIR and runoff). In the grumusol, soil loss in-

Table 3. Results of the stepwise linear regression analysis.

	Final infiltration rate				Soil loss			
		R^2				R^2		
Water†	Variable‡	partial	model	$P > F$	Variable	partial	model	$P > F$
DW	ESP (−)§	0.553	0.553	0.0360	Clay	0.590	0.590	0.0022
					ESP	0.196	0.786	0.0128
TW	ESP (−)	0.661	0.661	0.0007	Clay	0.441	0.441	0.0133
SW	ESP (−)	0.569	0.569	0.0029	ESP	0.479	0.479	0.0088
	Lime (−)	0.233	0.802	0.0064	Lime	0.290	0.769	0.0053
	OM	0.078	0.880	0.0394	Clay	0.092	0.861	0.0379
Total¶	EC	0.376	0.376	0.0001	Clay	0.376	0.376	0.0001
	ESP (−)	0.303	0.679	0.0001	ESP	0.148	0.524	0.0019
	Lime (−)	0.060	0.739	0.0078	EC (−)	0.097	0.621	0.0052
Without lime#								
Total	EC	0.376	0.376	0.0001				
	ESP (−)	0.303	0.679	0.0001				
	Silt (−)	0.044	0.723	0.0240				

† DW = distilled, TW = tap, SW = saline water.
‡ ESP = exchangeable sodium percentage; OM = organic material; EC = electrical conductivity.
§ A negative sign indicates a negative regression coefficient.
¶ Results of the regression of all data pooled together from the three water qualities.
# Results of the regression after omitting lime from the list of variables tested.

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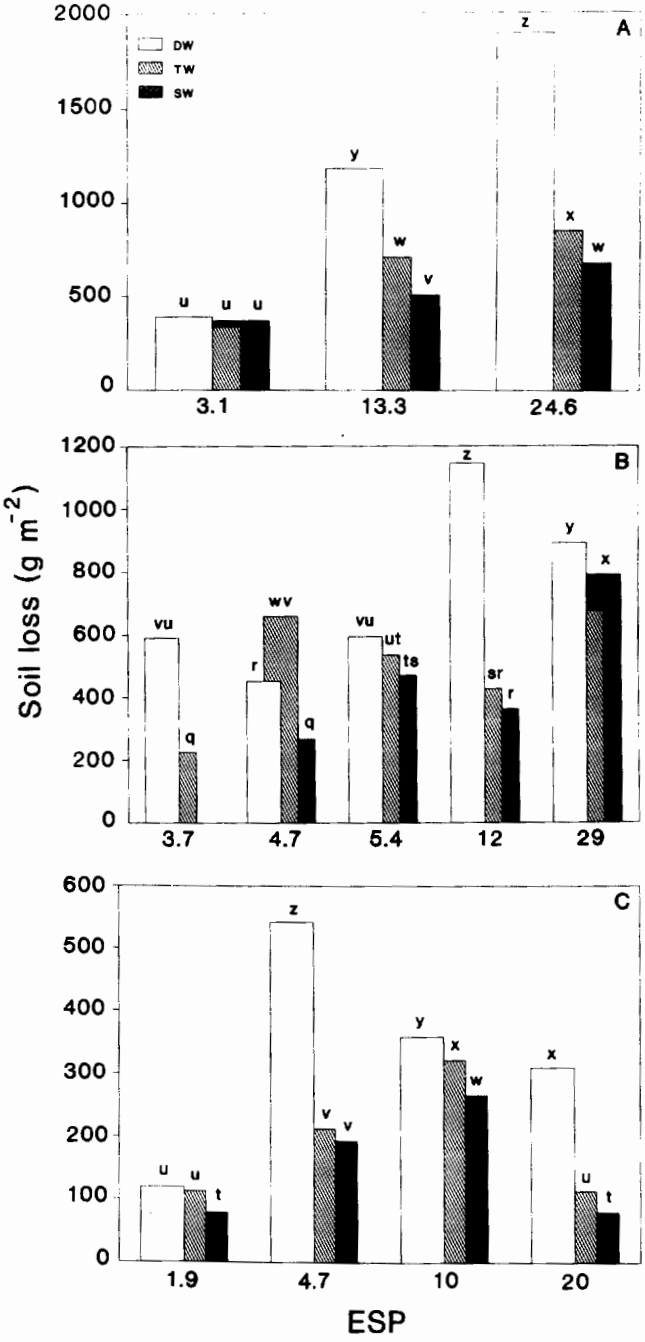

Fig. 4. Total soil loss as a function of water quality and exchangeable sodium percentage (ESP) for the (A) grumusol, (B) loess, and (C) hamra soils. Bars labeled with the same letter do not differ significantly at the 0.05 level.

creased with increases in soil ESP for each of the three solution concentrations (Fig. 4A). Also, for each ESP level, soil loss decreased with an increase in salt concentration. It seems that, in the grumusol, soil loss increased with soil dispersion. Conditions favorable for soil dispersion and aggregate disintegration lead also to interrill soil erosion. Conversely, in the loess and hamra soils, soil loss was not always affected by water salinity or soil ESP in a systematic way (Fig. 4B and 4C).

2. Whereas the FIR values of the three soil types were quite similar at comparable ESP levels, soil losses from the three soils differed. As can be noted from the scale of the soil loss axes for the different soils, soil losses increased with clay content in the soil. The grumusol had the highest interrill erodibility and the hamra soil was the least erodible.

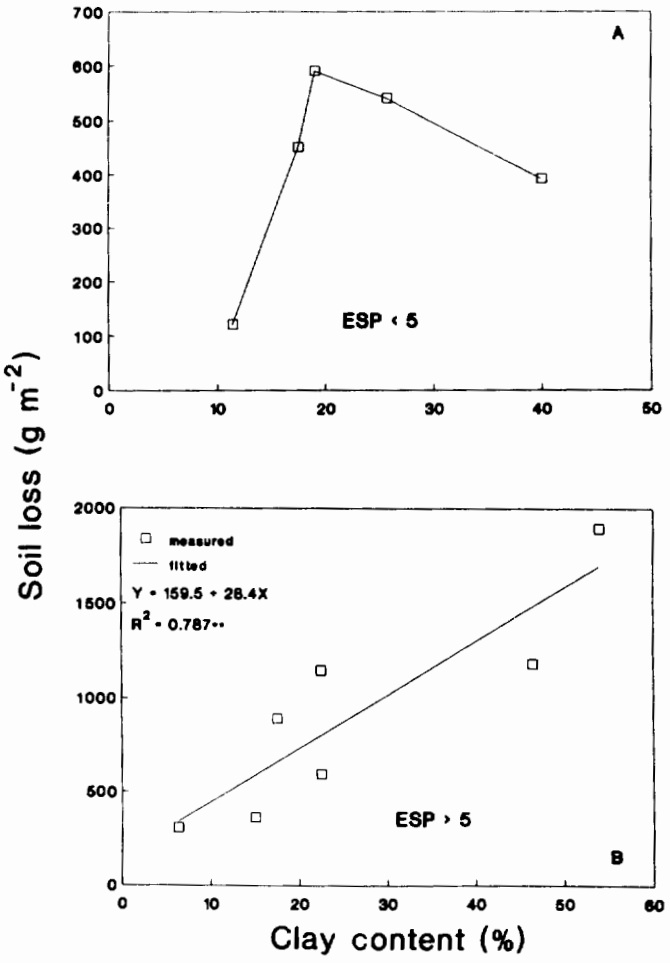

Fig. 5. Total soil loss as a function of clay content for samples with (A) exchangeable sodium percentage (ESP) <5 and (B) ESP >5.

A close examination of the soil loss data when DW water was used (Fig. 5), reveals that soil loss was a function of both soil ESP and its clay content. At the ESP <5 range, soil loss increased with an increase in clay content to a maximum at 19% clay content. A further increase in clay content resulted in a decrease in soil loss (Fig. 5A). A similar observation was made by Ben-Hur et al. (1985), who concluded that nonsodic soils with ≈20% clay were the soils most susceptible to seal formation and erosion. In soils with ESP >5, soil loss increased linearly with an increase in clay content (Fig. 5B). Understanding the role of clay in stabilization of (i) soil aggregates, and (ii) soil structure may explain the difference in the effect of clay content on soil erosion at the low and high ESP levels. Generally, aggregates' stability increases with an increase in clay content. But soil structure, on the other hand, might not, since at high clay content the cohesion forces between stable aggregates are low, leading to limited structural stability and high susceptibility to aggregate detachment and erosion.

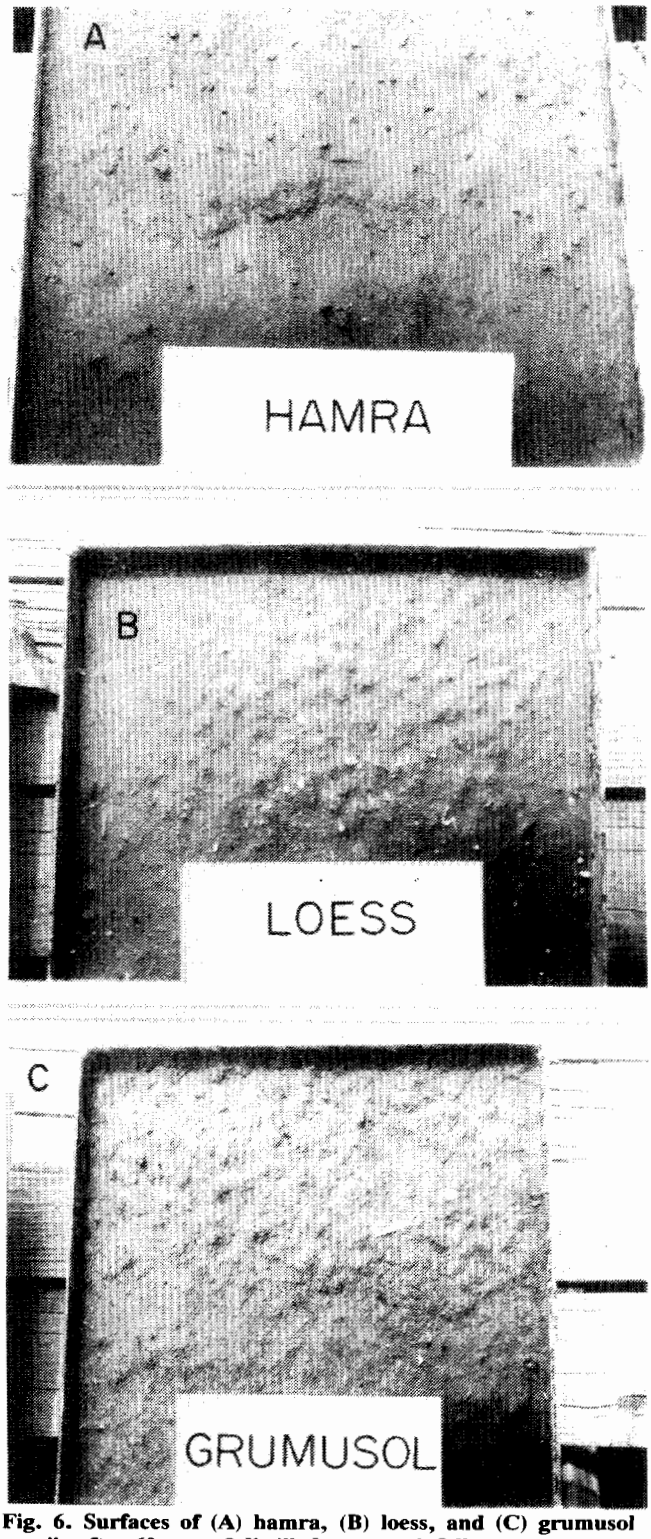

Fig. 6. Surfaces of (A) hamra, (B) loess, and (C) grumusol soils after 60 mm of distilled water rainfall.

In the sodic soils (ESP >5) this phenomenon was observed across the entire clay content range studied. In nonsodic soils (ESP <5), an increase in clay content up to ≈20% increased soil susceptibility to seal formation and erosion. The observed decrease in soil erosion with a further increase in clay content above 20% (Fig 5A) is explained by the fact that in nonsodic conditions the clay that was dispersed from the aggregates by the mechanical impact of the raindrops was in a flocculated state and could successfully cement between adjacent particles and increase the shear strength of the soil surface, which consequently results in reduced soil erosion (further discussed below).

When TW or SW was used, soil loss generally increased with the increase in clay content. When clay dispersion was prevented by the presence of electrolytes in the water used, a significant correlation (R = 0.67) was obtained between soil loss and clay content for the two saline water qualities tested.

In order to obtain a more quantitative estimate of the relative weight of soil ESP, water quality, and clay content in determining soil loss, the stepwise regression technique was employed. Significant relations, inverse for clay content and ESP and direct for water quality, were obtained between these properties and soil loss (Table 3). However, the variation in soil loss explained by clay content was more than two and three times that explained by soil ESP and water quality, respectively (Table 3). The observed effect of clay content on soil loss contradicted previously published data (e.g., Ben-Hur et al., 1985; Meyer and Harmon, 1984), probably because the former studies used samples with low ESP and good quality water.

The effect of clay content on soil loss, especially at the medium-to-high ESP range (>5), is explained by the effect of clay on the shear strength of the seal. It has been shown (Hardy et al., 1983) that when a disturbed soil surface is exposed to rain, the impact of the raindrops, in the initial phase, forms craters and pits in the soil surface. With an increase in rain depth, a seal is formed, the IR drops, and a smooth surface is obtained (Hardy et al., 1983; Fig. 5 and 6). The presence of craters and pits in the initial phase is an indication of the ability of the raindrops to break the aggregates at the soil surface. The presence of a smooth surface indicates the presence of a fully developed seal, the shear strength of which is high enough to prevent crater and pit formation by the impact of the subsequent rain drops. Hence, the degree of roughness of the soil surface could serve as an indication of the seal's shear strength. The rougher the soil surface (i.e., more crates and pits are present), the weaker the shear strength of the seal formed and the more susceptible the soil surface to detachment. The roughness of the seals formed in the three soil types studied following 60 mm of rain is in the following order: grumusol > loess > hamra (Fig. 6). The clay content of the three soil types is in the same decreasing order (Table 1). Thus, it is evident that high clay content is coupled with a high degree of roughness and low shear strength of the seal, which in turn translates into higher levels of soil loss.

It is postulated that soil texture determines the rate at which a rough surface turns into a smooth one. Sandy loam soils have low structural stability. Thus, low levels of energy are required to break most of the aggregates at the soil surface and produce enough clay to cement between the primary particles. Consequently, a smooth surface with a high shear strength and a reduced susceptibility to erosion is obtained after a relatively low level of energy (i.e., small depth of rain) has been applied to the surface. Clay soils have ordinarily stable aggregates

that do not break easily by the impact of the drops. But the cohesive forces between aggregates are relatively low compared with the stability of the aggregates per se. Thus aggregate detachment by the impact of the drops takes place and leads to soil erosion. Since there is a heterogeneity in the strength of the aggregates at the soil surface, a wide spectrum of energy levels is needed to cause their breakdown and detachment. Thus, a greater depth of rain is needed to break all the surface aggregates and form a smooth layer at the surface. The continuous breakdown of aggregates is the reason for the rough surface and the weak seal formed. It is also the source of transportable eroded sediment provided there is enough runoff to carry it, as is the case with soils having medium to high ESP levels.

SUMMARY AND CONCLUSIONS

Studying seal formation and interrill soil loss showed that both were critically affected by soil ESP and water quality. Nearly 70% of the variation in FIR (and seal formation) was explained by water salinity and soil ESP. Most of the variation in soil loss was explained by clay content, soil ESP, and water salinity. A moderate inverse correlation between the FIR and soil loss suggested that it is incorrect to draw inference from the FIR data as to soil susceptibility to interrill soil erosion. Except for the cases of soils with ESP <5 rained on with DW, soil loss increased linearly with an increase in clay content. Furthermore, it was noticed that the degree of surface roughness increased with a rise in clay content. Surface roughness can serve as a qualitative estimate for the strength and degree of development of the seal formed. The smoother the surface, the stronger and more developed the seal. It is thus concluded that, under conditions where soil loss is determined by the strength of the seal formed, clay content is a better tool than the FIR for predicting the potential for interrill erosion from soils susceptible to sealing.

ACKNOWLEDGMENTS

The authors wish to thank Mrs. H. Eisenberg for laboratory analyses. This research was supported by Grant no. C11-255 from the U.S.-Israel CDR program. The CDR support is gratefully acknowledged.

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0038-075X/94/1584-267$03.00/0
SOIL SCIENCE
Copyright © 1994 by Williams & Wilkins
October 1994
Vol. 158, No. 4
Printed in U.S.A.

ORGANIC POLYMERS AND SOIL SEALING IN CULTIVATED SOILS

I. SHAINBERG AND G. J. LEVY

The beating action of rain or sprinkler drops causes the breakdown of aggregates and clay dispersion, which subsequently leads to seal formation. Seal formation reduces infiltration rate and generates high levels of runoff. Chemical soil amendments (e.g., phosphogypsum, organic polymers) can improve aggregate stability and limit clay dispersion and thus prevent seal formation. This review discusses the effects of organic polymers on controlling seal formation as characterized by changes in soil infiltration rate and dependence on soil properties. Soil susceptibility to sealing depends on a number of soil properties, including soil texture and mineralogy, composition of the exchangeable cations, and water quality. Addition of small amounts of polymers (10–20 kg ha^{-1}), either sprayed directly onto the soil surface or added to the applied water, stabilizes and cements together aggregates at the soil surface, thereby increasing their resistance to seal formation. The infiltration rate of a polymer-treated soil subjected to distilled water rain is two to three times that of a non-treated soil. The efficacy of anionic polymers in preventing seal formation is enhanced when the soil clay is maintained in a flocculated state. The latter is achieved by addition of electrolytes (either in the "rain" water or phosphogypsum addition) in the soil solution at the soil surface. Combined application of anionic polymers with electrolytes results in final infiltration values of ~25 mm h^{-1}, which are 10 times higher than the control. Polymer effectiveness in controlling seal formation depends also on charge type and density and on the molecular weight of the polymer. The effect of polymers and water quality on seal formation is in good agreement with the effect of the polymers on the flocculation patterns of soil clays. Of the polymers currently available and under study, anionic polyacrylamide has been found to be the most effective in controlling seal formation, and soil erosion and has the longest residual effect.

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Received July 7, 1994; accepted July 9, 1994.

The formation of a seal at the soil surface, caused by the action of raindrops or sprinkler irrigation, is a common feature of many cultivated soils worldwide. Surface seals are thin (<2 mm) and are characterized by greater density, higher shear strength, finer pores, and lower saturated hydraulic conductivity than the underlying soil (McIntyre 1958; Bradford et al. 1987). Soil seals have a prominent effect on numerous soil phenomena, often decreasing infiltration, increasing runoff, and interfering with seed germination (Baver et al. 1972; Bradford et al. 1987).

A traditional measure to prevent seal formation and its undesirable effects is to spread mulch on the soil surface to protect it from waterdrop impact. Modification of some soil properties responsible for soil susceptibility to sealing serves as an alternative measure. Preventing clay dispersion and increasing aggregate stability at the soil surface significantly reduce seal formation. Improving aggregate stability and preventing clay dispersion can be accomplished by applying chemical soil amendments to the soil. The fact that seal formation is a surface phenomenon allows treatment of only the soil surface rather than mixing the soil amendments with the entire cultivated layer. This results in a reduction in the amounts of amendments required, thus making their use more cost effective.

This manuscript discusses the role of organic polymers and the interaction between soil and polymer properties in reducing seal formation in cultivated soils.

SOIL SEALING: ITS CHARACTERIZATION AND DEPENDENCE ON SOIL PROPERTIES

Seal formation

The formation of seals in soils exposed to the beating action of falling drops is caused by two mechanisms. One is soil aggregate breakdown caused by the impact action of the waterdrops. The destruction of the aggregates reduces the average size of the pores of the surface layer. The impact of waterdrops also causes compaction of the uppermost layer of the soil (McIntyre

1958; Chen et al. 1980). The second mechanism is a physio-chemical dispersion of the soil clays, which can then migrate into the soil with the infiltrating water, clog pores immediately beneath the surface, and form a layer of very low permeability, which is termed the "washed in" zone (McIntyre 1958).

The first mechanism is mechanical in nature; in the second, aggregate disintegration and clay dispersion resulting from chemical forces predominate.

Infiltration rate

In this review, the degree of seal formation in soils is quantified by the soil infiltration rate (IR). The IR, defined as the volume flux of water flow into the profile per unit of surface area of soil, has the dimension of velocity. In general, soil infiltration capacity is initially high, particularly when the soil is initially dry, but it tends to decrease monotonically until it asymptotically approaches a constant rate, the final or steady-state IR. In soils having stable surface structures, decreases in infiltration capacity result from the inevitable decrease in the matric suction gradient that occurs as infiltration proceeds (Baver et al. 1972).

Decreases in soil infiltration capacity from an initially high rate can also result from a gradual deterioration of soil structure and the formation of a surface seal. When a seal of very low hydraulic conductivity (HC) is formed at the soil surface, its reduced permeability determines the IR of the soil (Baver et al. 1972; Morin and Benyamini 1977).

Rain simulators, such as those developed by Morin et al. (1967) and Miller (1987), are commonly used for studying the effects of soil properties and irrigation water salinity on seal formation and IR. In these simulators, rain intensity and drop impact energy can be controlled, and water chemistry can be changed according to experimental design.

Soil properties and seal formation

Soil susceptibility to seal formation depends on a number of soil properties (e.g., cationic composition of the exchange phase, soil texture, clay mineralogy) and water quality.

The effect of exchangeable sodium percentage (ESP) on the IR and seal formation of four smectitic soils from Israel was studied by Kazman et al. (1983) using deionized water (DW) in a rain simulator. In each of the four soils, IR was highly sensitive to low levels of ESP. The results for a sandy loam (Typic Rhodoxeralf) are presented in Fig. 1. Even at the lowest sodicity (ESP 1.0), a seal was formed and the IR dropped from a high initial value to a final IR of 7.0 mm h^{-1}. An ESP value of 2.2 was enough to cause a further drop in the final IR of the sandy loam (final IR of 2.4 mm h^{-1}). The amount of rain required to approach the final IR was also affected by ESP (Fig. 1). As the ESP of the soil increased, the depth of rain required to reach the final IR decreased. Kazman et al. (1983) postulated that the differences in IR curves for the various soil samples differing in their ESP were the result of chemical dispersion caused by sodicity.

Chemical dispersion of the soil surface may be prevented by "raining" with solutions of various EC levels using the rain simulator. Agassi et al. (1981) observed that the IR values for the same soil increased markedly as the electrical conductivity of the applied water increased in the range between 0.0 (i.e., DW) and 5.6 dS m^{-1}.

The effect of soil texture and $CaCO_3$ content on the IR of soils was studied by Ben-Hur et al. (1985). They observed that soils with 10–30% clay were the most susceptible to seal formation and had the lowest IR. With increasing clay content, soil structure was more stable and seal formation was diminished. In soils with lower clay contents (<10%), the amount of clay avail-

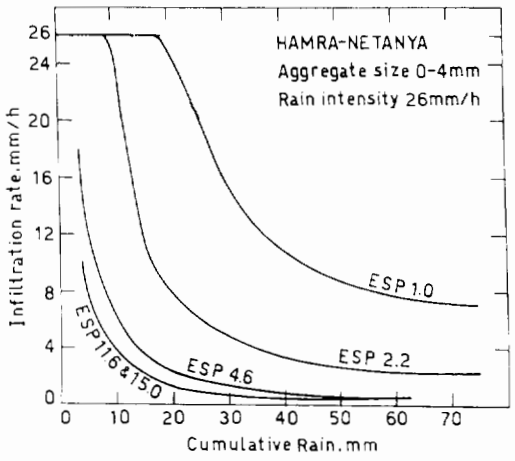

FIG. 1. The effect of the soil exchangeable sodium percentage (ESP) on the infiltration rate of the Netanya soil as a function of the cumulative rain (adapted from Kazman et al. 1983).

able to disperse and clog the soil pores was limited and, as a result, an incomplete seal was formed. Silt and $CaCO_3$ content have no effect on the final IR (Ben-Hur et al. 1985), but the rate at which the IR decreases increases with an increase in silt content (Moldenhauer and Long 1964; Ben-Hur et al. 1985). However, it should be noted that seal strength, as measured with a fall-cone apparatus, increases with an increase in silt content (Bradford and Huang 1992).

Most of the studies of seal formation and runoff were conducted on soils in which the dominant clay minerals were smectites. These clay minerals are known to be more dispersive than kaolinitic clays. The dominant clay mineral in the Alfisols of the Transvaal, South Africa and the Ultisols of the southeastern US is kaolinite, and these soils are known to form seals and have low IR values when exposed to rainstorms (Miller 1987; Stern et al. 1991a). However, these soils vary in their susceptibility to sealing.

The kaolinitic soils were divided by Stern et al. (1991a) into two groups, stable and unstable (dispersive) soils having final IR values of >14.5 mm h^{-1} and <4.2 mm h^{-1}, respectively. The susceptibility of the unstable kaolinitic soils to seal formation was similar to that of smectitic soils (Kazman et al. 1983). Based on the mineralogy of the soils, Stern et al. (1991a) concluded that soils in which either kaolinite or illite clay predominates, but which do contain small amounts of smectite, were dispersive and as susceptible to seal formation as smectitic soils. Conversely, soils that do not contain smectite are more stable and less susceptible to seal formation.

REDUCING SEAL FORMATION

Increasing aggregate stability at the soil surface and preventing clay dispersion reduces seal formation. The use of organic polymers, mainly polysaccharides (PSD) and polyacrylamides (PAM), for improving aggregate stability and clay flocculation and reducing seal formation has recently been studied (Helalia and Letey 1988 a and b; Ben-Hur and Letey 1989; Shainberg et al. 1990; Smith et al. 1990; Warrington et al. 1991).

For seal reduction, it is preferable to add the polymer to the soil surface in solution form rather than as a dry powder or granules (Wallace and Wallace 1986). In order to prevent seal formation under natural rains, concentrated polymer solutions (0.5–5 kg m^{-3}) are sprayed on the soil surface before the rainy season. With overhead sprinkler irrigation, polymers can either be sprayed on the soil surface or dissolved in the irrigation water to form very dilute solutions (5–20 g m^{-3}). The discussion on polymer efficiency in controlling seal formation is divided into two sections according to the method of polymer application.

Application of Dilute Polymer Solution

Studies of the effect on seal formation and run off of dilute concentration of polymer in irrigation water have indicated that the efficacy of the polymers depends on polymer molecular weight, sign and density of electric charge, and water quality. Ben-Hur and Letey (1989) studied the effect of type of charge and charge density of polysaccharides (PSD), guar derivatives with relatively low molecular weight (200,000–2 million d), on the infiltration of a sandy loam soil. They studied high-charge density (T-4141) and low-charge density (CP-14) PSDs. They also studied a nonionic PSD (HP-8) and an anionic PSD (T-4246). Ben-Hur and Letey (1989) added the polymers to the water to form solutions of very low polymer concentration (0–10 g m^{-3}). They observed that in DW, addition of nonionic and anionic PSDs had no beneficial effect on the IR (Fig. 2). Conversely, 10 g m^{-3} of cationic PSD had a significant beneficial effect on the IR compared with the control. Also, the higher

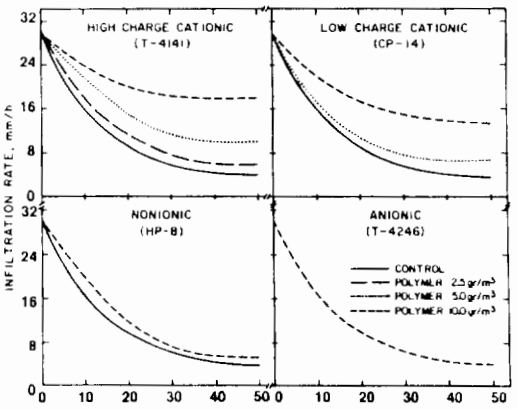

FIG. 2. Infiltration rate as a function of cumulative water application for four polymer types at different concentrations in the water applied (the anionic polymer, the control, and 10 g m^{-3} polymer treatments have the same line) (Ben-Hur and Letey 1989).

charge cationic PSD was more effective than the lower charge one in maintaining high final IR (Fig. 2). The relative effect of the polymers' properties on seal IR changed when the polymers were added to water containing some electrolytes (Levy et al. 1992). They compared the effects of an anionic PAM with a molecular weight of 10–15 million daltons, and a low charge cationic PSD when dissolved in irrigation water (EC = 0.8 dS m^{-1}) on the IR of Israeli soils. Levy et al. (1992) found that a low concentration of PAM in the irrigation water was very effective in maintaining a high IR and that a lower concentration of PAM (10 g m^{-3}) than PSD (20 g m^{-3}) was needed for an optimal effect on infiltration and runoff. For these treatments, the final IR was generally higher in the PAM than in the PSD treatment (Levy et al. 1992). Thus, based on the results of Ben-Hur and Letey (1989) and Levy et al. (1992), it can be concluded that the electrolyte concentration in the applied water greatly affects the efficacy of the polymers added to the water.

The effect of the polymer properties and water quality on seal formation correlates well with the effect of the polymer on the flocculation patterns of soil clays. Polymer added to a colloidal suspension can act as a dispersant or flocculent, depending on polymer properties and electrolyte concentration in the solution (Sato and Ruch 1980). Polymers with a charge opposite that on the clay surface are adsorbed by electrostatic attraction; if the polymer and clay have similar charges, electrostatic repulsion will occur. Multivalent cations can bridge between negatively charged polymers and negatively charged clay particles. For adsorption of uncharged and negatively charged polymers on clays, entropy changes caused by water desorption are another major driving force (Theng 1982; Lyklema and Fleer 1987). Entropy changes associated with neutral molecule adsorption increase with the increase in molecular weight (Theng 1982; Lyklema and Fleer 1987).

Aly and Letey (1988) studied the adsorption and flocculation patterns of Na-montmorillonite clay with three anionic and one nonionic PAM and with cationic, nonionic, and anionic polysaccharides. Cationic and nonionic polysaccharides were adsorbed much more than the anionic polysaccharides (Aly and Letey 1988). Adsorption of anionic polymers (both PAM and PSD) in well water (EC 0.7 dS m^{-1}) was greater than in canal water (EC = 0.05 dS m^{-1}). In the presence of electrolytes, negative charge and the thickness of the diffuse double layer at the clay and polymer surfaces is suppressed, resulting in decreased repulsion forces and greater adsorption of anionic polymer. The reverse is observed in the case of the cationic polymer, where cations compete with the positive polymers and cationic polymer adsorption from well water is less than from canal water. The adsorption of anionic PAM was very low in both waters because of electrostatic repulsion. The anionic polymer (40J) with high charge density is adsorbed to a lesser extent than the anionic polymer with low charge density (Aly and Letey 1988).

Significant effects of polymer and water quality interactions on flocculation of montmorillonite were also observed (Aly and Letey 1988). Anionic polymers promoted flocculation in solutions of EC = 0.7 dS m^{-1} for polymer concentrations >5 g m^{-3}, but reduced flocculation in water with EC = 0.05 dS m^{-1}. Adsorption of cationic and nonionic polymers in 0.05 dS m^{-1} water promoted flocculation, and the effectiveness increased with increased polymer concentration.

The adsorption and flocculation data are in good agreement with seal formation and IR data. Cationic polymers are effective in flocculating the clay (Aly and Letey 1988) and maintaining high IR even in DW (Ben-Hur and Letey 1989). Conversely, anionic polymers are effective in flocculating soil clay (Aly and Letey, 1988) and stabilizing soil structure at the soil surface and maintaining high IR values (Levy et al. 1992) only in electrolyte solutions.

The effect of polymers added to the irrigation water depends also on the sodicity level of the soil and applied water. Studies indicate that the relative beneficial effect of PSD tends to decrease with increasing sodicity in the applied water (El-Morsy et al. 1991). Ben-Hur et al. (1992) observed that for ESPs of 8.5 and 30.6, addition of 10 or 50 g m^{-3} of cationic PSD to the irrigation water had no significant effect on the final IR.

The residual effect of cationic PSD on controlling seal formation and maintaining high IR values in subsequent simulated rainstorms was found to be negligible (Ben-Hur et al. 1989; Levy et al. 1992). Conversely, the latter investigators reported that an anionic PAM had some residual

effect on the IR in subsequent irrigations. Levy et al. (1992) suggested that the difference in the residual effects of the two polymers stems from the difference in their adsorption to the soil. The PSD, being a cationic polymer, is highly adsorbed to the soil and hence is less mobile and penetrates to a very shallow depth. During consecutive irrigations, soil loss exceeded the volume of soil treated with PSD, and hence no polymer was left to stabilize the surface aggregates. PAM on the other hand, is adsorbed to a lesser extent than PSD and thus penetrates to a greater soil depth. The amount of soil removed by erosion in the subsequent irrigation was small compared with the volume of the soil layer treated by PAM. Hence, PAM treated aggregates were left to stabilize the soil surface at subsequent irrigations (Levy et al. 1992).

Polymer addition to the soil surface

Mixing polymers with water is possible only under irrigation. In order to prevent seal formation during rainstorms, the polymer solution must be sprayed on the soil surface prior to the rain. The effect of applying a concentrated polymer solution on preventing seal formation has been studied extensively under both laboratory and field conditions. In the early seventies, Gabriels et al. (1973) showed that surface application of a small amount (38 kg ha^{-1}) of an anionic PAM was highly successful in maintaining high IR values and preventing runoff. Similarly, Shainberg et al. (1990) studied the effect of surface application of a high molecular weight, low charge density anionic PAM on seal formation. They applied 10, 20, and 40 kg ha^{-1} of PAM and found that the beneficial effect of the amount above 20 kg ha^{-1} was insignificant, compared with 20 kg ha^{-1}, in maintaining high IR. Conversely, when an anionic polymer with a medium molecular weight was used (Shaviv et al. 1986), 80 kg ha^{-1} of the polymer was the most effective treatment. These results suggest that higher molecular weight polymers are more effective in controlling seal formation, and a smaller application is required.

In addition, Shainberg et al. (1990) also found that the beneficial effect of the polymer on the IR was dramatically enhanced by the presence of electrolytes in the simulated rain (Fig. 3). For instance, the infiltration rate in the PAM treatment in DW was two to three times that of a nontreated soil. But, when PAM application was

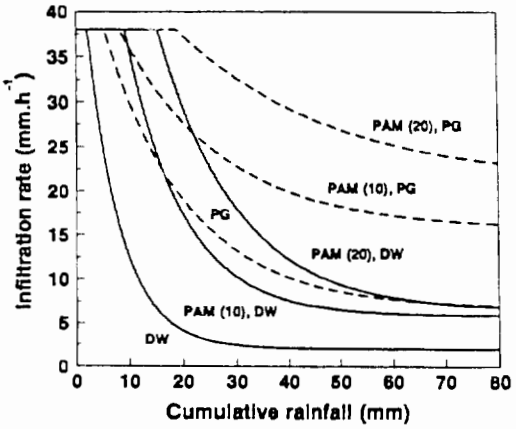

FIG. 3. Infiltration rate of loess treated with polyacrylamide (PAM) as a function of cumulative rainfall, water quality (DW and TW), and phosphogypsum (PG) application. Numbers in () indicate amount of PAM added in kg ha^{-1}. (Shainberg et al. 1990).

supplemented with the spreading of 5 Mg ha^{-1} of phosphogypsum (PG) on the soil surface, the final IR was about 10 times higher than the control (Fig. 3). Both tap water (TW, EC = 0.97 dS m^{-1}) and PG treatments increased the beneficial effect of PAM, but PG, which maintains a higher EC in the soil solution, was more beneficial (Fig. 3). Shainberg et al. (1990) concluded that flocculation of the soil clay is apparently a precondition for the cementing and stabilization of aggregates at the soil surface by anionic polymers. This conclusion was supported by data obtained in other studies (e.g., Levin et al. 1991; Smith et al. 1990).

The efficacy of polymers in controlling seal formation depends also on rain kinetic energy. Smith et al. (1990) studied the interaction between the impact energy of the drops, water quality, and anionic PAM treatments on the IR of a sandy loam Alfisol. Increasing the impact energy increased seal formation and reduced the IR in all treatments. Addition of PAM in the presence of electrolytes (either PG or TW) increased both final IR and cumulative infiltration by 7- to 8-fold compared with the control and was much more effective than PAM, PG, or TW alone at all impact energy treatments. The beneficial effect of PAM was more pronounced under high energy rain. This interaction between impact energy, water quality, and PAM treatments should be considered in managing unsta-

TABLE 1

Effect of combined application of polyacrylamide (PAM, 20 kg ha^{-1}) and phosphogypsum (PG, 5 Mg ha^{-1}) on percent runoff from natural rainstorms[1]

Soil classification	Clay mineralogy[2]	Rain mm	Ratio of runoff to annual rainfall	
			Control %	PAM+PG %
Paleudalf	K, I	214	40.2	20.7
Rhodustalf	K, I	107	72.5	27.9
Haplustalf	I, K	122	40.9	15.3

[1] Adapted from Stern et al. 1991b.
[2] K = kaolinite; I = illite.

ble soils from semi-arid regions under sprinkler irrigation.

The effectiveness of polymers in improving IR was also observed in field scale experiments. Field studies in South Africa (Stern et al. 1991b) showed that a combined treatment of PAM and PG, added in the form of solution and powder, respectively, to the soil surface of soils exposed to natural rainstorms, was very effective in controlling runoff. Annual runoff percentage from PAM+PG-treated plots was significantly lower than that from the nontreated (control) and PG-treated plots (Table 1). Another study was conducted in Israel on a cultivated grumusol (Typic Chromoxerert) irrigated with a center pivot sprinkler irrigation system (Levy et al. 1991). Percent runoff was significantly lower from plot surfaces on which PAM (at a rate of 20 kg ha^{-1}) was sprayed before the irrigation season compared with the control plots (Fig. 4). The results of these field experiments (Table 1 and Fig. 4) clearly demonstrate that spreading a small amount of PAM at the soil surface has an effect on stabilizing the aggregates at the soil surface and reducing runoff that lasts over the entire rain/irrigation season.

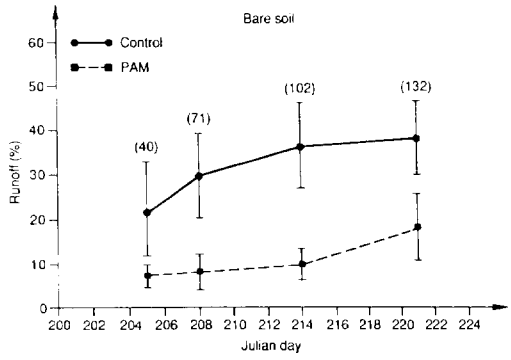

FIG. 4. Percent of total amount of water applied that is runoff at each irrigation to the plots in Negba grumusol. Vertical lines indicate two standard deviations. Numbers in () indicate cumulative depth of irrigation (mm) (Levy et al. 1991).

SUMMARY AND CONCLUSIONS

Cultivated soils are structurally unstable and form a seal at the soil surface when exposed to rain. The formation of a seal determines rain infiltration, runoff, and erosion. The seal formed is a thin layer located at the soil surface and, thus, can be stabilized easily by application of small amounts of amendments.

Addition of small amounts of polymers (10–20 kg ha^{-1}), either sprayed directly on the soil surface or added to the applied water, stabilizes and cements together aggregates at the soil surface and thus increases their resistance to seal formation. Polymer efficiency depends on charge type and density and the molecular weight of the polymer, as well as the electrolyte concentration of the soil solution. When anionic polymers are used, their efficacy is enhanced with the addition of electrolytes (either in the "rain" water or the PG addition). Of the polymers currently available and under study, anionic PAM has been found to be the most effective in controlling seal formation and soil erosion and has the longest residual effect.

PAM efficiency in reducing seal formation extends over a wide range of conditions and to soils of varying mineralogy. Hence, this soil amendment may be considered as a universal stabilizing agent for cultivated soils and earth structures.

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WATER DROP ENERGY AND SOIL SEAL PROPERTIES

Paper #3

I. BETZALEL,[1] J. MORIN,[1] Y. BENYAMINI,[1] M. AGASSI,[1] AND I. SHAINBERG[2]

Rain properties (depth, drop size, and impact velocity) affect the infiltration rate (IR) curve and final IR (FIR) of soils. Because the IR is not a unique function of rain depth or rain energy, the objective of this study was to find a unique function of rain properties that determines the IR of the soil. Simulated rain of constant intensity (40 mm h^{-1}), with 2.53- and 3.37-mm-diameter drops, was applied from heights of 0.4, 1.0, 2.0, 6.0, and 10.0 m on two soil samples: Ruppin hamra (sandy loam, mixed, Typic Rhodoxeralf), and Ruhama loess (silty loam, mixed, Calcic Haploxeralf). The FIR of the two soils decreased with increasing kinetic energy (KE) of the drops. The sandy loam was less stable than the silty loam, and seal formation in it was more susceptible to the KE of the drops. The infiltration decay process was better correlated with rain momentum than with rain depth or KE. Thus, prediction of infiltration rate decay for a given soil exposed to rains of various drop sizes and velocities is best based on drop momentum and the soil stability constant.

The formation of a surface soil seal as a result of the action of rain or sprinkler drops is a common feature of many cultivated soils in the world. Surface seals are thin (<2 mm) and are characterized by greater density, higher shear strength, finer pores, and lower saturated hydraulic conductivity than those of the bulk soil (McIntyre 1958; Bradford et al. 1987). Seal formation is caused by the breakdown of soil aggregates as a result of raindrop impact and by physico-chemical dispersion of the soil clays that deposit in and clog the pores immediately beneath the surface (McIntyre 1958; Agassi et al. 1981).

Surface seal reduces the rate of rain infiltration into the soil. Seal formation is the main reason for the decay in infiltration rate (IR), and the final stage of seal formation is characterized by the final IR (FIR). Models of water infiltration into surface-sealed soil (Hillel and Gardner 1969; Ahuja 1974; Moore 1981) assume steady state condition and that the seal hydraulic conductivity is a constant parameter. The first and third models use analytical solutions, and the second is based on a numerical solution of Richards' equation. Edwards and Larson (1969) developed numerical models that predicted infiltration into surface-sealed soil under conditions of time-varying soil hydraulic conductivity. Freebairn et al. (1991) found that the development of a crust was delayed when the surface was made up of aggregates larger 19 mm in diameter. They suggested that total rainfall or rainfall energy would be better parameters than rainfall intensity for describing soil crust development. An equation presented by Morin and Benyamini (1977) has been used successfully to describe sealing and infiltration and suggests that the IR of soils exposed to rain is dependent upon the cumulative rainfall and the soil stability constants.

$$I_t = I_f + (I_i - I_f)^* \exp - (\Gamma pt) \qquad (1)$$

where:

I_t = the IR at time t (mm h^{-1}),
I_i = the estimated initial IR (mm h^{-1}),
I_f = the final IR (mm h^{-1}),
p = rainfall intensity (mm h^{-1}),
Γ (mm^{-1}) = a soil stability constant,
t = time (h).

Morin and Benyamini's equation was chosen here for further development for two reasons: (i) Rain intensity and rain amount are major parameters of the equation and (ii) the equation allows easy transformation of the rain parameters into rain-energy expressions.

According to this equation, the decrease in the IR of a given soil is determined solely by the amount of rain hitting the ground. The effects of drop size, drop impact velocity, rain kinetic energy, and rain momentum on seal formation and infiltration rate were not considered; they were evaluated in the present study.

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Contribution from the Agricultural Research Organization, The Vocani Center, Bet Dagan, Israel. No. 1398-E, 1994 series.
Received Dec. 16, 1993; accepted Aug. 1, 1994.

Several parameters have been suggested [illegible] represent raindrop activity in splash erosion [illegible] seal formation. Meyer (1965) introduced the kinetic energy (KE) ($KE = 1/2\ mv^2$ in J kg^{-1}) or the momentum (M) ($M = mv$ in N s kg^{-1}), either for unit mass of rain or for unit impact area, in order to quantify the rain erosive power (where m is the mass (kg), and v is the impact velocity of drops (m s^{-1})). Rose (1985) showed good correlation between drop momentum and splash erosion.

The effect of drop KE on seal formation has been studied by several investigators (Agassi et al. 1985; Thompson and James 1985; Mohammed and Kohl 1987; Shainberg and Singer 1988). Agassi et al. (1985) showed that when soil was exposed to drops with KE less than 0.01 J mm^{-1} m^{-2}, no seal was formed. When KE of 23.0 J kg^{-1} (1 mm m^2 = 1 kg H_2O), a value typical of rainstorms in Mediterranean climates, was applied, a surface seal with a very low hydraulic permeability was formed. Seal formation in soils with stable aggregates may occur only when the soils are exposed to high-energy rain. Conversely, in soils with an unstable structure, a seal may be formed under low-energy rain by the process of slacking (aggregate breakdown caused by air exclusion) (Le Bissonnais 1990), which occurs when dry aggregates are quickly wetted. Shainberg and Singer (1988) observed that sodic soils were more susceptible to sealing by low-impact drops than were calcic soils. The effect of rain KE on seal formation depends on soil properties such as aggregate stability, soil sodicity, clay mineralogy, and organic matter content. Specific objectives of the present study were to evaluate the effect of rain depth and drop impact parameters (KE and M) on the IR [illegible] tive of this study was to [illegible] of rain properties that determines the IR [illegible] given soil. This knowledge is needed to [illegible] evaluation of the effect [illegible] and sprinkler irrigation on soil sealing.

MATERIALS AND METHODS

Soil samples of the cultivated layer (<20 cm in depth) of two loamy soils, representing the two main arable soils existing in Israel, were used in this study. Some of the physical and chemical properties of these soils, Ruhama loess and Ruppin hamra, are presented in Table 1. The soil samples contained low concentrations of organic matter (0.5–0.7%), low sodicity (<2%), and moderate clay contents (22 and 12% for Ruhama loess and Ruppin hamra, respectively). Air-dried soil samples with aggregates <4 mm were packed into 20-mm-deep 300 × 500-mm perforated trays placed over an 80-mm layer of coarse sand and were exposed to simulated rain. This aggregate size distribution simulates the seedbed for small grain seeding in Israel.

Infiltration, runoff, and erosion were studied using a drip-type rain simulator. The simulator consisted of a 750 × 600-mm closed water chamber placed in a variable-height raindrop tower. Rain was generated by allowing water to fall through approximately 1000 hypodermic needles arranged in a 20 × 20-mm array, to form a chosen droplet size. Water-drop diameters of 2.53 and 3.37 mm were used in this experiment. The effective drop diameter was calculated by measuring the average weight of a number of drops, which [illegible] sizes, and the five heights are summarized in Table 2. A peristaltic pump was operated to maintain a constant rain intensity of 40 mm h^{-1}.

The soil trays were placed horizontally under the rain simulator and slowly saturated with tap water (electrical conductivity (EC) of 0.5 dS m^{-1}) from below by the capillarity wetting, taking special care to prevent any water ponding on the surface. The soil was saturated to avoid aggregate breakdown caused by air exclusion. A preliminary experiment showed that the tap water and distilled water were interchangeable when used for soil saturation. Following saturation for 30 min, excess water was allowed to drain, and the trays were positioned at a 5% slope. The soils were then subjected to simulated rainfall of distilled water (EC < 0.01 dS m^{-1}). Water percolating through the soil was collected at the bottom of the tray, and IR was recorded. Water flowing over the soil surface was collected and recorded as runoff volume.

The initial IRs of the saturated soils, as measured with mist-type rain at an intensity of 150 mm h^{-1}, were approximately 60 and 116 mm h^{-1} for Ruhama loess and Ruppin hamra soil, respectively. Each experiment was repeated four times. The infiltration data obtained from the rainfall simulator were analyzed using Eq. (1). A nonlinear regression program (Marquardt [illegible] the soil during a rainfall event was designated CIF and was calculated using the infiltration rate curves derived from Eq. (1). Significance of difference among treatments for the infiltration parameters was determined using Tukey's procedures for a multiple-range test (Steel and Torrie 1960).

RESULTS AND DISCUSSION

Figure 1 presents the IR curves calculated by means of Eq. (1). Figure 1 also shows the variation in IR of Ruppin hamra and Ruhama loess, as affected by cumulative rain depth, rain-drop size, and fall heights. The value of Eq. (1) parameters, as calculated from the IR data, are presented in Table 3. Two properties were used to analyze statistically the changes in hydraulic conductivity of the soil when exposed to rainfall with different impact velocities and drop diameters: (i) the measured IR at steady infiltration (after 80-mm rain depth), referred to as the FIR and (ii) the calculated cumulative infiltration (CIF). The results of a multifactor analysis of variance indicated significant interactions between height and drop diameter (Tables 4, 5). Consequently, a multiple-range test was used to determine differences among FIR values and CIF values of individual treatments within each

TABLE 1

Physical and chemical properties of the soils used

Soil type	Suborder	Mechanical composition			CEC[a]	ESP[b]	$CaCO_3$	Organic matter
		Sand	Silt	Clay				
		g kg^{-1}			cmol$^+$ kg^{-1}	%	g kg^{-1}	%
Ruhama loess	silty loam mixed, Calcic Haploxeralf	400.0	380.0	220.0	19.2	1.9	150.0	0.7
Ruppin hamra	sandy loam mixed, Typic Rhodoxeralf	790.0	90.0	120.0	8.0	1.5	2.0	0.5

[a] CEC—Cation exchange capacity.
[b] ESP—Exchangeable sodium percentage.

TABLE 2

Droplet impact velocity,[a] kinetic energy, and momentum as a function of fall height and drop diameter

Drop diameter	Fall height	Drop impact velocity	Kinetic energy[b] (KE)	Momentum[b] (M)
mm	m	m s^{-1}	J kg^{-1}	N s kg^{-1}
	0.40	2.50	3.12	2.50
	1.00	4.00	8.00	4.00
2.53	2.00	5.28	13.94	5.28
	6.00	6.96	24.22	6.96
	10.00	7.30	26.65	7.30
	0.40	2.50	3.12	2.50
3.37	1.00	4.03	8.12	4.03
	2.00	5.52	15.23	5.52
	6.00	7.61	28.95	7.61

[a] From Epema and Riezebos, 1983.
[b] Values per unit of mass.

Fig. 2) Considering Figs. 1 and 2 and the Table 3, the following may be

Effect of falling heights on infiltration

• The IR curve for a given soil is not a unique function of rain depth. The IR curves also depend on fall height and drop size (Fig. 1). The parameters of Eq. (1) as a function of drop size

and both soils were susceptible to sealing. When the soil surface was exposed to drops with high impact energies (e.g., drops with a diameter of

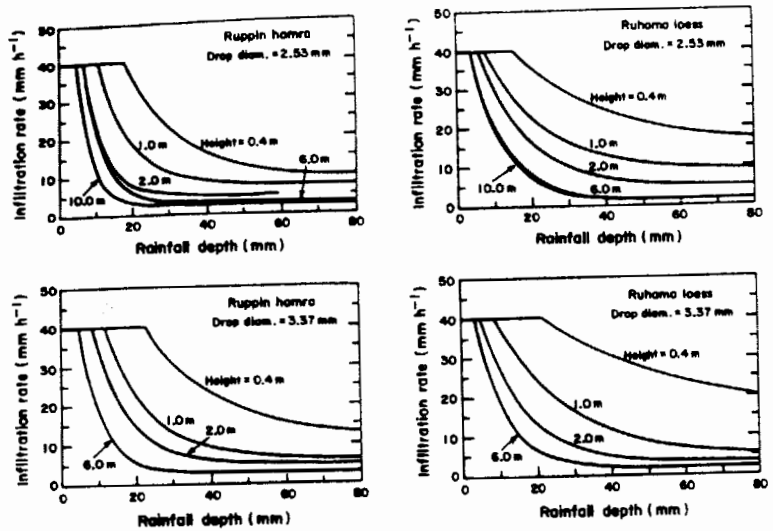

FIG. 1. Infiltration rate as a function of rain depth for Ruppin hamra and Ruhama loess soils exposed to simulated rain of two drop sizes (d = 2.53 and 3.37 mm) falling from various heights (h = 0.4, 1.0, 2.0, 6.0, and 10.0 m).

TABLE 3

Final infiltration rate and the soil stability constant of the Ruppin hamra and Ruhama loess soils as functions of fall height and drop diameter

Drop diameter	Fall height	Soil: Ruppin Hamra					Soil: Ruhama Loess				
		Γ[a]		FIR		R^2	Γ[a]		FIR		R^2
		average	SD[b]	average	SD[b]		average	SD[b]	average	SD[b]	
mm	*m*	*mm⁻¹*		*mm h⁻¹*			*mm⁻¹*		*mm h⁻¹*		
	0.40	0.070	0.002	9.3	0.42	0.88	0.041	0.0006	15.66	0.18	0.96
	1.00	0.116	0.002	7.4	0.24	0.96	0.067	0.0010	9.46	0.18	0.98
2.53	2.00	0.181	0.002	4.8	0.15	0.99	0.080	0.0030	5.50	0.30	0.92
	6.00	0.180	0.003	2.7	0.24	0.94	0.120	0.0030	2.03	0.28	0.93
	10.00	0.252	0.005	2.3	0.15	0.90	0.114	0.0034	1.99	0.30	0.93
	0.40	0.054	0.0008	11.5	0.22	0.91	0.028	0.0007	14.40	0.33	0.92
3.37	1.00	0.089	0.0007	6.0	0.11	0.97	0.053	0.0008	4.32	0.17	0.96
	2.00	0.115	0.0010	4.9	0.13	0.97	0.088	0.0010	3.07	0.14	0.99
	6.00	0.174	0.0020	2.8	0.13	0.97	0.128	0.0020	1.64	0.17	0.96

[a] Γ—(Eq. 1).
[b] SD—Standard deviation.

Ruppin hamra	Height		4	[illegible]	[illegible]
sandy loam	Drop diameter		[illegible]	[illegible]	[illegible]
mixed, Typic	Height × diam		[illegible]	13.284	[illegible]
Rhodoxeralf	Error		27	8.309	
Corrected total		35		447.352	
Ruhama loess	Height		4	1470.658	706.766	*
silty loam	Drop diameter		1	18.804	36.147	*
mixed, Calcic	Height × diam.		3	3p.582	19.596	*
Haploxeralf	Error		27	14.046		
Corrected total		35		1515.455		

* Significant at the 0.05 probability level.

TABLE 5

Analysis of variance for the cumulative infiltration was obtained after 80 mm of rainfall in the various treatments of fall heights and drop diameter in each soil

Soil	Source	*df*	Sum of squares	F value	Significance
Ruppin hamra	Height	4	4315.607	158.956	*
sandy loam	Drop diameter	1	52.506	7.736	*
mixed, Typic	Height × diam.	3	49.779	2.445	*
Rhodoxeralf	Error	27	183.260		
Corrected total		35	4827.576		
Ruhama loess	Height	4	7187.504	647.040	*
silty loam	Drop diameter	1	115.710	41.666	*
mixed, Calcic	Height × diam.	3	70.732	8.490	*
Haploxeralf	Error	7	74.980		
Corrected total		35	7333.941		

* Significant at the 0.05 probability level.

2.53 mm falling from a height of 10.0 m), the IR dropped quite steeply from initial values of 61 and 116 mm h^{-1} to final values of 2.0 and 2.3 mm h^{-1} for Ruhama loess and Ruppin hamra, respectively (Fig. 1). Similar final IR values were obtained for a fall height of 6.0 m and drop diameters of 2.53 and 3.37 mm (Fig. 1).

• The decay rates of infiltration in both soils significantly increased and their final IR significantly decreased, as the drop fall height increased (Figs. 1 and 2). This suggests that the rate and intensity of seal formation increase with increasing drop velocity. For example, the final IR of the Ruppin hamra, exposed to 2.53-mm-diameter drops, decreased from 9.3 mm h^{-1} for h = 0.4 m to 2.3 mm h^{-1} for h = 10.0 m. The corresponding final IR values for Ruhama loess were 15.7 and 2.0 mm h^{-1}, respectively (Figs. 1 and 2 and Table 3).

Effect of drop size

Figure 2 presents the effects of drop diameter (2.53 and 3.37 mm) on the FIR and CIF for different heights. It should be noted that the comparison is based on rain depth. Therefore: (i) 1 mm of rain water per m^2 contained 1 kg of water, with 50,000 large drops or 117,600 small drops; (ii) the velocity of the drop increased with drop size (Table 2); (iii) the drop velocities at h = 0.4 and 1.0 m were quite similar for the small and large drops and increased with drop size at greater heights (Table 2). Based on these facts, the results presented in Figure 2 are explained as follows:

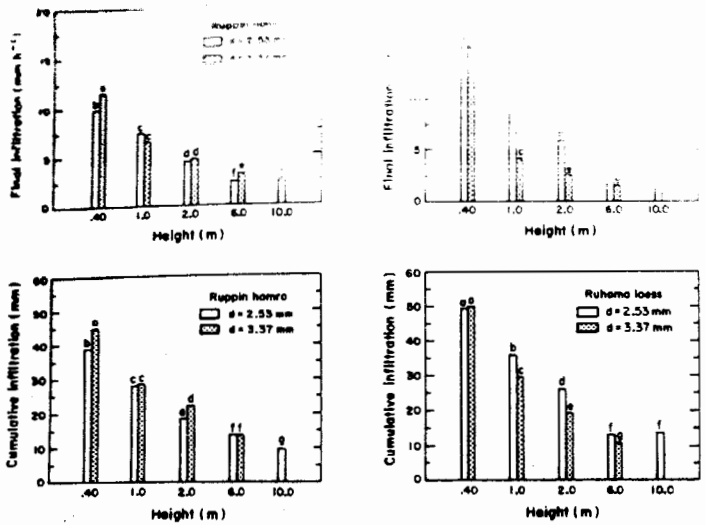

FIG. 2. Cumulative infiltration and final infiltration rate for five drop fall heights, two drop diameters, and two soil types. Bars with the same letter do not differ significantly at the 0.05 level.

- The effects of drop size on FIR and CIF are significant for most heights;
- In the Ruppin hamra the FIR and the CIF were smaller for small drops at most fall heights. Conversely, in the Ruhama loess, the FIR and CIF were smaller for big drops. The fact that rain of small drops contain more than twice the number of drops per kg of rain may help to explain this observation. Small drops (with many impacts per kg) were more effective in forming a seal on Ruppin hamra, whereas big drops were more effective in forming a seal on Ruhama loess (Fig. 2). In the Ruppin hamra, which is less stable and more susceptible to sealing, small drops are effective in seal formation. Conversely, in the more stable Ruhama loess, only the big drops were effective in forming a seal.

Effect of raindrop KE and momentum on IR

Figure 3 presents the IR as a function of cumulative KE and cumulative M for both soils exposed to 3.37-mm-diameter drops. A similar picture was obtained for 2.53-mm-diameter drops (not shown). In considering seal formation as a function of both cumulative KE and cumulative M, a distinction should be made between the rate of seal formation and the FIR of the seal (Fig. 3):

- The rate of seal formation was estimated from the rate of decline in the IR curve. Contrary to expectations, the rate of seal formation as a function of cumulative KE was highest for raindrops falling from 0.4 m, and the rate decreased with increasing drop impact energy. For example, the IR of Ruppin hamra at a cumulative KE of 200 J m^{-2} was 14.3, 18.0, 30.0, and 40.0 mm h^{-1} for drops falling from 0.4, 1.0, 2.0, and 6.0 m, respectively. The depths of rain needed for a cumulative KE of 200 J m^{-2} were 64.1, 24.6, 13.1, and 6.9 mm for drops with KE of 3.12, 8.12, 15.23, and 28.95 J kg^{-1}, respectively. Much rain of low impact energy had to be applied to deliver a given cumulative KE (e.g., 200 J m^{-2}), and many drops of low KE were more effective in forming a seal than fewer drops of high KE. The rate of seal formation as a function of cumulative KE increased with increasing numbers of drops impacting the soil surface. The effects of cumulative rain KE on IR were similar for Ruhama loess and Ruppin hamra, but less pronounced for the former (Fig. 3). In the more stable Ruhama loess, rain with low KE was less effective in forming the seal than in the Ruppin hamra. A similar conclusion was presented in the previous section.
- The rate of seal formation, as a function of cumulative momentum, is also presented in Figure 3. The curves of IR as a function of cumulative momentum, resemble those of IR as a function of rain depth (Fig. 1). In both cases, the rate of seal formation increased with increasing fall height. However, when the IR was presented as a function of cumulative momentum, the curves seemed to be closer together and the effect of height was less pronounced (except for the h = 0.4 m treatment). This observation suggests that the IR decrease is a unique function of cumulative rain momentum and is independent of the drop parameters.

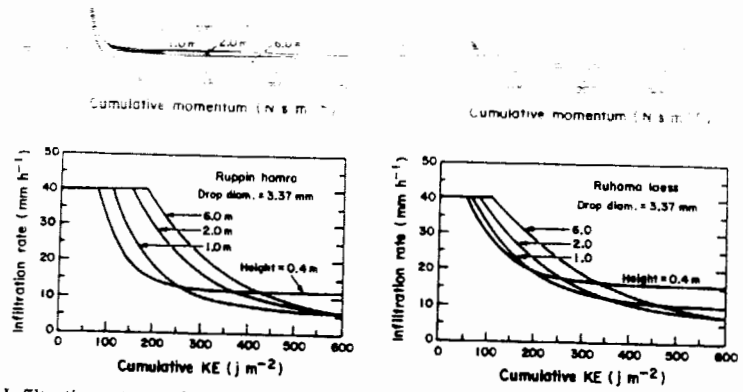

FIG. 3. Infiltration rate as a function of cumulative kinetic energy (KE) and cumulative momentum (M) for Ruppin hamra and Ruhama loess soils exposed to simulated rain falling from various heights (h = 0.4, 1.0, 2.0, and 6.0 m).

Effect of momentum on the FIR of the seal

The FIR is a function of drop impact energy or momentum. As the drop impact momentum increased, the FIR decreased (Fig. 4 and Table 3). Figure 4 presents the relationship between FIR and the impact momentum per unit mass of the rain for Ruppin hamra and Ruhama loess soils. Similar curves were obtained for FIR as a function of KE (not shown). Figure 4 shows M increments above 6 N s kg^{-1} caused only slight decrements in FIR values for both soils. Similar observations were made for the FIR as a function of KE, and KE values do not cause a significant decrease in FIR.

The surface soil consists of aggregates of various strengths, and drops of low impact energy cannot break down the more stable aggregates. Thus, the soil surface, when exposed to drops of low impact energy, will maintain a high final IR that is independent of rain depth or cumulative energy. Only drops with an impact energy exceeding a threshold value typical of the soil would be capable of breaking down the stable aggregates and forming a seal.

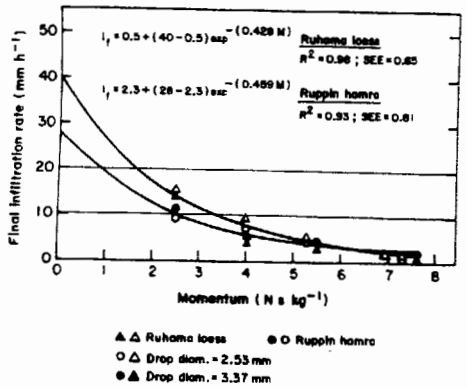

FIG. 4. Final infiltration rates (FIR) as a function of drop impact momentum per unit mass, for Ruppin hamra and Ruhama loess soils exposed to simulated rain of two drop sizes (d = 2.53 and 3.37 mm), falling from various heights (h = 0.4, 1.0, 2.0, 6.0, and 10.0 m). R^2 = correlation coefficient.

The relationship between FIR and raindrop momentum per unit mass of rain for any fall

[illegible] drop size, might be [illegible]

$I_{[illegible]} = I_{f(M)} + (I_{[illegible]} - I_{f(M)})$ [illegible]

where

[illegible] is a constant that is relat[illegible] properties and is obtained by nonlinear regression analysis from the experimental final IR and the relevant M value (Tables 2 and 3);

$I_{f(M)}$ is the lowest IR obtained for the highest values of βM;

I_f is the final IR for rain with very low momentum (mist);

$I_{f(M)}$ is the final infiltration rate as a function of momentum (for any given set of drop size and velocity);

M is the drop momentum per kg of rain.

Figure 4 presents the FIR as a function of momentum per unit mass. The calculated line shows a good correlation between calculated and measured FIR (R^2 = 0.98 and 0.93 for Ruhama loess and Ruppin hamra, respectively). This correlation enables us to predict the FIR of the two soils from the momentum of rain drops. The parameters of Eq. (2) for Ruppin hamra and Ruhama loess soils are presented in the equations included in Fig. 4.

[illegible] drop size and fall height [illegible] Table 6. The high variability of I is also demonstrated by the high coefficient of variation (CV), which ranges between 42 and 44%. An attempt is made to formulate an equation capable of predicting seal formation and IR according to parameters related to rain and soil properties, which are independent of each other. It also follows from the previous discussion that IR should be considered as a function of rain impact energy.

In order to distinguish between soil and rain effects on the rate of seal formation, new soil stability constants, α, α' and α'' were defined. These parameters depend on soil properties, but are independent of rain properties.

$$\alpha = \Gamma/M \ (\mathrm{mm^{-1}\ N^{-1}}) \quad (3)$$

$$\alpha' = \Gamma/M/d \ (\mathrm{N^{-1}\ s^{-1}}) \quad (4)$$

$$\alpha'' \ \Gamma/KE \ (\mathrm{mm^{-1}\ J^{-1}}) \quad (5)$$

where d is the diameter of the drops.

These parameters are also given in Table 6,

TABLE 6

Soil parameters stability describing the relationship between infiltration rate and rain energy

Drop diameter	Falling height	Soil							
		Ruppin Hamra				Ruhama Loess			
		Γ^a	α^b	α'^c	α''^d	Γ^a	α^b	α'^c	α''^d
mm	*m*	*mm*$^{-1}$	*(N s mm)*$^{-1}$	*(N s)*$^{-1}$	*J*$^{-1}$ *kg*	*mm*$^{-1}$	*(N s mm)*$^{-1}$	*(N s)*$^{-1}$	*J*$^{-1}$ *kg*
	0.4	0.07	0.028	0.071	0.022	0.038	0.015	0.038	0.012
	1.0	0.116	0.029	0.073	0.015	0.068	0.017	0.043	0.008
2.53	2.0	0.181	0.034	0.087	0.013	0.091	0.017	0.044	0.007
	6.0	0.180	0.026	0.065	0.007	0.119	0.017	0.043	0.005
	10.0	0.252	0.035	0.087	0.009	0.114	0.016	0.040	0.004
	0.4	0.054	0.022	0.073	0.017	0.028	0.011	0.038	0.009
	1.0	0.089	0.022	0.074	0.011	0.053	0.013	0.044	0.006
3.37	2.0	0.115	0.021	0.070	0.008	0.088	0.016	0.054	0.006
	6.0	0.174	0.023	0.077	0.006	0.128	0.017	0.057	0.004
AVERAGE		0.137	0.027	0.075	0.012	0.081	0.015	0.044	0.007
ST. ERROR		0.061	0.005	0.007	0.005	0.034	0.002	0.006	0.002
CV %		44.26	18.72	9.20	41.66	42.37	12.47	13.88	35.22

[a] Γ, [b] α, [c] α' and [d] α'' are soil stability parameters for infiltration rate as a function of rain depth, cumulative momentum, cumulative momentum divided by drop diameter, and kinetic energy, respectively.

[a] Γ (Eq. 1), [b] α (Eq. 3), [c] α' (Eq. 4), [d] α'' (Eq. 5).

[illegible] Eq. (4). Thus, a prediction of IR as a function of the cumulative momentum of the rain [illegible] given by Eq. (6):

$$I_t = I_{f(M)} + (I_i - I_{f(M)})\exp-(\alpha'(M/d)pt) \quad (6)$$

[illegible] means of the momentum expression [illegible] and (6)), using average values of [illegible] for both soils, gives result that are very close to those that are presented in Fig. 3. Figure 5 shows

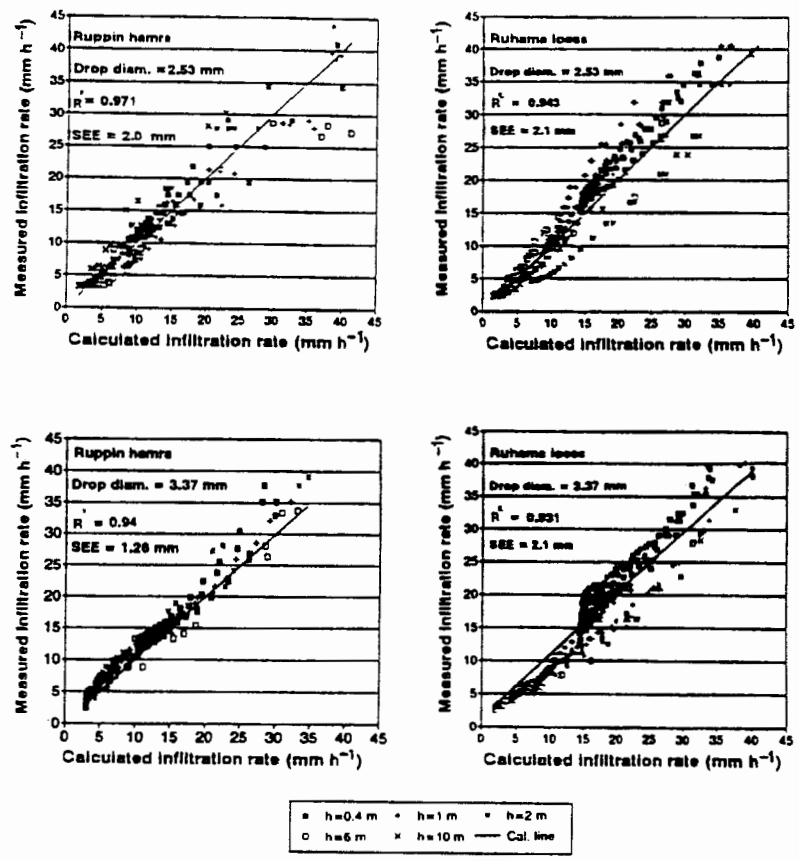

FIG. 5. Regression between measured infiltration rate data and infiltration rate calculated (from Eqs. (2) and (6)) for Ruppin hamra and Ruhama loess soils exposed to simulated rain of two drop sizes (d = 2.53 and 3.37 mm) falling from various heights (h = 0.4, 1.0, 2.0, 6.0, and 10.0 m). R^2 = correlation coefficient.

between experimental and calculated I_t for both soils by Eqs. (2) and (6). I_t parameters were taken from Eq. (2) and α' values are averages for each soil, as presented in Table 6. The high correlation soils between measured and calculated values for the two soils suggests that momentum is a better parameter for predicting infiltration decay process.

CONCLUSION

Disintegration of soil surface aggregates and seal formation is a cumulative process, involving rain impact force and soil dispersibility. Seal formation, as determined by changes in soil IR, depends on rain depth, drop size, and drop impact velocities. Drop diameters of 2.53 and 3.37 mm and drop fall heights of 0.4, 1.0, 2.0, 6.0, and 10.0 m were studied. As the drop impact energy increased, the IR for any rain depth decreased. Drops of low impact energy could not disintegrate and disperse stable aggregates and less seal formation was observed with such drops. The rate of seal formation, as determined by the rate of decline in the IR, curve depended on rain properties. The rate of seal formation as a function of rain depth or cumulative rain momentum was greatest for the highest fall (10.0 m), and the rate of seal formation declined as the impact energy of the drops decreased. Conversely, the rate of seal formation as a function of cumulative KE was the highest in raindrops falling from h = 0.4 m, and then it decreased with increasing drop impact energy. This is because much rain of low impact energy was needed to apply a given cumulative KE, and many drops of low KE were more effective in forming a seal than a few drops of high KE.

Rain momentum was found to be the best parameter for predicting the infiltration decay process. IR decay for rain of various drop sizes and velocities could be uniquely predicted from the drop momentum and the soil stability constant.

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Vol. 159, No. 1
Printed in U.S.A.

RELATIONSHIP OF BROMIDE AND ATRAZINE MOVEMENT IN SOIL TO PORE SIZE DISTRIBUTION, COMPACTION, AND SATURATION CYCLES[1]

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Repeated equipment traffic increases the bulk density and changes the pore size distribution (PSD) of soil. Spatial variability of chemical movement in soil may be partially explained by differences in PSD. The purpose of this study was to determine the relationships between soil pore size distribution and surface soil compaction on the transport of water, bromide, and atrazine (6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-1, 3,5-triazine-2,4-diamine) during multiple desaturation cycles. Undisturbed cores (8.2 cm diameter; 6.6 cm high) from a Crete silt loam (Pachic Argiustoll) were collected from wheel track (WT), non-wheel track (NWT), and row (ROW) locations in a conventionally tilled, continuous corn field. Atrazine (4.9 Kg ha^{-1}) and KBr (66 Kg Br^{-1}) were surface applied and equilibrated for 72 h. Effluent was collected at decreasing matric potentials between −1 and −100 kPa. The PSD indexes and bulk densities were significantly different among three locations (PSD indexes were 0.045 in WT, 0.061 in ROW, and 0.069 in NWT; bulk densities were 1.39 Mg m^{-3} in WT, 1.30 Mg m^{-3} in ROW, and 1.21 Mg m^{-3} in NWT). Effluent analysis revealed more water and bromide were eluted from cores with higher PSD indexes and lower bulk densities. However, the reverse was true for atrazine. These data indicate that water and atrazine transport can be influenced differently by PSD and bulk density.

Farm machinery and land structuring equipment can change soil pore geometry and solute movement. Repeated equipment traffic increases bulk density and changes pore size distribution (PSD) (Bauder et al. 1985; Ankeny et al. 1990; Hill and Meza-Montalvo 1990). O'Sullivan and Ball (1993) observed that compaction by wheel traffic on a fine-textured soil reduced median pore diameter from 48 to 4.5 μm.

Pore geometry (connectedness, uniformity or PSD, and shape) can alter solute pathways by influencing dispersion. The fingering pattern observed by Ghodrati and Jury (1990) of Acid Red 1 dye leached under varying irrigation regimes illustrated preferential transport. Preferential transport of solutes can increase agrichemical penetration and variability in soils. Large variations in herbicide concentration have been reported within a 25 × 15 × 15 cm block of soil (Robinson 1975). Various researchers have suggested that preferential movement occurs primarily in macropores (Shipitalo et al. 1990; Jabro et al. 1991; Rice et al. 1991) or pores with diameters greater than 1000 μm (Luxmoore 1981). Other researchers have attributed preferential movement to transport through interconnected pore sequences (Jardine et al. 1988; Ghodrati and Jury 1990; Rice et al. 1991).

The chemical properties of a solute can also profoundly influence the patterns of solute migration in soil. Large or negatively charged solute molecules can be excluded from smaller soil pores (Thomas and Swoboda 1970; Bohn et al. 1982). Harvey (1993) found that when water was applied immediately after bromide application, maximum bromide concentrations in the eluate occurred at low matric potentials, corresponding to drainage of large diameter pores.

Baer et al. (1992) found a correlation between PSD index of surface soils with atrazine concentrations in subsurface layers (10–20 cm depth) and observed that soils with a greater proportion of larger pores transported less atrazine. However, when soil cores were brought back to the laboratory and treated with atrazine, more atrazine was transported in cores having a greater proportion of larger pores. These conflicting observations between field and laboratory results were attributed, in part, to differences between time of water application after the herbicide

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Received April 7, 1994; accepted July 29, 1994.

Paper No. 4

Prewetting rate and aging effects on seal formation and interrill soil erosion

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Prewetting rate and aging effects on seal formation and interrill soil erosion

Abstract

Slaking of surface aggregates may affect seal formation and interrill soil erosion. An investigation was conducted of the effects of time-dependent variables, such as prewetting rate and aging duration, on seal formation and interrill soil loss in two soils exposed to simulated rain. Aggregates (4-9.5 mm) from a Calcic Haploxeralf and a Typic Chromoxerert were packed in pans, placed in a rainfall simulator, and prewetted by either (a) a water table 20 mm below the soil surface or (b) 5 mm of rain at rates of 1, 6 or 30 mm h^{-1}. After prewetting the soil pans were left to age for 15 min or 18 h, and then subjected to 60 mm of distilled water simulated rainfall. The final infiltration rate increased from 5.0 to 26.6 mm h^{-1}, percent runoff decreased from 59.1 to 2.5, and soil loss decreased from 302 to 5.4 g m^{-2} with a decrease in prewetting rate from 30 to 1 mm h^{-1} in the Typic Chromoxerert; similar effects were observed in the Calcic Haploxeralf. For both soils, aging was effective in increasing the infiltration parameters (infiltration rate and runoff) only when partial slaking was achieved by slow and moderate prewetting rates. Conversely, 18 h of aging effectively decreased soil loss also in the fast prewetting rates in both soils. Aggregate slaking, which occurred during prewetting by compression of entrapped air, enhanced aggregate breakdown by the impact of the raindrops, and both factors played an important role in surface crusting. Slaking was significantly reduced by slow prewetting of the

surface aggregates. Aging increased the cohesion forces between soil particles and reduced the latter's erodibility.

Abbreviations: CEC, cation exchange capacity; DW, distilled water; EC, electrical conductivity; ESP, exchangeable sodium percentage; IR, infiltration rate; FIR, final infiltration rate; OH, organic matter.

Introduction

The formation of a seal at the soil surface due to the action of raindrops or sprinkler irrigation, is a common feature of many cultivated soils worldwide. Seal formation is due to two complementary mechanisms (Agassi et al., 1981): (i) physical disintegration of the surface soil aggregates and their compaction caused by the impact action of the water drops, and (ii) physico-chemical dispersion of the soil clays which then migrate into the soil with the infiltrating water, clog pores immediately beneath the surface, and form a layer of very low permeability termed the "washed in" zone (McIntyre, 1958). The first mechanism is mechanical in nature and is determined primarily by the kinetic energy of the drops and the stability of the soil aggregates (Moldenhauer and Kemper, 1969). The second mechanism is controlled mainly by the concentration and composition of the cations in the soil and applied water (Agassi et al., 1981). The role of the physico-chemical dispersion in seal formation has been studied in detail and can be satisfactorly predicted from basic mineralogical and chemical properties of the soil (Shainberg and Levy, 1992, and references cited therein). Conversely, the role of the first mechanism in the process of sealing is more complicated, depending on both rain properties (intensity and energy) and the stability of the surface aggregates.

Aggregate stability, per se, has been associated commonly with various soil properties (e.g. organic matter, clay percentage and oxides content), which are linked by their representation of binding

processes in the soil (e.g. Kemper and Koch, 1966; Goldberg et al., 1988). However, it was realized recently that aggregate stability depends on a few-time dependent parameters such as initial water content in the aggregates, rate of prewetting and duration of aging (e.g. Francis and Cruse, 1983; Kemper and Rosenau, 1984; Truman et al., 1990).

The effect of the aforementioned time-dependent parameters on soil susceptibility to sealing has not been considered systematically. In many studies the soil was prewetted prior to exposure to rain without monitoring the rate of prewetting, perhaps because it was implicitly assumed that prewetting the aggregates eliminated the possibility of slaking due to entrapped air (e.g. Agassi et al., 1981; Ben-Hur et al., 1985; Kazman et al., 1983; Levy et al., 1986; Reichert and Norton, 1994). In other studies, no clear distinction was made between the time required for prewetting and the duration of aging (e.g. Truman and Bradford, 1990; Truman et al., 1990). Thus, in general, when prewetted soil was compared to air-dried soil, similar infiltration curves were obtained for the two treatments (e.g. Truman and Bradford, 1990).

A notable exception was the work of Le Bissonnais and Singer (1992), who compared sealing, runoff and erosion response to soil water content in a laboratory rainfall simulator; 100-mm-deep soil samples were prewetted for 24 h by a water table placed 100 mm below the soil surface. They obtained significantly higher infiltration rates and lower runoff and soil erosion levels for the prewetted samples than for the air-dry samples.

We hypothesized that the marked differences between the rainfall simulation results obtained by Le Bissonnais and Singer (1992) and those obtained by others could be ascribed to either or both of the following mechanisms:

1. The effect of rate of prewetting of the surface aggregates: It is postulated that in the Le Bissonnais and Singer study (1992), where a 10-mm soil layer was prewetted by a water table placed 100 mm below the soil surface, a slow wetting of the surface aggregates took place. In other studies where a 20-mm soil layer was prewetted with a water table placed 20 mm below the surface (e.g. Agassi et al., 1981; Kazman et al., 1983; Levy et al., 1986), fast wetting occurred. Fast prewetting resulted in aggregates slaking and the microaggregates were susceptible to the impact of the raindrops and disintegrated readily to form a seal. Slowly prewetted macroaggregates may withstand the impact of raindrops and not disintegrate easily; thus, soil susceptibility to seal formation will diminish.

2. The effect of aging: The longer the aging duration after prewetting the stronger the cohesive forces that develop and the more stable the aggregates.

It is further hypothesized that an interaction may exist between the prewetting rate and aging duration. The development of cohesive forces between soil particles during a short aging may be more effective in partially slaked aggregates (slow prewetting) than in severely slaked ones (fast prewetting). In the study of Le Bissonnais and Singer (1992), both slow prewetting and 24-h aging might be

responsible for the low runoff and erosion obtained in the prewetted soil samples.

The objectives of the current study were to test the validity of these two hypotheses and to evaluate the relative importance of the proposed mechanisms in controlling seal formation, infiltration and interrill soil erosion.

Materials and Methods

Samples from the top 0-250 mm layer of a typic loess (Calcic Haploxeralf) from the northern Negev, and a dark brown grumusol (Typic Chromoxerert) from the Pleshet plains, Israel, were brought to the laboratory and analyzed. Some physical and chemical properties of the soils are given in Table 1.

Infiltration, runoff and interrill soil erosion were studied using a drip-type rainfall simulator, which consisted of a 750 x 600 x 80 mm closed water chamber which generated rainfall of a known constant drop size by means of a set of ~1000 hypodermic needles arranged at 20 Xx20 mm spacing. The average droplet diameter was 2.97±0.05 mm. A drop fall of 1.6 m was used to obtain drops with an impact velocity of 4.98 m s^{-1} and a kinetic energy of 12.4 J mm^{-1} m^{-2} (Epema and Riezebos, 1983). Application intensity was maintained at 30 or 33 mm h^{-1} using a peristaltic pump.

Air-dried aggregates in a size range of 4.0-9.5 mm were packed in 200 x 400 mm pans, 20 mm deep, over a 5-mm-thick layer of coarse sand. Two types of prewetting procedures were used prior to the rain simulation: (i) the soil samples in the pans were prewetted with

distilled water (DW) for 1 h at a matric potential of -0.2 kPa. I; and (ii) the soil pans were placed in the rain simulator at a slope of 15% and prewetted by 5 mm of DW rain. Three prewetting rates were studied, 30 mm h^{-1}, 6 mm h^{-1} and 1 mm h^{-1}, with, respectively, the soil was exposed to 10 min of 30 mm h^{-1} rain; 0.5 min of 30 mm h^{-1} rain followed by a 2-min break, with the procedure lasting 50 min; and to 0.5 min of 30 mm h^{-1} rain followed by a 14.5-min break, the procedure lasting 5 h. After completion of the wetting in both types of procedure, the soil was allowed to age in the simulator for either 15 min or 18 h.

After the predetermined aging time the soil was exposed to 60 mm of DW rain with an intensity of 33 mm h^{-1}. During the rain, the volume of water percolating through the soil was collected and recorded as a function of time. Runoff water was collected continuously throughout the "storm". Thereafter, the runoff water in the buckets was mixed thoroughly and 0.25 L subsamples were dried, the weight of eroded material was determined and the total amount of soil removed by the runoff water during the entire "storm" was calculated. Three replicates were performed concurrently for each treatment.

The infiltration data obtained from the rainfall simulator were analyzed using the non-linear equation proposed by Morin and Benyamini (1977). A non-linear regression program calculated the parameters of the equation that gave the best coefficient of determination (R^2) between paired calculated and measured infiltration rate values. The total depth of runoff water from a single rain event was calculated using the instantaneous infiltration rate

derived from Morin and Benyamini's (1977) equation. Calculated runoff values were preferred to measured values because of water splash from the soil boxes. The significance of differences among treatments for the infiltration and erosion parameters studied were determined using Tukey's procedure for a multiple range test.

Results and Discussion

Infiltration studies

The calculated infiltration curves for the various treatments are presented in Figures 1, 2 and 3. The R^2 between paired calculated and measured IR values was >95% in all the treatments.

The effects of prewetting the 20 mm thick soil layer in the pans with a water table placed 20 mm below, and ofing duration (15 min and 18 h) on the IR of the grumusol, are shown in Figure 1. Also presented, for comparison, is the infiltration curve obtained by Le Bissonnais and Singer (1992) for <15 mm aggregates of a Solano silty loam packed to a depth of 100 mm and prewetted at a matric potential of -1.0 kPa during 24 h. The results show that the IR of the Solano changed only slightly during the rain. Conversely, the IR of the prewetted grumusol decreased markedly during the rain and reached low IR levels (<8 mm h^{-1}) after 60 mm of rain. The IR curves for the prewetted grumusol for both aging durations were similar but higher than the IR curve obtained for the dry soil (Fig. 1). Similar results were observed for the loess (data not presented).

The Israeli soils and the Solano soil had similar texture and low ESP values (<5%), and were subjected to DW simulated rain of similar characteristics. Nevertheless, the susceptibility of the

Israeli soils to sealing differed from that of the Solano. It was assumed, therefore, that the observed differences in the IR curves of the soils resulted from differences in the stability of the surface aggregates of the soils, and their resistance to disintegration by the kinetic energy of the raindrops. The surface aggregates of the Solano soil did not break when exposed to the impact of the raindrops, and thus seal formation and low IR were prevented. The Solano aggregates remained stable owing to the prolonged and slow prewetting procedure used. Conversely, the surface aggregates in the grumusol were susceptible to the impact energy of the raindrops and to seal formation (a sharp decrease in the IR). The rapid prewetting of the surface aggregates of the grumusol led to aggregates slaking and seal formation. Leaving the prewetted soil to age for 18 h resulted in an IR curve similar to that of the sample that was left to age for only 15 min. Shainberg et al (1995) reported that during 24 h of aging, cohesive forces developed in the aggregates of a grumusol (similar to the one used in the current study), which significantly increased their resistance to detachment by rill flow. In the current study, the similarity in the IR curves for the two different aging periods indicated that the cohesive forces which developed during the 18 h of aging in aggregates that were slaked by fast prewetting, were not strong enough to overcome the impact energy of the raindrops whose energy was two orders of magnitude higher than that applied by the shearing force of water in rill flow. Comparison of the two IR curves of the prewetted grumusol and the IR curve for the Solano soil suggested that rate of aggregate prewetting carried a more important weight than aging in determining aggregate stability

and the resultant soil susceptibility to seal formation and decreased IR.

Comparison of the IR curves of the prewetted grumusol samples with the dry soil showed that the IRs at the end of the 60 mm rain did not differ significantly, but percent runoff was significantly lower in the prewetting treatments than in the dry soil (Table 2). Hence, percent runoff is a better indicator than IR for the process involved in seal formation. We assume that prewetting at a matric potential of -0.2 kPa is slower than wetting with 30 mm h^{-1} rain. The significant difference in runoff percentage between the prewetted samples and the dry soil thus amplified the devastating effect that fast wetting of the surface aggregates (by raindrops at a rate of 30 mm h^{-1}) had on aggregates stability and on the resultant soil susceptibility to seal formation.

The effect of prewetting the grumusol samples with 5 mm of rain at three different rates (1, 6 and 30 mm h^{-1}) is depicted in Figure 2. The IR curves for the three prewetting rates with 15 min of aging differed distinctly. Upon increasing the wetting rate from 1 mm h^{-1} to 6 and to 30 mm h^{-1}, depth of rain to ponding (which is a measure of the rate of seal formation) decreased from 43 mm to 29 and to 4 mm, respectively (Fig. 2). Furthermore, significant differences were observed in the IR at the end of the 60-mm rain and percent runoff among the three prewetting rate treatments (Table 3). Slow prewetting of the surface aggregates prevented their slaking by compressed entrapped air, and thus made them significantly more resistant to raindrop impact. Consequently, seal formation was prevented, and a high IR and low level of runoff were maintained.

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The effect of 18 h of aging on the IR curves of the prewetted samples depended on the rate of prewetting (Fig. 2). For fast prewetting (30 mm h^{-1}), 15 min and 18 h of aging resulted in similar IR curves. These curves were also similar to the IR curves obtained for the grumusol prewetted by a water table at a depth of 20 mm (Fig. 1). For prewetting at 6 mm h^{-1}, the IR curves differed for the two aging periods, and the percent runoff and IR after the 60-mm rain differed significantly for the two aging treatments (Table 3). The effect of aging duration on the IR curves for the slow prewetting (1 mm h^{-1}) cannot be discussed quantitatively, because the entire IR curve for the 18 h aging treatment was controlled by the rain intensity applied (33 mm h^{-1}), indicating that the final IR of the soil was greater than 33 mm h^{-1} (Fig. 2). These results suggested, however, that 18 h aging was effective in the slow prewetting treatment. The observed dependence of IR on aging and on the rate of prewetting suggested that 18 h of aging in the grumusol prewetted at 6 mm h^{-1} was not enough for the development of inter- and intra-particle cohesive forces that could re-form stable aggregates which, in turn, could resist disintegration when exposed to raindrops. The fact that aging was effective at the 6 mm h^{-1} prewetting rate and not at the 30 mm h^{-1}, suggests that the favorable role of the cohesive forces development in improving aggregate stability was effective only when a partial degree of slaking of the aggregates by the prewetting process took place.

The IR curve for the grumusol prewetted at 1 mm h^{-1} and aged for 15 min was similar in nature to that obtained by Le Bissonnais and Singer (1992, Fig. 2) for the Solano soil (Fig. 1). This similarity,

as well as the interaction between aging and rate of prewetting, supports the previously drawn conclusion that the rate of surface aggregate prewetting predominates in determining aggregate slaking and subsequent soil susceptibility to sealing and low IR, while aging plays a supportive secondary role.

The effect of prewetting the loess samples with 5 mm of rain at the three prewetting rates is shown in Figure 3. Prewetting at 1 mm h^{-1} prevented slaking of the loess aggregates and the subsequent formation of the seal (Fig. 3). No effect of aging could be noticed, because the IR of the loess exceeded the rain intensity. The IR curves for the fast and intermediate prewetting rates at the two aging periods were similar, and differed significantly from the slow prewetting IR curve. Aging for 18 h had some beneficial effect on increasing the FIR in the fast wetting treatment and on decreasing runoff in both the fast and the intermediate wetting treatments (Table 3). In the slow prewetting, no decrease in IR and hence no runoff was observed during the entire rain event in either aging treatment (Fig. 3 and Table 3). The similarity in the effects of fast and intermediate wetting on the infiltration parameters in the loess compared with their differing effects in the grumusol (Fig. 2), suggested that the loess aggregates were more sensitive than the grumusol to the prewetting rate. This greater sensitivity of loess aggregates to prewetting rates could also explain their previously reported greater susceptibility to seal formation (e.g. Levin et al., 1991), which had been ascribed to the higher silt-to-clay ratio in the loess compared with the grumusol (Table 1).

Soil erosion

Total soil losses from each rain event from the grumusol and the loess for the various prewetting and aging treatments are presented in Figure 4. For both soils, the slower the prewetting rate, the lower the amount of soil eroded. At the slow prewetting rate the amounts of soil loss were marginal (<12 g m^{-2}) because there was hardly any runoff in either soil and either aging period (Table 3). Increasing aging duration had a significant effect on reducing soil loss at the fast and intermediate wetting rates.

The ratio of runoff data obtained from the intermediate prewetting to those obtained from the fast rate, was compared with the same ratio for the soil erosion data. Similarly, the ratio of the runoff data obtained from the long aging to those obtained from the short aging, were compared with the same ratio for the soil erosion data (Table 4). These comparisons indicate that, in general, soil erosion was more affected by the prewetting and aging treatments than was runoff. The current study measured interrill erosion, which involves soil detachment by raindrop impact and runoff shear, and transport of the detached material by raindrop splash and flowing runoff (e.g. Bradford et al., 1987). Although not measured in our study, it has been shown that greater size of detached particles is also partially responsible for smaller wash losses from slowly prewetted soil (Le Bissonnais, 1990). It is therefore postulated that with slower prewetting rate and/or a longer aging period, larger particles were detached from the surface aggregates. These particles tended to settle out of the runoff water and thus result in low sediment losses. It is further suggested that the lower levels of

runoff associated with slower prewetting and/or longer aging had smaller shear forces which also enhanced settling out of particles from the runoff water. Subsequently, soil loss decreased to a greater extent than that to be expected based on the decrease in runoff volume.

Summary and Conclusions

Seal formation, runoff and erosion are often considered to depend on basic soil properties such as soil texture, clay mineralogy, composition of exchangeable cations (e.g. ESP), organic matter and sesquioxides content, etc. In this study it was demonstrated that seal formation, runoff and erosion depended also on time-dependent parameters, namely, rate of soil prewetting and duration of aging. Wetting rate of aggregates determines their slaking (i.e., breakdown as a result of the compressed entrapped air), and indeed slow prewetting of soils reduced aggregate slaking and the soils became less susceptible to seal formation and erosion. Aging increases the cohesive forces between soil particles, and hence decreases their tendency to seal and erode. However, the favorable role of cohesive forces in improving aggregate stability became ineffective once extensive slaking of the aggregates took place. Prewetting the soil with water table 20 mm below the soil surface was found to produce fast prewetting. This prewetting slakes soil aggregates as does rain on dry soils. These observations explain why, in many rainfall simulation studies, there was no effect to prewetting on seal formation and soil erosion.

Acknowledgments

This study was supported by grant No. C11-255, U.S.-Israel Cooperative Development Research Program, Office of the Science Advisor, U.S. Agency for International Development (AID). This support is gratefully acknowledged.

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Table 1: Some physical and chemical properties of the soils used.

Soil	Classification	ESP[1]	Particle size distribution			CEC[2]	OM[2]	$CaCO_3$
			sand	silt	clay			
		%	----------	g kg^{-1}	--------	$cmol_c$ kg^{-1}	g kg^{-1}	g kg^{-1}
Grumusol	Typic Chromoxerert	1.7	310	225	465	38.7	20.7	151
Loess	Calcic Haploxeralf	3.1	500	310	190	17.5	14.9	182

[1] ESP = Exchangeable sodium percentage.

[2] CEC = Cation exchange capacity.

[3] OM = Organic matter content.

Table 2: Mean final measured infiltration rates (FIR) after 60 mm of rain and calculated percent runoff for prewetting by matric gradient and for various aging durations.

Soil	Prewetting[1] mm	Aging	FIR mm h^{-1}	Runoff %
Grumusol	none	none	4.1 a[2]	31.2 a
	20	15 min	6.8 a	52.7 b
	20	18 h	6.2 a	49.3 b
Solano[3]	100	-	35.0	92.5

1 Depth to water table. The values of 20 and 100 mm depth to water table correspond to matric potentials of 0.2 and 1.0 kPa.

2 Within a column, numbers followed by the same letter do not differ significantly P = 0.05.

3 Data from Le Bissonnais and Singer (1992).

Table 3: Mean final measured infiltration rates (FIR) ~~at the end of~~ 60 mm of rain ~~(FIR)~~ and calculated percent runoff for 5 mm of prewetting by rain and for various aging durations.

Soil	Prewetting rate	Aging	FIR		Runoff	
	mm h^{-1}		mm h^{-1}		%	
Grumusol	1	15 min	26.6	b[1]	2.5	d
	1	18 h	33.0	a	0.0	d
	6	15 min	13.6	d	19.2	b
	6	18 h	23.4	c	4.1	c
	30	15 min	5.0	e	59.1	a
	30	18 h	3.9	e	57.4	a
Loess	1	15 min	33.0	a	0.0	a
	1	18 h	33.0	a	0.0	a
	6	15 min	6.5	b	43.2	c
	6	18 h	7.9	b	36.7	b
	30	15 min	4.2	c	49.4	c
	30	18 h	6.9	b	34.5	b

Within a column and a soil, numbers followed by the same letter do not differ significantly at ~~the~~ $P = 0.05$ ~~level~~.

Table 4: Ratio~~s~~ of runoff and soil erosion data obtained from the ~~medium~~ intermediate prewetting rate, to those obtained from the fast wetting, ~~respectively,~~ and ratio~~s~~ of runoff and soil erosion data obtained from the long aging ~~duration~~ to those obtained ~~at~~ from the short aging duration, ~~respectively,~~ for the two soils studied.

Soil	Prewetting rate	Aging	Ratio studied[a]	Runoff	Soil loss
Grumusol	6 mm h^{-1}		L/S	0.21	0.68
	30 mm h^{-1}		L/S	1.0	0.44
		15 min	I ~~M~~/F	0.32	0.27
		18 h	I ~~M~~/F	0.07	0.42
Loess	6 mm h^{-1}		L/S	0.85	0.23
	30 mm h^{-1}		L/S	0.70	0.21
		15 min	I ~~M~~/F	1.0	0.63
		18 h	I ~~M~~/F	1.0	0.69

[a]L=long aging duration, 18 h; S=short aging duration, 15 min; ~~M=medium~~ I=intermediate prewetting rate, 6 mm h^{-1}; F=fast prewetting rate, 30 mm h^{-1}.

Figure legends

Fig. 1: Effects of prewetting with a water table 20 mm below the soil surface and of aging, on the infiltration rate of the grumusol.

Fig. 2: Effects of rate of prewetting by rain (slow= 1 mm h^{-1}, intermediate medium= 6 mm h^{-1}, fast = 30 mm h^{-1}), and of aging, (the infiltration rate of the grumusol.

Fig. 3: Effects of rate of prewetting by rain (slow= 1 mm h^{-1}, intermediate = 6 mm h^{-1}, fast = 30 mm h^{-1}), and of aging, on tl infiltration rate of the loess.

Fig. 4: Effects of rate of prewetting by rain and of aging on soil loss from the grumusol and loess.

Figure legends

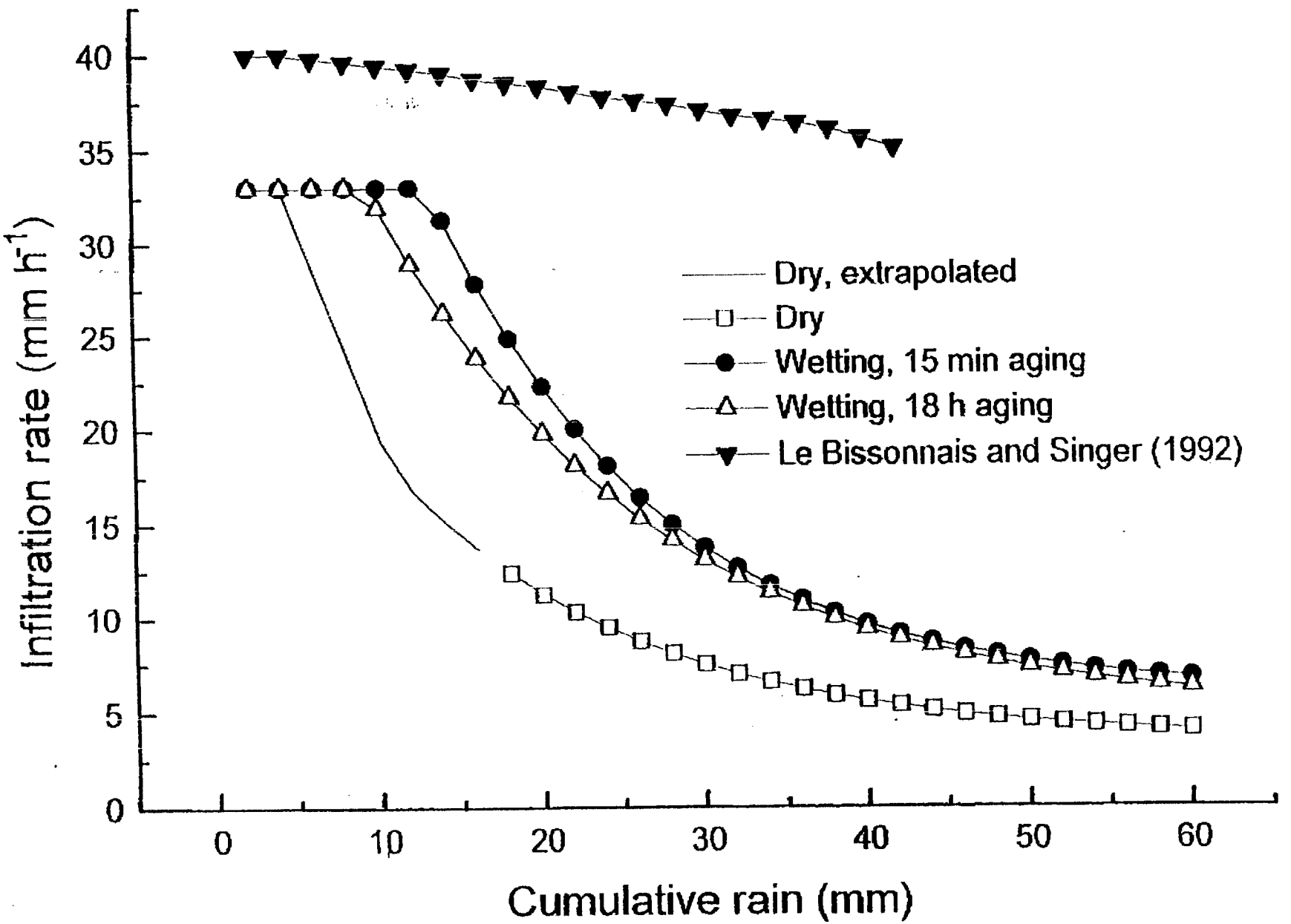
Fig. 1: Effect of prewetting with a water table 20 mm below the soil surfa and of aging on the infiltration rate of the grumusol.

Fig. 2: Effect of rate of prewetting by rain (slow= 1 mm h^{-1}, medium= 6 mm h^{-1}, high= 30 mm h^{-1}) and of aging on the infiltration rate of the grumusol.

Fig. 3: Effect of rate of prewetting by rain (slow= 1 mm h^{-1}, medium= 6 mm h^{-1}, high= 30 mm h^{-1})and of aging on the infiltration rate of the loess.

Fig. 4: Effect of rate of prewetting by rain and of aging on soil loss from the grumusol and loess.

Fig. 1


Infiltration rate (mm h-1)
Cumulative rain (mm)
0
5
10
15
20
25
30
35
40
0
10
20
30
40
50
60
Dry, extrapolated
Dry
Wetting, 15 min aging
Wetting, 18 h aging
Le Bissonnais and Singer (1992)

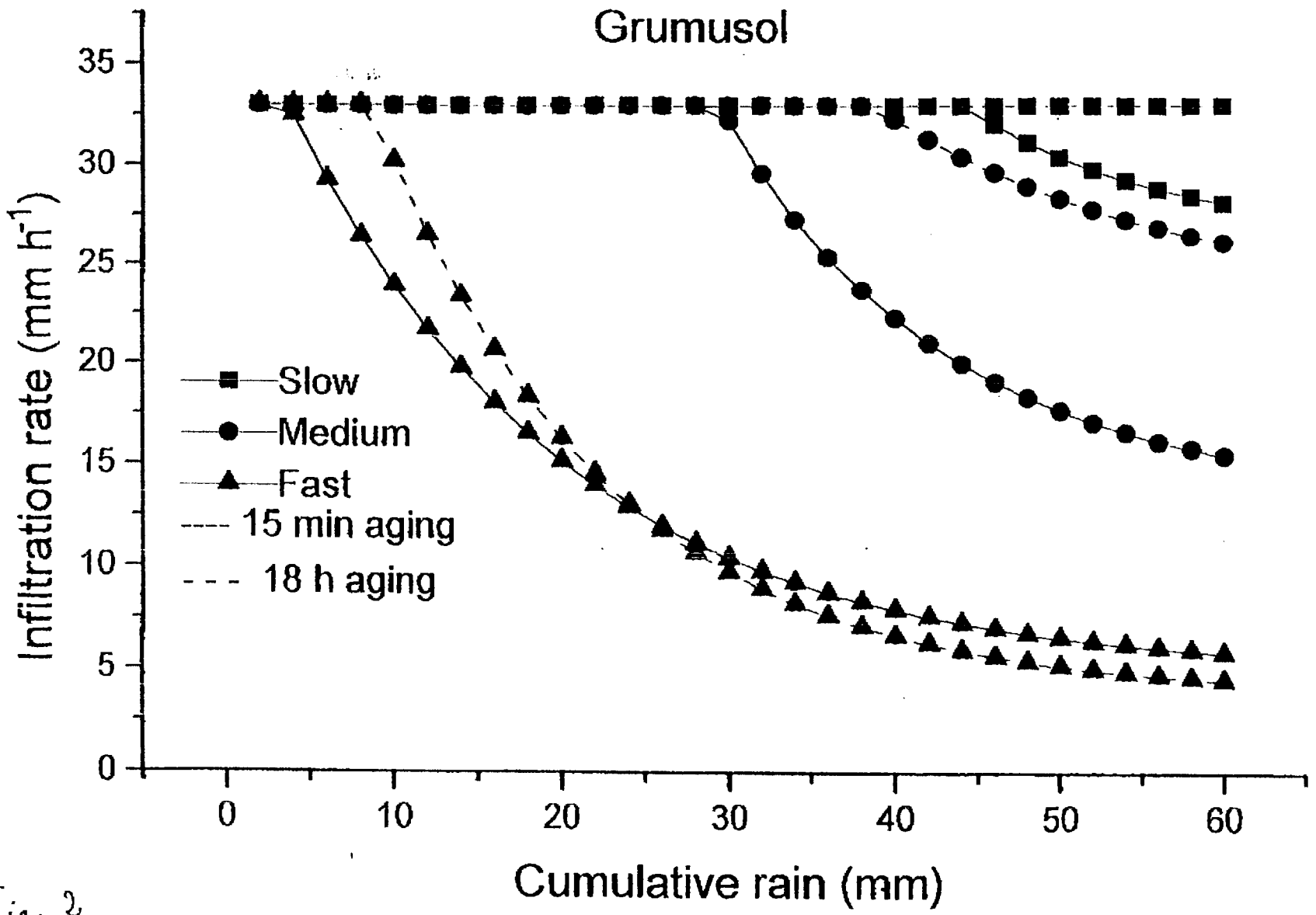
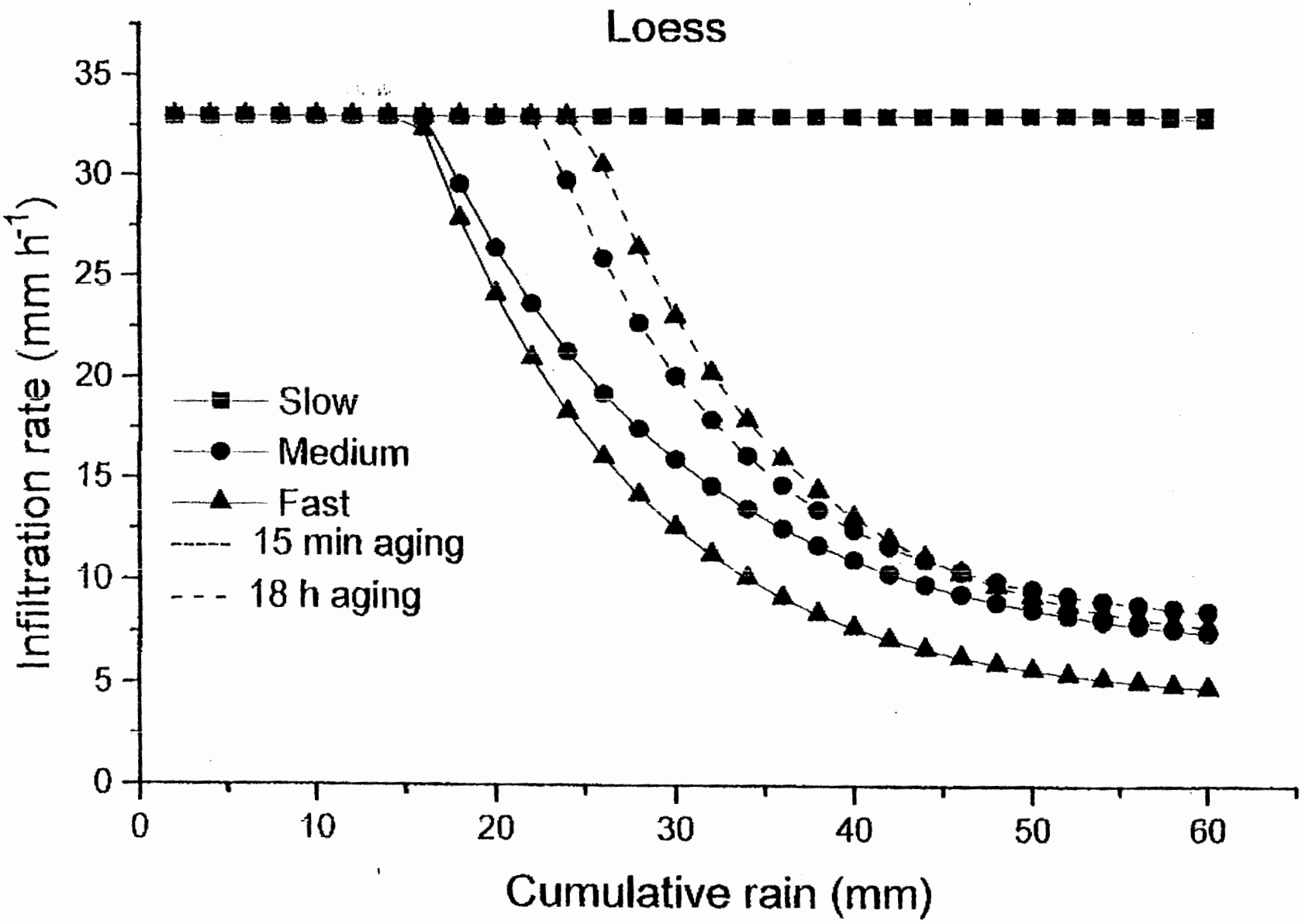

Grumusol
Infiltration rate (mm h-1)
Cumulative rain (mm)
Slow
Medium
Fast
15 min aging
18 h aging
0
5
10
15
20
25
30
35
0
10
20
30
40
50
60

Fig. 2


Loess
Infiltration rate (mm h-1)
Cumulative rain (mm)
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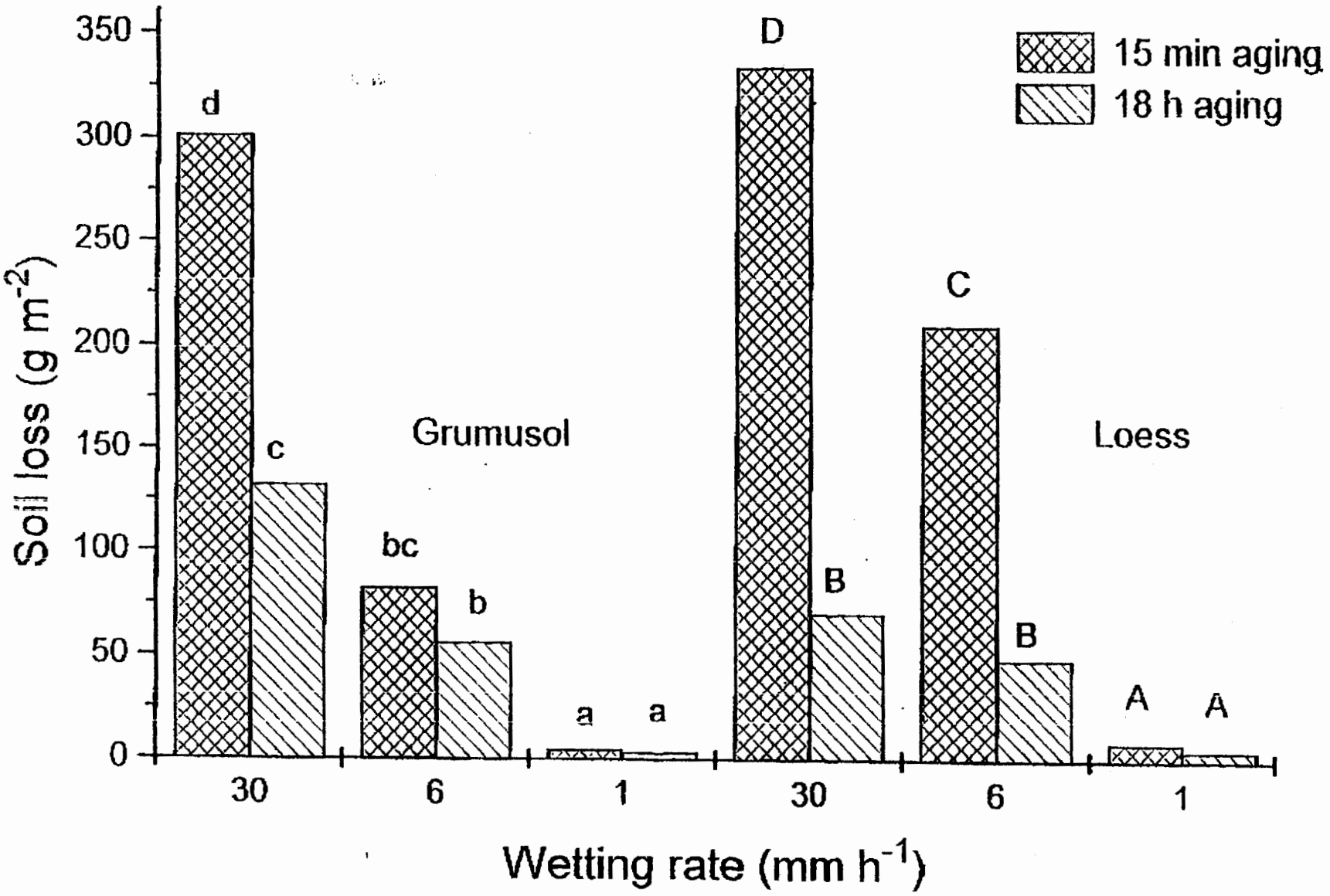
5
10
15
20
25
30
35
0
10
20
30
40
50
60
Slow
Medium
Fast
15 min aging
18 h aging

Fig. 3


Soil loss (g m-2)
350
300
250
200
150
100
50
0
d
c
bc
b
a
a
D
B
C
B
A
A
Grumusol
Loess
15 min aging
18 h aging
30
6
1
30
6
1
Wetting rate (mm h-1)

15/6/95
Paper No. 5

AGGREGATE SIZE AND SEAL PROPERTIES

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AGGREGATE SIZE AND SEAL PROPERTIES

Abstract

The formation of a disrupted layer and a seal at soil surfaces exposed to the impact of raindrops is a common feature of many cultivated soils. A distinction was made in this study between a disrupted layer and a seal. The effect of aggregate size on seal permeability, the thickness of the disrupted layer, and on aggregate stability in two soils exposed to simulated rain was studied. Aggregates with sizes of <4, 2-4, 4-9.5 and 9.5-12.0 from a Typic Chromoxerert and a Calcic Haploxeralf were used for the study. Seal formation was determined in samples exposed to distilled water (DW) rain with a kinetic energy of 12.4 J mm^{-1} m^{-2}. The thickness of the disrupted layer was estimated from petrographic microscope observations of air-dried samples exposed to rain. Aggregate stability was determined by bombarding 3-7 g of dried aggregates, placed on a sieve with a size opening of 0.3 or 0.8 mm, with drops of 3.1 J mm^{-1} m^{-2} kinetic energy. Aggregate stability, the thickness of the disrupted layer and cumulative infiltration increased with aggregate size. These observations suggest that the rate of seal formation increased with a decrease in aggregate size. Conversely, the final infiltration rate (IR) of the fully developed seal in both soils was low (<4 mm h^{-1}) and was not affected by aggregate size. The results indicate that in soils exposed to rain aggregate disintegration is the first process in seal formation and clay dispersion determine seal permeability. The permeability of the

seal rather than that of the disrupted layer determines the equilibrium IR of the soil.

Abbreviations: CEC, cation exchange capacity; CI, cumulative infiltration; DW, distilled water; ESP, exchangeable sodium percentage; EPP, exchangeable potassium percentage; IR infiltration rate; FIR, final infiltration rate.

Introduction

The formation of a disrupted layer and/or a seal at soil surfaces exposed to the impact of raindrops or sprinkler irrigation, is a common feature of many cultivated soils, worldwide. However, a distinction should be made between a disrupted layer and a seal. A disrupted layer is formed by aggregate slaking and disrupted aggregates rearrangement into a compacted layer formed by the impact action of the water drops (Farres, 1978; Chiang et al., 1994). This mechanism is physical in nature and is determined by the kinetic energy of the drops and the stability of the aggregates (Moldenhauer and Kemper, 1969). By contrast, seal formation depends on an additional mechanism which is the physico-chemical dispersion of the soil clays which then migrate into the soil with the infiltrating water, clog pores immediately beneath the surface and form a layer of very low permeability termed the "washed in" zone (McIntyre, 1958; Agassi et al., 1981; Gal et al., 1984; Onofiok and Singer, 1984). The "washed in" layer was formed only in easily-dispersed soils (McIntyre, 1958). The physicochemical mechanism may operate only in soils where breakdown of aggregates took place and a disrupted layer was formed. The clay dispersion mechanism is controlled mainly by the concentration and composition of the cations in the soil and applied water (Agassi et al., 1981).

Aggregate breakdown and physicochemical dispersion of clay particles are two consecutive mechanisms in seal formation (McIntyre, 1958; Agassi et al., 1981). Aggregate breakdown and

sealing were both related to the cumulative effect of drop energy (Morin and Benyamini, 1977). However, aggregate breakdown occurs much faster than seal formation (Shainberg et al., 1992). Shainberg et al., 1992, found that only 9 mm of 3.6 J mm^{-1} m^{-2} rain (= cumulative energy of 32.4 J m^{-2}) were needed to disintegrate the aggregates, compared with > 40 mm of the same rain (cumulative energy of > 144 J m^{-2}) needed for seal formation. It should be noted also that no relationship was found between aggregate stability and infiltration parameters related to seal formation (Roth and Eggert, 1994). Only when the size distribution of particles produced by aggregate breakdown was considered, the variations in sealing susceptibility between soils was explained. Soils in which aggregate breakdown produced fine particles were susceptible to seal formation (Roth and Eggert, 1994).

The role of time and aggregate size in the sealing processes was studied by Farres (1978). Areal observations showed that seal formation was a rapid event with respect to time. A similar conclusion was arrived at from studying the vertical development of the seal. Within < 10 mm of rain the equilibrium depth of seal was obtained. The thickness of the seal depended on aggregate size. With increase in mean aggregate diameter form 1.68 mm to 6.73 mm, the mean equilibrium seal thickness increased from 1.4 to 3.08 mm, respectively (Farres, 1978).

The infiltration of simulated rain as a function of aggregate size was studied by Freebairn et al., 1991 and Unger and Jones, 1994. Both groups of scientists found that the equilibrium in IR was independent of aggregate size. Conversely,

the cumulative infiltration increased with an increase in aggregate size for aggregates in the range of up to 50 mm diameter. Both groups concluded that the development of a soil seal was delayed when the surface was made of big aggregates but the final IR was not affected significantly by aggregate size.

Hillel and Gardner (1969) showed that the IR through a sealed soil decreased with increasing hydraulic resistance of the seal. The hydraulic resistance of the seal is directly proportional to the thickness of the seal. Consequently, and based on Farres (1978) studies, one would expect that equilibrium IR would decrease with seal thickness and hence, with aggregate size. However, Freebairn et al., 1991 and Unger and Jones, 1994, demonstrated that the IR was independent of aggregate size.

The objective of this study was to clarify the relation between aggregate size and aggregate stability and seal properties, namely permeability and thickness by studying these parameters on the same soils exposed to the same simulated rain.

Materials and Methods

Samples from 0-250 mm depth of a typic loess (Calcic Haploxeralf) from the northern Negev, and a dark brown grumusol (typic Chromoxerert) from the Pleshet plains, Israel were brought to the laboratory, sieved into aggregate sizes of 2-4 mm (or < 4 mm), 4-9.5 and 9.5-12.0 mm, and analyzed. Some physical and chemical properties of the soils and the three aggregate sizes are given in Table 1.

Infiltration Studies

Infiltration and runoff were studied using a drip-type rainfall simulator. The simulator consisted of a 750 x 600 x 80 mm closed water chamber which generated rainfall of a known constant drop size by means of a set of hypodermic needles (approximately 1000) arranged at 20 x 20 mm spacing. The average droplet diameter was 2.97±0.05 mm. A drop fall of 1.6 m was used to obtain drops with an impact velocity of 4.98 m s^{-1} and a kinetic energy of 12.4 J mm^{-1} m^{-2} (Epema and Riezebos, 1983). Application intensity was maintained at 33 mm h^{-1} using a peristaltic pump.

Air-dried aggregates of the three size ranges were packed into 200 x 400 mm pans, 20 mm deep, over a 5 mm thick layer of coarse sand. The soil samples in the pans were prewetted with distilled water (DW) rain. After completion of the prewetting, the soil was allowed to reach equilibrium for 15 min, and then the soil was exposed to 70-100 mm of DW rain with intensity of 33 mm h^{-1}. During the rain, the volume of water percolating through the soil was collected and recorded as a function of time. Runoff water was collected continuously throughout the storm. Three replicates were performed concurrently for each treatment.

Following the rain, the soil samples in the pans were air-dried, and samples of the upper 20 mm of the sealed soil in the pans were taken. A petrographic microscope was used to semiquantitatively estimate the thickness of the disrupted layer The thickness of 15-20 samples of the sealed surfaces from each

of the aggregate size was determined and the average values are presented.

The infiltration data obtained from the rainfall simulator were analyzed using the non-linear equation proposed by Morin and Benyamini (1977). A nonlinear regression program calculated the parameters of the equation that gave the best coefficient of determination (R^2) between paired calculated and measured infiltration rate values. The total depth of runoff water from a single rain event was calculated using the instantaneous infiltration rate derived from Morin and Benyamini's (1977) equation. Calculated runoff values were preferred over measured values because of water splash from the soil boxes. The significance of differences among treatments for the infiltration and erosion parameters studied were determined using Tukey's procedure for a multiple range test.

Aggregate Stability Studies

Aggregate stability was studied using a miniature type of laboratory rainfall simulator. A 0.12-m (I.D.) plastic cylinder with hypodermic needles (similar to those used in the rain simulator) at the bottom, spaced 20 mm apart, served as the solution reservoir. Rain intensity of 60 mm h^{-1} was controlled by the height of a Mariotte bottle that supplied the solutions to the reservoir. Drop-fall heights were 0.4 m. The impact velocity and kinetic energy of the drops were 2.5 m s^{-1} and 3.1 J mm^{-1} m^{-2} (Epema and Riezebos, 1983), respectively, for the 0.4-m height. A rotating fan was placed in front of the simulator to ensure

that drops will hit the aggregates at random rather than fixed locations.

Approximately, 3, 5 and 7 g of dried soil aggregates with sizes between 2.0 and 4.0, 4.0 and 9.5 and 9.5 and 12.0 mm, respectively were placed over the sieve. Two sieves with size openings of 0.3 and 0.8 mm were used. The dry aggregates were then exposed to up to 30 min of distilled water (DW) rain of 60 mm h^{-1} intensity. Following the predetermined rain depth, the dry weight of the aggregates remaining on the sieve (herein referred to as stable aggregates) was determined, and their percent of the dry weight of the aggregates initially placed on the sieve was calculated. Each treatment was replicated three times.

Results and Discussion

Infiltration studies

The calculated infiltration curves for the two soils and the three aggregate sizes are presented in Figures 1 and 2. A coefficient of determination (R^2) between paired calculated and measured IR values was >95% in all the treatments.

Both soils were susceptible to seal formation and the final IR of the soils dropped to values < 4.0 mm h^{-1}. The soils were susceptible to sealing because of the low percentage of organic matter (< 15 g kg^{-1}), moderate values of exchangeable sodium percentage (ESP) (ESP values between 2.9 and 4.7 in the grumusol and ESP < 2.7 in the loess), and the smectitic mineralogy (Table 1 and Agassi et al., 1981; Kazman et al., 1983; Stern et al., 1991). Aggregate size had a small and insignificant effect on the

final IR of the two soils (Figures 1 and 2 and Table 2). Conversely, aggregate size had a significant effect on the depth of rain to ponding (i.e., the point where soil properties determine the IR, rather than rain intensity) and cumulative infiltration. The depth of rain to ponding, which is an indication of the rate of seal formation, and increased from 2 to 6 and to 22 mm for the grumusol; and from 0 to 18 and to 33 mm for the loess for aggregate sizes of <4, 4-9.5 and 9.5-12.5, respectively, for the grumusol. The effect of aggregate size was even more pronounced in the loess (Fig. 2). Similarly aggregate size had a significant effect on cumulative infiltration with an increase in aggregate size, there was also an increase in cumulative infiltration (Table 2). Both depth of rain to ponding and cumulative infiltration are measures of the rate of seal formation. Evidently, aggregate size has an effect on the rate of seal formation but not on the properties of the seal in its final stage. Breakdown of the big aggregates into small aggregates which are susceptible to the processes of seal formation, determines the rate of seal formation.

Seal thickness

The effect of aggregate size on seal thickness is presented in Table 3. Seal thickness increased with aggregate size from 1.5 mm for aggregates < 4 mm to 4.3 mm for aggregate size of 9.5 - 12.0 mm. Similar results were obtained by Farres (1978). The thickness of the seal as a function of aggregate size can be predicted from the model presented in Figure 3. Breaking down of big aggregates represented by spheres with diameter of D into

microaggregates which fill the big pores between the big aggregates results in a seal with thickness, d_l of

$$d = \frac{\pi}{6} D \qquad (1)$$

In the calculations it was assumed that bulk density of the seal is similar to the bulk density of the original aggregates. Our results (Table 3) and those of Farres (1978) agree with predictions of seal thickness based on the simple model presented in Fig. 3.

The IR data in Figures 1 and 2 and those reported by others (e.g. Freebairn et al., 1991; Unger and Jones, 1999) demonstrated that the final IR of the soils was not affected by seal thickness.

The IR of a sealed soil depend (Hillel and Gardner, 1969) on the hydraulic conductivity of the seal (K), the suction head at the interface between the seal and the underlaying of soil (h) and the thickness of the seal (d).

$$IR = K\ h/d \qquad (2)$$

If the IR of the seal is not affected by seal thickness, then Kh must increase with aggregate size in the same manner as seal thickness. The likelihood for the numerator in Eq. 2 to increase with aggregate size in the same rate as that of seal thickness, for different soils (e.g. our studies and those of Freebairn et al., 1991, and Unger and Jones, 1994) is slim. Also, it is not likely that the equilibrium hydraulic

conductivity of the seal will depend on the original size of the aggregates. At equilibrium, a disrupted layer made of broken aggregates is formed in all aggregate sizes. Thus, in Eq. 2 both K and h are not likely to depend on the original aggregate size, and the IR of the soil should decrease. However, our results indicated that the final IR were independent of aggregate size. Thus, our assumption that the thickness of the disrupted layer, as measured with an optical microscope, determines the final IR does not apply. It is more likely that the final IR of soils is determined by the thickness of the physico-chemical seal which consist of the "washed out" and "washed in" layers (McIntyre, 1958) as measured with SEM microscope. The properties of this seal which determine the final IR, depends on soil ESP and the electrolyte concentration of the soil solution and do not depend on aggregate size.

Aggregate stability

The effect of rain depth and aggregate size on the percentage of stable aggregates in the two soils over the two sieve openings are presented in Figures 4-7. The percent of stable aggregates decreased with an increase in rain depth (i.e. increase in cumulative energy). The rate of aggregate disintegration depended on aggregate size; small aggregates disintegrate faster than the bigger aggregates. Following 10 mm of rain, the percent of stable grumusol aggregates that remained on the 0.8 mm sieve were 10, 55 and 80 percent for aggregate sizes of 2-4, 4-9.5 and 9.5-12.5 mm, respectively, (Fig. 4). Similar results were obtained for the loess aggregates (Fig. 5).

Aggregate stability depended also on aggregate size and size of sieve openings (Figures 4-7). It took a greater rain depth to disintegrate the original aggregates into microaggregates (< 0.3 mm) than was needed for the breakdown into macroaggregates (< 0.8 mm). However, the difference was not significant (Figs. 4-7).

Aggregate stability varied for the two soils studied. Aggregates of the loess were less stable compared with aggregates of the grumusol. It took 20 mm of rain to disintegrate to equilibrium values aggregates of loess compared with 30 mm rain depth for the grumusol. The two soils varied in their clay content, 19% and 46.5% for the loess and grumusol, respectively. It seems that aggregate stability increases with clay content and that the clay acts as a cementing agent (Kemper and Koch, 1966).

The bombardment of the wet aggregates with water droplets of low energy caused aggregates to disintegrate. It is suggested that aggregates broke down despite the low energy water droplets used because they were wet. By wetting an aggregate, the hydration of exchangeable cations and clay surfaces, measured in KJ per gram of soil (Keren and Shainberg, 1975), weakens the bonds between soils' colloids. The forces bonding dry clay particles together in a dry aggregate are very strong and the mechanical energies of the drops are too small to disintegrate aggregates. Only when the aggregates were wetted by water, the binding forces within the aggregates are weak enough to be affected by the impact energies of the drops.

The fact that 10 mm of low energy rain is enough for aggregate disintegration should not come as a surprise if it is remembered that in the most common method for measuring aggregate

stability - the wet sieve method (Kemper and Koch, 1966) - the disintegration force exerted on the soil is the water flow shear which is an order of magnitude less than the force of drops' impact (Truman et al., 1990).

The depth of rain that was needed to form a seal on those soils was > 60 mm for all aggregate sizes (Figures 1 and 2). It is thus evident that aggregate disintegration proceeds at a rate faster than that of seal formation.

Similar observations were made by Farres (1978) and Hardy et al. (1983), who showed that short rainfalls (< 10 mm) were enough to break the structure of the soil surface and to maintain the equilibrium seal thickness. These observations suggested that breakdown of aggregates by the impact of raindrop and the formation of disrupted layers is a rapid process compared with the physico-chemical process of clay dispersion. Consequently, the latter controls the rate of seal formation and the final IR.

Summary and Conclusions

In the two soils studied (a clay and silt loam), aggregate size, in the range < 12.0 had an insignificant effect on the final IR. Final or steady-state IR were similar for both soils and all aggregates sizes. Conversely, in both soils, aggregate size had a marked influence on both aggregate stability and the equilibrium thickness of the disrupted layer at the soil surface exposed to rain. The thickness of the disrupted layer and aggregate stability increased as aggregate size increased.

The formation of a disrupted layer at the soil surface exposed to the impact of raindrops is attributed to aggregate

breakdown and is a rapid process. Former studies also have shown that both surface smoothness and the equilibrium thickness of the disrupted layer maintain the steady-state values in rain depth < 15 mm. Conversely, the IR of the soils exposed to rain reaches its steady-state values only at rain depth > 50 mm.

These observations suggest that seal formation is due to two complementary mechanisms: (i) a rapid process of surface aggregate disintegration by the impact of raindrops and the formation of a disrupted layer whose thickness is determined by aggregate size and (ii) a physico-chemical dispersion of the soil clays which then migrate and clog pores immediately beneath the surface and form a layer of very low permeability (the "washed in" zone). The second mechanism control the IR of dispersive soils.

Acknowledgment

This study was supported by Grant No. C11-255 U.S.-Israel Cooperative Development Research Program, Office of the Science Advisor, U.S. Agency for International Development (AID). This support is gratefully acknowledged.

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Table 1: Some physical and chemical properties of the soils used.

Soil	Classification	Particle size distribution Sand	Silt	Clay	$CaCO_3$	Aggregate size, mm	CEC[1]	ESP[2]	EPP[3]
		-----g kg^{-1}------							
Grumusol	Typic Chromoxerert	310	225	465	151	2-4	31.1	2.9	4.9
						4-9.5	30.7	3.6	4.7
						9.5-12.5	29.6	4.7	3.6
Loess	Calcic Haploxeralf	500	310	190	182	2-4	20.0	1.5	13.5
						4-9.5	21.1	2.7	8.7
						9.5-12.5	21.0	2.3	7.8

[1] CEC = Cation exchange capacity

[2] ESP = Exchangeable sodium percentage

[3] EPP = Exchangeable potassium percentage

Table 2: Effect of aggregate size on final infiltration rate (FIR), cumulative infiltration (CI) and seal thickness.

Aggregate Size mm	Grumusol				Loess			
	FIR mm h^{-1}	CI mm	Seal thickness mm	SD	FIR mm h^{-1}	CI mm	Seal thickness mm	SD
0 - 4	1.5	35.4	1.5	0.15	2.2	23.0	1.7	0.36
4 - 9.5	2.42	42.4	2.6	0.20	3.2	39.4	2.7	0.42
9.5 - 12.0	3.63	49.5	4.3	0.30	4.7	48.3	4.2	0.26

FIR = Final infiltration rte

TSL = Total soil loss

CI = Cumulative infiltration

Figure Legend

Fig. 1: Effect of aggregate size on the infiltration rate of the grumusol.

Fig. 2: Effect of aggregate size on the infiltrtion rate of theloess.

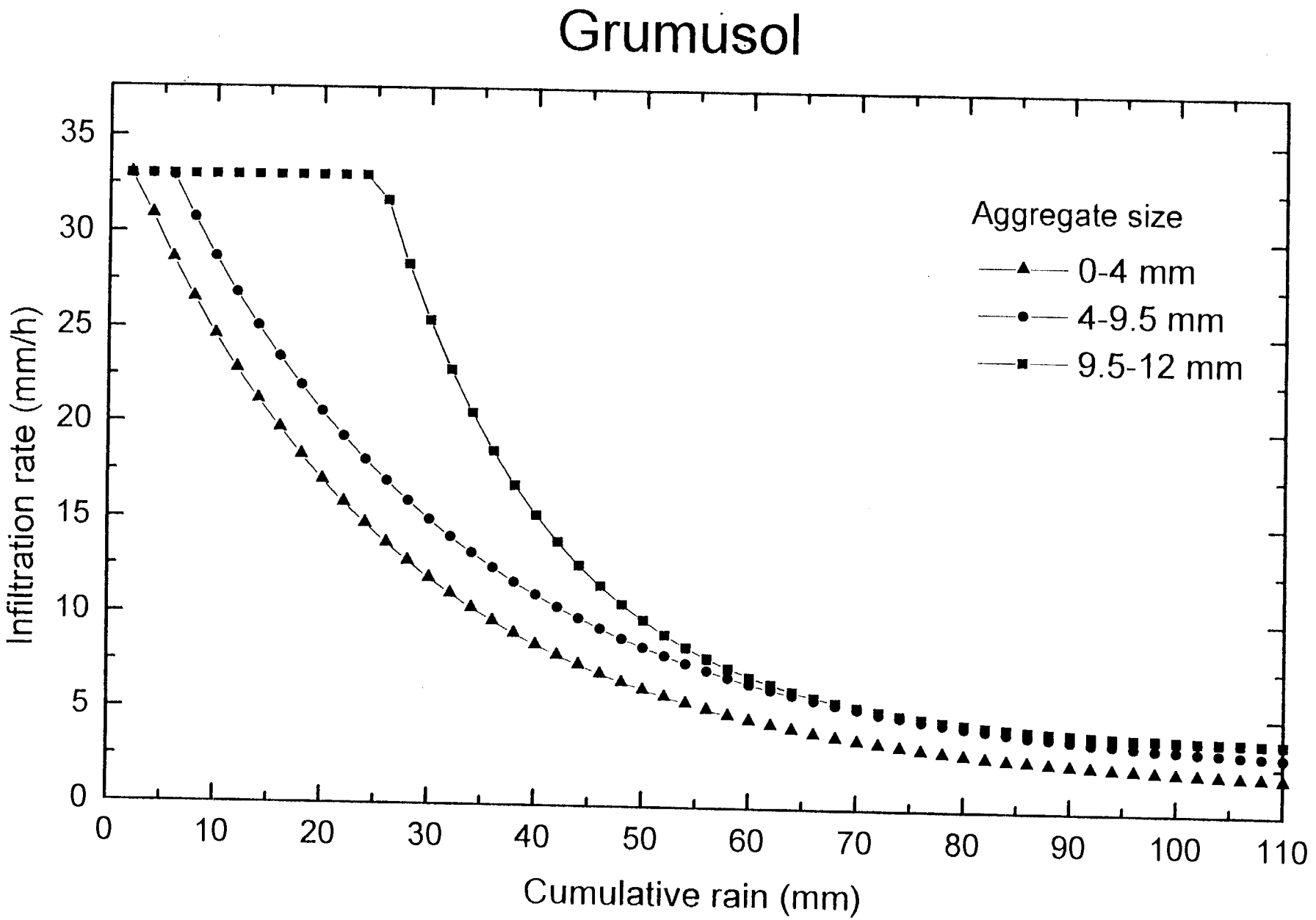
Fig. 3: A schematic preesentation of agggregate disintegrtion into a disrupted layer.

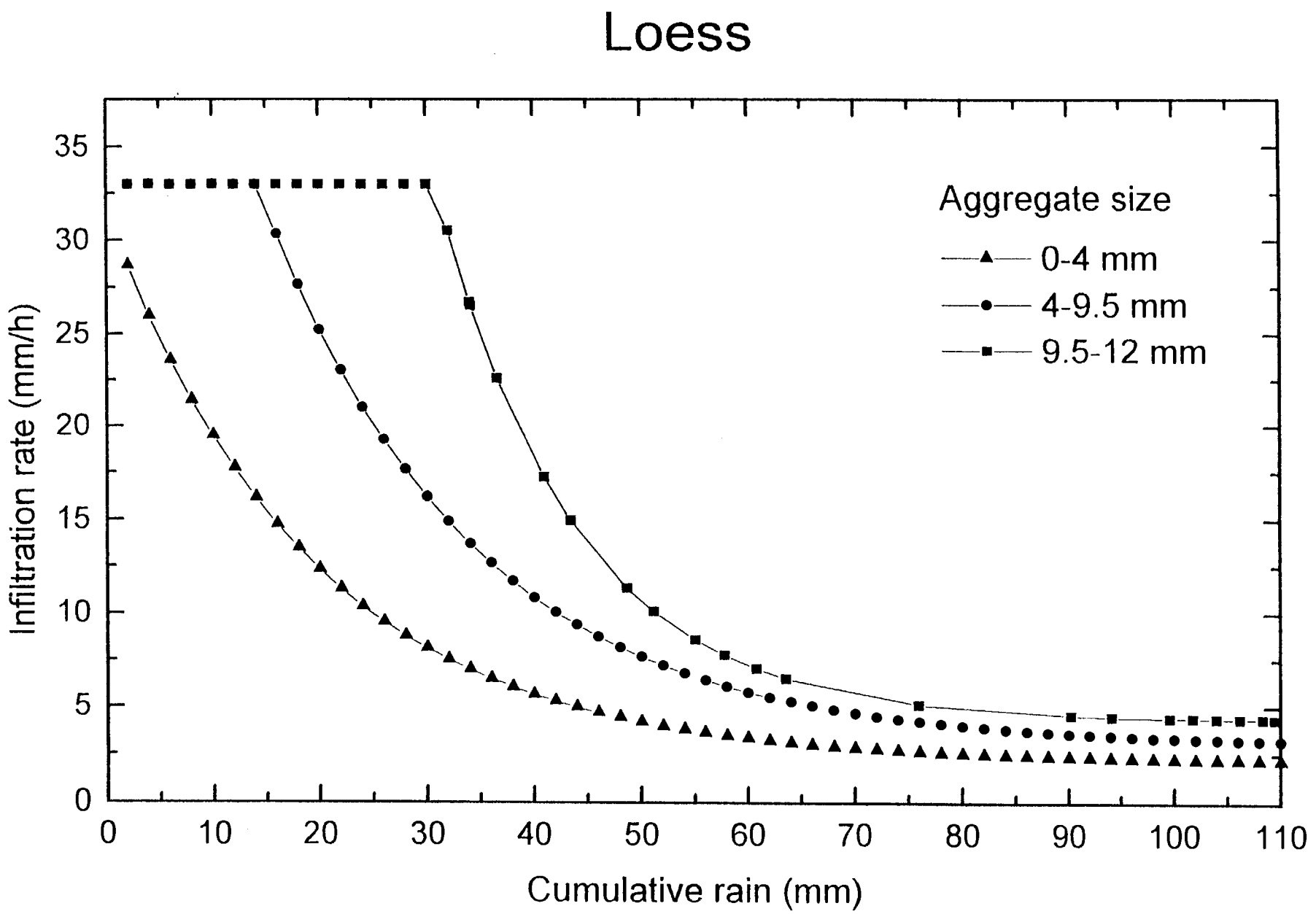
Fig. 4: Effect of aggregate size on percent stable aggregates in the grumusol using a sieve with 0.8 mm opening.

Fig. 5: Effect of aggregate size on percent stable aggregates in the loess using a sieve with 0.8 mm opening.

Fig. 6: Effect of aggregate size on percent stable aggregates in the grumusol using a sieve with 0.3 mm opening.

Fig. 7: Effect of aggregate size on percent stable aggregates in the loess using a sieve with 0.3 mm opening.

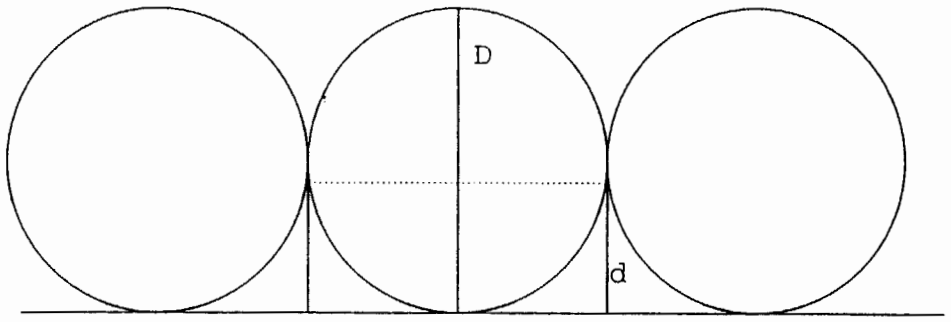

Grumusol
Aggregate size
0-4 mm
4-9.5 mm
9.5-12 mm
Infiltration rate (mm/h)
Cumulative rain (mm)
0
5
10
15
20
25
30
35
0
10
20
30
40
50
60
70
80
90
100
110


Loess
Aggregate size
0-4 mm
4-9.5 mm
9.5-12 mm
Infiltration rate (mm/h)
Cumulative rain (mm)
0
5
10
15
20
25
30
35
0
10
20
30
40
50
60
70
80
90
100
110

Thickness of disrupted layer (d)

$$V_A = \frac{1}{6}\pi D^3$$

$$V_d = D^2 d$$



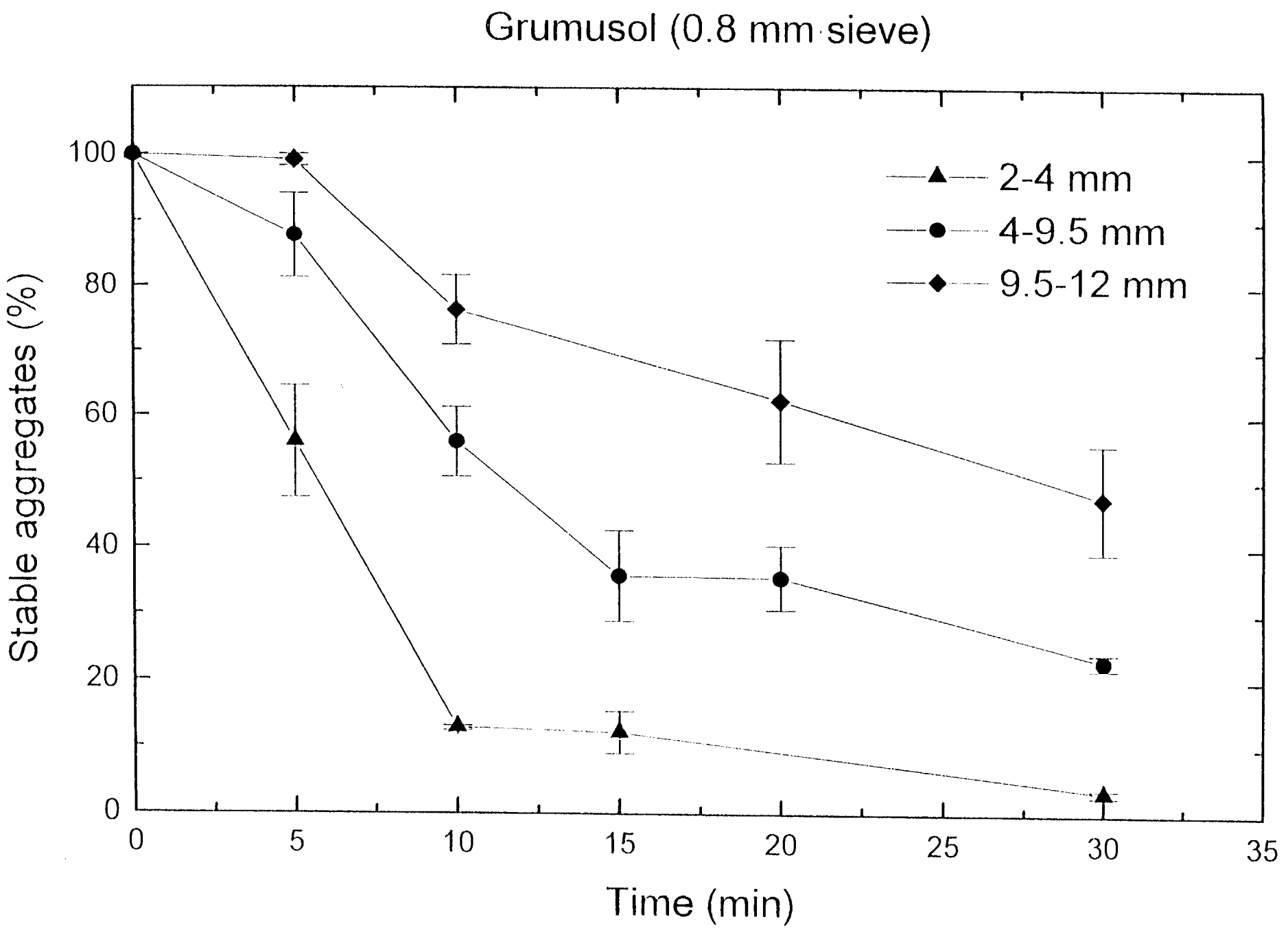
Assuming that bulk density of disrupted layer and original aggregates are similar

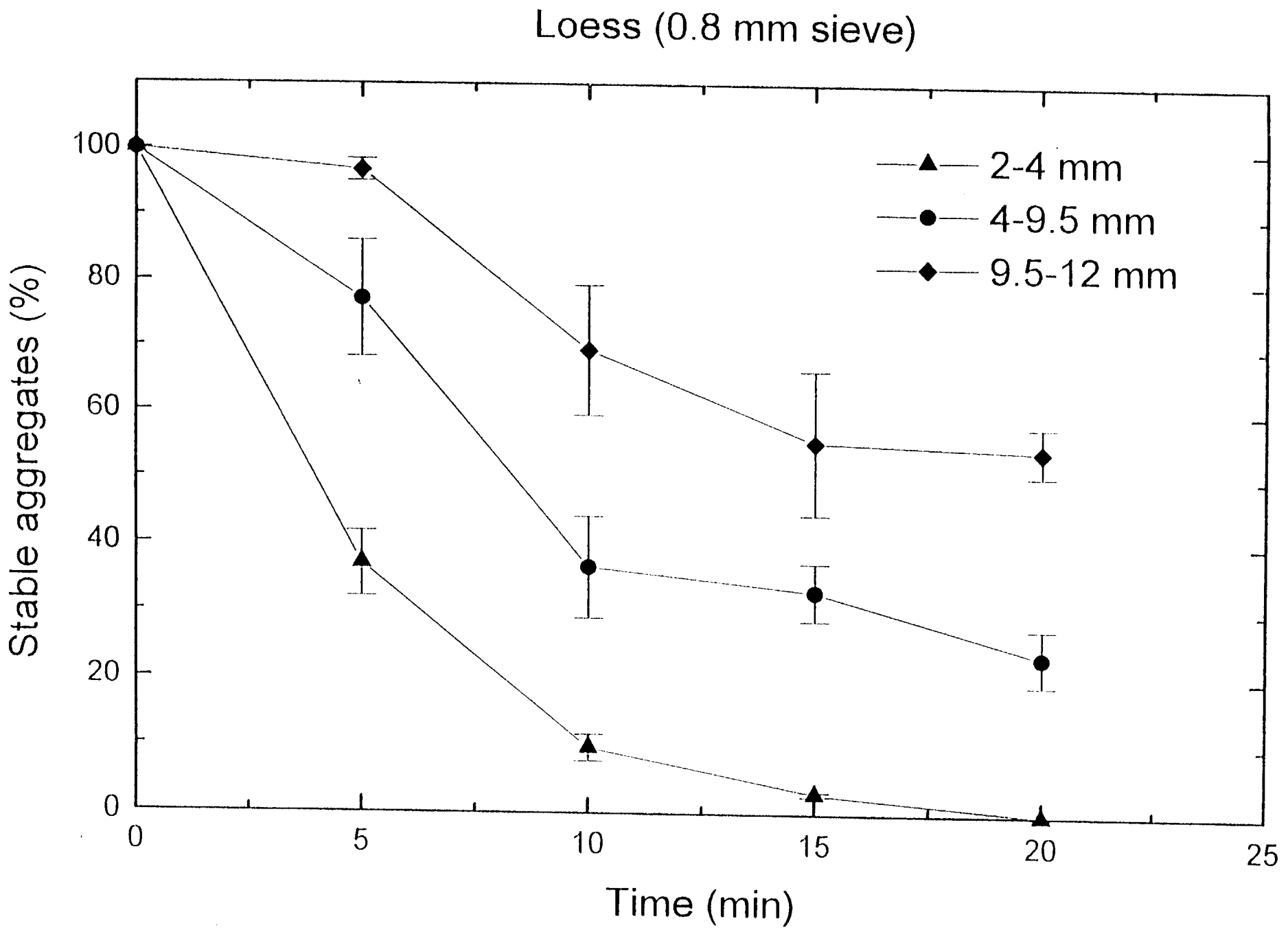
$$V_d = V_A$$

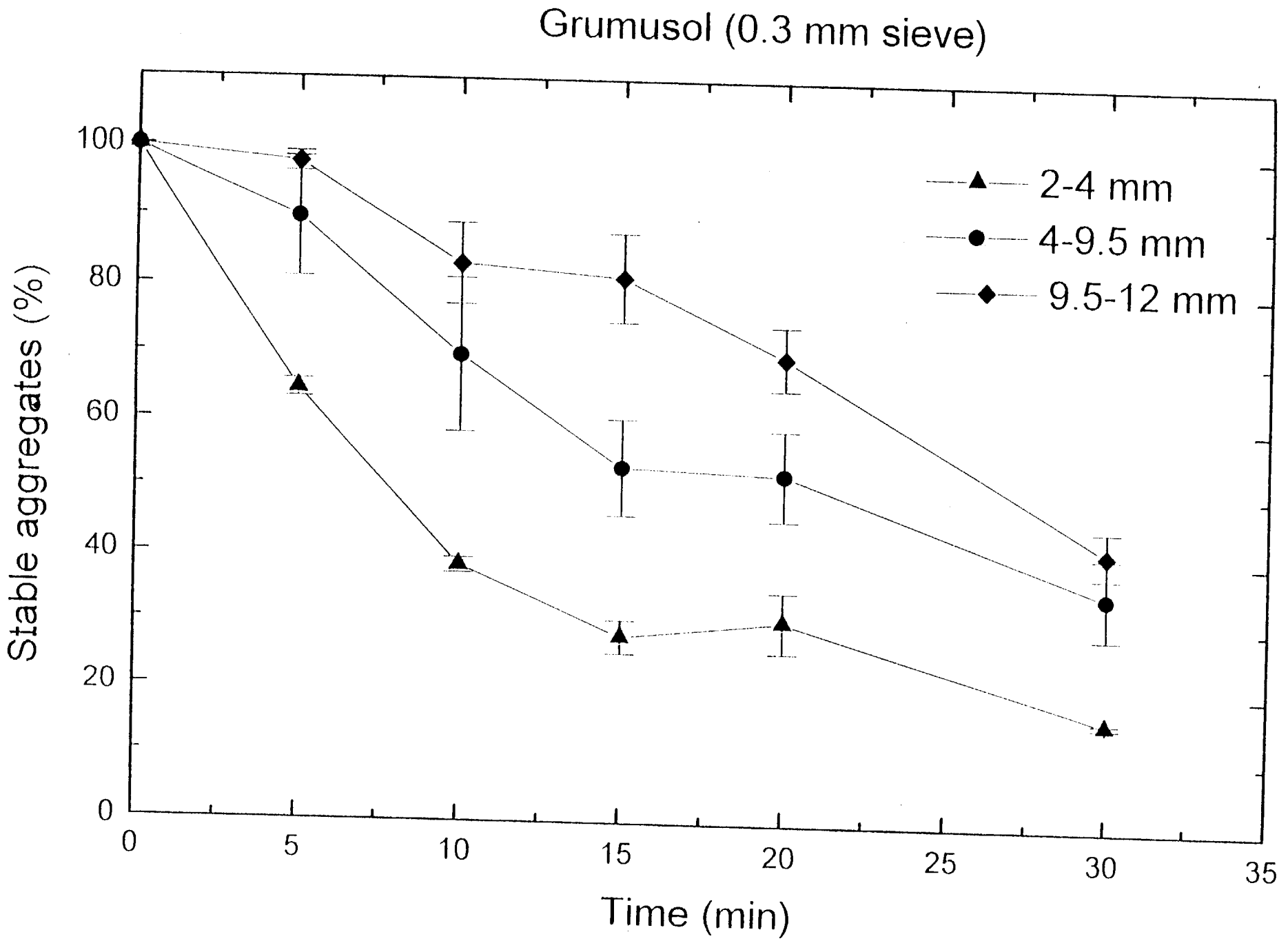
$$D^2 d = \frac{1}{6}\pi D^3$$

$$d = \frac{\pi}{6} D$$

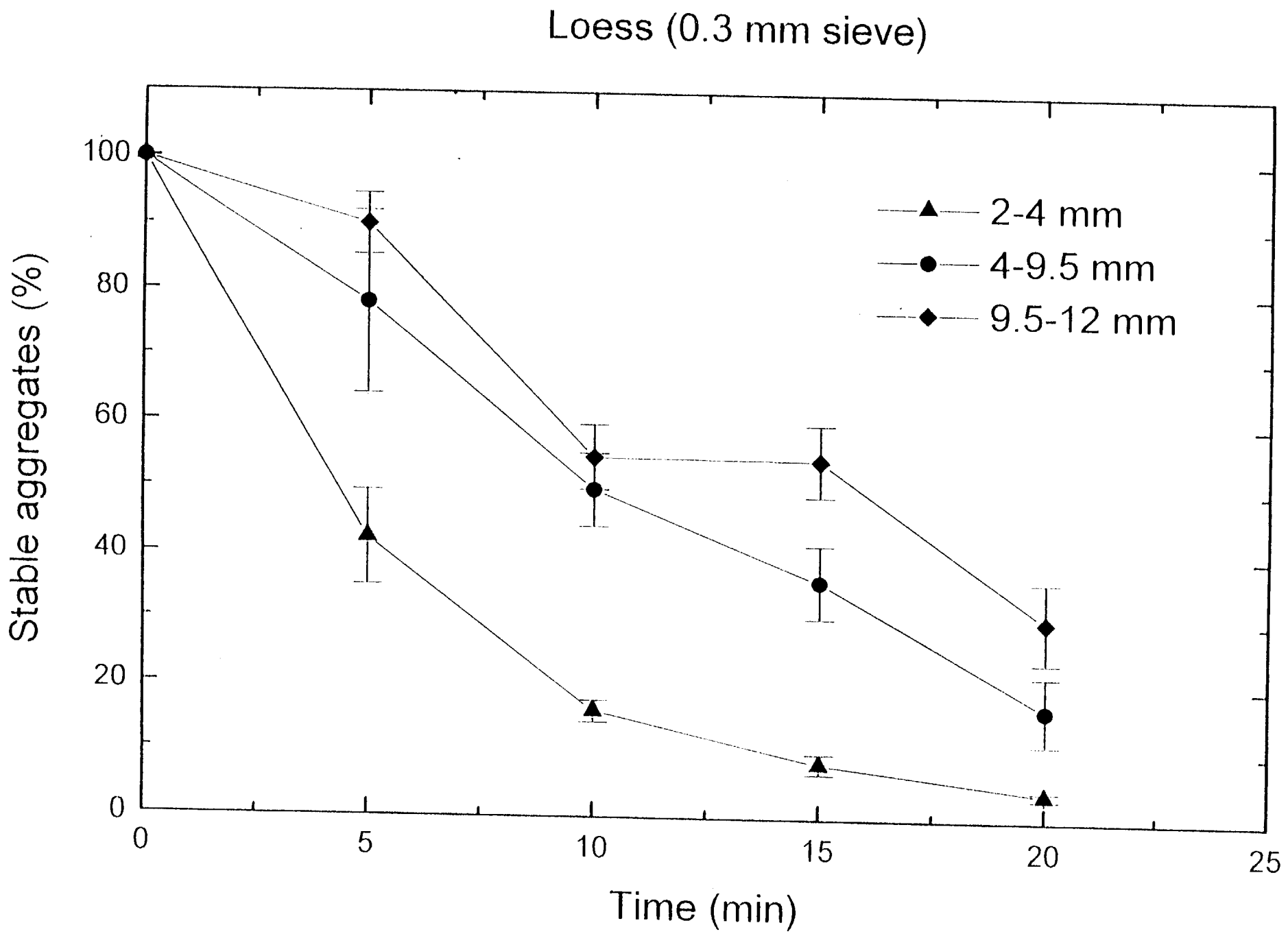
where
- D - Aggregate Diameter
- d - Disrupted Layer Thickness
- V_A - Aggregate Volume
- V_d - Disrupted Layer Volume


Grumusol (0.8 mm sieve)
Stable aggregates (%)
Time (min)
2-4 mm
4-9.5 mm
9.5-12 mm
0
20
40
60
80
100
0
5
10
15
20
25
30
35


Loess (0.8 mm sieve)
Stable aggregates (%)
Time (min)
2-4 mm
4-9.5 mm
9.5-12 mm
0
20
40
60
80
100
0
5
10
15
20
25


Grumusol (0.3 mm sieve)
Stable aggregates (%)
Time (min)
2-4 mm
4-9.5 mm
9.5-12 mm
0
20
40
60
80
100
0
5
10
15
20
25
30
35

H=40cm


Loess (0.3 mm sieve)
Stable aggregates (%)
Time (min)
2-4 mm
4-9.5 mm
9.5-12 mm
0
20
40
60
80
100
0
5
10
15
20
25