Runoff prediction and management models for the Njemps Flats, Baringo District, Kenya.

By

MICHAEL MWANGI WAIRAGU

A thesis submitted in conformity with the requirements for the award of the degree of Master of Science in Forestry in the University of Toronto.

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Master of Science in Forestry

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We approve this thesis and affirm that it meets the departmental oral examination requirements set down for the degree of Master of Science in Forestry.

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ABSTRACT

This thesis examines the possibility of using artificially derived runoff parameters to estimate the runoff potential of natural rainfall on the Njemps Flats of Baringo district (Kenya), and to obtain necessary hydrological data used to formulate guidelines for effective natural runoff harvesting and management for reforestation in the area.

Simulated rainfall was used to derive artificial runoff parameters which were subsequently applied to monthly rainfall data to obtain estimates of runoff potential. Derived runoff data were then used to determine monthly runoff probability, optimum microcatchment plot sizes, and some optimal silvicultural practices, all of which were found to closely agree with observations made under natural rainfall conditions nearby.

It was found that runoff on the Flats is principally a function of storm characteristics (depth, intensity and frequency) which account for up to 90% of its variation. Runoff events can be predicted from the probability of effective storms, i.e., those exceeding 7mm depth and 10mm/hr intensity in the area. Rain can occur on the Flats in any month and with the low threshold rainfall of about 7mm, the monthly runoff probability ranges from about 0.2 in the driest month to more than 0.77 in the wettest. Runoff harvesting can be a reliable reforestation support technique in the area.

Though the mean annual rainfall of 640mm on the Flats is not enough to support tree growth, and a large moisture deficit ranging from 960 to 1600mm per annum exists in the area, it has the potential to produce 132mm of runoff. This runoff potential would require an optimum plot size ranging from 7 to 12 m^2 to collect sufficient water to support the growth of seedlings through the dry season. Such a plot size unfortunately has the potential to collect excess runoff in the wettest months whose potential effects such as erosion and seepage need further study.

Since the probability of runoff occurence is higher from March to August, the former is the ideal planting time to ensure that the trees make use of all the wet season. However, the dry season between November and February demands that a tree species like Prosopis with acceptable growth and moderate water use be used as its chances of surviving this drought are much higher than those of faster growing, high water-consuming species such as Eucalyptus camaldulensis and Leucena leucocephala.

The methodology of deriving optimum plot size and other information needed for runoff management from both artificial runoff parameters and natural rainfall as used in this study can be extended to other areas, provided the specific variations in rainfall- runoff relationships and other factors are fully established.

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May God, the ultimate source of all goodness reward all this generosity in equal measure.

1.0 INTRODUCTION

1.1 PROBLEM STATEMENT

Global demands for more food and fibre have led to a growing awareness of the agricultural value of arid and semi-arid lands if sufficient and economical water supplies can be developed. Water harvesting, a technique for precipitation collection, is being used with increasing frequency to provide drinking water for people, livestock, and wildlife, and for agriculture and forestry. Major progress has been made in the development of methods and materials for water harvesting applications but many details still need additional research. Packages of proven water harvesting methodologies need to be developed and tested for target areas to ensure smooth and successful adoption of this technique which promises a new lease of life in arid and semi-arid environments.

The Njemps Flats of Baringo District in Kenya is one such area. With a Moisture Availability Index (rainfall/ potential evaporation) of 25%, the area is classified as semi-arid with a huge moisture deficit. Severe destruction of the vegetation cover due to overgrazing ensures that in each rainy season the area is endowed with large quantities of surface runoff from occasionally torrential storms. The end result has been chronic soil erosion which is clearly apparent from the dense gully network in the area and more clearly from the perpetual siltation of the nearby Lake Baringo.

To arrest and reverse this vicious cycle, reforestation has been recommended and initial attempts to tap surface runoff and use it for reforestation have proved very successful in the area. Local donor-aided afforestation and pasture improvement projects using runoff harvesting have demonstrated that, by using a system of microcatchments, it is possible to concentrate runoff and use it to help seedlings grow in an otherwise hostile environment until they can root deep enough to tap underground water layers. The method has therefore met a lot of approval and there is widespread recommendation for its adoption. Apart from facilitating the growing of trees, the system also breaks the movement and speed of surface runoff along the slope, thereby reducing its erosive power.

Largescale adoption of the system on the Flats requires detailed knowledge of runoff behaviour which is not presently available. Also lacking is essential data on spatial and temporal rainfall response which, among other things, determines the runoff potential and subsequently, optimal microcatchment sizes. An understanding of runoff behaviour would facilitate the identification of potentially suitable sites as well as the economic evaluation of runoff harvesting packages suited to the area.

Quantification of runoff generation potential as well as its annual variability cycles would also facilitate the formulation of badly needed management guidelines on such issues as ideal planting time, species selection, and the like, all of which would make reforestation in such areas possible. All these are questions which this thesis project aimed at answering.

1.2 OBJECTIVES OF THIS STUDY

The objectives of the study are:-

(i) To develop runoff prediction models for the Njemps Flats to predict the runoff-yielding potential of the area from available rainfall data.

(ii) To assess the possibility of using available information on rainfall and site characteristics to determine optimum microcatchment plot sizes to harvest enough water for trees in the area, and assess the possibility of adapting this methodology to other areas.

(iii) To provide vital information such as runoff behaviour and probability in addition to suitable silvicultural practices such as planting dates and optimal species all neccessary planning successful runoff harvesting.

2.0 LITERATURE REVIEW

2.1 RUNOFF HARVESTING: A HISTORICAL PERSPECTIVE

Runoff harvesting has been used since historical times to facilitate farming in the arid and semi-arid belts of the world. In the Negev Desert of Israel, archaeologists have discovered complex runoff farms which were used by the Nabateans more than 4000 years ago. Reconstruction of these farms accompanied by modern hydrological recording equipment has facilitated studies which continue giving a lot of insight on the original functioning of these ingenious techniques (Evenari et al., 1982: Yair, 1983). In the Indian desert, similar runoff farms, 'khadins', dating back to the 15th century have been discovered and rehabilitated (Arid Lands Newsletter, 1987) and discoveries have also been reported from the Mediterranean coast of North Africa, north eastern Mexico and many others areas.

Though all the systems discovered have different designs depending on the cultural environment, they all had a common basic structure as they consisted of a catchment area where runoff was collected and a basin area where the runoff was stored and used to grow plants. The collected runoff was channelled down the valley bottoms where it could accumulate and be stored safe from evaporation, thus allowing crops to be successfully grown. Studies on the reconstructed farms in Israel have supplied a lot of information on the hydrological base of these farms. It as been found that even in dry years, the valley farms in the Negev Desert were capable of receiving an equivalent of 200 to 300mm of rainfall from runoff in addition to the 100mm of direct rainfall (Evenari et al., 1982).

The runoff yield from the catchment slopes was quite low as the runoff coefficients rarely exceeded 10% and this necessitated the use of very large catchment area to planting basin ratios ranging from 17:1 to 30:1. This literally meant that in the Negev Desert, one hectare of farmland required between 17 to 30 hectares of catchment slopes to harvest enough water for crops (Evenari et al., 1982; Hillel, 1971). The same authors argued that runoff was mainly generated on the gentle colluvial slopes where the thin loess soils crust heavily on wetting, leading to high runoff yields. This theory was soon disputed by Yair (1983) and by Yair et al., (1987) whose studies demonstrated that runoff collection was from the steep rocky slopes whose runoff magnitude and frequency were much higher than those of the colluvial and loess-covered slopes. Yair (1983) also argued that paved conduits were used to convey runoff to the valley farms across the deeply porous colluvial slopes where losses due to infiltration would otherwise have been too high. The colluvial slopes were therefore not capable of yielding runoff, as held by the other school of thought. As the debate continues, one wonders why very high catchment to planting basins had to be used as claimed by Evenari et al, (1982) if runoff was collected from the rocky slopes whose runoff efficiencies were shown by Yair et al., (1987) to be quite high. A possible reason is that much of the catchment slopes were colluvial covered and could not contribute runoff sufficiently and this, coupled with the need to supply sufficient water in the dry months, necessitated the use of large catchment to planting area ratios.

From most reviews of the ancient runoff systems, it is apparent that the ancient farmers across the arid and semi-arid world favoured the use of small farms in valley bottoms (Evenari et al., 1982; Arid Lands

Newsletter, 1987). However, recent studies have developed and modified a new technique called "microcatchment", which, as the name implies, is a system of collecting runoff from a small area and storing it in the rooting zone of an adjacent tree in the infiltration basin (Fig. 1). In the infiltration basin, there may be a single tree, bush or annual crop.

The aim of the microcatchment is to harvest and store enough water in the soil profile below the plant during the rainy season to cover the water requirement of the crop during the growing season (Boers et al., 1986a). Compared to the small farms in valleys, the microcatchments have low maintenance and construction costs as they do not require high technological inputs, and they have little risk of damage in the event of overtopping in the case of huge storms, as compared to big engineering works (Oron and Enthoven, 1987). Detailed comparative studies on the two water harvesting systems also revealed that microcatchments yield more runoff per unit area and have higher runoff frequencies compared to the small watersheds (Evenari et al., 1982), all of which would make the probability of crop success in them quite high.

All these factors in addition to their simplicity have led to the widespread adoption of microcatchments. Recent surveys have revealed that the technique is to be found in the West African Sahel (Wright and Bounkoungou, 1986), in the Californian Desert (Dutt et al., 1981), in India (Sharma, 1986; Das, 1985), in the North Eastern Mexico Desert (Anaya, 1980), in Kenya's semi-arid North (Barrow, 1983; BPSAAP,1984), to mention just a few.

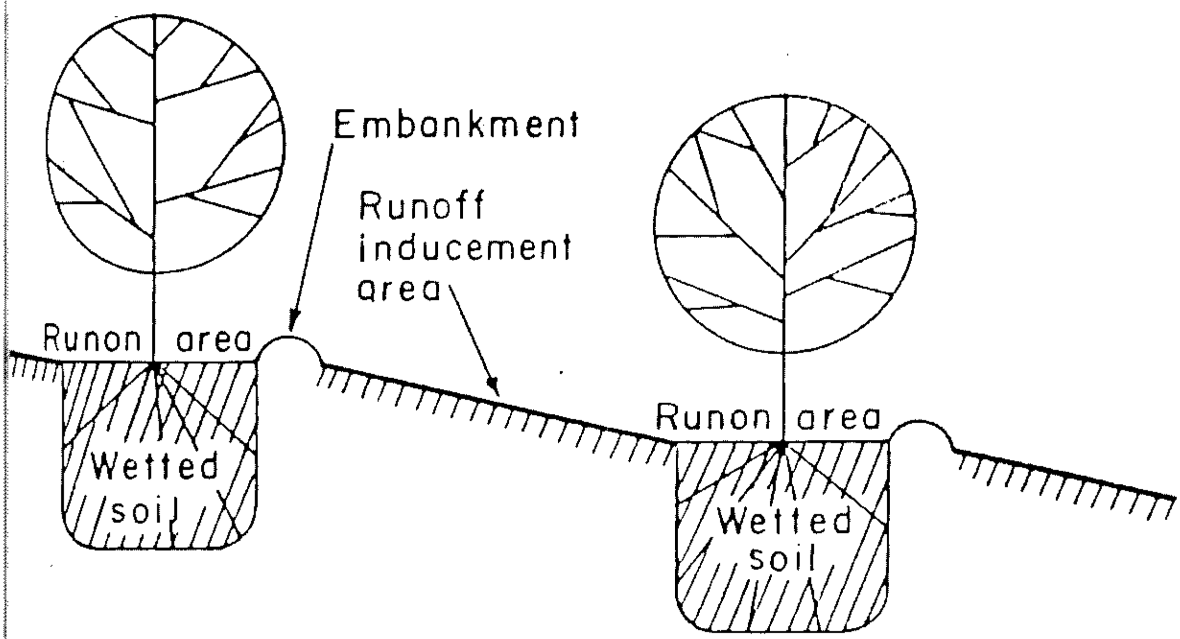


Fig. 1: A cross section of a microcatchment unit.
(After Hillel, 1981)

The bulk of the few studies that have been conducted on microcatchment runoff harvesting have focussed mainly on biomass gains through improved survival and growth of plants. These include studies by Evenari et al., (1982); Ehrler et al., (1978); Smith and Critchley, (1983); Fink and Ehrler, (1983); Roberts, (1988); BPSAAP, (1984); FAO, (1987); Barrow, (1983) among others. Only the few studies described below have been directed toward understanding runoff occurrence and behaviour in areas where its harvesting is desired.

2.2 RUNOFF GENERATION IN ARID AND SEMI-ARID LANDS.

The Hortonian overland flow model (Horton, 1933; 1939; Beutner _et al_., 1940) was the earliest attempt to study runoff generation as a process. According to this model, the soil at any point has a maximum rate at which it can take in water, which is termed the infiltration capacity. Horton found that the infiltration capacity changed constantly with time during a storm a process he described with the following equation.

$$F = fo + (fo - fc)\ e^{-kt} \qquad \text{(i)}$$

where (F) is the infiltration capacity, (fo) is initial infiltration capacity, (fc) is final infiltration capacity, (k) is the infiltration coefficient and (t) is time in minutes. According to this theory, infiltration capacity decreases constantly during a storm until it falls below the storm intensity, when runoff generation is initiated.

Though the applicability of this classical Horton overland flow model in humid areas with inherently high infiltration capacities has been questioned and largely rejected (Hewlett and Hibbert, 1965; Betson, 1964; Dunne and Black, 1970), it has been identified as the mode of runoff generation in arid and semiarid lands (Yair and Klein, 1973; Morin and Benjamin, 1977; Evenari, _et al_, 1982; Hillel, 1971).

Despite the observed prominence of Horton overland flow in arid and semi-arid lands, recent studies by (Bryan et al. 1978; Yair et al. 1980; Yair 1983; Yair et al. 1987) have revealed that its generation in such areas is non-uniform, a fact that has cast a lot of doubt on the credibility of watershed data extrapolated from runoff plot studies. Yair, (1983) associated this non-uniformity of spatial runoff generation with spatial variation of slope and storm characteristics in arid lands. The characteristics of a slope that lead to this non-uniformity of runoff yield are mainly soil type and cover conditions.

Texture, structure and sodicity have been identified as the soil hydrological factors strongly influencing rainfall response on soils. Krantz (1981) did substantial research in India on Alfisols and Vertisols, which are the most widespread soil types in semi-arid tropics. He concluded that vertisols, despite their low intrinsic hydraulic conductivities, have high initial water uptake rates due to cracking, which reduces their runoff yield compared to Alfisols where limited cracking ensures no infiltration loss. This confirmed earlier reports by Kampen (1980) and by Jain and Singh (1980) who found Alfisols to have a runoff potential 3 times higher than that of Vertisols at Hydrabad. El-Swaify et al., (1984), though admitting a high natural variability, argued that conventionally cropped Alfisols in semi-arid tropics generally experience runoff which makes them quite prone to erosion.

Huibers (1985) discussed the red soils in India (mainly sandy loam Alfisols associated with Inceptisols and Entisols) and concluded that they have poorly developed structure which causes a rapid aggregate dispersion on wetting, after which sealing ensures runoff generation even before profile saturation. Other studies have also shown that sodic soils are strongly dispersed on wetting which lowers their infiltration capacity. Kamura et al. (1985) estimated that sodic soils in the Indogangetic Plains of India have an infiltration rate only 3% that of normal soils. So strong is sodic dispersion that sodium salts are now widely used to induce surface sealing on soils where surface runoff is desired.

Despite the influence of texture, structure and the presence or absence of sodium salts discussed above, the hydrological properties of soils are greatly modified by surface conditions mainly the nature of vegetation cover and gravel and stone layers on its surface. Much has been published on the role of vegetation on runoff generation through interception effect (Thurlow et al., 1987; Clarke, 1940; Murphy and Knoerr, 1975), through dissipation of raindrop energy (Moldenhauer and Long, 1964; Hudson, 1981; Morin and Benyamin, 1977) and through enhancement of the infiltration capacity (Weltz and Wood, 1986; Parker, 1951). Other studies have found vegetation to influence runoff yield by transpiring moisture from the soil, thus creating moisture deficits and expanding the soil moisture reservoir (Boughton, 1970, Buckhouse and Cortharp, 1976).

Unlike the influence of vegetation, that of gravel and stone surface layers has received very little attention except in the Negev desert where, unfortunately, their study has raised more questions than answers (Yair, 1983; Evenari et al., 1982). The same authors reported runoff yield increases from stone clearing to occur only during big storms and argued that infiltration was a two-phase process. During small storms, infiltration is high as air escapes through cracks between stones while under long-duration storms, the stones are fully concreted into the soil and their impermeability leads to high runoff yield. Stone-covered slopes therefore require long-duration storms to generate runoff, a factor that makes them unsuitable for runoff generation in arid and semiarid lands where high-intensity storms are normally shortlived.

Apart from soil type and its cover condition, storm characteristics have been identified as influencing spatial runoff generation on a site (Yair, 1983). For runoff to occur, certain rainfall thresholds have to be exceeded. Either rainfall intensity exceeds the infiltration capacity or total storm depth exceeds the soil storage capacity. The characteristics of an individual storm, namely, intensity, duration and frequency, determine its partition into infiltration, surface runoff or evaporation loss, all of which determine how much of rainfall becomes available for plant use as soil moisture. The frequency with which a storm of a particular depth and intensity occurs is also important in that, apart from raising the runoff frequency on a site, it influences the antecedent moisture condition of the soil. Several studies have shown that antecedent moisture strongly influences storm effectiveness through its influence on soil moisture saturation deficit which influences both the runoff coefficient and threshold loss (Ahunja et al., 1976; Henninger et al., 1976; Tamir, 1960). The frequency of individual storms and the probability of certain critical thresholds being exceeded are therefore very useful criteria for evaluating the potential of runoff generation on a site and they are very effective tools for long-term runoff potential modelling (Kutsh, 1983).

2.3 RUNOFF PREDICTION MODELS

Since rainfall is the main source of runoff in arid lands, runoff prediction attempts to establish the quantity of rainfall that forms runoff on a long-term basis on a site and this involves the development of rainfall runoff relationships. The latter have to be based on rainfall and runoff data. However, during the collection of basic runoff prediction data, precipitation records are more often available than runoff records and in most cases, some sort of rainfall record is all one can hope for. In such cases, runoff modelling involves simulating runoff yield from the rainfall data and techniques to do this will be reviewed below.

Where some runoff records are available, regression equations and graphs relating them to corresponding rainfall data are fitted for use in future predictions. Hillel (1971), applied the linear regression model to determine runoff parameters from rainfall data. He fitted a linear equation of the form

$$R= B\ (P-A) \qquad \text{(ii)}$$

where (R) is storm runoff (mm), (P) is storm depth (mm) and (A) and (B) are runoff coefficients. The coefficient (A) was the X axis intercept and estimated the threshold rainfall, while (B), the slope of the line, estimated the runoff coefficient.

Evenari *et al*. (1982) applied the same model to rainfall and runoff data from runoff plots and small watersheds to derive an annual rainfall- runoff relationship. The derived models facilitated the prediction of the runoff potential of different annual rainfall depths and also revealed that up to 30 to 50mm out of the 100mm of annual rainfall were lost as threshold rainfall in the Negev Desert. The model also showed that microcatchments yield more runoff per unit area than small watersheds. Unfortunately, these models could not be used to predict runoff from individual storms, nor could they predict runoff response under different combinations of site and storm characteristics.

Shanan and Schick, (1980) working in the same experimental site, produced the Hydrological Model of the Negev Desert Highlands by adding functions to deal with spatial rainfall variability on slopes, soil infiltration rates, slope and surface cover conditions to the model described above. By relating daily rainfall (Pd) to daily runoff (Rd), a linear relationship of the form

$$Rd = bPd + a \qquad \text{(iii)}$$

where (a) and (b) are coefficients, was obtained. Both coefficients were found to vary annually but were unrelated to annual rainfall. Coefficient (a) was regarded as the daily threshold rainfall required to generate runoff and it ranged from 2-3mm in the Negev Desert. The model showed that both coefficients were strongly site-dependent and varied strongly with slope angle and surface cover and responded differently to different storm types. Using the model, the effects of different combinations of site and storm characteristics on runoff could be evaluated and it formed a useful tool for use in identifying runoff harvesting sites. It also accounted for the differences in runoff yield from small watersheds and runoff plots, which were due to the high variability in the former which led to higher infiltration capacity.

On a more advanced level, elaborate runoff simulation models for designing runoff harvesting structures have been developed. Oron and Enthoven (1987) used the rainfall and runoff data from the Sde Boquer area of the Negev Desert to determine the optimal microcatchment layout for runoff harvesting to ensure maximum returns. They applied the linear regression model to individual storms to derive runoff yield estimates which were summed for the whole year to give annual water supply to a seedling from a unit of area. Assuming that runoff supply to a tree would increase with plot size while return per unit area would decline, computer simulation data were used to arrive at the plot size that gave the highest return per acre.

Earlier, Oron et al., (1983) had applied the same model to evaluate the financial returns from microcatchments fitted with a tube that increased moisture supply to a seedling by promoting infiltration and subsequently reducing evaporative water loss. The model component was used to derive runoff water supply from rainfall while the water balance component was used to estimate the amount of additional water available to plants through improved infiltration and reduced evaporative loss. This facilitated the economic evaluation of the additional water supply.

Boers et al. (1986b) combined the linear regression model with a soil water balance component to establish the design criteria for microcatchments, such as optimum catchment-to-infiltration area ratio to nsure efficient runoff use. The model component provided the water input estimates in form of runoff from rainfall while the water balance component estimated the water loss through evaporation and seepage, both of which the design aimed at minimising. By solving the water balance equation for different catchment and basin sizes, the combination of sizes that resulted in the highest water use efficiency was achieved. Sharma (1986) also applied linear regression models to monitor microcatchment runoff behaviour and determine optimum microcatchment characteristics for runoff harvesting in the arid zones of India.

From this account, it is clear that the linear regression model of rainfall runoff relationships has become a handy tool for runoff prediction purposes. The assigning of physical meaning to the regression parameters has also allowed the influences of site characteristics on runoff yield to be evaluated and predicted. Due to this, the use of the model has been expanded to include not only evaluation of storm-runoff-yielding potential under different conditions (Fink and Frasier, 1977), but also the evaluation of performance of different runoff inducement treatments on catchments (Emmerisch et al., 1987; Hillel, 1971). Other scientists have found it a very useful tool to test the accuracy of recording instruments such as rain gauges and weirs (Fink and Frasier, 1977), which shows the extent of its potential use in surface hydrology for prediction purposes. With different modifications, its use can be extended to many hydrological computations.

2.4 SIMULATION MODELS

Where runoff data are missing, the alternative has always been to use simulation models to derive them from precipitation records. The precipitation records mostly used are daily data which unfortunately almost always lack information on duration and intensity. Several authors have attempted to derive information on rainfall intensity from rainfall depth records. Evenari et al. (1982) used the relationship

$$I = K\, T^{1/2} \qquad \text{(iv)}$$

where (I) is rainfall intensity (mm/hr), T is storm duration (min) to estimate rainfall intensity from storm depth and found it to work well for Israel conditions while Rawitz and Hillel (1971) attempted to derive regional rainfall intensity patterns from the frequency distribution of rainfall events observed on certain rainfall stations.

The same authors (Rawitz and Hillel, 1971) studied patterns of rainfall data from the Sede Boqer area and developed a method of estimating runoff production from rainfall patterns and for estimating actual runoff yields from areas with known infiltration rates. The basis of their analysis was scaling storm segments (intensity vs duration) for several seasons to obtain a distribution of precipitation depth as a function of rainfall intensity from which hypothetical runoff depths for known infiltration values could be computed.

Morin et al. (1984) took the method a step further and calculated expected runoff depths and rates from functions of soil infiltration capacity and storm intensity patterns and then used storm probability distribution functions to predict long-term runoff yield from different sites. By providing much desired data on runoff yield and possible rates from local storms, the method provided a useful guide for evaluating the runoff potential of sites as well as for estimating the design specifications for optimum microcatchment plot sizes. Unfortunately, this method is based on rainfall intensity data which is rarely available. As well, the high spatial variability of infiltration capacities on which it is based, reduces the precision of the predicted runoff data.

Another method similar in design to the phi-index method described above is the Rational formula for peak runoff prediction. It states that

$$Q = C\ I\ A \qquad (v)$$

where (Q) is peak runoff in cubic feet per second, (C) is ratio of runoff to rainfall at the equilibrium runoff state, (I) is rainfall intensity during time of concentration, while (A) is the area of the catchment in hectares. Though this method is only good for predicting peak discharge from storms, where an idea of storm duration exists it can be used to compute runoff depth from storms and subsequently to compute annual runoff yield. The main weakness with this method is the broad reliance on coefficients, which ignores natural variability.

Yet another modelling method rapidly gaining in popularity is the use of rainfall simulators. They come in very handy to shortcut the long periods needed to collect runoff data under natural rainfall conditions. By imposing known quantities of rainfall at controlled rates and measuring the resultant runoff, rainfall-runoff equations which provide insight on the behaviour of the site under natural rainfall can be derived. The method also yields good data on threshold rainfall, runoff efficiency, and infiltration rates (Emmerisch et al. 1987) and it has also been used to study complex slope processes (Yair 1983; Bryan 1973; Dunne and Black, 1970).

The reliability of data derived from rainfall simulations was confirmed by several authors (Morin et al. 1984; Stroosnijder and Hoogmoed, 1984) and very recently by Navar (1988) who used rainfall simulation data to model stemflow generation on certain semi-arid growing shrubs. The method therefore offers a rapid technique for deriving information on the runoff behaviour of a site. The derived runoff parameters can then be applied to natural rainfall data to predict runoff yield, thus facilitating the quantification of runoff potential in sites where runoff data is not available. This is the method that was applied in this study to derive runoff data for the Njemps Flats where only a record of monthly rainfall data was available. The experimental procedure is described below.

3.0 METHODOLOGY

3.1 DESCRIPTION OF STUDY AREA.

3.1.1 LOCATION

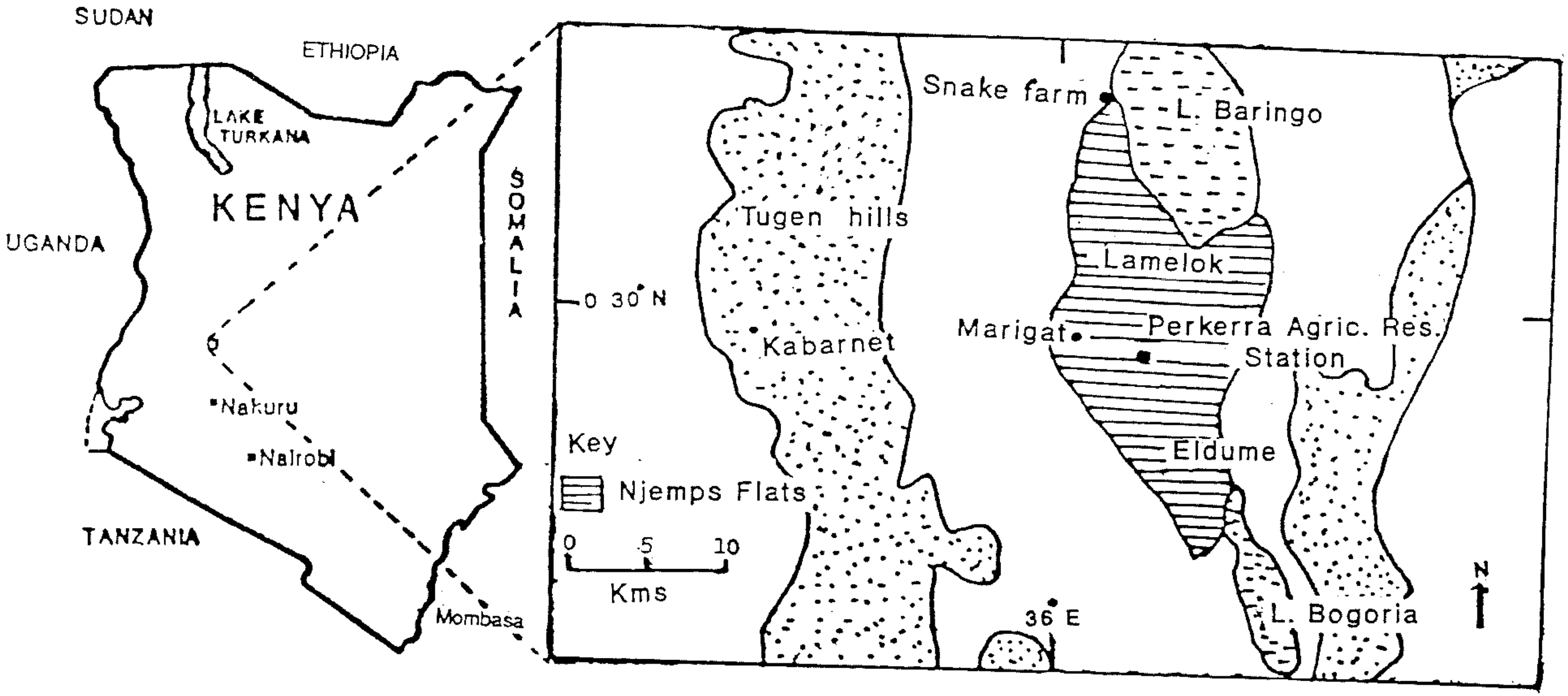
The Njemps Flats is located in the Lake Baringo trough in the semi-arid Baringo District in Kenya at latitude 36° 00 E and 00° 30 N longitude. The area extends westwards and southwards from Lake Baringo towards Lake Bogoria and is boundered by the Laikipia escarpment to the East and the Tugen Plateau to the West (Fig. 2).

3.1.2 SOILS AND DRAINAGE

The Lake Baringo trough was formed about 7 million years ago and is infilled with fluvio-lacustrine sediments of Late Pleistocene to Recent Age. The sediments consist of alluvial sands and gravels and lacustrine silt derived mainly from the weathering rocks in the Tugen hills. The Njemps soils are mainly classified as Eutric Fluvisols with a sodic phase and Calcalic Fluvisols with saline and sodic phases. They are well drained, deep to moderately deep with high silt content and are therefore classified as silty loams and silty clay loams. Their base saturation is over 50% between 20 and 50 cm. They have a sodic phase where exchangeable sodium is over 6% within 100cm of the surface and a saline phase where electrical conductivity of the saturation extract is 4mmhos/cm.

Some sources report that the Eutric Fluvisols have high sodium

Fig. 2: Map of study area.



contents which causes high dispersion of clay and silt particles on wetting and which greatly reduces their infiltration capacities thereby encouraging severe erosion. However, chemical analysis of these soils in this study revealed that Ca^{2+} and not Na^{+} is the main cation in the exchange complex in these soils, thus differing with reports such as by B.P.S.A.A.P (1984).

3.1.3 RAINFALL

Rainfall data for the Flats have been available at the Perkerra Irrigation Research Station (Fig. 2) since 1958 and at the nearby Snake farm since 1964, However, analysis by Rowntree (1988) revealed no statistical difference between the records from the two sites but the rainfall data from Perkerra Irrigation Station was prefered for this study to allow easy comparison with other meteorological data such as pan evaporation and Penman evapotranspiration computation data, which are only available at the same place. A supplemental raingauge network is operated in the project area by BPSAAP and this gives reliable information especially on rainfall characteristics in the area. Appendix 1 gives the statistics of rainfall at Perkerra Irrigation station . The mean annual rainfall in the area is 640mm with a range of 450-860mm. The rainfall is distributed throughout the year and it can occur in any month, though two peaks, in April and August, are apparent.

The monthly rainfall is very variable, as shown by the high standard deviation of the mean in each month (Appendix 1). The bulk of monthly rainfall falls in only a few days, which are followed by extremely dry spells. Mean number of rainy days ranges from 4 to 14 in the dry and wet months respectively while mean rain per rainy day averages 5mm (BPSAAP 1984). According to Rowntree (1988), cumulative frequency of daily storms decreases with their size, with storms less than 10mm having a cumulative frequency greater than 60% though contributing only 20% of the annual rainfall total.

Pilot rainfall studies on the Flats (BPSAAP, 1984) revealed that daily rainfall total is strongly correlated with intensity. Though the analytical methods used are questionable, maximum one-hour intensities were shown to increase with depth. The same studies revealed that in 94% of total storm durations, the intensity is between 0-15mm/hr within which time 68% of the annual rainfall is received. This potrays the Njemps storms as having very low intensities. Despite this, a significant 18% of the annual rainfall is produced by storms with intensities ranging from 20-40 mm/hr and maximum one-hour intensities of up to 80mm/hr have been recorded. These medium intensity storms were thought to be the most significant with respect to soil erosion and damage of soil and water conservation measures (Rowntree 1987).

3.1.4 RUNOFF MODELLING ON THE FLATS.

As early as 1964, Pratt concluded that some form of water harvesting was necessary for successful revegetation of the Njemps Flats and several projects have attempted runoff harvesting in the area, citing huge moisture deficits, rainfall unreliability and high surface runoff rates as the main justifications (Barrow 1983; BPSAAP 1984; FAO 1988; Roberts 1988). All have had some success but none has ever attempted to investigate the characteristics of runoff which they all aimed at utilising. In particular, none has attempted to study runoff yield variation on different sites and therefore the optimal microcatchments sizes that need to be used.

Of the few investigations conducted on runoff in the area, the most notable include the study by Smith and Critchley (1984), who reported very high runoff potential in the area, followed by Rowntree (1988) who studied the characteristics of local storms and produced monthly probabilities of different storm categories. The results of the latter study made it possible to predict runoff events from monthly rainfall data, should rainfall-runoff relationships for the area be developed. It therefore formed a vital starting point for runoff prediction studies in the area. Unfortunately, this study failed to provide intensity duration diagrams for the local storms which could have made it possible to predict the return periods of storm events from their intensities and facilitated the derivation of the return intervals of runoff events from the corresponding rainfall events. Its use for runoff prediction is therefore limited.

Modelling runoff potential on the Flats is hampered by lack of runoff data. The only available runoff data is that collected on a $4m^2$ runoff plot at Marigat (BPSAAP 1984) where a one-year data record was analysed to yield an exponential rainfall-runoff relationship, described by the equation

$$Q= P- 35+ 29.06\ e^{0.0107} \qquad \text{(vi)}$$

The data is too deficient to be used for characterising runoff behaviour on the whole Flats as it represents only a 4 m^2 plot and only a one-year period.

Despite the lack of reliable runoff data in the area, a 27-year rainfall record exists at the Perkerrra Irrigation station, as described above and attempts were made to quantify the runoff potential of local rainfall from this data. The experimental methodology had three stages as described under experimental procedure below.

3.2 EXPERIMENTAL PROCEDURE

3.2.2 RUNOFF EXPERIMENTS

These were conducted in the period May to July 1988, on two soils (Eldume and Lamelok) on the Njemps Flats. On each soil, 3 plot sizes 3, 10 and 20 m^2 in area were used. Each plot size was replicated three times though one plot size on each soil had an extra replicate to give a total of 20 plots. The experimental design was completely randomised blocks using soils and sizes as blocks and treatments, respectively.

On each plot, rainfall was applied using a field rainfall simulator developed by Luk and Hamilton (1986). The instrument basically consists of a water reservoir, a 3HP water pump, a plastic hose pipe and 2 pressure gauges. Water was sprayed from a nozzle mounted on a 5m pipe riser supported by a double tripod rope system. This fall height ensured that the terminal velocity of the falling drops approached that of natural rainfall. Desired rainfall intensity was obtained by adjusting the pressure gauges.

The design storm used for the rainfall simulations was 30mm/hr at 45-minute durations which, according to Rowntree (1987) has an annual exceedance probability of 0.95 and a recurrence interval of 1.05 years. It was, therefore, a common Njemps storm whose reliability and probability allow it to be used for planning runoff harvesting.

Each plot was delineated by a 20cm- high iron sheet driven into the ground along the plot edge. Rainfall depth readings were made every five- minutes on 4 rain gauges placed at each corner of the plot. Runoff discharge rate (mls. per. sec.) was measured at 5 minute intervals by use of a Gerlach trough placed at the lower end of each plot.

Before each storm event, undisturbed soil samples were taken at the periphery of each plot and were later analysed for antecedent soil moisture (gravimetric) and bulk density. In addition, composite soil samples were collected from each plot and used for further laboratory experiments.

3.2.3 LABORATORY EXPERIMENTS

These were of two types :

3.2.3.1 SOIL ANALYSIS

The composited soil samples from each plot were analysed for texture through the hydrometer method which is based on differences in settling velocities of different particle sizes. Cation exchange capacity was determined through electrophotometer ionisation of cations obtained through ammonium acetate leaching of soil samples, while other measurements, such as pH, were conducted following the analytical methods described by (Black, 1975).

3.2.3.2 SEEDLING WATER-USE EXPERIMENTS

Seedlings of 4 semi-arid growing species Eucalyptus camaldulensis, Prosopis juliflora, Leucena leucocephala and Cassia siamea, were grown in pots at the Glendon Hall greenhouse until age six months, after which measurements on water use and drought stress resistance were initiated. Water use studies based on the water balance equation (vii) below were undertaken and computations made as follows:

$$IRR = Et + \triangle s + ROFF + S \qquad \text{(vii)}$$

where (IRR) is irrigation watering; (Et) is plant water use; (ROFF) is runoff fom the pots (S) is seepage and ($\triangle$s) is soil moisture content change. In this case both seepage and runoff out of the pots were eliminated and direct evaporation was assumed to be constant for all the pots. The water balance equation thus reduced to

$$\text{consumptive water use} = \text{original weight} - \text{dry weight}. \qquad \text{(ix)}$$

The original weight represents the weight after watering and free drainage had stopped while the dry weight was taken several days later. Their difference, therefore, represented water loss through evapotranspiration.

DATA TREATMENT AND ANALYSIS

The rainfall depth data were converted to intensity at five-minute intervals and plotted into a hyetograph while the runoff data (mls./sec.) were converted into runoff intensity and plotted to yield a hydrograph for each plot. Subtracting the hydrograph from the hyetograph gave the infiltration capacity curve, the level part of which indicated the equilibrium infiltration capacity. Hydrographs were integrated to yield runoff depth, at five minute intervals. Cumulative runoff was plotted against cumulative rainfall for each plot to yield a line whose X - axis intercept estimated the threshold rainfall while its slope estimated the runoff coefficient for each runoff plot as described by Evenari et al., (1982), Emmerisch et al., (1987), and by Hillel (1971). It is clear from hydrological principles that, the relationship during initial stages of infiltration, before equilibrium infiltration is reached is, in fact, curvilinear. However, the very rapid decay of infiltration curves for these soils means that for practical management purposes the assumption of a straight line relationship can be justified.

The derived runoff and its parameters in addition to rainfall and soil characteristics on each plot, were analyzed for variance due to plot size and soil type using the Statistical Analysis System (SAS Institute Inc. 1985) while Duncan's Test (Steel and Torrier, 1980) was used to separate means which were significantly different. Regression equations relating runoff and its parameters to rainfall and soil characteristics were fitted using the Least Squares Method according to the Statistical Analysis System (SAS Institute Inc. 1985).

To quantify runoff potential from rainfall data, information on the rainfall-runoff relationships and runoff parameters, mainly runoff coefficient and threshold rainfall, had to be derived experimentally and then applied to available rainfall data. Though daily rainfall records for 27 years and automatic rainfall records for 10 years exist at the Ministry of Water Development Headquarters (Nairobi), only a record of monthly rainfall and corresponding number of rainy days was available at Toronto. This was the rainfall record on which runoff computations were based and it required the making of several assumptions, as described under computations below. The result was monthly runoff estimates which were totalled to yield annual runoff data.

4.0 RESULTS

4.1 EXPERIMENTS

4.1.1 TEXTURAL AND CHEMICAL COMPOSITION OF NJEMPS SOILS

The results of the analysis of the 2 soils used for this study are given in Table 1. The soils were classified as clay loams, though at 40.3% silt, 39% clay and 20.7% sand, the Lamelok soil was found to be at the clay end of this classification.

The first impression of such a textural class is that the drainage characteristics of these soils are poor and this may explain the high surface runoff rates due to the low permeability of clay. However, information on the dominant clay mineralogy, soil structure and chemistry of these soils is necessary in order to make conclusive inferences on drainage characteristics.

Judging from the texture of both soils, they should have favourable water retention capacities which implies that they are good reservoirs for plant moisture if rainfall is allowed enough time to soak into them. Runoff harvesting and detention has, therefore, a lot of potential benefit on these soils.

All the samples for this analysis were collected from a radius of 20 metres to reduce as much variability as possible but despite this, the results obtained do not represent the whole area as other classes such as silt loam and clay have been reported close to the study sites, especially in Lameluk (BPSAAP, 1984).

The implications of these results for field management is that a lot of caution is necessary when prescribing management operations in the area. Large scale-prescriptions should be replaced by site-specific measures based on a thorough understanding of the characteristics of each area.

The Lameluk soil has a cation exchange capacity almost double that of Eldume. This possibly resulted from the high clay content in the Lamelok soil, implying the presence of more colloids and cation exchange sites in this soil and a possibly higher agricultural potential. The chemical analysis also showed a statistically clear difference of cation composition in both soils, with the Lameluk soil showing a higher level of divalent cations than Eldume, though the latter had decidedly more potassium.

Such a difference in chemical composition can lead to differences in aggregation and dispersion characteristics on both soils though this may not be enough to physically influence hydrological, behaviour as exemplified by the almost identical results discussed below. Another possible influence would be on plant nutrient availability whose significance can only be established through agronomic studies.

Table 1 indicates that both soils are dominated by divalent cations in the exchange complex which differs with observations that Eutric Fluvisols on the Flats have high sodium contents, which causes high dispersion of clay and silt particles on wetting. With the high

Table 1: Main properties of the Eldume and Lameluk soils. Means followed by the same letter are not significantly different.*

Soil	Particle size comp. (%)			Texture class	Exchangeable cations (meq/100g)					pH
	sand	clay	silt		cec	Na	K	Ca	Mg	
Lam.	20.7B	39.0A	40.3A	clay loam	40.00A	0.94A	1.19B	32.35A	3.4A	7.2
Eld.	39.7A	29.6B	30.7B	clay loam	23.47B	0.52B	2.57A	20.40B	1.1B	7.4

* (See appendices 3 and 4 for details of ANOVA).

percentage of both magnesium and calcium in both soils, the possibility of 'sodium induced dispersion 'of clay and silt in both soils is very limited and it may imply the highly variable nature of these soils while calling for more studies to identify the main factors responsible for both sheet and gully erosion on both soils.

4.1.2 RUNOFF YIELD FROM PLOTS

The decision to use three different plot sizes was based on reports that runoff yield per unit area decreases with increase in plot size (Evenari et al., 1982; Oron and Enthoven, 1986) and the aim was to find out whether such a trend exists on the Njemps Flats. All plot sizes behaved differently on both soils (Tables 2 and 3). In Lameluk, both runoff yield and runoff coefficient were highest on the 20 and 3 m^2 plots and very low on the $10m^2$ plots.

The lack of any discernible trend between runoff yield and plot size,in addition to the soil and storm conditions shown in table 2,imply that this was more a result of experimental variation rather than size influence. The runoff coefficient varied strongly with rainfall intensity and antecedent moisture content, both of which were higher on the $20m^2$ and $3m^2$ plots compared to the $10m^2$ ones. Though the differences in these factors were not statistically significant, they were high enough to physically affect infiltration rates and hence runoff yield leading to the differences in runoff yield observed.

Table 2. Analysis of variance due to plot size and Duncan's separation of means of rainfall characteristics, runoff parameters and site factors on the Lameluk soil. Means followed by the same letter are not significantly different.

Plot size	Rainfall parameters		Runoff parameters				Soil Factors			
	P (mm)	Ri (mm/hr)	Q (mm)	Tr (mm)	Rc	Trg (min)	Bd (g/cc)	Ic (mm/hr)	Wd (cm)	Mc (%)
3	20.9A	30.7A	8.3A	4.8A	0.5A	5.7B	1.3A	15.5A	6.5A	14.0A
10	13.7B	20.5A	2.5B	7.0A	0.25A	22.2A	1.3A	14.7A	4.5A	7.5A
20	21.2A	28.2A	9.3A	4.5A	0.55A	7.7B	1.1B	12.4A	3.9A	12.1A

P = rainfall depth, Ri = rainfall intensity, Q= runoff depth, Tr= threshold rainfall , Rc= runoff coefficient, Trg= time to runoff generation, Bd = bulk density, Ic= final infiltration capacity, Wd = wetting depth and Mc = antecedent moisture respectively.

Table 3. Analysis of variance due to plot size and Duncan's separation of means of rainfall and runoff variables and soil properties for Eldume. Means followed by the same letter are not statistically significant.

Plot size	Rainfall parameters		Runoff parameters			Soil factors				
	P (mm)	Ri (mm/hr)	Q (mm)	Tr (mm)	Rc	Trg (min)	Bd (g/cc)	Ic (mm/hr)	Wd (cm)	Mc (%)
3	20.1A	27.6A	7.1A	5.0A	0.45A	6.3A	1.37A	14.7A	5.4A	15.1A
10	21.0A	28.0A	9.2A	6.0A	0.44A	6.7A	1.30A	16.9A	6.4A	11.6A
20	20.1A	31.5A	11.5A	3.9A	0.65A	6.7A	1.33A	12.3A	5.7A	14.8A

Notation is as overleaf.

Despite such an influence, the results obtained from Eldume (Table 3), where all the experimental factors were almost constant, indicate an increase, though not significant, of both runoff and runoff coefficient with plot size. It may well be that for small plots, specific runoff increases with plot size up to a point after which it decreases. Such a trend was observed by Evenari et al., (1982) who attributed it to the fact that water loss along the plot boundary tends to increase with reduction in plot size in a process termed "boundary effect". It is also indicated by the fact that the $3m^2$ plot yielded less runoff than the 20 m^2 one, though rainfall intensity and antecedent moisture were similar in both.

The exact influence of plot size cannot be determined conclusively from the results obtained in this study as it appears to have been masked by rainfall intensity and antecedent moisture. It is commonly believed that runoff coefficient decreases as a function of plot size, and large plots produce higher absolute runoff but lower runoff per unit area (Boers and Ben-asher, 1985; Boers et al., 1986a; Evenari et al., 1982) mainly because they have higher variability which increases infiltration losses (Oron and Enthoven, 1987; Yair et al, 1987; Ben-Asher and Wallick, 1987; Bruins, 1986). However, such observations have normally been made when small plots are compared to small watersheds where variations in infiltration rates are large and no records of studies investigating runoff behaviour on small-sized plots are available. This study, therefore, needs to be repeated under controlled variability to establish the real influence of plot size, but for the purposes of the present project, effects of plot size on specific runoff yield will be disregarded.

Table 4. Analysis of Variance due to soil and Duncan's separation of runoff parameters for Eldume and Lameluk. Means followed by different letters are significantly different at the 0.05 level.

Soil	Parameter				
	Q (mm)	TR (mmO	Trg (min)	Ic (mm/hr)	Wd (cm)
Lameluk	6.9A	6.4A	12.1A	11.5A	5.1A
Eldume	8.0A	4.3A	5.9B	16.4A	5.7A

Q=runoff yield, Tr= threshold rainfall, Trg= time to runoff generation, Ic= final infiltration capacity and Wd= wetting depth.

4.1.3 HYDROLOGICAL BEHAVIOUR OF THE ELDUME AND LAMELUK SOILS

Table 4 implies that there is no significant difference in runoff yield from both soils. This is intriguing in light of the differences, though not statistically significant, observed in their textural composition. Broadly speaking, this observation can be explained by the fact that both soil and site characteristics were observed to exert very little influence on runoff generation in the area; and the latter was mainly a function of storm characteristics. This explains the apparently higher runoff yield from Eldume despite the fact that it had a higher infiltration capacity than Lameluk.

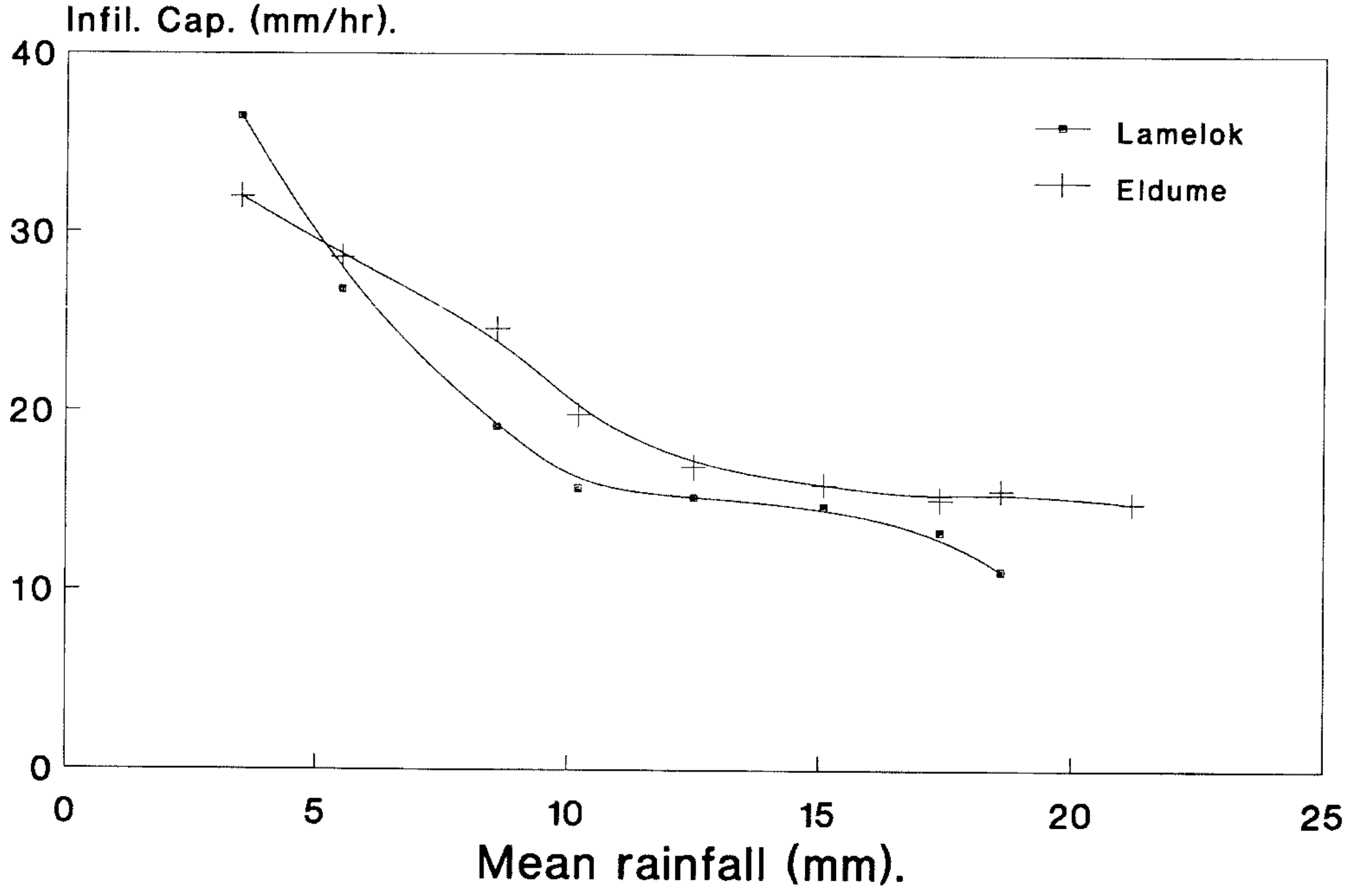
The high threshold rainfall and time to runoff in Lameluk could have resulted from high initial infiltration rates created by slightly more cracking in this soil. Though no data are available, differences in cracking intensity were observed on both soils and they were associated with differences in surface seal thickness. The seals on Lameluk were observed to be thicker than those on Eldume and this could have led to the differences observed in cracking. Such observations are also cited by BPSAAP (1984) for Lamelok. The influence of cracking on initial infiltration has been described by Ben-Hur _et al_; (1985) and it is likely that high clay content caused more cracking in Lamelok, which explains its high initial infiltration as apparent in fig. 3 and the high threshold rainfall loss shown in table 4.

Figure 3 shows the average infiltration capacity curves for both soils. This may have been the single most important result of this study as it gives an insight on how water behaves on both soils. The most striking feature is the almost gentle decay of the Eldume curve compared to the sudden decay of the one for Lameluk. This difference could have resulted from possible sealing of the surface cracks discussed above, which led to sudden drops in infiltration capacity. The 5mm/hr difference in infiltration capacity between both soils is not significant statistically nor is it strong enough to physically influence runoff generation. It therefore explains the almost similar runoff yield from both soils.

Both curves show equilibrium infiltration capacities of 16.4 and 11.5mm/hr for Eldume and Lameluk, respectively, measured at the end of storms exceeding 25mm/hr intensities and 45-minute duration. The lower infiltration capacity of the Lamelok soil is believed to result from the influence of high clay content which could have reduced its permeability to water. On the other hand, the higher sand content of Eldume soil possibly led to higher infiltration capacities

It was not possible to isolate evaporative losses during the storms, as a result of which the infiltration capacities shown in Fig.3 could be slightly inflated. Despite this, they are typical of poorly managed grazing land as described by Dunne and Leopold (1978). The equilibrium infiltration capacities of 16.4 and 11.5mm/hr indicated in Fig. 3 indicate that, any storm not exceeding similar intensities will need a duration greater than 45 minutes to form runoff on the Flats. According to Rowntree (1988), the mean intensity of one-hour duration

Fig.3: Infiltration capacity curves for Eldume and Lamelok



storms exceeding 10mm on the Njemps Flats is 14.2mm/hr. When this figure is compared with the above infiltration capacities it becomes clear that such storms can generate runoff easily in the area. Such storms have a cumulative frequency of about 50% which implies a very high frequency of runoff events and since they contribute up to 60 % of the annual rainfall (Rowntree, 1988) the potential runoff yield from them is quite high.

In the present study, runoff generation was also observed from storms of less than 10mm depth where sufficient intensity was attained. It is possible that the storms with less than 10mm depths, which Rowntree (1988) categorised as 'ineffective' but which contribute more than 200mm of annual rainfall on the Flats, do generate runoff where sufficient intensity is gathered. They should, therefore, be incorporated in runoff prediction models, which would also have the effect of raising the runoff frequency discussed above.

4.1.4 RAINFALL RUNOFF RELATIONSHIPS

A major objective of this study was to establish the relationship between rainfall and runoff on the Flats. This was achieved by plotting total runoff from a plot against the corresponding rainfall depth. Tables 5 and 6 show the relevant regression equations while Figs. 4 and 5 are their graphical presentations. From the equations and graphs, it is apparent that runoff is linearly related to rainfall depth and intensity, which agrees with other observations (Frasier et al., 1979; Emmerisch et al., 1987). It however disagrees with the exponential rainfall runoff relationship (equation (v)) obtained from the $4m^2$

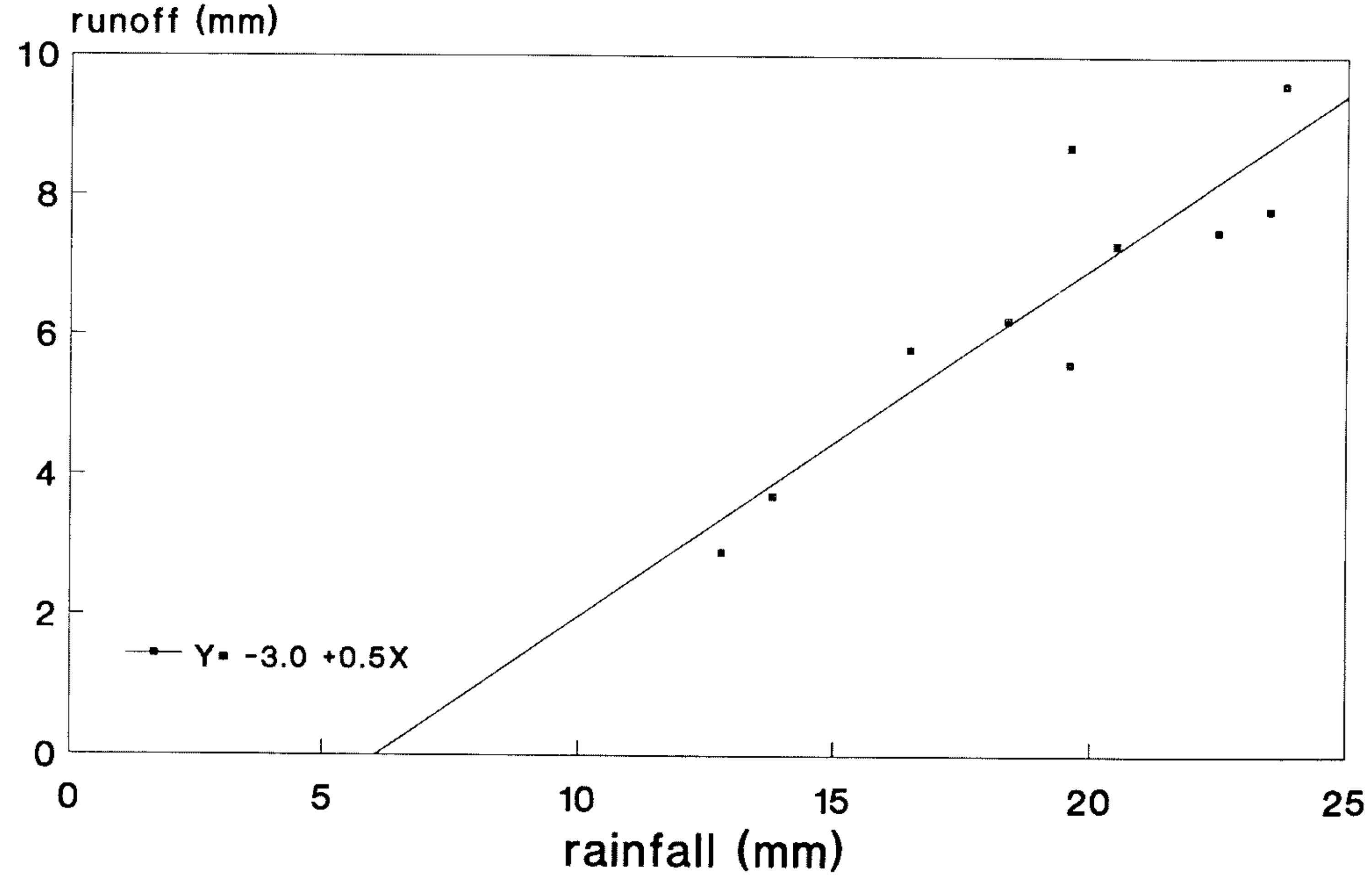
runoff plot operated by BPSAAP in the study area. This difference most likely resulted from the high variability met in this study as 20 different plots and two different soils were used compared to the BPSAAP plot which represented only one soil and an area of 4 m^2.

The relationship for Lameluk shows a big scatter which explains the low correlation coefficients of the regression equation. The scatter possibly resulted from variations due to antecedent moisture and rainfall intensity since their incorporation in multiple regressions improved the correlation coefficients (Tables 4). Rainfall depth, intensity and antecedent moisture accounted for up to 90% of the variation observed in runoff yield on this soil. Such results are typical of overgrazed compacted soils where runoff is almost purely a function of rainfall depth (Dunne and Leopold, 1978; Sharma, 1986).

The rainfall-runoff curves for both soils (figs. 4 and 5) have slopes of 0.5, which is the mean runoff coefficient on the Flats. Such a runoff coefficient implies that more than 50% of any effective storm forms runoff on the Flats and it describes the high runoff rates and erosional severity in the area. It can be explained by the generally poor vegetation cover and low infiltration capacities which lead to low soil moisture storage by both soils.

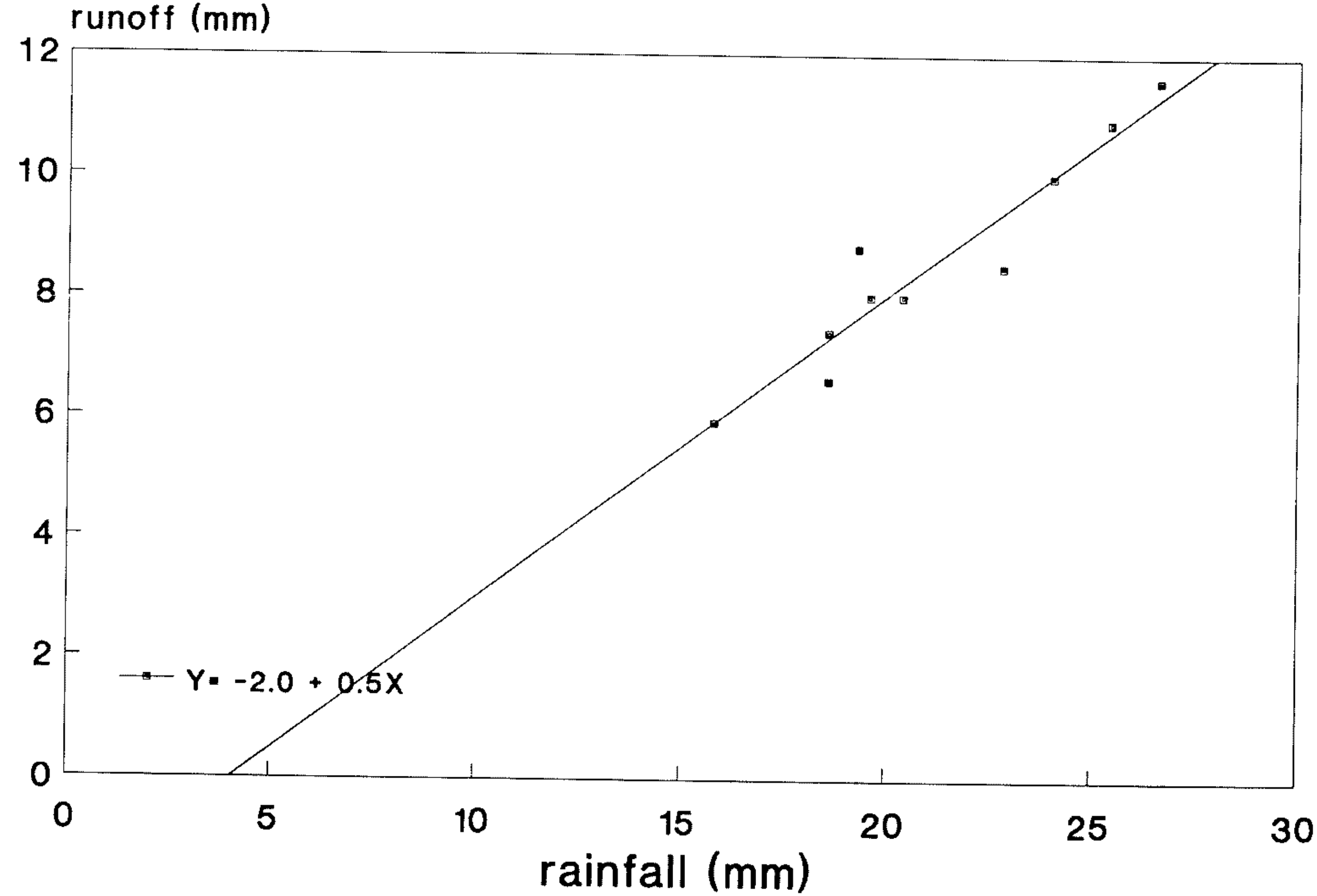
Some reports (Kenya Soil Survey, 1982) describe the Njemps soils as being moderately well drained, meaning that waterlogging is absent. However, with such a high runoff coefficient, most of the rainfall runs off the surface of these soils rather than draining through them. This is also supported by the low hydraulic conductivities of both soils as

FIG. 4: Rainfall-Runoff relationship for Lameluk.



r-sq=0.81; P>F= 0.001; n= 10.

Fig 5. Rainfall runoff relationship for Eldume.



r-sq= 0.91; P>F= 0.006; n= 10.

Table 5: Regression equations relating runoff and runoff parameters to rainfall and site characteristics in Lameluk .

Parameter	Equation	r^2	cov	P>F
Runoff depth				
	Q= -3.0 + 0.5P	0.81	32.78	0.001
	Q= 9.8- 0.39 Mc	0.66	24.8	0.004
	Q= 1.96+ 0.69P- 0.1Ri- 0.06Mc	0.9	25.5	0.01
Threshold rainfall				
Tr	Tr= 11.5- 0.22 Ri	0.44	24.8	0.004
	Tr= 9.8 - 0.4Mc	0.66	24.8	0.004
	Tr= 12+0.54P- 0.40Ri- 0.4Mc-0.1S	0.8	24.8	0.06
Time to runoff generation				
Trg	Trg= 43.7- 1.2 Ri	0.6	50.69	0.006
	Trg= 33.6- 1.9 Mc	0.8	37.37	0.0005
	Trg= 39.0- 1.48Mc- 0.39 Ri	0.83	37.1	0.002

Table 6: Regression equations relating runoff and runoff parameters to rainfall and site characteristics for Eldume

Parameter	Equation	r^2	COV	P>F
Runoff depth				
	Q= -2.0 + 0.5 P	0.91	18.5	0.006
	Q= 0.53 (Ri-6.7)	0.77	19.3	0.0009
	Q= 7.7- 0.09Mc	0.02	38.8	0.7
Threshold rainfall				
Tr	Tr= 9.6- 0.34Mc	0.62	23.79	0.007
Tr	Tr= 11.7- 0.28Mc- 0.1Ri	0.56	27.27	0.02
Time to runoff generation.				
Trg	Trg= 12.5- 0.48Mc	0.93	9.55	0.0001

demonstrated by the low rainfall penetration depths. Maximum rainfall penetration depth observed in this study was 8cm after 45 min.; 30mm/hr-intensity storms had fallen and both hydrological characteristics tend to imply poor drainage properties. Such observations may again point to very high variability on both soils, thus demanding a lot of caution in prescribing management operations based on available reports.

4.1.4 INFLUENCE OF RAINFALL CHARACTERISTICS ON RUNOFF PARAMETERS

According to Fig. 6, threshold rainfall has a negative linear relationship with rainfall intensity upto intensity levels of 25mm/hr beyond which no relationship exists. This possibly reflects the threshold level kinetic energy necessary for complete sealing of the soil surface. At high rainfall intensities, a little rainfall is enough to supply this energy while more is needed at low intensity, and below certain thresholds, sealing may not occur. In similar studies, runoff generation was observed to cease when the rainfall energy was removed by screens (Moldenhauer and Long, 1982; Hudson, 1981), and by mulches (Morin and Benjamin, 1971) which indicates the importance of rain-drop energy in runoff generation. It is therefore apparent that rainfall intensity plays a major role in determining the effectiveness of storms on the Flats and this effect should be reflected in any runoff prediction models for the area.

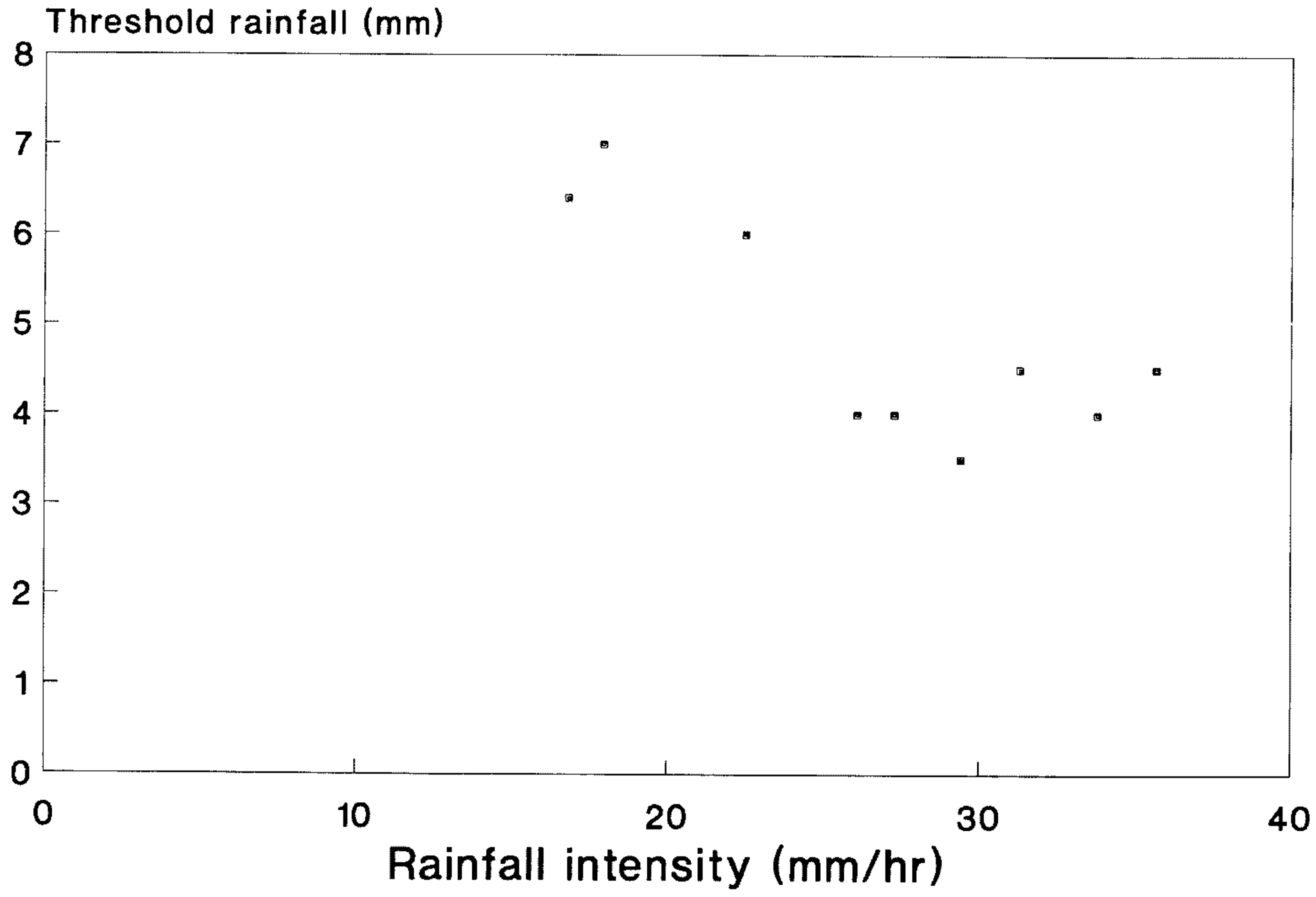
On the other hand, there was no distinct relationship between rainfall intensity and both runoff threshold and time to runoff in Eldume. This may imply either a very high variability of the surface properties or that rainfall-induced sealing plays a minor role in runoff generation on this soil. More study of the surface response of this soil to raindrop action is necessary.

4.1.5 THE INFLUENCE OF ANTECEDENT MOISTURE

In Lameluk, runoff yield increased linearly with antecedent moisture (Fig.7). Similar relationships were found between this factor and both threshold rainfall and lag time to runoff generation (Figs 9 and 10). This influence of antecedent moisture possibly resulted from the fact that in already wet soils, the microporosity is already filled with water and the only infiltration possible is through macropores which are quite limited in soils dominated by clay and silt. Infiltration losses in Lameluk under high antecedent moisture are therefore expected to be minimal, which would lead to high runoff yield, as observed. Such findings were also reported by Henninger et al. (1976) and by Ahunja et al. (1976) who found strong correlations between soil moisture saturation deficit and runoff yield.

Many soils dominated by swelling clays have completely impervious surface seals when wet (Ben-Hur et al., 1985). This has the effect of reducing both depression storage and initial infiltration through cracks. The opposite applies in dry soils where the wide cracks lead to high initial infiltration and depression storage losses, both of which increase the threshold loss and subsequently reduce the runoff coefficient.

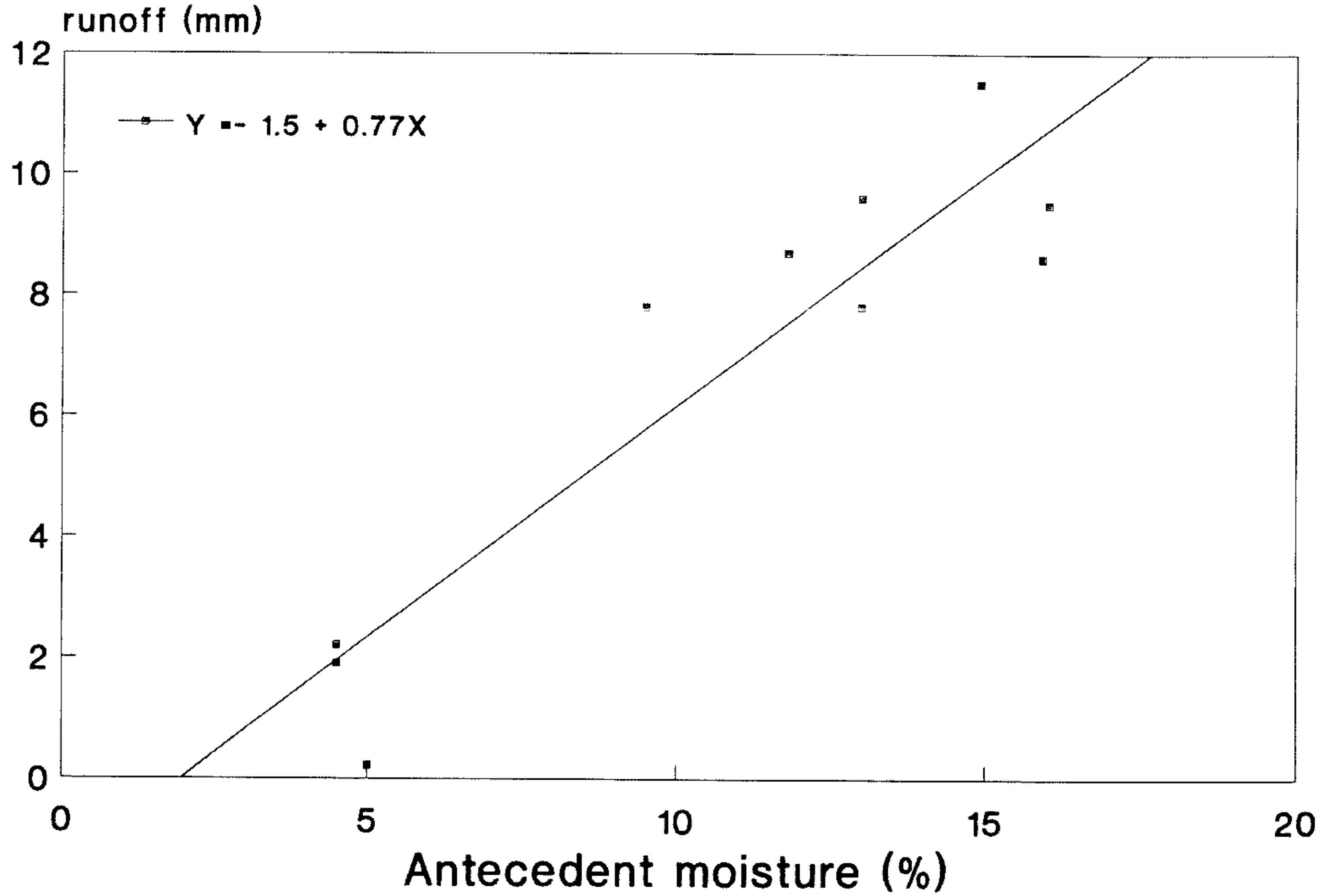
Fig. 6: Threshold rainfall- rainfall intensity relationship for Lameluk.



No relationship beyond 25mm/hr intensity

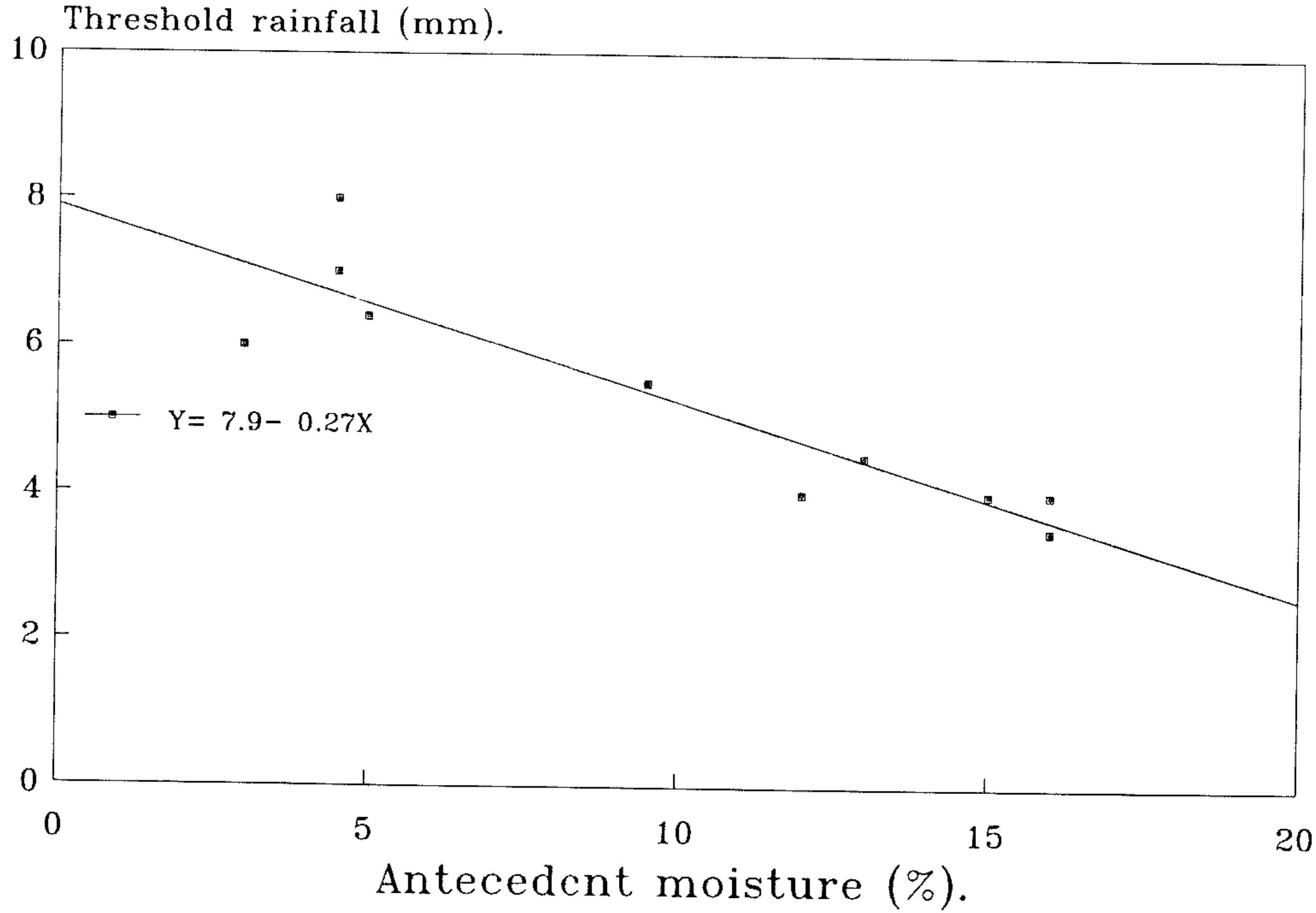
No discernible correlations were found between antecedent moisture and either runoff yield, threshold rainfall or time to runoff generation in Eldume. This possibly resulted from experimental errors as the antecedent moisture in Eldume was almost constant for all the ten rainfall simulations. This, coupled with the relatively high sand content of this soil, made it impossible for the effects of antecedent moisture on runoff parameters to be picked out. It is, however expected that these parameters may not be significantly affected by antecedent moisture since infiltration rate on this soil remains fairly high as a result of the sand.

Fig.7: Relationship between antecedent moisture and runoff on the Lameluk soil.



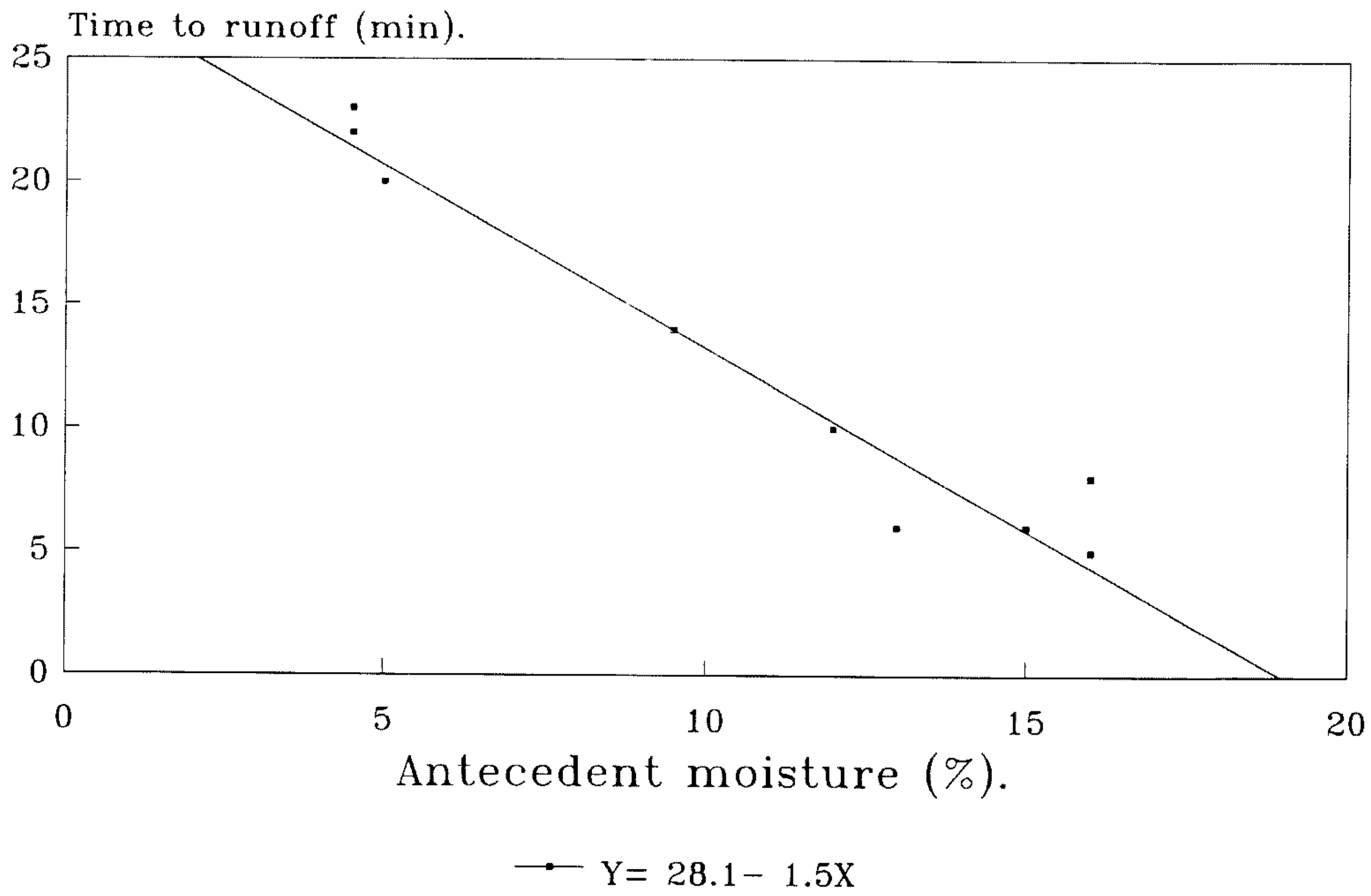
r-sq= 0.85; P>F= 0.004; n= 10.

Fig. 8: Regression of threshold rainfall on antecedent moisture in Lameluk.



r-sq= 0.82; P>F= 0.004; n= 10.

Fig. 9: Regression of time to runoff on antecedent moisture in Lameluk.



r-sq= 0.93; P>F=0.0005; n=10.

4.2 CONSUMPTIVE WATER-USE BY SEEDLINGS

Table 7 shows the daily water use for the 4 tree species, accompanied by their height at age 9 months. Since this was a greenhouse experiment, the water use data does not represent actual field conditions and it is expected that the field water-use rates are more than double those shown in table 7. Despite this, the data gives a good insight of how the 4 species behave with unlimited supplies of water. It is apparent that daily consumptive water use by the 4 species ranges from 0.56 litres for Eucalyptus camaldulensis to 0.18 litres for Cassia siamea at age 7 to 8 months. This implies that under conditions of unlimited water supply, the 4 species would consume not less than betweem 66 to 203 litres of water in the first season in the greenhouse. Owing to the high evapotranspiration demands on the Njemps Flats, estimates of seasonal water consumption at double the above rates may be conservative.

Another feature of the results is the high growth rates of both the Eucalyptus and Leucena. A height of 2 metres in less than one year shows that under unlimiting moisture conditions, both trees can yield good volumes of wood and fodder in addition to supplying much desired soil cover in very short durations. They therefore seem ideal for rehabilitation of wasted environments. Despite this, it is doubtful whether such growth rates can be maintained under field conditions in the Njemps Flats as both tree species were observed to always exhaust the moisture reservoir in their soils and wilted each third day after watering. Their ability to withstand short-term moisture stress is questionable. On the other hand, both Prosopsis and Cassia never wilted at any time, possibly due to their low water consumption rates thus seeming to be well suited for survival on the Flats.

Table 7: Tree Water use and growth data. Means followed by the same letter are not significantly different.*

Species	Daily water-use (lts)		Mean height (m)	
Eucalyptus	0.56	A	2.81	A
Leuceana	0.41	B	2.75	A
Prosopsis	0.17	C	1.76	B
Cassia	0.16	C	0.67	C

* See appendices 5 and 6 for details of ANOVA.

4.2 COMPUTATIONS

4.2.1 GENERAL REMARKS

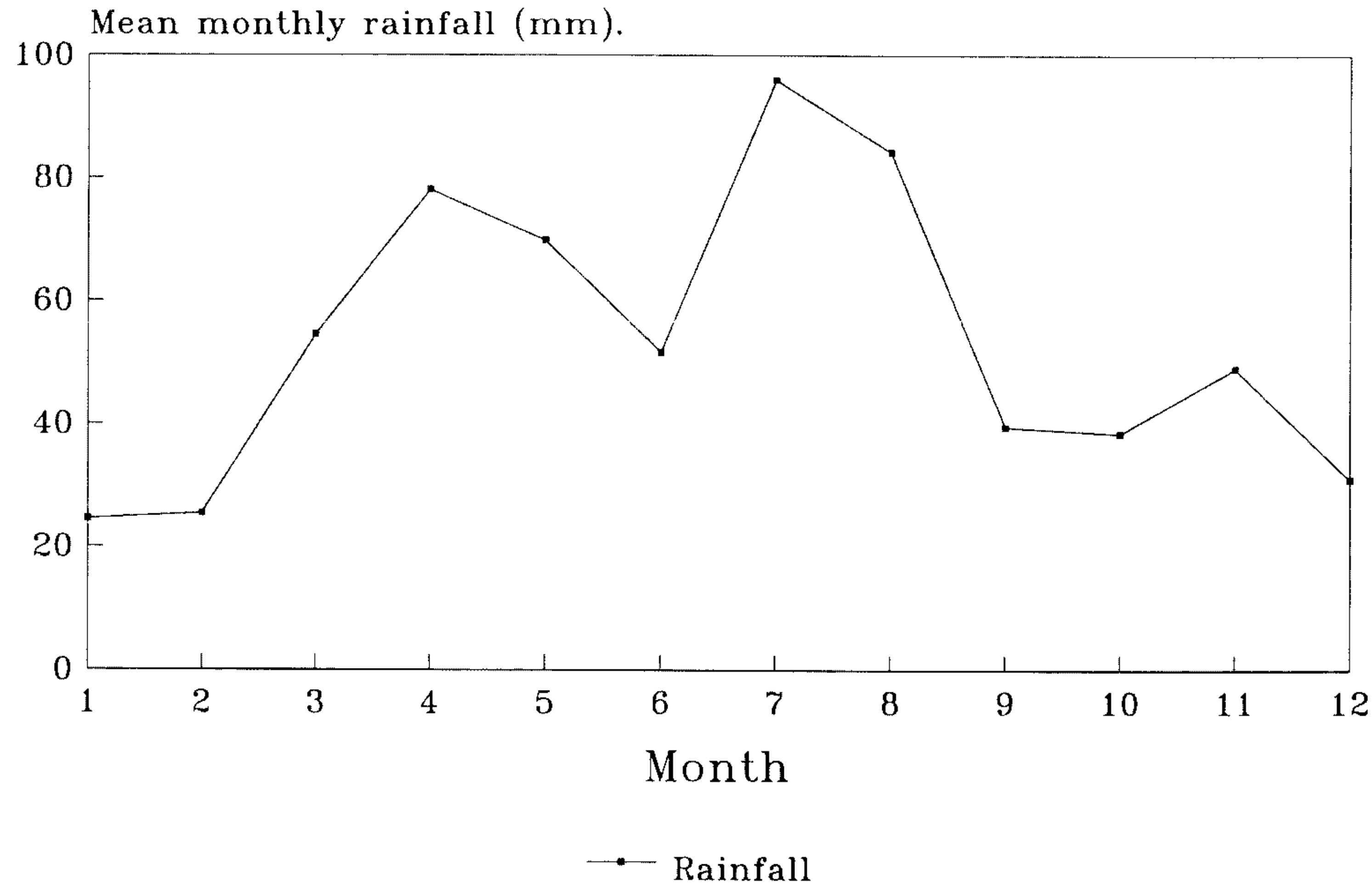
This section deals with the application of the runoff parameters and correlations derived from the field study to natural rainfall data to obtain estimates of runoff potential and other related information.

4.2.2 ANNUAL RUNOFF POTENTIAL ON THE FLATS

Following the continuity equation, runoff is a function of rainfall inputs, interception, change in soil moisture storage, evapotranspiration and deep seepage losses. Interception, soil moisture storage and deep seepage losses depend on soil type and surface conditions both of which were observed to exert very weak influences on runoff on the Flats as exemplified by the high runoff coefficients, low threshold rainfall and infiltration capacities observed in the field study. As well, the strong rainfall runoff relationships obtained imply that runoff generation on the Flats is predominantly a function of storm characteristics. Monthly runoff can therefore be confidently predicted from the corresponding monthly rainfall probabilities.

Should the above be the case, Fig. 10, which shows mean monthly rainfall on the Flats implies that the region is quite well suited for runoff harvesting as each month is capable of receiving some rainfall. Rowntree, (1988) stated that the probability of 10mm being exceeded on the Flats ranges from 0.29 in the driest month to 0.86 in the wettest. However, if a lower runoff threshold as was derived in this study is

Fig. 10: Mean monthly rainfall on the Flats.



adapted, the probability of monthly rainfall rises higher. Such a high probability of effective storms implies that runoff harvesting is not only feasible but reliable on the Flats.

To quantify the runoff producing potential of natural rainfall on the Njemps Flats, the linear regression model described by Oron and Enthoven, (1987) was applied to monthly rainfall data. Before a storm (P) can generate runoff, it must satisfy the threshold rainfall (A). Any excess rainfall forms runoff as a function of the runoff coefficient (B). Thus

$$Q = B\ (P - A) \qquad \text{vii.}$$

In a month, the total threshold rainfall (MA) was derived by multiplying (A) by the number of rainy days (D) and the total monthly runoff yield (MQ) was given by

$$MQ = B\ (MP - PA). \qquad \text{viii}$$

where (MP) is total monthly rainfall. The main assumption in these computations was that all storms in a month were capable of yielding runoff. This may have over-estimated monthly threshold loss by assuming that a threshold loss was incurred by all storm events and by so doing, it could have under-estimated monthly runoff. However, it was assumed that such an error would cancel out in the long run. It was also assumed that all rainfall exceeding the threshold value yielded runoff, though this does not always happen in nature as the intensity of a storm changes constantly. However, owing to the short-duration nature of storms in the area, it was assumed that the segments of the Njemps storms when intensity is below the infiltration capacity are quite short. The validity of this statement is supported by the findings of Rowntree (1988). According to her analysis, the highest intensity ever recorded for a 30-minute duration storm on the Flats was 80mm/hr. This storm lasted for 5 hours with a total depth of 82mm, 40mm of which were recorded in the first half hour, 35mm in the second half hour and 7mm in the remaining 4 hours. It is therefore quite unlikely that high intensities will be maintained for long durations as intensity characteristically drops markedly after the first half hour. Despite such an observation, this computation would be greatly improved by deriving the cumulative frequencies of the intensities of various depth categories of the Njemps storms.

Results of field studies (Fig. 9) showed that both the threshold rainfall and runoff coefficient on the Flats are strongly influenced by antecedent soil moisture. To accomodate this influence, two categories of both parameters were used depending on antecedent conditions. A high antecedent moisture content was assumed in a month with more than 10 rainy days and values of 0.6 and 4 mm were used for runoff coefficient and threshold rainfall, respectively. Low antecedent conditions were assumed for months with less than 10 rainy days and values of 0.4 and 7mm were used for runoff coefficient and threshold rainfall, respectively.

Computed monthly runoff was totalled to give annual runoff yield which was plotted against corresponding annual rainfall total to give an annual rainfall runoff curve (Fig. 11). The curve is based on 27 years of data and it is described by the equation

$$Y = 0.4\ (X - 250) \qquad \text{ix}$$

where Y is annual runoff total, and X is total annual rainfall. The curve bears a close similarity to those obtained for individual storm events in the field studies (Fig 4 and 5) and from it, the following can be inferred about annual runoff yield on the Flats.

--that runoff is linearly related to rainfall depth on an annual basis,

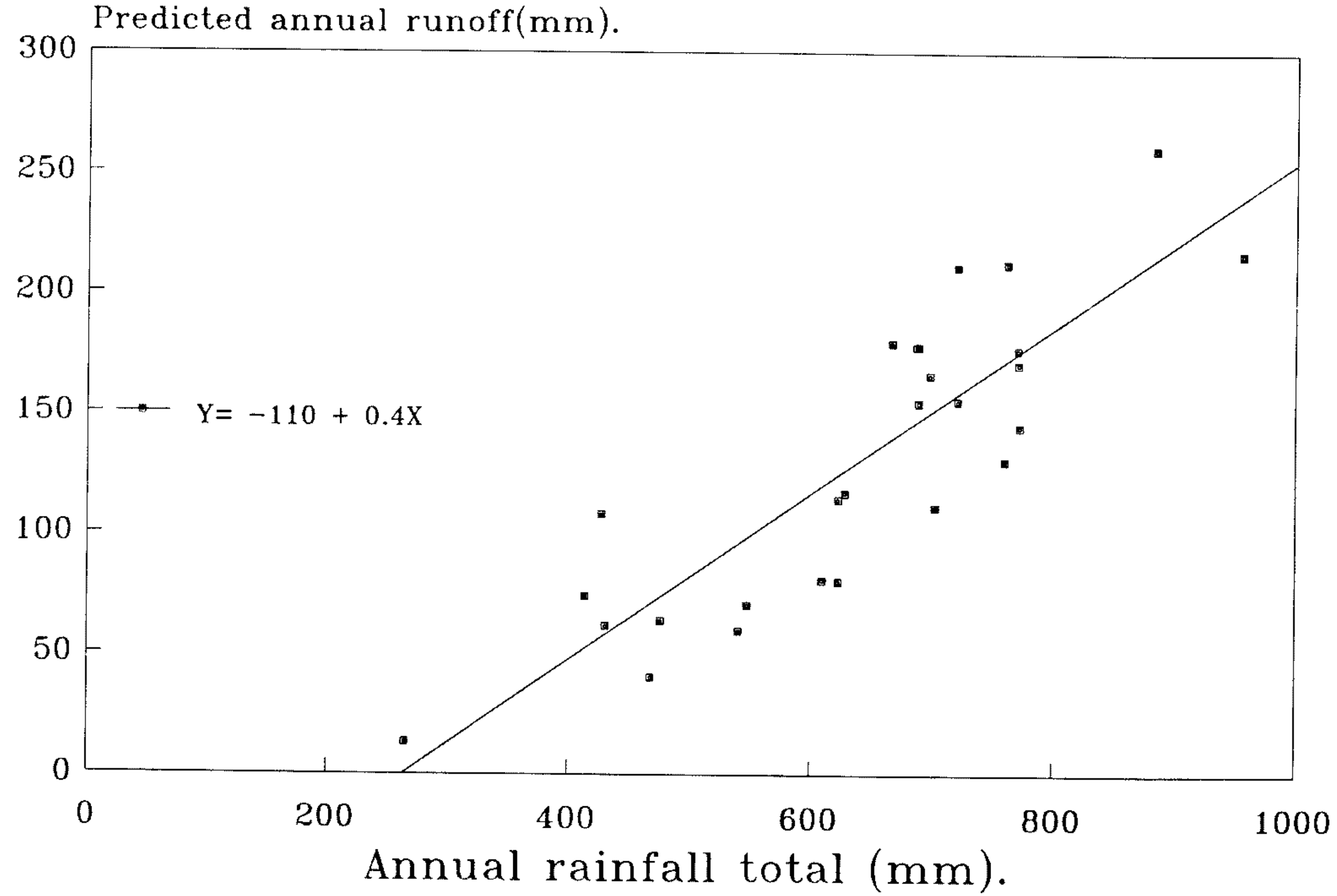
--that the mean annual rainfall of 640mm is capable of yielding about 130mm of runoff in a season,

-- about 250mm of annual rainfall is lost as threshold rainfall on the Flats, and

--the annual runoff efficiency on the Flats is about 40%.

Fig. 11 shows a big scatter which explains the low correlation between annual rainfall and runoff. This was a result of the influence rainfall distribution, as two months with equal rainfall depth but different number of rainy days had different runoff yields. Inclusion of a factor of rainfall distribution (number of rainy days) in the rainfall-runoff model raised the correlation coefficient to 0.88, showing the strong effect of this factor due to its strong influence on antecedent moisture. The latter was found to strongly influence storm effectiveness.

Fig. 11: Annual rainfall–runoff relationship on the Flats.



R–sq= 0.82; P>F= 0.0001; n= 26.

The remaining 12% of the runoff variability was most likely contributed by rainfall intensity whose effects could not be taken into account in computing runoff from monthly rainfall data and these observations bear out the observation that runoff yield can very confidently be predicted from information on the depth, intensity and frequency of local storms.

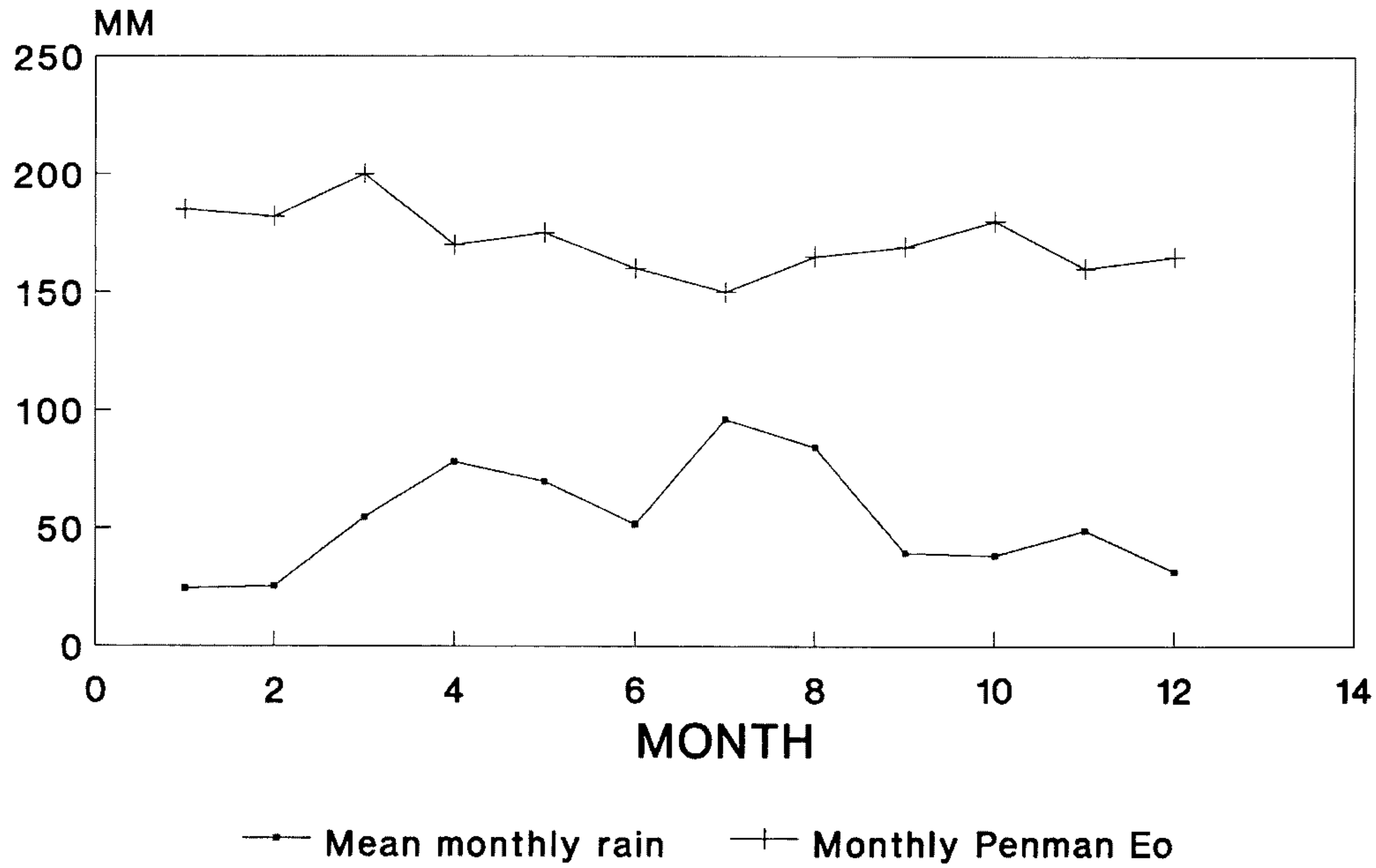
The apparent disparity between the seasonal runoff coefficient of 40 % observed (Fig. 11) and the 50 % observed in the field studies (Figs. 4 and 5) most likely resulted from an over-estimation of monthly threshold rainfall by assuming that all storms in a month incurred an equal threshold rainfall. In practice, only one big storm may fall in a month, followed by others which do not even approach the minimum threshold rainfall. It is therefore possible that these computations over-estimated monthly threshold rainfall at the expense of monthly runoff.

4.2.3 MOISTURE DEFICIT AND OPTIMUM PLOT SIZE DETERMINATION.

Runoff harvesting is applied to supplement rainfall in areas with a moisture deficit. The determination of the ideal plot size to harvest enough runoff for a seedling in a season must therefore start from computations of both the moisture deficit and runoff potential.

According to the Agroclimatic zoning system (Kenya Soil Survey, 1982), the Njemps Flats falls in zone V-2 with a Moisture Availability Index (rainfall/potential evaporation) of 25-40%, which is typically semi-arid with a large moisture deficit. Fig. 12 is an ambrothermiic diagram for the area which was fitted by imposing Penman evaporation

FIG. 12: AVAILABLE MOISTURE DEFICIT ON THE NJEMPS FLATS (27 YRS.MEAN).



estimates (BPSAAP, 1984) on monthly rainfall data. The diagram indicates a huge moisture deficit ranging from 960 to 1660mm per annum. Mean monthly rainfall never exceeds potential evaporation throughout the year. mean monthly rainfallhas exceeded potential evaporation in only 12 instances in 26 years of record taking (BPSAAP, 1984). This implies that even in the wettest month, tree growth on the Flats is always under stress which, no doubt, constraints biomass productivity.

The huge moisture deficit is aggravated by the high runoff coefficients in the area which result in more than 60% of the effective rainfall being lost as runoff with very little being stored in the soil for plant use. The little that infiltrates is picked up by evaporation almost immediately while the remainder is held in the soil at tensions which make it almost unavailable to plants. This makes the moisture deficit more acute than it appears in Fig. 12 and it justifies the conclusion that some form of runoff harvesting is neccessary for successful revegetation of the Flats' soils (Pratt, 1964).

The moisture deficit estimate on the Flats indicates the amount of water that must be supplied to supplement rainfall in the area. Since tha annual runoff potential is also known, both can be used to compute the plot size that can collect enough water to satisfy this deficit. This is so, assuming that the optimum plot size is the factor by which the runoff potential will be multiplied to equal the moisture deficit. A problem arises in that a microcatchment plot size cannot be altered within the season while the runoff yield keeps on fluctuating following the monthly rainfall totals. A plot size which will collect nearly optimum amounts of water at all seasons is therefore necessary.

However, with such a plot size, some surplus runoff will exist in the wettest month followed by a deficit in the dry season.

In computing the optimum plot size, several authors have used the formula

$$CCA = \frac{\text{Crop water requirement - Design rainfall}}{\text{(Design rainfall * Runoff coefficient)*Efficiency Factor}} \quad (x).$$

(CCA) is the catchment-to-cropping area ratio, while the efficiency factor is assumed to represent the effectiveness of the water-harvesting structure in collecting the generated runoff. The design rainfall was normally represented by a storm whose probability of occurrence was greater than 50% and from which runoff was therefore guaranteed.

While the above formula appears mathematically sound, it has several operational shortcomings. By multiplying the design rainfall by the runoff coefficient, the formula assumes that all of the design rainfall forms runoff and therefore disregards the threshold rainfall loss which can be quite high, as on the Flats. This can result in an overestimation of the runoff potential leading to the use of inefficient plot sizes. Instead of a factor of design rainfall, its effective fraction could be used to give more realistic estimates of runoff potential as it is almost certain that all of it forms runoff.

As well, the crop water requirement adopted underestimates the real water use as it is below either potential or actual evaporation. Crop water use is compounded by evaporation which always accompanies transpiration and it is not normally easy to separate the two. In addition, no data on consumptive water use by arid-growing seedlings are available and it is not clear what value was attached to this factor. The applicability of this term in the above formula is therefore questionable.

To compute the optimum plot size for the Flats, the above formula was by substituting effective rainfall for design rainfall and potential evaporation for crop water requirement. The result was equation

(xi) below

$$CCA = \frac{Eo - P}{\left[\sum_{i=1}^{24}\sum_{j=1}^{n}(MQ)\right] * 0.037} \qquad xi$$

where Eo and P are the 27-year averages of potential evaporation and precipitation respectively while the denominator term is the 27 years predicted average runoff potential. This formula simply reduces to

$$CCA = \frac{\text{Annual Moisture Deficit}}{\text{Annual runoff potential}} \qquad xii$$

Both the runoff potential and moisture deficit were computed through the stages described above and the values obtained are likely to represent real field conditions as compared to those used in equation (x) above. This formula was solved for the Njemps Flats to yield an optimum plot size of between 7 and 12 m^2 and the reliability of such values will be discussed below.

5.0 DISCUSSION

5.1 RELIABILITY OF DERIVED VALUES AND CONCLUSIONS

It has often been argued that data from rainfall simulators should be applied for large-scale field prediction operations with a lot of caution as they rarely replicate natural storms. This is because the simulated rainfall occurs almost at constant intensity, unlike natural storms where intensity changes frequently both in space and time. Application of raindrop energy at a constant rate is likely to bring differences in rainfall impact on the soil surface and hence differences in infiltration and runoff generation.

The simulated storms also tend to have high evaporative loss as they occur at periods of intense solar radiation compared to natural storms which occur either at night or under clouds when evaporation is quite low. Navar (1988) reported evaporation rates during simulated rainfall to be about three times the normal rates and this may lead to an overestimation of the soil moisture storage component in the water balance of the simulated storm.

The terminal velocity of the simulated storms is also often lower than that of natural ones. As a result, soil surface response under simulated rainfall could be slightly different from that under natural storms. As such, where the aim is to characterise the site response to rainfall, simulators cannot give precise information as the data obtained cannot fully replicate those under natural conditions.

Despite such shortcommings, rainfall simulators have been found to be quite reliable. Morin et al. (1984) gave an exhaustive treatment of data obtained from simulators and concluded that they reliably predict natural runoff in the Negev Desert. This was followed by Stroosnijder and Hoogmoed (1984) who strongly advocated their use for research in the Sahel. Yair (1983) also found close agreement between results from both rainfall simulation and natural rainfall and such observations in addition to those of others (Bryan, 1973; Dunne and Black, 1970) imply that the use of this technique for characterising natural conditions is not far-fetched.

Regarding the reliability of the data derived from rainfall simulators on the Njemps Flats both the runoff coefficient and threshold rainfall values for the Flats derived in this study were found to closely agree with those derived on nearby sites under natural rainfall (Sutherland, 1988; BPSAAP, 1984) and are not different from those derived for the West African Sahel (Wright and Bounkougou, 1986). Rainfall simulators can therefore closely estimate natural runoff parameters on the Flats. In addition to these findings, it should be noted that in actual field practice, management decisions will be made whether or not firmly based field recommedations have been developed, and information to allow this is normally lacking. For this reason, the utility of a model based on the interpretation of any field-collected data cannot be overemphasised.

5.3 RUNOFF PREDICTION ON THE FLATS

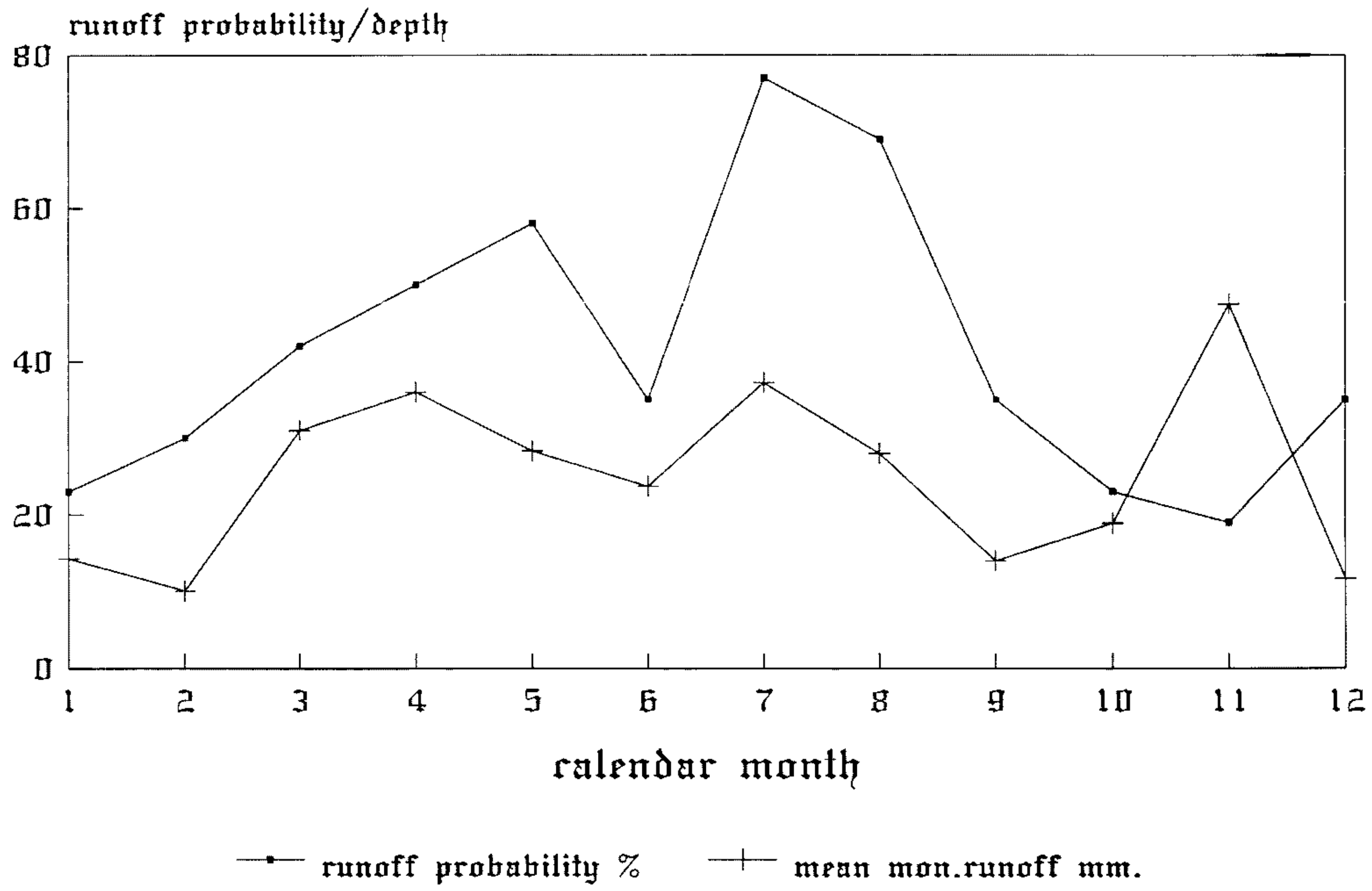
In the field study, simple proportional relationships between rainfall and runoff were developed which could predict runoff to acceptable levels of accuracy. However, the large scatters found in relationships require much care in applying such models in large-scale field operations because of the high natural variability. In addition, tests to characterise runoff on both soils should be designed to eliminate major sources of variation such as antecedent moisture, size, surface porosity and vegetation, which was not possible in this study due to various limitations.

The same study revealed that rainfall characteristics, mainly depth, intensity and frequency through its influence on antecedent moisture, accounted for more than 90% of all the variation in runoff yield suggesting that site factors play a very small role in influencing runoff yield from rainfall. The implication, as already stated above, is that, runoff can be predicted from the depth, intensity and distribution of local storms. For this reason, the multiple regression models in tables 4 and 5 as well as equation (xi) can give more realistic runoff estimates, compared to the simple linear regression models.

Another implication of the above finding is that it is impossible to predict runoff beforehand. With 90% of all runoff variability being explained by rainfall characteristics, one would have to predict these in order to predict runoff yield thus making it impossible to anticipate expected runoff yield before a storm occurs. This being the case, the next best alternative is to derive the probability of occurrence of monthly runoff events from rainfall records, which, no doubt, can be quite useful for management purposes. Using 10mm as the minimum depth needed to generate runoff on the Flats, Rowntree (1988) showed the monthly runoff probability to range from 0.2 to 0.95 in the driest and wettest month, respectively. From this study using runoff parameters derived in the field experiments, and, monthly rainfall data, monthly runoff probability was shown to range between 0.19 and 0.77 in the driest and wettest months, respectively (Fig. 13) and no doubt these values would have been more precise if data on individual rain storms and their intensity had been available. Despite this, the close agreement between the above figures and those derived by Rowntree (1988) adds further credibility to the methodology used in this study.

According to fig. 13, the probability of runoff increases into the growing season until it peaks in July which shows that the probability of runoff occurence in the crucial period of tree seedling establishment on the Flats is quite high. Runoff harvesting is therefore a reliable support technique for tree growing in the area. Despite this, a dry season exists between October to February when monthly runoff probabilty is low despite some occasional storms. Such a drought is only severe for small seedlings which rely entirely on rainfall for their water needs as opposed to mature trees which are believed to tap deep water layers buried beneath the soil surface in the area. As well, since very little runoff is expected during this drought, measures to raise the runoff coefficient to facilitate runoff generation from any incidental storms should be applied. This would raise the probability of runoff generation and thus improve seedling survival in the area. It, however, needs to be analysed critically in relation to the expected returns.

Fig.13: Mean monthly runoff and associated probabilities on the Flats.

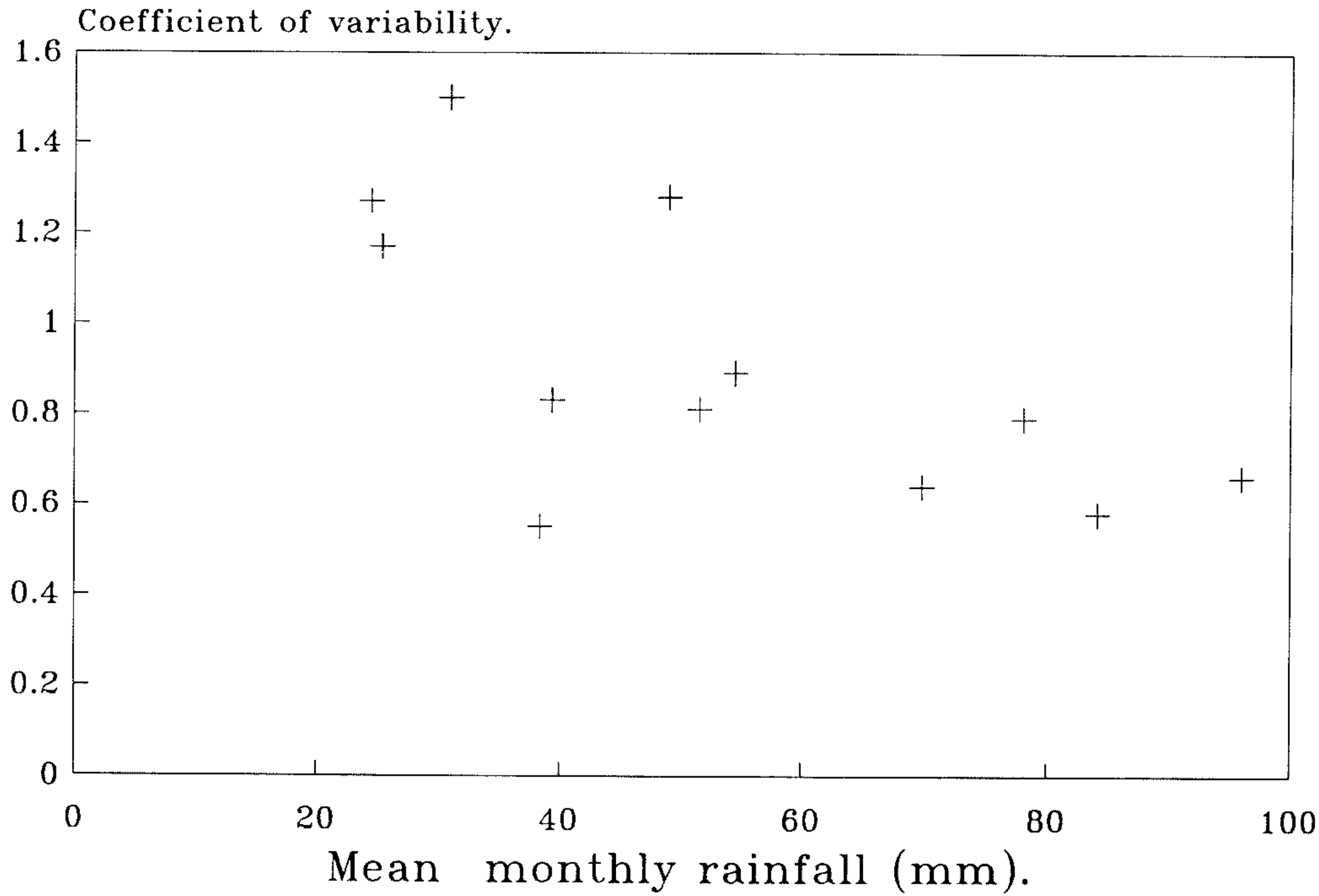


According to Fig. 11, a minimum of 250mm of annual rainfall is needed to generate runoff on the Flats. If this threshold is not realised, as happened in 1984, no runoff events are expected, which would lead to massive failure. Though an average runoff potential of 130mm is expected on the Flats, fluctuations ranging from 13 to 300mm are possible owing to the high variability of annual rainfall. This inaddition to the high variability of monthly rainfall implies a high frequency of droughts which requires the planting of torelant tree species. Related to the problem of rainfall variability is that of excessively wet months. The water balance of the infiltration basin is represented by

$$RIN + P = \triangle s + Et + S + ROFF \qquad \text{xiii}$$

where (RIN) is runoff into the infiltration basin, (P) is direct rainfall into the basin, ($\triangle$s) is soil moisture storage, (Et) is evapotranspiration on the basin, (ROFF) is runoff out of the basin and (S) is seepage. In cases where runoff out of the basin is absent, there is likely to be surplus water in the infiltration basin which cannot be evapotranspired fast enough. This water is likely to seep into the the ground water table. In the wettest month on the Flats, the potential of this process is high as the available water is more than double the potential evaporation demand. Seepage of this water into the groundwater table in dry environments has been associated with elevation of water tables and salinization both of which are detrimental to plant growth. It could also lead to piping of erodible soil profiles (Bryan and Ul-Haq, 1988). There is, therefore, an urgent need to assess the potential danger from this process in the area mainly because runoff harvesting has only aimed at

FIG. 14: Variability of mean monthly rainfall on the Flats.



promoting tree growth quite oblivious of the fate of the excess water. As well, there exists a problem of excess runoff disposal in the early stages of reforestation, which needs immediate attention.

5.4 A METHOD FOR DERIVING OPTIMUM MICROCATCHMENT PLOT SIZES

The optimum plot size range of 7 to 12 m^2 in this study agrees with the 10 m^2 established through trial and error on the Flats thus suggesting that the methodology used here can be relied on to give scientific foundations for field management decisions. As well, though the estimates of runoff potential and optimum size derived above are specific for the Njemps Flats, the methodology used has potential for application in other areas where values of runoff coefficient and threshold rainfall can be derived and the used to compute runoff from rainfall data. In such computations, the rainfall-runoff relationships for specific sites should be considered. A major hypothesis in this study was that both runoff parameters could be estimated from site factors. However, on the Flats, rainfall characteristics were found to explain up to 70% of the variability of these parameters implying weak control by site factors. It was, therefore, not possible to develop predictive correlations between runoff parameters and site characteristics as used in the Rational Method for peak discharge prediction. This means that these parameters have to be derived experimentally for every site and this is largely impossible owing to technological constraints. Means of overcoming this shortcoming should therefore be explored.

Another unfortunate aspect of this methodology is that optimum plot size and therefore plant stocking density, was determined almost purely by moisture deficit. However, as found from the greenhouse experiments, consumptive water use by seedlings is much lower than potential evapotranspiration. As such, use of measures that control direct evaporation would greatly reduce the moisture deficit leading to smaller plot sizes. This is an area that will greatly benefit from currently ongoing mulching studies in the area.

On the Flats runoff potential was found to be almost sorely determined by rainfall characteristics, but in other areas especially those dominated by heavily cracking montmorillonitic vertisols, infiltration may be quite high (Krantz, 1981), leading to weak rainfall-runoff relationships, low runoff coefficients and low runoff yield. In such cases, special measures to raise the runoff coefficient may be necessary. They include clearing vegetation, soil surface compaction and smoothing, removing stone and gravel layers, use of soil dispersing agents, and use of hydrophobic substances and wax sealants (Hillel, 1971). The runoff inducement method chosen will depend on the finances available and characteristics of local storms (intensity, duration and frequency). It should also be matched to other site characteristics, mainly soil type and topography, in addition to the water requirements.

5.5 OPTIMAL SILVICULTURAL PRACTICES FOR THE AREA.

This thesis would not be complete without some comments on certain silvicultural practices such as suitable planting dates and species selection. In areas which experience a moisture deficit, the matching of the growing cycles of different crops to the periods of moisture availability has become the most important preoccupation of the agricultural climatologist dealing mainly with annual crops (Brown and Cochene, 1969). Unfortunately for the foresters, tree crops and other woody perennials require a continous moisture supply throughout the year and this is the biggest challenge to reforestation in dry areas.

Drawing from Fig. 13, it is clear that the probability of runoff events increases from March to August. Planting can therefore take place in March after any storm exceeding 16mm has fallen. This depth ensures a soil misture storage enough to fully saturate the planting hole soil and support the seedling for a month. Such a planting date would ensure that the trees take full advantage of the wet season to develop roots which can tap deep moisture layers buried beneath them, by the onset of the October drought. On the other hand, a dry season exists between October and March with some possible soil moisture replenishment from occasional November storms. This drought requires that species which economise water use and tolerate drought be planted.

Of the 4 tree species tried for possible adoption on the Njemps Flats, both Eucalyptus and Leucena have to be rejected since, despite their high wood and forage yields, their water consumption is too high (table 7). They are unlikely to survive seasonal drought. Of the remaining two, Prosopis seems the better although its water use is similar to that of Cassia because its biomass yield is almost double. It is therefore the best of the tested species for reforestation in the area. Theses are however tentative conclusions. It was impossible to make conclusive statements on the survival probability of the four species tried as only greenhouse water use data were available. Further studies are needed to establish the real water-use rates of the four species under field conditions.

6.0 CONCLUSION

Rainfall simulators can be used to predict natural runoff behaviour on the Njemps Flats reliably. As well, the technique used to quantify runoff potential and subsequently use it to derive optimum microcatchment plot size from records of both rainfall and potential evapotranspiration not only gives reliable results but it has potential for adaptation to other areas.

On the Njemps Flats, rainfall characteristics, mainly depth and intensity, and frequency, through its effect on antecedent moisture, account for up to 90% of all the observed variation in runoff yield, implying that site factors only account for the remaining 10%. As a result, it is not possible to predict runoff parameters from site factors along the lines of the Rational Method for peak discharge. Should this be a general trend in all semi-arid lands, runoff parameters for use in runoff computations have to be derived experimentally for each site, which is a big drawback to this technique. Possibilities of eliminating this tedious step should be explored.

Lastly, further detailed studies should be conducted to link up all the stages of this study into a physical model such that it would be possible to punch in inputs of certain variables on one end and come up with specific runoff yield, optimum plot size and ideal silvicultural practices for different sites.

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Appendix 1: Rainfall data from Parkerra Irrigation station.

Year	J	F	M	A	M	J	J	A	S	O	N	D;
1958	68.3	86.2	42.4	57.4	33.3	53.6	152.4	54.9	106.9	37.6	3.8	54.1
1959	8.1	22.6	87.4	36.6	171.2	53.3	57.4	94.7	25.9	16.0	33	16.8
1960	0	25.4	81.5	36.6	34.5	7.4	55.1	66.0	34	18	23.6	1.8
1961	6.1	11.9	55.1	29.7	31.8	40.1	128.8	94.2	24.6	96.0	298.7	139.2
1962	61	0.25	64.5	39.4	134.6	37.8	62.7	48.8	38.6	21.3	24.1	14.5
1963	22.9	15.2	70.9	71.9	100.6	1.5	63.2	160.8	3.6	19.3	40.6	210.8
1964	2.3	26.9	108	98.6	18.5	34.3	176	121.2	88.1	51.6	11.4	24.1
1965	77.8	2.03	33.5	39.9	53.1	11.4	19.6	17.8	2.8	43.2	22.9	68.6
1966	3.0	48.3	33.5	174.8	12.4	36.8	85.3	75.9	65.8	32.8	31.5	5.3
1967	6.4	3.6	55.1	77.7	129	100.8	101.3	101.9	4.6	44.7	94.7	1.0
1968	0	89.4	55.4	107.4	62.7	45.6	74.4	64.3	6.1	52.1	53.4	5.6
1969	54.9	14.2	134.9	2.8	96.5	2.0	66.3	15.7	63.8	51.1	20.3	0.8
1970	88.9	2.0	131.8	46	36.8	79.2	76.7	115.3	16.8	31.5	25.7	25.9
1971	25.7	0	1.5	76.7	138.2	174.2	53.8	150.4	53.2	32.5	13.5	51.1
1972	1.8	59.7	1.5	43.2	67.3	136.4	28.4	45.9	37.8	67.8	30.9	19.7
1973	18.5	9.4	0	32	65.6	30.1	109.8	100.2	21.6	8.9	34.9	0
1974	1.8	13.8	127.3	44.1	31.5	35.6	134.8	206.4	43.8	41.8	2.7	3.3
1975	1.5	12.8	24.5	149.9	99.8	66.4	186.7	125.1	61.3	30.5	9.9	1.4
1976	0.7	6.6	3.3	61.7	101.7	47.8	99.7	51.2	37.6	10.8	15.7	38.9
1977	58.1	1.0	0.8	281.6	121.9	89.4	224	56.8	43.4	55.2	139.1	14
1978	52.8	74.3	123.4	33.6	8.8	37.1	185.5	53.3	58.7	58.8	26.4	43.7
1979	90.5	92.1	42.5	48.4	30.6	114.6	82.2	69.2	135	14.2	36.5	16.4
1980	8.6	2.1	17.6	169.1	87.6	41.2	8.5	28.1	2.9	10.2	37.7	0
1981	0	9.6	152.2	133	68.6	65	42.5	65	28.9	64.6	24.2	35.8
1982	0.6	12.3	18.7	140.4	94.8	18.3	29.9	114.2	7.0	49.5	157.6	23.4
1983	1.4	43.6	3.9	45.6	47.6	14.1	241.7	162.3	40.8	56.0	20.2	12.1
1984	0.6	0.1	0	31.7	6.4	19.2	45.1	13.7	11.5	20.7	89.8	26.3

```
PROC MEANS;
RUN;
```

N Obs	Variable	N	Minimum	Maximum	Mean	Std Dev
27	J	27	0	90.5000000	24.5296296	31.1539331
	F	27	0	92.1000000	25.3844444	29.7655472
	M	27	0	152.2000000	54.4888889	48.6018307
	A	27	2.8000000	281.6000000	78.1407407	61.7459576
	MA	27	6.4000000	171.2000000	69.8296296	44.9482250
	JU	27	1.5000000	174.2000000	51.6000000	41.7134916
	JL	27	8.5000000	241.7000000	95.9925926	63.0272647
	AG	27	13.7000000	206.4000000	84.1962963	48.8138417
	SE	27	2.8000000	135.0000000	39.4481481	32.7670727
	O	27	8.9000000	96.0000000	38.3962963	21.1910627
	N	27	2.7000000	298.7000000	48.9925926	62.7094517
	D	27	0	210.8000000	31.6518519	46.3150281

Appendix 2: RAINFALL RUNOFF RELATIONSHIP ON THE FLATS
(BASED ON PREDICTED RUNOFF)

```
       Plot of RUNOFF*RAINFALL.  Legend: A = 1 obs, B = 2 obs, etc.
          (NOTE: 1 obs had missing values.)
   300 +
       |
       |                                                      A
       |                                                          A
   200 +                                            A  A
       |                                         ABA     B
RUNOFF |                                          A A    A
       |                                     B          A
   100 +                  A                          A
       |                 A  A    A    A
       |                  A  A    A
       |           A
     0 +
       ---+-------------+-------------+-------------+-------------+--
         200           400           600           800          1000

                                  RAINFALL
```

General Linear Models Procedure

Number of observations in data set = 27

NOTE: Due to missing values, only 26 observations can be used in this analysis.

General Linear Models Procedure

Dependent Variable: RUNOFF

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	72376.65071	72376.65071	77.21	0.0001
Error	24	22496.86967	937.36957		
Corrected Total	25	94873.52038			

R-Square	C.V.	Root MSE	RUNOFF Mean
0.762875	23.19769	30.61649	131.980769

General Linear Models Procedure

Dependent Variable: RUNOFF

Source	DF	Type I SS	Mean Square	F Value	Pr > F
RAINFALL	1	72376.65071	72376.65071	77.21	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
RAINFALL	1	72376.65071	72376.65071	77.21	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate

INTERCEPT	-86.41579103	-3.38	0.0025	25.56932073
RAINFALL	0.34044670	8.79	0.0001	0.03874408

Appendix 3: Analysis of variance and Duncan's separation of means for variable Exchangeable cations.
Soil 1-----Lamelok
Soil 2------Loboi

Number of observations in data set = 18

Group	Obs	Dependent Variables
1	17	NA K CEC
2	18	CA MG

Analysis of Variance Procedure
Dependent Variable Information

NOTE: Variables in each group are consistent with respect to the presence or absence of missing values.

Analysis of Variance Procedure

Dependent Variable: NA

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.70965008	0.70965008	8.24	0.0117
Error	15	1.29190286	0.08612686		
Corrected Total	16	2.00155294			

R-Square	C.V.	Root MSE	NA Mean
0.354550	38.25962	0.293474	0.76705882

Analysis of Variance Procedure

Dependent Variable: NA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
SOILT	1	0.70965008	0.70965008	8.24	0.0117

Analysis of Variance Procedure

Dependent Variable: K

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	7.85951605	7.85951605	98.02	0.0001
Error	15	1.20269571	0.08017971		
Corrected Total	16	9.06221176			

R-Square	C.V.	Root MSE	K Mean
0.867285	16.12638	0.283160	1.75588235

Analysis of Variance Procedure

Dependent Variable: K

Source	DF	Anova SS	Mean Square	F Value	Pr > F
SOILT	1	7.85951605	7.85951605	98.02	0.0001

Analysis of Variance Procedure

Dependent Variable: CEC

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	1124.915126	1124.915126	182.47	0.0001
Error	15	92.474286	6.164952		
Corrected Total	16	1217.389412			

R-Square	C.V.	Root MSE	CEC Mean
0.924039	7.480037	2.482932	33.1941176

Analysis of Variance Procedure

Dependent Variable: CEC

Source	DF	Anova SS	Mean Square	F Value	Pr > F
SOILT	1	1124.915126	1124.915126	182.47	0.0001

Analysis of Variance Procedure

Duncan's Multiple Range Test for variable: NA

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 15 MSE= 0.086127
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 8.235294

Number of Means 2
Critical Range 0.308

Means with the same letter are not significantly different.

Analysis of Variance Procedure

Duncan Grouping	Mean	N	SOILT
A	0.938	10	1
B	0.523	7	2

Analysis of Variance Procedure

Duncan's Multiple Range Test for variable: K

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 15 MSE= 0.08018
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 8.235294

Number of Means 2
Critical Range 0.297

Means with the same letter are not significantly different.

Analysis of Variance Procedure

Duncan Grouping	Mean	N	SOILT
A	2.569	7	2
B	1.187	10	1

Analysis of Variance Procedure

Duncan's Multiple Range Test for variable: CEC

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 15 MSE= 6.164952
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 8.235294

Number of Means 2
Critical Range 2.603

Means with the same letter are not significantly different.

Analysis of Variance Procedure

Duncan Grouping	Mean	N	SOILT
A	40.000	10	1
B	23.471	7	2

Analysis of Variance Procedure

Dependent Variable: CA

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	634.0936900	634.0936900	34.89	0.0001
Error	16	290.8179600	18.1761225		
Corrected Total	17	924.9116500			

R-Square	C.V.	Root MSE	CA Mean
0.685572	15.76779	4.263346	27.0383333

Analysis of Variance Procedure

Dependent Variable: CA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
SOILT	1	634.0936900	634.0936900	34.89	0.0001

Analysis of Variance Procedure

Dependent Variable: MG

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	25.02196694	25.02196694	313.92	0.0001
Error	16	1.27532750	0.07970797		
Corrected Total	17	26.29729444			

R-Square	C.V.	Root MSE	MG Mean
0.951503	11.86521	0.282326	2.37944444

Analysis of Variance Procedure

Dependent Variable: MG

Source	DF	Anova SS	Mean Square	F Value	Pr > F
SOILT	1	25.02196694	25.02196694	313.92	0.0001

Analysis of Variance Procedure

Duncan's Multiple Range Test for variable: CA

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 16 MSE= 18.17612
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 8.888889

Number of Means	2
Critical Range	4.280

Means with the same letter are not significantly different.

Analysis of Variance Procedure

Duncan Grouping	Mean	N	SOILT
A	32.347	10	1
B	20.402	8	2

Analysis of Variance Procedure

Duncan's Multiple Range Test for variable: MG

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 16 MSE= 0.079708
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 8.888889

Number of Means	2
Critical Range	0.283

Means with the same letter are not significantly different.

Analysis of Variance Procedure

Duncan Grouping	Mean	N	SOILT
A	3.434	10	1
B	1.061	8	2

Appendix 4: Analysis of variance and Duncan's separation of means for variable texture.
Soil 1-----Loboi
Soil 2-----Lamelok

Number of observations in data set = 6

Analysis of Variance Procedure

Dependent Variable: SAND

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	507.2881500	507.2881500	155.31	0.0002
Error	4	13.0653333	3.2663333		
Corrected Total	5	520.3534833			

R-Square	C.V.	Root MSE	SAND Mean
0.974891	6.048190	1.807300	29.8816667

Analysis of Variance Procedure

Dependent Variable: SAND

Source	DF	Anova SS	Mean Square	F Value	Pr > F
SOILT	1	507.2881500	507.2881500	155.31	0.0002

Analysis of Variance Procedure

Dependent Variable: CLAY

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	136.5174000	136.5174000	840.45	0.0001
Error	4	0.6497333	0.1624333		
Corrected Total	5	137.1671333			

R-Square	C.V.	Root MSE	CLAY Mean
0.995263	1.172395	0.403030	34.3766667

Analysis of Variance Procedure

Dependent Variable: CLAY

Source	DF	Anova SS	Mean Square	F Value	Pr > F
SOILT	1	136.5174000	136.5174000	840.45	0.0001

Analysis of Variance Procedure

Dependent Variable: SILT

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	140.4568167	140.4568167	90.77	0.0007
Error	4	6.1896667	1.5474167		
Corrected Total	5	146.6464833			

R-Square	C.V.	Root MSE	SILT Mean
0.957792	3.507878	1.243952	35.4616667

Analysis of Variance Procedure

Dependent Variable: SILT

Source	DF	Anova SS	Mean Square	F Value	Pr > F
SOILT	1	140.4568167	140.4568167	90.77	0.0007

Analysis of Variance Procedure

Duncan's Multiple Range Test for variable: SAND

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 4 MSE= 3.266333

Number of Means	2
Critical Range	4.105

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	SOILT
A	39.077	3	1
B	20.687	3	2

Analysis of Variance Procedure

Duncan's Multiple Range Test for variable: CLAY

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 4 MSE= 0.162433

Number of Means	2
Critical Range	0.915

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	SOILT
A	39.147	3	2
B	29.607	3	1

Analysis of Variance Procedure

Duncan's Multiple Range Test for variable: SILT

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 4 MSE= 1.547417

Number of Means 2
Critical Range 2.825

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	SOILT
A	40.300	3	2
B	30.623	3	1

Appendix 5: Analysis of Variance Procedure for daily evapotranspiration (cc)

Class Level Information

Class	Levels	Values
SPECIES	4	1 2 3 4

Number of observations in data set = 101

Analysis of Variance Procedure

Dependent Variable: EVAP

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	2822780.072	940926.691	228.71	0.0001
Error	97	399061.589	4114.037		
Corrected Total	100	3221841.661			

R-Square	C.V.	Root MSE	EVAP Mean
0.876139	19.48001	64.14076	329.264465

Analysis of Variance Procedure

Dependent Variable: EVAP

Source	DF	Anova SS	Mean Square	F Value	Pr > F
SPECIES	3	2822780.072	940926.691	228.71	0.0001

Analysis of Variance Procedure

Duncan's Multiple Range Test for variable: EVAP

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 97 MSE= 4114.037
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 25.22231

Number of Means	2	3	4
Critical Range	35.89	37.74	38.94

Means with the same letter are not significantly different.

Analysis of Variance Procedure

Duncan Grouping	Mean	N	SPECIES
A	556.44	26	1 (eucalyptus)
B	410.14	26	2 (leuceana)
C	171.73	24	4 (prosopsis)
C			
C	160.12	25	3 (cassia)