THE EFFECTS OF RAINFALL AND CATCHMENT CHARACTERISTICS ON RUNOFF YIELD IN SEMI-ARID AREAS OF TANZANIA

BY

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ABSTRACT

A complete randomised block design (CRDB) experiment with three replications (viz: at 6%, 15% and 18% slope) was conducted in Kisangara, Tanzania from November, 1994 to May, 1995. The experiment consisted of catchment length (viz: 6 m and 12 m) and soil surface cover treatments (viz: natural vegetation and bare-and-compacted). The study period covered two rainy seasons, short rainy season (locally known as *Vuli*) and long rainy season (locally known as *Masika*). The objectives of the study were to investigate effects of rainfall and catchment characteristics on runoff yield and to use the data obtained to develop and test an empirical model for semi-arid conditions of Tanzania.

Runoff yield from 60 m^2 (10 m x 6 m) and 120 m^2 (10 m x 12 m) catchments was measured using a runoff collecting system. Rainfall, soil particle size distribution, soil moisture, infiltration rate and soil bulk density for the catchments were also monitored throughout the two rainy seasons.

The results showed that catchments at 18 percent slope generated a significantly higher mean runoff yield than the catchments at 6 percent slope ($p < 0.05$) at rainfall amount equal to or more than 6 mm. Similarly, catchments at 15

percent slope generated a significantly higher mean runoff yield than catchments of 6 percent slope ($p< 0.05$) at a rainfall amount equal to or more than 6 mm. However, the mean runoff yield generated from catchments at both 15 and 18 percent was not significantly different ($p< 0.05$). The mean runoff yield per unit area of catchment was not significantly different from the 6 m and 12 m length catchments. However, the total mean runoff yield generated from the 6 m length catchments was 9 percent more than the total mean runoff yield generated from the 12 m length catchments for the two rainy seasons studied. The mean runoff yield from bare and compacted catchments was significantly different from the mean runoff yield generated from natural vegetated catchments ($p< 0.01$). The mean runoff yield from bare and compacted catchments at 18 percent slope was highly correlated with the rainfall characteristics ($r> 0.95$).

Overall correlation coefficient between mean observed and mean predicted runoff of the empirical model developed was high (0.84) indicating that the model is suitable for semi-arid conditions of Tanzania and can reliably be used to predict runoff in areas where no such measurements are made to design the optimal micro-catchments for rain water harvesting.

DECLARATION

I, **SAMSON OSCAR FRACKSON OJESI**, do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is my original work and that it has never been submitted for a degree at any other university.

Signature..... Date...29/11/96.....

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I wish to convey my sincere and heartfelt gratitude to my supervisors Dr H. Mahoo and Prof B. Kayombo for their tireless assistance, guidance and encouragement throughout the course of my study. I also thank all those who in one way or the other contributed to the successful completion of my study. Lastly, I thank SACCAR/GTZ for the financial support during the study period.

DEDICATION

To my beloved mother.

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ABBREVIATIONS

Abbreviation	Meaning
R	Multiple correlation coefficient
R^2	Coefficient of determination
%	Percent
cm	Centimetre
mm	Millimetre
km	Kilometre
RO	Runoff
R	Rainfall amount
RD	Rainfall duration
RI	Rainfall intensity
r	Simple correlation coefficient
^0C	Degrees Celcius
<	Less than
>	Greater than
LRDC	Land Resources Development Centre
SARI	Selian Agricultural Research Institute
FAO	Food and Agricultural Organisation
UNESCO	United Nations Education Scientific and Culture Organisation
me	Milliequivalent
CEC	Cation exchange capacity

g	Gramme
cm^3	Cubic centimetre
m^2	Square metre
m^3	Cubic metre
h	hour
SWMRP	Soil Water Management Research Project
ns	Not significant
s	Significant
DMRT	Duncan's Multiple Range Test
NV	Natural vegetation
BC	Bare-and-compacted
$	American Dollar
l	Litre

1 INTRODUCTION

1.1 Background information

As land pressure increases, more and more marginal areas in the world are being used for agriculture. Much of this land is located in the arid or semi-arid belts where rain falls irregularly and much of the precious water is soon lost as surface runoff. Recent droughts have highlighted the risks to human beings and livestock, which occur when rains fail (Critchley, 1986).

Tanzania is characterized by its variety of environmental conditions. Rainfall, temperature, altitude, topography, vegetation and soils vary enormously within the country. However, about 80% of Tanzania receives less than 1,000 mm of seasonal and unreliable rainfall which is not adequate for food security and self-sufficiency (Griffths, 1972; Hatibu *et al.*, 1993; Lameck, 1994). However, in the past, there has been a tendency to see irrigation as a universal panacea against unreliable rainfall. As a result, many irrigation projects failed in Tanzania (Griffiths, 1972; Hatibu, 1993). Experience has shown that irrigation potential in the semi-arid areas is limited mainly by non availability of perennial sources of water. On the other hand, the cost of development of irrigation projects which is between

15 - 20, 000 US$ per hectare is out of reach for most farmers in the semi-arid areas of Tanzania (Griffths, 1972; Hatibu, 1993).

The rainfall in the semi-arid areas of Tanzania is not only relatively inadequate but also of high variability. Normally, the rainfall comes with high intensity causing much of it to run off unused. Potential evapotranspiration in these areas exceeds rainfall during more than nine months of the year (SWMRP, 1993; Lameck, 1994). These production problems have been normally further aggravated by low rainfall occurring during the critical period of moisture requirement in most crops resulting in crop failure (Ngana, 1983). Therefore, it is rational that efforts should be made to capture, conserve and efficiently utilize the scarce rain water. To accomplish this, there is a need for improved soil management techniques that maximise the holding of water in the soil, together with cultural practices which ensure the most optimum use of the available soil-water by plants. Better management of rain-water especially in the semi-arid areas is not only necessary for enhancing plant production and thus, reducing the impact of the prevalent hunger, but also promotes the household income of resource poor inhabitants in these areas by selling their surplus produce. Furthermore, it promotes the land from

wasteful run off that causes erosion and downstream flooding and siltation. As a result, the potential for later agricultural expansion to meet the security needs of a Tanzanian population growing at less than 3% annually would be enhanced (Hatibu *et al.*, 1993).

The present government policy is to encourage people to shift from the highlands and slopes to the low sem-arid lands (Hatibu *et al.*, 1993). The success of this policy will however depend on increased water supplies in the semi-arid lowlands to enable the farmers to grow the crops they need. Rain water harvesting (RWH) is one of the important tools which can be used to manage the scarce rainfall. RWH is the process of collecting runoff from one area (normally uncropped) for various agricultural uses such as provision of domestic and livestock water, production of crops, fodder and tress and to less frequently water supply for fish and duck ponds (Pacey and Cullis, 1986; Reij *et al.*, 1988; Critchley *et al.*, 1991; Mwakalila, 1992; Hatibu, 1993; Lameck, 1994). Through RWH, there is a potential to sustainably increase crop production in semi-arid areas of Tanzania where rainfall is one of the major limiting factors of production.

Both catchment and rainfall characteristics are among the

most important factors that influence the amount of runoff that can be harvested from a catchment. Generally, large catchments generate higher runoff than small catchments. However, the runoff yield generated per unit area of catchment for relatively small catchments is higher than the runoff yield generated from relatively big catchments (Shanan and Tadmor, 1979; Pacey and Cullis, 1986; Reij *et al.* , 1988). On the other hand, catchments on a higher slope yield more runoff than catchments on a low slope. Bare and compacted catchments generate more runoff than uncompacted bare or vegetated catchments. Similarly, high rainfall amount and high rainfall intensity produce high runoff yield than low rainfall amount and low rainfall intensity, respectively (Gupta, 1979; Shanan and Tadmor, 1979; Linsely *et al.*, 1982). These relationships are not well and documented in many of the semi-arid areas of Tanzania. Therefore, there is a need for precise information on the effects of rainfall and catchment characteristics on runoff yield in order to design optimal macro-catchments for RWH in semi-arid areas of Tanzania. The information could be used as a tool in aid of RWH techniques to boost agricultural activities. It is against this background that a study was initiated at Kisangara (in Mwanga district) aimed at investigating the effects of rainfall and catchment characteristics on runoff

yield.

The specific objectives of the study were as follows:

(a) To assess runoff yield from different catchments;

(b) To assess the effect of rainfall amount, rainfall duration and rainfall intensity on runoff yield;

(c) To develop and test a slope specific empirical model that uses rainfall characteristics as inputs to predict runoff generated under different catchments.

2 LITERATURE REVIEW

2.1 Overview

Runoff is a component of rainfall which appears in surface streams of either perennial or intermittent form (Gupta, 1979). The runoff may be harvested from roots, ground surfaces as well as from intermittent or ephemeral streams. The strategy normally used in RWH is to collect runoff from a large area which can be bare or bare and compacted or naturally vegetated. RWH is of great interest in the arid and semi-arid regions, where agricultural production is limited primarily by low and erratic rainfall (Mwakalila, 1992; Hatibu, 1993). The methods of RWH can be split into two main categories, namely: micro-catchment water harvesting and runoff farming (Boars and Ben-Asher, 1982; Lameck, 1994). Micro-catchment water harvesting is a method of collecting surface runoff from a catchment area over a flow distance of less than 100 meters and storing it for consumptive use in the root zone of an adjacent cropped area. On the other hand, runoff farming is a method of collecting surface runoff from a catchment, and storing it in reservoirs for later application to cropped area.

2.2 Background information of RWH

2.2.1 Historical perspectives

Various forms of RWH have been used traditionally throughout the century. Some of the very earliest agriculture, in the Middle East, was based on techniques such as diversion of "wadi" flow (spate flow from normally dry watercourses on to agricultural fields. In the Negev desert of Israel, RWH systems dates back 4000 years or more (Evaneri *et al.*, 1971; Lameck, 1994). These schemes involved the clearing of hill sides from vegetation to increase runoff, which was then directed to fields on the plains. Floodwater farming has been practised in the desert areas of Arizona and northwest New Mexico for at least 100 years (Reij *et al.*, 1988). Pacey and Cullis (1986) described micro-catchments techniques for tree growing, used in southern Tunisia, which were discovered in the nineteenth century by travellers. In the "khadin" system of India, floodwater is impounded behind earth bunds, and crops then planted into the residual moisture when the water infiltrates.

A growing awareness of the potential of RWH for improved production arose in the 1970s and 1980s, with the widespread droughts in Africa leaving a trail of crop failures (Evaneri

et al., 1971). However, much of the experience with RWH gained in countries such as Israel, USA and Australia has limited relevance to resource-poor areas in the semi-arid regions of Africa and Asia (Pacey and Cullis, 1986). In Israel, research emphasis is on the hydrological aspects of micro-catchments for fruit trees such as almonds and pistachio nuts. In USA and Australia, RWH techniques are mainly applied for domestic and livestock water supply. That is why more research is now directed towards improving runoff yields from treated catchment surfaces (Pacey and Cullis, 1986).

2.2.2 Recent Developments

RWH has been shone to work under varying environmental conditions and for different purposes around the world (Reij *et al.*, 1988). However, the importance of traditional, small scale systems of RWH in Sub-Saharan Africa has just been recently recognized (Critchley, 1986). Simple stone lines are used, for example, in some West African countries, notably Burkina Faso, and earth bunding systems are found in Eastern Sudan and the Central Rangelands of Somalia. The main objective of RWH projects is to combat the effects of drought by improving crop production (usually annual food crops) (Critchley, 1986; Lameck, 1994). However, few of the projects

have succeeded in combining technical efficiency with low cost and acceptability to the local farmers or agropastoralists. This is partly, due to the lack of technical "know how" but also often due to the selection of an inappropriate approach with regard to the prevailing socio-economic conditions.

2.3 RWH in Tanzania

In Tanzania, farmers practice some kind of RWH through valley farming, which involves intensive cultivation of valley floors, where runoff from slopes is concentrated. In parts of Tabora, Shinyanga and Dodoma regions farmers have developed a system of water harvesting which involves diversion of water from ephemeral streams, to valleys where fields are subdivided by bunds of 25 - 100 cm height to form cultivated reservoirs (paddies). The collected runoff is stored in these reservoirs for use by transplanted rice crop (Mwakalila, 1992; Hatibu, 1993; Lameck, 1994). Previous research has shone that there is a significant yield benefit due to RWH. For example, Lameck (1994) reported a mean yield benefit of 3.22 t/ha and 2.95 t/ha for maize and sorghum, respectively, attributable to runoff harvested from different catchments.

2.4 Review of previous work on effects of rainfall and catchment characteristics on runoff yield

2.4.1 General

The ideal way to study rainfall, soil and surface runoff under different land use practices is to study small catchments under different characteristics. Studies of this type have been carried worldwide (Fogel, 1976). On-site conditions of a catchment (viz: catchment characteristics) and rainfall characteristics are the most important factors that influence the amount of runoff that can be harvested from a catchment. The rainfall characteristics that affect runoff yield are: amount of rainfall, intensity of rainfall, duration of rainfall, distribution of storm intensity on the catchment, direction of storm movement, soil moisture and other climatic factors that affect evaporation and transpiration. The catchment characteristics that affect the amount of runoff yield include: landuse, type of soil, size (catchment length), shape, elevation, slope, orientation, type of drainage network and extent of indirect drainage. Chaves and Nearing (1991) reported that rainfall parameters (amount, intensity and duration) and the parameters that affect infiltration such as antecedent precipitation, soil characteristics, vegetal cover, slope and aspect of the surface have the biggest impact on the runoff generated.

All runoff has rainfall as its primary source. Gupta (1979) reported that significant amounts of overland flow can result from a broad spectrum of circumstances. These are those storms that cause overland flow into stream channels despite the capacity of the catchment soil profile to store more of the rainfall. Runoff can occur because of an infiltration limitation; the soil profiles are unable to absorb the rainfall before it reaches the stream channels. This may result from storms of high rainfall intensity or in areas where surface soils are of low permeability.

2.2.4 Effects of rainfall characteristics on runoff yield

2.2.4.1 Rainfall amount

Generally, high rainfall amount generates high runoff. However, the effect of rainfall amount on runoff yield to some extent depends on rainfall intensity and the soil moisture. High rainfall amount governed by low rainfall intensity can produce low runoff than a relatively low rainfall amount that falls with a high intensity (Gupta, 1979; Pacey and Cullis, 1986). As the amount of rainfall increases, so does the soil moisture content resulting in a reduction in infiltration rate of the soil due to decrease in capillary potential. As the rainfall continues the infiltration capacity of the soil attains moisture constant

value. As a result of this, even a small amount of rainfall can produce a significant surface runoff. If the rain fells after a dry long spell when the soil is dry and can absorb large amounts of water, during such conditions, even a considerable amount of rainfall may fail to produce an appreciable runoff (Gupta, 1979; Linsely *et al.*, 1982; Pacey and Cullis, 1986).

2.4.2.2 Rainfall intensity

Generally, rainfall of high intensity generates more runoff than rainfall of low intensity though the amount of rainfall may be the equal (Gupta, 1979; Pacey and Cullis, 1986). Linsely *et al.*, 1982) stated that surface runoff is generated when and where the rainfall intensity exceeds the rate at which water can enter the soil. Other storms are able to cause overland flows before infiltration rates in the catchment have been greatly reduced by high moisture levels that reduce capillary heads in catchment soil profiles. Capacity limitations under natural conditions are normally for high percentages of rainfall becoming runoff. rainfall exceeding the infiltration capacity of the soil generates surface runoff very rapidly with the increase in rainfall intensity.

2.4.2.3 Rainfall duration

Rainfall duration has no significant effect on runoff yield. This is because the effect of rainfall duration on runoff yield totally depends on rainfall amount and rainfall intensity (Gupta, 1979; Linsely *et al.*, 1982; Pacey and Cullis, 1986). High intensity rainfall of short duration generates more runoff than low intensity rainfall of long duration. Similarly, high rainfall that fall falls within a short period of time generates more runoff than low rainfall that falls for a long period of time (Gupta, 1979; Linsely et al., 1982; Pacey and Cullis, 1986).

2.4.3 Effects of catchment characteristics on runoff yield

2.4.3.1 Surface ground cover

Close and thick vegetal cover significantly reduces runoff yield generated from a catchment though a number of ways. This is particularly because vegetation influences the rainfall-runoff system through interception, obstruction to flow of surface runoff by their roots and litter thereby allowing more time for the water to infiltrate into the soil. In addition, transpiration by the vegetation reduces soil moisture and thus, increases the infiltration capacity of the soil (Gupta, 1979; Shanan and Tadmor, 1979; Critchley *et al.*, 1991). However, all of these factors vary both temporally and

spatially (Griffths, 1972; Shanan and Tadmor, 1979; Linsely *et al.*, 1982; Mahoo *et al.*, 1994b, Unpublished). Jones *et al.* (1991) observed that in areas where adequate amount of ground cover were produced (either by the natural vegetation or crops), the effect had been an increase in the infiltration rate, reduced runoff, and improved water conservation through reduced evapotranspiration.

In USA, Chaves and Nearing (1991) observed that when wheat and sorghum were grown on two different equal plots on the same slope, at the end of the growing season, there was higher runoff obtained from the sorghum plots than from the wheat plots. The reason given was that wheat provided excellent ground cover which intercepted most of the raindrop impact and the closer spacing among the wheat plants provided sufficient time for the water to infiltrate into the soil resulting in less water to flow as surface runoff. SWMRP (1993) reported that the catchments under natural vegetation (NV) yielded very little or no runoff at all during the short rainy season (*Vuli*) at Kisangara.

Rapp *et al.* (1972) concluded that runoff, from semi-arid pediment areas of East Africa with poor vegetation cover, can reach 30-40% of the rain season precipitation for catchment

areas of a few kilometres in size. Surface runoff from small erosion plots in some parts of Central Tanzania have also been reported (Staples, 1938; Van Rensburg, 1955). However, in large catchments, proportionally more of the rainfall is infiltrated into large areas of sandy rivers, sandy fans and "Mbugas." Staples (1938) compiled and analyzed existing runoff data at Mpwawa. The results demonstrated that in the semi-arid areas of Tanzania, severe losses of soil and water are associated with land clearance, cultivation and over grazing.

Bare soil is always subjected to intense rainfall impact resulting in generation of a lot of runoff. This is due to decreased infiltration rate that comes as a result of reduction in soil moisture deficiency, mechanical compaction of the soil by the raindrops and in wash of fine soil particles. Morin and Benjanim (1977) reported that when crop covers are not adequate to protect the soil from the kinetic energy of rainfall, as is often the case with dry land cropping in the semi-arid areas, then soil crusting can occur which can increase the surface runoff thereby reducing the infiltration and water conservation.

2.4.3.2 Management practices

Management systems or practices done on the land have an important influence on the runoff generated. SWMRP (1993) reported that bare and compacted catchments at Kisangara generated up to 26% runoff higher than the natural vegetated catchments during *Vuli* in October/November, 1993. In Morogoro, Mahoo *et al.* (1994a, Unpublished) observed a higher runoff yield from bare and compacted catchments than in both low managed crop and bare catchments. SWMRP (1995, Unpublished) reported that in Hombolo, catchments under tied ridges produced the least runoff yield while zero tillage and strip catchment tillage treatments produced high runoff yield on average than all the tillage treatments in all the rainfall events.

2.4.3.3 Catchment size

Generally, large catchments generate higher runoff than small catchments (shanan and Tadmor, 1979; Pacey and Cullis, 1986; Reij *et al.*, 1988). Lal (1992) reported that forested areas of 44.3 ha and 10.6 ha on a slope of 2.8% discharged runoff of 3.5 mm and 0.9 mm from 199.2 mm of rainfall,respectively. However, the runoff yield generated per unit area of catchment for relatively small catchments is higher than runoff yield generated from relatively big catchments (Shanan

and Tadmor, 1979; Pacey and Cullis, 1986; Reij *et al.*, 1988).

In Morogoro, Mahoo *et al.* (1994a, Unpublished) observed a 10% increase in total yield generated in one rainy season from the 5 m catchments as compared to the 10 m catchments.

2.4.3.4 Catchment slope

Catchments which are steep have high velocity of flow and runoff takes less time to reach the lower end of the catchments resulting in higher runoff yield than gentle slope catchments (Shanan and Tadom, 1979; Pacey and Cullis, 1986). In Morogoro, it has generally observed that there is a significantly higher runoff yield generated ($p < 0.05$) from catchments whose slope is 6-8% than those catchments whose slope is 3-4% (SWMRP, 1993; Mahoo *et al.*, 1994a, Unpublished).

2.5 Modelling

In most fields of agricultural research, increasing numbers of decision-aid packages or simulation models have been developed for many agricultural uses. RWH is a system which seeks to encourage runoff from the catchments to the cropped area. It is necessary that the amount of runoff that can be discharged from a catchment be adequately be quantified or

estimated in order to avoid erosion or waterlogging down the catchment. In addition, prediction of surface runoff from the catchment can provide the necessary runoff data for various agricultural uses. For example, it can be used as a basis for the choice of crops to grow in an area where RWH is to be practised based on the expected runoff yield and the crop water requirement of the crops in question. Prediction or estimation of runoff from the catchment is normally done trough the use of empirical models. Application of the model takes into account assumptions that are governed by these models. However, most of the empirical models developed are site specific (Sheridian, 1994).

Many researchers have used analysis of variance of factorial experiments because it has proved to be a valuable exploratory exercise to investigate the interaction effects of catchment characteristics and rainfall characteristics on runoff yield (Walkman and Skaggs, 1994). Such analyses are useful in identifying the key effects and the interactions in the system which can then be recommended for use or investigated further. Models of this type generally use approximate relationships developed from available catchment size and slope (Walkman and Skaggs, 1994).

One of the main groups of models commonly used in hydrological related fields are the empirical models that are primarily based upon relationships derived from regression analysis. Usually, these require large amounts of data for their development. These types of models can not be applied outside the region for which they were developed (Walkman and Skaggs, 1994).

One of the empirical models used to calculate amount of runoff produced from a site following a rainfall is the semi-empirical curve number method (USDA, Soil Conservation Service, 1985). In this method the amount of runoff is given by:

$$R = \frac{(P-0.2S)^2}{P} + 0.8S \qquad (1)$$

Where P is the rainfall amount, and S is a relation parameter which is the maximum potential difference between rainfall and runoff at the beginning of the rainfall event. If P is equal or less than 0.2S then the method assumes that there is no runoff and all the rainfall is absorbed by the soil. The maximum value of the retention parameter (S_{max}) is determined from:

$$S_{MAX} = 254\left(\frac{100}{CN} - 1\right) \qquad (2)$$

Where CN is the curve number for the driest antecedent (i.e. prior to rainfall) moisture condition and is related to the curve number for average antecedent moisture by an empirical equation.

Chong and Teng (1986) showed that it is possible to relate the curve number of a soil to various hydrological properties through a variety of empirically derived regression equations. In particular, they studied relationships the retain parameter, S, saturated hydraulic conductivity K_{sat}, sorptivity S_0, and rainfall intensity R and found a strong relationship, between K_{sat} and curve number which can be improved by the inclusion of S_0. However, the curve number appears unaffected by rainfall intensity.

Sheridian (1994) stated that hydrologic runoff prediction concepts may be stressed to the development of the "rational method" for estimating peak rate of discharge as a function

of watershed time concentration (tc). The time area-curve approach which later incorporated the time-of-concentration concept introduced conceptually the influence of watershed characteristics, i.e. distance from outflow and physical characteristics of share and area. The problem with this approach is that though it includes channel and surface effects, it does not consider catchment effects.

Cooper *et al.* (1992) used CREAM model (Kinsel, 1980) to predict runoff from New Zealand grazed pasture. The results showed that the model was unbiased predictor. However, the CREAM model has limitations in representing the dynamics of the grazed pastures. The model used is as follows:

$$Q_p = 0.3064\,(A)^{0.7}\ (CS)^{0.159}\,(Q)^{0.197\,A^{0.0166}}\,(LW)^{-0.187} \qquad (3)$$

Where:

Q_p = peak runoff rate (m^3/s)

A = Drainage area (ha)

CS = Mainstream drainage slope (m/m)

Q = Daily runoff volume (mm)

LW = Length - width ratio of the watershed

Lundgren (1980) modelled runoff at Usambara Mountains in Tanzania using throughfall, slope (gentle and steep), month and year as dependant variables. With the help of multiple regression, the following results were found:

Site 1: Variation in runoff explained by the four variables was approximately 70%.

Site 2: The amount of monthly runoff values > 0.1 mm was too small and the material could not be used for multiple analysis.

Site 3: Variation in runoff variables was approximately 70%. However, Lundgren did not take into account the effect of surface cover of the catchments.

Borah (1986) developed a dynamic watershed model which recently had been renamed RUNOFF. The model uses efficient algorithms and requires information on watershed topography, soil and land use characteristics and time varying rainfall records. the only model parameters are the SCS (Soil Conservation Service) runoff curve number and the Manning's roughness coefficient. The model is simpler and easier to apply to watershed where sufficient data are not available. Once the curve number value is estimated, the following relations are used to compute the direct runoff for given rainfall event. The model is as follows:

$$Q_r = \frac{(P-0.2S_r)}{P + 8S_r} \quad (4)$$

$$S_r = \frac{25400}{CN} - 254 \quad (5)$$

Where:

Qr = the direct runoff or the rainfall excess, mm.

P = the accumulated rainfall, mm.

CN = the runoff curve number.

Sr = soil moisture, mm.

In Morogoro, Mahoo *et al.* (1994b, Unpublished) developed a four parameter empirical model relating runoff to rainfall characteristics and land-use. The model is as follows:

RO = 0.01144R + 0.002616RI + 0.00024415RD (Treatment = NV)

RO = 0.20632R + 0.1051RI + (-0.001556RD) (Treatment = LCM)

RO = 0.2999R + 0.2115RI + (-0.002935RD) (Treatment = B)

RO= 0.22385R + 0.21297RI + 0.001697RD (Treatment = BC)

Where:

RO = Runoff (mm)

RI = Rainfall intensity (mm/h)

RD = Rainfall duration

NV = Natural vegetation

LCM = Low managed crop

B = Bare

BC = Bare-and-compacted

However, Mahoo's model did not take into account the effect of different slopes on runoff yield.

2.6 Synthesis of the Literature Review

In adequate, unreliable and irregular rainfall have been reported as characteristics of the rainfall in arid and semi-arid areas of the tropics. The insufficient rainfall has caused inadequate water supply for agricultural activates. As a result, there has been insufficient food security and lack of self-sufficiency in most semi-arid areas of the tropics. This situation has prompted researchers to engage in RWH activities in order to ensure efficient utilization of scarce rain water for crop production.

Runoff is harvested from catchments with different treatments. The amount of runoff harvested from a catchment depends on both rainfall and catchment characteristics. Many researchers have reported that amount and rainfall intensity are some of the rainfall parameters that influence the amount of runoff that can be harvested from an area. In addition, catchment size (length), surface ground cover, management systems or practices and the slope of the catchment are also other parameters that been reported to affect runoff yield. The amount of runoff that can be discharged from a catchment can be accurately quantified or estimated to avoid erosion or waterlogging down the catchment through the use of empirical models.

Experience has shone that both rainfall and catchment characteristics vary temporally and spatially and their effect on runoff is considerable especially in the tropics where agriculture is rainfall dependant. The information obtained from the effects of rainfall and catchment characteristics can be used to develop an empirical model relating runoff to rainfall and catchment characteristics. This information cold be useful in the design of optimal micro-catchments for RWH to boost agricultural activities in the semi-arid areas of the tropics like Tanzania.

3. MATERIALS AND METHODS

3.1 Description of the experimental Site

3.1.1 Location

The experiment was conducted at Kisangara within the Karimjee Sisal Estate eight kilometres south of Mwanga township in Kilimanjaro region. The area is located at latitude 3^0 43′ S, longitude 37^0 35′ E and at an altitude of 870 m above mean sea level (Figure 3.1).

3.1.2 Agro-Ecological Zones

According to LRDC (1987), Tanzania has been classified into six agro-ecological zones according to soil type, altitude, mean annual rainfall and duration of the growing season. These are: (1) Coast, (2) Arid Lands, (3) Semi-Arid Lands, (4) Plateaux, (5) Southern and Western Highlands, and (6) Northern Highlands and isolated granitic mountains. Mwanga district (Figure 3.1) falls under two major agro-ecological zones, namely the highlands and the lowlands. The highlands divide the lowlands into the eastern and western lowlands. The landscape is dominated by slopes, sometimes very steep (40%). The Pare mountains are located in the South East OF Kilimanjaro region between 600 m and 2 424 m above mean sea level. On the eastern side of the mountain slope, there is a green crown of crops and forests.

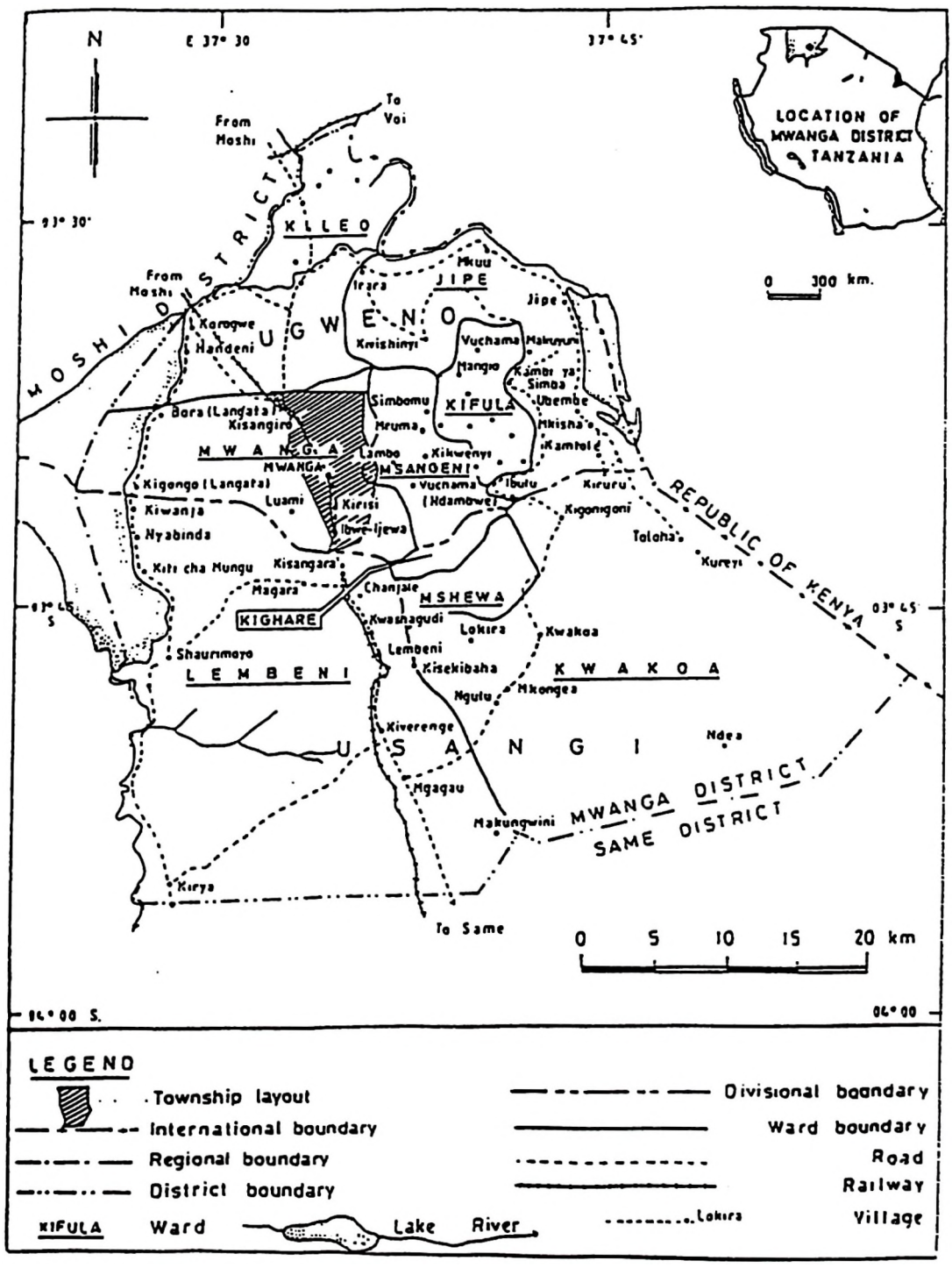

Fig. 3.1 Map of Mwanga district

3.1.3 Climate

3.1.3.1 Rainfall

Kisangara is characterised by a short rainy season (locally known as *Vuli*) extending from November to December and a long rainy season (locally known as *Masika*) from February to May. This bimodel rainfall pattern influences landuse pattern with some crops planted to take advantage of the short rains and others planted for long rains. The yearly average rainfall at Kisangara is 688 mm (Hatibu *et al.*, 1993; SARI, 1995).

3.1.3.2 Evaporation

Potential evapotranspiration exceeds rainfall in almost all months of the year with exceptions of some few months during long rains (Hatibu *et al.*, 1993; SARI, 1995). In fact, rainfall exceeds evapotranspiration briefly in December and April, actually more in December than in April.

3.1.3.3 Temperature

Only slight temperature variations occur from month to month. The coolest months are: May, June and July when average daily temperature ranges from about 16^{0}c to 18^{0}c. The warmest temperature is experienced just prior to and after the long rainy season (January and February, and August to October, respectively) (Hatibu *et al.*, 1993; SARI, 1995).

3.1.4 Soils of the experimental site

Due to long history of sisal cultivation, the top 0-10 cm depth of the soil is dominated by a high density of sisal root network. According to the Selian Agricultural research Institute (SARI, 1995) the soil in the study area is highly influenced by the topographical position. The dominant soil order occurring in the area is Luvisol. The cation exchange capacity (CEC) of this soil is less than 15 me/100 g soil.

Ferric Luvisol occupies nearly 90% of the experimental site. These soils occur intensively on the middle (3-6%) and lower slope (3%) position of the area. Ferric Cambisol and Plinthic Luvisol covers approximately 8% of the experimental area. These soils occupy the northwest corner, immediately below the northern boundary of the area. Chromic Luvisol occupies the remaining 2% of the experimental area located at the north-east of the existing sisal field. A summary of the detailed description of the soils at the experimental site is shown in Appendix 3A and 3B.

3.1.5 Vegetation

At the site, the most dominant vegetation is sisal and grass. The sisal plantation surrounds almost the entire experimental area except in the upper slope area (15% to 20% slope area).

Most of the grasses at the site are 50-120 cm high and are of different species of *Pennisetum* (locally named *Masai* Grass) (Plate 1-2). Normally, the density of the grass is high in the middle slope (3-6%) and in the lower slope (3%) than in the upper slope (above 7%) of the experimental area. The difference is more pronounced during the rainy seasons. In the middle slope area there are also small patches of Rhodes grass and Star grass which are not present in the upper and lower slope areas. During the dry seasons, the sisal is the only distinct vegetation since most of the grass species dry out.

3.2 Experimental Methods

3.2.1 Experimental Layout

The experiment was laid out on three different slopes (6%, 15% and 18%) based on the following factors: topographical position of the area, the available area and the experimental design. Figure 3.2 shows how the plots in each block were laid out.

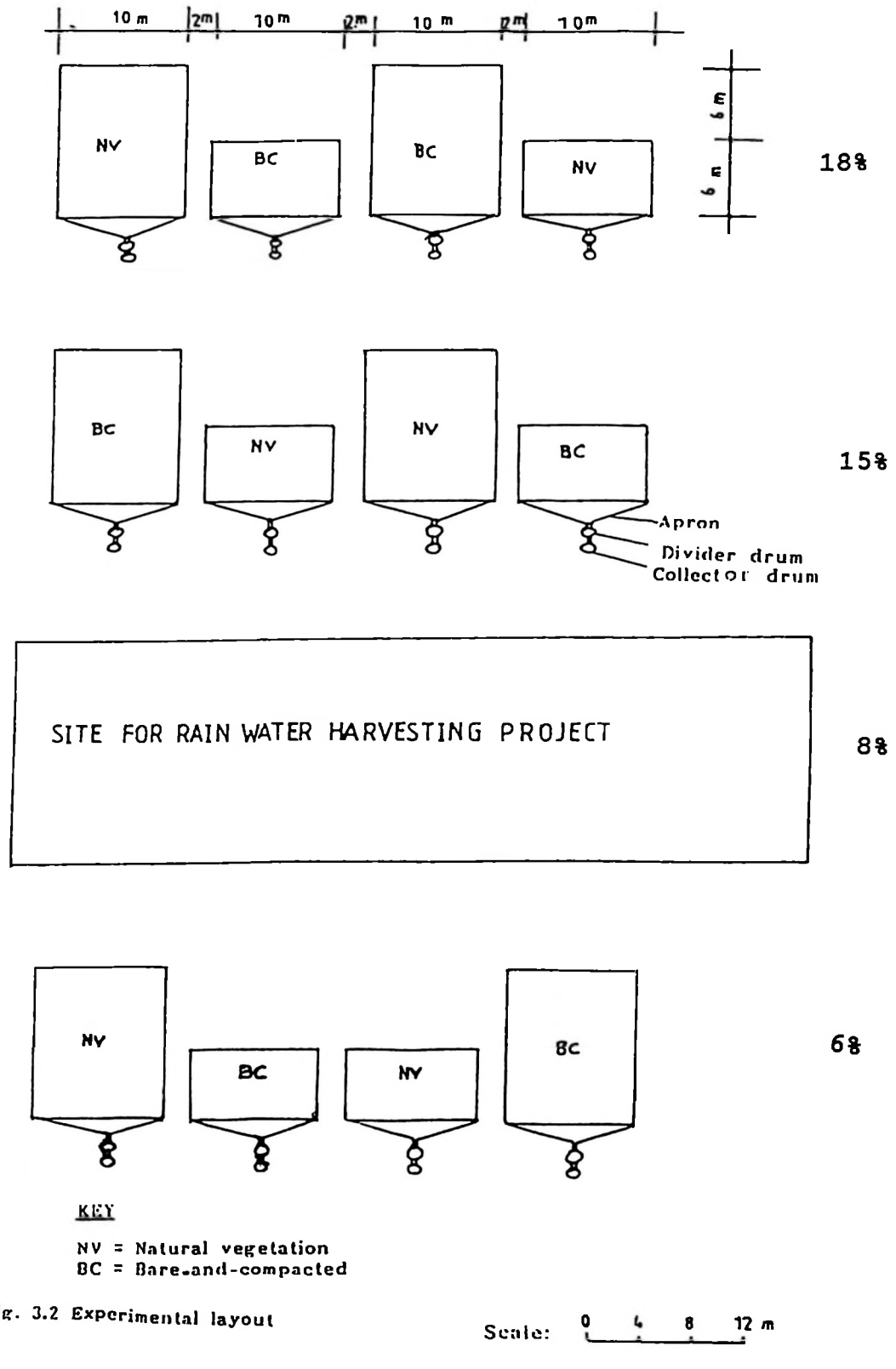

Fig. 3.2 Experimental layout

3.2.2 Experimental design and treatments

A field experiment consisting of catchment length and soil surface cover treatments (viz: natural vegetation and bare-and-compacted) was laid out on a complete randomised block design (CRBD) with three replications (viz: at 6%, 15% and 18% slope). Catchment length treatments consisted of 6 m and 12 m. Catchment length and soil surface cover treatments were both replicated twice at each slope (Figure 3.2).

3.3 Instrumentation and data collection

A clinometer was used to determine the slope of the three blocks. The first block had a slope of 18%. The second block had a slope of 15% and the third block a slope of 6%. Hand hoes were used to prepare the blocks.

3.3.1 Plots preparation

Four plots were prepared in each block, two plots of size 12 m x 10 m and two plots of size 6 m x 10 m. At each block, two plots (one of size 12 m x 10 m and another of size 6 m x 10 m) were left with their natural vegetation (species of *Pennisetum*). The other two plots in the same block were cleared of all the vegetation by a hand hoe and then compacted using a manually hand operated compact roller of about 250 kg at six passes. Both, plot length and surface

catchment treatment were randomly imposed in each block (Figure 3.2). A bund was constructed on the edge of each plot to avoid runoff from surrounding areas entering the plots and also to avoid escape of runoff from the runoff plots. At the lower end of each runoff plot, a cemented apron of 4 m^2 was constructed to lead the runoff into the pipe that connected the apron and the divider drum (Figure 3.3).

3.3.2 Runoff drums installation and calibration

At the lower end of each runoff plot, two drums (a divider drum and a collector drum both of 200 litres capacity) were installed on a levelled cement base leaving about 15 cm of each drum above the ground. A spirit level was used to level the horizontal alignment of the drums in the soil (Figure 3.3). Each drum was calibrated according to the method outlined by SWMRP (1993). In this case, different volumes of water (5l, 10l, 20l, 40l, 80l, 140l, 140l, and 200l) were poured at the apron at different times. The depth of water collected in the drums was measured using a 100 cm steel ruler after a particular volume of water was poured at the apron. A depth to volume calibration curve was established for each drum.

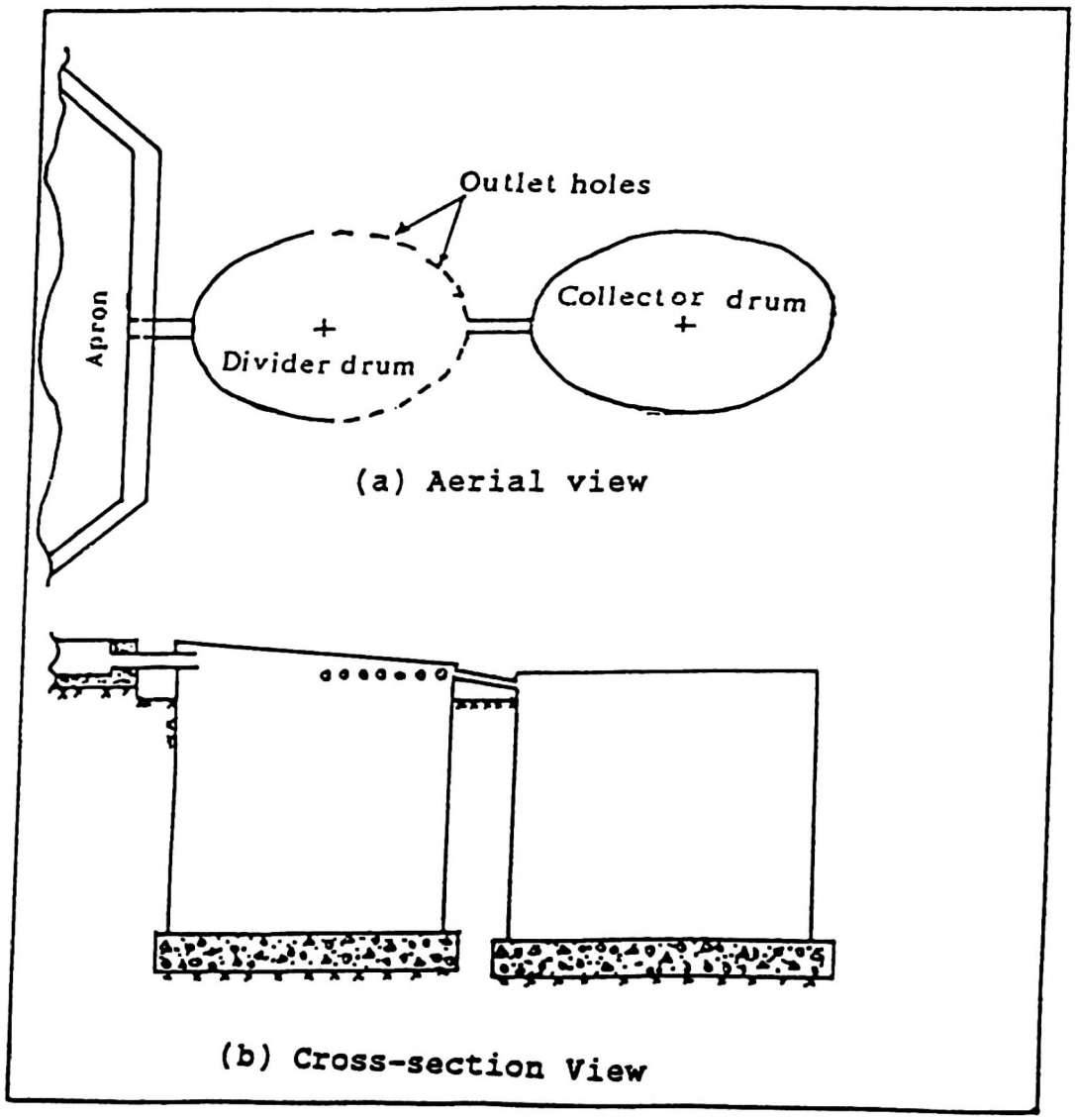

Fig. 3.3 Runoff collection system

3.3.3 Data collection

Data collection included climatic data, soil hydrological properties and runoff volumes. The steady state infiltration rate, soil moisture content and soil bulk density were determined before imposing the catchment treatments (at the start of *Vuli*), at the end of *Vuli*, and at the start and at the end of *Masika*.

3.3.3.1 Steady state infiltration rate

The steady state infiltration rate for the site was determined using the double ring infiltrometer method (Klute, 1986).

3.3.3.2 Soil moisture content

Gravimetric soil moisture content was determined using the standard method (Klute, 1986). Soil samples were collected at a depth of 0-10 cm. The gravimetric moisture content was converted into volumetric moisture content using the standard method (Klute, 1986).

3.3.3.3 Soil bulk density

Soil bulk density was determined using the standard method (Klute, 1986). Soil samples were collected at a depth of 0-10 cm.

3.3.3.4 Soil particle size distribution

Soil samples from all plots were collected at a depth of 0-10 cm for particle size analysis before imposing the catchment treatments. The hydrometer method (Klute, 1986) was used to analyze the soil. The particle size distribution was used to determine the textural classes of the soil from each plot.

3.3.3.5 Rainfall

Rainfall amount and duration was measured using a Dines tilting siphon recording rain gauge. The rainfall amount and duration was calculated from the rainfall charts. Rainfall intensity was determined by dividing rainfall amount by its duration (Appendix 2A and 2B).

3.3.3.6 Temperature

At the Kisangara meteorological station, maximum daily temperature was measured using an ordinary mercury-in-glass thermometer while the minimum daily temperature was measured by an alcohol-in-glass thermometer.

3.3.3.7 Evaporation

The source of evaporation data was SWMRP-Kisangara meteorological station. At the meteorological station,

evaporation was measured using a modified class A pan made of galvanised iron 25.40 cm deep and 120.6 cm inside diameter.

3.3.3.8 Runoff

Runoff was collected and measured using the system shown in Figure 3.3. The system consists of a divider drum with 15 outlet holes of diameter 1.9 cm. The central outlet hole is connected to the collector drum by a hose pipe. The overflow outlet holes of the divider drum were adjusted such that the overflow volume draining into the collector drum was between 1/12 and 1/18 of the total flow. Calibration of the runoff collection system was done in order to obtain the actual ratio of the overflow that drained into the collection drum. This ratio was used to calculate the total runoff from the catchment area (Appendix 1). A depth to volume calibration curve was established for each drum. After each rainfall event, the runoff yield collected in each drum was measured using a 100 cm steel ruler. The runoff collected in litres was converted to runoff depth (mm) by dividing it with its respective catchment area (m^2) (SWMRP, 1993) based on the following assumptions:

(a) each catchment area had an impervious layer resulting in no loss of runoff due to deep percolation as observed by the depth of the impervious layer in all the

catchments during the soil sample collection.

(b) evaporation was very minimal and uniform in all the catchments since measurement was done after every rainfall event and in case of rain falling at night, measurement was done early in the morning of the following day.

(c) amount of sediment in the divider and collector tanks was negligible.

(d) there was uniform rainfall distribution in all the catchments.

3.4 Data analysis

A statistical software computer package version of MSTATC was used to analyze runoff data, and to develop and test an empirical model to predict runoff as follows: Analysis of variance (ANOVA) was used to test the effect of catchment length and surface catchment cover on runoff yield. Duncan's Multiple Range Test (DMRT) was used to compare the mean runoff from the three slopes (18%, 15% and 6%). Multiregression analysis was used to test the effects of rainfall characteristics (rainfall amount, rainfall duration and rainfall intensity) on runoff yield. The multiregression analysis was also used to develop and test an empirical model. Tables of means and graphs were used to analyze climatic and soil data.

4 RESULTS AND DISCUSSION

4.1 Characteristics of the climate during the study period

4.1.1 Rainfall

Table 4.1 shows that the total and mean rainfall at Kisangara meteorological station from November 1994 to May 1995 were 818.6 mm and 116.9 mm, respectively. However, the total rainfall during *Vuli* season (November to December, 1994) was 328 mm while the total rainfall during *Masika* season (February to May 1995) was 490.6 mm. Similar results were reported by Hatibu *et al.* (1993) and SARI (1995).

4.1.2 Evaporation

Table 4.1 shows that the total and mean potential evaporation from November, 1994 to May, 1995 was 1489 mm and 212.7 mm, respectively. In addition, Table 4.1 and Figure 4.1 show that monthly potential evaporation exceeded monthly rainfall during the study period except in April and December. In fact, the excess rainfall in December is probably more significant than that in April. Similar results were observed by Hatibu *et al.* (1993) and SARI (1995).

4.1.3 Temperature

The highest monthly mean maximum temperature of 32.8^{0}C was recorded in February. The lowest monthly mean minimum

Table 4.1 Summary of climatic data from November, 1994 to May, 1995 at Kisangara

Month	Rainfall (mm)	Epan (mm)	Mean Tmax. (°C)	Mean Tmin. (°C)
November	99.6	190.6	30.43	19.10
December	228.4	206.5	29.68	19.24
January	0.0	331.0	32.47	18.83
February	53.0	270.5	32.82	19.41
March	190.0	231.0	31.52	19.58
April	149.8	143.3	30.50	19.52
May	97.8	116.1	27.15	18.46
Total	818.6	1489.0	-	-
Mean	116.9	212.7	-	-

Source: SWMRP (1995) - Kisangara Meteorological Station

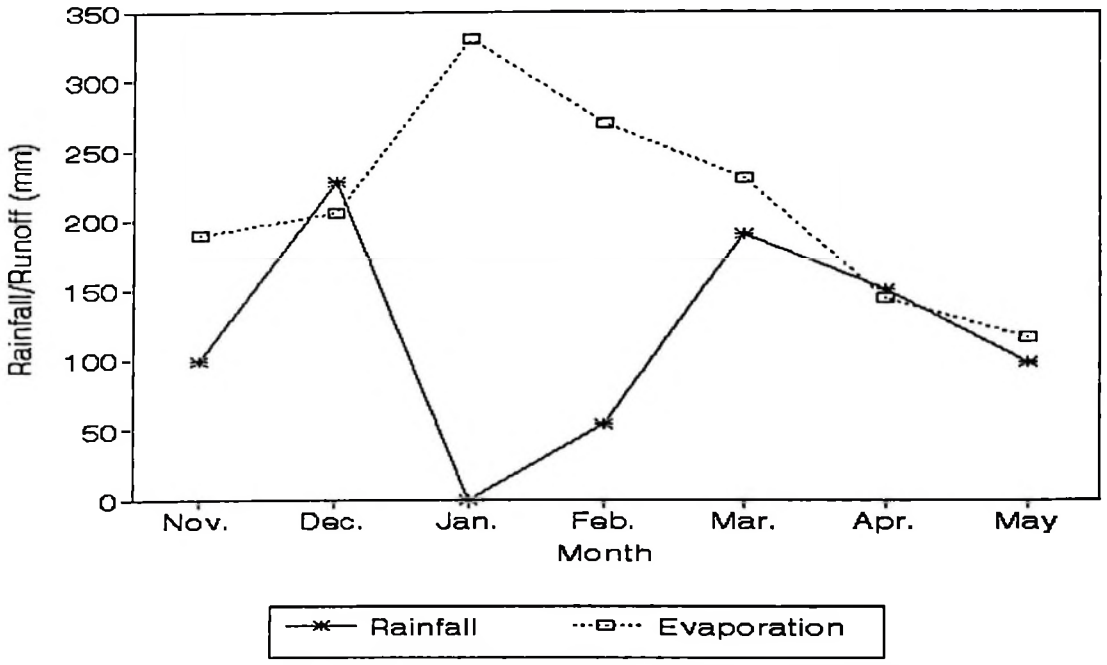

Fig. 4.1 Rainfall and Evaporation from November, 1994 to May, 1995 at Kisangara

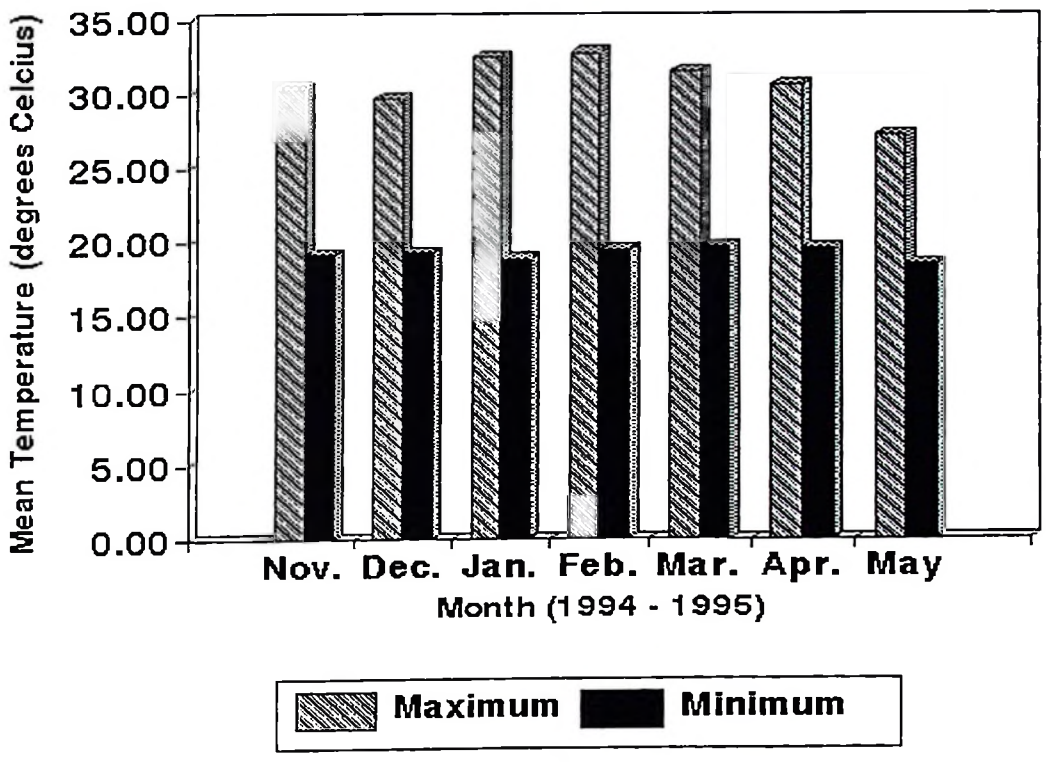

Fig. 4.2 Mean temperature variations from November, 1994 to May, 1995 at Kisangara

temperature of 18.5°C was recorded in May (Table 4.1 and Figure 4.2). These results agree with the findings by Hatibu *et al.* (1993) and SARI (1995).

4.2 Soil hydrological properties

4.2.1 Infiltration rate

Figures 4.3 to 4.6 show a higher steady state infiltration rate in natural vegetated (NV) treatment catchments than in the bare-and compacted (BC) treatment catchments. This was due to the lower bulk density observed in the NV treatment catchments than in the BC treatment catchments (Figure 4.8). However, the steady state infiltration rate at the beginning of both rainy seasons was higher than at the end of both rainy seasons in both treatment catchments (Figures 4.3 to 4.6). This was attributed to the lower soil moisture at the beginning of the rainy seasons than at the end of the rainy seasons (Figure 4.7). Similar results were observed by Shanan and Tadmor (1979), and Morin and Benyamin (1993).

4.2.2 Soil moisture content

Figure 4.7 shows that the soil moisture content was 13.9 mm before imposition of the surface catchment treatments at the beginning of *Vuli*. This shows that there was insignificant difference ($P< 0.05$) between soil moisture content in the NV

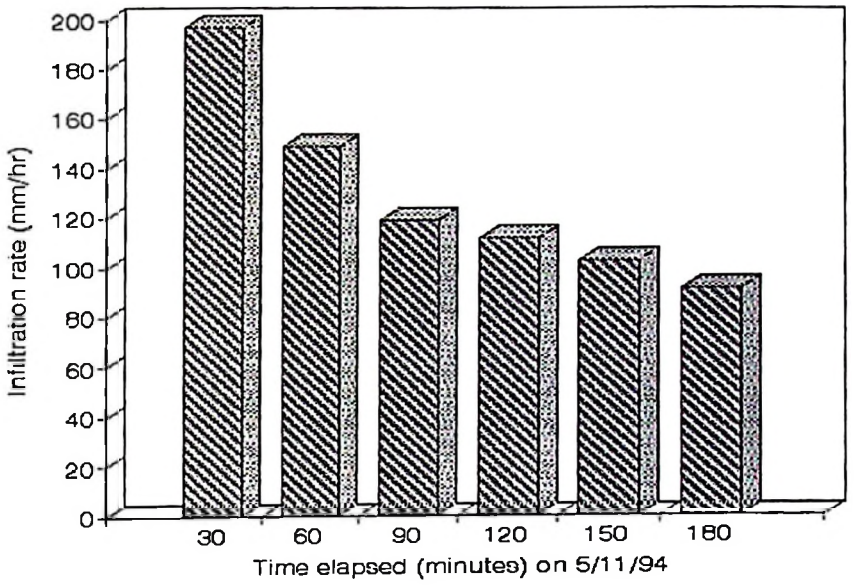

Fig. 4.3 Steady state infiltration rate before imposing catchment treatments (at the start of **Vuli**)

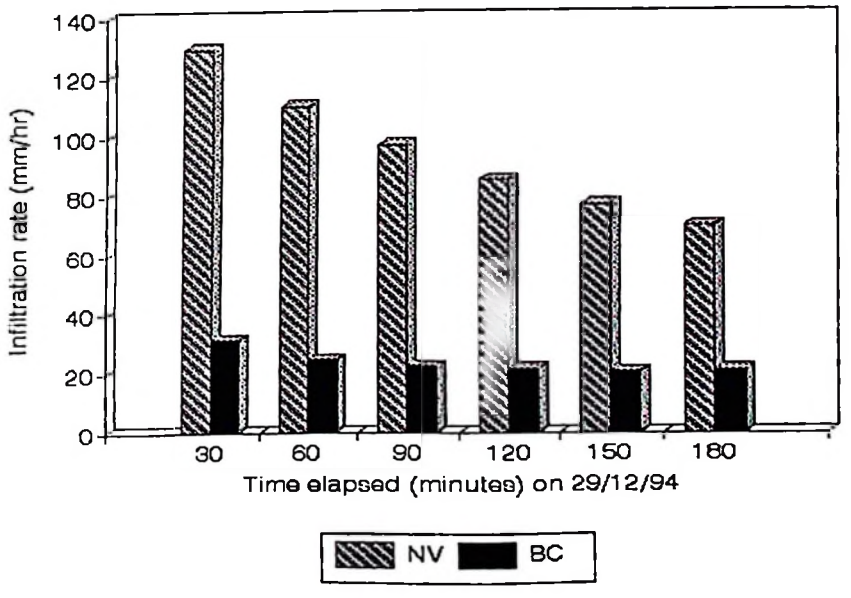

Fig. 4.4 Steady state infiltration rate at the end of **Vuli**

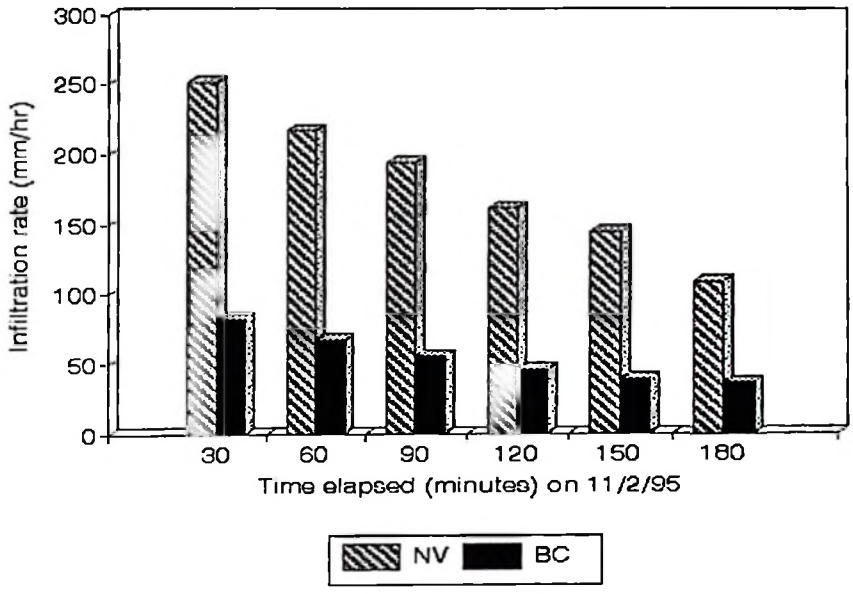

Fig. 4.5 Steady state infiltration rate at the start of **Masika**

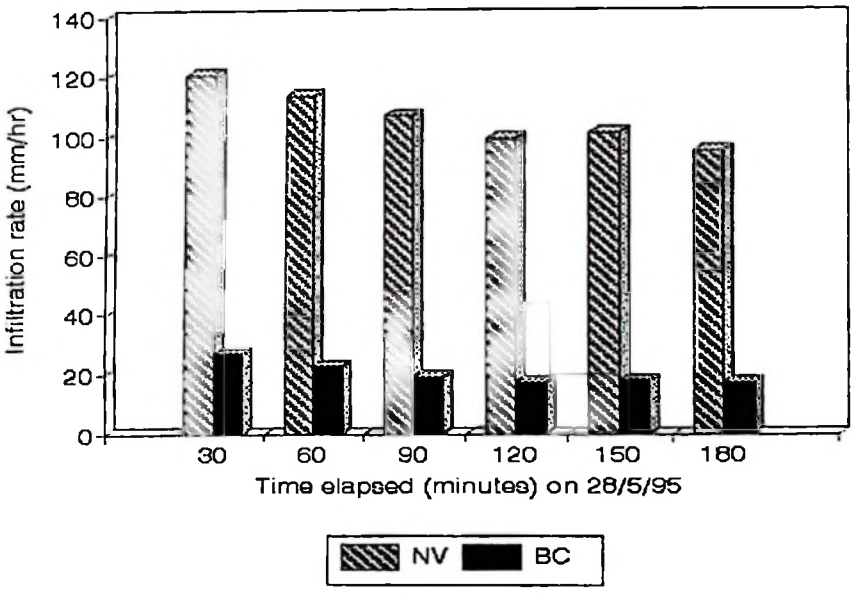

Fig. 4.6 Steady state infiltration rate at the end of **Masika**

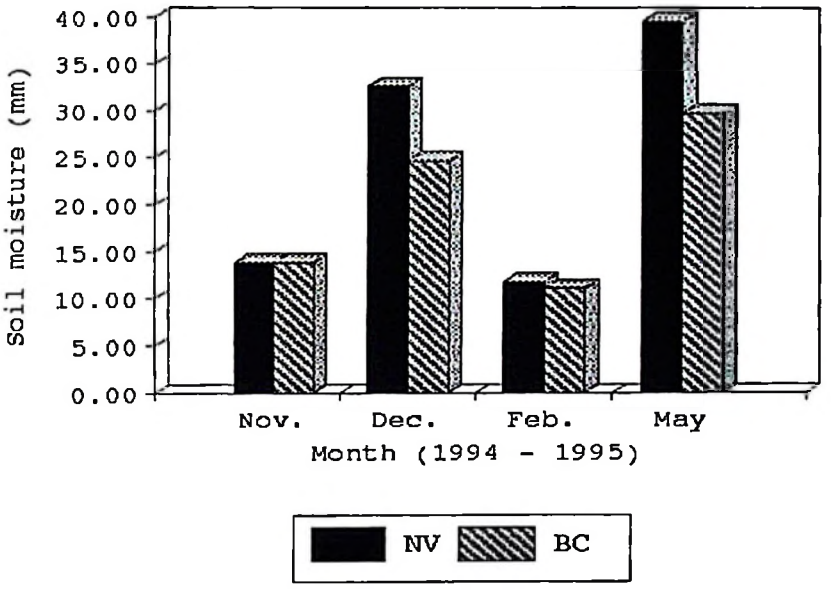

Fig. 4.7 Soil moisture at 0-10 cm depth

Table 4.2 Mean soil moisture content (mm) at 0-10 cm depth

	NV	BC
Start of *Vuli*	13.9	13.9
End of *Vuli*	32.7a	24.7b
Start of *Masika*	11.7a	11.1a
End of *Masika*	39.5a	29.1b

Means in the same row followed by the same letter or none are not significantly different at 5% probability by DMRT.

and BC catchments at the beginning of *Vuli* (Table 4.2). The soil moisture content rose to 32.7 mm and 24.7 mm for NV and BC catchments, respectively, at the end of *Vuli*. Thus, at the end of *Vuli*, the soil moisture content was highly significant ($P< 0.05$) in the NV catchments than in the BC catchments (Table 4.2). At the beginning of *Masika*, the soil moisture content decreased to 11.7 mm and 11.1 mm for NV and BC catchments, respectively. This mean that there was insignificant difference ($P< 0.05$) between soil moisture content in the NV and BC catchments at the beginning of *Masika* (Table 4.2). The soil moisture content increased from 11.7 mm and 11.1 mm to 39.5 mm and 29.7 mm for NV and BC treatments, respectively, at the end of *Masika*. The soil moisture content was relatively low at the beginning of both rainy seasons (*Vuli* and *Masika*) because of a long dry spell of about two months that occurred before the commencement of the rainy seasons. The soil moisture content increased for both treatment catchments (NV and BC) at the end of both rainy seasons due to the replenishment of the soil moisture by the rainfall events that fell during the rainy seasons (Figure 4.7). However, there was a significant higher soil moisture content in the NV catchments than in the BC catchments at the end of both rainy seasons ($p< 0.05$) (Table 4.2). This was due to high infiltration rates and low soil

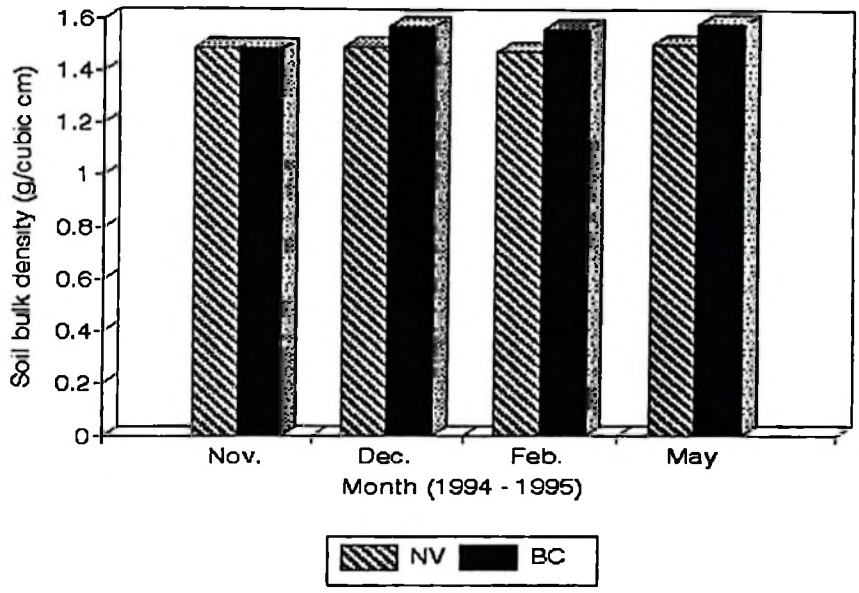

Fig. 4.8 Soil bulk density variations at 0-10 cm depth

bulk density observed in the NV treatment catchments (Figures 4.3 to 4.6 and Figure 4.8). Similar results were reported by Boers and Ben-Asher (1982) and Critchley (1986).

4.2.3 Soil bulk density

Figure 4.8 shows that there was no significant variation in soil bulk density in the NV treatment catchments during the study period. However, the soil bulk density in the NV treatment catchments increased slightly from 1.48 g/cm^3 before the imposition of the catchment treatments (at the start of *Vuli*) to 1.50 g/cm^3 at the end of *Masika* possibly

due to raindrop impact. This agrees with the findings by Olaitan and Lombin (1987) who reported that the soil bulk density of uncultivated soils ranges from 1.0 g/cm^3 to 1.6 g/cm^3. In the BC treatment catchments, the soil bulk density increased significantly from 1.48 g/cm^3 before the imposition of the catchment treatments at the start of *Vuli*) to 1.57 g/cm^3 at the end of *Vuli*. This is due to the fact that the compaction process greatly decreased the macropores in the soil. This in turn, greatly increased the micropores in the soil (Braver, *et al.*, 1972). The soil bulk density increased slightly from 1.56 g/cm^3 at the beginning of *Masika* to 1.58 g/cm^3 at the end of *Masika* possibly due to raindrop impact.

4.2.4 Soil particle size distribution

Table 4.3 shows that although the textural class of the soil from the three slopes (18%, 15% and 6%) was clay, the proportion of sand, course silt, fine silt and clay particles from the three slopes were different. Catchments at 18% slope had a highest mean proportion of sand particles (39%) while catchments at 15% slope had an intermediate mean proportion of sand particles (28%). The lowest mean proportion of sand particles (17.5%) was found in catchments at 6% slope (Table 4.3). On the other hand, catchments at 6% slope had the highest mean proportion of clay particles (79%) while

Table 4.3 Mean proportion of soil particles at the experimental area

Slope (%)	% Sand	% Course silt	% Fine silt	% Clay	Textural Class (TC)
18	39.0	2.5	1.5	57.0	Cl
15	28.0	2.0	2.5	67.5	Cl
6	17.5	1.5	2.0	79.0	Cl

Cl = clay

catchments at 15% slope had an intermediate mean proportion of clay particles (67.5%). The lowest mean proportion of clay particles (57%) was from catchments at 18% slope (Table 4.3). This may imply that catchments at 18% slope had the highest macropores than catchments at 15% and 6% slope. Likewise, catchments at 6% slope might have the highest micropores than catchments at 15% and 6% slope. Similar results were reported by Braver, *et al.* (1972). Chong and Teng (1986) reported that more macropores in the soil result in increased infiltration rate which in turn reduces runoff. Likewise, more micropores in the soil result in reduced infiltration rate which in turn increases runoff.

4.3 Effects of catchment characteristics on runoff yield

4.3.1 Effect of length of catchment on runoff yield

Tables 4.4 and 4.5 show that mean runoff yield per unit area of catchment was not significantly different from the 6 m and the 12 m length catchments ($p < 0.05$) except for three rainfall events. On 15/12/94, 11/4/95 and on 3/5/95, the 6 m length catchments produced significantly higher mean runoff yield per unit area than the 12 m length catchments ($p < 0.05$). Generally, the mean runoff per unit area of catchment from the 6 m length catchments was generally higher than the 12 m length catchments except on 14/12/94, 17/12/94, 9/2/95, 29/4/95, 11/5/95 and on 18/5/95). In fact, the total mean runoff yield per unit area of catchment for the two rainy seasons (*Vuli* and *Masika*) from the 6 m length catchments was 9% higher than the total mean runoff yield per unit area of catchment from the 12 m length catchments. The reason is that in the 6 m length catchments, the runoff took a relatively shorter time (approximately half as much time) to move from the furthest point to the lowest point (where the runoff measuring system was installed) than in the 12 m length catchments. Similar results were also reported by Shanan and Tadmor (1979); Critchley (1986); Pacey and Cullis (1986).

Table 4.4 Mean runoff yield as affected by length of catchment during *Vuli* (1994)

Date	Rainfall (mm)	Plot length (m) 6	12	Statistical inference
30.11.94	13.0	2.01	1.81	ns
1.12.94	25.0	4.98	4.57	ns
4.12.94	5.0	0.85	0.84	ns
5.12.94	9.0	1.83	1.40	ns
6.12.94	10.0	0.99	0.91	ns
8.12.94	13.0	2.62	2.31	ns
9.12.94	25.0	3.29	2.82	ns
10.12.94	2.5	0.25	0.18	ns
12.12.94	3.0	0.24	0.12	ns
14.12.94	21.0	2.30	2.47	ns
15.12.94	4.0	0.03	0.01	*
16.12.94	23.0	4.67	4.60	ns
17.12.94	33.0	7.09	7.45	ns
23.12.94	10.0	1.11	0.76	ns
28.12.94	4.0	0.72	0.65	ns
29.12.94	2.0	0.07	0.04	ns
30.12.94	1.9	0.06	0.03	ns

* = significant at 5 % level

ns = not significant

Table 4.5 Mean runoff yield as affected by length of catchment during *Masika* (1995)

Date	Rainfall (mm)	Plot length (m) 6	12	Statistical inference
9.2.95	35.0	4.23	4.35	ns
12.2.95	5.0	0.05	0.05	ns
15.2.95	6.0	0.05	0.00	ns
19.2.95	17.0	2.79	2.39	ns
2.3.95	4.5	0.02	0.01	ns
3.3.95	50.0	11.95	10.94	ns
6.3.95	7.0	0.20	0.07	ns
7.3.95	3.5	0.33	0.20	ns
13.3.95	59.0	12.02	10.68	ns
14.3.95	5.0	0.52	0.34	ns
15.3.95	30.0	5.87	6.59	ns
22.3.95	2.0	0.05	0.03	ns
24.3.95	2.5	0.02	0.01	ns
26.3.95	2.0	0.01	0.01	ns
29.3.95	2.5	0.01	0.00	ns
30.3.95	22.0	4.52	4.52	ns
7.4.95	5.0	0.40	0.24	ns
11.4.95	3.5	0.04	0.01	*
14.4.95	5.5	0.69	0.63	ns
15.4.95	5.5	1.38	0.78	ns
20.4.95	8.0	0.53	0.25	ns
23.4.95	5.0	0.63	0.43	ns
24.4.95	8.0	1.47	0.96	ns
25.4.95	41.0	8.53	8.12	ns
26.4.95	39.0	8.38	8.10	ns
27.4.95	2.3	0.02	0.01	ns
28.4.95	4.0	0.67	0.43	ns
29.4.95	17.0	2.73	2.94	ns
30.4.95	7.0	1.44	1.35	ns
1.5.95	2.0	0.03	0.02	ns
3.5.95	2.8	0.02	0.00	*
11.5.95	3.0	0.01	0.02	ns
17.5.95	9.0	0.97	0.68	ns
18.5.95	17.0	2.77	2.94	ns
19.5.95	23.0	4.15	3.01	ns
22.5.95	14.0	2.43	1.99	ns
28.5.95	13.0	1.61	1.23	ns
29.5.95	9.0	1.64	1.09	ns
30.5.95	5.0	0.85	0.60	ns

* = significant at 5 % level; ns = not significant.

4.3.2 Effect of catchment surface cover on runoff yield

Tables 4.6 and 4.7 show that mean runoff yield generated from BC treatment was significantly higher that the mean runoff yield generated from NV treatment ($p< 0.01$) except on 12/12/94, 12/2/95, 15/2/95, 6/3/95, 29/3/85, 27/4/95, 1/5/95 and on 11/5/95. This is explained by the low infiltration rate and the high soil bulk density observed in the BC catchments (Figures 4.3 to 4.6 and Figure 4.8). However, at the beginning of *Masika* the runoff generated from both treatments was not significantly different ($p< 0.05$). This is because at the beginning of *Masika*, very little vegetation cover was available in the natural vegetated catchments (Plate 1). Another reason is that at the beginning of *Masika* there was low moisture available in the soil (Figure 4.7). Therefore, low rainfall amounts (5.0 mm and 6.0 mm on 12/2/95 and 15/2/95, respectively) at the beginning of *Masika* season, ended up being intercepted by the vegetation in the NV catchments and the little rain water that passed through the vegetative cover infiltrated into the soil leaving little, if any, to flow as surface runoff. Similarly, in BC catchments, most of the rain water infiltrated into the soil leaving trace runoff ($p< 0.05$) flowing on the soil surface. Worse still, some of the low rainfall events that produced the low runoff yield ($p< 0.05$) fell following a dry spell of two or

Table 4.6 Effect of surface characteristics on runoff yield during *Vuli* (1994)

Date	Rainfall (mm)	Surface characteristics NV	BC	Statistical inference
30.11.94	13.0	0.79	3.03	**
1.12.94	25.0	1.58	7.97	**
2.12.94	35.0	1.48	10.64	**
4.12.94	5.0	0.35	1.33	*
5.12.94	9.0	0.53	2.70	**
6.12.94	10.0	0.37	1.53	**
8.12.94	13.0	1.09	3.84	*
9.12.94	25.0	0.95	5.15	*
10.12.94	2.5	0.05	0.38	*
12.12.94	3.0	0.04	0.32	ns
14.12.94	21.0	0.71	4.06	**
15.12.94	4.0	0.01	0.03	*
16.12.94	23.0	1.89	7.38	**
17.12.94	33.0	2.42	12.12	**
23.12.94	10.0	0.20	1.68	*
28.12.94	4.0	0.25	1.12	*
29.12.94	2.0	0.00	0.11	*
30.12.94	1.9	0.00	0.08	**

** = significant at 1 % level
* = significant at 5 % level
ns = not significant

Table 4.7 Effect of surface characteristics on runoff yield during *masika* (1995)

Date	Rainfall (mm)	Plot length (m) NV	BC	Statistical inference
9.2.95	25.0	1.22	7.37	**
12.2.95	5.0	0.01	0.06	ns
15.2.95	6.0	0.00	0.05	ns
19.2.95	17.0	0.28	4.89	*
2.3.95	4.5	0.00	0.03	*
3.3.95	50.0	4.34	18.54	**
6.3.95	7.0	0.01	0.25	ns
7.3.95	3.5	0.03	0.50	*
13.3.95	59.0	3.86	18.83	**
14.3.95	5.0	0.07	0.78	*
15.3.95	30.0	2.20	10.25	**
22.3.95	2.0	0.01	0.07	*
24.3.95	2.5	0.00	0.02	*
26.3.95	2.0	0.00	0.02	*
29.3.95	2.5	0.00	0.01	ns
30.3.95	22.0	1.64	7.40	**
7.4.95	5.0	0.01	0.63	*
11.4.95	3.5	0.00	0.04	*
14.4.95	5.5	0.08	1.24	*
15.4.95	5.5	0.10	2.05	*
20.4.95	8.0	0.06	0.72	*
23.4.95	5.0	0.07	0.99	*
24.4.95	8.0	0.09	2.34	*
25.4.95	41.0	2.71	13.94	**
26.4.95	39.0	2.56	13.92	**
27.4.95	2.3	0.00	0.03	ns
28.4.95	4.0	0.07	1.02	*
29.4.95	17.0	0.67	5.00	**
30.4.95	7.0	0.38	2.41	*
1.5.95	2.0	0.00	0.05	ns
3.5.95	2.8	0.00	0.02	**
11.5.95	3.0	0.00	0.01	ns
17.5.95	9.0	0.04	1.61	*
18.5.95	17.0	0.88	4.61	*
19.5.95	23.0	1.13	6.03	*
22.5.95	14.0	0.29	4.13	**
28.5.95	13.0	0.06	2.77	*
29.5.95	9.0	0.32	2.41	*
30.5.95	5.0	0.06	1.39	*

** = significant at 1 % level; * = significant at 5 % level; ns = not significant.

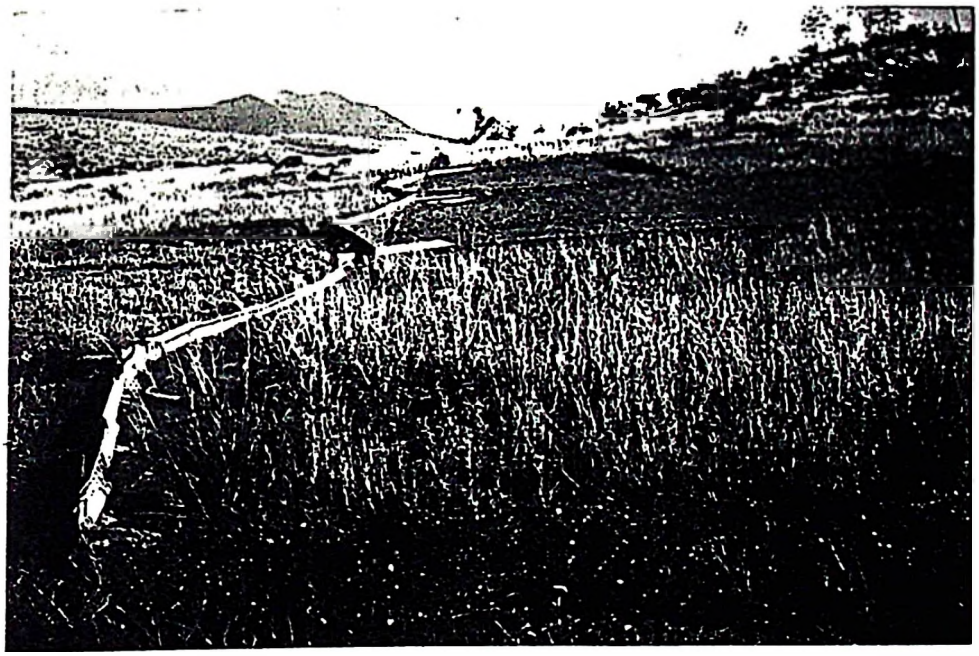

Plate 1: Catchment surface cover at the beginning of *Masika* (1995)

three days after the previous rainfall event (Tables 4.6 and 4.7) resulting in most of the rain water infiltrating into the soil. This also explains the low runoff yield produced ($p< 0.05$) in both catchments (NV and BC) on 12/12/94 during *Vuli* and on 29/3/95, 27/4/95, 1/5/95 and on 11/5/95 during *Masika*. Table 4.5 does not show a similar pattern of insignificant runoff generated ($p< 0.05$) during the onset of the *Vuli* because *Vuli* began in October before the experiment was laid out. Consequently, when data collection commenced on 31/11/94, it was already mid *Vuli* when the surface treatment effect was already distinct (Plate 2).

From the middle to the end of both *Vuli* and *Masika* there was high density vegetation covering the soil surface (Plate 2) that intercepted the raindrop impact, obstructed the flow of surface runoff with its stems, roots and litter thereby increasing the infiltration rate of the soil in NV catchments (Figures 4.3 to 4.6). In addition, transpiration by the vegetation reduced the soil moisture (Figure 4.7) thereby increasing the infiltration rate in NV catchments (Figure 4.3 to 4.6). This in turn reduced the runoff yield in NV catchments (Tables 4.6 to 4.7). Similar results were reported by Van Rensburg (1955), Pathak *et al.* (1990) and Jones *et al.* (1991).

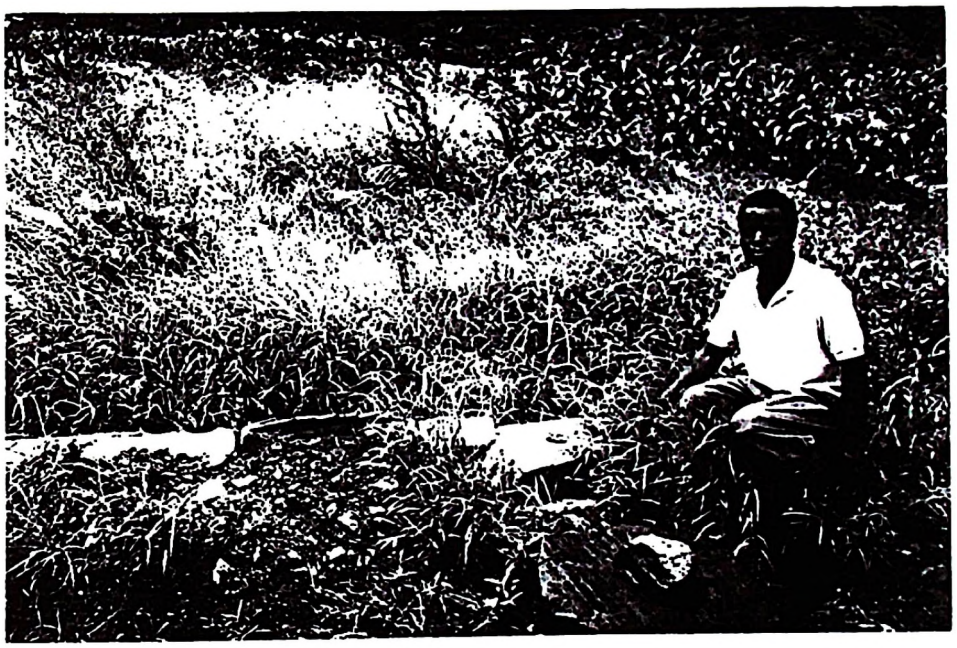

Plate 2: Catchment surface cover at the end of *Vuli* (1994) and *Masika* (1995).

4.3.3 Effect of slope on runoff yield

Tables 4.8 and 4.9 show that the mean runoff yield generated from catchments at 18% slope was significantly higher than the mean runoff yield generated from the catchments at 6% slope ($p< 0.05$). The runoff generated from catchments at 18% took a relatively short time to flow from the furthest point to the lowest point (where the runoff collecting system was installed) than catchments at 6% slope. Similarly, the mean runoff yield generated from catchments at 15% slope was generally significantly higher than the mean runoff yield generated from the catchments at 6% slope ($p< 0.05$) except on 23/12/94, 25/4/95 and on 29/5/95. However, there was an insignificant difference in mean runoff yield generated from catchments at 18% slope and 15% slope ($p< 0.05$) except on 1/12/94, 5/12/94, 16/12/94 during *Vuli*, and on 15/4/95 and 24/4/95 during *Masika* (Tables 4.8 and 4.9). The reasons for this are as follows: There is a small difference in slope between the catchments at 18% slope and the catchments at 15% slope. Moreover, the mean proportion of sand particles in catchments at 18% slope is higher than the proportion of sand particles in catchments at 15% slope (Table 4.3). Similar results were reported by Gupta (1979); Linsely *et al.* (1982); Chong and Teng (1986).

Table 4.8 Mean runoff yield generated from catchments at different slopes during *Vuli* (1994)

Date	Rainfall (mm)	Intensity (mm/h)	Mean runoff yield from slopes 6 %	15%	18%
30.11.94	13.0	7.78	0.50b	2.20a	3.03a
1.12.94	25.0	15.24	1.71c	5.49b	7.14a
2.12.94	35.0	13.01	2.22b	7.45a	8.51a
4.12.94	5.0	14.71	0.24b	1.06a	1.23a
5.12.94	9.0	12.86	0.87c	1.68b	2.30a
6.12.94	10.0	8.62	0.38b	1.18a	1.28a
8.12.94	13.0	21.67	0.57b	3.11a	3.72a
9.12.94	25.0	6.81	0.76b	3.97a	4.43a
10.12.94	2.5	27.78	0.04a	0.27a	0.34a
12.12.94	3.0	18.75	0.01a	0.18a	0.35a
14.12.94	21.0	6.09	0.57b	2.70a	3.88a
15.12.94	4.0	9.52	0.00	0.02	0.04
16.12.94	23.0	18.70	1.61c	4.88b	7.41a
17.12.94	33.0	30.84	3.27b	8.97a	9.57a
23.12.94	10.0	9.71	0.06b	0.89ab	1.86a
28.12.94	4.0	36.36	0.12b	0.75ab	1.17a
29.12.94	2.0	10.53	0.00a	0.06a	0.10a
30.12.94	1.9	19.00	0.02a	0.06a	0.06a

Means in the same row followed by the same letter or none are not significantly different at 5% probability by DMRT.

Table 4.9 Mean runoff yield from catchments at different slopes during *masika* (1995)

Date	Rainfall (mm)	Intensity (mm/h)	Mean runoff yield from slopes 6%	15%	18%
9.2.95	36.5	17.55	1.22b	5.25a	6.00a
12.2.95	5.0	4.85	0.00a	0.03a	0.07a
15.2.95	6.0	0.45	0.00a	0.06a	0.02a
19.2.95	17.0	6.25	0.28b	3.01a	4.47a
2.3.95	4.5	25.00	0.01	0.02	0.02
3.3.95	50.0	16.50	5.95b	13.27a	15.11a
6.3.95	7.0	4.46	0.00a	0.15a	0.25a
7.3.95	3.5	13.46	0.13a	0.26a	0.41a
13.3.95	59.0	8.21	4.53b	14.65a	14.86a
14.3.95	5.0	6.49	0.10b	0.41ab	0.78a
15.3.95	30.0	27.52	2.02b	7.95a	8.72a
22.3.95	2.0	14.29	0.01a	0.05a	0.05a
24.3.95	2.5	4.31	0.01	0.02	0.02
26.3.95	2.0	8.33	0.00	0.02	0.01
29.3.95	2.5	3.01	0.00	0.01	0.00
30.3.95	22.0	19.13	2.09b	5.55a	5.92a
7.4.95	5.0	7.46	0.05a	0.45a	0.46a
11.4.95	3.0	15.00	0.01	0.03	0.03
14.4.95	5.5	11.00	0.00b	0.94a	1.04a
15.4.95	5.5	14.47	0.19c	0.94b	2.10a
20.4.95	8.0	5.06	0.02a	0.44a	0.71a
23.4.95	5.0	4.07	0.11a	0.63a	0.85a
24.4.95	8.0	13.33	0.09c	1.49b	2.07a
25.4.95	41.0	21.03	3.74b	8.91ab	12.32a
26.4.95	39.0	16.12	3.48b	9.62a	11.63a
27.4.95	2.3	3.29	0.00a	0.00a	0.04a
28.4.95	4.0	16.00	0.08a	0.54a	1.03a
29.4.95	17.0	22.67	0.98b	3.44a	4.08a
30.4.95	7.0	35.00	0.33b	1.66ab	2.20a
1.5.95	2.0	4.00	0.00	0.00	0.01
3.5.95	2.8	2.41	0.00	0.01	0.02
11.5.95	3.0	3.00	0.00	0.00	0.01
17.5.95	9.0	4.39	0.04b	1.12ab	1.32a
18.5.95	17.0	23.29	0.87b	3.06ab	4.32a
19.5.95	23.0	8.78	1.24b	4.08a	5.42a
22.5.95	14.0	13.59	0.75b	2.66ab	3.22a
28.5.95	13.0	8.13	0.23b	1.81ab	2.21a
29.5.95	9.0	6.43	0.21b	1.38ab	2.49a
30.5.95	5.0	4.81	0.10a	0.88a	1.19a

Means in the same row followed by the same letter or none are not significantly different at 5% probability by DMRT.

During low rainfall events (rainfall amount of equal to or less than 4 mm) the mean runoff yield from the three slopes (6%, 15% and 18% slope) were not significantly different ($p< 0.05$) regardless of the magnitude of their intensities (Tables 4.8 and 4.9). The rainfall ranging between 5 mm and 8 mm also produced insignificantly different mean runoff yield from the catchments at the three slopes ($p< 0.05$) when their intensities were less than 15 mm/h (Tables 4.7 and 4.8). During high rainfall events (equal to or greater than 9 mm) such as on 23/12/94 and on 29/5/95, there was a significantly higher mean runoff yield generated from the catchments at 15% slope than that from catchments at 6% slope. This is due to the difference in slope between catchments at 6% slope and catchments at 15% slope. Another possible reason could be due to spatial and temporal differences in rainfall amount and rainfall intensities between the two slopes (6% and 15% slope). Similar results were observed by Staples (1938).

4.4 Effects of rainfall characteristics on runoff yield

4.4.1 General

Runoff generated from each catchment was compared by the rainfall characteristics (rainfall amount, rainfall duration and rainfall intensity) and the resulting regression

Table 4.10 Mean runoff yield as affected by rainfall characteristics

Slope (%)	Treatment	R coeff.	RD coeff.	RI coeff.	R^2
18	NV	1.0259×10^{-1}	-3.8271×10^{-2}	1.3619×10^{-2}	0.807
	BC	4.7503×10^{-1}	-1.8954×10^{-1}	4.5957×10^{-2}	0.948
15	NV	7.9281×10^{-2}	-1.4849×10^{-2}	1.3968×10^{-2}	0.752
	BC	4.2658×10^{-1}	-1.0101×10^{-1}	3.7439×10^{-2}	0.905
6	NV	2.6300×10^{-2}	-7.8336×10^{-3}	-8.6407×10^{-4}	0.630
	BC	1.6444×10^{-2}	-9.0047×10^{-2}	1.5622×10^{-2}	0.719
Overall runoff from all catchments		2.1179×10^{-1}	-7.0765×10^{-2}	2.3159×10^{2}	0.797

R = Rainfall amount
RD = Rainfall duration
RI = Rainfall intensity
coeff. = coefficient

coefficients are presented in Table 4.10. The results show that at 18% slope, rainfall characteristics accounted for 80% and 95% of the variations observed in mean runoff yield produced from the NV catchments and BC catchments, respectively. The rainfall characteristics at 15% slope accounted for 75% and 90% of the variations observed in mean runoff yield produced from the NV catchments and BC catchments respectively. Similarly, the rainfall characteristics at 6% slope accounted for 63% and 72% of the variations observed in mean runoff yield produced from the NV

catchments and BC catchments, respectively. The relatively low coefficient of determination (0.63) for NV catchments at 6% slope indicates that both natural vegetation and low slope are effective in reducing the amount of runoff yield from a catchment. This agrees with the high steady state infiltration rate and the low soil bulk density observed in the NV catchments (Figures 4.3 to 4.6 and Figure 4.8). Likewise, a high coefficient of determination (0.95) for BC catchments at 18% slope indicates that both BC treatment and high slope promote generation of runoff yield from a catchment. These results comply with the low steady state infiltration rate and the high soil bulk density observed in the BC catchments (Figures 4.3 to 4.6 and Figure 4.8). These results obtained agree with the findings by Critchley (1986), and Walkman and Skaggs (1994).

4.4.2 Effect of rainfall amount on runoff yield

Figure 4.9 shows that high rainfall amount generated high runoff yield (in December during *Vuli* and in March and April during *Masika*) and low rainfall amount generated low runoff yield (in November during *Vuli*, and February and May during *Masika*). Similarly, Tables 4.3 to 4.8 indicate that there was relatively lower runoff resulting from rainfall events with low amounts than that resulting from rainfall events with

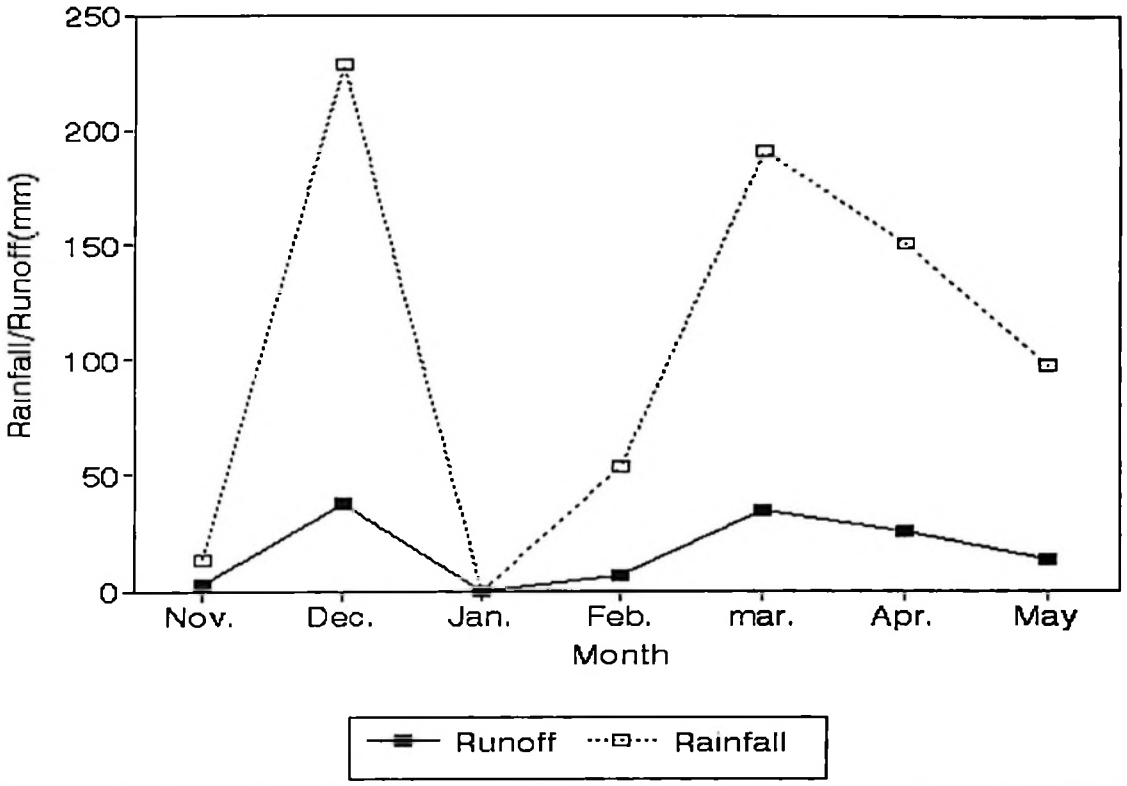

Fig. 4.9 Runoff and Rainfall from November, 1994 to May, 1995 at Kisangara

high rainfall amounts. On the other hand, high amount of rainfall that fell after a dry spell (such as on 9/2/95 and 19/2/95) generated low runoff yield (Tables 4.4 to 4.9) since most of the rain water infiltrated into the soil due to low soil moisture content (Figure 4.7). Similarly, low rainfall amount produced a significantly high mean runoff yield

($p < 0.05$) when the rain fell after a consecutive (daily) rainfall events (Tables 4.4 to 4.9) due to high soil moisture content (Figure 4.8). Similar results were reported by Mahoo *et al.* (1994a, Unpublished).

4.4.3 Effect of rainfall intensity on runoff yield

Tables 4.8 and 4.9 show that generally, high rainfall intensity generated significantly higher runoff yield than low rainfall intensity ($p < 0.05$). This is because during high rainfall intensity the water had less time of contact with the soil. This in turn caused rapid accumulation of water to flow as surface runoff. Gupta (1979); Linsely *et al.* (1982); Pacey and Cullis (1986) had reported similar results.

4.4.4 Effect of rainfall duration on runoff yield

Rainfall events of equal or similar duration generated either significantly or insignificantly different runoff yield depending on the rainfall amount and the rainfall intensity (Tables 4.8 and 4.9). The explanation could be that rainfall duration itself had insignificant effect on runoff yield. The results obtained by Gupta and Linsely *et al.* (1979, 1982) also showed that the effect of rainfall duration on runoff yield depends on rainfall amount and rainfall intensity.

4.5 Development of slope specific empirical model

Table 4.11 shows the multiple regression coefficients for an empirical model relating runoff to rainfall characteristics. The model assumes that the catchments are homogeneous with respect to soil, uniform rainfall distribution within the catchments, and uniform density of vegetation in the vegetated catchments. Both NV and BC regression coefficients for the empirical model were developed on rainfall events for two rainy seasons (*Vuli* and *Masika*) and, showed a high correlation ($R= 0.898$ and $R= 0.974$ at $p< 0.01$, respectively) between the runoff yield and rainfall characteristics at 18% slope. Both 15% and 6% slopes showed a similar pattern except that the parameters were less highly correlated with the runoff at $p< 0.01$. These results agree with the findings by Mahoo *et al.* (1994a, Unpublished).

Table 4.11 Regression coefficients for three parameters empirical model relating runoff to rainfall characteristics

Slope (%)	Treatment	Model	R^2	R
18	NV	RO=0.10259R+(-0.038271RD)+0.013619RI	0.807	0.898
	BC	RO=0.47503R+(-0.18954RD)+0.045957RI	0.948	0.974
15	NV	RO=0.079281R+(-0.014849RD)+0.013968RI	0.752	0.867
	BC	RO=0.42658R+(-0.10101RD)+0.0374390RI	0.905	0.951
6	NV	RO=0.0263R+(-0.00783RD)+(-0.0008641RI)	0.630	0.794
	BC	RO=0.016444R+(-0.090047RD)+0.0156220RI	0.719	0.848

RO = Runoff (mm)

4.5.1 Model testing

4.5.1.1 Introduction

The empirical model developed requires slope, surface cover, rainfall amount (R), rainfall duration (RI) and rainfall intensity (RI) as inputs to simulate or predict runoff (RO). From these parameters the predicted runoff is calculated. Figures 4.10 to 4.15 show the predicted against the observed runoff at each slope for each treatment. The results showed a systematic pattern in that there is an overestimation for

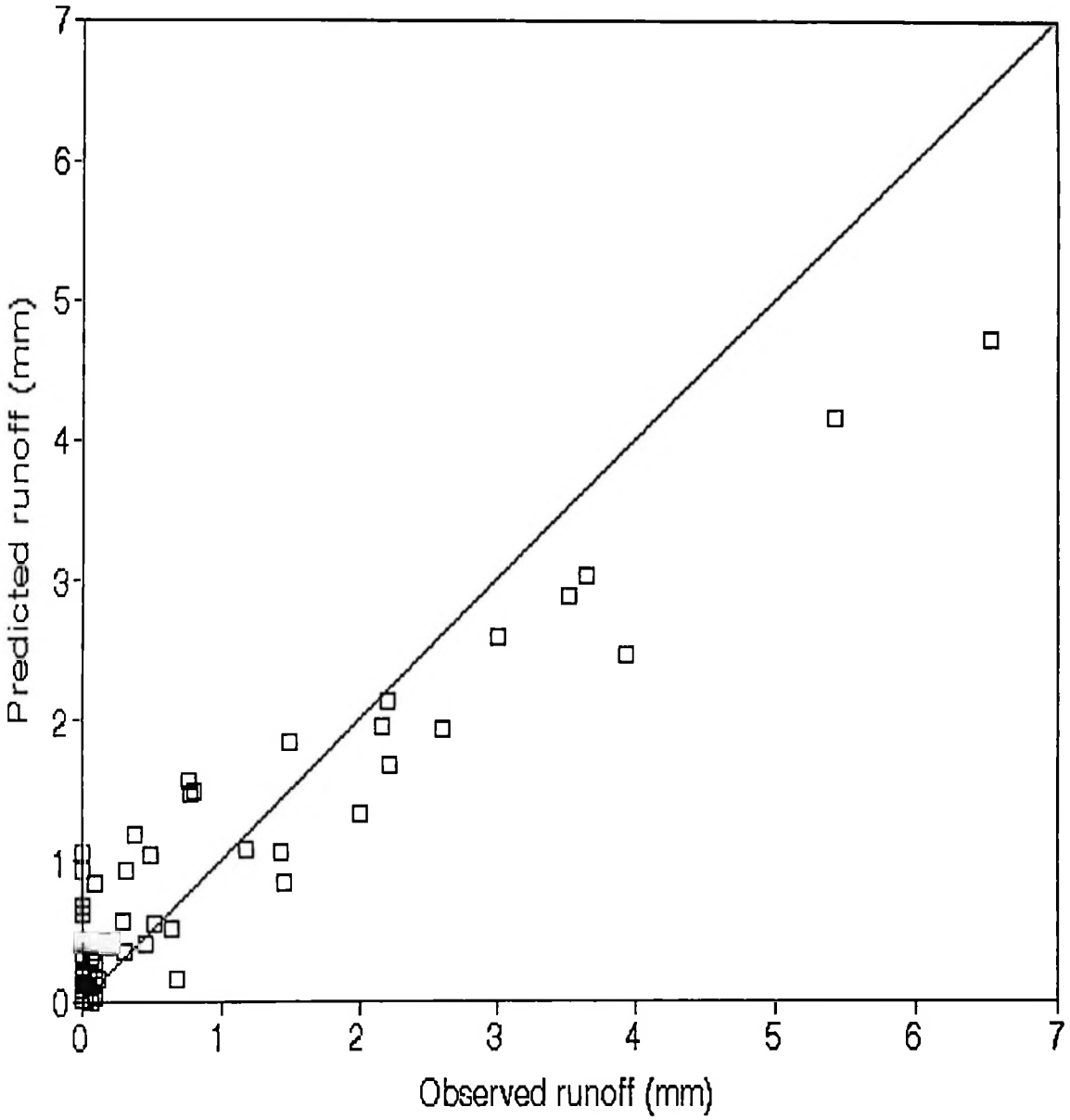

Fig. 4.10 Predicted against Observed runoff for NV catchments at 18% slope

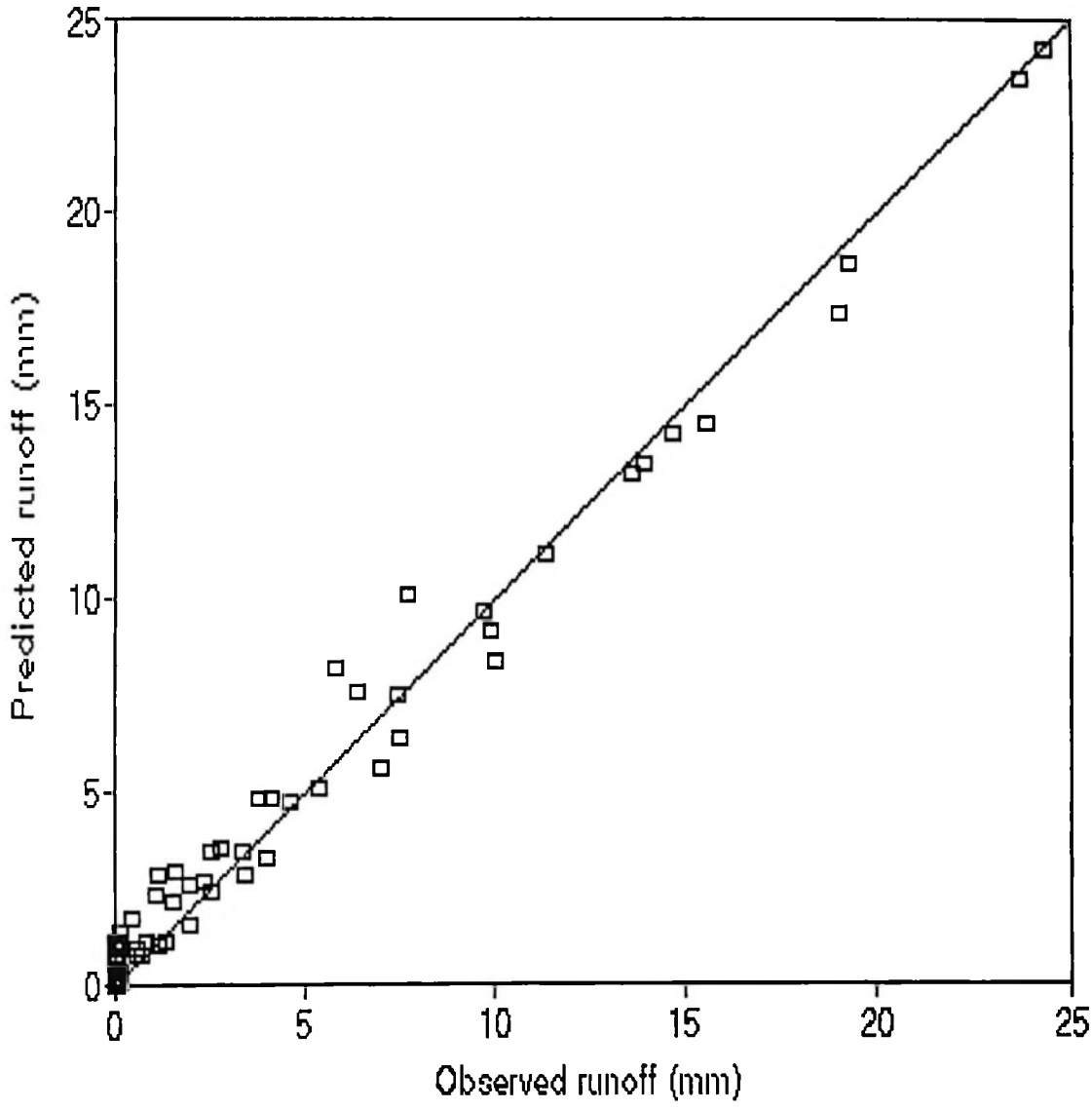

Fig. 4.11 Predicted against Observed runoff for BC catchments at 18% slope

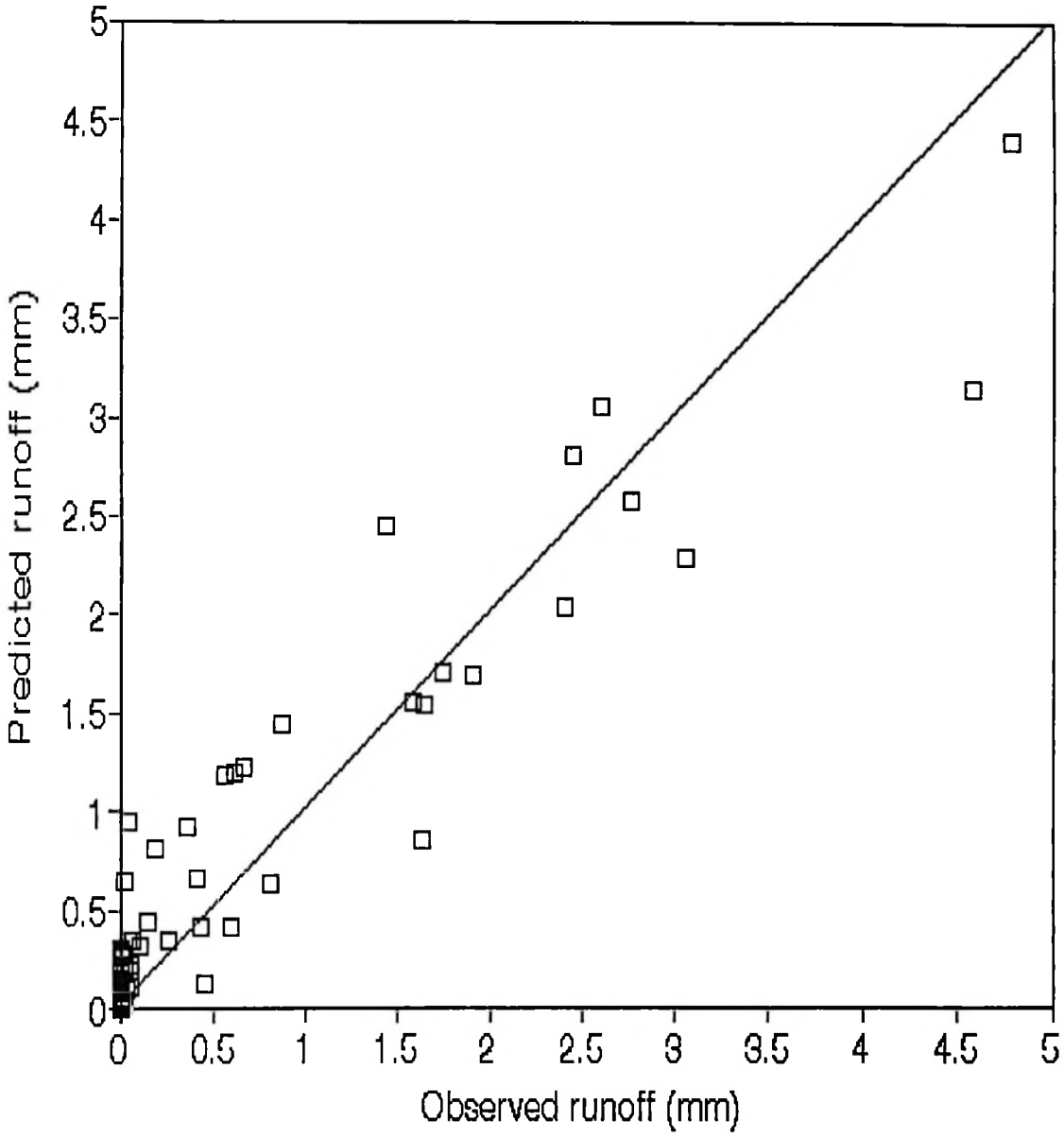

Fig. 12 Predicted against Observed runoff for NV catchments at 15% slope

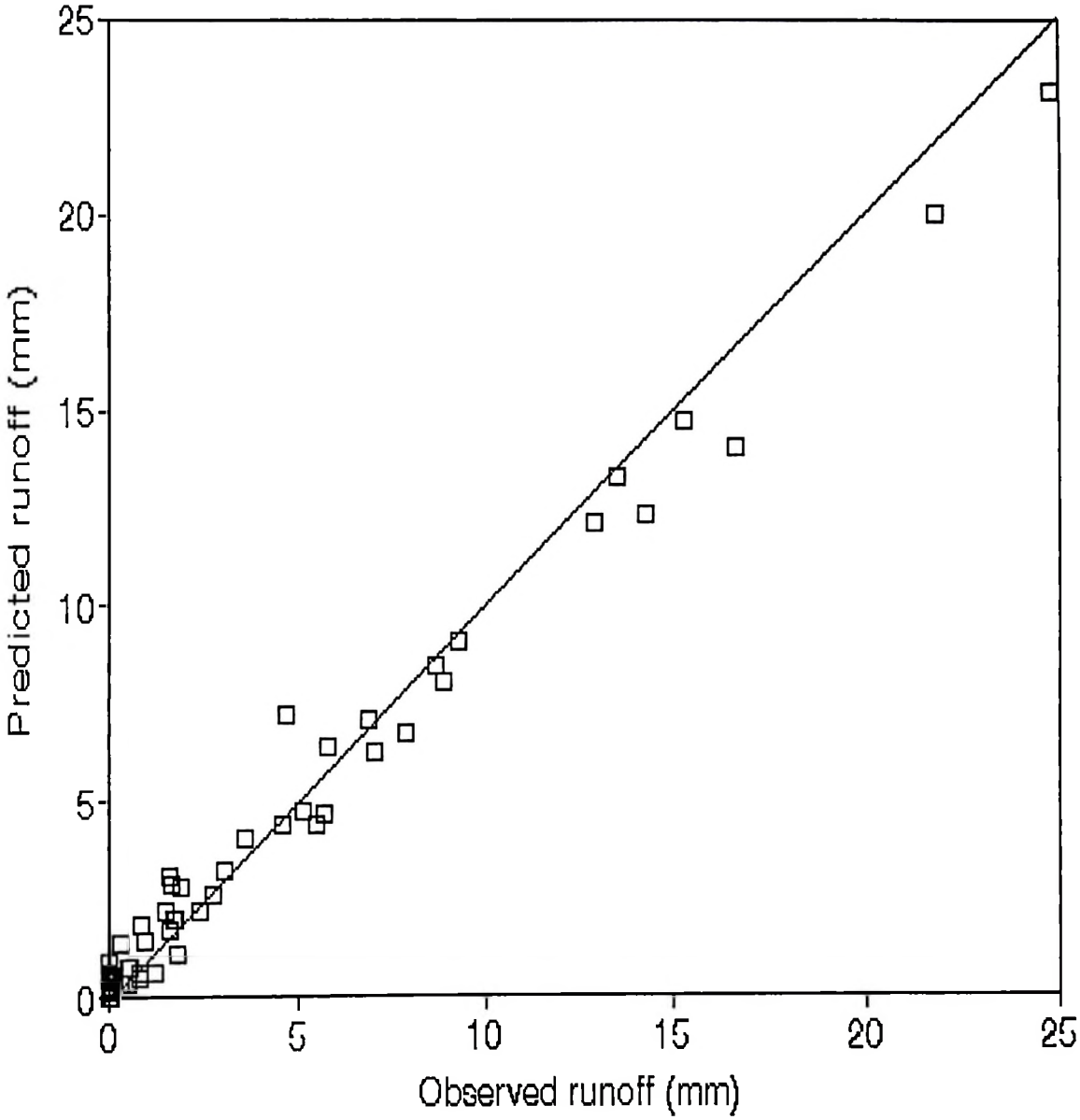

Fig. 4.13 Predicted against Observed runoff for BC catchments at 15% slope

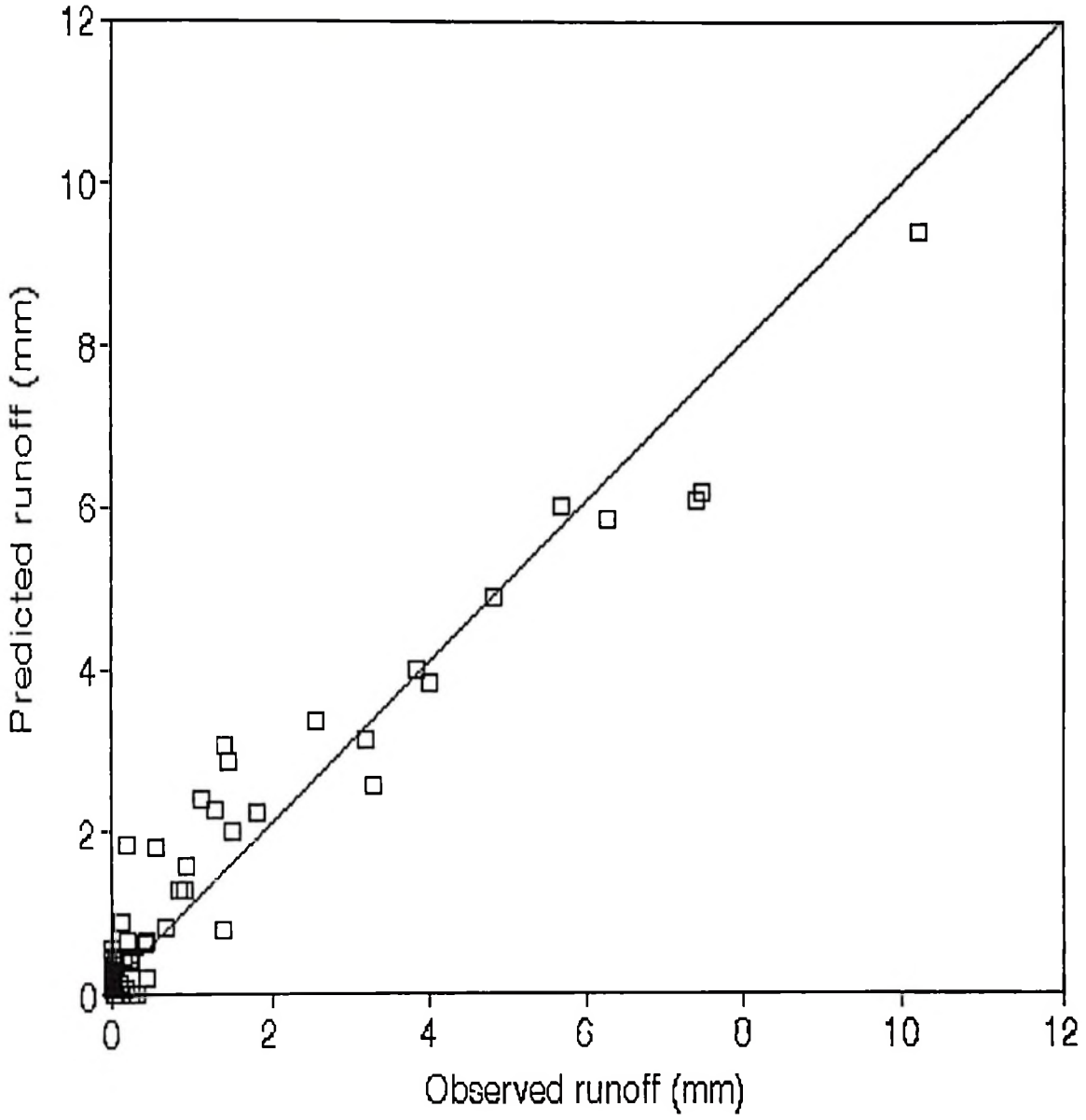

Fig. 4.15 Predicted against Observed runoff for BC catchment at 6% slope

low runoff events and an underestimation for high runoff events as shown by scattered points along a 45^0 line through the origin in Figures 4.10 and 4.15. All the points above the 45^0 line overpredict the runoff while all the points below the 45^0 line underestimate the runoff. The overprediction at low runoff amounts could probably mean that there is a process in operation where by runoff does not occur until rainfall has reached a certain threshold level (Pacey and Cullis, 1986).

4.5.1.2 Model testing using data that had been used to develop the model

Table 4.12 shows the mean observed runoff, the mean predicted runoff, correlation coefficients of predicted against observed runoff at each slope for each treatment and the overall correlation coefficient of all treatments. The range of the correlation coefficients for BC treatment is between 0.87 at 6% slope and 0.98 at 18% slope. On the other hand, the range of the correlation coefficients for NV treatment is between 0.58 at 6% slope and 0.88 at 18% slope indicating that the parameters are less highly correlated for NV treatment than BC treatment. The overall correlation coefficients for all the treatments is 0.84.

Table 4.12 Correlation coefficients between mean observed and mean predicted runoff at different slopes under different treatments using data that had been used to develop the model

Slope (%)	Treatment	Correlation coefficient	Mean runoff (mm)	
			Observed	Predicted
18	NV	0.882	0.76	0.89
	BC	O.982	4.98	4.95
15	NV	0.783	0.69	0.93
	BC	0.971	4.72	4.15
6	NV	0.580	0.16	0.27
	BC	0.867	1.33	2.99
Overall		0.839	2.01	2.28

Table 4.13 Correlation coefficients between mean observed and mean predicted runoff at 6-8 percent slope under different treatments using data collected from Morogoro site during the 1994 rainy season

Slope (%)	Treatment	Correlation coefficient	Mean runoff (mm)	
			Observed	Predicted
6-8	NV	0.799	2.23	3.96
	BC	0.428	0.28	0.39

4.5.1.3 Model testing using data collected from Morogoro site during the 1994 rainy season

Further testing of the model was done using data collected from Morogoro during the 1994 rainy season. The results showed the correlation coefficient of 0.80 and 0.43 for BC and NV, respectively, at 6-8% slope (Table 4.13). However, no runoff data from catchments above 8% slope was available from Morogoro site for further testing of the performance of the model.

Generally, these results indicate a very good performance of the empirical model developed. However, there is reduced performance of the model under NV catchments at a low slope (6%). A close look at Figures 4.10, 4.12 and 4.14, indicate that the vegetated catchments are the most difficult to predict. This is because vegetation influences the rainfall-runoff system through interception, obstruction to flow by roots and litter, reduces movement of water running as runoff thereby increasing infiltration and also the infiltration is increased along the root channels. In addition, transpiration by plants reduces soil moisture. This in turn increases the infiltration capacity of the soil. All of these factors vary both temporally and spatially making prediction difficult under natural vegetated conditions. Similar results were

reported by Pathak *et al.* (1990), Mahoo *et al.* (1994b, Unpublished) and Walkman and Skaggs (1994).

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study was aimed at investigating the effects of rainfall and catchment characteristics on runoff yield to provide information necessary in the design of optimal micro-catchments for RWH in semi-arid areas of Tanzania. To achieve this, the effects of length of catchment, slope of catchment, catchment surface cover, rainfall amount, rainfall duration and rainfall intensity on runoff yield were investigated. In addition, an empirical model relating runoff to rainfall characteristics under different catchment characteristics was developed. The model was further tested using the data that was used for its development and the data collected from Morogoro site to predict runoff.

From the study, it can be concluded that:

1. Bare-and-compacted catchments generated significantly higher mean runoff yield than natural vegetated catchments.
2. Catchments at 18% and 15% slope generated significantly higher mean runoff yield than catchments at 6% slope.
3. 6 m length catchments yielded higher mean runoff per unit area of catchment than 12 m length catchments.

4. Rainfall characteristics (amount, duration and intensity) accounted for more than 90% and more than 60% of the runoff generated from bare-and-compacted catchments and natural vegetated catchments, respectively.
5. The empirical model developed is fairly accurate and suitable for semi-arid conditions of Tanzania. Consequently, the model could be used reliably with confidence to predict runoff under conditions similar to those under which it was developed (Semi-arid areas).

5.2 Recommendations

In view of the above findings, the following recommendations can be made:

1. Future work is recommended to test the empirical model developed using long term data from other semi-arid areas of Tanzania to check its performance in those areas.
2. The empirical model developed needs to be used with caution when predicting runoff under natural vegetated catchments at low slopes (6%) because of its low correlation coefficient under such conditions.

REFERENCES

Borah, D.K. (1986). Runoff simulation Model for small watersheds. *Transactions of the American Society of Agricultural Engineers* 32(3): 881-886.

Braver, L.D., Gardner, W.H. and Gardner, W.R. (1972). *Soil physics* (4th edition). John Willey and sons. Inc. New York. pp 284-285.

Boers, Th.M. and Ben-Asher, J. (1982). *A review of rain water harvesting. Agricultural Water management.* Elsevier Science B.V, Amsterdam. pp 145-158.

Chaves, H.M.L. and Nearing, M.A. (1991). Uncertainty analysis of the WEEP Soil Erosion Model. *Transactions of the American Society of Agricultural Engineers* 34(6):2437-2444.

Chong, S.K. and Teng, R.M. (1986). Relationship between the run-off curve number and hydrologic soil properties. *Journal of Hydrology* 84:1-7.

REFERENCES

Borah, D.K. (1986). Runoff simulation Model for small watersheds. *Transactions of the American Society of Agricultural Engineers* 32(3): 881-886.

Braver, L.D., Gardner, W.H. and Gardner, W.R. (1972). *Soil physics* (4th edition). John Willey and sons. Inc. New York. pp 284-285.

Boers, Th.M. and Ben-Asher, J. (1982). *A review of rain water harvesting. Agricultural Water management.* Elsevier Science B.V, Amsterdam. pp 145-158.

Chaves, H.M.L. and Nearing, M.A. (1991). Uncertainty analysis of the WEEP Soil Erosion Model. *Transactions of the American Society of Agricultural Engineers* 34(6):2437-2444.

Chong, S.K. and Teng, R.M. (1986). Relationship between the run-off curve number and hydrologic soil properties. *Journal of Hydrology* 84:1-7.

Cooper, A.B., Smith, C.M. and Bottcher, A.B. (1992). Predicting Runoff of Water, Sediment, and Nutrients from a Zealand Grazed Pasture using CREAMS. *Transactions of the American Society of Agricultural Engineers* 35(1):105-112.

Critchley, W., Siegert, K. and Chaphan, C. (1991). *FAO manual for the design and construction of Water Harvesting schemes for plant production*. FAO, Rome. pp 125.

Critchley, W.R.S. (1986). Some lessons from water harvesting in Sub-Sahara Africa. In: *Proceedings of a workshop held in Baringo, Kenya, 13 - 17 October, 1986*. World Bank, Eastern and Southern Africa Projects Department, Washington D.C., pp 5.

Eveneri, M., Shanan, L. and Tadmor, N. H. (1971). *The Negev, The Challenge of a desert*. Harward climersity press, Cambridge, Mass. pp 27-63.

Fawley, A.P. (1956). *Msalatu Reservoir*, Dodoma. Reconnaissance Geological Survey Tanganyika, Vol. 111, Dar es Salaam. pp 3.

Fogel, M.M. (1976). Vegetation Management Guidelines for Increasing Water yields in a Semi-arid region: An Arizona case study. In: *Conservation in arid and semi-arid zones. FAO Conservation guide (3)*, (Edited by Kunkle, S. H. and Thames, J. L.), United Nations, Rome. pp 54-65.

Griffiths, J.F. (1972). *Climates of Africa: its people and resources*. Morgan, T.W. (Ed). Elseviers, New York. pp 107-118.

Gupta, B.L. (1979). *Water Resources Engineering and Hydrology. Standard Publishers Distributors*, Culcatta. pp 456.

Hatibu, N. (1993). Techniques for Soil- water Management for dry land agriculture in semi-arid areas. In: *Proceedings of the Research planning workshop,* (Edited by Hatibu, N. and T.E. Simalenga, T.E.), January 13 - 15, 1993. Dodoma, Tanzania. pp 5-20.

Hatibu, N., Kayombo, B., Mahoo, H., Jones, J.E., Senkondo, E.M. and Simalenga, T.E. (1993). *Evaluation and Promotion of Rain - Water Harvesting in Semi-arid areas of Tanzania*. Rapid Rural Appraisal of Mwanga District. Sokoine University of Agriculture, Morogoro. pp 1-20.

Jones, O.R., Hauser, V.L. and Pophan, T.W. (1991). No tillage effects on infiltration, run-off and water conservation on dryland. *A paper presented at the Transactions of the American Society of Agricultural Engineers*. March - April, 1991. Vol. 37, No. 2. pp 411-419.

Klute, A. (ed.) (1986). *Methods of soil analysis* part 1, 2nd edition. Physical and mineralogical methods, Wisconsin. pp 361-392.

Kinsel, W.G. (ed.) (1980). CREAMS: A field scale model for chemicals, runoff, and erosion from agricultural management systems. *Conservation Research Report* No. 26. Washington D.C: USDA - SEA. pp 5-35.

Lal, R. (1992). *Tropical Agricultural Hydrology and Sustainability of Agricultural Systems*. Ohio. pp 61-109.

Lameck, P.G.M. (1994). Crop performance attributable to Rain Water Harvesting in Semi-arid Central Tanzania. MSc. thesis, Sokoine University of Agriculture. pp 5-89.

Linsely, R.K., Kohler, M.A. and Paulhus, J.L.H. (1982). *Hydrology for Engineers*, third Edition, McGraw, New York. pp 442.

LRDC, (1987). Tanzania: *Profile of Agricultural Potential*. Overseas Development Agency, U.K. pp 3-14.

Lundgren, L. (1980). *Comparison of Surface Runoff and Soil loss from runoff plots in Forest and Small-Scale agriculture in Usambara Mts.*, University of Dar-es-Salaam, Tanzania. pp 28-54.

Morin, J. and Benyamin, Y. (1977). Rainfall infiltration into the soils. *Water Resources Research*. 13(5), USA. pp 813-817.

Mwakalila, S.S. (1992). Evaluation of rain-water harvesting for Paddy Production in Tanzania. MSc. thesis, Sokoine University of Agriculture. pp 45.

Ngana, J.O. (1983). *Rainfall and Agriculture Drought and Famine in Dodoma District. Institute of Resource Assessment Research Paper No. 60.* University of Dar-es-salaam. pp 1-2.

Olaitan, S.O. and Lombin, G. (1987). *Introduction to Tropical Science.* Mac millan Publishers Ltd, London. pp 26-29.

Pacey, A. and Cullis, A. (1986). *Rainwater Harvesting: Rainfall and Collection of runoff in rural areas.* IT publication, London, Uk. pp 458.

Pathak, P., Lanyea, K.B. and Sudi, R. (1990). A runoff model for Small watersheds in semi-arid Tropics. *Transactions of the American Society of Agricultural Engineers* 33(3): 839-849.

Rapp, A., Berry, L. and Temple, P. (Eds). (1972). *Studies of erosion and Sedimentation in Tanzania.* Geografiska, Annaler, 54. A(3-4): pp 24.

Reij, C., Mullder, P. and Begeman, L. (1988). *Water Harvesting for plant production.* World Bank Technical paper No. 91. World Bank, Washington D.C. pp 1-19.

Ngana, J.O. (1983). *Rainfall and Agriculture Drought and Famine in Dodoma District. Institute of Resource Assessment Research Paper No. 60.* University of Dar-es-salaam. pp 1-2.

Olaitan, S.O. and Lombin, G. (1987). *Introduction to Tropical Science.* Mac millan Publishers Ltd, London. pp 26-29.

Pacey, A. and Cullis, A. (1986). *Rainwater Harvesting: Rainfall and Collection of runoff in rural areas.* IT publication, London, Uk. pp 458.

Pathak, P., Lanyea, K.B. and Sudi, R. (1990). A runoff model for Small watersheds in semi-arid Tropics. *Transactions of the American Society of Agricultural Engineers* 33(3): 839-849.

Rapp, A., Berry, L. and Temple, P. (Eds). (1972). *Studies of erosion and Sedimentation in Tanzania.* Geografiska, Annaler, 54. A(3-4): pp 24.

Reij, C., Mullder, P. and Begeman, L. (1988). *Water Harvesting for plant production.* World Bank Technical paper No. 91. World Bank, Washington D.C. pp 1-19.

Selian Agricultural Research Institute, (1995). *Report on soils of Rain Water Harvesting experimental site at Kisangara*. Arusha, Tanzania. pp 24.

Shanan, L.Y. and Tadmor, N.H. (1979). *Micro-catchments systems for arid zones development*. Hebrew University, Jerusalem. pp 398.

Sheridian, J.M. (1994). Hydrograph Time Parameters for flatland Watersheds. *Transactions of the American Society of Agricultural Engineers* 37(1):103-113.

Staples, R.R. (1938). *Report on runoff and soil erosion test at Mpwapwa in Semi-arid Tanganyika*. Annual Report for the Department of Veterinary Science and Animal Husbandry, Tanganyika. pp 13.

Soil Water Management Research Project, (1993). Evaluation and Promotion of Rain Water Harvesting in Semi-arid areas of Tanzania Research project. *1st Interim Annual Technical Report*, Sokoine University of Agriculture, Morogoro. pp 44.

Soil Water Management Research Project, (1993). *Field and Laboratory Manual*. Sokoine University of Agriculture, Morogoro. pp 17.

USDA Soil Conservation Service. (1985). *National Engineering Handbook, section 4, Hydrology*. Washington DC:GPO. pp 23.

Van Rensburg, H.J.(1955). Runoff and soil erosion tests, Mpwapwa, central Tanganyika. E.A.Agric. J.20:228-231.

Walkman, S.R. and Skaggs, R.W. (1994). Sensitivity of Water Management models for Determining Soil Hydraulic Properties. *Transactions of the American Society Agricultural Engineers* 37(1):95-101.

APPENDICES

APPENDIX 1: Runoff data collection sheet

Site ..... Block ..... Date..... .....

1 Plot	2 Apron size (m^2)	3 Collector tank			4 Overflow check			5 Total volume overflowing from divider tank (L) 3(c)*1/4(c)	6 Divider tank			7 Total volume entering divider tank (L) (5+6c)	8 Rainfall since last measurement (mm)	9 Volume collected from apron (L) (2x8)	10 catchment /Plot runoff (L) (7-9)	11 Runoff coef. (10/8) (%)
		(a) Depth (cm)	(b) Vc*	(c) Volume (L) (3a)x(3b)	(a) 10L	(b) 20L	(c) Average fraction		(a) Depth (cm)	(b) Vc*	(c) Volume (L) (6a)x(6b)					

APPENDIX 2: Rainfall data from November, 1994 to May, 1995

Table 2A: Short rainy season (*vuli*): Nov. - Dec. 1994

Date	Rainfall (mm)	Time (hours)	Intensity (mm/h)
1.11.94	0.5	0.67	0.75
4.11.94	2.8	2.75	1.02
5.11.94	3.5	0.33	10.61
7.11.94	1.9	0.67	2.84
8.11.94	0.5	0.17	2.94
11.11.94	20.8	0.80	26.00
16.11.94	12.3	1.33	9.25
17.11.94	4.0	1.08	3.70
18.11.94	0.3	1.00	0.30
19.11.94	0.5	0.67	0.75
20.11.94	0.2	0.72	0.28
21.11.94	13.5	1.77	7.63
28.11.94	20.0	0.80	25.00
29.11.94	5.8	0.42	13.81
30.11.94	13.0	1.67	7.78
1.12.94	25.0	1.64	15.24
2.12.94	35.0	2.69	13.01
4.12.94	5.0	0.34	14.71
5.12.94	9.0	0.70	12.86
6.12.94	10.0	1.16	8.62
8.12.94	13.0	0.60	21.67
9.12.94	25.0	3.67	6.81
10.12.94	2.5	0.09	27.78
12.12.94	3.0	0.16	18.75
14.12.94	21.0	3.45	6.09
15.12.94	4.0	0.42	9.52
16.12.94	23.0	1.23	18.70
17.12.94	33.0	1.07	30.84
23.12.94	10.0	1.03	9.71
28.12.94	4.0	0.11	36.36
29.12.94	2.0	0.19	10.53
30.12.94	1.9	0.10	19.00

Source : SWMRP (1995) - Kisangara Meteorological Station

Table 2B: Long rainy season (*masika*): Feb. - May 1995

Date	Rainfall (mm)	Time (hours)	Intensity (mm/h)
9.2.95	36.5	2.08	17.55
12.2.95	5.0	1.03	4.85
15.2.95	6.0	1.25	4.80
19.2.95	17.0	2.72	6.25
2.3.95	4.5	0.18	25.00
3.3.95	50.0	3.03	16.50
6.3.95	7.0	1.57	4.46
7.3.95	3.5	0.26	13.46
13.3.95	59.0	7.19	8.21
14.3.95	5.0	0.77	6.49
15.3.95	30.0	1.09	27.52
22.3.95	2.0	0.14	14.29
24.3.95	2.5	0.58	4.31
26.3.95	2.0	0.24	8.33
29.3.95	2.5	0.83	3.01
30.3.95	22.0	1.15	19.13
7.4.95	5.0	0.67	7.46
11.4.95	3.0	0.20	15.00
14.4.95	5.5	0.50	11.00
15.4.95	5.5	0.38	14.47
20.4.95	8.0	1.58	5.06
23.4.95	5.0	1.23	4.07
24.4.95	8.0	0.60	13.33
25.4.95	41.0	1.95	21.03
26.4.95	39.0	2.42	16.12
27.4.95	2.3	0.70	3.29
28.4.95	4.0	0.25	16.00
29.4.95	17.0	0.75	22.67
30.4.95	7.0	0.20	35.00
1.5.95	2.0	0.50	4.00
3.5.95	2.8	1.16	2.41
11.5.95	3.0	1.00	3.00
17.5.95	9.0	2.05	4.39
18.5.95	17.0	0.73	23.29
19.5.95	23.0	2.62	8.78
22.5.95	14.0	1.03	13.59
28.5.95	13.0	1.60	8.13
29.5.95	9.0	1.40	6.43
30.5.95	5.0	1.04	4.81

Source : SWMRP (1995) - Kisangara Meteorological Station

APPENDIX 3A: Summary of detailed description of soils of the experimental site

A. Soils at upper slope of the area (> 7 % slope)

(i) The soil has lowest nutrient level as compared to the soil from other lower slopes (Appendix 3B).

(ii) The dormant soil is Plinthic Luvisol and Ferric Cambisol.

(iii) Soils on the surface as well as on the underlying horizons have generally the most coarse texture (up to 49% sand content) when compared with soils on the lower slope position (< 7% slope).

(iv) Soils are well to rapidly drained, fairly deep yellowish red in colour.

(V) Soils are acidic in reaction with low base status and are likely to be deficient in phosphorus and nitrogen.

(vi) Soils have very little horizonation.

(vii) Soils have low organic matter content and high sand content that causes a low water holding content.

B. Soils of the middle slope (3-6% slope)

(i) Soils have developed from acidic granulite parent material.

(ii) Soils are lithic to shallow, well drained, reddish

brown, stony, and sand clay loam in texture.

C. Soils of the lower slope position (< 3 % slope)

(i) The soil is Luvisol with an accumulation of clay content in the sub surface horizon.

(ii) The soil has a higher fertility status than soils in the upper slopes.

(iii) The clay content tend to increase with depth.

APPENDIX 3B: Soil chemistry and nutrient distribution of the two horizons (10-30 cm)

				NUTRIENT ANALYSIS			IONIC ANALYSIS (Meq/100g OF SOIL)						
IDENT. (%)	DEPTH Slope (CM)	pH H_2O	KCl	E.C (ds/m)	TOTAL N %	AVA. P (ppm)	C.E.C	Ca	Mg	K	Na	O.C (%)	B.S (%)
> 7	0-10	5.9	5.1	0.22	0.43	6.7	8.8	1.31	3.42	1.28	1.86	1.48	89.7
	10-30	5.2	4.3	0.13	0.31	2.9	9.7	0.82	2.60	0.94	2.23	1.07	70.6
3-6	0-10	5.4	4.5	0.06	0.60	4.0	7.9	2.45	1.75	0.49	2.00	1.46	81.1
	10-30	4.3	3.7	0.03	0.41	0.9	9.7	1.70	1.46	0.29	1.96	1.01	74.3
< 3	0-10	5.5	5.1	0.13	0.65	2.1	7.3	3.80	0.93	0.90	2.09	1.36	96.1
	10-30	4.7	4.2	0.06	0.83	0.2	8.7	2.75	0.76	1.87	2.00	0.75	84.2

Source: SARI (1995)