THE INFLUENCE OF VEGETATIVE COVER ON RUNOFF AND SOIL LOSS - A STUDY IN MUKOGODO, LAIKIPIA DISTRICT.
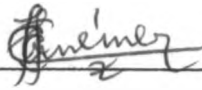
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A thesis submitted in partial fulfillment of the requirements for the degree of Master of science in Agricultural Engineering in the University of Nairobi.
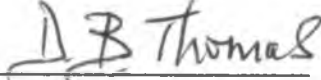
1995.

DECLARATION

This is my original work and has not been presented for a degree in any other University.
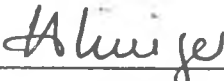
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This thesis has been submitted for examination with our approval as the University Supervisors.

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    Dr. H.P. LINIGER.

DEDICATION

To my father, John Mutunga, and my mother, Esther
Ndinda, for being the great educators they are.

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

ABSTRACT

The influence of rainfall, vegetative cover and soil characteristics on runoff and soil loss were investigated on the semi-arid area of Mukogodo, Laikipia District, Kenya. This study was carried out between July 1992 and August 1993. Two site conditions with respect to vegetation cover and two management systems were the treatments. They were designated as Perennial Enclosed (PE), Perennial Open (PO), Bare Enclosed (BE) and Bare Open (BO). Three runoff plots (each 2 by 10 metres) were designed and set up in each of the above treatments.

Rainfall parameters (amount and intensity) were measured. Storm kinetic energies and erosivities were determined using the formula $E = 11.9 + 8.7 * \log I$ (Wischmeier et al, 1958). Runoff and sediment yield from each plot were measured after each rainfall event. Soil moisture was monitored in each treatment using a Neutron probe up-to 75 cm deep. Vegetative cover and soil surface condition were also monitored in all the plots.

Over the study period, the Bare plots (BE and BO) lost over 50% of rainfall as runoff. The Perennial plots (PE and PO) had runoff less than half the runoff from the Bare plots. Total runoff values for BE and BO were

not significantly different at p<0.01, and thus closure to grazing did not reduce rainwater loss from the Bare plots. There was a significant difference (p<0.01) between total values of runoff for the PE and PO plots. This showed that closure to grazing reduced rainwater loss from the Perennial plots.

The total values of soil loss for the Bare plots were above the acceptable limit of 10 t/ha/yr (Hudson , 1981), while the Perennial plots recorded acceptable soil loss values. Closure to grazing did not lead to an improvement in vegetative cover in the Bare plots. A fast cover recovery was observed in the Perennial plots after the short rains. High crust strength values were recorded in this study. The Bare plots had crust strength values which were 15-30% higher than the crust strength values recorded in the Perennial plots.

In all treatments, available soil water was between 25% of Available Water Capacity (AWC) and 2% of AWC most of the time. As compared to the Bare plots, the Perennial plots had higher total available soil water at the beginning of each season. Soil moisture results also showed that very little water (less than 2 mm) was recorded below the 50 cm depth for all the treatments.

Multiple regression analysis revealed that rainfall,

erosivity and vegetative cover accounted for 65% of the variability in rainwater loss. Similarly, rainfall, erosivity, and runoff accounted for 72% of variation in the in the soil lost. Vegetative cover significantly (p<0.05) reduced runoff, while the impact on soil loss was not statistically significant.

Important implications for developing a strategy to reclaim denuded land arise from the results of this study. The results show that vegetative cover reduces runoff. It can be expected that a reduced runoff will lead to a reduced soil loss. This means that vegetative cover should be encouraged as a means to improve denuded land. From the results, zones with some cover of perennial grasses will recover by closure alone. The high runoff from the Bare areas shows that easy recovery is impossible unless some measures are taken to get water into the ground.

1.0 INTRODUCTION

1.1 Background Information

The need to increase the productivity of every kind of land available in Kenya has long been recognized. This has been mainly due to the steady increase in Kenya's population with the resulting increase in land pressure. The demand for food, fuel and shelter therefore has to be sustained. For such a goal to be achieved, the marginal areas must be given closer attention.

The arid and semi-arid lands constitute 80% of Kenya's land area. These areas are characterized by rainfall to evaporation ratio of 0.25 to 0.40, with rainfall ranging from 400-800 mm (KSS, 1980). Depending on altitude, high ambient temperatures (minimum 16°c and maximum 36°c or higher) are experienced (Barrow, 1983). The semi-arid areas are more critical than arid areas because they are more erosion susceptible. This is due to higher rainfall and greater population pressure(both from humans and livestock) than in the arid lands (Barrow, 1983). Erosion is also more of a threat in semi-arid areas because in this zone some crop production can be practiced while in arid areas crop production is impossible.

Environmental degradation(soil erosion and vegetation) in the semi-arid regions is fast and sometimes irreversible. Water limiting conditions are caused by high runoff which is induced by the high intensity and short duration nature of rainfall, characteristic in these areas. According to Thomas and Barber (1983), excessive loss of soil and water (through runoff) is a feature of much of the semi-arid areas. Such hydrologic conditions necessitate an efficient water management policy (Panda, 1988).

Land degradation in the rangelands is aggravated by the limited rainfall and soil moisture. The processes of range degradation involve loss of vegetative cover and loss of topsoil through various agents of erosion (Oba, 1992). Ogutu (1989) noted that inadequate assessment of the potential of plants for re-vegetation and the failure to make long-term commitment to soil conservation practices are probably the major hindrances to erosion control in the semi-arid rangelands. Communal land tenure can also be a hindrance.

Several methods of preventing further land denudation or reclaiming denuded land exist. Adoption of any of these methods depends on its implementation costs vis-a-vis the productivity of the land. Mututho (1986) argues that most physical soil conservation measures on grazing lands have met with very limited success due to

their unjustifiable capital requirements. Heavy
input(labour and money) physical measures like terraces
and cutoff drains are not only uneconomical but are
also hazardous to livestock under rangeland conditions.
This has therefore led to the need for concentration of
efforts and research in low cost measures for marginal
areas.

One such low cost measure is to use vegetation as a
protection measure and to allow or enhance re-
vegetation. This can be achieved by allowing the land
to rest for some time. The resulting vegetation reduces
erosion by intercepting raindrops and absorbing their
kinetic energy. Vegetation also retards run-off and
provides a stabilizing influence through the mechanical
action of the roots. Liniger (1992) showed that a
permanent grass cover reduced runoff rates to less than
1/3 and erosion rates to less than 1/30 compared with
an overgrazed area with a permanent cover of less than
10%.

Dunne (1977a) described two basic approaches to the
study of erosion rates. The first involves monitoring
sediment transport rates past a point in the river
channel at the outlet of a drainage basin. In the
second approach, erosion processes are measured at a
number of sampling sites within a catchment.

Although measurements are relatively easy to make in

the first approach, it is hard to decide what is going on within the drainage basin from a point measurement at the outlet. This is because the measurements integrate the effects of erosion over the whole area(Dunne, 1977a). Data collection for the second approach is difficult, but this approach has obvious advantages in providing information about the spatial distribution, controls and local effects of the erosion processes within the catchment.

An understanding of the fundamental mechanics of the basic processes at work in the semi-arid regions can probably best be done through the use of run-off plots, whereby small homogeneous areas can be isolated in relatively controlled conditions. The various factors at work can be isolated, their influences measured separately, and later synthesized and traced into larger watersheds (Hayward, 1968). The complexity of even small watersheds masks the detailed working of the hydrological processes; and therefore run-off plot studies have been recommended as a complementary technique (Ward, 1971).

This study was done in Mukogodo Division of Laikipia District between July 1992 and August 1993. The Division is a semi-arid area with extensive areas of denuded or partly denuded land. Land-use in the area is communal grazing. The area was chosen for the study because the Laikipia Research Programme (LRP) has an

hydrological station at the site and some of the installed equipment was to be utilized in data collection. The study carried out investigations aimed at providing a better understanding of the hydrological processes active in the semi-arid areas.

1.2 Importance of the study

There is a distinct lack of ready-to-use research data on run-off patterns and on erosion factors causing detachment and transport of soil in the semi-arid rangelands. In these areas, where soil moisture availability is the chief limiting factor and soils are readily eroded, quantitative data on runoff and soil erosion are of particular value (Temple, 1972). The goal of improving the semi-arid regions can be approached by having a sound estimate of the actual production and an estimate of potential productivity. Research can ask questions and test hypotheses on the potential productivity and the mechanisms for reaching the potential. According to Box (1990), the most pressing research needs are in the area of understanding the mechanisms of change in rangelands.

Soil erosion control in the rangelands should be aimed at improving soil moisture, ground cover and forage production (Oba, 1992). Re-vegetation includes a group of practices aimed at restoring the productivity of the land to its full potential. It should always be the

initial step in improving semi-arid rangelands because it is least costly and an easy route to follow (Heady, 1990). Degraded range sites can be re-vegetated using vegetation enclosures. To make progress, attributes such as the hydrologic processes, runoff patterns and erosion factors causing detachment and transport of soil need to be monitored. The moisture regime in the soil, plant species composition, plant productivity, total plant cover, changes in plant population structure, litter accumulation; and percentage of bare ground also need to be followed (Oba, 1992). Other factors like drought, which affect plant cover even in the absence of grazing, need to be taken into account when monitoring land recovery (Le Hou'erou, 1980).

It is important to have some understanding of different range sites and how they respond to different degrees of use. However, the effect of the resulting vegetative cover on erosion in the semi-arid climate can be hindered by soil crusting, sealing and salinity. These factors are common in the semi-arid regions. Thus the extent to which the regenerated vegetative cover influences runoff and soil loss needs to be assessed. The investigation may help in revealing the methods to be adopted to counter denudation in the semi-arid areas.

Although numerous erosion measurements have been made under different plant covers for comparison with that

from bare ground, only few researchers have examined the relationship between soil loss and changes in the extent of cover (Morgan, 1986). Rowntree (1983) also notes that few studies have explicitly followed up the relationship between rainfall and vegetation cover in the assessment of erosion risk. The justification of any research in the semi-arid lands should be geared towards the improvement of scientific and technological knowledge, and should aim to bring about the use of this knowledge for the improvement of the living conditions of mankind, and in particular the inhabitants of deserts and semi-desert regions (Odingo, 1989).

Soil conservation must be cost-effective if it is to be acceptable to a farmer. Terracing of the grazing lands is too expensive and labour intensive relative to expected returns; to be contemplated by most farmers (Simiyu et al, 1990). To halt the damage and to reverse the processes of desertification; many of the "corrective activities" have tended to be guided by the often false assumption that technology has the answer to all the problems being addressed (Odingo, 1989).

The semi-arid regions are characterized by communal grazing. The low value of production from the soils in these areas mean that only cheap and simple solutions are appropriate. A better understanding of the hydrological processes active in the semi-arid areas is

therefore necessary.

1.3 Objectives:

The objectives of this study were as follows:-

(i). <u>Main Objective</u>

To determine the influence of rainfall (amount and intensity), vegetation cover and soil characteristics on runoff and soil loss.

(ii). <u>Specific Objectives</u>

(a). To find out in what way the initial conditions of vegetation cover and soil characteristics (crusting, organic matter, moisture status) determine infiltration, runoff and soil loss.

(b). To find out the effect of different management treatments (open or closed to grazing) on vegetation cover and soil characteristics (crusting, organic matter, moisture status).

(c). To find out how changes in vegetation cover and soil characteristics (crusting and organic matter), that may take place under different management situations, affect infiltration, runoff and soil loss under different rainfall events.

2.0 LITERATURE REVIEW

2.1. Runoff

Runoff is the remainder of rainfall after interception and infiltration processes have taken place. Finkel (1986) defines runoff as that portion of rainfall which is neither absorbed into the ground, stored on the surface, nor evaporated, but which flows over the land. Over a long period, the total volume of runoff must equal the difference between precipitation and evaporation; while over shorter periods, the rainfall runoff relation will be further governed by a great number of intermediate reservoirs or storages of various nature inherent to the specific local conditions as regards vegetal, soil, geological and topographic factors (Kraijenhoff Van de Leur, 1979).

There are two main paths by which water moves from the soil surface to the stream: along the soil surface and through the groundwater reservoir. However, water that has already penetrated into the soil may move over a shallow layer of low permeability to be forced out again at a lower point of the slope where it changes into overland flow. This is called the sub surface storm-flow or inter-flow (Kraijenhoff van de Leur, 1979). On the other hand, water moving along the soil surface may still become groundwater when it gets to a

surface with a higher infiltration capacity and it consequently infiltrates into the soil.

Overland flow becomes surface runoff after it has arrived safely in the channel system and is transported through the outlet of the drainage basin (Kraijenhoff van de Leur, 1979). Surface runoff together with inter-flow make up the direct runoff, which moves swiftly through the drainage basin to the outlet(Fig. 1).

Morgan (1986) reports that overland flow is rarely in the form of a sheet of water of uniform depth. It is commonly a mass of braided water courses with no pronounced channels. Water loss through runoff during and shortly after rainfall events has two major consequences (Liniger, 1991b):-

(a). Reducing the available water for the plants through the reduction of the water which could be stored in the soil, and hence causing a reduced production.

(b). Erosion and a long term decrease of the soil fertility.

According to Morgan (1986), the hydraulic characteristics of overland flow are described by its Reynolds number (Re) and its Froude number (F), defined
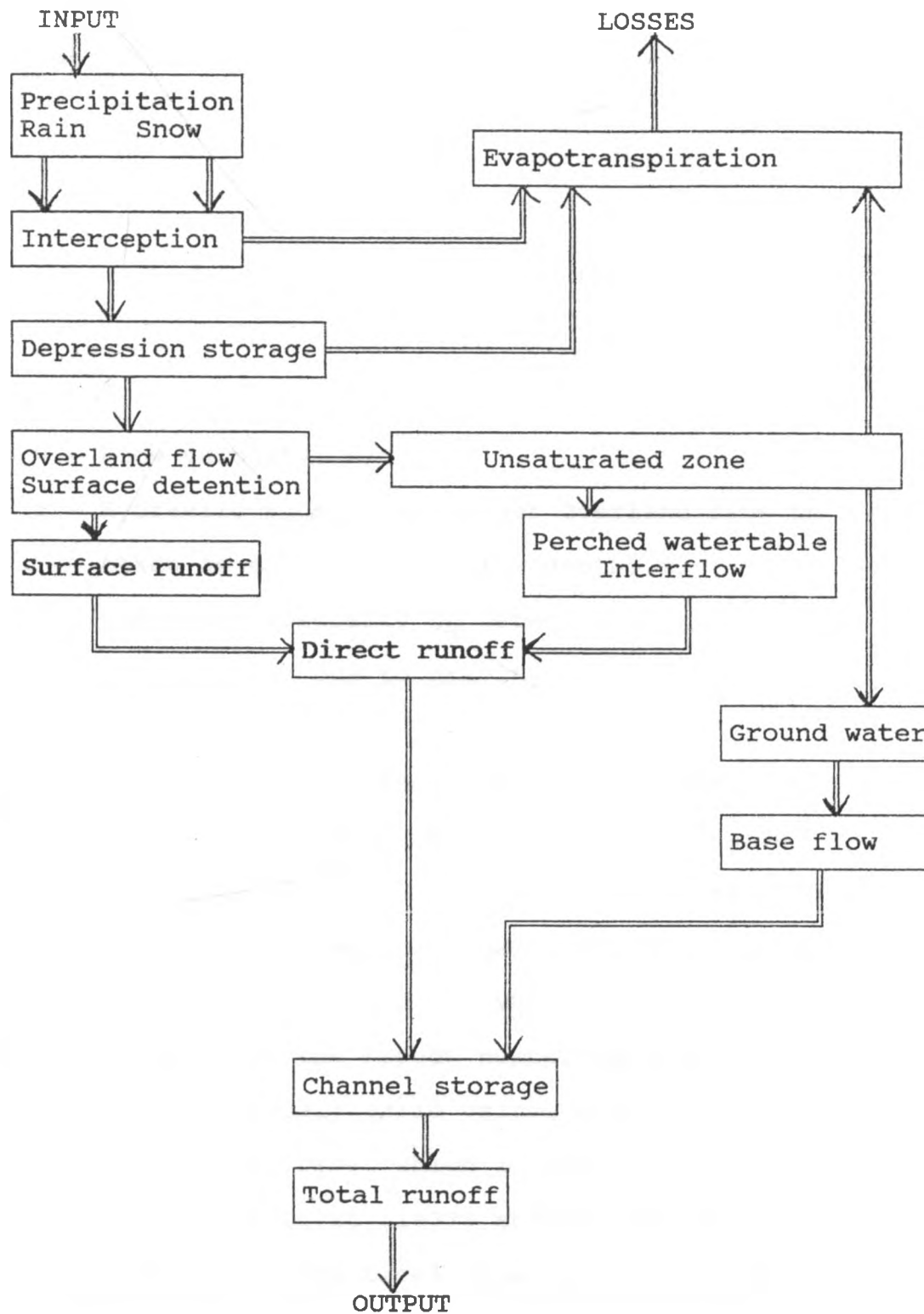
FIGURE 1: Flow chart of the hydrologic cycle (Kraijenhoff Van de Leur, 1979).

by eqns. (1) and (2).

$$Re = \frac{Vr}{v} \qquad (1)$$

and

$$F = \frac{V}{\sqrt{gr}} \qquad (2)$$

Where

V = Flow velocity, m/s.

r = Hydraulic radius, which for Overland flow is taken as equal to the flow depth, m.

$\vee$ = Kinematic viscosity of water, m²/s

g = acceleration due to gravity, m/s²

Reynolds number indicates the turbulence of the flow. The greater the turbulence, the greater the erosive power generated by the flow. At numbers less than 500, laminar flow prevails and at values above 2000 the flow is fully turbulent. Intermediate values indicate transient flow. When the Froude number is less than 1.0 the flow is subcritical; while values greater than 1.0 denote supercritical flow, which is more erosive. From laboratory studies, Savat (1977) showed that most overland flow is supercritical. However, field studies show Reynolds numbers less than 75 and Froude numbers less than 0.5 for overland flow (Morgan, 1980).

Estimation or prediction of runoff is of primary

importance in the design of conservation measures, since flowing water is both a cause of erosion and a source of water supply (Finkel, 1986). Runoff constitutes the hydraulic "load" that a conservation structure or channel must withstand (Schwab et al, 1981). The estimation of runoff volume is normally done by estimating direct runoff (surface runoff plus inter-flow runoff). In arid and semi-arid areas the contribution of the inter-flow is very small. This is because the soil forms surface crusts which seal off the surface, thereby inhibiting infiltration. Surface sealing decreases macro and micro-pore openings at the air/soil interface causing a decrease of air exhaust from the soil as water fills the pore spaces. The resulting back pressure of trapped air decreases infiltration (Dodd and Skinner, 1990).

The proportion of rain which becomes runoff depends on many factors:- the topography, the vegetation, the infiltration rate, the soil storage capacity, and the drainage pattern (Hudson, 1981). Although erosion results from complex natural processes, runoff is a major cause (Holy, 1984). The theory of water erosion should therefore be oriented to the laws of sheet-flow and concentrated runoff; and to transport processes caused by water. To control soil erosion by water, conservation practices must be designed to use land wisely and manage runoff properly. One of the principles of conservation is to control the flow of

water as close as possible to the place where it starts (Finkel, 1986).

Livestock trampling in semi-arid areas has an effect on the resulting runoff and soil loss. Harrington (1980) believes that livestock trampling with moderate stocking promotes water infiltration, whereas with increased stocking, trampling may result in soil compaction and reduction in water percolation. Savory (1983) advocates that "hoof action" in a brittle environment increases water infiltration by breaking soil surface crust, although there is no good evidence to support this. Dunne (1977b) found that livestock trampling and associated soil compaction did not influence water percolation; rather, they increased soil loss by reducing cover and through mechanical breaking of soil structure.

Other studies (Dagar, 1987, Webb and Wilshire, 1980) supported the view that livestock trampling compacts the soil, reducing water infiltration and increasing surface runoff and soil erosion. Warren et al (1986) showed that treading increased runoff and erosion; both of which positively correlated with bulk density.

Rain-splash and surface runoff are probably the most important causes of erosion (Rapp et al, 1972). Both have the potential to detach soil and to transport sediment, but their mode of operation is different

(Meyer, 1981). When raindrops strike a bare soil surface, soil particles may be thrown through the air over distances of several centimetres. This is how rain-splash erosion takes place. Running water and wind are further contributors to the detachment of soil particles. Runoff is the major transport agent. According to Meyer (1981), runoff does not cause rill erosion until the flow's shear forces exceed the soil's resistance to them and the flow's sediment transport capacity is greater than the available detached material.

2.2 Rainfall erosivity

Soil erosion is essentially a work process (Hudson, 1981). A comparison between the available energy in falling rain and that from surface runoff shows that rain has several times more kinetic energy than surface runoff. This explains why splash erosion is so vital in the erosion process (Hudson, 1981; Morgan, 1986). The potential ability of rain to cause erosion is termed as erosivity (Hudson, 1981). A suitable expression of the erosivity of rainfall is an index based on the kinetic energy of the rain. The erosivity of a rainstorm is thus a function of its intensity and duration, and of the mass, diameter and velocity of the raindrops (Morgan, 1986).

Storm energy is widely used as the basis of indices of storm erosivity (Rowntree, 1983). The product of the

kinetic energy of a storm and the 30-minute intensity is a measure of erosivity described as the EI index. The 30-minute intensity is the greatest average intensity experienced in any 30-minute period during a storm. Wischmeier et al (1958) found out that the EI index was the best estimator of soil loss. The index can be computed for individual storms, and the storm values can be summed over periods of time to give weekly, monthly, or annual values of erosivity.

Other erosivity indices have also been used. Working in Africa, Hudson (1981) developed an erosivity index written as KE>25. This index consists of the total kinetic energy of all the rain falling at more than 25 mm per hour and is based on the fact that little erosion takes place at low intensities. Lal tested the EI, KE>25, and other possible parameters in Nigeria. He found that the best correlation of soil loss from small plots was with an index denoted by AI_m , where A is the amount of rain and I_m the maximum intensity over a 7.5 minute period (Hudson, 1981).

2.3 Soil loss

Erosion does not only mean quantitative loss of soil. It also exerts a qualitative action on the elements of the soil. Any amount of soil removed from the land surface results in a loss in the productivity of the soil. Soil depth and water holding capacity of a soil also decrease. Reductions in soil depth are

particularly serious in semi-arid areas, where soils
are often shallow and the quantity of available water
frequently the most limiting factor in crop production
(Barber, 1983).

Ideally, rates of soil erosion should be restricted to
soil formation rates. In most cases, and particularly
where terraces are graded to permit discharge, it is
extremely difficulty if not impossible to restrict
erosion even to 1.1 t/ha/yr (Mccormack and young,
1981). Hurni (1990), working in the Ethiopian highlands
reported of soil loss values from grassland which were
3-10 times lower than from cultivated land. He also
observed that soil loss rates exceeded formation rates
by a factor of 4 to 10 on cultivated land, and of 0.8
to 2.3 on grassland, depending on the agro-climatic
zone.

Using laboratory experiments, D'souza and Morgan (1976)
showed that soil loss varies with the Reynolds number
(Re) of the runoff flow. Rates of soil loss of the
order of 0.5-1.0 mm/year, equivalent to about 7-15
t/ha/yr are commonly quoted as "acceptable" or
tolerable, but this assumption is questionable (Young,
1976). It is not yet known whether erosion at such
rates will lead to irreversible soil degradation.

Wishmeier and Smith (1978) define soil loss tolerance
(T) values as the maximum permitted soil loss rates

that will permit a high level of crop productivity to be maintained economically and indefinitely. The T value for a particular soil can help in selecting appropriate land-use types and management practices, to ensure that the resultant rate of the soil loss does not exceed the T value. However, Zöbisch (1989) stated that defining rates of tolerable erosion was usually an arbitrary exercise, and strongly depended on the assumptions made. He suggested that minimum required soil depths could be set for any crop. The minimum soil depths would constitute major determinants for the definition of acceptable levels of soil loss.

Rapp et al (1972) reported rates of about 1 cm/year in an overgrazed catchment near Dodoma, Tanzania. However, this was based on the indirect evidence of tree mounds. Moore et al (1979), using a simulated rainstorm of 69 mm/hr for 1 hr on small plots showed that high rates of soil erosion can occur on bare, overgrazed soil in a semi-arid area of Machakos, Kenya. This study also showed that a grass cover can reduce soil losses, with most reduction occurring at basal cover densities up-to 20 percent, with little further reduction at higher basal covers. Their experimental data shows that basal covers greater than 15 to 20 percent can reduce annual erosion losses to less than 12.5 t/ha.

2.4 Runoff plot equipment design

2.4.1 Introduction

Runoff plots are used in many developing countries for erosion studies (Sheng, 1990). Plot design, instrumentation, and data collection procedures vary greatly from place to place. According to mutchler (1963), the basic runoff equipment consists of a plot boundary to prevent water and soil from entering or leaving the plot; a collector which serves as a weir at the end of the plot; a conveyance channel to handle the flow of soil and water; a sludge tank to contain the sediment and water; a multislot divisor with a precision plate to accurately measure out a portion of the overflow from the sludge tank; and one or more aliquot tanks to contain the measured overflow (Fig. 2).

In some experiments, all the runoff and sediment is collected in one large tank and there is no arrangement for divisors or aliquot sampling. The first such system in Kenya was installed by Tefera (1983) at Kabete. Liniger (1991b) also used a similar set up in Laikipia District.
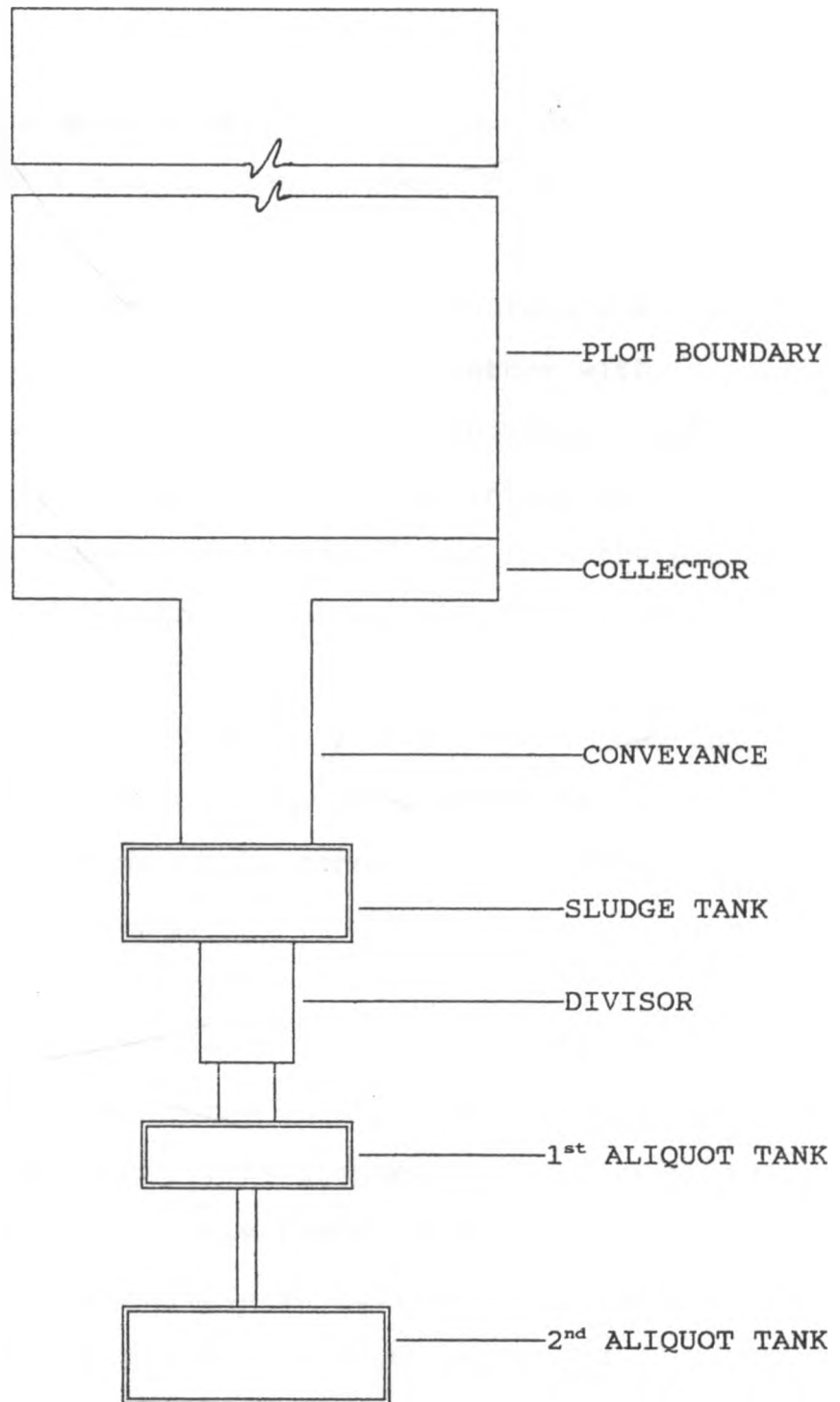
FIGURE 2: Typical plan of runoff plot equipment.

There are three general approaches which have been used to monitor runoff and erosion on small plots (USDA, 1979):-

(a) Use of pre-calibrated flumes to accurately measure changes in runoff during an event, together with discrete sediment samples taken over the hydrograph or a device to proportionally sample the entire event;

(b) The entire runoff and sediment load from the plot is captured or a fixed fraction of the runoff and sediment load is taken;

(c) Use of a tipping bucket to measure the volume and rate of runoff during a storm. This method has a counting device which can be connected to a data logger for automatic recording.

Although in the second approach the hydrologic information over the course of the event is lost, this type of sampling strategy is simpler and less prone to equipment malfunction. This factor should be a major consideration when the site is located in a remote region so that the difficulty in obtaining and repairing more sophisticated equipment is avoided.

2.4.2 Equipment design criteria

Erosion plot equipment must be adequate to collect runoff and soil loss from the plot and to store all or

a part for measurement and analysis (Mutchler, 1963). This requires an estimate of maximum runoff and soil loss, both rate and amount.

In USA, total runoff and soil loss storage required was estimated by using 100 percent of the 24-hour-duration rainfall amount expected once in 100 years (Mutchler, 1963). However, this assumed that the 1 in 100 year storm came when the soil profile was completely saturated. Maximum runoff rate was estimated by using 100 percent of the 5-minute- duration rainfall intensity expected once in 100 years. Storage was allowed for about 120 tonnes per hectare soil loss (Mutchler, 1963). This design basis is unsuitable for a semi-arid area in the tropics. In these regions the soils are rarely saturated.

Conveyance pipes or channels should be designed to carry the flow under open channel conditions at supercritical velocities. In this way sedimentation in the channel is minimized. Channel size is determined by the assumption that the design flow equals critical flow of the channel shape chosen. Minimum slope is determined either by the figure obtained for critical flow at the entrance or by the figure that gives 0.61 m/s (2 feet per second) velocity at 20 percent flow, whichever is larger (Mutchler, 1963).

2.4.3 Plot boundaries

Plot boundaries can be made from earth ridges, wood or asbestos-cement planks, sheet metal strips, etc. Each has advantages and disadvantages (Ulsaker, 1982). Strips of 16-gauge galvanized steel approximately 23 cm high by 2 to 4 m long, with corrugations running across the small dimension, make excellent boundaries for cultivated plots. These are comparatively easy to install and maintain (Mutchler, 1963). A jig made up of two planks spaced apart the depth of the corrugations can keep the boundary aligned during installations.

Veloz and Logan (1985) used boundaries constructed from local available materials (cement block and concrete). These materials provided the necessary strength and could be used for a long time. In Ethiopia, the Soil Conservation Research Project (SCRP, 1981) used borders which were removable during field operations and later returned back. Such a design ensured that cultivation practices were not simulated and hence approximated the natural conditions very well. Whatever material is used to make the boundaries, it should be ensured that they are stable and prevent seepage into or out of the plot.

2.4.4 Runoff collector

Many different designs and materials can be used. The collector generally acts as a weir across the bottom of the plot and a channel for runoff to the sampling unit. Sheet-metal construction is preferred to concrete (Mutchler, 1963).

The collector trough acts as a channel for the sediment runoff mixture. The trough is usually designed to reach across the entire width of narrow plots. It is best to concentrate runoff from wider plots before collecting it. During installation, the trench for the collector must be deep enough so that the lip of the collector is just level with the soil surface (Mutchler, 1963). The major elements of the collector trough design are depth, width and bottom slope.

If a flume is used, depth of the collector is controlled by the size of the approach channel required by the flume. When no rate measurement is done, the collector depth is based on the pipe size needed to carry the runoff load, plus a free board of approximately 12 cm (Mutchler, 1963). The trough should be wide enough for easy cleaning and narrow enough to form an efficient channel. The bottom section should have a 5 percent slope.

2.4.5 Measuring flumes

When it is desirable to have a runoff hydrograph from erosion experiments, the H and Hs flumes are recommended as rate-measuring devices (Mutchler, 1963). These measuring instruments require an anti-sedimentation device when high silt or sand content causes deposition in the flume.

2.4.6 Aliquot sampling

Large storms produce high amounts of runoff which are too voluminous to collect in total. A method of aliquoting is therefore recommended (USDA, 1979). Several devices have been used for this kind of sampling:-

(a) The Coshocton - type rotating - slot sampler, and

(b) The Geib multislot divisor.

The Coshocton - type sampler involves a small sampling error because it extracts a small aliquot from the total runoff (Mutchler, 1963). The major problem of this equipment however, is its inaccuracy due to silting of the H-flume. The use of the multislot divisor requires a large amount of labour. It is a precision device that is quite reliable and still preferred by many in erosion research (Mutchler, 1963).

2.4.7 Multislot divisor

This equipment is based on the premise of a uniform horizontal flow velocity throughout head variations. The divisor's function is to divide water from one tank into several equal parts, and directing only one (or sometimes two) amounts into the next container (Sombatpanit et al, 1990).

Multi-slot divisors can be of various types. Veloz and Logan (1985) used a Multi-slot divisor having a two-compartment cement block tank with horizontally placed plastic tubes on the sides of the tank and one tube to carry a fraction of the flow from the first compartment to the second. Sombatpanit et al, (1990) constructed a divisor which could divide water twice within its body (a double- split divisor). Such a divisor has a higher dividing ratio and can make research less laborious by significantly reducing the amount of aliquots. Mutchler (1963) gives the design principles of multislot divisors as to include the following:-

1. Slot similarity of size, shape and position.
2. Approach flow smoothness, eg. no sharp protruding edges to disturb the flow.
The approach channel and divisor must be level in cross-section.

2.4.8 Storage units

Tanks are used to store all the sludge and aliquot of the soil loss-runoff mixture. The sludge tank unit retains all the heavy soil material and passes only a suspended sediment mixture to the divisor unit; and also stores sludge. Turbulence in the sludge tank is reduced by placing screens across the flow through the sludge tank. The screens also keep trash from clogging the divisor. The aliquot tank merely functions as a storage tank.

The tanks should be easy to clean. This means that the screens should be removable and the tank bottoms should have drains. Liniger (pers. comm.) recommends that if the tanks are placed in pits, the pits must be drained or covered to prevent the inflow of water and floatation of the tanks.

2.5 Soil Moisture

2.5.1 Introduction

The Mukogodo area where this study was carried out is characterized by low and erratic rainfall. Soil moisture thus becomes an important factor because its availability dictates the level of plant growth. Many processes affect the rainfall-streamflow relationship within agricultural watersheds. The storage of water in the soil mantle is one of the most significant (USDA, 1979). Vegetative growth depends on the amount and

distribution of available water in the soil profile. In terms of total volume, soil moisture accretion is often the largest abstraction from rainfall, and thus an important factor in the performance of a watershed.

Monitoring of soil water in order to define the amount of water available and how it changes throughout a season provides very important information for plant performance and water balance (Liniger, 1991b). The measurements should be taken on a regular schedule as often as feasible.

Soil moisture content is expressed either in percent by weight or percent by volume. Moisture percent by weight is based on dry weight of the soil and is expressed as follows:-

$$P_w = \frac{(W_w - W_d)}{W_d} \times 100 \qquad (3)$$

where

    P_w = Moisture percent by weight

    W_w = Wet weight of soil

    W_d = dry weight of the soil

For determining moisture percent by weight, the data is obtained from soil samples taken in the field.

In many cases it is more useful to express soil moisture percent by the volumetric moisture percent, Pv, expressed as:-

$$P_v = \frac{V_w}{V_s} \times 100 \qquad\qquad (4)$$

where

    V_w = Volume of water in the sample

    V_s = bulk volume of the sample.

The volumetric moisture percent is usually not determined directly because of the difficulties involved in determining both the volume of the water and the volume of the soil. The moisture percent by weight and moisture percent by volume are related by eqn. (5) (USDA, 1979) :-

$$P_v = P_w(\rho) \qquad\qquad (5)$$

where

    ρ = bulk density of soil.

2.5.2 Soil moisture determination

Soil moisture determination is the direct or indirect determination of soil moisture content or soil moisture potential or energy status (USDA, 1979). There are numerous procedures and types of equipment for the determination of soil moisture. Each has advantages and limitations. This means that it is necessary to consider both the purpose for which the determinations are to be made and the features of each possible method, including the costs of buying equipment, operation and maintenance (USDA, 1979).

Liniger (1991b) asserts that the measurement of soil water is very problematic due to the unavailability of simple instruments. Most of the commercial devices available for field installations except the neutron meter consist of a porous material, which attains equilibrium with soil moisture (USDA, 1979). These devices measure the soil capillary potential and not the soil moisture content. As a result, they must be calibrated against soil moisture content.

It is difficult to establish a calibration for simple conductivity blocks and gypsum blocks. Tensiometers are not suitable for semi-arid conditions because their limited range excludes dry conditions. According to Liniger (1991b), it is only the expensive and sophisticated neutron probe method which can be used satisfactorily in semi-arid conditions.

The gravimetric method of moisture determination is the standard method to which all other methods are compared (USDA, 1979). It consists of drying a sample at 105°c (221°F) to a constant weight (usually 16 to 24 hours). If a sample is dried at a lower temperature all the water may not be removed, and if it is dried at a higher temperature, other volatile matter may be driven off in addition to the water. However, during sampling, augering disturbs the soil.

2.5.3 The Neutron scatter method

This method uses a probe containing a fast neutron source and a thermal neutron detector for moisture determination. If a radioactive source emitting high energy of fast neutrons is placed in the soil, the neutrons will travel away from the source at high speed, colliding on their way with nuclei of various elements in the soil. When a fast neutron collides with a heavy nucleus, its direction will be changed but its energy will be relatively unaffected (USDA, 1979). However, when the fast neutron collides with a light nucleus, an appreciable part of its energy will be transformed to this nucleus and the neutron will continue as a slow or thermal neutron characterized by a lower speed and energy.

In the soil, hydrogen is the most common atom with a light nucleus (Cpn Corp, 1984). Most of the hydrogen found in the soil is a component of water. The majority of neutron-moderating collisions that take place occur between the fast neutrons and hydrogen atoms associated with water. The fast neutron source in the soil will therefore be surrounded by a cloud of slow thermal neutrons whose density and radius will be a function of both the rate of fast neutron emission by the source and of the volumetric moisture content of the soil(USDA, 1979).

Excluding the presence in the soil of hydrogen atoms

not due to water and of other atoms with light nuclei which may also participate in fast neutron moderation, it can be concluded that the higher the volumetric moisture content of a soil, the greater the likelihood that any single fast neutron will collide with an hydrogen atom and become moderated within a given distance from the source (USDA, 1979). The converse is true. If a detector unit is placed in such a sampling plane, it will measure the flux rate of slow neutrons which will be a function of source strength, soil moisture content, and the geometry of the system. The moisture detectors in neutron probe gauges "see" the slow neutrons (Cpn Corp., 1984).

Most slow neutron detection systems consist of a tube filled with boron trifluoride enriched with boron-10 to increase efficiency (USDA, 1979). Slow neutrons react with atoms of boron which emit positively charged alpha particles that are detected electronically. The amplified signal is transmitted through a cable from which the probe is suspended in the soil to a scaler or rate meter.

To take probe readings at different depths, observation holes, encased with thin-walled access tubing are used. Access tubes may be made of any material for the purpose including aluminium, steel, copper or even plastic. Aluminium is most nearly transparent to neutrons, giving the highest counting

efficiency of any material (USDA; 1979). It is also available in the desired dimensions. The top opening of an access tube should be covered to prevent rain, water, and dirt from falling into the tube. Different drilling methods for the installation of the access tubes have been used. Whichever method is adopted, the closeness of fit of the access tube within the bore hole should be the criterion for effectiveness (USDA, 1979).

It is important to calibrate neutron soil moisture meters. The calibration curve is useful for checking the efficiency and reliability of the neutron moisture meters performance. Field calibration is ideal (USDA, 1979). Since the precision of measurement is a function of the total number of counts, a sufficiently long count should be taken at each measurement depth. According to USDA (1979), stony and non-uniform soils are difficult to calibrate in the field. It is also difficult and, in some situations impossible, to duplicate in a container the heterogeneous arrangement of a field soil, particularly a stony soil.

2.6 Vegetative cover

2.6.1 Introduction
Whereas ground cover is very important for supporting livestock, the area under study (a livestock zone) lacks it. Greig-smith (1964) defines cover as the

proportion of the ground occupied by perpendicular projection onto it of the aerial parts of individuals of the species under consideration. Plant covers can play an important role in reducing erosion provided that they extend over a sufficient proportion of the soil surface (Morgan, 1986). Vegetative cover has been shown to substantially reduce runoff, even on steep slopes; and is hence a decisive factor in soil erosion control.

According to Stocking (1988), promotion of vegetation as an approach to soil conservation has much to offer because:-

(i) Vegetation is the factor most easily manipulated by careful management.

(ii) Better vegetative growth and hence better protection of soil almost always provides direct economic benefits in terms of yield and production.

(iii) It is a goal achievable by small or large, rich or poor farmers alike.

Vegetation protects the soil from erosion by intercepting raindrops and absorbing their kinetic energies harmlessly. Vegetation has also a stabilizing influence on soil through the mechanical action of the roots. The roots absorb, store and recycle water and mineral elements within a plant, hence reducing nutrient losses and further soil degradation. Vegetation intercepts run-off and consequently

increases infiltration. Plant cover dissipates the energy of running water and imparts roughness to the flow, thereby reducing its velocity (Morgan, 1986). The litter which accumulates under vegetation also helps to improve infiltration and reduces the rainfall impact on the soil. This has an overall effect of reducing splash erosion and minimizing soil surface sealing.

The effectiveness of a plant cover in reducing erosion depends upon the continuity of the canopy, the density of the ground cover and the root density (Morgan, 1986). The height of vegetative cover above the ground surface is important (Stocking, 1988; Morgan, 1986). This is because water drops falling from high distances may attain their terminal velocity and hence behave similar to raindrops. Further, raindrops intercepted by the canopy may form larger droplets, which on falling to the ground may accelerate sufficiently to have sizeable kinetic energy (Stocking, 1988). This explains why erosion can occur under trees if the ground is bare.

2.6.2 Determination of cover

Cover can be estimated directly in percentage. According to Bonham (1989) cover can be measured for vegetation in contact with the ground (basal cover) or by projected aerial parts of vegetation onto the ground (foliage cover). All methods of measuring cover depend on interception of the plant by a quadrat, the area of

which may be very close to zero for a point and yet is still on a two or three-dimensional basis. A measurement of cover percentage provides a single assessment at one point in time in the growth period of vegetation. If a rainfall event were to occur at that exact time, the cover value is equal to the percentage of rainfall likely to be intercepted before reaching the ground (Stocking, 1988). Various techniques have been used to estimate cover.

Bounded areas (plots) of ground surface, formed by placing a quadrat of a given area on the surface can be used to estimate cover. The sizes of plots used range from a fraction of a square centimetre to several square meters. According to Bonham (1989), a popular plot used by range ecologists in the US is the loop, which can be either 1 or 2 cm in diameter. Hutchings and Holmgren (1959) noted that since the 2 cm loop is in reality a small plot, frequency is actually determined rather than hits of a blunt point. These loops are placed along intervals of a tape and checked for the plant that occupies the most area. That plant only is recorded and all such observations are tallied for a given number of placement. Totals are used to estimate relative cover (Bonham, 1989).

The line-intercept method involves laying out a transect and measuring the length of a species intersected. Objectives of the study determine whether

to measure basal cover or foliage cover for each species (Risser, 1984; Bonham, 1989). Line-intercept data are more accurate, and data are obtained more rapidly than by the use of quadrats in communities with different-sized individuals of plant species (Bonham, 1989). The major drawback of this method is that it is time consuming and measurement has to be done over a large area (Heady et al, 1959). A line is also difficult to stretch between two points in tall, dense vegetation.

The point sampling method represents the reduction of a quadrat down to a dimensionless point (Drew, 1944; Bonham, 1989). Bonham (1989) notes that the use of points is considered the most objective way to estimate cover. Cover may be sampled by employing pins as physical points and using the percentage of pins that touch the vegetation as a measure of the cover of vegetation. This method is good for short and sparse vegetation but it is difficult to use on tall or dense vegetation. There is minimal error for personal bias when a point is used (Bonham, 1989). However, errors can occur from other sources such as movement of plants by wind or improper lowering of the pins by the observer. Several methods of point sampling have been developed:-

The point frame usually contains ten pins passing through two holes in a frame. Spacing of pins within a

frame is, in general, closer for intensive studies, and further apart for general surveys (Bonham, 1989). The pins are sharpened to a point. Each pin is lowered and the species which the pin touches is recorded. Basal and or aerial cover can be sampled. After all the ten pins have been lowered and data recorded, the point frame is moved to a new location. Various investigators have used pins inclined at different angles (Tinney et al, 1937; Winkworth, 1955; Warren-wilson, 1960).

Point sampling can also be done on a transect with point readings taken at intervals along a tape (Heady et al, 1959). The line-point method involves point readings along a transect and may be faster than the line intercept (Bonham, 1989). The length of the transect and spacing between points can vary. The points should be pre-determined. More points are preferable for dense vegetation and fewer for sparse vegetation.

For rapid survey purposes, Evans and Love (1957) described the point-step method. A notch or mark on the tip of the boot is used as the point as the observer paces across the area.

2.7 Soil surface sealing and crusting

2.7.1 Introduction

Soil surface sealing and crusting is a major impediment

to infiltration of rainwater in the area under study. A soil surface seal is a thin layer of fine soil particles and clay colloidal particles on the soil surface that are bound together by surface tensional forces (Chiti, 1991). According to Chen et al (1980), a seal forms due to fine soil particles that adhere to coarse soil particles. During a rainstorm, the coarse soil particles are exposed at the soil surface and subsequently, these are washed away, leaving a skin or seal. Using simulated rainfall studies, Norton (1987) explained deposition of fine soil particles as the main way in which surface seals are formed.

Brady (1984) defines a soil surface crust as a surface layer on soils, ranging in thickness from a few millimetres to perhaps as much as 3 cm, that is much more compact, hard and brittle when dry than the material immediately beneath it. Studies of crust development under simulated rainfall show that crusts have a dense surface skin or seal, about 0.1 mm thick, with well oriented clay particles. Beneath this is a layer, 1 to 3 mm thick, where the larger pore spaces are filled by finer washed-in material (Tackett and Pearson, 1965).

The foregoing discussion shows that soil surface crusting is therefore a special phenomenon of physical soil degradation. It results from non-soil loss processes such as soil compaction, breakdown and

dispersion of soil aggregates and physical translocation of fine soil particles. Morgan (1986) states that crustability decreases with increasing contents of clay and organic matter since these provide greater strength to the soil. Thus loams and sandy loams are the most vulnerable to crust formation.

The most important effect of a surface crust is to reduce infiltration capacity and thereby promote greater surface runoff (Morgan, 1986). According to Downes (1946), overgrazing and removal of vegetation cover cause crusting of the surface soil, resulting in greater runoff. Morin et al (1984), from measurements on a sandy soil in Israel showed that crusting reduces the infiltration capacity from 100 mmh^{-1} to 8 mmh^{-1} and on a loess soil from 45 mmh^{-1} to 5 mmh^{-1}. The infiltration capacity on sandy soils in Mali ranges from 100 to 200 mmh^{-1}, but where crusting has developed it reduces to 10 mmh^{-1}. Only a few storms are needed to bring about this change ; a 50 percent reduction can occur in one storm (Hoogmoed and Stroosnijder, 1984).

2.7.2 Types of crusts

Chen et al (1980) recognized two types of crusts from the mechanism of formation: Structural crusts and depositional crusts. Structural crusts were the crusts formed from raindrop impact while depositional crusts resulted from the translocation and deposition of fines. Hoogmoed (1987) classified crusts into thick

crusts and thin crusts. Thick crusts are the ones
easily visible large crusts, with a thickness of a few
millimetres. Thin crusts are hardly noticeable with an
effective thickness of less than 0.10 mm.

2.7.3 Conditions of soil crusting

The soil crusting phenomena is prevalent in hot dry
regions which include arid and semi-arid areas
(Valentin, 1985). According to Hadas and Stibbe (1977),
light textured soils high in silt content or fine sand
are highly prone to crusting. The texture of the
topsoil in this respect is important in determining the
degree of crusting. Other conditions influencing
crusting are soil moisture content, type and amount of
clay and organic matter content, percentage of
exchangeable sodium (ESP), electrolyte concentration of
percolating water and the content of calcium carbonate
(Painuli and Abrol, 1986). Cultural practices such as
tilling the soil to a fine tilth, grazing management
and cover crop management also influence the formation
of crusts (Hadas and Stibbe, 1977; Mullins et al,
1987).

Le Bissonais (1990) observed that rainfall augments the
formation of crusts. High intensity, but short duration
rainfall is highly conducive to surface sealing and
subsequent crust formation during dry spells. Morgan
(1986) argues that raindrops are agents of both
consolidation and dispersion. The consolidation effect

is best seen in the formation of a surface crust, usually only a few millimetres thick, which results from the clogging of the pores by soil compaction.

The wetting and drying cycles are important for crust strength. The disoriented aggregates are consolidated by the first wetting and drying cycle in which the wetting tends to weaken the aggregates while drying stabilizes the configuration resulting in a strong hard soil (Kemper et al, 1975). The slower the drying rate, the greater the crust strength and vice versa, Particularly in soils containing divalent ions (Gerald, 1965).

2.7.4 Formation of crusts

Hillel (1960) explained crusting by the collapse of the soil aggregates on saturation, but Farres (1978) shows that raindrop impact is the critical process. Raindrop impact on a bare soil surface disperses the finer soil particles (silt and clay) from the soil aggregates or clods (Bisal, 1960). The particles are then washed and compacted into pore spaces to form a dense surface layer. When the soil dries, it becomes hard (Hoogmoed, 1987).

High splash rates, at the beginning of a storm, are instrumental in the formation of crusts (Farres, 1985). Raindrop impact on alkaline soils disperses (deflocculates) colloidal clay particles which subsequently inhibit air and water movement down the

soil profile. This results in surface sealing and
crusting (Agassi et al, 1981). Crust hardness increases
with an increase in clay content and with a decrease in
organic matter and moisture contents (Sharma, 1985;
Hegarty and Royle, 1978; Debicki and Wontroba, 1985).

Boiffin (1985) identified two stages in the formation
of crusts. The first stage involved the development of
structural crusts, while in the second stage
depositional crusts were formed. The second stage was
marked by puddling and the development of runoff.
Boiffin also observed that the rate of expansion and
thickening of crusts was controlled by initial soil
surface morphology.

2.7.5 Assessment of crusting

Scientists have used several methods to asses surface
crusting. These are visual observation,
micromorphological studies and the indices of crust
strength. The visual observation method involves the
investigation of visible features of a crust
(occurrence, form and size). It is qualitative and very
subjective and is hence not widely applied in
scientific studies of assessing crusting.

Micromorphological studies enable particular features
of crusts (thickness, compactness, porosity and general
configuration) to be easily analyzed and characterized
(Luk et al, 1990; Kooistra and Siderius, 1985, Farres

1985). This method involves slicing a cross-section of a crust and examining it using an electron microscope. Microphotographs of the cross-section can be made. The method does not measure crust strength.

The indices of crust strength use either the cone index or the modulus of rupture index to measure the strength of a crust. Since other soil properties such as the moisture content, organic matter content, aggregation and clay content influence the strength of a crust, they are reflected in the measurement, albeit implicitly. The cone index uses a penetrometer. It is a static method of probe penetration which consists of pushing a metal rod or a cone into the soil at a constant rate (Bradford, 1980). The probe is designed to measure either:-

(i) The point resistance and the lateral friction acting on a moveable sleeve located above the point and surrounding a central rod,

(ii) The total resistance (point plus sleeve resistance); or

(iii) The point resistance only.

Davidson (1965) defined a penetrometer as any device forced into the soil to measure resistance to vertical penetration. Another method of advancing the probe into the soil, the dynamic penetration method, consists of counting the number of blows required to advance the probe a set distance into the soil (Bradford, 1980).

The modulus of rupture (MOR) concept relates to the breaking strength of beams. It is an index of maximum stress in the material when the fracture occurs in bending (Reeve, 1965)

3.0 MATERIALS AND METHODS

3.1 The study site

This study was carried out in Mukogodo Division on a site which is one of the research stations of the Laikipia Research Programme (LRP). Mukogodo Division covers roughly 1,100 km² in the North-eastern edge of Laikipia District. Laikipia District extends from the North-eastern foot of the Aberdares to the Western foot of Mt. Kenya (Appendix 7.1). The Division also constitutes the North-eastern edge of the Laikipia Plateau. On its fringe, elevation drops from 1,800-2,200 m to the lowlands of Isiolo District at about 1000 m (Herren, 1991). The Division constitutes a semi-arid area used for communal grazing, and this land use has led to severe erosion rates and land denudation (Jaetzold and Schmidt, 1983).

In Mukogodo, long term mean annual rainfall declines from Southwest to Northwest, from 700 to 500 mm/year. Rain falls mainly during the dominance of the inter-tropical convergence zone: "Long rains" in March to May, while "short rains" fall in October and November (Herren, 1991). Soils in the Division are developed on the metamorphic basement complex rocks. They are well drained to excessively drained, shallow to extremely deep and red in colour with a hue of 5YR

to 2.5YR when compared with the Munsell colour chart (Kironchi, 1992).

Most of the Division has a rugged, hilly terrain with *Acacia* Savanna vegetation (Herren, 1991). The *Acacia* species which are abundant include *Acacia melifera, Acacia etbaica, Acacia tortilis* and *Acacia nilotica.* There are extensive areas of denuded or partly denuded land, some of which is in the open and some under tree cover. This study concentrated its attention on land which is in the open.

3.2 The experiment

3.2.1 Experimental layout
vegetative cover was investigated as a major determinant of runoff and soil loss on a 3-5% slope. Two distinct cover situations were identified as representing the basic condition in the area, and two types of management were applied to each. The cover situations were:-
(a) Poor cover, perennial grasses absent;
(b) Moderate cover, indicated by the presence of perennial grasses (plates 1 and 2).

PLATE 1: The first cover situation: Poor cover, Perennial grasses absent.

PLATE 2: The second cover situation: Moderate cover, Perennial grasses present.

In the first cover situation the ground was almost entirely bare, the surface sealed; and there were no signs of perennial grasses. If they were there in the past they had died out. It was expected that this situation would lead to the maximum rates of run off and soil loss. In the second cover situation there was some cover (<5%) of intensively grazed perennial grasses. The ground in between the patches of grass was sealed but it was expected that the grass cover would exert a significant degree of control on the rate of run-off and soil loss.

The first management situation applied was that prevailing in the Division. This was a system of continual grazing which effectively prevented land recovery. The second management situation was that which could occur under a system of controlled grazing, whereby land which had become denuded was rested to allow the recovery of perennial grasses.

The experiment aimed to study and understand what was happening in a real situation of heavily grazed rangeland. It started with what was already there and aimed to find out what would happen if there was no change in management and what might happen with the simplest management technique of closure to grazing.

3.2.2 Treatments

Two site conditions with respect to vegetation cover and two management systems were the treatments. They were designated as follows (Fig 3):-

<u>1. Perennial Enclosed (PE):</u>

-Some perennial grasses present but heavily grazed

-Vegetation cover more than 5%

-Area protected from further grazing by thorn hedge.

<u>2. Perennial Open (PO):</u>

-Some perennial grasses present but heavily grazed

-Vegetation cover more than 5%

-Area open to normal grazing by livestock

<u>3. Bare Enclosed (BE):</u>

-No perennial grasses

-Vegetation cover less than 5%

-Area protected from further grazing by thorn hedge

<u>4. Bare Open (BO):</u>

-No perennial grasses

-Vegetation cover less than 5%

-Area open to normal grazing by livestock

<u>NB:</u> The vegetation cover mentioned in 1 to 4 was foliage cover measured during the dry season.

Three run-off plots, each measuring 2 by 10 meters were installed on sites representing each of the above

N

0 _____ 50 m

Slope 3 - 5 %

```
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         ********************
         *                  *
         *                  *
         *  ┌──┐┌──┐┌──┐     *
         *  │PE││PE││PE│     *
         *  │1 ││2 ││3 │     *
         *  └──┘└──┘└──┘     *
         *                  *
         *                  *
         *                  *
         ********************
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┌──┐
│RO│
│1 │
└──┘

┌──┐
│RO│
│2 │
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┌──┐
│RO│
│3 │
└──┘

┌──┐┌──┐┌──┐
│PO││PO││PO│
│1 ││2 ││3 │
└──┘└──┘└──┘

┌──────────┐
│   │
│ MET.   │
│ STATION │
│   │
└──────────┘

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│BO│    *  ┌──┐  ┌──┐┌──┐  ┌──┐
│1 │    *  │BE│  │BE││BE│* │BO│
└──┘    *  │1 │  │2 ││3 │* │3 │
        *  └──┘  └──┘└──┘  └──┘
┌──┐    *                    *
│BO│    *                    *
│2 │    *                    *
└──┘    *                    *
Wc1 dc1 *     dc2 wc2        *
        **********************
```

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**************
* STATION    *
* RESIDENCE  *
**************
```
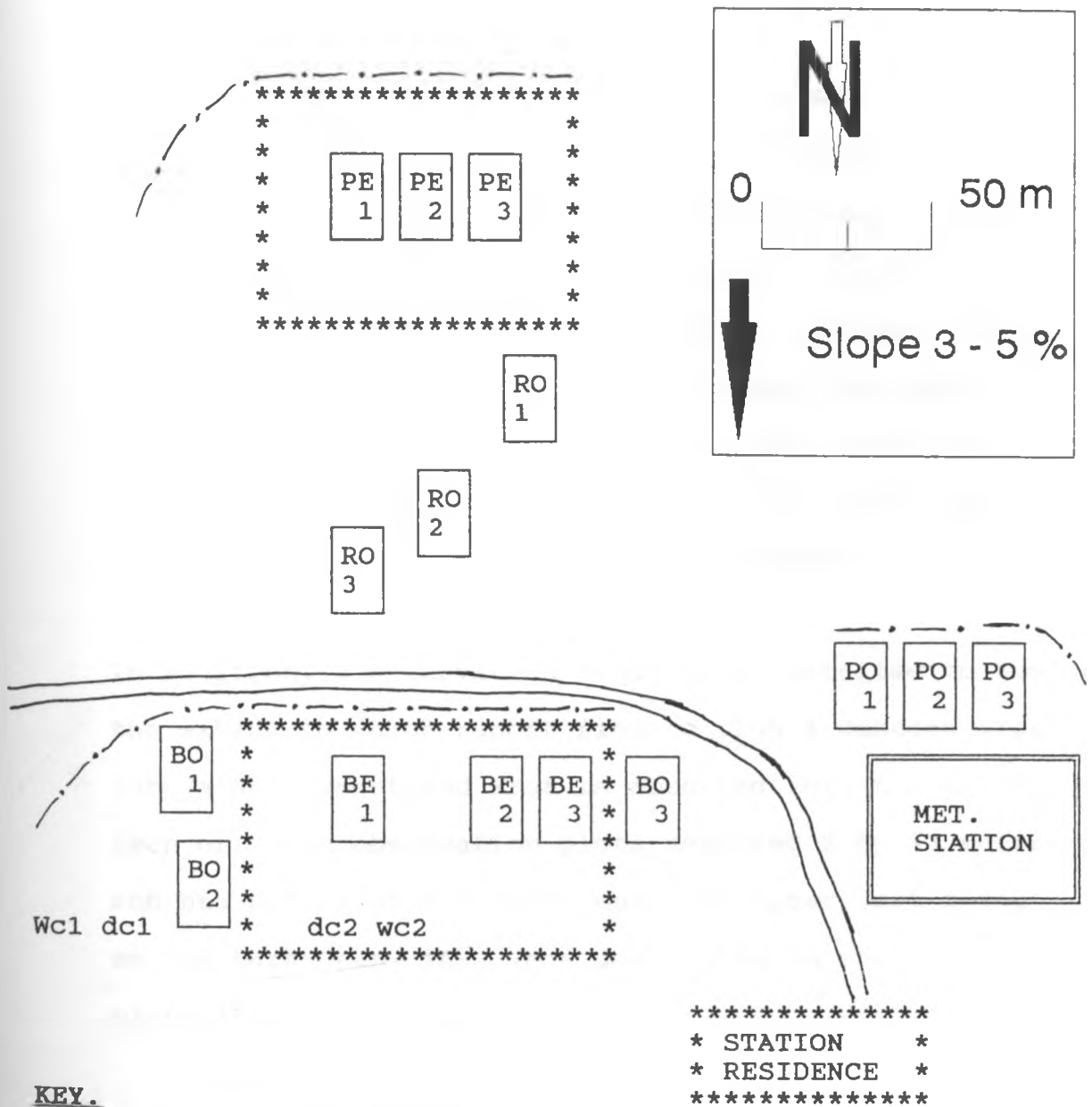
KEY.
PE——— Perennial enclosed.
PO——— Perennial open.
BE——— Bare enclosed.
BO——— Bare open.
RO——— Run-on.
***——— Thorn edge
wc1——— Wet calibration site 1.
dc1——— Dry calibration site 1.
wc2——— Wet calibration site 2.
dc2——— Dry calibration site 2.
—·—·—·~ Cut-off drain for experiment.
⟩⟩⟩⟩ Access road

FIGURE 3: Field layout.

treatments (Fig.3). Each run-off plot consisted of a plot boundary to prevent soil and water from entering or leaving the plot; a collector which served as a weir at the end of the plot; and a conveyance channel to guide the flow of soil and water into a storage tank. A removable drum was placed in the storage tank below the inflow spout. This helped in reducing the time required to sample and clean up after small storms; and also improved the accuracy of volume measurements.

In addition, 3 observation plots were installed to test the extent to which runoff flowing from a denuded area into a well vegetated area is absorbed into the ground. Each of these observation plots measured 2 by 13 meters and had a tree at the lower end, the upper part being as the Bare Open. They were designated as the Run-On plots (RO). (Fig. 3).

3.2.3 Data collection

Rainfall parameters (amounts and intensities) were measured by means of an automatic rainfall recorder; soil moisture by means of a neutron probe; and soil surface condition by means of a cone penetrometer. Vegetative cover in all the plots was measured by the point method ; care being taken to avoid excessive trampling in the enclosed plots. Runoff and sediment yield from each plot were measured after each rainfall event. Details on the measurement of each of the above

parameters are given on sections 3.4 through 3.9.

3.3 Runoff equipment installation

3.3.1 Plot boundary

The plot boundaries were made from strips of 28 gauge plain galvanized iron sheets 25 cm high by 200 cm long. The boundaries were installed at 12 cm depth by first making a trench round the plot. Earth was packed around the boundary end plate joint and the outside of the boundaries to prevent leaks. To achieve a 10 metre boundary (length of the plot), the strips were fastened together using 8 mm diameter iron rods. The rods were bent to form a hook, which held the strips firmly together, and then hammered 63 cm into the ground (on the outside of the plot).

3.3.2 Runoff collector

The collector was constructed from galvanized iron sheet metal (gauge 16). It acted as a weir across the lower end of the plot and also as a channel for runoff-soil mixture flowing into the sampling unit. The collector trough was designed to reach across the entire width of the plot. It was 20 cm deep, 20 cm wide and had a 5% bottom slope (Fig. 4).

M = D = depth.

W = Width.

Z = Bottom slope.
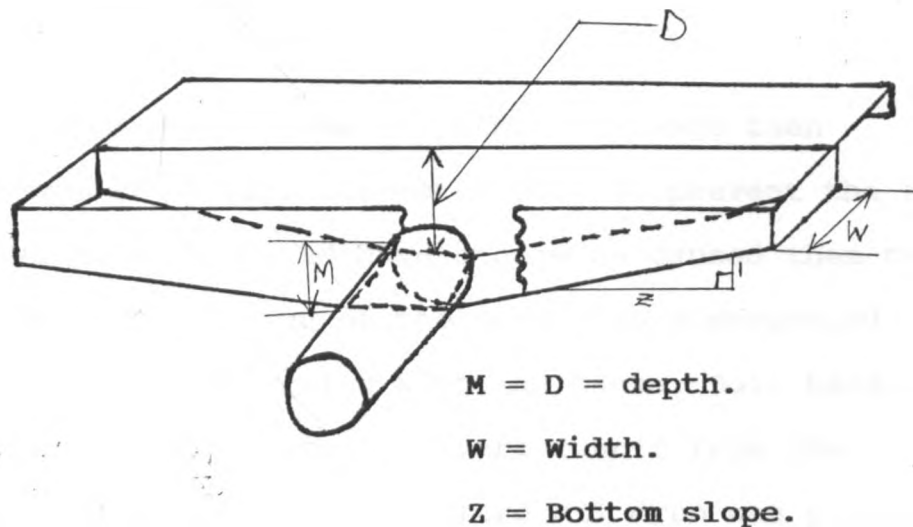
FIGURE 4: The runoff collector.

3.3.3 Conveyance channel

A low-pressure PVC pipe slipped over the runoff collector outlet, was used to convey runoff to the storage tank. It was 110 mm in diameter and 2 m long.

3.3.4 Storage tank

A single tank was used for each plot to store all the soil loss-runoff mixture. The tank was constructed from 24-gauge corrugated iron sheets. Its capacity was 1.15 m^3(0.85 m high, 1.31 m in diameter; and could store 57.5 mm of runoff). This volume was calculated by assuming a 3 hr storm with an intensity of 20 mm/hr whose infiltration rate was 5 mm/hr. A maximum of 100 tonnes/ha sediment with a bulk density of 1200 kg/m^3 was allowed. To prevent fast rusting, the tanks were

had a lid to ensure that direct rainfall never got into the tank.

The tanks were placed in pits. They were then surrounded by well compacted soil to prevent the inflow of water which could have otherwise caused them to float. The coverage of the pits also discouraged vandals from tampering with the tanks. Soil bands were built round the pits to divert runoff from the surrounding areas. A 200-litre oil drum was placed inside the tank, below the inflow spout of each plot. The drum helped in reducing the time required to sample and clean up after small storms.

3.4 Measurement of runoff and soil loss

The procedures as outlined in Liniger (1991a) were basically followed, with some modifications. Two categories of runoff events were received and data collection was done as described below.

3.4.1 Small runoff events

These were the events produced by storms whose runoff from the entire plot was adequately stored in the oil drum, without any overflow into the big tank. The following sampling procedure was used for such events:-

(a) The collector and conveyance was checked for plant residue. These were removed whenever present.

(b) Any soil in the collection trough was flushed into

tank A (oil drum) by using water from tank A. The flush water was carefully taken from Tank A, with a jug having a pouring spout. An allowance of 5 minutes was given for the sediment to settle.

(c) During this time the plot was inspected for any technical faults e.g. water entering from outside or runoff from the plot not being collected. Any problem discovered was noted and the mistake corrected after having finished the day's data collection.

(d) The water depth to the top of the sediment surface in tank A was measured at 3 different places and recorded in the proper spaces on the field form (Appendix 7.2).

(e) The water above the sediment in tank A was removed carefully (without stirring), bucket by bucket. From each bucket, a 0.5 litre sample was taken. All the samples from this tank were then poured into a bucket and stirred vigorously. A 0.5 litre sample was then taken to represent the water above the sediment in this tank. The date of sampling and the tank number were indicated on the sample bottle.

(f) Tank A was lifted out of tank B (storage tank). The sediment in tank A was scooped out into a clean pre-weighed bucket and weighed to the nearest 0.05 kg. The sediment was thoroughly mixed till it formed uniform consistency and about 0.5 kg sediment sample taken. This sample was placed into a plastic bag and on it the date of sampling and the tank number indicated.

(g) Tank A was cleaned and put in the right position to be ready for the next storm.

3.4.2 Large runoff events

These heavy runoff events produced overflows from tank A into tank B. The following sampling procedure was used:-

(a) Steps (a)-(d) in section 3.4.1 were followed.

(b) The water depth to the bottom of tank B was measured at 3 different places. If there was any sediment, the folding meter was pushed through it during the depth measurement.

(c) The water and sediment in tank B were stirred well and removed bucket by bucket. From each bucket, a 0.5 litre sample was taken. The water at the bottom of the tank was removed by soaking it up using a piece of foam sponge and transferred into the bucket. All the samples from this tank were poured into a bucket and stirred vigorously. A 0.5 litre sample was then taken to represent the water in the tank.

(d) Steps (e) - (g) in section 3.4.1 were then followed to complete the sampling.

3.5 Laboratory analyses

3.5.1 Suspended sediment samples

All samples in bottles were analyzed for suspended sediment. The following steps were followed:-

1. A filter paper was weighed, folded and placed into a funnel. The funnel was placed into a collecting bottle.

2. The bottle containing the sample was shaken vigorously and the sample emptied into the funnel.

3. Some little water was put into the bottle which had contained the sample. Later, when the filtration had continued for sometime, the water in the sampling bottle was shaken vigorously and added into the funnel. The arrangement was left for a day for the filtration process to be complete.

4. The filter containing the residue was carefully removed and put into an oven. It was then dried at 105 degree Celsius until it reached a constant mass. This mass was recorded.

5. The mass of the sediment in the sample could now be determined and the mass in the total runoff calculated.

3.5.2 Sludge dry mass

The sludge sample was weighed and the plastic bag containing it opened up. The sample, still in the plastic bag, was placed in the oven and dried at 105 degrees Celsius until it reached a constant mass. (The plastic bag used was special in that it could withstand this temperature). This constant mass was recorded. The mass of sediment in the sludge sample could now be determined; and the mass in the total sludge calculated.

3.6 Calculation procedures

3.6.1 Runoff volume

The volume of runoff from each plot for each storm was calculated in 3 steps:-

(a) The volume of runoff above the sediment in tank A was calculated as

$$V_1 = \frac{\pi d^2}{4} h \qquad (6)$$

where V_1 = Volume of runoff above sediment, cm^3.

d = diameter of tank A, cm.

h = average water depth to sediment surface, cm.

The average water depth to sediment surface, h was calculated as:-

$$h = \frac{(h_1 + h_2 + h_3)}{3} \qquad (7)$$

Where h_1, h_2 and h_3 were the water depths to the sediment surface at the three places.

(b) The volume of water in the sludge from tank A was calculated as:-

$$V_2 = \frac{(w_1 - w_2)}{w_1} W \qquad (8)$$

where V_2 = Volume of water in sludge , cm^3.

w_1 = Mass of sludge sample, g.

w_2 = Dry mass of sludge sample, g.

W = Total mass of sludge; g.

(c) The volume of runoff in tank B was calculated as :-

$$V_3 = \frac{\pi}{4}(D^2 - d^2)H \qquad (9)$$

where V_3 = Volume of runoff in tank B, cm³

D = Diameter of tank B, cm.

d = Diameter of tank A, cm.

H = average water depth in tank B, cm.

The average water depth in tank B, H was calculated as:

$$H = \frac{(H_1 + H_2 + H_3)}{3} \qquad (10)$$

where H_1, H_2 and H_3 were the water depths in tank B at the three places.

The volume of runoff for the plot for the storm, V was finally computed as:-

$$V = (V_1 + V_2 + V_3), cm^3 \qquad (11)$$

3.6.2 Soil loss

The steps as shown below were followed in the computation:-

(a) The soil in the runoff from tank A was calculated as

$$S_1 = \frac{(w_4 - w_3)}{500} V_1 \qquad\qquad (12)$$

where S_1 = total soil in the Runoff from tank A, g

w_3 = mass of filter paper, g

w_4 = mass of filter paper and dry soil, g

(b) The soil in the runoff from tank B, S_2 was calculated as :-

$$S_2 = \frac{(w_4 - w_3)}{500} V_3 \qquad\qquad (13)$$

(c) The soil in the sludge from tank A, S_3 was calculated as :-

$$S_3 = \frac{w_2}{w_1} W \qquad\qquad (14)$$

The total soil loss for the plot for the storm, S was finally calculated as:-

$$S = (S_1 + S_2 + S_3), g \qquad\qquad (15)$$

3.7 Measurement of Vegetative cover

3.7.1 Field data

The line-point method for cover estimation was used. A string was used. The points were pre-determined by making knots, spaced 40 cm apart on the string. Three

transects were marked inside each runoff plot, along the length of the plot. The transects were 50 cm away from the plot borders and 50 cm apart. The position of the transects was marked by driving wooden pegs on the outside of the upper end of each plot and again on the outside of the lower end of each plot.

Cover measurements were taken on weekly intervals. During each measurement, the string would be stretched on each transect such that the knots were inside the plot. The string ends would then be tied on the wooden pegs at the upper and lower ends of the plot. A sharp pointed rod would be dropped at each knot, starting from one end of the string, towards the other end. The hits or misses of above ground cover would be recorded on a field data sheet (Appendix 7.4). For each hit, it would be indicated on the data sheet whether the cover was an annual or perennial and whether it was green or dry cover.

3.7.2 Cover calculation

For each runoff plot, the percentage cover was calculated as:

$$\%Cover = \frac{n}{N} \times 100 \qquad (16)$$

where

n = Total no. of hits from the three transects,

N = Total points on the three transects.

Since each transect had 25 points, the total points on the three transects was 75. The percentage cover was therefore calculated as:-

$$\%Cover = \frac{n}{75} \times 100 \qquad (17)$$

3.8 Measurement of soil moisture

3.8.1 Installation of access tubes

Holes for the access tubes were drilled by using hand soil augers. Since the access tubes were 5 cm in diameter, the augers used had a diameter slightly larger than 5 cm. Two people were used per auger to ensure that the auger hole was vertical. After the 1 m depth was achieved, the aluminium access tube was cut, the total length being 110 cm. This was to ensure that a 10 cm length of the access tube was left above the soil surface after the access tube was installed.

The tube could only go freely into the augered hole for the first 40-50 centimetres. The insertion was therefore accomplished by placing a wooden plank on the upper end of the tube and then hammering the plank to force the tube down. After the desired depth was achieved, soil was tightly packed around the access tube. This was to ensure that no air spaces were left

around the access tube; and that water could not flow
in along the tubes. Each access tube was covered by a
lid to keep out direct rainfall.

3.8.2 Using a neutron probe

A neutron probe CPN 503 (Campell Pacific Nuclear Corp.)
hydroprobe was used. The instrument has a radioactive
source, which if properly handled is not dangerous. The
readings were taken from the aluminium access tubes.
For every treatment, 3 access tubes had been installed
outside the runoff plots. The Neutron probe readings
were taken at weekly intervals.

The procedure for taking Neutron probe readings as
described by Liniger (1991a) was followed. Readings
were taken at 15, 30, 45, 60, and 75 cm depths.

3.8.3 Calibration of the Neutron probe

A calibration was carried out to establish the
calibration equation for predicting volumetric water
content of the soil from count ratio measurements. The
relationship between the count ratio and the volumetric
water content is linear (Greacen, 1981). The
calibration was done in two stages: a 'dry' and a 'Wet'
calibration. A combination of the 'dry' and 'wet'
calibrations provides moisture data covering the whole
soil moisture range (Greacen, 1981; Liniger, 1991b).
Some access tubes had been installed specifically for

this purpose. The calibrations were done on march 24, 1993 ('dry' calibration) and between June 17 to 24, 1993 ('wet' calibration).

PLATE 3: The Neutron probe used to measure soil moisture.

The 'dry' calibration was performed at permanent wilting point. This condition was indicated by the drying of grass. At each measuring depth (15, 30, 45, 60, and 75 cm), the probe reading was recorded five times. At each depth also, five soil samples were taken from a radius of 5 cm from the access tube. Core rings of 1000 cm^3 capacity were used (Plate 4). The soil samples were put into plastic bags and weighed before and after oven drying.

A tube installed about 3 m away from the access tube

used for 'dry' calibration was used in the 'wet'

calibration. The wet calibration was carried out at

field capacity. The soil was moistened to field

capacity by applying water. An area of 1.5 metres

diameter around the access tube was bounded by sheet
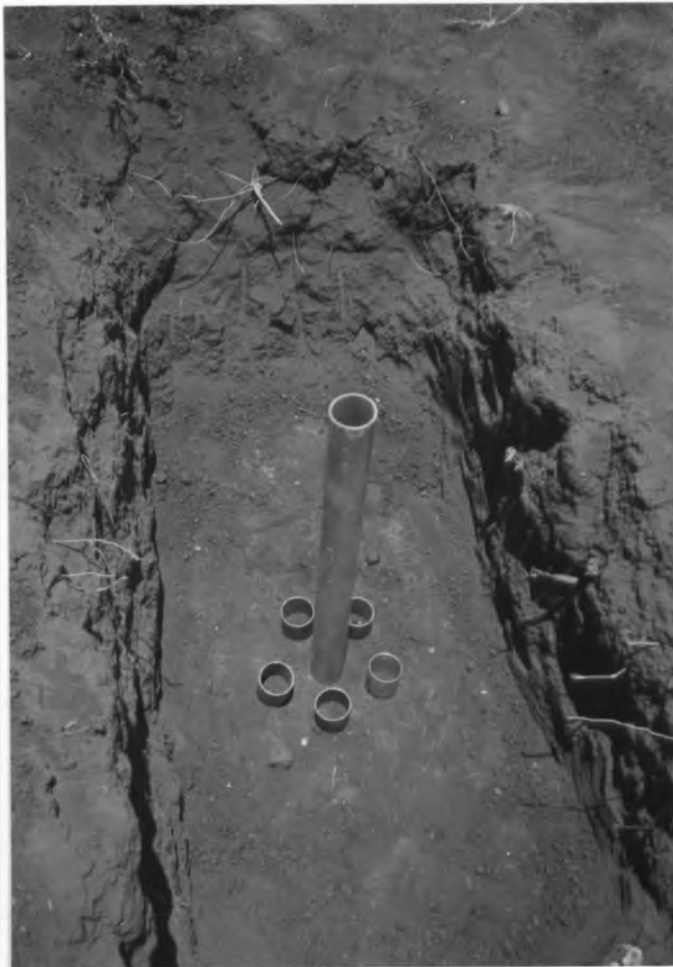
PLATE 4: Soil sampling using core rings for the Neutron probe calibration.

metal 25 cm high which was inserted 12 cm deep into the

soil. Water was applied into the bounded area for 4 to

5 days. To avoid evaporation from the soil surface, the

surface of the bounded area was covered by a layer of

grass and a plastic paper. This arrangement was left

for 1.5 days after the last day of water application.

This was done to allow drainage of gravitational water. The same procedure as the one used in 'dry 'calibration was used to take the soil samples and probe readings.

3.9 Assessment of crust strength

3.9.1 The instrument

A hand held cone penetrometer for top soil layers (type 1B, Eijkelkamp Equipment) was used in this study (Plate 5). This instrument measures the penetration resistance by means of a compression spring. The instrument is composed of a cone, a sounding rod, an extension rod, and a measuring device. It has 2 cone types (0.25 cm² and 0.5 cm²) and 3 kinds of compression springs (50 N, 100 N, 150 N). A particular combination of a cone and a compression spring can be selected depending on the penetration resistance to be expected.

When the cone encounters a resistance as it is driven into the ground, the spring within the penetrometer is compressed. A slip ring on a graduated scale is taken along as the spring is compressed and so it indicates the maximum compression measured. By using the spring constant and the cone area , this compression can be translated into penetration resistance.

Cone penetrometer measurements were taken (when the instrument was available) after each runoff. This was

done in order to access the crust strength and relate it to the amount of runoff received. Each plot had been divided into 1 m by 2 m plots. A measurement was taken on each small plot once, and the reading on the scale entered on the appropriate place on the data sheet (Appendix 7.6). The ten readings were then averaged to give the penetrometer resistance reading for the particular plot.

3.9.2 Penetration resistance

Cone resistance, R is given by

$$R = \frac{F}{A} \qquad (18)$$

where

    R = Cone resistance (N/cm^2),

    F = Total force (N),

    A = cone area (cm^2).

but R can also be expressed as

$$R = L \times \frac{K}{A} \qquad (19)$$

where

    L = Compression of spring, cm.

    K = Spring constant, N/cm.

For a selected combination of spring and cone the factor K/A is a constant, Q. Thus the penetration

resistance was calculated as:-

$$R = L \times Q. \qquad\qquad (20)$$
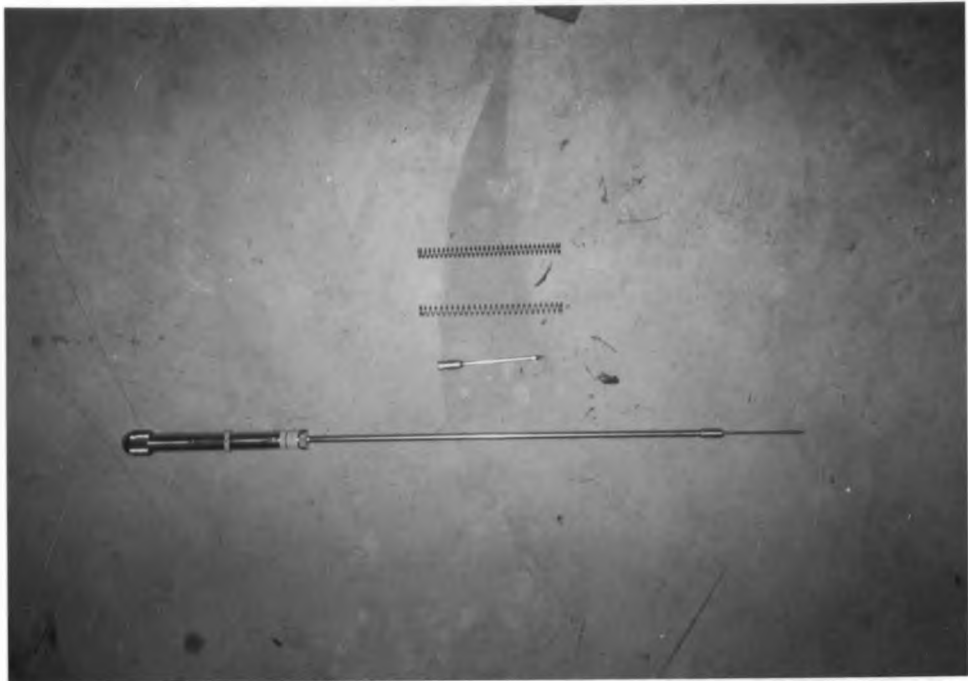
PLATE 5: The cone penetrometer used for crust strength assessment.

4.0 RESULTS AND DISCUSSION

4.1 Soil Chemical and Physical parameters

Table 1 provides order-of-magnitude data for some chemical and physical soil parameters in the study area. Soil texture ranges from sandy clay to sandy loam. The soils in the study area typically have a zone of higher clay content in the profile due to illuviation of particles from the upper horizons (Kironchi, 1992).

Comparing corresponding depths, the Bare plots (Bare Open and Bare Enclosed) have a clay content that is about twice that in the perennial plots (perennial open and perennial enclosed). Brady (1984) notes that a zone of accumulation of clays is a B horizon in a soil profile. Thus the soil surface in the perennial plots lies between the O and A horizons, while the soil surface in the Bare plots is in the B horizon. A possible explanation is that an illuviated clay horizon is now on the surface of the Bare plots, after the upper horizons have been eroded. From the results, the upper horizons in the perennial plots are still intact.

From table 1, bulk density has a narrow range of 1.32

Table 1: Soil Chemical and Physical data for the study area.

TREATMENT	BE			BO			
DEPTH (cm)	15	30	45	15	30	45	15
BULK DENSITY (g/cm^3)	1.32	1.35		1.34	1.38		1.44
% SAND	46.3	46.4	40.5	50.2	46.3	39.5	59.1
% SILT	12.8	9.8	9.5	11.8	7.9	10.8	24.5
% CLAY	40.9	43.8	50.0	38.0	45.8	49.7	16.4
TEXTURAL CLASS	SC	SC	C	SC	SC	C	SL
ORGANIC CARBON (%)	1.22	1.14	0.68	0.95	0.91	0.57	1.25
ORGANIC MATTER (%)	2.11	1.97	1.17	1.64	1.57	0.99	2.16

KEY.

BE: Bare Enclosed. BO: Bare Open. PE: Perennial Enclosed. PO

SC: Sandy clay. C: Clay. SL: Sandy loam. SCL: Sandy clay loam.

to 1.44 g/cm³. It generally shows an increasing trend with depth. According to Brady (1984), bulk density may vary from 1.20 to 1.80 g/cm³ in sands and sandy loams. The values observed thus lie in this range. Working in the same area, Kironchi (1992) recorded bulk density values ranging from 1.32-1.64 g/cm³.

The percentage of organic carbon values range from 0.57 to 1.94. All the values are less than 2. The soil in the study area can therefore be rated as having a "very low" organic carbon content according to Landon (1984).

The organic matter values shown in table 1 were obtained by multiplying the organic carbon percentage by a conversion factor of 1.729 (Landon, 1984). The values range from 0.99 to 3.35 and decrease with depth for each treatment. The perennial Open plots have about 1% higher organic matter values at each depth as compared to the Perennial Enclosed plots, yet cover development in the latter was better. The Bare plots have about the same organic matter values as the Perennial Enclosed plots although cover development in the former was very poor. The data thus shows no clear relation between organic matter and cover development.

4.2 Rainfall amount and distribution

The monthly total rainfall received in the study period
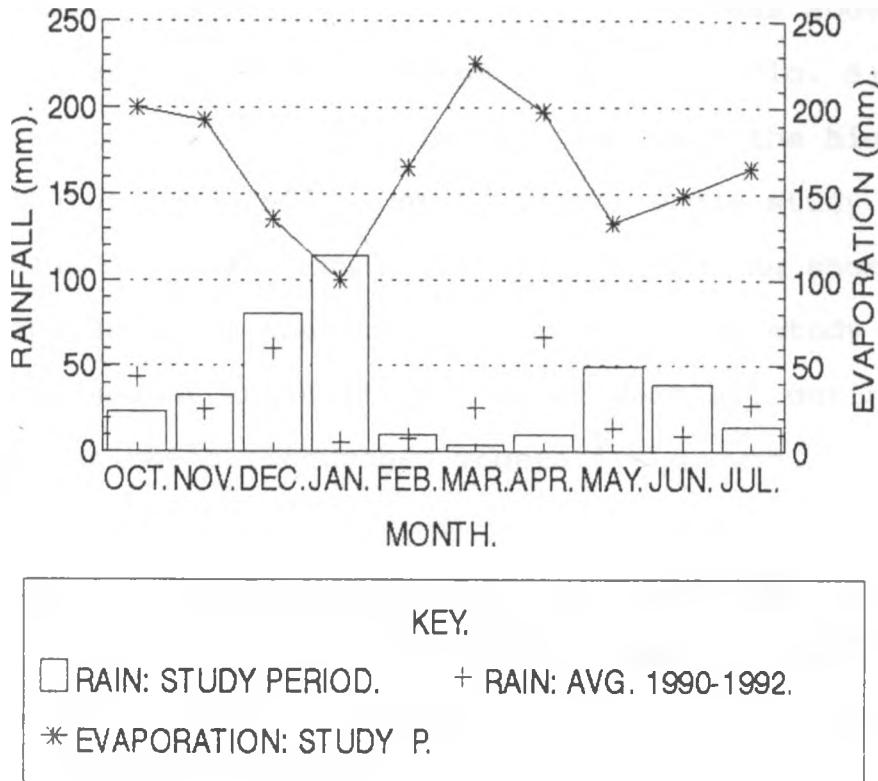
FIGURE 5: Monthly rainfall and Evaporation (mm) over
the study period (Oct. 1992-July 1993) at Mukogodo.

(Oct.1992 to July 1993) is shown in Fig. 5. A total of
377 mm was received. In the short rains (Oct. 1992 to
Feb. 1993) 261 mm of rain was received, while the long
rains (March to July 1993) recorded 117 mm. Fig. 5 also

shows the average monthly total rainfall for the years 1990-92 and the monthly pan evaporation over the study period.

Monthly rainfall in the short rains was above the three-year average except in October (Fig. 5). January recorded 114 mm of rainfall. This was the highest monthly rainfall recorded in the whole study period (43.7% of total rainfall received during short rains and 30.2% of the total rainfall in the study period). The amount and distribution of rainfall during the short rains encouraged vegetative growth.

The long rains (March-July 1993) received low amount of rainfall (Fig. 5). The month of May recorded the highest rainfall amount (50 mm). Rainfall amounts during the long rains were generally below the three-year average. Compared with the short rains, the rainfall amount and distribution in the long rains was poor. High pan evaporation values were recorded throughout the study period (Fig. 5). Pan evaporation was higher than the monthly rainfall except in the month of January. This shows the need and importance of reducing the rainwater lost as runoff, if vegetative growth is to be encouraged.

4.3 Runoff

Rainwater loss by runoff on the Bare plots (Bare Enclosed and Bare Open) was high. Figure 6 shows monthly rainfall (only those events producing runoff) and mean runoff for the various treatments over the study period. In storms of more 10 mm rain and over seven erosivity units, more than 50% of the rainwater was lost (Table 2). This compares favourably with results by Moore et al (1979). Using a simulated rainstorm of 69 mm/hr for 1 hr with an erosivity value of 51 $J.m^{-2}.cm.h^{-1}$, they showed that 63% of the rainstorm was lost as runoff in a semi-arid area of Machakos District. Liniger (1992) also showed that over half of rainwater was lost as runoff on overgrazed land in the semi-arid highlands Northwest of Mount Kenya.

The fact that 50% of rainfall is lost from the Bare plots clearly shows that recovery on these plots will not take place easily unless measures are taken to get water into the ground. This could be achieved by using techniques such as pitting, ripping, slashing of bush and piling of trash lines, etc.

On the Perennial Enclosed plots runoff was below 30% of the rainfall, while on the Perennial Open plots runoff

Table 2: Percent cover, runoff, soil loss and rainfall characteristics in Mukogodo from November 1992-July 1993 (All treatments).

Date	Rain	Cover (%)				Runoff (% of rain)					Soil loss (t/ha)					Rainfall characteristics			
																Intensity (mm/h)		Energy	Erosivit
	(mm)	BO	BE	PO	PE	BO	BE	PO	PE	RO	BO	BE	PO	PE	RO	I15	I30	(J/m2)	EI30/10
30/11/92	8.6	0.0	0.0	5.1	7.8	33.2	39.3	13.5	0.0	1.4	0.470	0.209	0.154	0.000	0.007	13.6	6.8	173.2	
06/12/92	7.9	0.0	0.0	5.3	8.9	29.7	33.6	11.6	0.0	2.6	0.363	0.184	0.096	0.000	0.006	20.2	11.6	155.6	
10/12/92	20.7	0.0	0.0	5.3	8.9	52.2	56.3	24.1	12.0	20.9	2.860	1.755	1.887	0.436	0.849	38.4	24.0	441.2	
12/12/92	10.1	0.0	0.0	6.2	9.8	34.8	40.6	11.1	0.8	5.6	0.221	0.051	0.017	0.001	0.007	6.0	5.0	172.5	
17/12/92	22.5	0.0	0.0	6.2	9.8	78.7	79.5	55.5	39.8	39.0	3.718	2.358	2.589	0.719	0.800	38.0	24.6	599.0	
27/12/92	5.0	0.0	0.0	18.1	25.2	24.9	31.8	1.3	0.0	0.0	0.034	0.123	0.002	0.000	0.000	6.8	4.4	144.6	
07/01/93	27.6	0.0	0.0	20.0	30.5	75.9	84.0	43.6	8.3	29.5	1.693	1.095	0.667	0.070	0.239	17.2	24.8	679.1	
13/01/93	6.6	0.0	0.0	20.4	32.5	17.6	23.0	0.0	0.0	0.0	0.020	0.008	0.000	0.000	0.000	4.4	3.0	108.8	
17/01/93	4.8	0.0	0.0	19.3	33.0	23.8	26.6	1.9	0.0	1.3	0.035	0.025	0.001	0.000	0.002	9.0	4.8	199.6	
18/01/93	8.0	0.0	0.0	18.7	33.2	48.2	51.9	5.1	0.0	5.0	0.088	0.129	0.010	0.000	0.007	6.8	6.0	168.7	
19/01/93	8.2	0.0	0.0	17.8	33.9	49.0	52.6	10.8	0.7	11.7	0.248	0.225	0.009	0.000	0.010	8.4	8.2	152.4	
20/01/93	14.4	0.0	0.0	17.0	33.0	66.2	68.4	41.0	14.2	35.2	2.441	1.432	0.287	0.040	0.476	24.0	22.2	300.2	
30/01/93	34.5	8.0	5.3	33.7	42.0	45.7	47.9	10.6	1.3	15.9	1.584	0.792	0.067	0.006	0.210	32.0	19.4	640.0	
10/02/93	5.1	10.6	7.1	30.8	34.4	19.8	20.9	0.0	0.0	2.0	0.012	0.015	0.000	0.000	0.001	NA	NA	13.2	
27/03/93	3.2	4.4	2.6	10.7	18.8	2.0	4.3	0.0	0.0	0.0	0.001	0.003	0.000	0.000	0.000	3.2	3.2	58.3	
18/04/93	7.9	4.0	3.9	13.0	20.5	4.8	13.0	0.0	0.0	0.0	0.018	0.014	0.000	0.000	0.000	7.6	6.4	132.3	
06/05/93	11.9	4.5	1.8	6.5	13.0	91.2	91.8	62.7	26.4	59.9	5.631	3.866	1.338	0.145	1.138	60.0	30.8	419.4	
11/05/93	5.4	5.0	2.2	8.0	17.8	92.0	96.9	27.4	0.0	25.4	2.216	1.152	0.087	0.000	0.069	28.8	15.0	181.3	
12/05/93	6.3	5.0	2.2	8.0	17.8	49.8	53.3	15.0	0.0	16.0	0.352	0.212	0.024	0.000	0.022	8.8	7.2	124.7	
20/05/93	17.3	5.3	3.1	10.7	28.5	92.8	88.7	64.7	28.1	54.0	4.738	3.830	2.126	0.306	0.653	51.2	40.2	548.7	
08/06/93	8.0	3.5	3.5	6.0	14.5	29.9	41.4	0.0	0.0	1.4	0.181	0.125	0.000	0.000	0.002	18.0	13.6	180.0	
09/06/93	12.6	3.5	3.5	6.0	14.5	19.8	30.0	2.2	0.0	1.5	0.302	0.197	0.014	0.000	0.001	7.6	6.0	220.7	
10/06/93	7.1	3.5	3.5	6.0	14.5	10.7	10.0	0.0	0.0	0.0	0.087	0.133	0.000	0.000	0.000	5.2	3.6	102.8	
11/06/93	6.5	3.5	3.5	6.0	14.5	7.3	11.2	0.0	0.0	0.0	0.027	0.049	0.000	0.000	0.000	7.2	5.4	55.1	
19/07/93	14.6	4.5	3.5	11.5	23.6	56.8	60.5	28.8	0.5	22.3	2.563	2.106	0.770	0.003	0.270	43.6	24.2	305.8	
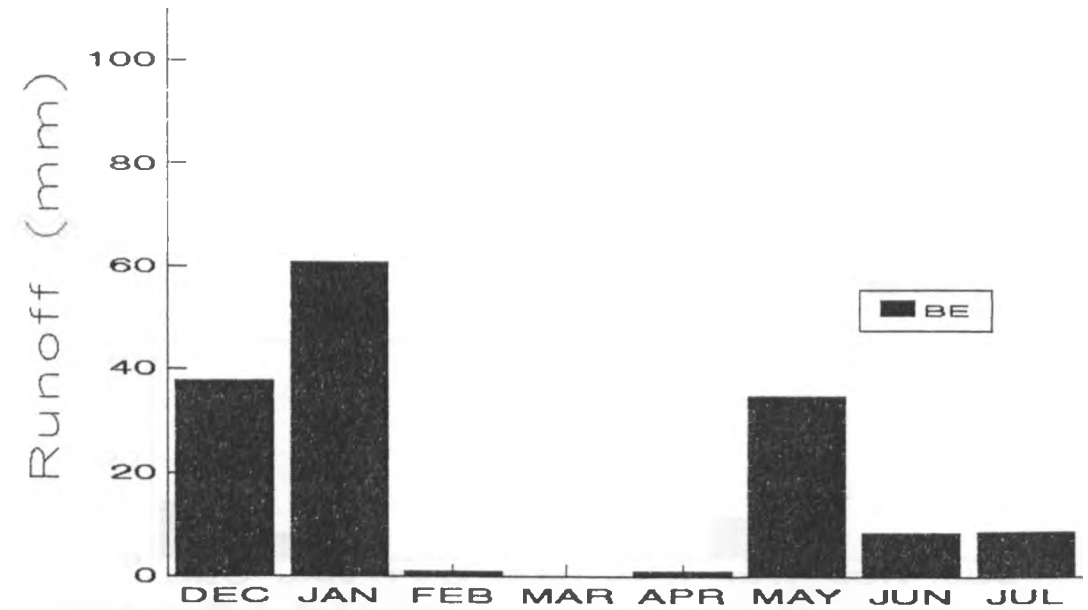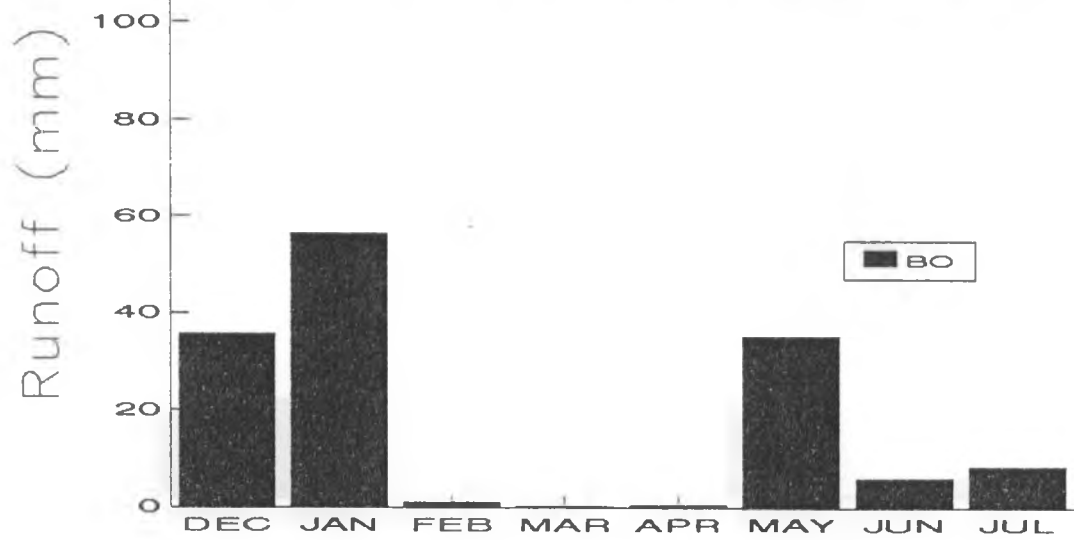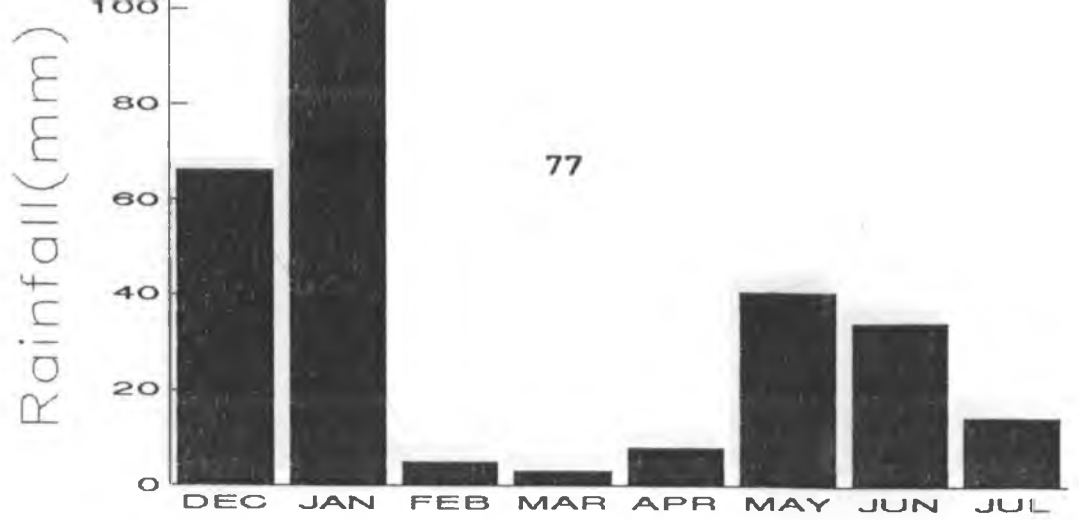
FIGURE 6a: Rainfall and mean runoff for the Bare Open and Bare Enclosed plots over the study period.
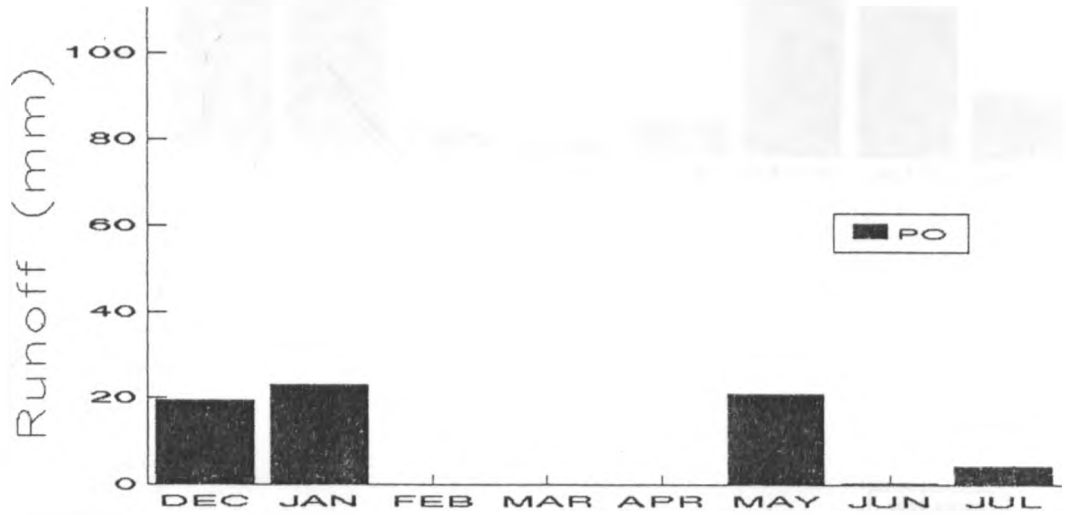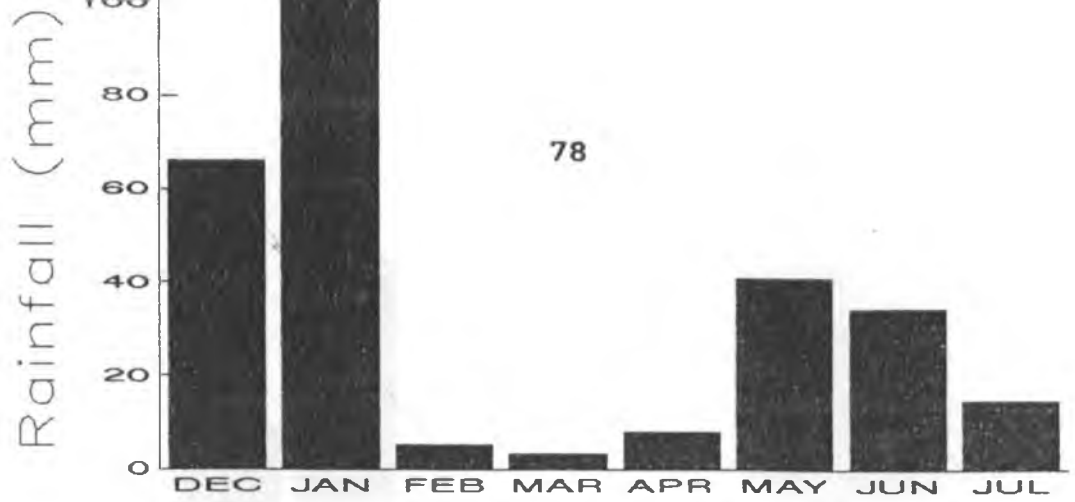
FIGURE 6b:Rainfall and mean runoff for the Perennial
Open and Perennial Enclosed over the study period.
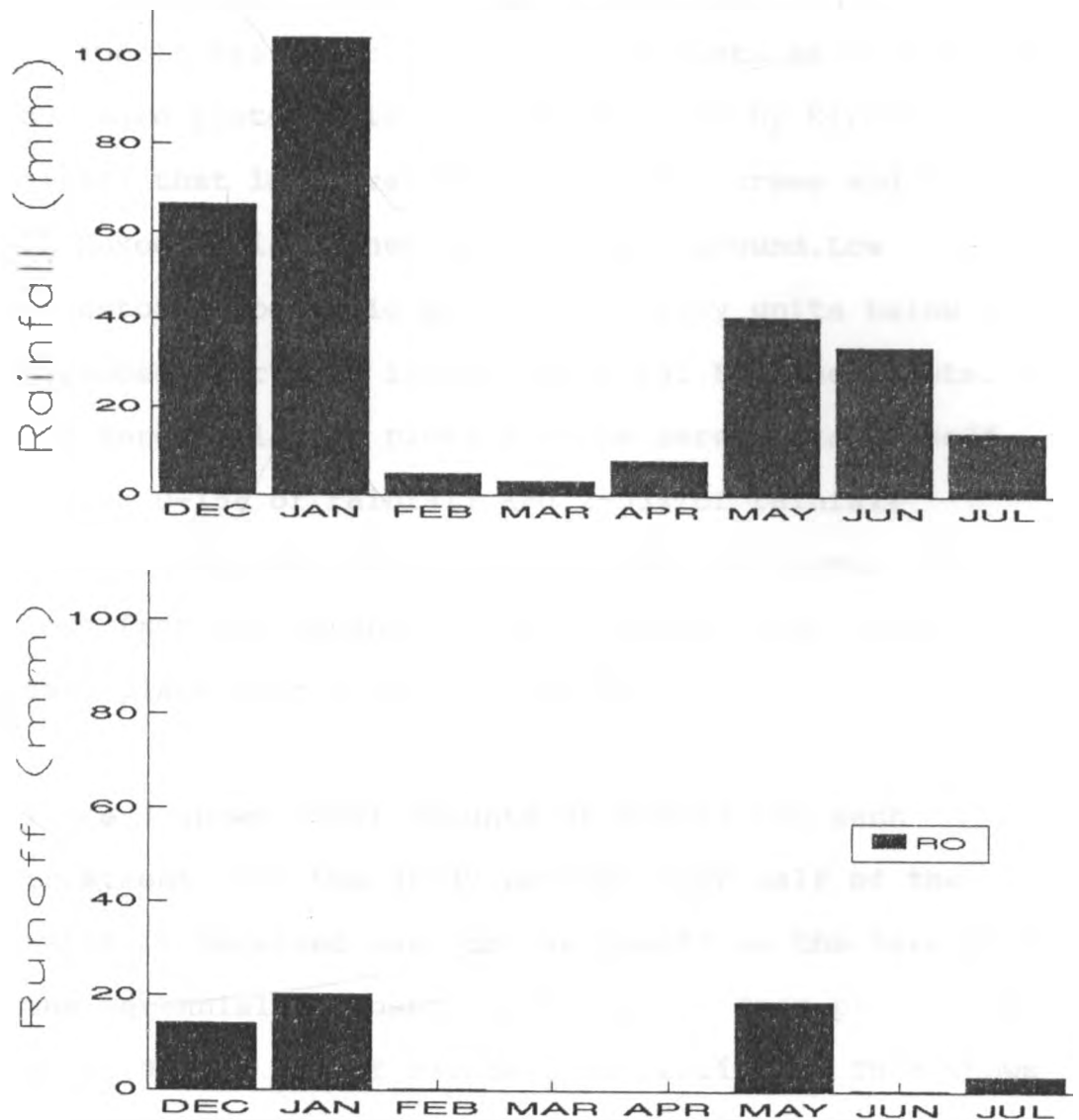
FIGURE 6c: Rainfall and mean runoff for the Run-On plots over the study period.

averaged 20-60% of the rain for the heavy storms.

Values of runoff on the Run-On plots was between those

of the Perennial Enclosed and Perennial Open plots

(Table 2). Although the Run-On plots were larger than

the other plots, the results show that rainwater loss as runoff was lower in the Run-On plots as compared to the Bare plots. This confirms results by Kironchi (1992) that infiltration rates under trees and bushes in Mukogodo is higher than on Bare ground.Low rainstorms (below 10 mm and erosivity units below 7) produced no runoff in the Perennial Enclosed plots. In the Perennial Open plots and the Bare plots, runoff ranged 0-15% of rainfall and 2-53% of rainfall respectively for these storms. The low levels of water loss from the Perennial plots suggest that recovery can take place easily on these plots.

Table 3 shows total amounts of runoff for each treatment over the study period. Over half of the rainfall received was lost as runoff on the Bare plots. The Perennial Enclosed and Perennial Open plots lost about 9% and 24% of rainfall respectively. This shows that vegetative cover development influenced runoff in the Perennial Open and Perennial Enclosed plots.

Total runoff values for the Bare Enclosed and Bare Open plots were not significantly different (at p <0.01) according to Duncan's New Multiple Range test (Steel and Torrie, 1980). This indicates that no significant

Table 3: Total and percent runoff for each treatment over the study period (Nov.1992 to July 1993) *·

TREATMENT	BO	BE	PO	PE	RO
TOTAL RUNOFF** (mm)	145.8^a	156.5^a	69.3^b	24.4	56.6^b
STANDARD ERROR	3.4	6.4	9.1	5.7	14.0
TOTAL RUNOFF (% of total rain)	51.2	55.0	24.3	8.6	19.9
TOTAL RAIN (mm)	284.8				

KEY

BO Bare Open, BE Bare Enclosed, PO Perennial Open, PE Perennial Enclosed, RO Run-On.

* Totals with the same letter superscript are not significantly different at p<0.05 according to Duncan's New Multiple Range test.

++ Each total is a mean of 3 replicates.

cover development occurred in the Bare Enclosed as compared to the Bare Open plots; and thus closure to grazing had no impact on runoff loss for these plots. Total runoff values for the Perennial Enclosed and Run-On plots were not significantly different at P<0.01 , though significantly different at P<0.05. There was a significant difference (P<0.01) between mean values of runoff for the Perennial Open and Perennial Enclosed plots.

4.4 Soil loss

The total monthly amounts of soil loss for each treatment and the corresponding monthly erosivities are shown in Fig. 7a-c. Soil loss was high on the Bare Open and Bare Enclosed plots. Single erosive storms (with an erosivity unit above 7) caused a loss of 1.6 - 5.6 t/ha of soil from the Bare Open plots and 0.8 - 3.9 t/ha of soil from the Bare Enclosed plots (Table 2). The Perennial Open and Perennial Enclosed plots showed low amounts of soil loss even for these erosive storms. In the Perennial Open plots soil loss ranged from 0.1 - 2.6 t/ha while for the Perennial Enclosed it ranged from 0 - 0.7 t/ha.

Low storms (erosivity unit below 7) generally recorded no runoff in the Perennial Enclosed plots and hence no soil loss was recorded. In the

Perennial Open plots soil loss was 0-0.2 t/ha. for low storms. Soil loss was 0-2.2 t/ha and 0-1.2 t/ha for Bare Open and Bare Enclosed plots respectively, for these low storms (Table 2).

The soil loss totals for each treatment for the observation period (Nov.1992 to July 1993) are shown in table 4. The highest soil losses were recorded for the Bare plots, about 30 t/ha and 20 t/ha for the Bare Open and Bare Enclosed respectively. Hudson (1981) quotes the value of 10 t/ha per year as an often acceptable limit. The values (for the Bare plots) recorded in this study are well above this limit, and this shows the seriousness of soil loss for the area under study. The Perennial Open, Perennial Enclosed and Run-On plots recorded

Table 4: Total soil loss for each treatment over the study period (Nov.1992 to July 1993)[*].

TREATMENT	BO	BE	PO	PE	RO
SOIL LOSS[++](t/ha)	29.9	20.1	10.1[a]	1.7[b]	4.8[ab]
STANDARD ERROR	4.0	1.1	3.1	0.6	1.2

[*] Totals with the same letter superscript are not significantly different at $p < 0.05$ according to Duncan's New Multiple Range test.

[++] Each value is a mean of 3 replicates.
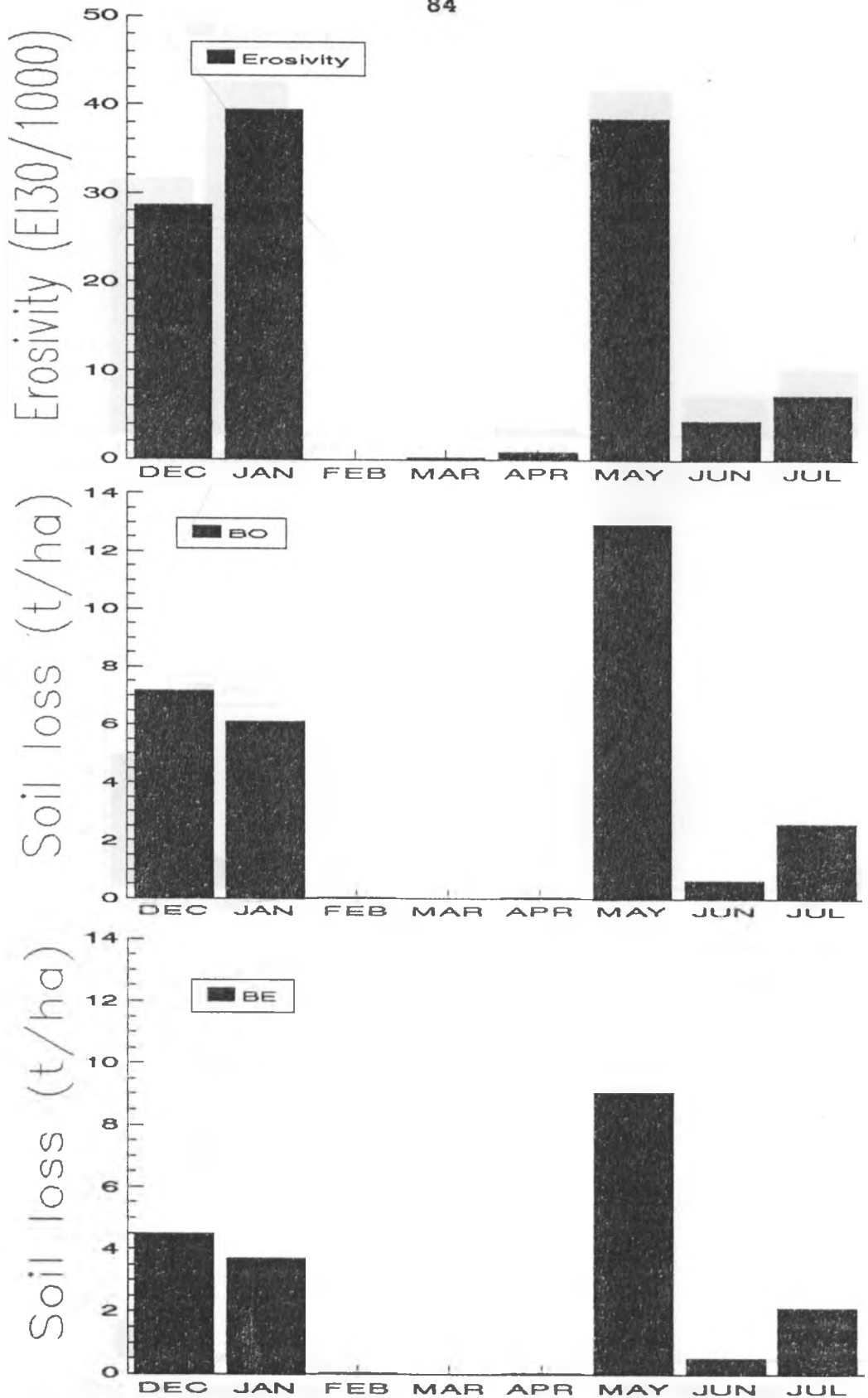
FIGURE 7a: Erosivity and total soil loss for the Bare Open and Bare Enclosed over the study period.
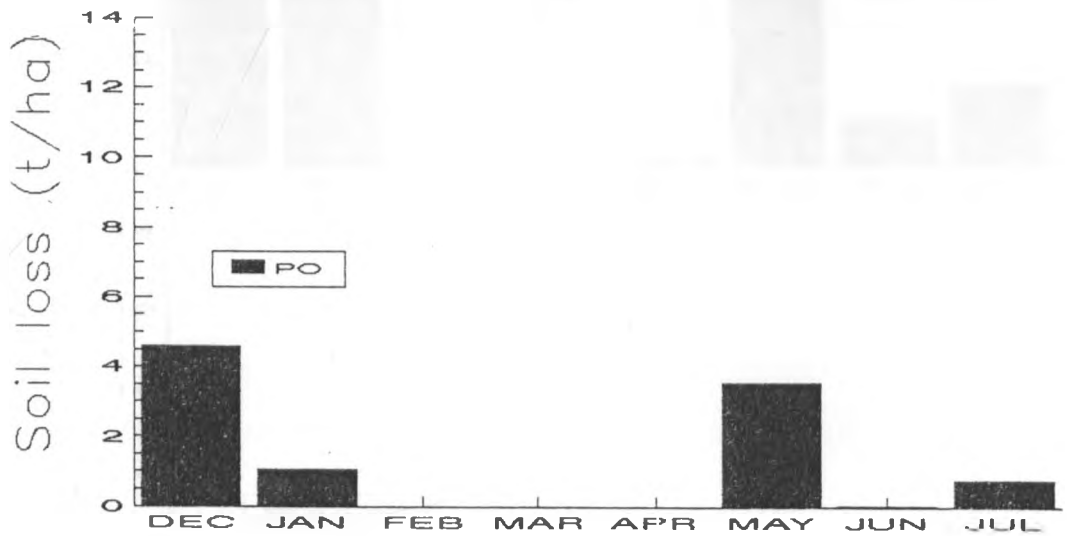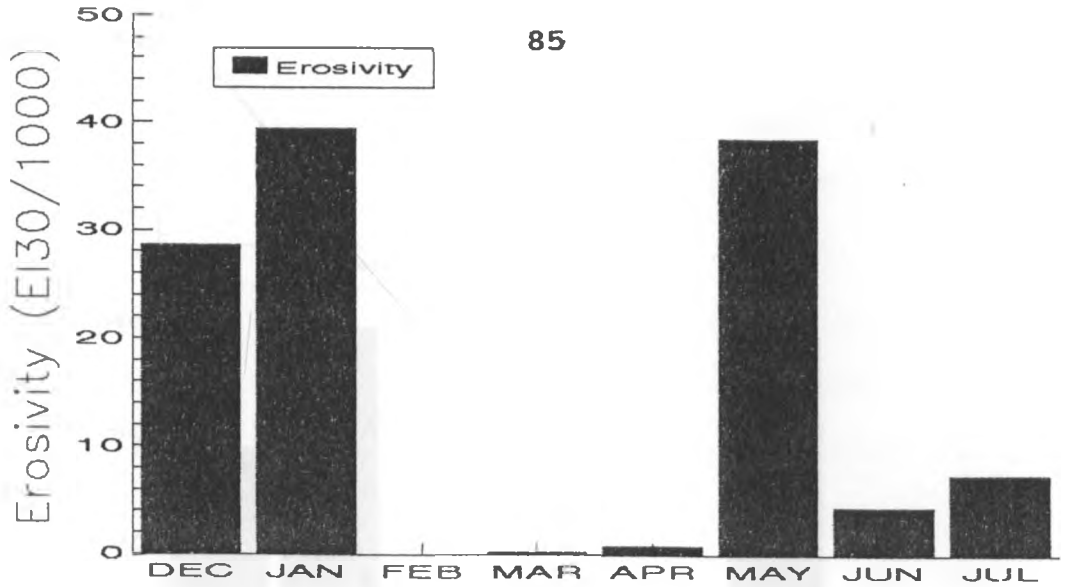
FIGURE 7b: Erosivity and total soil loss for the Perennial Open and Perennial Enclosed over the study period.
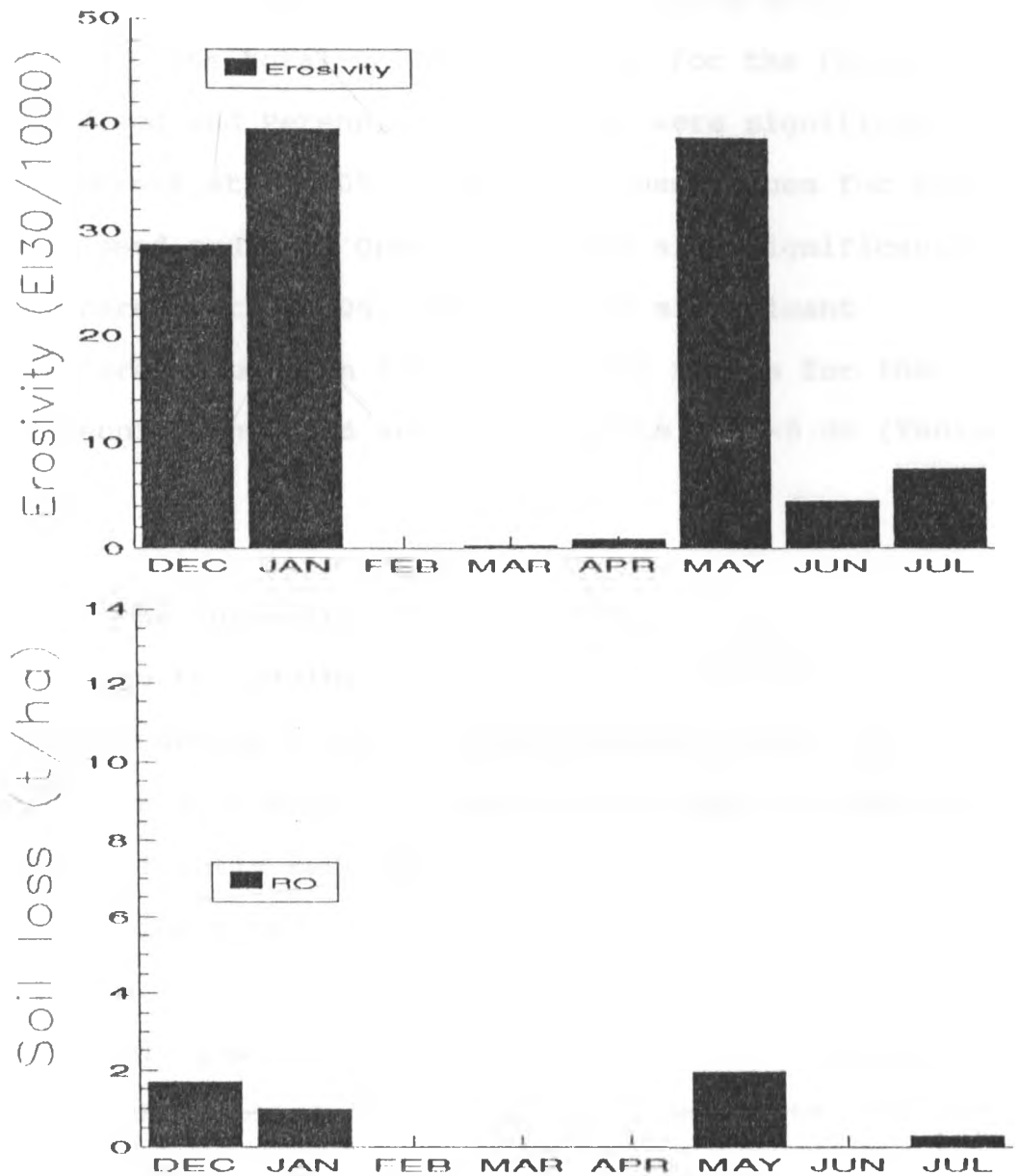
**FIGURE 7c: Erosivity and total soil loss for the Run-On plots over the study**

NB: The totals in Figs. 7a-c are means of 3 replicates.

acceptable values of soil loss (Table 4). According to Duncan's New multiple range test, total soil loss

values for the Perennial Enclosed, Perennial Open
and Run-On plots were not significantly different at
P<0.01. The total soil loss values for the Perennial
Enclosed and Perennial Open plots were significantly
different at P<0.05. Total soil loss values for Bare
Enclosed and Bare Open plots were also significantly
different at P<0.05. There was no significant
difference between total soil loss values for the
Perennial Enclosed and Run-On plots at p<0.05 (Table
4).

From the foregoing discussion, the results show that
closure to grazing significantly influenced both
runoff and soil loss in the Perennial plots. The
results also show that although closure to grazing
significantly reduces soil loss, it has no
significant impact on runoff loss on the Bare plots.

The soil lost from the Bare Open plots is 49% more
than that lost from the Bare Enclosed plots, yet the
runoff recorded from the Bare Enclosed plots is 7%
more than that from the Bare open plots (Tables 3
and 4). Although the total runoff values for Bare
Open and Bare Enclosed were not statistically
different, this suggests the effect of livestock
trampling. Whereas animals walked on the Bare Open
plots, they had no access to the Bare Enclosed

plots.

A broken surface crust (e.g due to trampling) can cause high infiltration rates. However, since runoff in both the Bare Open and the Bare Enclosed were high, soil particles could have been easier to transport in the areas where animals trampled (the Bare Open plots). This could have caused the high soil loss in the Bare Open plots.

4.5 Vegetative Cover

Vegetative cover development over the observation period for all the treatments is shown on Fig. 8. The Perennial Enclosed plots had the best response after the short rains. A maximum of about 46 percent cover was recorded towards the end of the first season; and this shows that closure to grazing had an impact on these plots. The Perennial Open plots had also some cover development but due to the constant grazing pressure, lower cover values were recorded.

The common vegetation species observed in the plots were as follows:-

Perennial plots:

Perennial grasses: *Cynodon plectostachyus,*
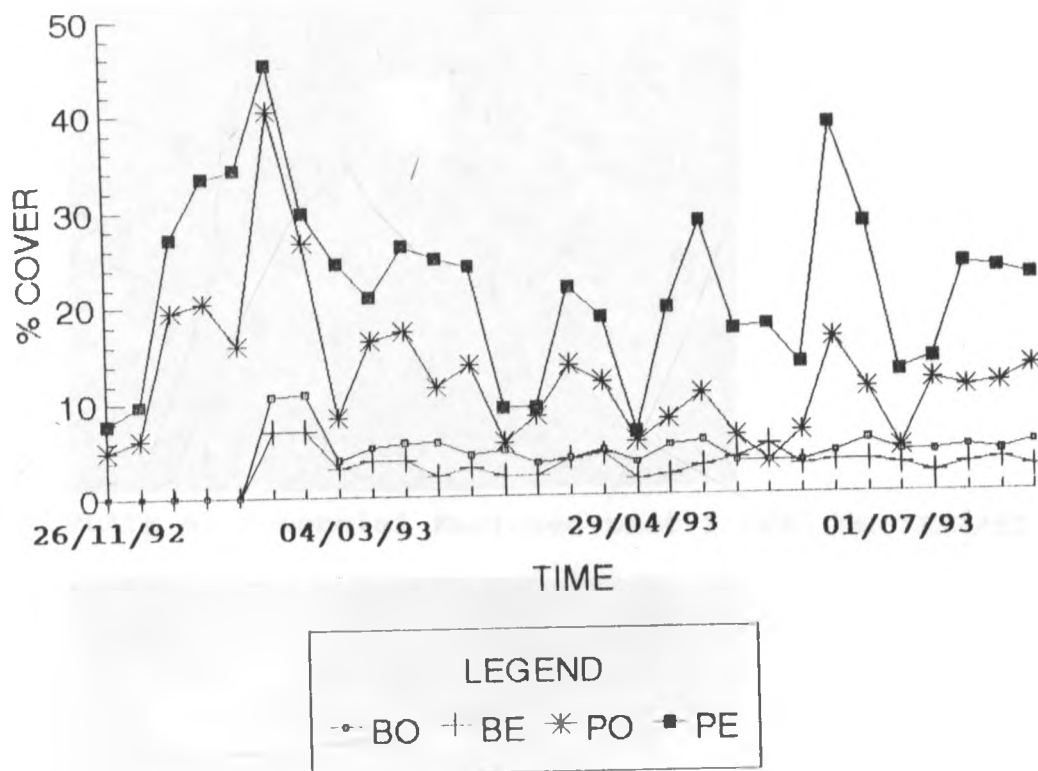
FIGURE 8: Vegetative cover development over the observation period.

Pennisetum stramineum, Cenchrus ciliaris, Oropetium capense.

Annual grasses: *Tragus beteronianus, Eleusine multiflora.*

PLATE 6: Perennial Enclosed plot 1 (PE) on 13/2/92.

PLATE 7: Perennial Open plot 1 (PO1) on 13/2/92.

PLATE 8: Bare Enclosed plot 3 (BE3) on 13/2/93.

PLATE 9: Bare Open plot 1 (BO1) on 13/2/93

PLATE 10: PE1 on 11/5/93.

PLATE 11: PO1 On 11/5/93.

PLATE 12: BE3 on 11/5/93.

PLATE 13: BO1 on 11/5/93.

<u>Forbs:</u> *Tribulus terrestris, Brassica rapa, Oxygonum sinuatum, Ipomea sp., Cyperus sp.*

<u>Bare plots:</u>

<u>Perennial grasses:</u> Nil.

<u>Annual grasses:</u> *Eragrostis tenuifolia,* * *Aristida keniensis.*

<u>Forbs:</u> *Heliotropium sp., Chenopodium sp.*

<u>NB:</u> * can also behave as a short-lived perennial.

The soil chemical and physical data shown on table 1 suggests that the vegetative cover recovery on the Perennial plots (Perennial Open and Perennial Enclosed) must be due to soil texture and less runoff; and not due to increased organic matter. The lower clay content on the Perennial plots eases water infiltration and thus ensures that the plants do not die easily and they recover faster whenever there is rain. This has important implications for developing a strategy to reclaim denuded land. The poor recovery of the Bare plots as compared to the Perennial plots indicates that for meaningful rehabilitation, we have to be able to distinguish areas which can recover by closure alone and areas which cannot.

The Bare plots had very poor cover development. It was only towards the end of the short rains that measurable cover was recorded. None of the Bare

plots (Bare Enclosed and Bare Open) recorded a cover value above 15%. This shows that closure to grazing had almost no impact on vegetative cover development for the Bare plots. Cover development for each category of plots is shown on plates 6 to 13.

4.6 Neutron probe calibration and profile available soil water

4.6.1 Neutron probe calibration

The calibration exercise was carried out at two sites in the catchment. Site 1 was more stony than site 2. The count ratio for the wet calibration in 60 cm, 75 cm, and 90 cm depths did not relate well with the volumetric moisture content for site 1. This was most likely due to the stoniness of the site, and hence wet calibration values at 60 cm, 75 cm, and 90 cm depths from site 1 were excluded in computing the calibration curve. According to USDA (1979), stony and non-uniform soils are difficult to calibrate in the field. At site 2, a band of stony soil was encountered at the 75 cm depth in both dry and wet calibration (Kinyua, In prep.). Thus the dry and wet calibration values at 75 cm depth from site 2 were also excluded from calibration curve computation.

The data collected at both sites (excluding 60 cm, 75 cm, and 90 cm wet calibration values at site 1

and the 75 cm dry and wet calibration values at site
2) was combined to obtain a calibration curve. The
calibration curve that relates the volumetric
moisture content with the count ratio is shown in
Fig. 9. The linear regression equation (r2 = 0.95)
obtained was

$$V = 20.15R-7.25 \qquad\qquad (21)$$

where   V = % moisture by volume.

R = Count ratio (the ratio of a reading
to the standard count)

4.6.2 Profile available soil water

The Available Water Capacity (AWC) for each depth
was calculated as the difference between the upper
limit(Field Capacity, FC) and the lower
limit(Wilting Point, WP). The field capacities for
the depths were approximated to the volumetric water
contents during wet Neutron probe calibration;while
the wilting points were taken to be the values
during the dry calibration. The AWC values for the
various depths are shown in table 5.
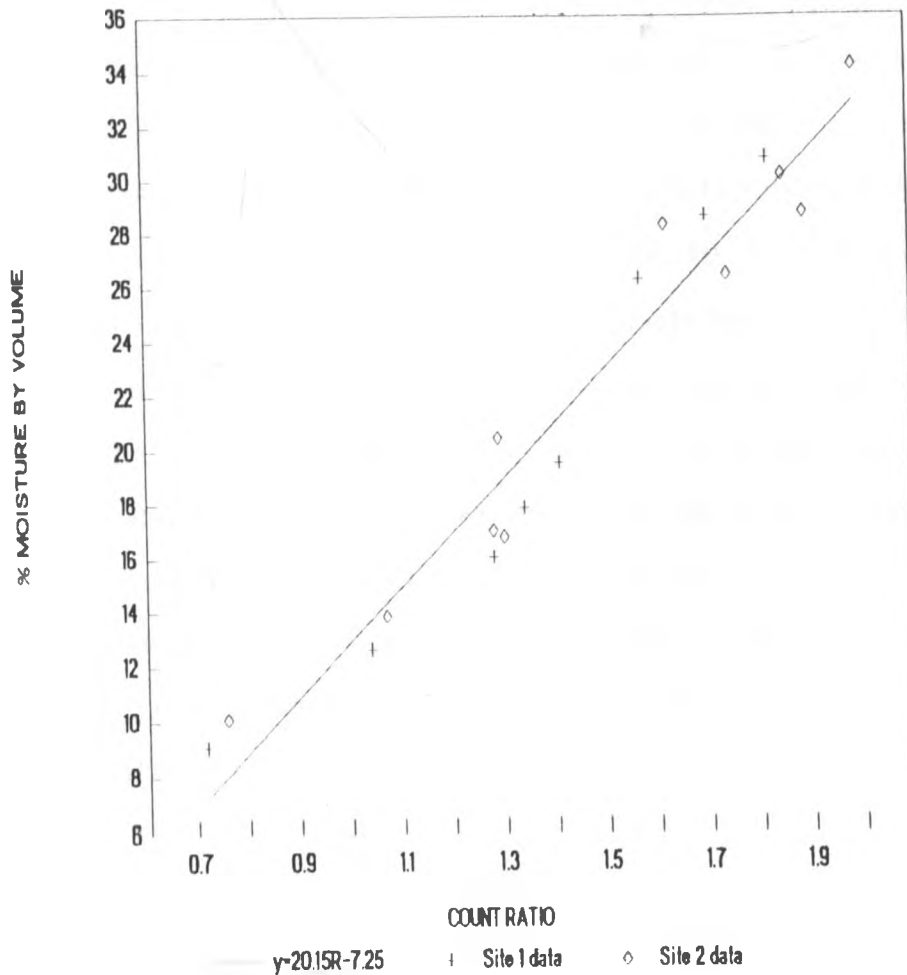
FIGURE 9: Neutron probe calibration curve.

Table 5: Available water capacity (AWC) for various depths.

DEPTH (cm)	FC (%V)	WP (%V)	AWC (%V)
18	26.3	9.1	17.2
30	28.7	12.6	16.1
45	30.8	16.1	14.7
60	35.9	19.5	16.4
75	29.7	13.3	16.4

The available soil water for each depth on each
measurement date was calculated. It was presented in
categories ranging from 5 (at or above FC) to -1
(below WP). The categories for each treatment over
the study period are shown in Table 6. The available
soil water for the Perennial Enclosed and the
Perennial Open ranged from 3 (above 50% of AWC) to -
1 (below WP). The categories for the Bare Enclosed
and Bare Open ranged from 2 (above 25% of AWC) to -
1. This result explains why the Perennial plots
could support vegetation for some time; while the
Bare plots hardly supported vegetation. All the
treatments had available soil water in category 1
most of the time.

4.6.3 Total available soil water

The total available soil water for 0-40 and 50-70 cm
depths is shown on Figure 10. The total available
soil water for the Perennial plots (Perennial
Enclosed and Perennial Open) was about 2 times the
available soil water for the Bare plots (Bare
Enclosed and Bare Open) at the beginning of the
short rains. This soil water reduced considerably as
the season progressed, due to evapotranspiration.

24/02	03/03	10/03	17/03	24/03	31/03	07/04	14/04	21/04	28/04	05/05	12/05	19/05	26/05	02/06	09/06	16/06	24/06	30/06
55	62	69	76	83	90	97	104	111	118	125	132	139	146	153	160	167	175	181
1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	0	-1	0	1	1	1	1	1	1	1	1	1
1	1	1	1	0	1	1	0	0	1	0	1	0	1	0	1	0	1	0
1	1	1	1	0	1	1	0	1	1	1	1	0	0	1	1	1	1	1
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0

24/02	03/03	10/03	17/03	24/03	31/03	07/04	14/04	21/04	28/04	05/05	12/05	19/05	26/05	02/06	09/06	16/06	24/06	30/06
55	62	69	76	83	90	97	104	111	118	125	132	139	146	153	160	167	175	181
1	1	1	1	0	0	0	-1	1	0	1	1	1	1	1	1	1	1	1
1	1	1	1	1	0	0	0	0	0	-1	1	0	0	1	0	1	1	1
1	1	1	1	0	0	1	0	0	1	-1	0	0	1	0	1	1	1	0
1	1	0	0	1	0	1	0	1	1	0	1	0	0	0	0	0	0	0

24/02	03/03	10/03	17/03	24/03	31/03	07/04	14/04	21/04	28/04	05/05	12/05	19/05	26/05	02/06	09/06	16/06	24/06	30/06
55	62	69	76	83	90	97	104	111	118	125	132	139	146	153	160	167	175	181
1	1	1	1	1	1	0	0	1	1	0	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	0	1	-1	0	0	1	1	1	1
1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	0	1	1	0
1	1	1	1	1	1	0	1	0	1	0	1	1	0	0	0	0	1	0
1	1	1	1	1	0	1	0	0	1	1	1	0	1	1	1	0	1	1

24/02	03/03	10/03	17/03	24/03	31/03	07/04	14/04	21/04	28/04	05/05	12/05	19/05	26/05	02/06	09/06	16/06	24/06	30/06
55	62	69	76	83	90	97	104	111	118	125	132	139	146	153	160	167	175	181
1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	1	1	1
1	1	1	1	1	1	1	1	1	1	0	1	1	0	0	0	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0
1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0

After the start of the long rains, the available soil water for the Perennial Enclosed plots was twice that for the other treatments. The total available soil water for the Bare Open plots was the lowest at the beginning of every season. It also shows a decreasing trend as the season progressed, most likely due to evaporation from the soil surface. The available soil water for the Bare Enclosed and the Perennial Open was in between those of the Perennial Enclosed and Bare Open for most of the study period.

Total available soil water for the 50-70 cm depth was less than 2 mm for all the treatments throughout the study period. This shows that the soil horizons below 40 cm received no water through percolation. For the Bare plots this can be attributed to the high runoff (see section 4.3) and direct evaporation from the soil surface. In the Perennial plots runoff was reduced, but due to the vegetation cover, water was used for transpiration.
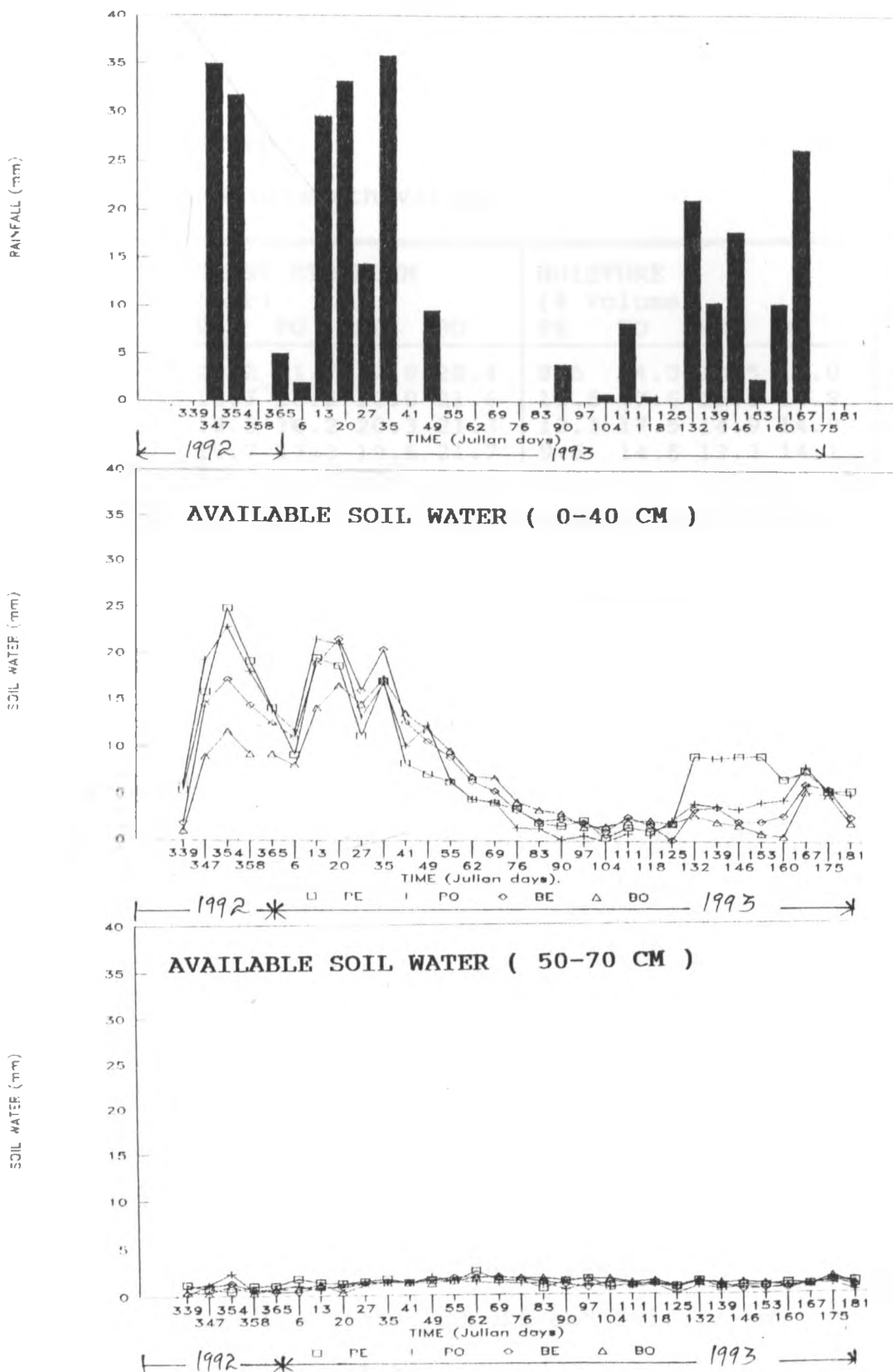
FIGURE 10: Total available soil water for 0-40 and 50-70 cm depths (All treatments).

4.7 Crust strength

Table 7. Crust strength values.

DATE	CRUST STRENGTH (bar)				MOISTURE (% Volume)			
	PE	PO	BE	BO	PE	PO	BE	BO
8/12/92	20.2	21.7	27.6	28.4	8.6	14.0	12.5	13.0
15/12/92	15.7	18.2	20.0	21.6	12.5	17.6	15.0	14.8
20/12/92	16.5	16.2	20.3	21.3	13.3	17.5	14.9	14.9
29/12/92	15.7	17.3	19.5	21.7	9.6	14.5	13.3	14.1
9/1/93	20.1	20.3	22.4	24.3	9.4	15.0	13.8	14.7
13/6/93	18.6	20.7	21.9	24.1	7.4	11.6	10.3	11.5

Crust strength data for all the treatments is presented on table 7. Few measurements were made because the cone penetrometer was not available all the time during the study period. Within the data, no clear trends are apparent for relating crust strength with time or with moisture. However, crust strength values for the Bare plots are generally higher than those for the Perennial plots. This shows that the Bare plots formed stronger crusts compared to the Perennial plots. The Bare plots produced higher runoff (Table 3). To some extent therefore, the crust strength must have had some influence in the amount of runoff produced. This again explains the higher runoff and failure to recover in the Bare plots.

Other researchers (Taylor and Gardner, 1962; Gerald, 1965; Hegarty and Royle, 1978) also studied crust strength characteristics. The crust strength values observed in this study are on the higher side. This could be due to the fact that the measurements were done in-situ and also because the soils in the study area are very prone to crusting.

4.8 Multiple Regressions

Multiple regression analysis was carried out to determine the amount of variation in runoff and soil loss which could be "explained" by the investigated parameters. This analysis was done using all the parameters measured for each storm over the study period.

4.8.1 Rainfall, erosivity, cover and runoff

The variables used for this regression are defined in table 8a. The predictive equation evolved $(r^2=0.65)$ is

$$Y = 32.13 - 0.57X_1 + 3.30X_2 - 1.42X_3 \tag{22}$$

Table 8a: Dependent and independent variables used in the regression between rainfall, erosivity, cover and runoff.

code	variable	units.
Y	Runoff	% of rainfall
X_1	Rainfall	mm
X_2	Erosivity	EI30/1000 units
X_3	Vegetative cover	%

A one-tailed t test of the regressors was done. The results are summarized in table 8b.

Table 8b: One-tailed t- test of rainfall, erosivity and cover regressed against runoff.

Variable	Coefficient.	Std. Error.	t ratio.
X_1	-0.57	0.36	1.58
X_2	3.30	0.44	7.50*
X_3	-1.42	0.16	8.88*

* Ratios exceed the t value at 5% level.

The results from table 8b show that within the range of investigated parameters only erosivity (x_2) and cover (X_3) are statistically significant at 5% level.

This means that rainwater loss as runoff is mostly influenced by vegetative cover and rainfall erosivity. The t ratio for cover is the highest (Table 8b). This shows that cover influences runoff more than erosivity.

4.8.2 Rainfall, erosivity, cover, runoff and soil loss

Table 9a: Dependent and independent variables used in the regression between rainfall, erosivity, cover, runoff and soil loss.

Code	Variable	Units
Y	Soil loss	t/ha
X_1	Rainfall	mm
X_2	Erosivity	EI30/1000 units
X_3	Vegetative cover	%
X_4	Runoff	% of rainfall

This regression used the variables given in table 9a. Soil loss was related to rainfall, erosivity and runoff by eqn. 23 ($r^2 = 0.72$). This regression equation excluded vegetative cover.

$$Y = -0.07 - 0.03X_1 + 0.10X_2 + 0.02X_4 \tag{23}$$

Table 9b shows the results of a one-tailed t test of the regressors.

Table 9b: One-tailed t test of rainfall, erosivity, cover and runoff regressed against soil loss.

Variable	coefficient	Std error	t ratio
X_1	−0.0317	0.013	2.44*
X_2	0.1010	0.020	5.05*
X_3	0.0002	0.008	0.03
X_4	0.0212	0.004	5.30*

* Ratios exceed the critical t value at 5% level.

Within the range of investigated parameters, rainfall (X_1), erosivity (X_2) and runoff (X_4) are the statistically significant factors ($p<0.05$) influencing soil loss.

The results from sections 4.8.1 show that vegetative cover significantly influences the percentage of rainfall that becomes runoff ($p<0.05$). However, from the results of section 4.8.2, it is evident that the impact of vegetative cover on soil loss did not reach a statistical level of significance. Since runoff significantly influences soil loss (Table 9b), it follows that an increased vegetative cover will reduce runoff;and this reduced runoff will

result in a reduced soil loss. The fact that the impact of cover on soil loss does not appear to be significant can be explained by the lack of substantial rainstorms after the cover had developed (i.e after January 1993). Research elsewhere has clearly shown the impact of vegetative cover in controlling soil loss and it can be expected that the current experiment would give similar results if carried on for a longer period and under heavier rainfall.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

1. Rainwater loss as runoff was very high on the Bare plots. In these plots, runoff over the study period was more than half of the rainfall received. Runoff from the Perennial plots was generally less than half the runoff from the Bare plots.

2. Total runoff values for Bare Enclosed and Bare Open plots over the study period were not significantly different at $p < 0.01$. Thus closure to grazing did not reduce rainwater loss from the Bare plots. There was a significant difference($p < 0.01$) between total values of runoff for the Perennial Open and Perennial Enclosed plots. This shows that closure to grazing influenced rainwater loss from the Perennial plots.

3. The total values of soil loss recorded for the Bare plots were 2-3 times the acceptable limit according to Hudson (1981). The Perennial plots recorded acceptable values of soil loss.

4. Closure to grazing did not lead to an improvement in vegetative cover in the Bare plots. The Perennial

Enclosed plots showed a fast cover development after the short rains.

5. The crust strength values observed in this study are high. The Bare plots showed crust strength values which were 15-30% higher than the crust strength values recorded in the Perennial plots.

6. Profile available soil water for all the treatments was between 25% of Available Water Capacity (AWC) and 2% of AWC most of the time. Very little water reached below 50 cm in all treatments.

7. From multiple regressions; rainfall, erosivity and vegetative cover accounted for 65% of the variation in rainwater loss. Similarly, rainfall, erosivity and runoff accounted for 72% of variation in the soil lost. Increasing vegetative cover significantly reduced runoff ($p < 0.05$) while the impact on soil loss was not statistically significant. Runoff was the most significant factor ($p < 0.05$) influencing soil loss. Research elsewhere has shown the impact of vegetative cover in controlling soil loss. It can be expected that the current experiment would give similar results if carried on for a longer period and under heavier rainfall.

5.2 Recommendations

1. Closure to grazing resulted in fast vegetative cover development in areas where there was some cover of perennial grasses (the Perennial plots). Rainwater loss as runoff was reduced and soil loss was at acceptable levels. Closure to grazing did not lead to an improvement in cover development in the Bare plots. In these plots, over half of the rainfall was lost as runoff, and soil loss was at unacceptable levels. These results have very important implications for developing a strategy to reclaim denuded land. For viable rehabilitation it is necessary to distinguish areas which can recover by closure alone and areas which cannot. The results from this study show that those zones which have some cover of perennial grasses can recover by closure alone. Recovery will be in terms of fast cover development, reduced runoff and soil loss; and hence reduced sedimentation in the catchment. The Bare areas will not recover easily simply by closure alone.

2. The Bare plots had high crust strength values as compared to the Perennial plots. This crust strength coupled with the poor vegetative cover development explain the high runoff and soil loss in the Bare plots. The fact that over 50% of the rainfall is

lost from the Bare plots is of major importance and clearly shows that recovery will not take place easily unless measures are taken to get water into the ground by techniques such as pitting, ripping, slashing of bush and piling of trash lines, etc.

3. From multiple regressions, vegetative cover had the highest influence on runoff. Since runoff is the main factor influencing soil loss;it means that a reduced runoff resulting from increased vegetative cover would also mean a reduced soil loss. Vegetative cover development should therefore be encouraged as a means of improving denuded land.

Further research is needed in the following aspects:-

(a) It is important to know how much vegetative cover would develop on all the plots after a longer period (e.g 5 years). The way in which this cover development influences the runoff and soil loss should be investigated.

(b) Techniques for getting water into the ground could be introduced in the Bare plots. It would be important to see how this affects the runoff/soil loss patterns and what impact the techniques have on soil degradation and vegetative cover recovery.

(c) The beneficial effects of the vegetation developing in the plots (to livestock or humans) over a longer period should be investigated.

(d) An investigation should be done to find out whether the runoff (especially from the bare plots) can be harvested for human consumption. The level of chemical treatment before consumption should also be looked into.

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APPENDIX 7.1: Location of the study area.
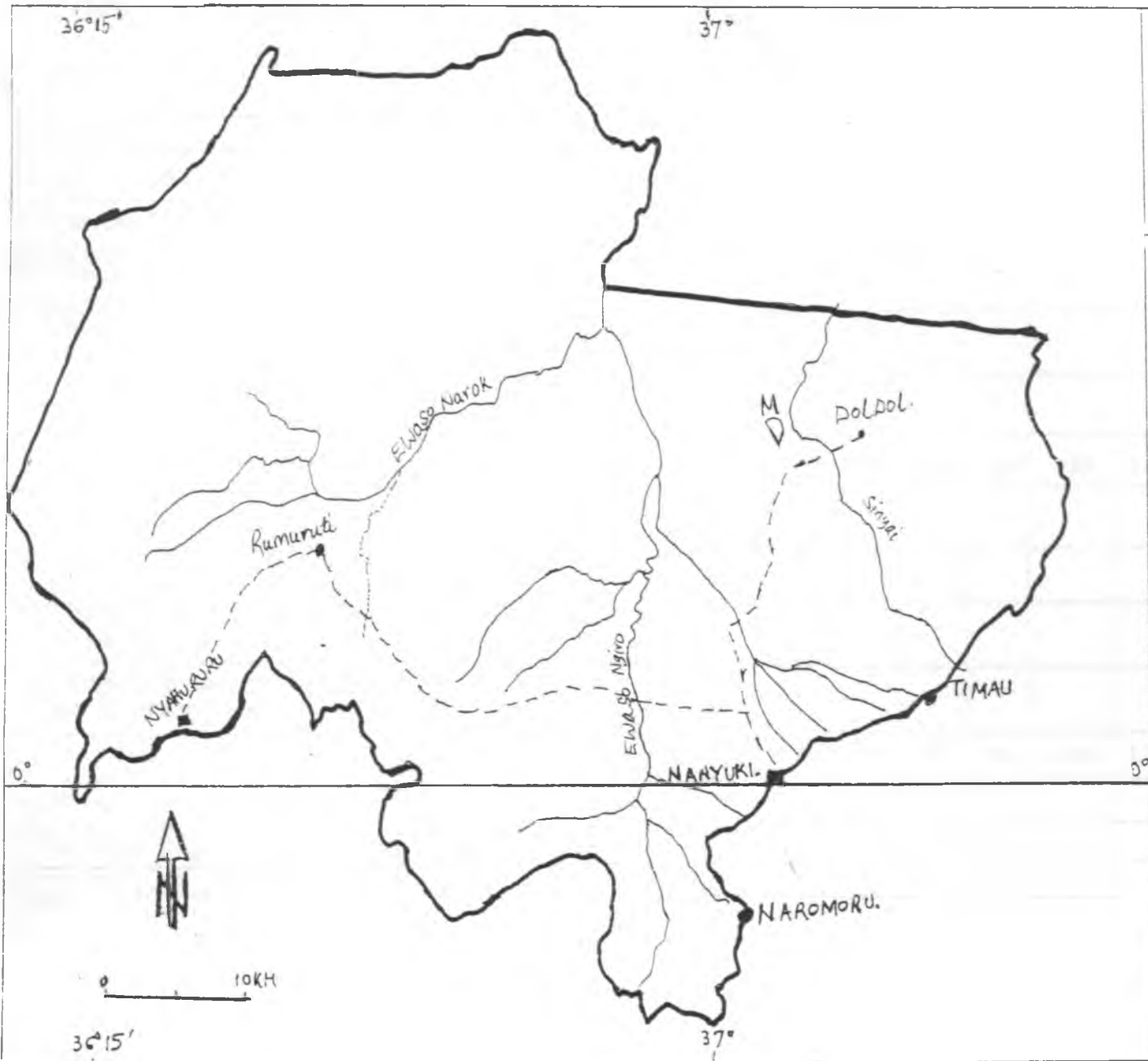
KEY.

M
♀ — MuKogodo Catchment.

----- — Motorable roads.

~~~ — Rivers.

▬▬ — District boundary.

APPENDIX 7.2: Runoff and Soil loss field data record sheet.

Date of runoff......   Collection date......
Rainfall in mm......   Field worker........

PLOT No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
TANK A (DRUM)	1A	2A	3A	4A	5A	6A	7A	8A	9A	10A	11A	12A	13A	14A	15A
(a)Water depth to sediment surface (cm).															
(b)Water depth to sediment surface (cm).															
(c)Water depth to sediment surface (cm).															
(d)AVERAGE WATER DEPTH TO SEDIMENT SURFACE (CM).															
TANK B (STORAGE TANK).	1B	2B	3B	4B	5B	6B	7B	8B	9B	10B	11B	12B	13B	14B	15B
(a)Water depth to tank bottom (cm).															
(b)Water depth to tank bottom (cm).															
(c)Water depth to tank bottom (cm).															
(d)AVERAGE WATER DEPTH TO TANK BOTTOM (cm).															
SOIL LOSS	1A	2A	3A	4A	5A	6A	7A	8A	9A	10A	11A	12A	13A	14A	15A
a)Weight of sediment and bucket (kg).															
b)Bucket empty weight (kg)															
c)Weight of sediment (kg)															

APPENDIX 7.3: Evaluation of runoff and Soil loss Lab. data sheet.

Rainfall (mm).......   Date of collection........

PLOT NO:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RUNOFF: a)TANK A:Vol. of water(l)															
b)TANK B:Vol. of water(l)															
c)TANK A:Water in sludge(l)															
d)Total runoff(a+b+c) (l)															
e)Runoff per area (mm)															
f)% Runoff in rain															
SOIL LOSS. Tank A. g)Wt. of dry soil+filter(g)															
h)Total soil in runoff(g)															
j)Wt. of sludge sample(g)															
k)Dry wt. of sludge sample(g)															
l)% Water in sample															
m)Total soil in sludge(kg)															
n)Total soil in tank A(h+m)kg															
TANK B: o)Wt. of dry soil+filter(g)															
p)Total soil in tank B (g)															
q)TOTAL SOIL LOSS (n+p) (kg)															
r)TOTAL SOIL LOSS (t/ha)															

APPENDIX 7.4: Vegetative cover assessment record sheet.
Date...........   Observer........

POINT / PLOT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	%
1																										
2																										
3																										
4																										
5																										
6																										
7																										
8																										
9																										
10																										
11																										
12																										

KEY: / =Green cover.   \ =Dead cover.   O =Dry cover.

APPENDIX 7.5: Neutron probe field data sheet.

LAIKIPIA RESEARCH PROGRAMME: SOIL MOISTURE HYDROPROBE DATA SHEET

SITE _____

OPERATOR _____

DATE _____

STANDARD COUNT — 7 out of 10 Within $\pm \sqrt{AVG}$ is normal.

TOTAL _____
AVG _____
$\sqrt{AVG. COUNT}$ _____

HI _____
$+\sqrt{}$ _____
$-\sqrt{}$ _____
LO _____
$\left. \right\} = \frac{7}{10}$

TUBE No. DEPTH	15	30	45	60	75	90		
COUNT								
RATIO								
H2O								
TUBE No. DEPTH	15	30	45	60	75	90		
COUNT								
RATIO								
H2O								
TUBE No. DEPTH	15	30	45	60	75	90		
COUNT								
RATIO								
H2O								
TUBE No. DEPTH	15	30	45	60	75	90		
COUNT								
RATIO								
H2O								
TUBE No. DEPTH	15	30	45	60	75	90		
COUNT								
RATIO								
H2O								
TUBE No. DEPTH	15	30	45	60	75	90		
COUNT								
RATIO								
H2O								
TUBE No. DEPTH	15	30	45	60	75	90		
COUNT								
RATIO								
H2O								
TUBE No. DEPTH	15	30	45	60	75	90		
COUNT								
RATIO								
H2O								

REMARKS:

APPENDIX 7.6: Cone penetrometer field data sheet.

Cone area..........cm²   Date................

Spring ....N   Observer...........

	a	b	c	d	e	f	g	h	i	j	AVG	R
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												
12												

REMARKS.

Appendix 7.7: Rainfall for single events producing runoff (Over study time).

Appendix 7.8: Erosivity of rainfall producing runoff (single events, over study time)
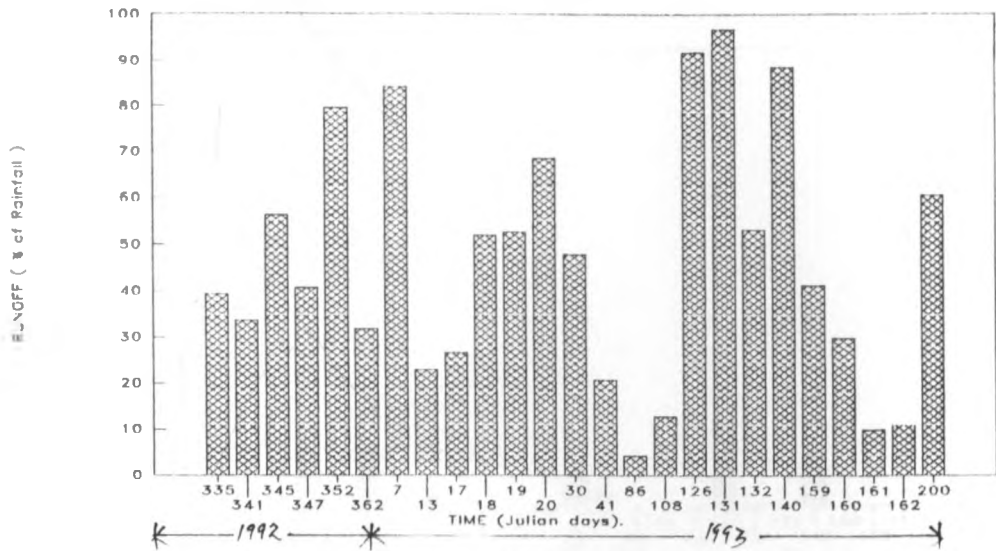
Appendix 7.9a: A graph of percent runoff against time for the Perennial Enclosed (PE) plots (Single events).
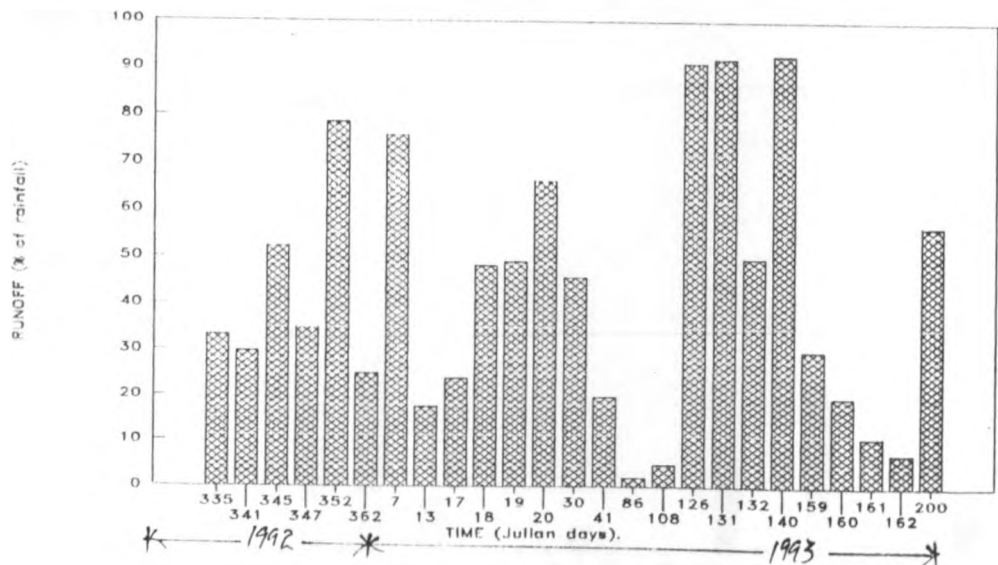

Appendix 7.9b: A graph of percent runoff against time for the Perennial Open (PO) plots (Single events).
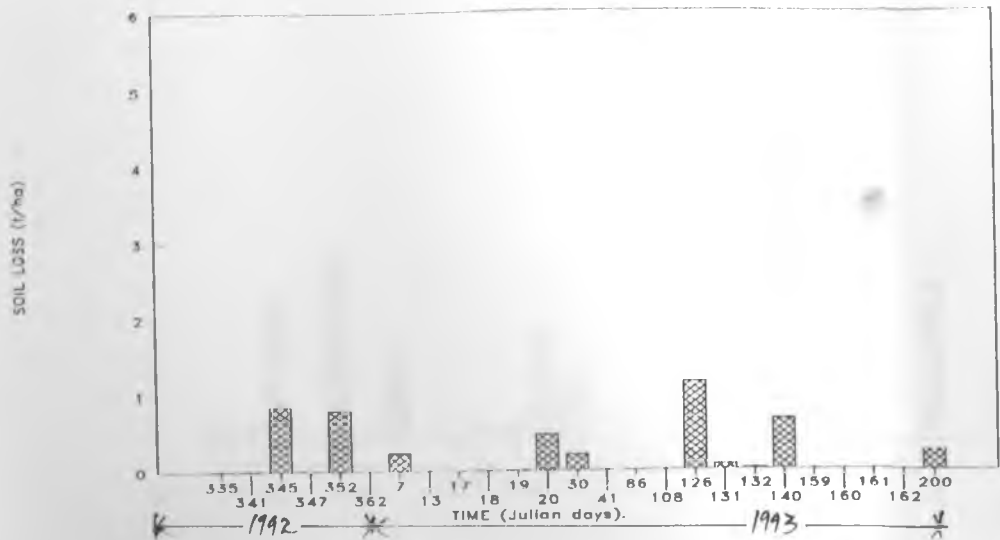
Appendix 7.9c: A graph of percent runoff against time
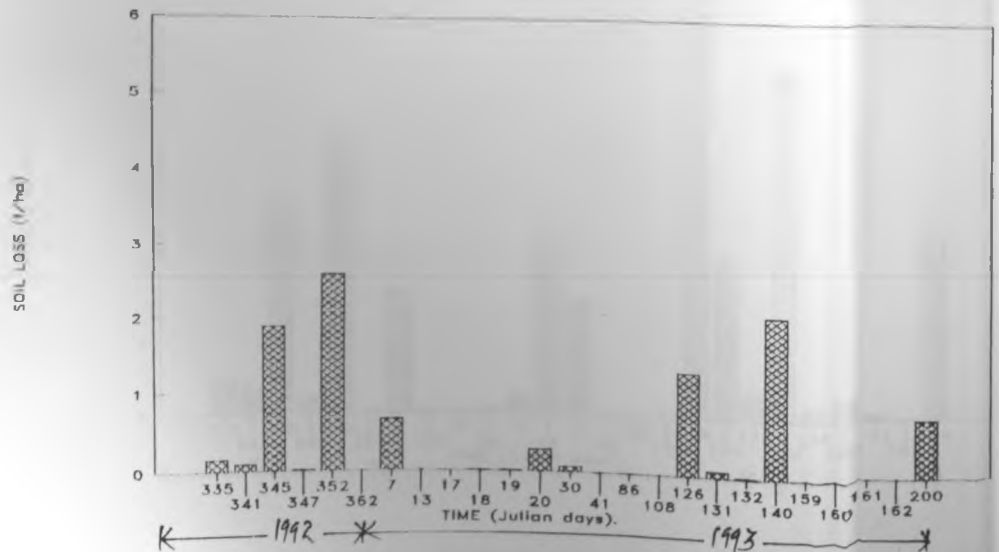for the Bare Enclosed (BE) plots (Single events)

Appendix 7.9d: A graph of percent runoff against time
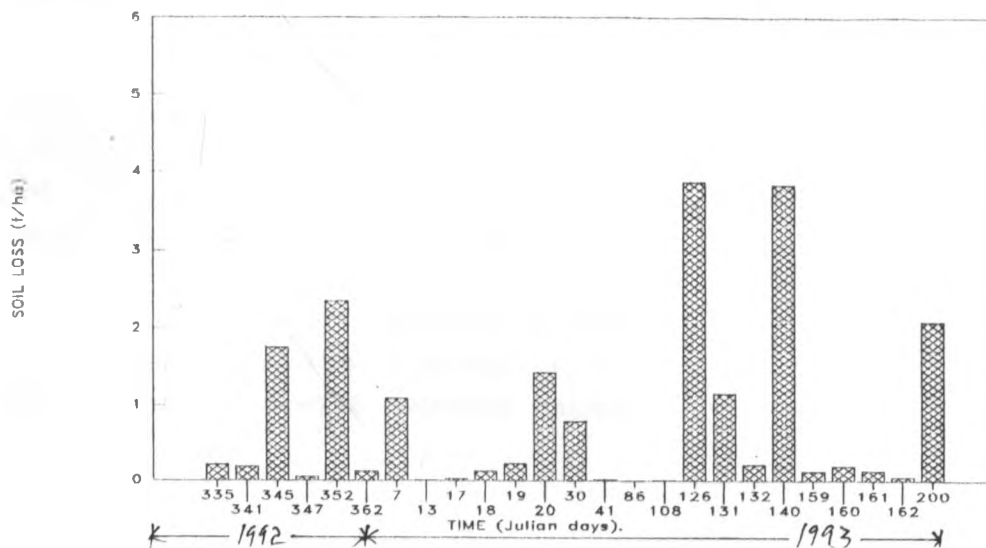for the Bare Open (BO) plots (Single events)

Appendix 7.10a: A graph of soil loss (t/ha) against time for the Perennial Enclosed (PE) plots. (single events).
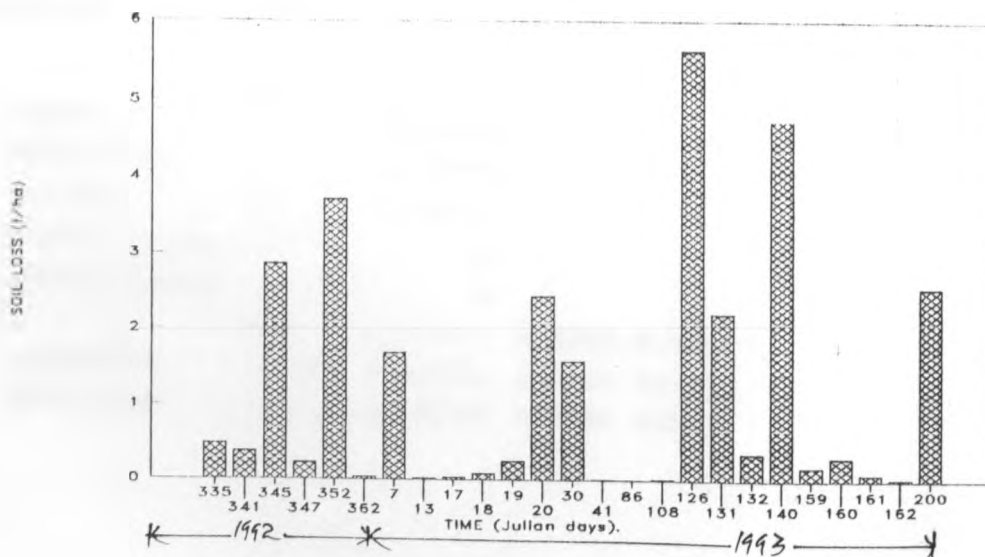

Appendix 7.10b: A graph of soil loss (t/ha) against time for the Perennial Open (PO) plots (single events).

Appendix 7.10c: A graph of soil loss (t/ha) against
time for the Bare Enclosed (BE) plots (single events).

Appendix 7.10d: A graph of soil loss (t/ha) against
time for the Bare Open (BO) plots (single events).

Appendix 7.11a: Multiple regression output of rainfall, erosivity and % cover regressed against runoff.

Constant	32.1327453
Std Err of Y Est	16.8706440
R Squared	0.65396725
No. of Observations	100
Degrees of Freedom	96

	RAIN	EROSIVITY	% COVER
X Coefficient(s)	-0.57064	3.30218608	-1.41597
Std Err of Coef.	0.363026	0.43926465	0.162530

Appendix 7.11b: Multiple regression output for rainfall, erosivity, % cover and runoff regressed against soil loss.

Constant	-0.0659076
Std Err of Y Est	0.61168659
R Squared	0.72007877
No. of Observations	100
Degrees of Freedom	95

	RAIN	EROSIVITY	% COVER	% RUNOFF
X Coefficient(s)	-0.03170	0.10095427	0.000187	0.021232
Std Err of Coef.	0.013330	0.02007436	0.007885	0.003700