Erosion Assessment for Large Basins
using Remote Sensing and GIS;

A Case Study of Lake Naivasha Basin, Kenya.

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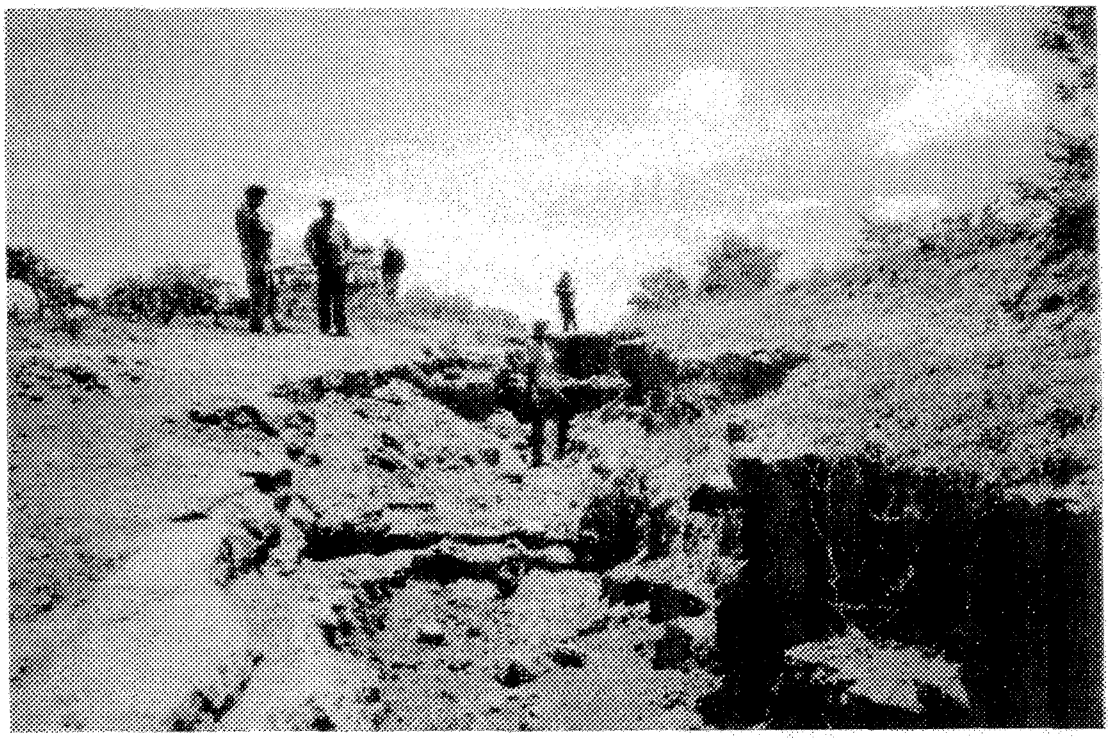

by

Byman H. Hamududu

ITC

(Water Resources Surveys,)

Erosion Assessment for Large Basins
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This thesis is submitted in partial fulfilment for the Degree of Master of Science in Water Resources Survey with emphasis on Watershed Management at the International Institute for Aerospace Survey and Earth Sciences (ITC), Enschede, The Netherlands.

Board of Examiners:

Prof. Dr. A.M.J. Meijerink (Head & Supervisor)
Dr. E. Seyhan (External Examiner)
Dr. W. Siderius
Dr. C.M. Mannaerts
Ir. H. De Brouwer

INTERNATIONAL INSTITUTE FOR AEROSPACE SURVEY AND EARTH SCIENCES, ITC.

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Abstract

The erosion assessment of Naivasha Basin has been carried out using the Terrain Mapping Units approach. This methodology combines the effect of rainfall, land cover and (TMU) soils, topography on the erosion process. The study aimed to assess the erosion processes occurring in the area that result from the hydrological behavior of the catchment.

Rainfall analysis was done within the basin to determine the spatial and temporal distribution of the rainfall. The results showed that the area experience varying amounts of rainfall both in space and time due to orographic effects. The central part (bottom of the Rift Valley) receives the lowest (yearly average 600-mm) amount of rainfall while the mountain ranges on both sides receive an appreciable amount of rainfall (average 1200 mm). In addition to this due to the topography of the area (rain shadow effect), the rainfall pattern differed from area to area. The average yearly rainfall ranges from 480 mm to 1300 mm. The rainfall pattern in the year is bi-modal, one peak in between April and June and the second one in October and November. The high erosive storm occur mostly in April, May and November.

The land cover is influenced by rainfall pattern of the area. At high altitudes (>2100 masl) where there is high rainfall, the land cover is mainly dense forest, while at lower altitudes, bottom of the rift valley (<2000 masl), the land cover is mainly scrub land and occasionally bare soil. This is clearly seen on the satellite image where forest appears black and the bare soil and scrubland appear almost white gray. The rest of the area is under heavy agricultural activities, which changes from season to season. The image interpretation was done and supervised classification carried out in ILWIS package. Six land cover classes were identified; Forest, Scrub, Bare soil, Agricultural crop, Lava flow, and Water.

The three data layers were prepared as described in the following sections. With relational modelling, 2-dimensional tables were prepared for each pair of data layers. The last 2-dimensional table was a result of the other two 2-dimensional tables used.

The 2-dimensional table was used to reclassify the maps into an erosion map by the assigned values or ratings. These ratings were assigned based on the knowledge from the field. The result was an erosion map with rainfall and TMU data, and cover factor.

The sediment concentrations and the annual sediment yields were also analyzed. The sediment concentrations were highest during the first storms. The concentrations were also found to be high in the long rainy season, followed by the dry period, were the least in the short rainy season (October and November). Only two rivers had enough sediment concentration data for analysis. These are Malewa and Turasha rivers. Rating curves for the seasonal sediment concentrations were calculated and the amount of sediment yield for the entire basin was estimated from these curves. The sediment data was also used for estimating the sediment yield from some TMUs in which drainage was well defined.

The Morgan assessment method has been applied to the basin in order to compare it with the TMU, and SOTER methodologies. The results show that the erosion process in the area is transport limited.

The results presented in this thesis do not give rise to great concern on the erosion processes of the area. However, in view of the low rainfall pattern that this area experiences, in the event of high rainfall storm the area would be eroded excessively. This is established by the result from the Morgan methodology. This method showed clearly that the processes are transport limited. The SWEAP methodology also estimates high erosion risk areas. The great concern, however, should be devoted to the wind erosion that is on the southern part of the basin. The winds that follow the Rift valley on the cultivated steep slopes without any wind breakers (trees) cause the erosion. Measures to protect this part of basin should be of great urgency to the authorities.

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I would like to thank all the organisations and people who have, in one way or another, contributed to the writing of this thesis. I will not mention everyone as space and time is limited.

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Byman, 1998

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Abbreviations

2 D	2 Dimensional table
AGNPS	Agricultural Non Point Pollution Source
AGRIC	Agriculture
CROPWAT	Crop Water Requirements program developed by FAO
CV	Coefficient of Variation
DBASE	Database
FAO	Food and Agriculture Organization
GIS	Geographical Information Systems
I-D-F	Intensity Duration Frequency curves
ILWIS	Integrated Land and Water Information System
ISRIC	International Soil Reference and Information Centre
ITC	International Institute for Aerospace Survey and Earth Sciences.
ITCZ	Inter Tropical Convergence Zone
KSS	Kenya Soil Surveys
KWSTI	Kenya Wild Life Services Training Institute
MASL	Metres Above Sea Level
MFI	Modified Fournier Index
NDVI	Normalised Difference Vegetative Index
PC1	Principal Component 1
PCII	Principal Component 2
PCs	Principal Components
RANKPLOT	Computer program for probability Calculations
SLEMSA	Soil Loss Equation Model for Southern Africa
SOTER	Soil and Terrain database
Ss	Suspended Sediments
SWEAP	Soil Water Erosion Application Program
TIMESPLOT	Computer program for time series plotting.
TMU	Terrain Mapping Units
UK	United Kingdom
USA	United States of America
USLE	Universal Soil Loss Eqaution
WEPP	Water Erosion Prediction Program

1 Literature Review

1.1 Regional Erosion Assessment

Our understanding of soil erosion mechanisms and rates originates in the work of the US Soil Conservation Service, which had the primary objective of combatting the soil losses that were occurring in US. The emphasis has always been pragmatic and the predictions have centered around the development and revising of the 'famous' USLE. The weakness and strength of the USLE lie in the estimation of soil loss as a product of a series of terms for rainfall, slope gradient, slope length, soil and cropping factors. This allows extensive tabulations of individual factors, incorporating the results of a vast experience, but it does not allow for any sort of non-linear interactions between these factors, and this may be a fatal flaw (Kirkby, 1980). Some authors argue that erosion is quite a complex process that cannot be estimated by a product of a series of terms. In this thesis, it is will be shown that much erosion can be determined (qualitatively) by image interpretation of aerial photos and satellite images. Later, an attempt to quantify erosion using sediment concentration data will be done.

1.2 Recent Studies

Erosion has been studied intensively by many Agro-scientists and Hydrologists for a quite a long time now. Models have been developed most of which deal with small plots. Many managers, to quantify and assess erosion rates of catchments, though not very accurate, use these models. The reason being that there are not yet accurate models to assess erosion rates on a basin scale. However, researchers are working hard to improve or modify these models to be applicable to the basin scale (e.g. RUSLE) in order to account for the inaccuracies in determination of sediment yield from basins. This study is another attempt being used to determine the sediment yield of a catchment.

1.3 Role of Modelling

All models have and must have an orienting value within the scope of their boundary conditions (De Ploey, 1991). Models are not reality but are always simplifications of reality (Rohdenburg, 1989). These statements show that, although models are often used to simplify reality, they always have limitations. For example the USLE has the major limitation (boundary condition) that the experimental limitation of field length of 22 m, implying that the equation may not be representative for the average soil loss in the catchment, especially those catchments with complex topography.

Models are used to transfer plot data to the catchment scale. Most of these models were designed for small agricultural plots. Two types of models exist; lumped, and physically based models. The lumped models are those that combine erosion from all processes into one equation (e.g. USLE). Input parameters are represented by empirical constants. There is ample evidence that the USLE yields quite a good estimate of amount of detached soil (Wischmeier *et al*, 1978). However, the problem is that on a regional scale, part of the eroded soil is deposited with the catchment before reaching the outlet. This is so because USLE does not account for any deposition within the catchment. This reduces the sediment production predicted.

The so-called physically based models (e.g. WEPP) require a lot of input parameters, which, in most cases, are not available especially in the developing countries. To determine these parameters is time consuming and costly. The estimates from such models are not any more accurate compared than from lumped models. This means that the practical application of such a model is still limited due to uncertainty in determination or specifications of some of these input parameter values and the differences in scale (Nearing *et al*, 1989).

It becomes apparent that, on one hand, much research in the field of erosion has concentrated in estimating the soil loss by modeling on a plot scale or detailed level. On the other hand, the exploratory scale has been used (SWEAP, SOTER) based on a scale of 1:1 000 000 which is less detailed, and too general to be used for conservation planning purposes.

Most watershed managers work between the detailed level and exploratory scale which can be termed a semi-detailed level. As none of the above can be used for this purpose, it becomes necessary to devise means of estimating the soil loss from a catchment.

The plot test results cannot be transferred to locations other than their original sites, as no two sites would be similar both in time series and spatial terms. The size of these plots, compared to the catchments, makes the extrapolation more difficult.

1.4 Assessments at Regional Scale

In efforts to provide regional erosion maps, ISRIC, through the SOTER database, has modified the USLE for estimation and eventually production of erosion assessment maps for large areas. A program called WEAP (Water Erosion Assessment Program) is used for extraction of parameters from the database. With this method large areas can be assessed from the 'office' and presented as erosion risk maps. However the accuracy of this method, without field inspection, casts a lot of doubt on the methodolgy.

Another method, proposed by ITC, involves the use of aerial photos and images for assessment coupled with field inspection. The method uses Terrain Mapping Units assisted by modeling as basis for the evaluation (Meijerink, 1988). Each of these units then can be assessed individually and the results combined to come up with soil loss from large areas. The advantage of this method is that the aerial photo gives the picture of what actually is taking place. Modeling can be applied just like the SOTER methodology.

1.5 Conclusion from the Studies

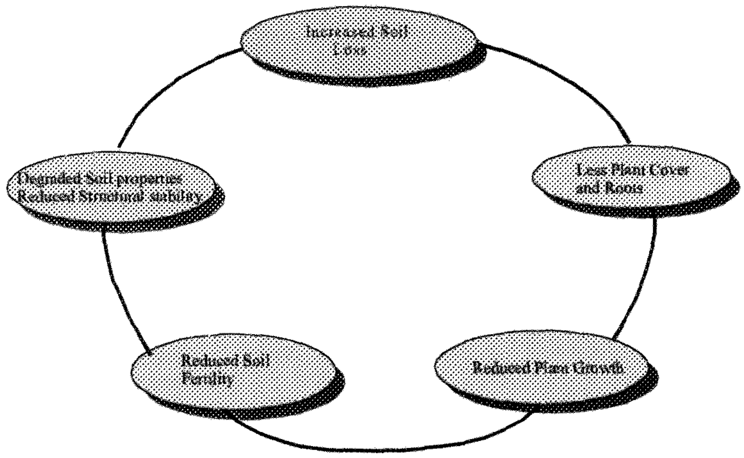
It becomes clear that better methods for estimating soil loss from large catchments are still required in this field other than extrapolating from plot data. The watershed managers use catchments as a basis for planning and controlling soil loss.

It is not feasible to extrapolate empirical hydrological and erosion data from small-scale plots and larger catchments (Mannaerts, 1992). He says that calibration of data sets between small and large drainage areas, even within one region, remains necessary in order to obtain viable predictions from the transposed relationships. He advances the idea that use of physically based water flow and sediment variables presents more scope for dealing with catchment size and scales in hydrological and erosion studies.

2 INTRODUCTION

2.1 Background

Over 70% of the people of Kenya live in rural areas, and almost all of them depend directly on their small holdings for a living. Although many people are moving to the cities, apparently mainly because they hope for a better standard of living there, it is common knowledge that even in the cities many people still try to cultivate small plots to obtain some of their food (IDRC 1993). Thus, it is clear that farming is by far the largest economic enterprise in Kenya, and it is vital for the well-being of most people in Africa as a whole.



Vicious Cycle of Soil Erosion

Figure 2.1 Vicious Cycle of Soil Erosion (after Nil, et al, 1997)

About 75 % of Kenya is either arid or semi-arid. The remaining 25 % is heavily populated leading to excessive use of the land. Population pressure has forced farmers to move to drier areas which are characterised by low and erratic rainfall which is sporadic and sometimes of high intensity. This leads to heavy soil losses through erosion in the already poor soils. Soil fertility loss by erosion is a self enhancing process (figure 2.1). One process affects the other and these processes are inter-linked in one way or another. Erosion reduces soil stability and fertility which leads to low infiltration with increased runoff. This also causes poor plant growth, cover and root soil interactions.

Soil erosion is not only a very serious threat to sustained agriculture production, but also a major cause of the deterioration of the agricultural potential of land and water resources in high, medium and low potential areas. The seriousness of the problem is more pronounced in the arid and semi arid areas (especially in grazing lands, figure 2.2) where, at times, high rainfall intensities, susceptibility of the soils to erosion and mis-management of land (through overgrazing) have accelerated and magnified soil losses by erosion and consequently reduced crop yield potential (Biamah, 1984). However, most times there are large areas without erosion problems. The puzzling question which remains is the spatial differences in erosion rates.

Sediments form a large portion of the floor of Lake Naivasha. These sediments originate from the surrounding volcanic rocks. The sediments reduce the volume of the lake and may change the environment near and in the lake. Brind (1957) suggested that the capacity of the lake was being reduced at all levels due to silting which can increase the surface area of the lake hence increase the water surface available for evaporation. Sediments are carried down in the rivers especially the Malewa river but surprisingly there is no evidence, as yet, of a serious problem (Phase I report, 1993).

Due to the volcanic nature of soils and faults, most of the area is characterised by steep slopes. This, together with the volcanic soils, seem to promote soil erosion. This can be seen through the erosion risk map created by SOTER. The method uses the SOTER database at a scale of 1:1 000 000. It uses the 'modified' USLE model. The soil, land use, climate, etc. are derived from SOTER database. The map shows that a great part of the area has a high risk of soil erosion. However, from the field investigations, there is no, or few signs of erosion except a few localised areas. The question that arises is whether it is possible to use a general criteria like SOTER for erosion mapping or do we need site specific approaches.

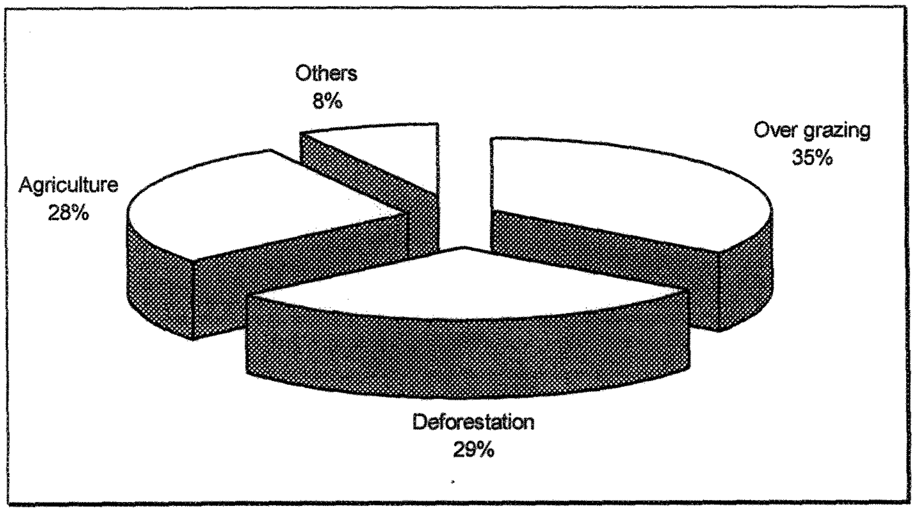


Figure 2.2 Main Causes of Soil Erosion

The major causes of erosion are depicted in figure 2.2. Overgrazing is estimated to contribute about 35 % while deforestation 29 % and agriculture 28 %. The others like road construction, etc. contribute up 8 % only. In the Naivasha basin overgrazing and agriculture are the major causes of erosion, followed by deforestation.

2.2 Research Objectives

- To study the processes and controls on erosion in the area in view of the developments during the last decades.
- To estimate the relative sediment yield by considering erosion and deposition within the catchment.
- To make use of a model which describes the erosion for catchments in the area. The model may be partly empirical (relational) and partly numerical.
- To analyse and estimate the sediment yield from suspended load observations.
- To apply the results for the identification of priority areas for conservation planning measures.

2.3 Research Questions

What are the main types and intensities of erosion and causative factors in the study area?

How can we map the erosion spatially? Do relational models give adequate answers?

If not, is it necessary to supplement the relational modelling by numerical soil erosion models?

What is the best way to protect the susceptible areas?

2.4 Methodology

The depicted methodology (figure 2.) was used in the assessment of erosion. The rainfall data was used to assess the rainfall erosivity. The aerial photos and the satellite image were used to evaluate the land cover classes of the basin. The terrain mapping units which combine the geology, soils, and topography were used as another data layer.

The three data layers were then combined for the assessment of erosion through the 2 dimensional tables of GIS.

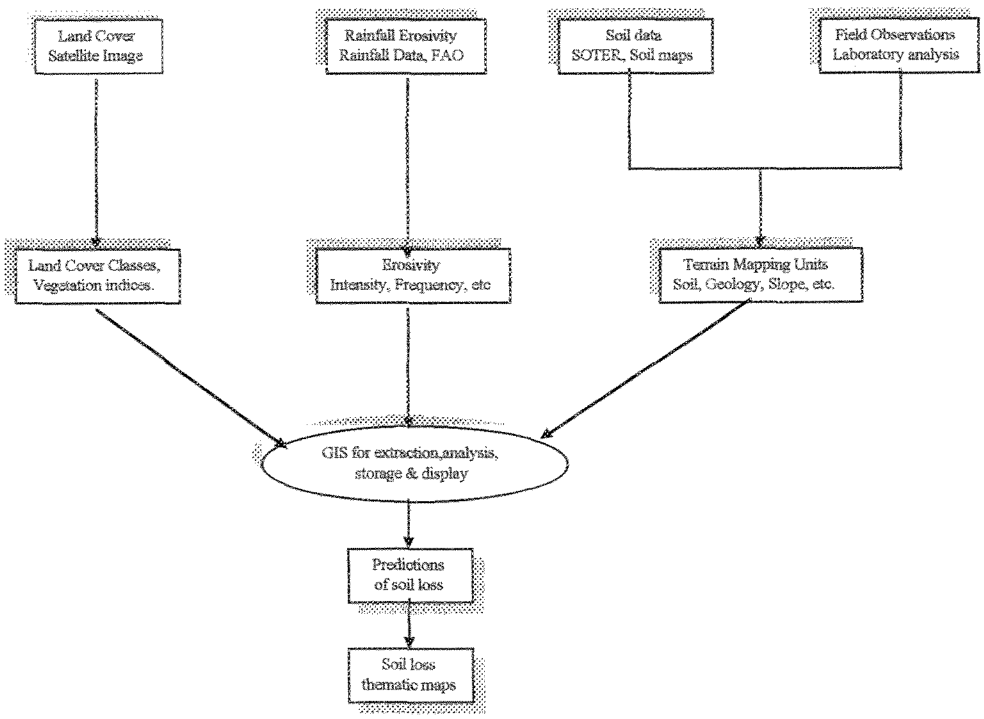


Figure 2.3 Flow Chart of the Assessment Methodology

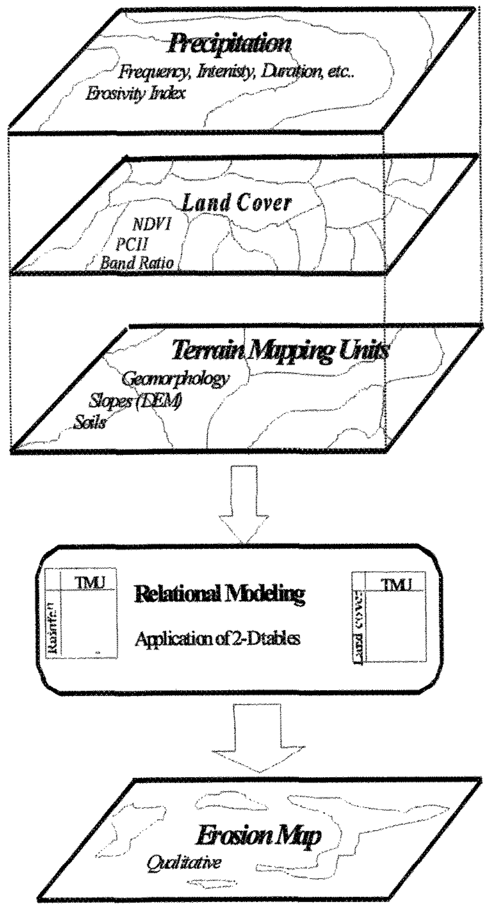


Figure 2.4 Methodology in GIS Maps used for Assessment

2.5 Location

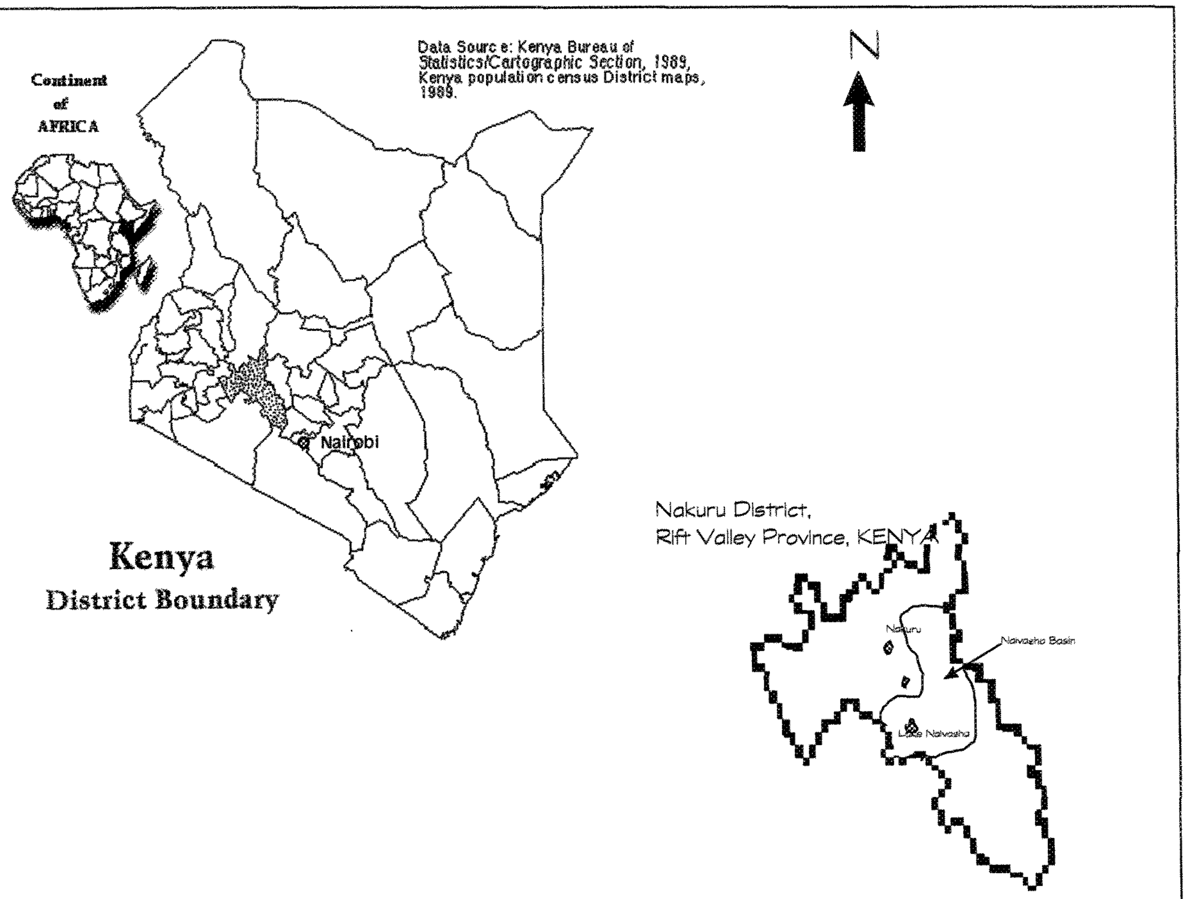


Figure 2.5 Location Map of Study Area

The Naivasha basin is situated in the East African Rift Valley, about 80 km north west of Nairobi. The basin is located approximately between 0° 00′ to 1° 00′ S and 36° 00′ to 36° 45′ E. This part of the Rift valley covers the three lakes of Nakuru, Elementeita and Naivasha to the south. All these lakes fall within the Rift Valley. The average height ranges from about 1900 around Naivasha to 1758 near Nakuru but on the sides lie the two mountain ranges which are well above 3000 metres.

On both sides of the Rift Valley are two mountain ranges; to the east is the Nyandarua mountains (Aberderes exceeding 3960 m above sea level) and to the west are the Mau mountains (exceeding 3000 m). To the south is the volcanic Longonot mountain while to the north is the Menangai crater. The Kinangop plateau forms a broad step in between the Nyandarua range and the Valley floor, on the eastern side of lake Naivasha. The Rift

Valley width ranges between 45 and 70 km in this part of Kenya. Figure 2.5 shows the general location of this basin.

Administratively, the lake and its immediate areas are situated in Naivasha division of Nakuru district in the Rift Valley province of Kenya.

2.6 Climate

The climate in the valley varies due to the altitude changes as described above. Although the lake is located within one degree of the equator, meaning that it is 'tropical', it generally experience relatively cool conditions determined by altitude. (Richardson, 1966)

2.6.1 *Rainfall*

The mean annual rainfall for the whole country averages 600 mm, ranging from less than 200 mm in the northern Kenya to 2000 mm on the slopes of Mount Kenya. The movement of the ITCZ provides for this region two main rainy season: March - June and October - November. Around Lake Naivasha, rainfall seems to be well distributed through out the year with some peaks in April. The average rainfall around Naivasha is 600 mm where as the eastern side Nyandarua mountain range receive as much as 1525 mm. This shows that Naivasha area is in the rain shadow area. The evaporation is approximately 1360 mm (around Naivasha). To the south, Nairobi receives about 4 times as much rainfall as Naivasha while Nakuru receives about twice as much. Naivasha basin therefore seems to be in deficit; evapotranspiration exceeding the rainfall. Figure 2.6 gives a general picture of the climatic differences among these towns.

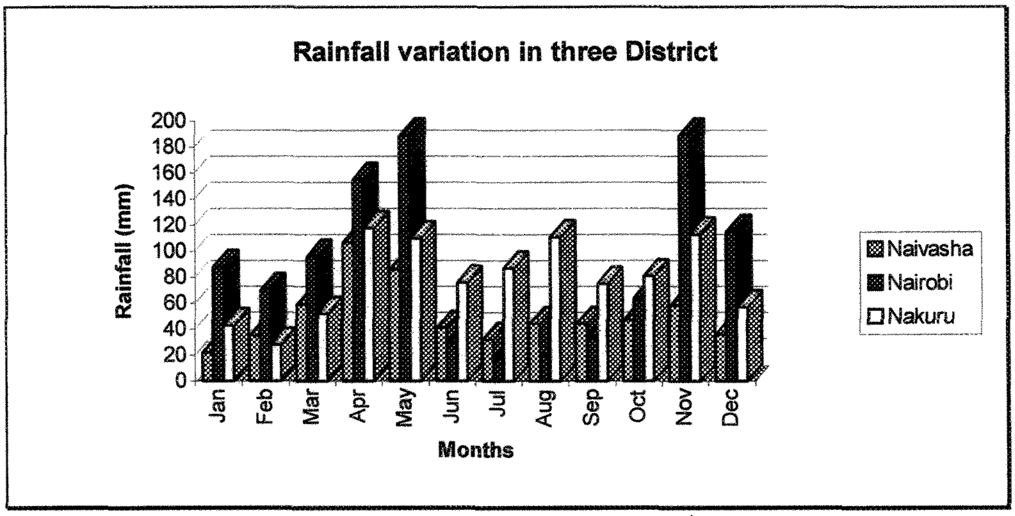


Figure 2.6 Rainfall Variation for Naivasha, Nairobi & Nakuru (Source: FAO, Cropwat)

2.6.2 Temperature

The mean monthly maximum temperature ranges from 24.6°C to 28.3°C. The highest temperatures occur in January and February. The mean monthly minimum temperature ranges between 6.8°C and 8.0°C with the coldest months being July and August. The average mean monthly temperatures ranges between 15.9°C and 17.8°C. The cold temperatures provide a well marked cold season and make it possible to grow grapes and deciduous fruits around the lake.

2.6.3 Winds

The winds are generally calm in the morning while in the afternoons wind speeds of 11 -15 km/h is typical of the area. The winds are strongest in months of August through to October when they reach a speed of 21 km/h. The wind direction is mainly from the south east and the north west depending on the season. Some extremely strong winds have been reported along the rift valley especially through the window between Longonot and Kinangop hills. The general climate is shown in table 2.5

Month	MinTemp °C	MaxTemp °C	Humid %	Wind km/day	Sun hours	Radiation $MJ/m^2/day$	Eto (Pen) mm/day
January	8.0	27.6	62	104	5.3	17.1	3.8
February	8.1	28.2	61	104	5.9	18.5	4.1
March	9.7	27.2	65	104	5.3	17.8	3.9
April	11.5	25.0	75	104	4.7	16.3	3.4
May	11.2	23.7	80	121	4.9	15.8	3.1
June	9.8	23.0	79	121	4.8	15.0	3.0
July	9.2	22.5	77	121	4.2	14.4	2.9
August	9.3	22.8	76	130	4.7	15.9	3.2
September	8.7	24.5	74	130	5.4	17.7	3.6
October	9.0	25.5	72	130	5.5	17.9	3.8
November	9.2	24.6	77	104	4.4	15.8	3.3
December	8.6	25.7	72	104	4.2	15.1	3.3
	9.36	25.03	72.5	114.75	4.94	16.44	3.45

Table 2.5 Monthly Reference Evapotranspiration Penman Monteith

Country: Kenya Meteorological station: Naivasha
Altitude: 1900m. Coordinates: 0°25′48″ South 36°15′36″ East
(Source: FAO's Cropwat)

2.7 Geology

In Geological terms, Lake Naivasha is very young and is said to be the remains of a once large lake that included lakes Nakuru, Elementeita and Naivasha. There is still much evidence of volcanic activity. Only 150 years ago, the lake was almost dry. (A three phase Environment Impact Study of Recent Developments around Lake Naivasha, Dec, 1993).

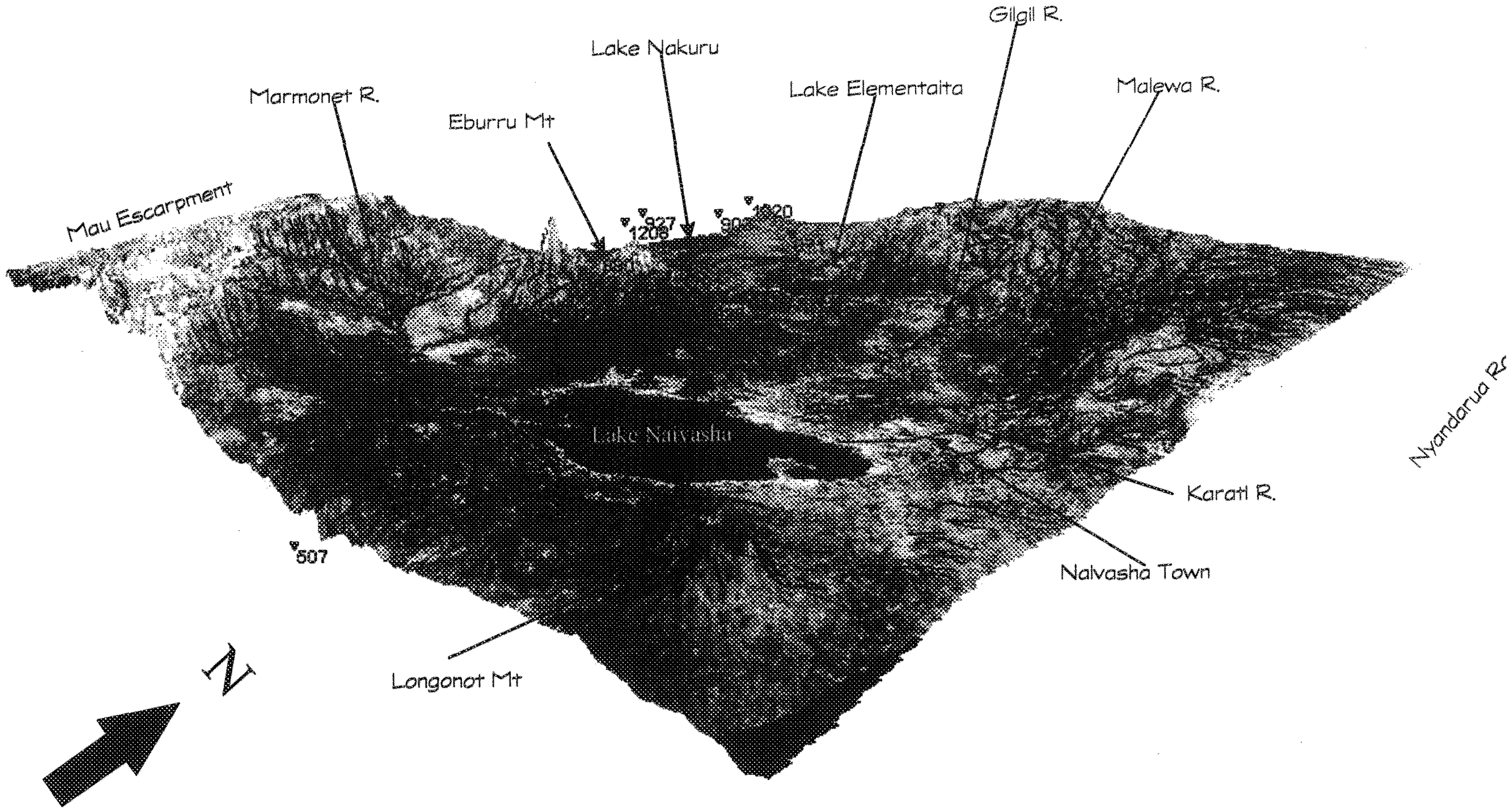
The Lake is located in the large east African Rift Valley system or the Gregory Rift valley which stretches from Jordan in the middle east to Mozambique in the south east Africa. Geological evolution has influenced the geomorphology of the study area. Two main geomorphological domains are distinguished: rift margins and the rift floor plains.

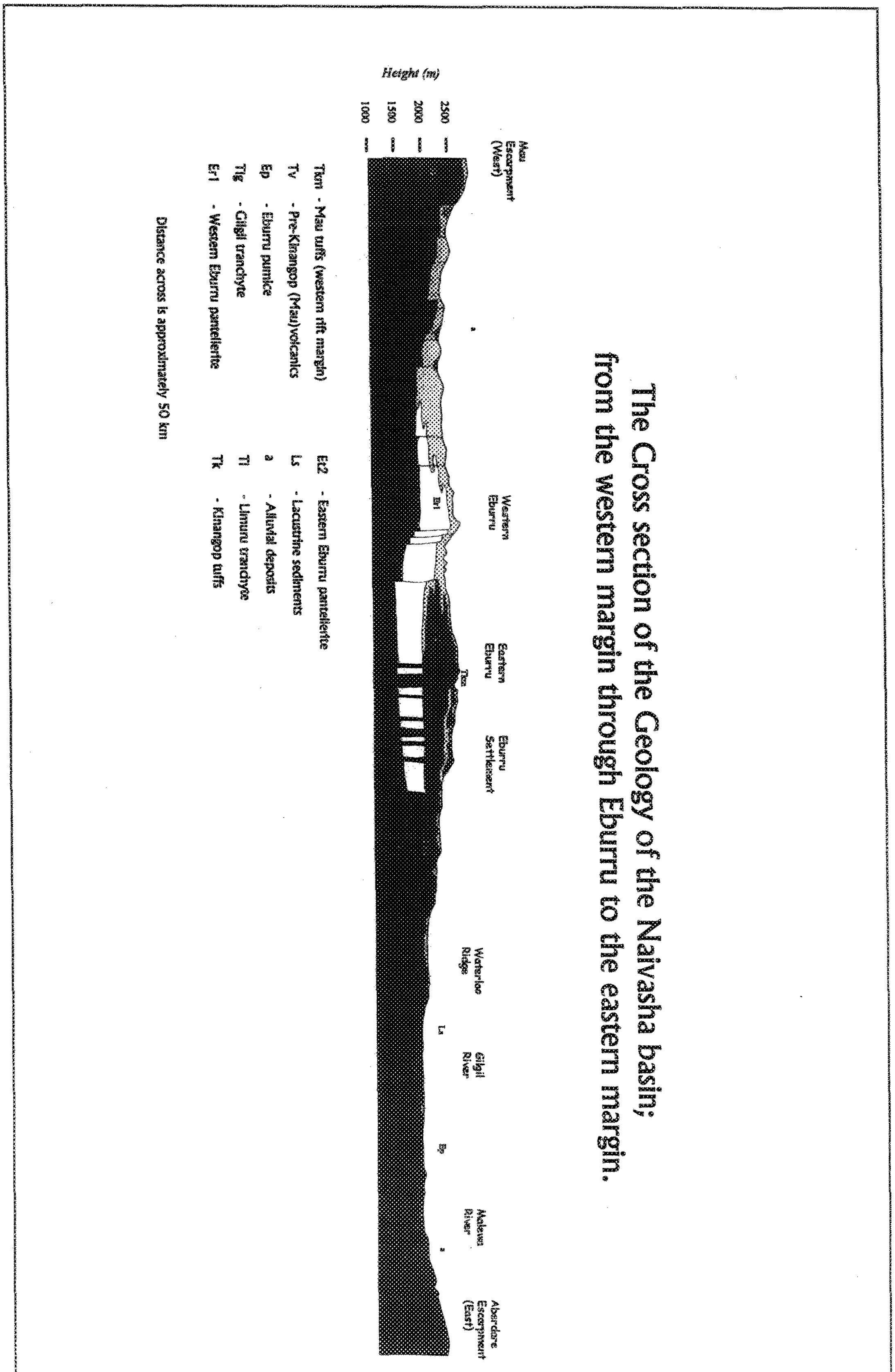
The Rift Valley margins border the study area on both the east and west sides. To the western, the Mau Escarpment has a maximum elevation of about 3080 metres decreasing in height in both north and south directions. The margins are defined by fault scarps which have steep and dissected slopes. Figure 2.2 shows the general 3 dimensional view of the area. The drainage lines appear in black with Lake Naivasha. The numbers on this view indicate the Rainfall stations within the basin. The value of this number is the average annual rainfall depth in millimetres. Figure 2.3 shows the cross section. The cross section runs from Mau Escarpment through Eburru to Kinangop plateau just before Nyandarua range. Figure 2.4 (sketch) shows the general location of main geological units from Lake Naivasha.

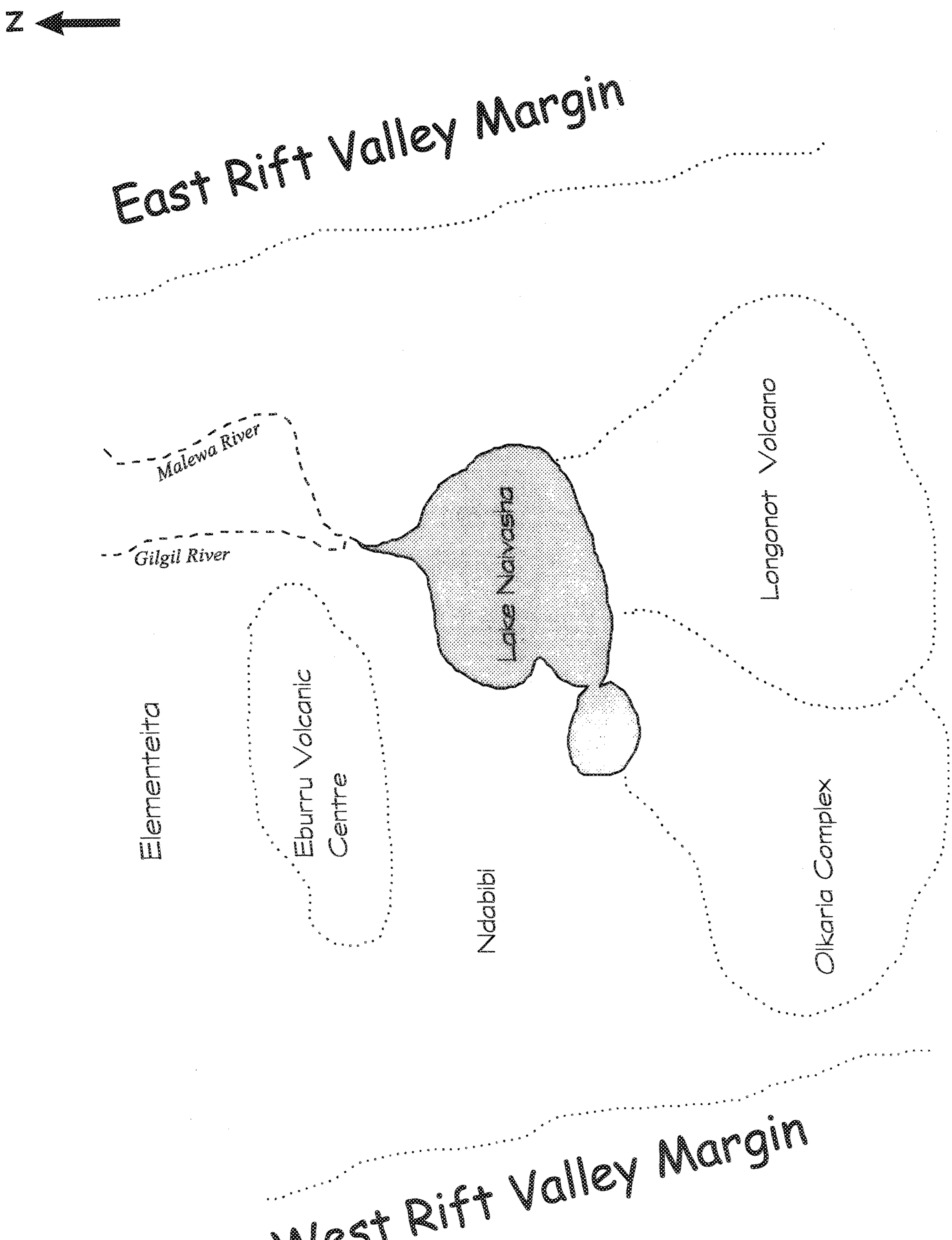
The eastern margin has more faults and fractures compared the western margin. In this formation lies the Bahati escarpment, Kinangop plateau and the south kinangop fault scarp. The maximum elevation is about 2740 metres on the kinangop plateau. Along its length, this plateau has very steep or sometimes vertical rock aces.

The Rift Valley floor margins includes all the three lakes. The average width of floor is about 57 metres. To the north is the Menengai with a height of 2267 metres, while to the south east is the longonot volcano with a height of about 2776 metres. The Eburru Volcanic complex is on the north western side of lake Naivasha. The highest point here is 2820 metres.

3-Dimensional View of the Study Area (*part*)




The Cross section of the Geology of the Naivasha basin;
from the western margin through Eburru to the eastern margin.
Height (m)
2500
2000
1500
1000
Mau Escarpment (West)
Western Eburru
Eastern Eburru
Eburru Settlement
Waterloo Ridge
Gilgil River
Malewa River
Aberdare Escarpment (East)
Tkm - Mau tuffs (western rift margin)
Tv - Pre-Kinangop (Mau)volcanics
Ep - Eburru pumice
Tig - Gilgil tranchyte
Er1 - Western Eburru pantellerite
Er2 - Eastern Eburru pantellerite
Ls - Lacustrine sediments
a - Alluvial deposits
Tl - Limuru tranchyte
Tk - Kinangop tuffs
Distance across is approximately 50 km



Sketch showing the Positions of Main Geological Formations

2.8 Soils

Soil represent the meeting point between the physical and biological worlds. Soil is a fundamental land resource because it allows and conditions the presence of vegetation and the utilisation of land for agricultural purposes.

The soils in the Naivasha basin are young and poorly developed and according to Jaetzold and Schmidt (1983), the two upper plateaus above 2060 metres are covered by an andoluviac phaeozem, which is a well drained, deep to very deep, dark brown and friable to little smeary soil. It consist of clay loam and clay. The soil, more commonly known as praire soil, has a high agricultural fertility, good workability and good water holding capacity.

In the major mountain ranges (Mau, Eburru & Nyandarua) and major scarps are the Regosols and Andosols. Here the slopes are about 30 % or steeper. The soils(M1) which were developed on ashes and other Pyroclastic rocks of very recent volcanoes. The regosols are excessively drained, deep, dark brown in colour and slightly smeary but strong calcareous, stony to gravel clay loam. The Andosols (M2) are well drained as they are developed on older ashes of volcanoes. They have humic top soils.

On the hills and minor scarps are the Cambisols (H4 & H6). The soils are well drained too, with a few outcrops. They are mainly clay loam in texture. The andosols in this unit are molic, a humic topsoil and gravely loam.

The plateaus and higher plains (average slope 8 %) are mainly composed of soil developed on ashes from of recent volcanoes. They are mainly the Planosols and Phaeozems (L20,L21,L22). Not well drained, the planosols are mottled clay under a silty loam layer, while the Phaeozems are well drained with a dark brown colour.

The rest of this high area is complex. The soils in complex are developed on ashes of recent volcanic rocks. They are the Regosols (Pv6) composing the loose sand and are stratified. They mainly silty loam soils.

The soils close and around Lake Naivasha are developed on sediments from volcanic ashes. They are deep, dark greyish brown to dark brown, firm, saline, sodic and little calcaric. They consist of silt loam and clay and are more or less water logged, depending on the water level in the lake. These soils have a low agricultural fertiltiy and poor workability but gives, nevertheless, very high yields, owing to the irrigation possibilities and good farming management. These soils are termed as Solonetz (PI7) in saline phase. In some areas the soils are developed on sediments from Lacustrine mud stones. These soils (Phaeozems) are mainly in the plains. Like the Solonetz, they are deep, friable and smeary. They are mainly composed of sandy clay loam to sandy clay with a humic top soil. Generally, soil conditions are often quite difficult to work with and sometimes communication may not be easy in some areas like the Ol Kalau plateau to the North east. Barber and Thomas (1981) showed that these soils (volcanic) have a very coefficient of 0.21, due to very quick sealing under intensive rainfall. The erodibility is also high, with a factor of 0.51

2.9 Drainage

The catchment drainage is wholly internal and flows down from the high altitudes. The Eburru hills separate the lake basin from the adjoining Lake Elementeita catchment. There are a number of rivers around the lake but the two with subsequent flows are the Malewa and Gilgil. The two rivers together constitute about 90 % of the total river flow

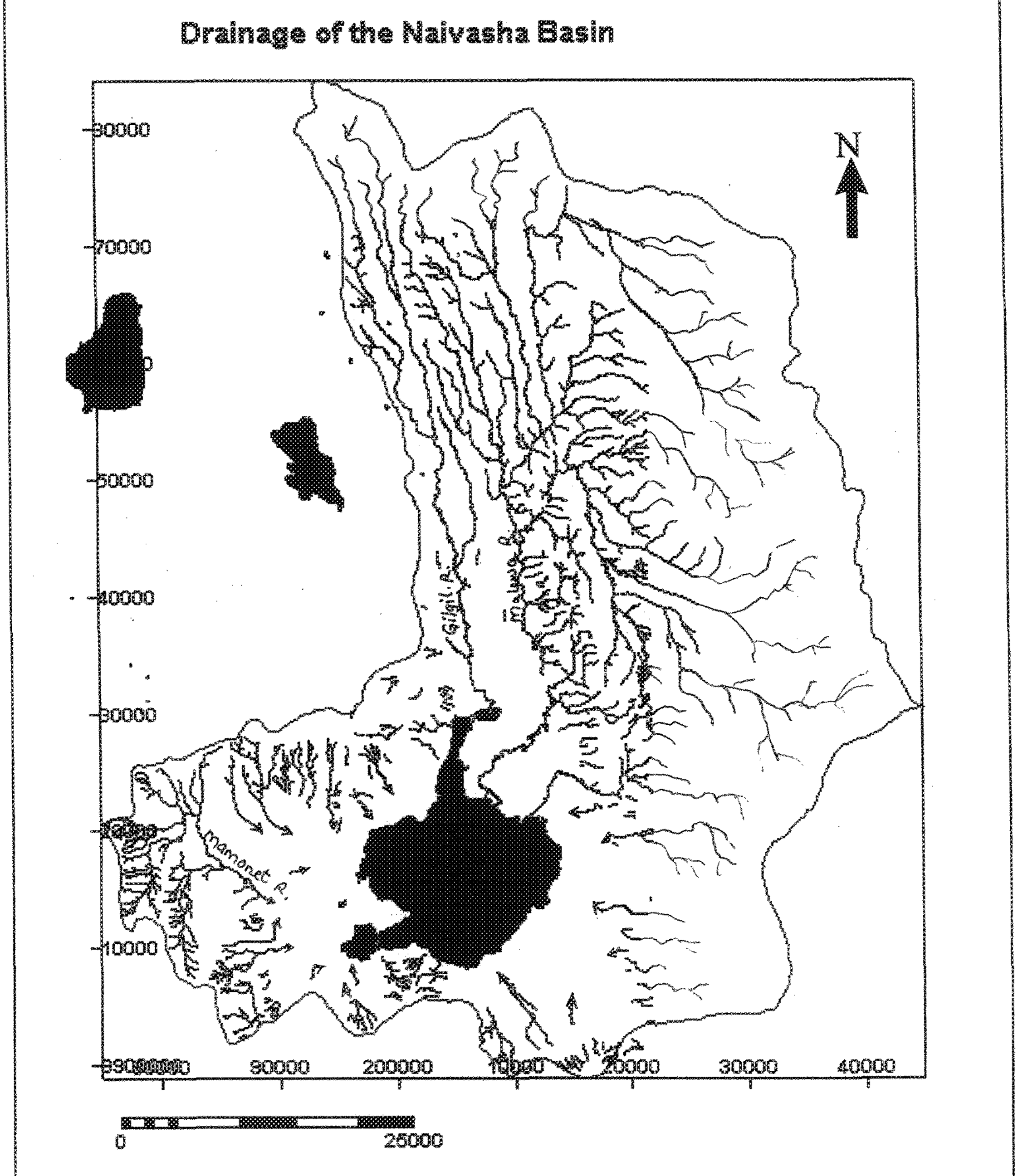


Figure 2.8 Drainage Map (in Part) of Naivasha basin

into the lake. Figure 2.6 shows the drainage of the basin though not in full.

The Malewa river rises on the western slopes of Nyandarua range at an altitude of about 3500 metres. The small streams flow westwards and develop into four main tributaries of Malewa; the Mugutyu, the Turasha, the Kitiri and Makungi. All the four streams flow to the north and south before turning west and joining the Malewa.

The Gilgil (Murindati) starts in the Bahati forest where it drains a long narrow basin. The river rises at 2640 metres in an area where rainfall is high, about 1300 mm per year. Only a few tributaries join this river.

The Karati also flows from the east and rises from the Kinangop plateau at an altitude of 2620 metres where there is annual rainfall of 800 mm. However, little water reaches the lake as the river only flows for a few months per annum at the most. Its contribution to lake water is normally ignored. Most of its water is lost into the porous soils, highly faulted and permeable strata of the area.

The Marmonet river originates in the Mau escarpments to the west of lake and descends to the lake through Ndabibi Estate. The flow also does not reach the lake but disappears by infiltration within the Ndabibi estate.

2.10 Land use and Vegetation

The natural vegetation in the south of Lake Naivasha, was an evergreen bush land with the characteristic species Euphorbia candelabrum (cactus-shaped) and the fire resistant acocanthera schimperi (Trump, 1967). Also several Acacia species and the many branched Leleshwa bush (Tarconanthus camphoratus) were more less natural in the landscape of the dry savannahs and grasslands. Nowdays, probably due to overgrazing, fire and down cutting, the whistling thorn tree (Acacia seyal) dominates. Near the lake, the "yellow fever tree" (Acacia xantophloea) is common. Other common species in the bushy secondary vegetation are the Tarconanthus camphratus, solanum incanum, Euphorbia candelbrum and Acacia nilotica. The common grasses are Themeda triandra and cynadon plectostachys (Fanden *et al* 1986).

An approximate crude landuse map was derived from the geometrically rectified satellite images (landsat TM, Jan, 1995) covering the whole study area. Supervised classification was carried out with the image processing software (ILWIS) using ground data collected from field survey. A thematic map containing spectrally distinct classes was produced. This was then simplified into a few classes: Forest, Pasture, Agriculture, Lava, Bare soil, Urban and Water by merging classes from more detailed map.

2.11 Water Balance

The water balance of the Naivasha basin is in deficit. The potential Evapotranspiration is over 1300 mm around Naivasha town which is more than the rainfall which is below 1000 mm annually. It would appear that only little runoff or inflow would come to the lake. The reason for the flow is that almost all the river system start in mountainous areas where the rainfall is very high (1300 mm). When the annual water balance of Naivasha is compared to annual Water balance of Nairobi, a remarkable difference is noticed. To the north, Nakuru has some surplus because it receives approximately twice as much rainfall as Naivasha. The lake (Naivasha) is situated on a rain shadow area, but the evaporation is still high. This is one of the reasons why there is irrigation around the lake. The graph is presented below. All the values in the table are averages for the entire basin:

***Table** 2.6* Long Term Average Water Balance (Average Monthly for the entire basin)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Precipitation	43	59	91	158	126	96	87	80	75	101	113	57	*1085*
Pet	110	116	128	103	99	94	96	103	112	119	96	108	*1283*
P-Pet	-67	-57	-37	55	27	2	-9	-23	-37	-18	17	-51	*-198*
Acc. Pot. Wl.	-118	-175	-213				-9	-32	-69	-87		-51	
Soil Moisture	89	32	-5	50	77	200	180	157	166	150	167	156	
ΔSoil Moisture	-67	-57	-37	55	27	123	-20	-23	9	-16	17	-11	
Aet	73	59	54	103	99	94	67	57	66	85	96	46	*898*
Deficit	37	57	74	0	0	0	29	46	46	34	0	63	*386*
Surplus	0	0	0	109	54	126	0	0	0	0	0	0	*289*
Total avail	1	1	0	110	109	180	90	45	23	11	6	3	
RO	1	0	0	55	55	90	45	23	11	6	3	1	*289*
Detention	1	0	0	55	55	90	45	23	11	6	3	1	

Pet = Potential Evapotranspiration,
P-Pet = difference between precipitation and Potential Evapotranspiration
Acc.Pot. Wl. = Accumulated Potential Water loss (adding the negative values)
ΔSoil Moisture = Change in soil moisture
Total Avail. = Amount of water available for Runoff
RO = Runoff

All the values in this table are millimetres. The Available water capacity is 200 mm with soil type Clay loam. The main vegetation is mainly scrubs (Brushy) woodland with rooting depth of approximately 80 cm. Using the table in appendices, 25 %(250 mm of water per 1000 mm depth of soil) is the Available Water Capacity for clay loam soils. (250 mm * 0.8 = 200 mm). Water retained in the soil was calculated from the accumulated potential water loss (see appendices) with 200 mm curve.

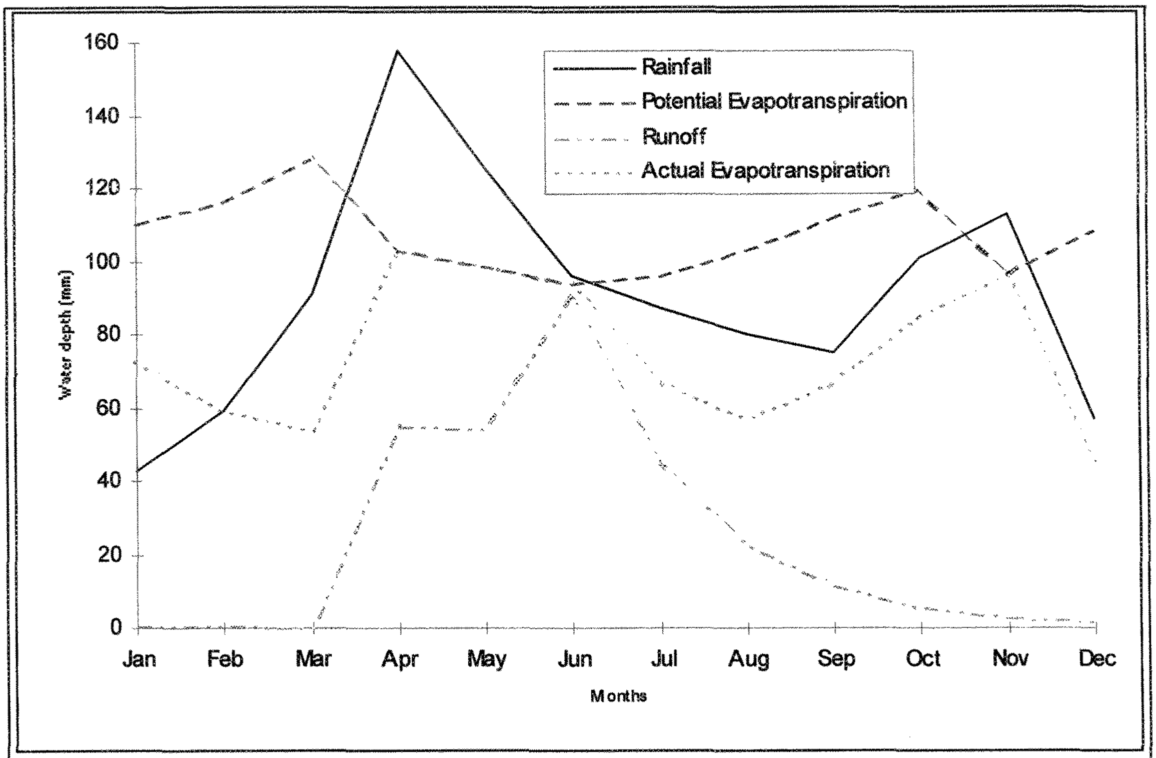


Figure 1.9 Graphic Representation of Long Term Average Monthly Water Balance of the Area

The method used is Thornthwaite's original methodology of calculating the water balance (Thornthwaite & Mather, 1957).

3 RAINFALL ANALYSIS

3.1 Introduction

A comprehensive understanding of precipitation and its distribution in time and space is essential for watershed modelling and evaluation of erosivity. Many factors determine the distribution of rainfall both in time and space and many of these have been studied effectively. Four major factors that affect the rainfall distribution in mountainous are the speed of ascending air, water vapour supply and speed and direction of the wind. Water vapour normally is responsible for the occurrence of storms, while wind speed is mainly related to rainfall intensity and is less related to its distribution. (Oki *et al.*, 1991)

The greatest part of the annual precipitation in Naivasha basin falls from April to June, whereas little precipitation falls in October and November the short rainy season. There is great variation in precipitation during the year. Further more variation in space is greater due to the irregular orography of the study area. In this analysis, 31 rainfall stations were used, all within and close to the catchment. The data is on monthly basis for an average period of 20 years. Most these stations lie above 2100 metres above sea level.

3.2 Probability and Return Period

The occurrence of rainfall is always characterized by its frequency. Below(figure 3.1 & 3.2) are the graphs showing return period and probability of (average) annual rainfall for the basin. For example, an annual rainfall of 700 mm could be expected with a probability of 50 % and return period of 2 years.

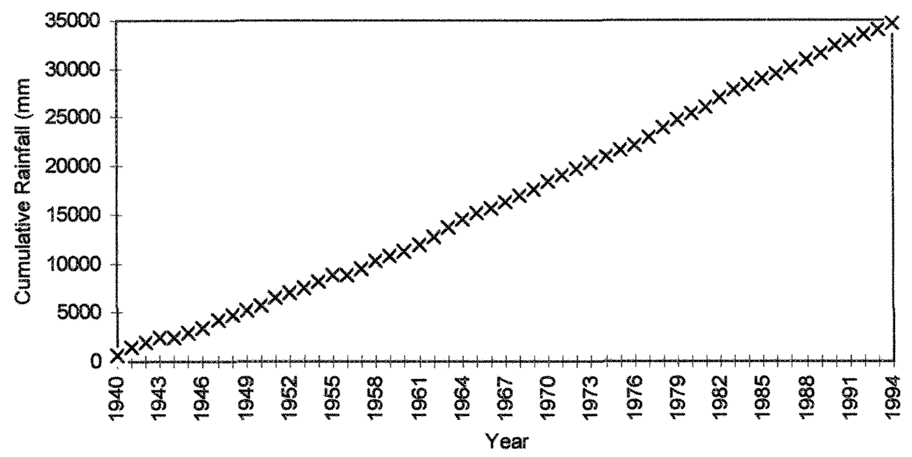


Figure 3.1 Mass curve of one of the Rainfall Stations on the southern shores of Lake Naivasha

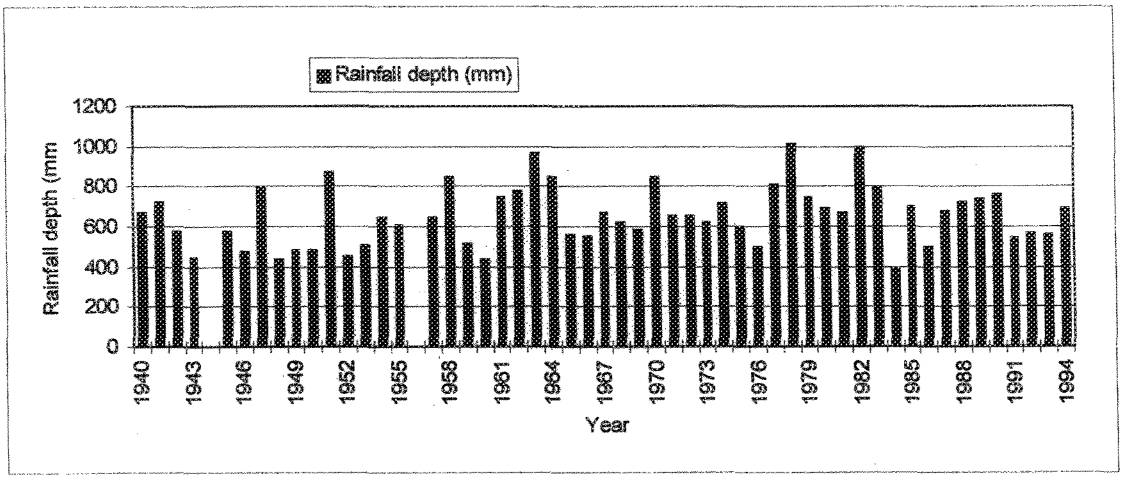


Figure 3.2 Annual Rainfall from 1940 - 1994 South of the Lake Naivasha (Marula farm)

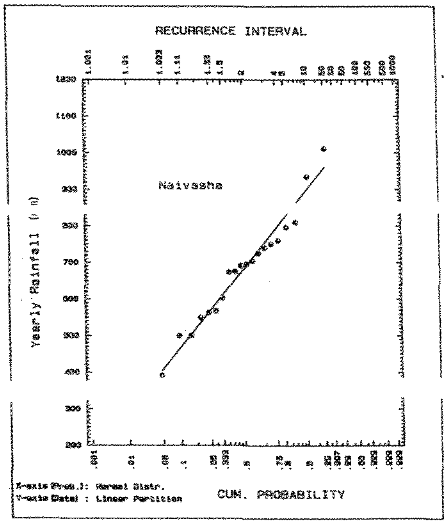


Figure 3.3 Probability of Mean Annual Rainfall

The summary below is not consistent with other values used latter in the analysis. This so because the values used here are average of rainfall stations for the entire basin where as latter in the analysis some figures are used without averaging them (stations).

Statistics

Number of observations: 20

Maximum Value: 1011 mm
Minimum Value: 391 mm

Mean 682 mm
Standard Deviation 148 mm

3.3 Temporal Variation

Variations in rainfall with time may be considered either in relation to the rainfall regime, the trends exhibited by the annual, seasonal or short term totals, or the statistical probability of a given areal pattern, individual rainfall total or intensity repeated within a period. Rainfall variability can be evaluated by using range, standard deviation, relative variability or other statistical parameters. In this analysis the temporal variability of monthly rainfall distribution with elevation and position of station will be analyzed by the coefficient of variation. The coefficient of variation is normally greatest at places of low latitudes in arid climates (Edward, 1992).

Figure 3.4 shows the distribution of mean monthly rainfall during the year within the catchment, average of all the stations. As can be seen, the area has dry period or low rainfall during December, January, February, July, August, and September. In addition the amount of rainfall in the rainy periods, represents more than 80 % of the annual rainfall.

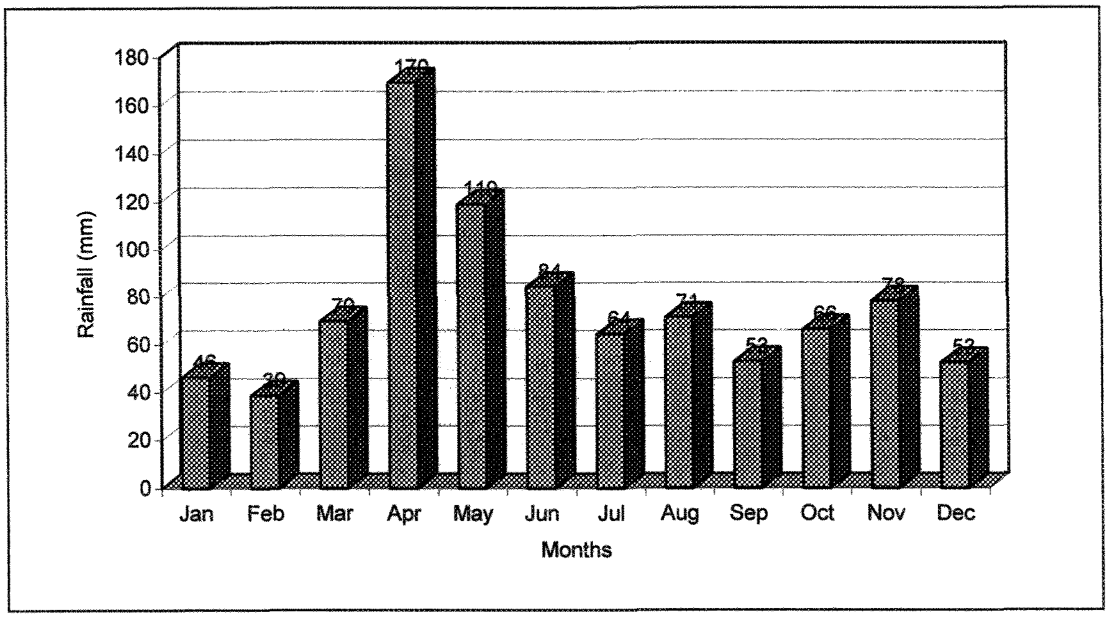


Figure 3.4 Mean Monthly Rainfall

The mean monthly rainfall of the stations is widely distributed ranging from 46.4 mm to 170 mm with a mean of 76.2 mm. The standard deviation of the monthly rainfall is about 36.1 mm while the coefficient of variation is 47.4 %.

The coefficient of variation is a relative measure of dispersion for different rainfall stations in a year. It was calculated by dividing the standard deviation by its mean. The stations with high CV has the highest fluctuations in year from one month to another.

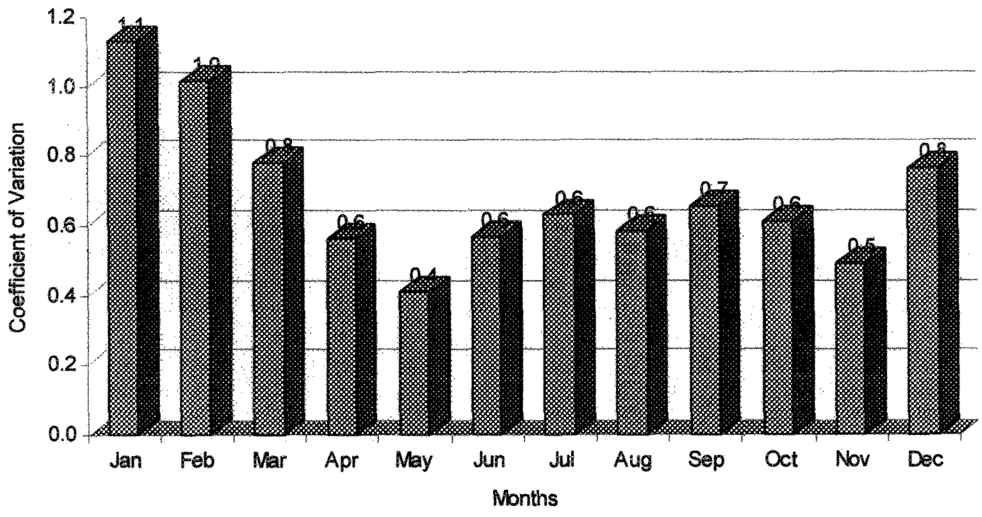


Figure 3.5 Coefficient of Variation for Monthly Rainfall

The distribution of the coefficient of variation in the individual months is shown in figure 3.5. The low values of this coefficient occur during the rainy periods (April - June and October - November). This means that the amount rainfall during this period (wet) does not vary by wide margins from year to year.

During the dry periods, the coefficient of variation is much higher, meaning that from one year to another there is much variability. Some years may be dry while others are not actually dry during these months. The month of January has the highest coefficient of variation but it is not necessarily the month with lowest mean monthly rainfall. The lowest mean monthly rainfall occurs in February.

3.4 Spatial Variation

The correlation between rainfall values at any two stations depends on the distance between, the kind of terrain, the type of rainfall, and whether it daily, monthly or annual precipitation in consideration. In general, the correlation is highest for stations which are close to each other.

In hydrology, it is well known that rainfall varies with elevation. Many studies show that there is a general increase in rainfall with increasing elevation (e.g. Smith, 1979, Jones, 1981). However in the study area this does not seem to be the trend. Figure 3.6 shows a scatter from monthly data that was available. An explanation to this scatter is that while some stations, located at high altitude, receive high rainfall other station at the same altitude may not receive as much rainfall if they located on rainy shadow (leeward) slopes. Even stations on low altitudes have low correlation between them. It can be concluded that one encounters greater rainfall as you ascend unless it is on the windward side of the mountain. It must be noted here that seasonal variation may have an effect on the correlation. Figure 3.6 shows the scatter in the relationship between elevation and amount of rainfall for the station in the catchment. Figure 3.7 is a graph showing the relationship between elevation and the correlation to Naivasha station. There is no good relationship at low altitudes and high ones too.

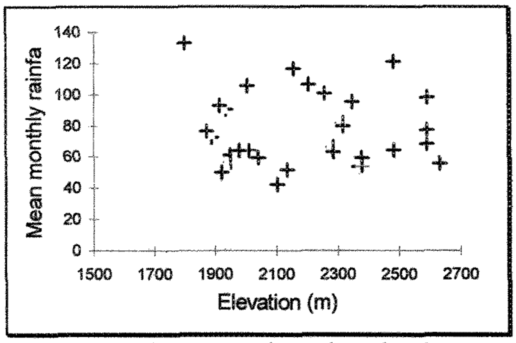


Figure 3.6 Elevation plotted with Mean Monthly Rainfall

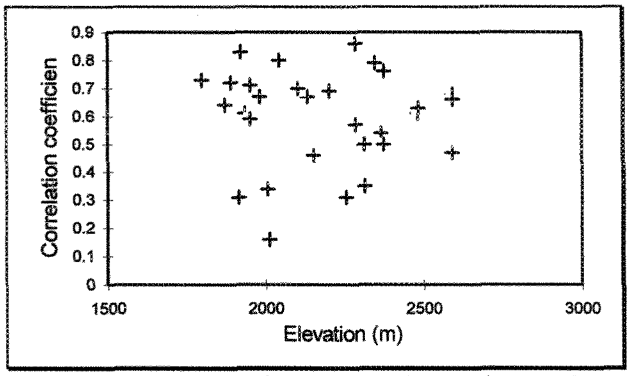


*Figure 3.7*Elevation of stations plot with correlation to Naivasha station (Correlation is against Naivasha)

In order to get an impression of the variability of rainfall, the distance between the stations were plotted against the correlation coefficient of rainfall of stations. From the graphs it can be seen the rainfall variability in this area is quite complex. Moving from one area to another does not necessarily result in a rise or a fall of the amount or even intensity of rainfall with respect to elevation. The erosivity therefore would follow the same complex pattern.

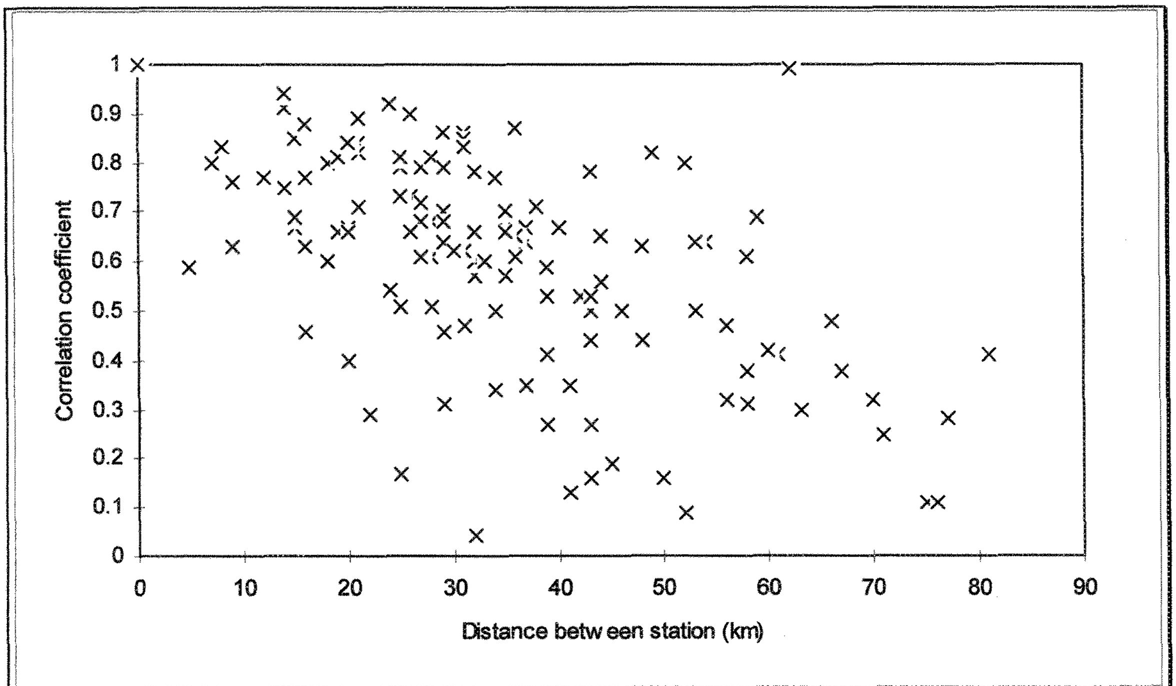


Figure 3.8 Distance between (some) station and their monthly correlation

It can be conclude, therefore, that there is no pattern detected in the change of coefficient of variation of rainfall with elevation. Further the gradient increase in rainfall with elevation is not well defined except that seasonal influence may come in.

3.5 Use of Vegetation Densities from satellite Image.

The vegetation pattern on the multispectral satellite image was observed to be influenced by the rainfall pattern. This was used to improve the existing rainfall stations in terms of distribution over the area. The vegetation on the satellite image shows areas with high rainfall. Using the satellite image areas with thick forests indicates that rainfall in those areas is high. Using the colour composites, these areas become visible and were delineated. The rainfall station (point map) was over laid on the false colour composite and the isohyets were drawn with the vegetation and rainfall depth of the stations available. The dense vegetation was associated with high rainfall. With the rainfall stations on the image, the rainfall depth for each isohyet line was estimated. The forest dense area; Mau escarpment on the west, the Eburru to the north west and the Aberdare' range to the eastern side were found to be high rainfall areas (above 1000 mm) line. The lower part of the rift valley was moderate 600 - 1000 mm while the area close to the lake was found to be below 600 mm annually (Figure 3.9). The vegetation (forest, agriculture) were associated with high water table and irrigation respectively. An Isohyetal map below shows rainfall pattern of the area in consideration. This is based on the average rainfall data available. In some stations it is more than 30 years of continuos record while others it is less and in some cases not even continuos.

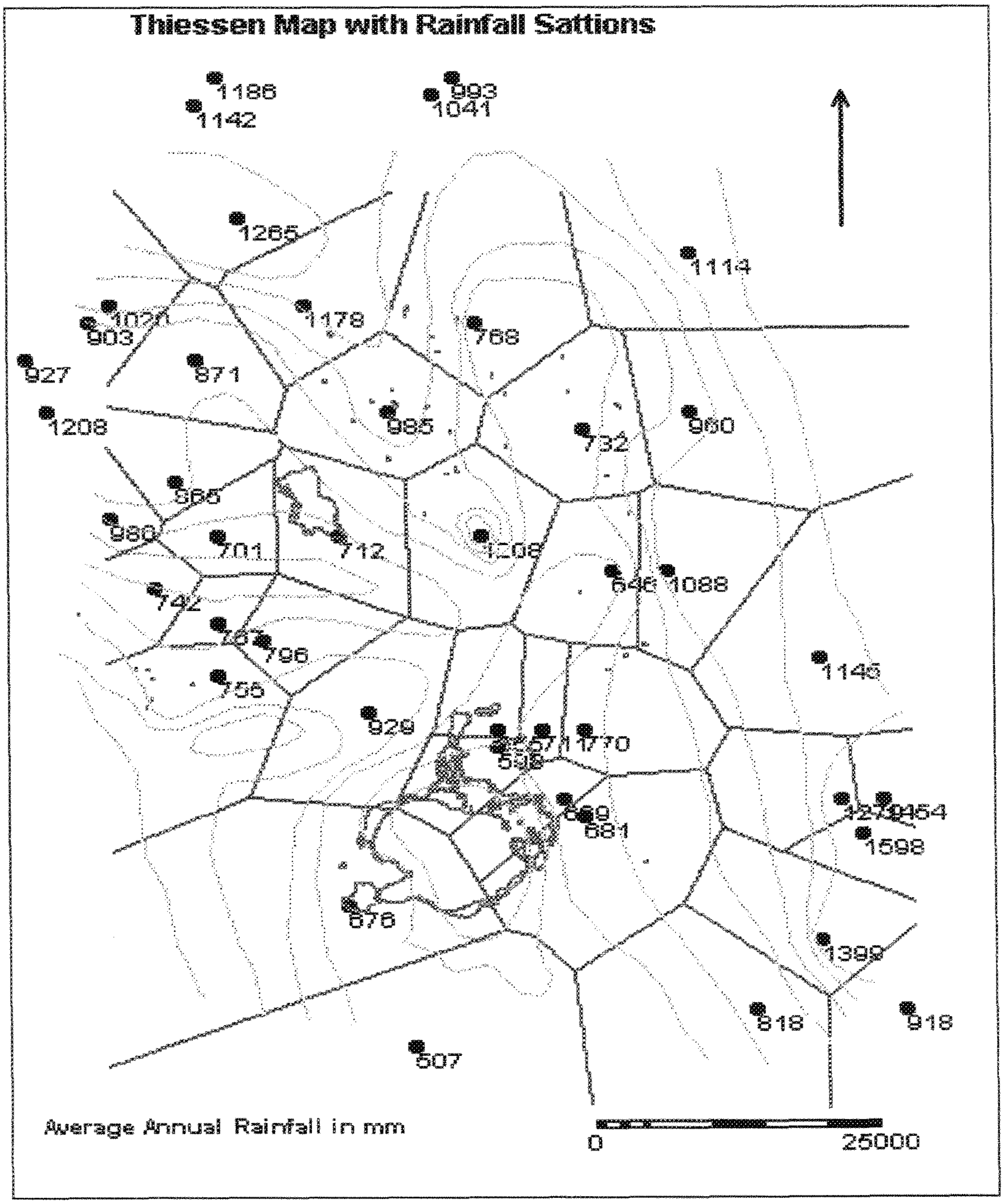


Figure 3.10 Thiessen Polygon map of the Study Area

The thiessen polygon map was prepared from the existing rainfall stations. The values on each dot indicate the average yearly rainfall in millimetres. However it must be noted here that number of years in record differ from station to station. Some stations (Naivasha D.O) has more than 30 years of record while others have only up to 10 years. The average in this case takes in account the number of years of recording.

3.6 Rainfall Erosivity Analysis

Although total rainfall may increase in the highlands with increasing altitude, intensities and erosivity does not seem to be so high in the mountains. For example, Thomas *et al*, (1981) working at an altitude of 1500-2000 m at Isuni in Machakos District, Kenya, only recorded five storms with intensities greater than 25 mm/hour (for a 15-minute duration) out of 30 storms recorded during November and December 1978. They concluded that Isuni was located in an area of low erosivity. Fournier (1962) has produced a map showing the expected erosion hazards throughout Africa.

Hudson (1981) also concludes that the vital difference is that in temperate rainfall about 95% of the rain falls at low non-erosive intensities, i.e. only 5% is heavy enough to cause erosion, whereas in the case of tropical rainfall, about 60% falls at intensities less than 25 mm/hour, and the remaining 40% contributes to soil erosion.

Although detailed information is still lacking on both the erosivity of the rains and the erodibility of the soils in many parts of Africa, it is clear that the risks of accelerated erosion are very high in these areas. Charreau (1974) pointed out that, on average, tropical rains have 6-10 times more erosive power than temperate rains. However in the study area, especially near the Naivasha town, the rainfall is quite low, less than 600

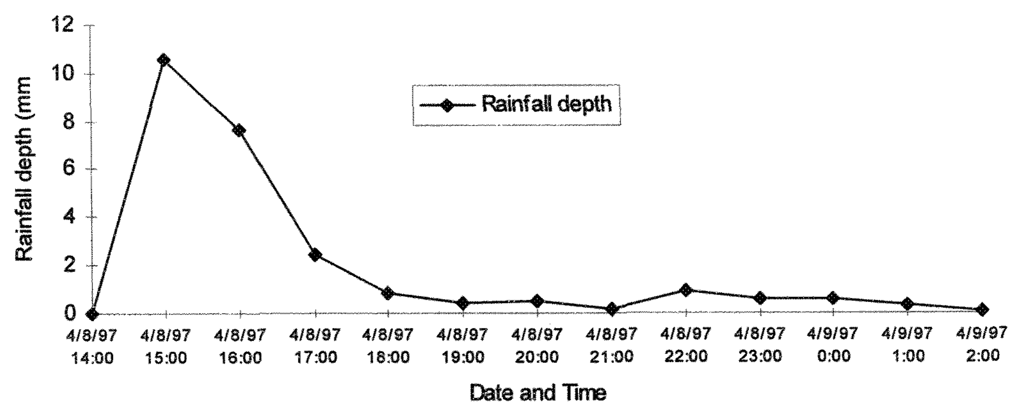


Figure 3.11 Typical Rainfall Storm Hydrograph during the Month of April, 1997

mm per annum. It is clear that the rainfall is of low intensity and less than 10 mm in a day for the whole month of October. This station is located at the Kenya wildlife Services Training Institute, where there is an automatic rainfall recorder. The total for the month of October, 1997during the field visit was 53 mm.

For erosivity, many formulae exist that are used in calculating the erosivity indices. The most prominent and widely used is the USLE's R factor (Wischmeier *et al* 1978). Bergsma, 1981, also recommended this factor. The only problem is that it has limitations of applicability to other areas apart from the USA, though it has been applied in some other parts of the world like Thailand. Research has continued and many indices have emerged, some of which are just modifications of the original R factor in USLE. Others include Morgan (1974) Roose, 1977, Bols (1978), Lombardi (1979), Moore, (1979), Sithen et al, (1982), Lo et al (1985), and Mannaerts (1992). All these were developed for different regions, mostly for tropical climates.

Hudson (1986) reported that, for southern Africa, only intensities higher than 25.4 mm/h caused significant splash. His index cannot be used in the study area because the intensities are much lower than 25.4 mm/h. Typical values were used that have been derived from local conditions of the region. The correlation between the Fournier index and the Wischmeier's R factor was weak but a better correlation can be found after adding some climatic 'constants'. These constants, *a* & *b* vary greatly with different climatic zones.

$$R = \sum_{i=1}^{12} \frac{p_i^{\,2}}{P}$$

where; R is the Erosivity index, p_i, is the rainfall in a month and P is the annual rainfall in mm. Using a local formula, $EI_{30} = 0.269{*}P_{ann}{+}113$ (Bresch, 1993) erosivity was calculated on average yearly basis. The yearly erosivity was 189 N/h. This figure was close to the value calculated for Nakuru with slightly higher annual rainfall of 827 mm with erosivity value of 224 N/h. The data used here was from the Naivasha District officie, which had long history of rainfall data.

For area, the erosivity for 1997 was calculated on monthly basis using the rainfall data from Kenya Wildlife Services Training Institute in Naivasha District. The automatic rainfall recorder had been in operation for about year. The data used in this analysis is from the sheet obtained from the recorder for the year 1997. The station is located in the rain shadow area. The calculations were based on the formula:

$$E = 0.29\left(1 - 0.72\exp(-0.05 * I)\right)$$

where E is the Erosivity (MJ/ha.mm/h)
I is the rainfall intensity (mm/h)

The recorded rainfall sheets were inspected and only rainfall storms greater than 10 mm depth were used for the erosivity calculation. Any storm less than 10 mm is said to be insignificant in terms of erosivity. Furthermore only storms separated by more six hours were taken as single storms. The total rainfall depth for year is 804 mm. This was above average year, especially in the month of December (1997).

Table 3.1 Typical example of a Rainfall storm and the intensity

Date -time	Cum Rainfall mm	Rainfall per hour mm	Kinetic energy MJ/ha	K.E.* intensity MJ/ha	Max Intensity*1.6 mm/hr	Total Erosivity MJ/ha.mm/hr
07-Apr-97 15:00	0	0	0.000	0		
08-Apr-97 15:00	10.6	10.6	0.167	1.771252		
08-Apr-97 16:00	18.2	7.6	0.147	1.118794		
08-Apr-97 17:00	20.6	2.4	0.105	0.251546		
08-Apr-97 18:00	21.4	0.8	0.089	0.07151		
08-Apr-97 19:00	21.8	0.4	0.085	0.034134		
08-Apr-97 20:00	22.3	0.5	0.086	0.043178		
08-Apr-97 21:00	22.5	0.2	0.083	0.016656		
08-Apr-97 22:00	23.4	0.9	0.090	0.081349		
08-Apr-97 23:00	24	0.6	0.087	0.052423		
09-Apr-97 00:00	24.6	0.6	0.087	0.052423		
09-Apr-97 01:00	24.9	0.3	0.084	0.025293		
09-Apr-97 02:00	25	0.1	0.082	0.008224		
	25	25		3.52678	16.96	59.8142

As can be seen from the figure below, the highest values occur during the long rain season, April - June. The short rainy season does not have high erosivity as can be seen in October and November.

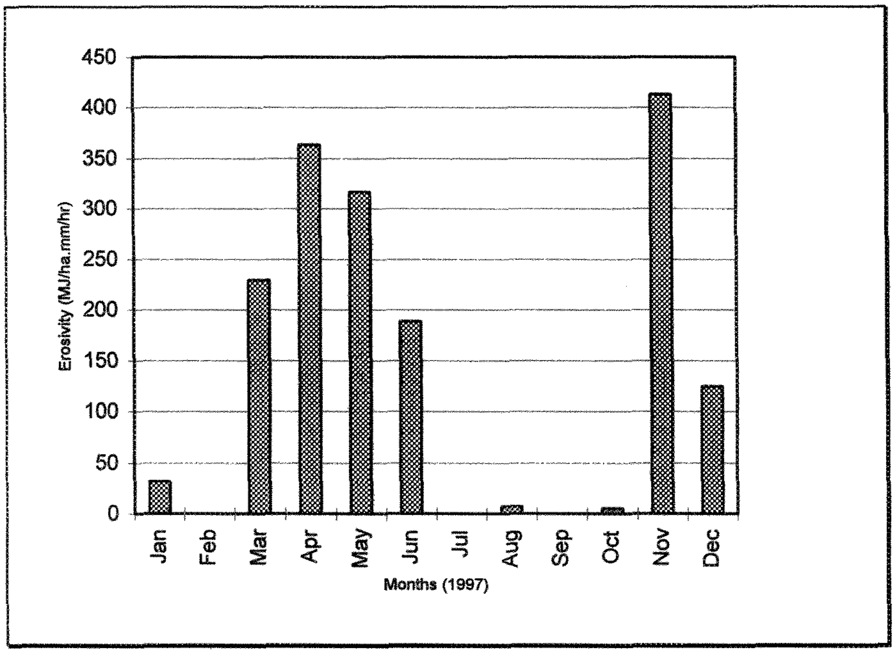


Figure 3.12 Monthly Erosivity for the Year, 1997

Figure 3.12 shows that the highest erosivity comes at the time when the vegetative cover is poor i.e. after a long dry period. This is the worst situation, little cover with high erosivity. From the field visit in October, 1997, it became very clear the vegetation in this area quickly recovers if rains is continuous. Within a few days six (6) days, the grass changed the whole scenario into green vegetation. This would reduce these high figures, especially in rain seasons.

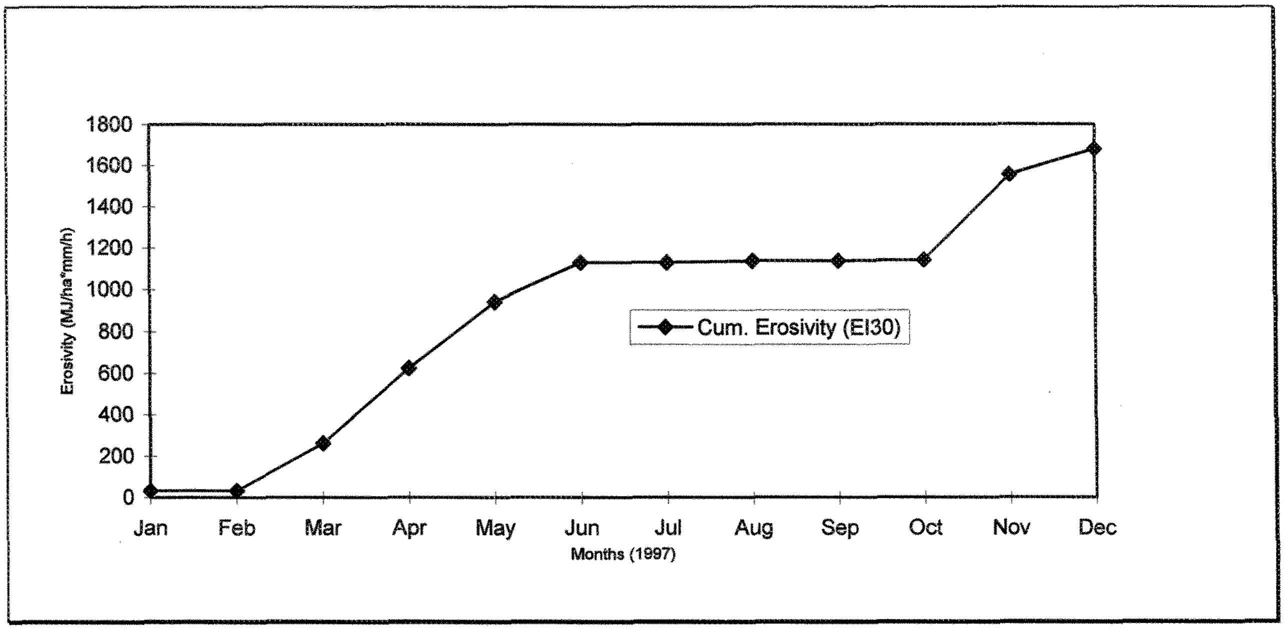


Figure 3.13 Cumulative Monthly Erosivity (1997)

Figure 3.13 shows that there are two periods in the year in which the erosivity increases; the April through June and October and November with December. These are the times when erosive storm occur and these are the same periods after a long period of no rain; meaning that the vegetation cover is poor, especially in April and October.

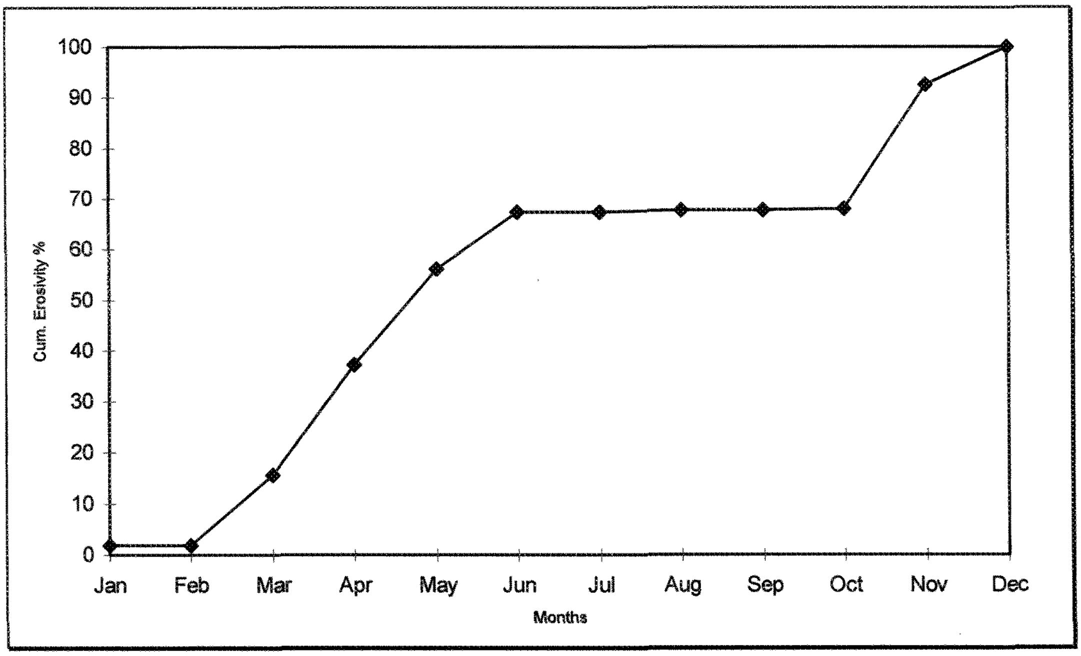


Figure 3.14 Cumulative Monthly % Erosivity

From the cumulative erosivity graph above (figure 3.14), it can be said that the erosive storms occur beginning of March up to June and the second period in October and November of the year. During the months of July, August, September and early October there are few erosive storms, if any. Rainfall is not continuos, there by resulting in low erosivity in these months. Figure 3.15 shows the distribution of rainfall during the year 1997.

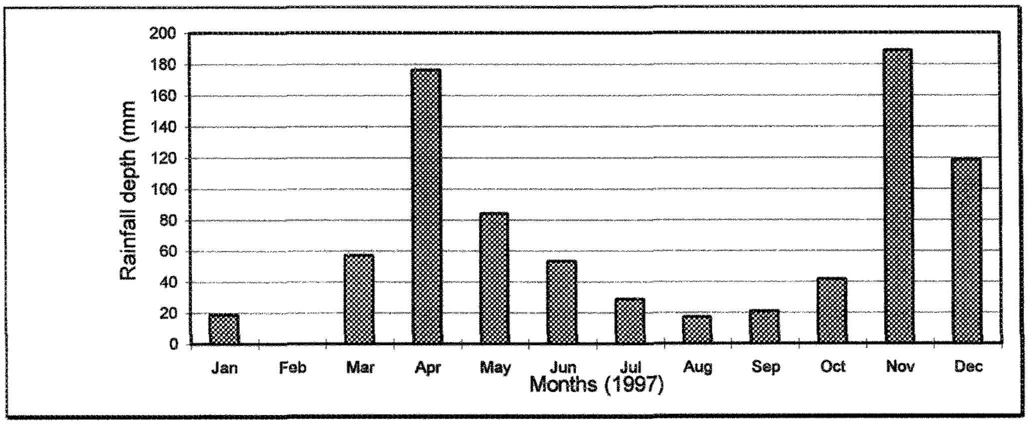


Figure 3.15 Monthly Rainfall (1997)

Figure 3.16 shows the relationship between the amount of rainfall ratio in every month compared to ratio of erosivity to the annual value. It therefore gives an idea of the month with high erosive storms. For example, in August, there is very little rainfall depth but still the few storms that occurred were highly erosive.

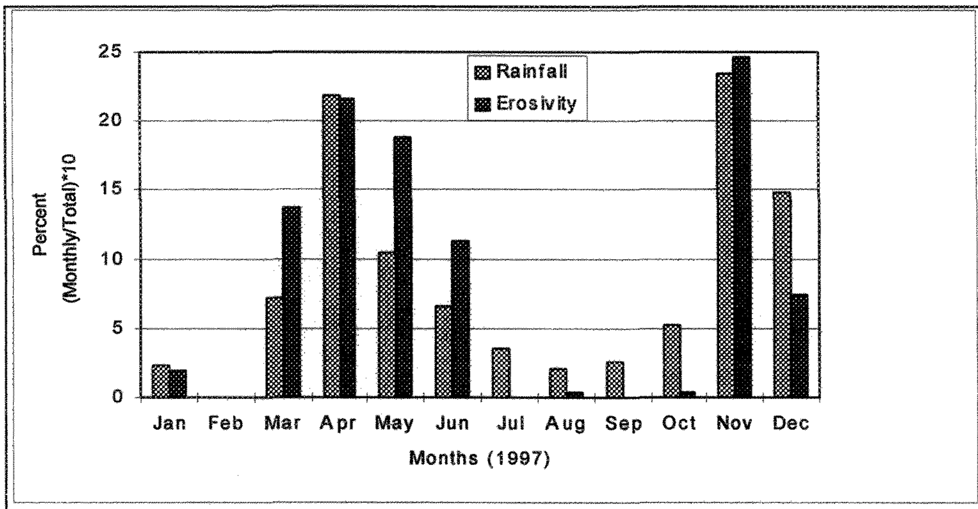


Figure 3.16 Monthly Percentage Rainfall / Erosivity to the Total of the Year (1997)

The relationship between monthly rainfall depth and erosivity was derived from the graphs in figures 3.17 & 3.18. It is rather difficult to derive a proper relation due to few data points available and is only for one year. A weak relationship could be derived from the graph, that is linear; months with high rainfall have high erosivity.

The correlation between the monthly rainfall and monthly erosivity is better but only a linear relationship seemed to occur. The storm depths that were used for this analysis were those above a threshold of 10 mm depth. This means that the equations below apply only for storm above this threshold. The relationships resulted in equations (see figures 3.17 & 3.18);

$$EI_{30} = 2.17P - 5.79 \qquad \text{(on monthly basis)}$$

$$EI_{30} = 8.28P - 86.22 \qquad \text{(on storm basis)}$$

$$EI_{30} = 0.0087P^{2.907} \qquad \text{(on storm basis)}$$

for rainfall depth greater than 10 mm threshold.

EI_{30}=Max. 30 minute storm erosivity (MJ/ha.mm/h)
P = monthly rainfall (mm);

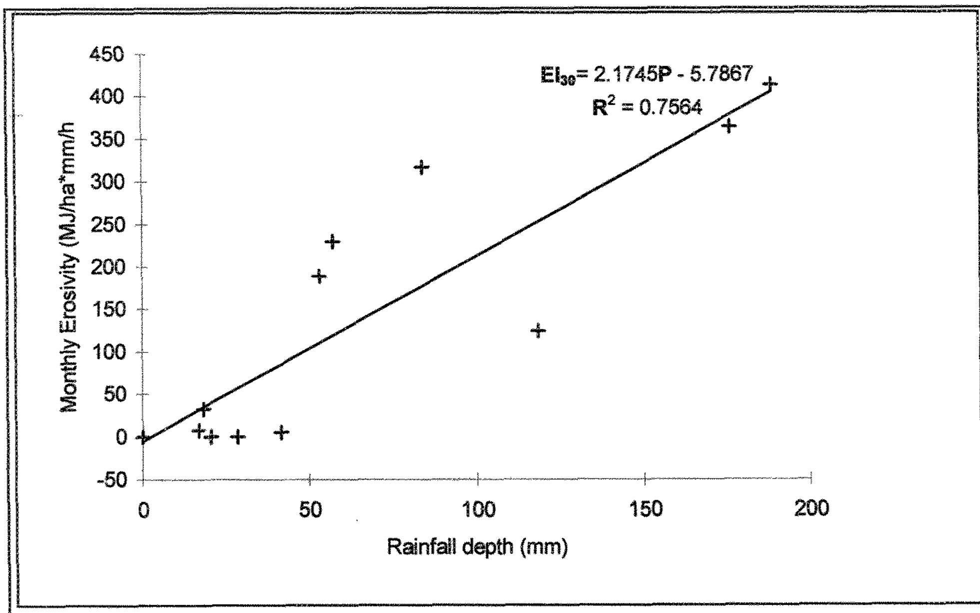


Figure 3.17 Relationship between Monthly Rainfall and Erosivity

A better relationship is seen when the individual storms with their erosivity are plotted. Though the correlation is low (0.62) it becomes clear that the storm depth and erosivity are highly related. This very weak relationship can be used for assessment of erosivity within the basin.

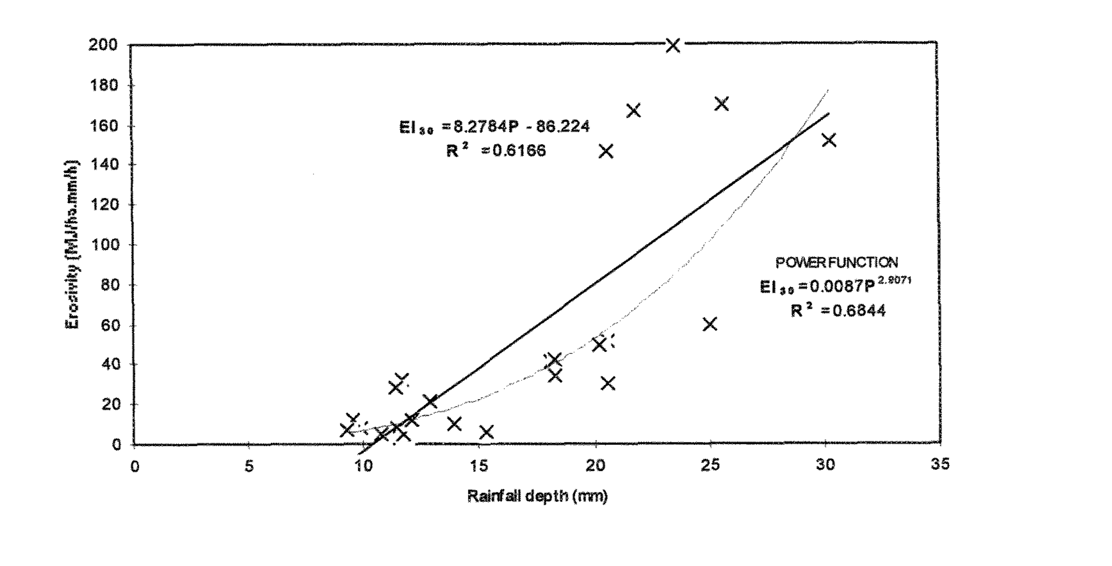


Figure 3.18 Relationship between Storm Depth and Erosivity

It should be noted here that these relationship are based on one year's data and therefore need to be checked before they applied as the rainfall pattern varies from year to year. For example, in the month of December the area does receive as much as 1997 during other normal years. For example, in average years, the month of December receives about 60 mm but in 1997, it recorded 120 mm twice as much. However, this gives the indication of the ranges of erosivity values expected in the area. With more detailed data more analysis should be made in order to get the average value over a long period which will be represent of what happens over the area.

4 RUNOFF AND SEDIMENT TRANSPORT

4.1 Introduction

Stream flows are responses to direct precipitation, base flow and catchment characteristics. How quickly the stream reacts to rainfall depends on these factors. Proper estimation and determination of factors requires experience and good judgement on the part of the hydrologist. All hydrological processes upstream can be determined if accurate factors are used.

There is a net loss of soil from a given section of land in an erosion eventuality when the amassed flux of sediments exceeds that which enters. The flux of sediment, q_s, (kg m^{-1} s^{-1}) is related to the volumetric water flux per unit width of flow, q, (m^3 m^{-1} s) and the concentration of sediments within the overland flow, c (kg m^{-3}). An equation that expresses this relationship:

$$q_s = q \times c$$

This expression indicates that soil loss depends equally on the surface hydrology, affecting q, and on factors that determine the sediment concentration, c. Thus estimating the generation and extent of overland flow is the first step in water erosion modelling.

4.2 Flow Component Separation

It, therefore, begins with the analysis of hydrograph. The various components of natural hydrograph are always separated into segments. One of the major components is the base flow that is, always, at the beginning of the hydrograph. This (base flow) is the groundwater contribution from aquifers bordering the river that goes on discharging more and slowly with time.

The dividing line between the direct runoff and the base flow is often very difficult to draw and can vary widely depending on the factors considered. To investigate its accurate position would require a detailed knowledge of the geo hydrology of the catchment, including the areal limits and transmissivity of the aquifers.

In the study area, a continuous hydrograph of the Malewa River was emulated in the TIMESPLOT program (Donker, 1995). The program was made for combining daily rainfall and runoff data into time series graphs. (See figure 4.1) The hydrograph was analysed and the base flow separation was performed. A filter parameter of 0.95 was used, an average value, in the filter described by Nathan and McMahon for the removal of base flow from high frequencies of quick flow. The program serves an efficient tool for the time series graphs. The total rainfall depth for the year 1982, was 1068 mm with only 177 mm as direct storm flow while the base flow is estimated as 856 mm. In 1980, with a total rainfall of 928 mm, 133 mm was the direct storm flow, and 795 mm was base flow.

The hydrograph was then digitised to estimate the amount base flow on the graphs within the period (one-year). The area under the curve being the amount of base flow and direct runoff (figure 4.2). The digitised drawing showed that the base flow for whole year was 842 mm while the direct runoff was 226 mm. This clearly shows that most of the flow in the rivers is not direct runoff but come as intermedite flow due to the nature of the soils in the catchment. The differences in base flow between the years shows that most of the runoff does not come immediately to the river channels within catchment but is delayed due high infiltration rates. At the end of the rain season the water table becomes low and keeps going down into the base flow system which then becomes active through the dry period. In the 1983 water year, the delayed flow was 306 mm while the base flow is 650 mm and 112 as direct storm flow.

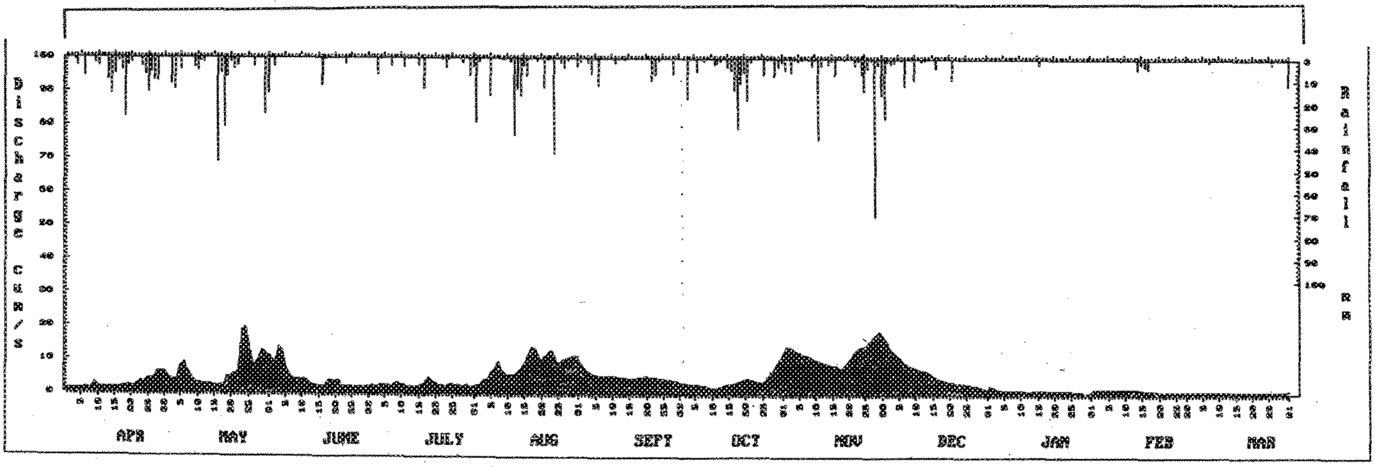


Figure 4.1 Time series plot for the year (1983) Rainfall (mm) and Runoff (m^3s^{-1})

The poor correlation between rainfall and discharge is caused mainly by factors; the size of the catchment and the characteristic of the catchment i.e. high infiltration rates. The large size of the catchment also determines how fast the flow in the river would respond to any storm at any site within the catchment. If the catchment was small, the response is quick, good correlation, if catchment has moderate infiltration rates. Secondly, Naivasha basin is characterised by soils with high infiltration rates resulting in low runoff coefficient of less than 0.21. This also determines how quickly the discharge in river would respond, in this case, Malewa's response to any storm is delayed hence the poor correlation.

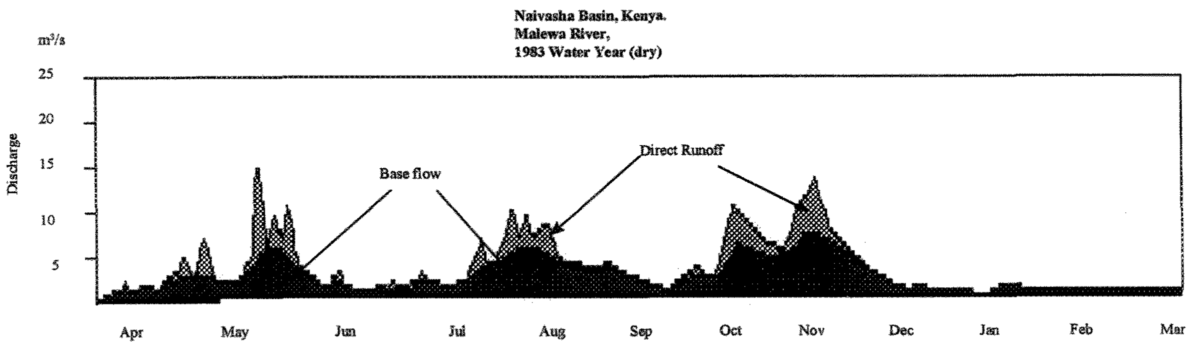


***Figure* 4.2** Intermediate flow, Malewa River (Base flow system) (1983)

There are two base flow system as can be seen from the figures above (figure 4.2 & 4.3); the intermediate flow and the base flow respectively. The delayed flow system is one which is active when there is continuos rain (e.g. during the rain period of April - June). At the end of the season, the base flow becomes active as there is no rainfall to continue adding to the delayed flow. The delayed flow disappears (goes down) and the base flow becomes the supply of water for the rivers. The year 1983 was chosen on the basis that it was a dry year and therefore would give representative picture of the flow system.

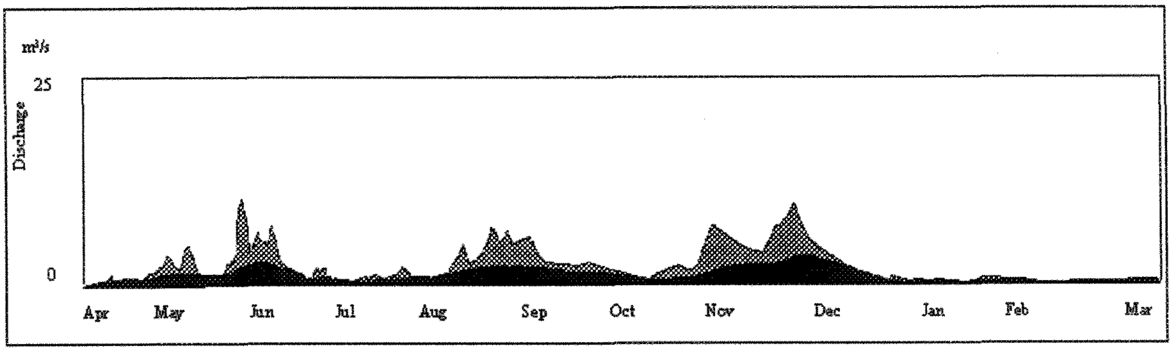


***Figure* 4.3** Base flow flow, Malewa River (Base flow system) (1983)

4.3 Sediment Yield from Suspended Load

Sediment yield estimates are required for studies of soil & water conservation and design of erosion control structures. For the planner, this is the information describing the erosion processes occurring in the upper catchment. One of the main problems faced is the quantification of sediments being brought down.

Several studies have been carried out trying to relate the sediment load to many contributing variables in the catchment. Attempts have been made in trying to relate the sediment yields of catchments to simple climatological indices such as annual rainfall (Langbein & Schumm 1958, Wilson 1973) , seasonality of rainfall (Fournier, 1960) and Runoff (Douglas 1967, Dendy & Bolton 1976). Wilson (1976) reviewed these studies and concluded that no single relationship is valid on a world wide basis, and that even within a relatively uniform area, the most important single control is land use (Dunne, 1979).

Presently suspended sediment load in streams is calculated by direct measurements, adjustments to regression lines and interpolation of the already existing data. Models are also available for the estimation of sediment load (e.g. USLE, AGNPS, etc.). However, most of these models do not take into the deposition process that occurs within large catchments and the result is overestimation of the erosion in the catchment. Suspended load gives only an idea of the soil loss in the catchment, as the sediment yield from a catchment is difficult to measure. The following are the drawbacks in using sediment yield for soil loss:

- Sediment yield measurements consist of only the suspended load while bed load is never taken into account and is difficult to measure. The bed load of most African rivers accounts for frequently between 5 and 10 % of the suspended load (Walling, 1979).

- The sediment delivery ratio varies with the size of catchment. The delivery ratio for large catchments is always lower than those of smaller catchments due to depositions in large catchments. Walling (1988) came up with relationship of decreasing SDR with increasing size of catchment.

- The soil loss from a catchment sometimes undergoes a series of cycles of being eroded and deposited before it finally reaches the outlet where the measurements are done. The suspended load may reflect soil loss of sometime in the past.

- Suspended load is not only as a result of sheet and or rill erosion. It sometimes includes landslides, gully, channel, stream bank erosion, etc.

Another problem is the timing of sampling the suspended load in rivers as the suspended load varies with time. Unless where the measurement is continuous (automatic recording), the hydrograph and the sedimentgraph do match or in phase. Williams (1989) classified the sedimentgraphs according to their position in relation to hydrograph peak into four (4) groups; (i) advanced, (ii) In-phase, (iii) delayed and (iv) multiple. These groups describe the detachment and transport patterns of catchment up stream. The advanced for example is one where most of detachment is done during the beginning of the storm, thereby sediments are transport before the peak of the hydrograph.

For sediment yield studies, it is important that these classifications are considered. It is also vital to know that in any particular catchment, each of these classification could take place, though the third (delayed) is not common (Jeje *et al*, 1991). Sampling, therefore, is quite an uncertain method though it is probably the most direct way of measuring the suspended sediment. In addition, the suspended load measurements do not include the bed load that forms a good portion of the eroded material.

In the study area, some suspended sediment data was collected for the period 1949 to 1956 for the main rivers in the catchment. The data source is Water Master Plans under the JICA project (Hydrology section, 1992). The accuracy of this data is very questinable but had to be used to be able to realise the relationship that exist between the discharge and the sediment load. The data was recorded using the depth -integration method at the time with discharge data. The suspended sediment data was plotted against the discharge. This method ensure that sampling is done at different depth of channel. The scatter was difficult to interpret and no relationship could be realised from the plot.

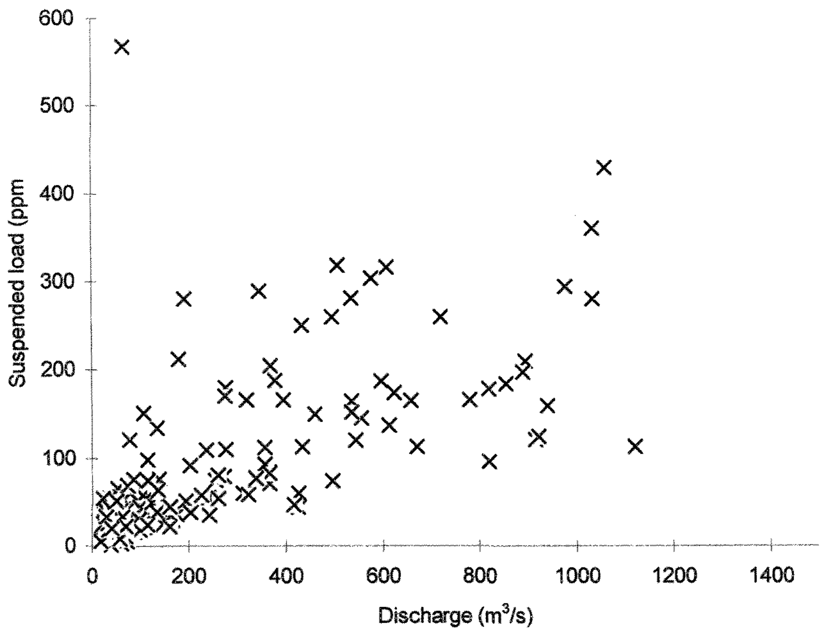


Figure 4.4 Suspended load and Discharge for the Malewa river (1950-1956)

Most of the data is scattered around the origin and efforts to put a line of best fit could not yield any good results. The question that always remains is the accuracy of the data. However there is a general trend of sediment yield increase with runoff. High runoff is always associated with heavy storms and their greater erosivity for the detachment process and transport of the eroded material. As can be seen from the graph (figure 4.4), some points are completely away from the cluster. An explanation for this is very difficult but assumptions may be put forward. The outlying points could be the result from a landslide upstream, animals cross the river, washing cultivation machinery like tractors, harrow, etc. Therefore such observations are omitted from the data set for analysis. Actually a lot of such points existed but for reasons of clarity the axis scale was reduced on the discharge axis. The segmentation was then the only way to obtain a relationship between the discharge and the suspended load. The data was then segmented into seasons, the long rain period as one season, the dry months as another and the short rain period for the other season. Some relationship seemed to show up at this point.

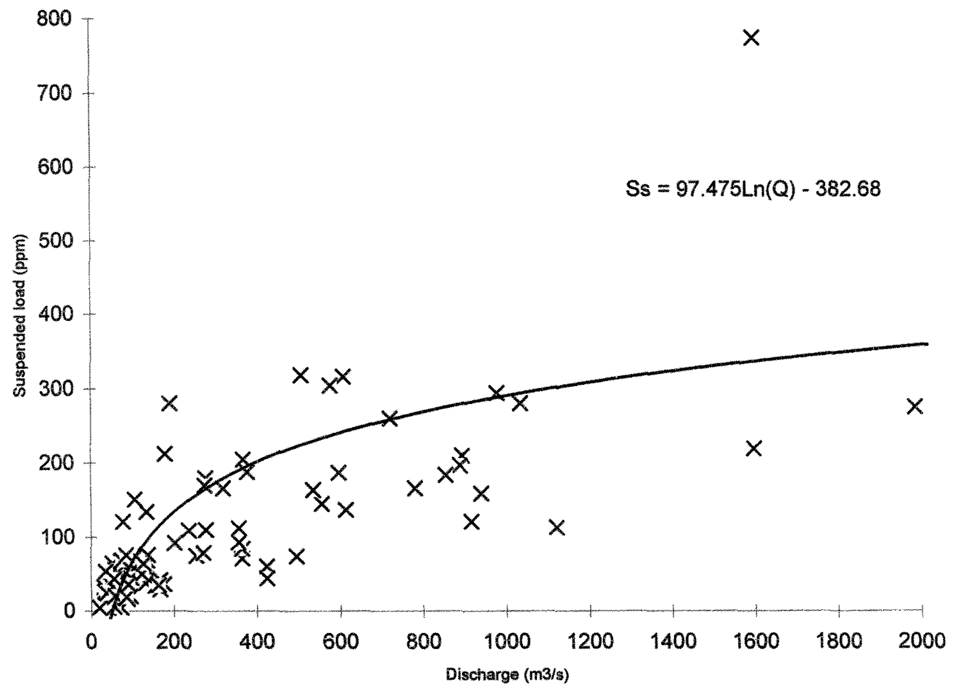


Figure 4.5 Discharge and suspended load during the long rains (April - June)

Figure 4.5 shows some relationship though not very clear. Certain behaviour of the stream can be interpreted here. A lot the sediments are carried by low discharge of the stream. Although occasional high discharge may carry more sediment, the frequency of these high discharges is low. It may be said that more than 3/4 of the sediment load are carried during the low discharge periods during the rainy season. The other reason is that Malewa River has a very big drainage zone. The varying land cover, geological, soil, slope formation from one end of the catchment to the other are more likely to be the influencing factors of the scatter. Sometimes rain falls on one side of the catchment that may not produce as much sediments as other parts resulting in high runoff with less suspended load. The vice versa is also correct and results in low discharges with high-suspended load.

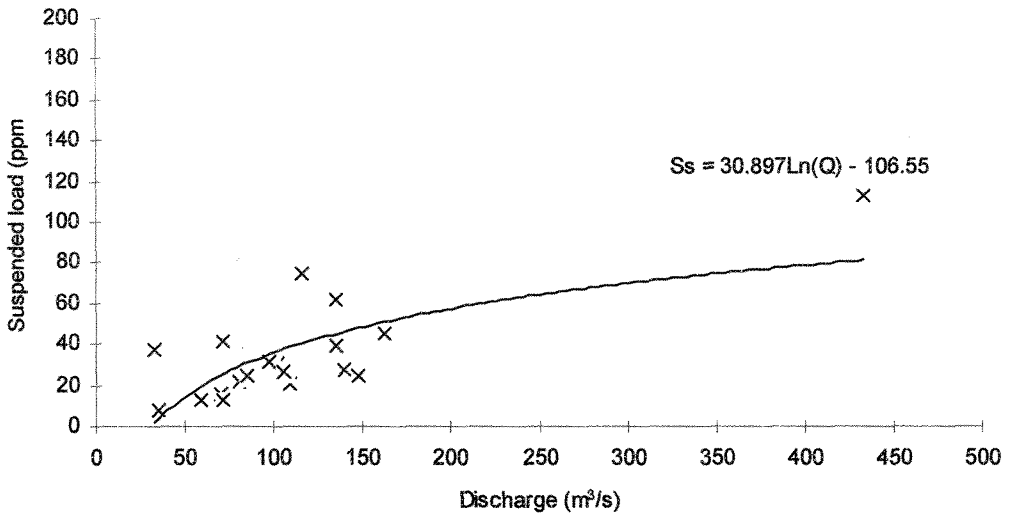


Figure 4.6 Discharge and suspended load in Malewa river during the short rainy season (Oct - Nov)

Similarly in figure 4.6, the data points are located very close to the original due to low sediment and discharge values in the season. In this season, the suspended load is normally less than 80 ppm. In this case, the sediment in the river can be considered to be very low.

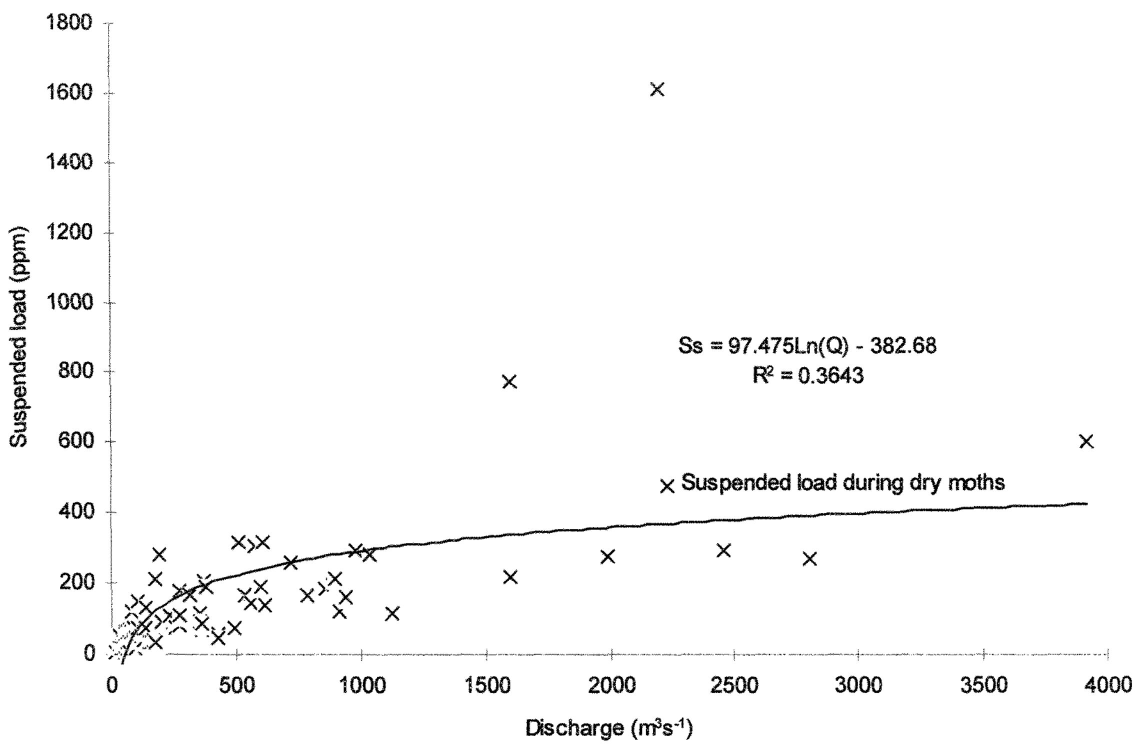


Figure 4.7 Discharge and suspended load in Malewa River during the dry months

The results were also put in a tabular form to find the average, the standard deviation for each season.

	Malewa River		*Turasha River*	
Season	**Mean**	**std.**	**Mean**	**std.**
Long rainy season	199	135	72	81
Short rainy season	25	35	26	16
Dry period	208	93	41	68
First Rains	110	204	57	62

Table 4.1 The Mean and the Standard Deviation of Suspended Load (ppm) for each season.

The table above (Table 4.1) shows the mean and the standard deviation of the suspended load for each season. The mean for dry period is higher than that of the short rainy season as the vegetation during the dry period is very low. However during the short rainy season, the vegetation quickly comes back as the rains are more or less continuos, unlike during the dry season when rainfall is sporadic. The first rains also produce a lot sediments as there is little or no cover on the ground when each time the first rains come. The high mean (208 compared to 199) during the dry period is due to fact that for any storm that occur during this period, the there is no or little cover to protect the soil. So even if the storm is not highly erosive, due to the absence of cover, the sediment load is high. In the long rain season most storms are quite erosive. See chapter three on rain analysis and erosivity. These differences are quite complex and can only established if careful studies are done with very accurate and long-term data.

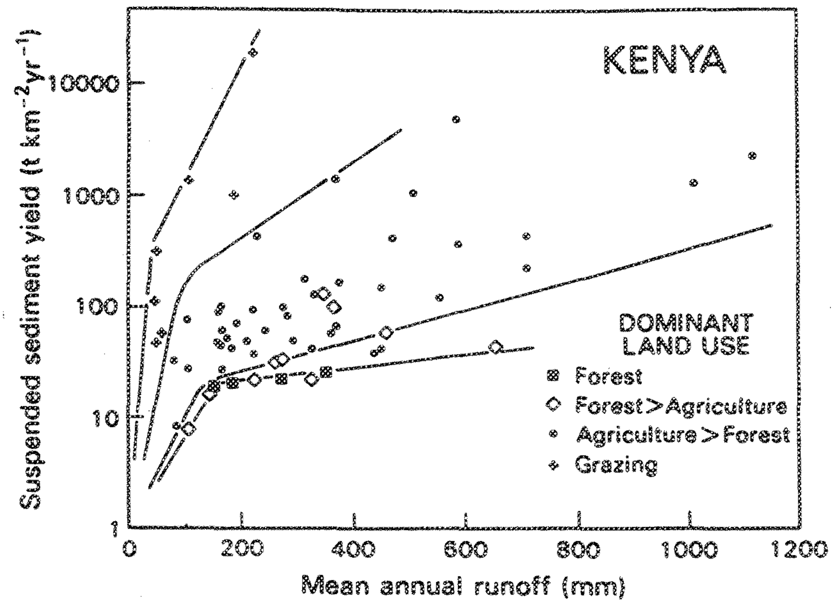


Figure 4.8 Mean Annual Runoff with Sediment Yield (after Dunne, 1979)

4.4 Erosion and Sediment yield

Dunne (1979) conducted a study in Kenya on sediment yield and land use in tropic catchments. He concludes that Land use is the main controlling factor in determining the amount of sediment yield of any catchment. He produced graphs showing different sediments yield with land use; i.e. Forest, Agriculture and Grazing land. (figure 4.8) In all cases, Dunne (1979) concludes that there is a positive relationship, for there was no evidence of reduced sediment yield at increased runoff levels.

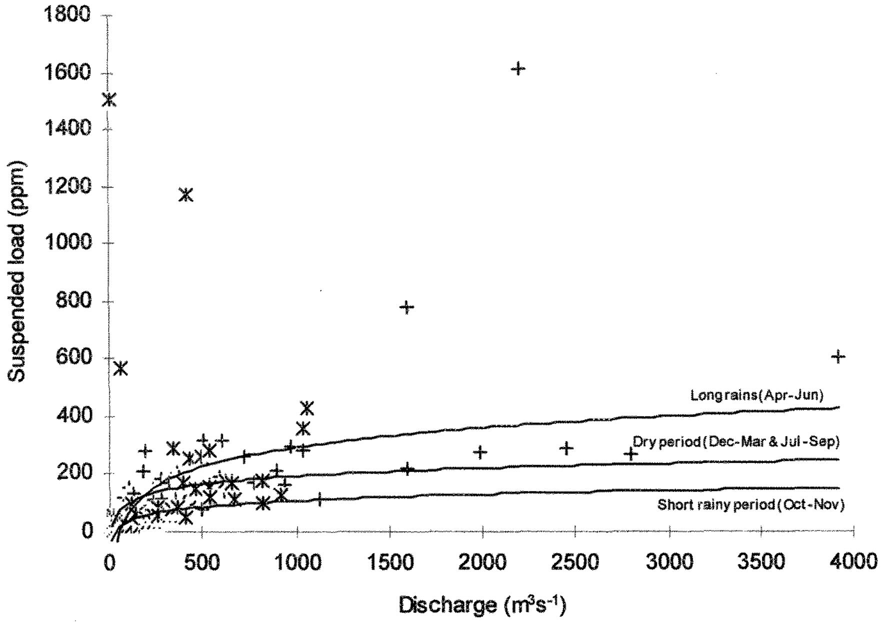


Figure 4.9 Discharge with suspended load for Malewa River, Kenya

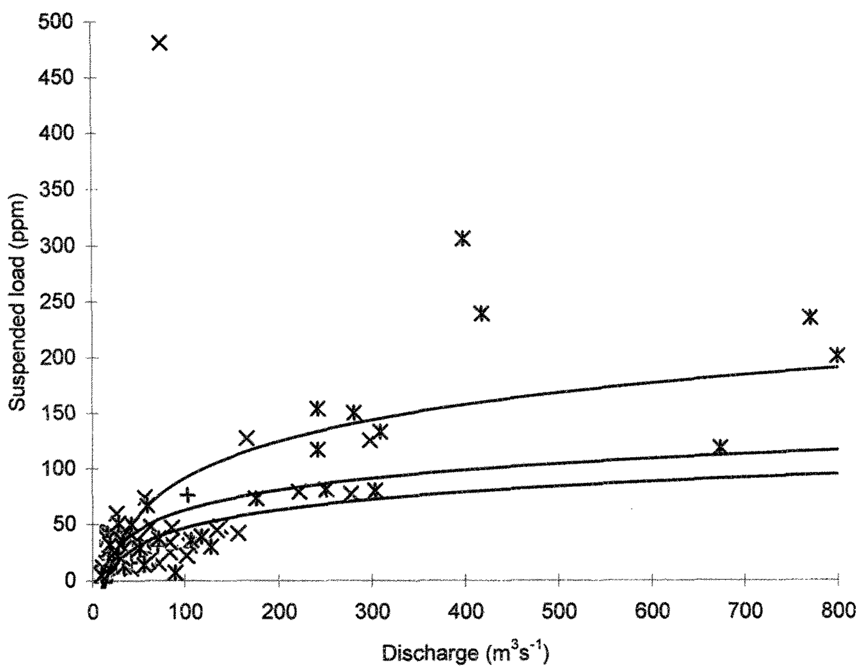


Figure 4.8 Discharge with Suspended Load for Turasha River, Kenya

Comparing the results (figure 4.8), the three seasons produce different sediment load concentration. The long rainy seasons that occur between April and June produce the highest load while the short rainy period in October and November produce the least. Surprisingly, the storms that occur in the dry months, which are high enough to produce runoff, have higher sediment concentration than the short rainy period. The reason is that during the dry period, the vegetation cover is very poor (almost non-in some areas) and the soil is loose from animals grazing, making it easily carried away. However, at low (figure 4.8, Q< 100 m^3s^{-1}) discharge volumes, clearly the suspended load is independent of the season.

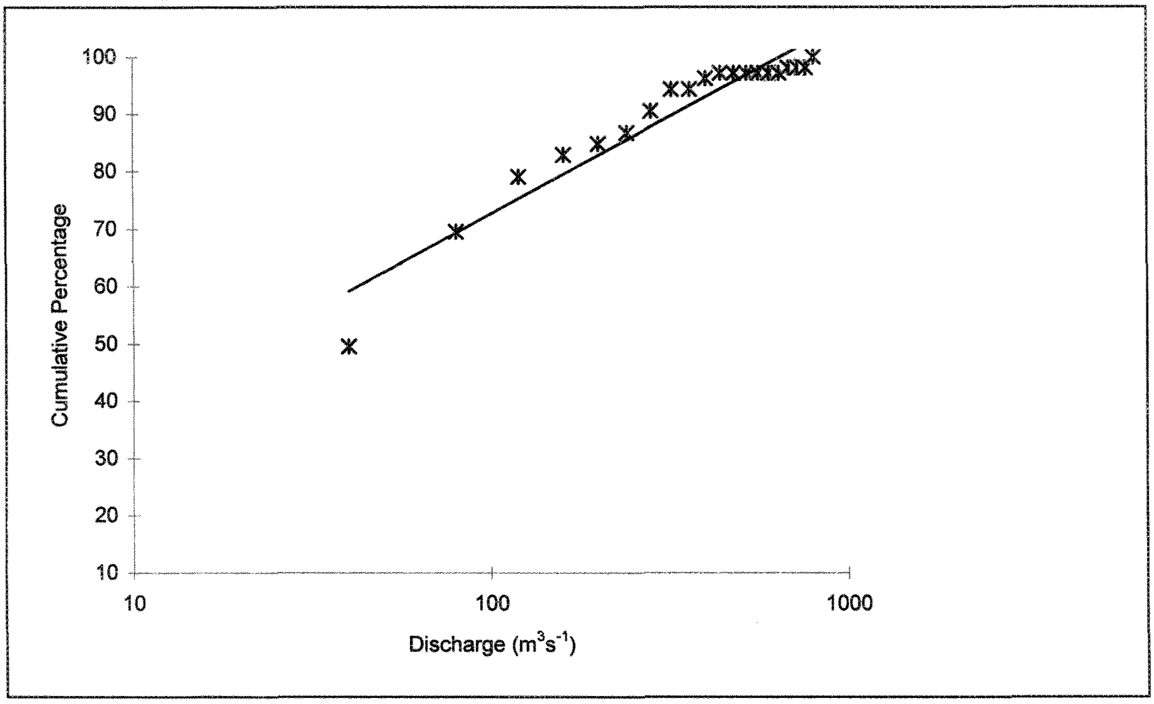


Figure 4.10 Probability of the Runoff in Turasha River (1949-1956)

The results in figure 4.8 for a tributary of Malewa, Turasha confirms this and the seasons also vary in the same pattern, like Malewa River.

4.5 Sediment Rating Curve

The estimation of the amount of sediments transported was done through a rating curve made using the suspended load data and the discharge. Figure shows the relationship between the suspended load and discharge. With the considerable scatter, it was difficult to find a good relationship but a polynomial function proved to provide some significant relation.

This relationship (rating curve) between the discharge and sediment yield was used to estimate the sediment yield of the catchment. With a discharge of 18 m^3/s, and suspended load of 93 ppm (mg/l) the sediment yield for the catchment is 14.7 ton/day or 3.56 tons/km²/yr during the long dry period. The sediment for the long rainy period increases to 12.44 tons/km²/yr. In short rain season of October and November, the sediment yields drop even further to 0.83 tons/km²/yr. Though this method of estimating the sediment yield from catchments is not very accurate, this must be understood to be an indication that if conditions change (increase or decrease in rainfall), the sediment yield would rise or fall quickly. However it must be mentioned here that the data may not be very accurate due to the equipment and methods in the 1950s. In addition the trend may have changed now as the land uses of the catchment have changed over this period as well.

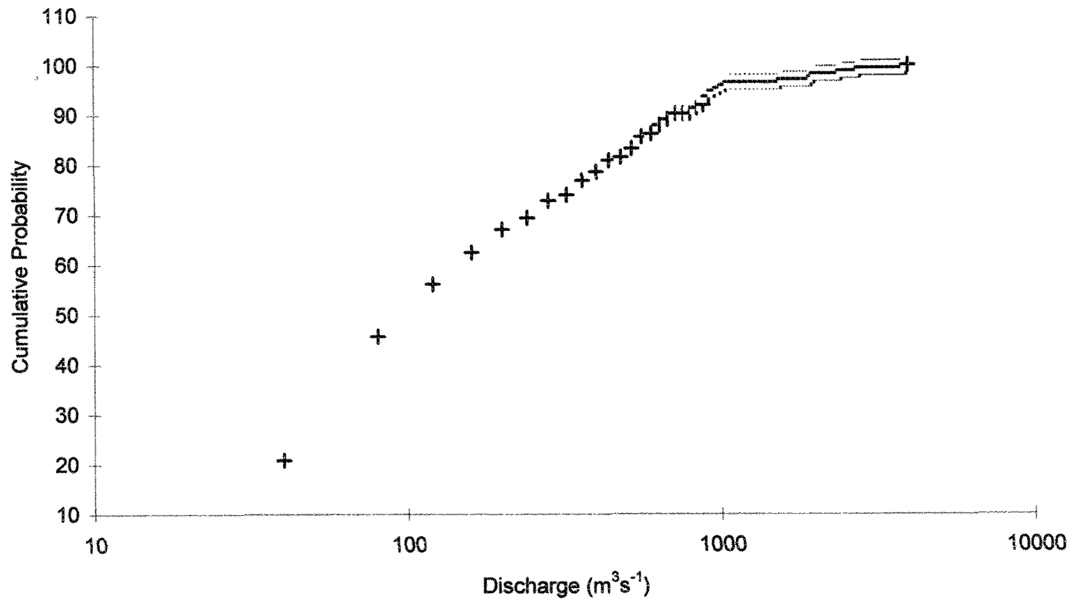


Figure 4.11 Cumulative Probability for Discharge in Malewa River

With an average flow of 229 million cubic metres per year in Malewa river, the average flow is 6.4 m^3/s. The average sediment yield of the catchment is about 129 metric tonnes per year. This value need to be increased by 10 % to include the bedload as it is not normally sampled during suspended load sampling. The annual sediment is therefore 142 tons.

Lake Sedimentation

With an annual value of 142 tons per year, expected to be deposited into the lake, the lake bottom is raised by 1 mm. Bulk density 1.1 kg/m^3 and surface area of lake 127 km^2. This has the effect of increasing the surface area of the water surface exposed to evaporation. As can be seen the increase is rather small and the changes in lake bottom is small for anyone to notice it. This ultimately increases the amount of water lost through evaporation. However due to large surface of the lake and climatic conditions, this increase in surface area become insignificant.

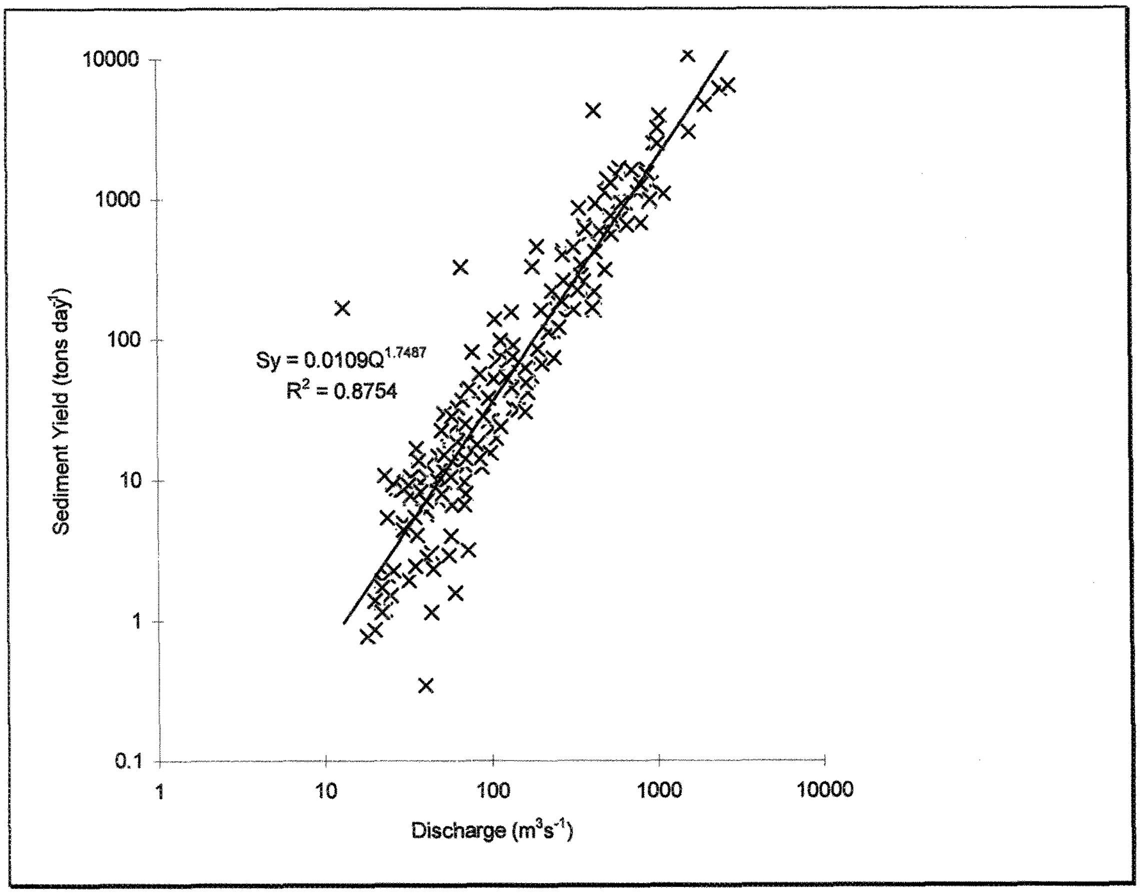


Figure 4.12 Sediment Rating Curve for Malewa River, Naivasha basin, Kenya

5 MODELLING EROSION

5.1 Introduction

The aim of modelling is to provide a prediction of the future performance of a system, predicting the process that will occur in the system. A model, therefore seeks to simplify the complexity of the real world by selectively exaggerating the fundamental aspects of a system at the expense of incidental detail. In simplifying the view of reality, a model must remain simple to understand and use, yet complex enough to be representative of the system (Anderson & Burt, 1985). This is a caution to all who are enthusiastic to simulate or model any process of any system. One of the difficult process to model is soil erosion. Though many models exist for soil erosion, none of these models adequately present the reality and the few that are close to reality become to complex and require a lot of input parameters.

5.2 Role of Models

Models are used to extrapolate point or site data that describe erosional process and the soil's resistance to erosion on large areas with limited soil, climatic and topographic data. Models, therefore are used for bridging the site measurements to the large scale areas with limited or no data; in other words scaling. With increased use of computer and digital databases, models are becoming the tools for assessing present and potential soil erosion. Unfortunately this is done across the board, from small areas to very large areas. The biggest question is whether the transformation or scaling gives realistic and representative results of the process in that basin.

The combination of empirical modelling methods with GIS would result in fairly accurate results of erosion assessment (Meijerink, 1994). First mapping units are used to assess the sheet and rill erosion. This is very easy in extreme cases, very low and very high erosion. For those areas in neither of the extremes modelling using Morgan or USLE may be used. The estimated sediment yield per unit can be multiplied with the sediment delivery ratio to give the estimated sediment yield of the whole catchment at the outlet.

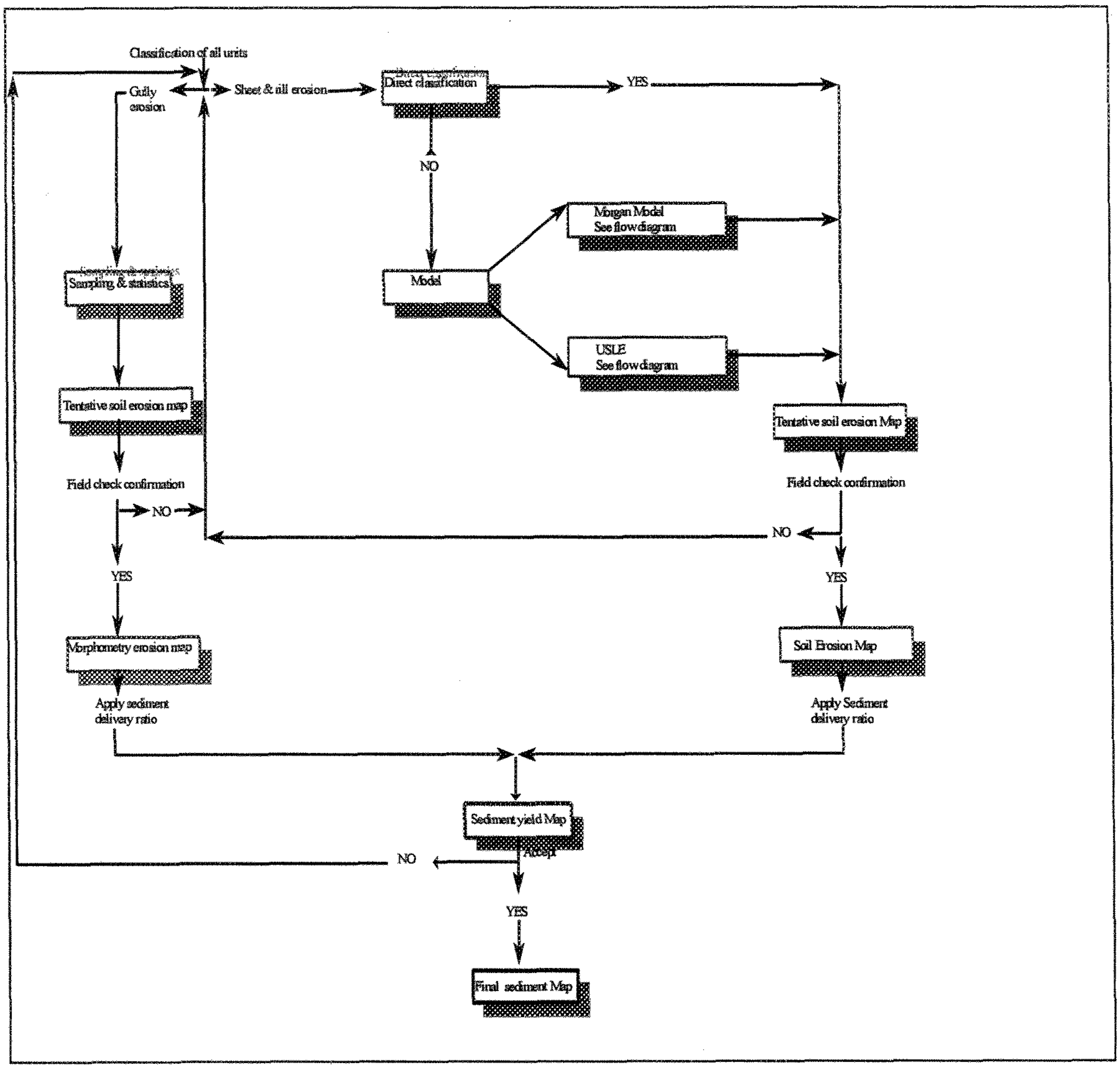


Figure 5.1 Hybrid method flow diagram; combining different modelling methods

5.3 Aspects of Scale

However, most of these models were developed on small plots while a only few at field level. Often times these models are used to simulate processes of scale different from the one it was developed. It is important therefore to realise that when models are developed, there are a lot of assumptions made, some of which are related to the initial scale. These assumptions sometimes have an influence on model predictions. Addiscot, (1993) suggested a series of questions to consider when translating a model from a small scale to an appreciably large one, these are;

⇒ Does the underlying hypothesis of the model remain the same?
⇒
⇒ Do the mechanisms of the model retain their meaning in a descriptive sense?
⇒
⇒ Is the model still being used within a range of parameter values for which it has been validated?
⇒
⇒ Can realistic, independently derived values still be assigned to the model's parameters?
⇒
⇒ Is the scale of modelling commensurate with the scale of the measurement from which the parameters were derived?
⇒
⇒ Do the parameters of the large scale differ appreciably from those of the smaller? If so, why?
⇒
⇒ Has the sensitivity of the model to its parameters changed? If so, why?
⇒
⇒ Has the classification of the model changed? (e.g. from physically based to lumped)
⇒
⇒ Is there anything in the use of the model on a larger scale that offends common sense?

The above questions are very important to avoid 'blind' application of models especially where the scale is different. This calls for better understanding of a model before applying it. With good understanding the above questions are answered even before they are brought up.

In addition, in small scale regional simulations, inputs ought to be only that data that has been recorded or can be derived at a regional scale. For example, 'worst cases' management such as bare soil or freshly tilled soil for erosion assessment can be applied in regional simulations to assess potential rates only. However, due to limitations with regional data, regional simulations should be limited to the development of indices and rankings rather than prediction of absolute values. With birth of GIS, regional model simulations are becoming a good alternative as aggregation of outputs can be done. Therefore regional assessment can still be quantified through GIS though local variability may mask important regional differences in rates and amounts.

The other emerging problem with models is data handling and complexes, where a models demands many inputs parameters. In soil erosion modelling, use of soil survey data as input into a simulation model may prove to be complex and handling sometimes becomes difficult. One the ways, to go round this problem of data complexes is to group it in units like the TMUs. In this thesis, the TMUs are used as basis for geologic, soil and topographic associations.

5.4 Upscale or Down Scaling

A lot of models have been used successfully to extrapolate soil erosion assessment to larger areas. However, the accuracy of the predictions remains a big question. In this study one such prediction will be tested. The SOTER methodology (SWEAP) to simulate and produce the soil risk map. The program uses the USLE and the SLEMSA which are both plot models.

The up scaling of these models has been difficult and modifications have been done over and over. The up scaling therefore is not an ease way of translating site models to large scale areas. Not much of the vice visa has been done, but coupling the simulation with GIS may be a better way to model large areas. Models for large scales require huge amount of data which is lacking at regional scale. It is therefore difficult to conclude whether it is up scaling of down scaling. But one thing is certain, up scaling is practically difficult. Down scaling should be used like it is being tried in this thesis. Through the TMUs and relational modelling an attempt is being made with down scaling.

very high erosion (a few) and those without erosion were identified. The rest of the area in between the high erosion and no erosion areas was modelled using the sediment concentration's regression equations in order to find the magnitude of soil loss.

The above system was employed in the study area for the TMUs and 11 units were identified. As the catchment was big 3285 km^2, the units are rather generalised. On a small scale within one unit more units would be identified. A total number of 79 photographs were available covering the entire catchment. However, these photos were rather old, dated 1972, which brought many differences between the satellite image and these photos. The scale of these photos was 1 : 50 000. Another set of recent (1984) aerial photos were available though they were only around the lake, but at a larger scale of 1:12 500. The satellite image was for 21 st Jan 1995, which falls in the dry month. The study area is located within the Volcanic East African Rift Valley; making the interpretation very difficult; as one unit would comprise of many small sub units, too many to be delineated individually.

The units that could be easily mapped were mainly, Volcanic Mountain, Volcanic Plateau, Volcanic Plain, Foot slope, Crater, Scarp, Lacustrine Plain (upper and Lower) and the River Valley. As stated earlier, these units were rather big but based the scale used, it was not possible to reduce the size of these units.

The lithology was derived from the geological map. As relationship between lithology and land form and soil characteristic exist, the geological map with stereo aerial photos' associations was delineated. The main parent materials were; the Pyroclastic rocks, Lava flows, Comendite, Basalts, Tuffs, Colluvium, Alluvium and Lacustrine sediments.

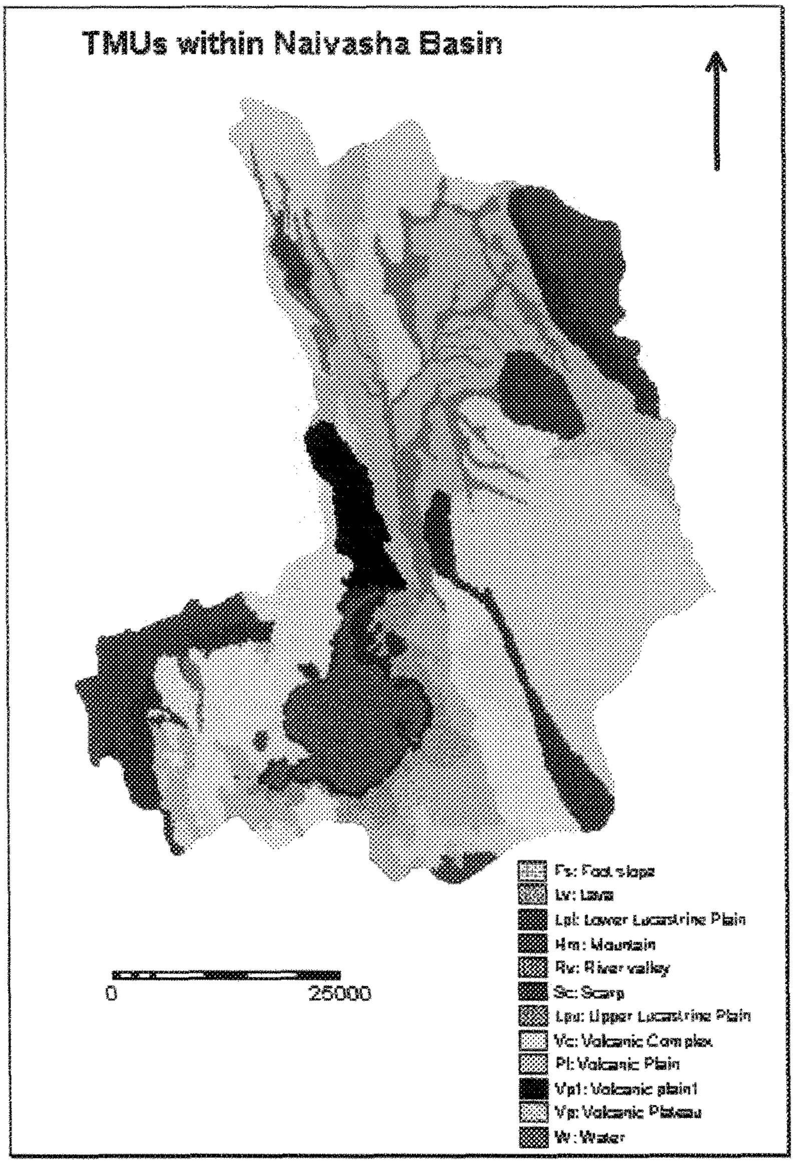


Figure 6.2 Terrain Mapping Units of Naivasha Basin.

6.3.1 *Internal Relief*

The internal relief is defined as the average height difference between drainage and drainage divides or lowest point and the highest point in each TMU. The Internal relief of each TMU was sampled through aerial stereo model and estimated. The topographic maps were used where it was not easy with the aerial photos The internal relief was high in the mountains and very low in the plains.

6.3.2 Drainage Density

The drainage density was estimated in each TMU through direct measurements on the topographic maps and aerial photographs. The total length of the drainage lines was divided by the total area of the TMU, as in formula;

$D_d = \frac{D_l}{A_{tmu}}$ D_d = Drainage density, D_l= drainage length km, A_{tmu}= Area of TMU km^2

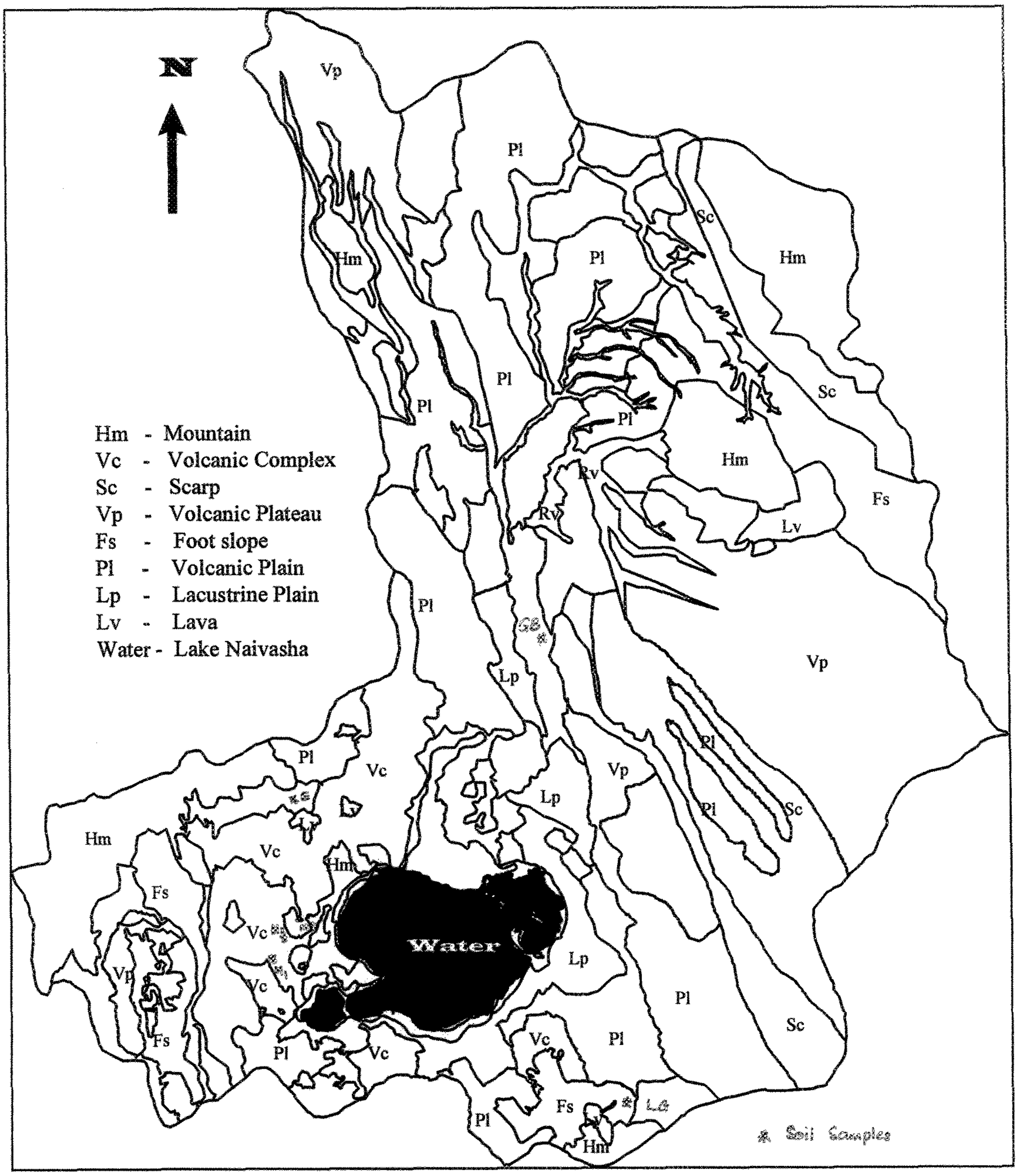


Figure 6.3 The TMU Interpretation from Aerial Photos

The process of estimating and measuring the drainage lines was time consuming and laborious especially in the mountain and Scarp TMUs. In these TMUs a lot of drainage lines could be seen. In the rest of the TMUs, the drainage was not as much as, in some no drainage at all. For example the Lacustrine plains. See the drainage map.

The slope was observed in the field in the different units and estimated for the areas that were not accessible using the aerial photos. In the field, a clinometer was used to measure the slopes. The estimated slopes were checked from the DEM created from the digitised contour map with contour interval of 40 metres. The accuracy of the DEM was not very good, with this large vertical interval. Due to the large size of the catchment and for handling purposes in GIS, this interval was used.

Volcanic Mountain (Hm)

This unit is the highest (above 2500 masl) in the area, with some mountains above 3000 masl. The parent material is mainly the Mau tuffs on the western side and the Kinangop tuffs on the eastern side of the Rift valley. The slope steepness is generally above 30 %. The internal relief is high (250 m). The soils are developed on ashes and other pyroclastic rocks of recent volcanoes. The texture is generally clay loam. The main land cover in this unit is natural forest with a few patches of agriculture but limited due to high slopes.

Volcanic Plateau and Plains (Vp)

This unit is gently undulating with the general slope steepness less than 8%. The main parent material is the tertiary volcanic rocks. Mostly it is the Eburru pumice and Waterloo ridge pantellerites. The elevation is differences within the unit are very low, internal relief less than 10 m. The soils are developed on ashes from recent volcanoes. The texture is clay loam to silty clays. The main land use in this unit is agriculture on small scale plots (0.2 ha).

Scarps (Sc)

The scarps are main between the mountain and the plateau units. The slopes range are over 40 %. They are faulted with parent material being the same as the mountain unit but in some place it the basalt tuffs. The drainage density here is higher than the mountain. The soils and land use are basically the same as the mountain.

Volcanic Complex (Vc)

The complex unit is composed of almost all the other units occurring together. To the south west of Lake Naivasha, the Olkaria comendite, lava flows form the main parent material. The soil differ but are generally sandy loam developed on aashes of recent volcanoes. The main land cover is the natural vegetation with very thin leaves.

Foot Slope (FS)

This unit falls just below the scarp. The parent material is mainly composed of colluvium (Igneuos) material. It is a unit which on which a lot sediments that may have been eroded on the mountain and scarps are deposited. In some areas small alluvial fans could be seen. The soil are developed on undifferentiated volcanic rocks (mainly the basalts). The texture is generally loam. The internal relief is low as the tend to flat to undulating. The main land use is agriculture.

Plain (Pl)

The plain is developed on the alluvial deposits. The plain is found on edges of the rift valley. The soil texture is generally silty loam to clay. It is developed on volcanic ashes. The slope is flat to undulating with very low drainage density. The land use is mainly agriculture, though some parts become bare depending on the season.

Lucastrine Plain (Lp)

The soil of this unit is developed on Lacustrine sediments deposited from older greater lake. The plains are divided into the upper and lower plains. The lower plains are at times flooded by the lake water. The upper lacustrine plain is basically the same as the lower but slightly higher in elevation than the former. The texture is mainly sandy clay loam. The upper plain (terrace) has agricultural activities while the lower one is mainly covered by forest and natural grass that grows along the Lake.

The photos from A - E show the different types of soils around the catchment. Photo A is along a road up in the upper catchment of Gilgil, Bahati forest. Here rainfall is much higher about 1300 mm per year. The soils are stick brown clays.

Photo B is in Eburru mountain. Here the soils are different in that they are more of loamy soils. Rainfall is not as high as in Bahati forest. The infiltration rates are high too.

Photo C shows the gullies in the longonot volcano slopes. This particular gully was near the road, probably old road. The soils are sand loamy.

Photo D and E are on the Eburru and they show the vertical section on a side of a road. The layers of volcanic ashes can be seen.

Table 6.1 Terrain Mapping Units with Attributes

Unit	Landform	Lithology	Slope	Internal Relief	Drainage density	Main Landcover
Hm	Mountain	Pyroclastic rocks, Recent volcanoes, Maiela pumice	25- 45	250	3.5	Forest
Vp	Volcanic plateau	Tertiary volcanic rocks	1.5-4	10	3.0	Agric crops Scrubs
Vc	Volcanic Complex	Olkaria Comendite, Lava flows, domes	9-25	120	2.0	Scrubs, Agric crops
Lv	Lava flow	Lava flow	2-5	15	0	Bare rock
Sc	Scarp	Basalts, Older tuff	15- 45	80	17	Scrub, agric crops
Fs	Foot slope	Colluvium (Igneous)	3.5 - 7	45	1.5	Agric crops, bare soil
Pl	Volcanic Plain	Alluvium, Pumice	0 - 2	3	2.0	Agric crops
LPu	Upper Lacustrine plain	Lacustrine sediments	0 - 2	2	1	Agric crops
Lpl	Lower Lacustrine plain	Lacustrine sediments	1.5	1	1	Natural grass, crops
Rv	River valley	Alluvium deposit	3		1	Agric crops

6.3.3 *Susceptibility to Erosion*

The erodibility of the soils are as summarised in table 6.2. Generally the erodibility is high in the area with values ranging from 0.3 - 0.6. The permeability too is very high with lowest being 0.66 and the highest permeability value of 1.4. The two properties of the soils determined the susceptibility of the soil to erosion. The high erodibility is due the type of soils which are developed on ashes from volcanoes. They are powdery and fine. The high permeability is due to soils which are not compacted.

Table 6.2 Erodibility and Permeability in TMUs.

TMU	Erodibility (tons/ha)	Permeability (m/day)
Hm	0.343	0.66
Vp	0.492	1.30
Sc	0.519	1.37
Vc	0.423	1.07
Pl	0.446	0.98
Lp	0.509	1.10
Fs	0.576	1.19

6.4. Remote Sensing for Land Cover

In this study, Remote Sensing was used to derive the land cover for the catchment. The classification of the satellite image of 21 st January 1995 was made. Remote Sensing was chosen as it contains and provides good spatial and temporal information about the area. The land cover changes with time and Remote Sensing has been used by many for extraction of land cover classes. Remote sensing is the only quick and 'cheap' way of gathering valid land cover data. This spatial information was to be merged with other data layers in GIS (Rainfall and TMU) which gives this method an advantage.

6.4.1 *Landsat TM image*

The Landsat TM images provide a quick way to interpret land use inexpensively and quickly. After pre processing, the image was assigned C-values indicating the land cover. A land cover map was prepared from the landsat image, using the aerial photos as the ground truth. The original bands were used as well as the PC_1, PC_2 and NDVI. The original bands were selected after preparing a correlation matrix (Table 6.2). The bands with the low correlation were used. Similarly, there is low correlation between the PC_1, and PC_2 because of orthogonal decomposition.

The land cover was not very detailed one as only the percentage Scrub land Bare soil, Forest, Agriculture and Water were the main cover units. These are the main units that have varying effects on erosion. The knowledge of relationships between cover types, interception, vegetal retardation to overland flow, erosion factors were used to determine the classes. A comparison of spectral samples from the image with the field classification was done.

6.5 Colour Composite.

A false colour composite (figure 6.2) was made bands 4 (red), 5 (green), and 3 (blue) after assessing the correlation matrix (table 6.1) made from the 7 bands available of the landsat TM image. The correlation between band 4 and 5 was 0.73 while the correlation between 4 and 3 is 0.59. The image revealed a lot of spectral information. The forest appears as red due to low reflectance and transmittance in the visible range (< 0.7μm) caused by the high absorption of chlorophyll. The absorption is low in the near infra red (band 4, 0.7-1.3 μm) thereby having high reflectance and transmittance. The bare soil was white green because of the linear relationship between the reflectance in the visible range and the near infra red range. The reflectance of the bare soil has general rise trend except between 1.3 to 1.5 μm where there is a low reflectance. The differences between visible and near infra red are not very big hence the whitish colour.

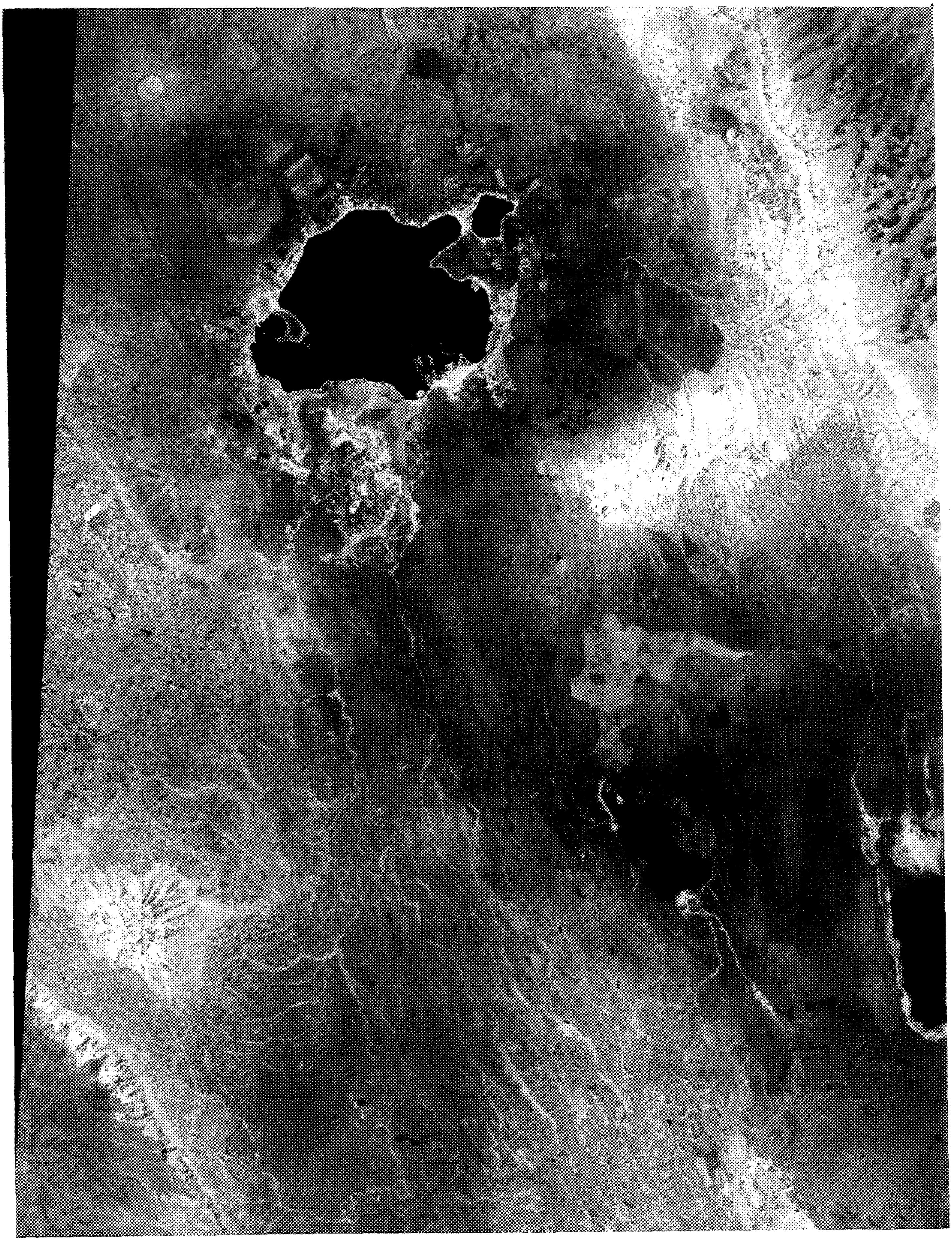


Table 6.2 Correlation Matrix for the TM bands

	Band 1	*Band 2*	*Band 3*	*Band 4*	*Band 5*	*Band 6*	*Band 7*
Band 1	1.00						
Band 2	0.97	1.00					
Band 3	0.91	0.96	1.00				
Band 4	0.66	0.68	0.59	1.00			
Band 5	0.81	0.86	0.90	0.73	1.00		
Band 6	0.91	0.82	0.72	0.65	0.73	1.00	
Band 7	0.80	0.85	0.92	0.55	0.95	0.69	1.00
Mean	48.91	23.05	27.47	51.54	72.84	133.24	32.37
Std	14.80	8.16	12.42	19.22	32.60	34.07	17.26

The correlation matrix revealed that the two bands (1 & 2) were highly correlated. Other bands were not except band 5 & 7 in the MIR.

6.6 Principal Components Analysis

The Principal component analysis operation is a method that reveals relationships among many bands and to reduce the amount of data needed to define the relationships. With principal component analysis each band is transformed into a linear combination of orthogonal common components (PCs) with decreasing variation. The linear transformation assumes the PCs will explain all of the variance in each variable. The first component represent a general picture of overall radiance intensities (Donker & Mulder, 1976). The rest of the components carry different information which is uncorrelated with each other.

Table 6.3 Eigen Vectors of PCs (Landsat TM)

	Band 1	**Band 2**	**Band 3**	**Band 4**	**Band 5**	**Band 6**	**Band 7**
PC_1	0.26	0.59	0.21	0.28	0.59	0.14	0.29
PC_2	-0.69	0.14	0.67	0.05	-0.10	0.16	-0.08
PC_3	0.12	0.13	0.19	0.91	0.01	0.05	0.32
PC_4	0.61	-0.26	0.51	0.15	-0.34	0.40	-0.06
PC_5	-0.11	0.02	-0.09	0.25	-0.46	-0.07	0.84
PC_6	0.12	0.74	-0.15	-0.03	-0.57	-0.01	-0.32
PC_7	0.21	0.00	0.42	0.05	-0.03	-0.88	-0.03

	PC_1	PC_2	PC_3	PC_4	PC_5	PC_6	PC_7
Variance (%)	82.08	10.72	5.35	1.47	0.27	0.09	0.02

Table 6.4 Eigen vectors without band 6

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
PC_1	0.30	0.37	-0.76	0.39	-0.01	-0.20
PC_2	0.74	-0.16	0.44	0.46	-0.15	0.03
PC_3	0.27	-0.67	-0.32	-0.40	-0.19	0.42
PC_4	0.34	0.06	0.03	-0.27	0.90	0.05
PC_5	0.17	-0.25	-0.34	-0.11	-0.02	0.88
PC_6	0.37	0.56	0.10	-0.63	-0.38	0.33

	PC1	PC2	PC3	PC4	PC5	PC6
Variance (%)	86.83	8.49	3.83	0.53	0.28	0.04

Table 6.5 Eigen vectors without Band 1, 6 & 7

	Band 2	Band 3	Band 4	Band 5
PC_1	0.19	-0.59	-0.06	-0.78
PC_2	0.41	-0.09	0.90	0.10
PC_3	0.29	-0.68	-0.27	0.61
PC_4	0.84	0.42	-0.33	-0.08

	PC2	PC3	PC4	PC5
Variance (%)	88.43	9.34	2.13	0.10

Table 6.6 Eigen vectors with only band 2, 3 & 4

	Band 2	Band 3	Band 4
PC_1	0.32	0.45	0.84
PC_2	0.39	0.74	-0.55
PC_3	-0.86	0.50	0.06

	PC2	PC3	PC4
Variance (%)	82.17	17.37	0.46

The last principal component analysis (Table 6.6) was found to be the most suitable. PC1 having the addition of the three bands, PC2 the difference between the visible and NIR bands, while PC3 only provided a small difference. The results of the principal component are as present in figure 6.4 and 6.5. The first principal component clearly showed the geomorphological features of the area including other spectral information (Figure 6.x). The second principal component did not show any relief but the vegetation showed very well on a flat surface. The reason for this was difference between the NIR and the visible as opposed to the addition in the first principal component. The third component was a little difficult to interpret with only 0.5 % spectral information (figure 6.4). The lava flows appeared dark without any further information. This is the difference between the colours in the visible range (band 3 and 2).

Principal component analysis was performed (See table 6.3 - 6.6) on the bands and PC_1 had a lot spectral information that otherwise could not seen from the individual bands (addition). All the information could be extracted from PC1 (82.17 %). This was due to the pseudo relief effect of the area on the intensity axis of the colour cube. PC_2 (17.37 %) showed much of the land form with colour information. This was due to the difference between band 1 (blue) and band 3 (red). PC3 was composed of mainly the band 4 (NIR). Other principal component numbers were inspected and did not have any additional data. PC_2 was used in the preparation of the TMUs in addition to the aerial photos. PC_1 was used as additional spectral information for the land cover classification.

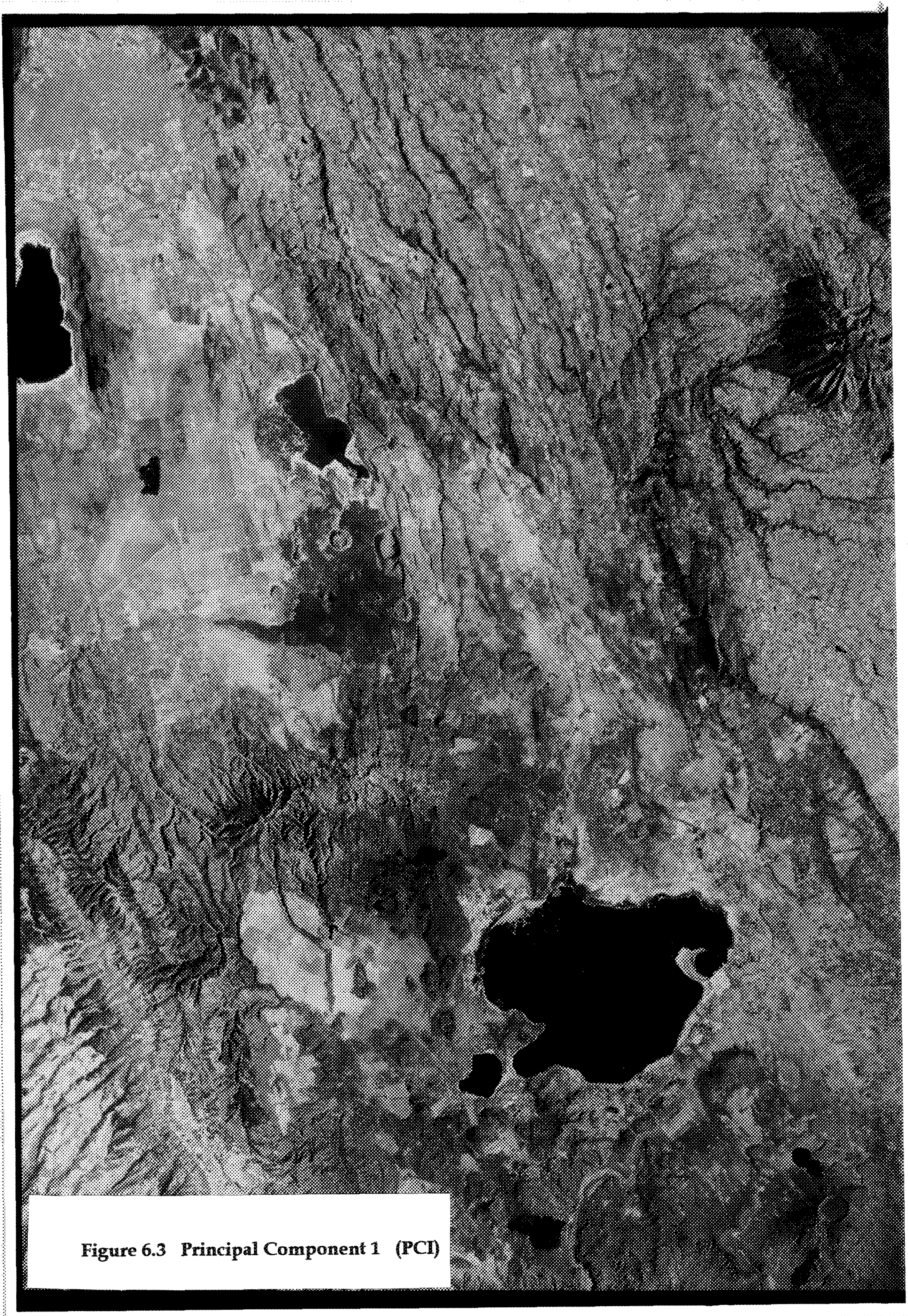


Figure 6.3 Principal Component 1 (PCI)

Figure 6.4 Principal Component 2 (PCII)

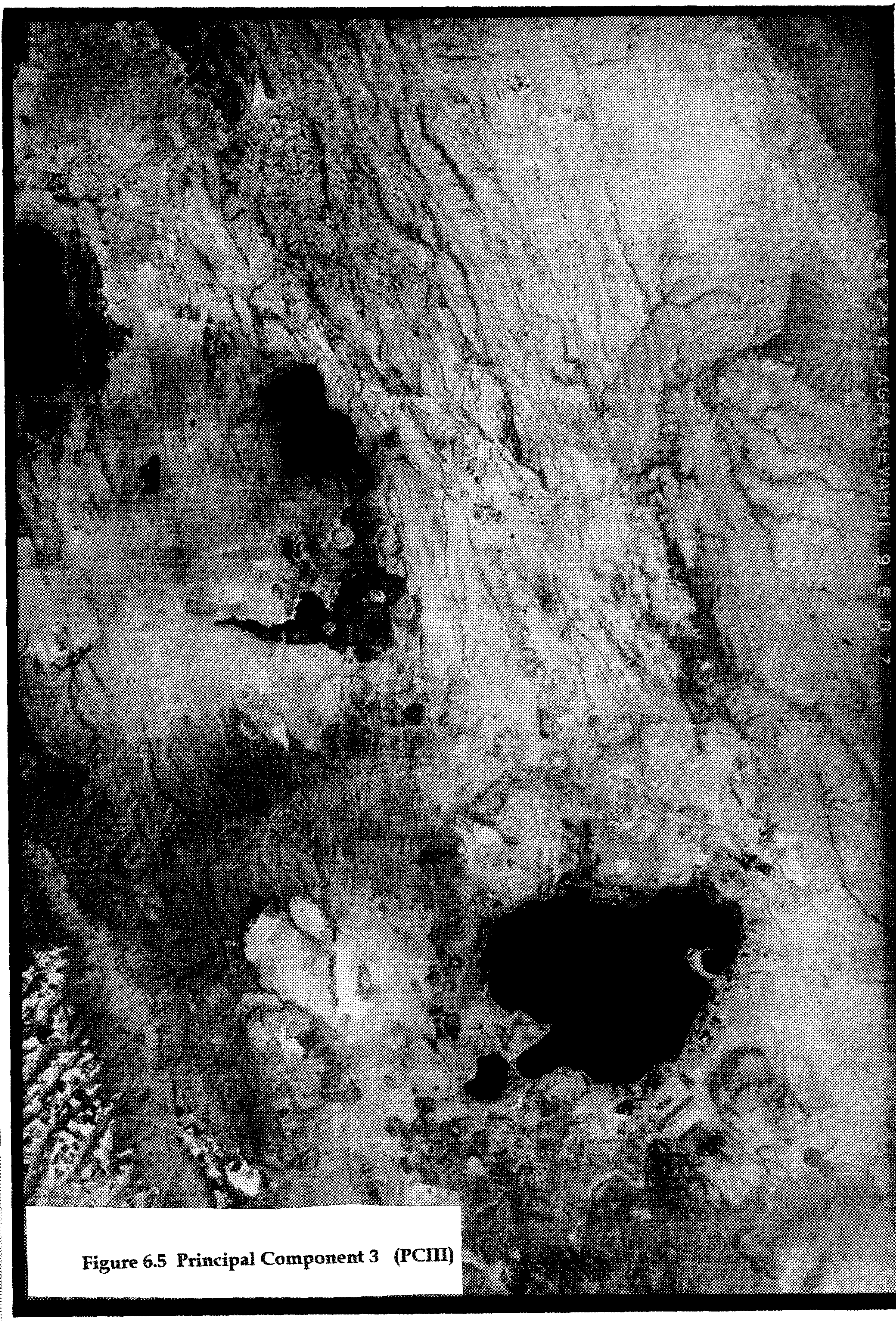


Figure 6.5 Principal Component 3 (PCIII)

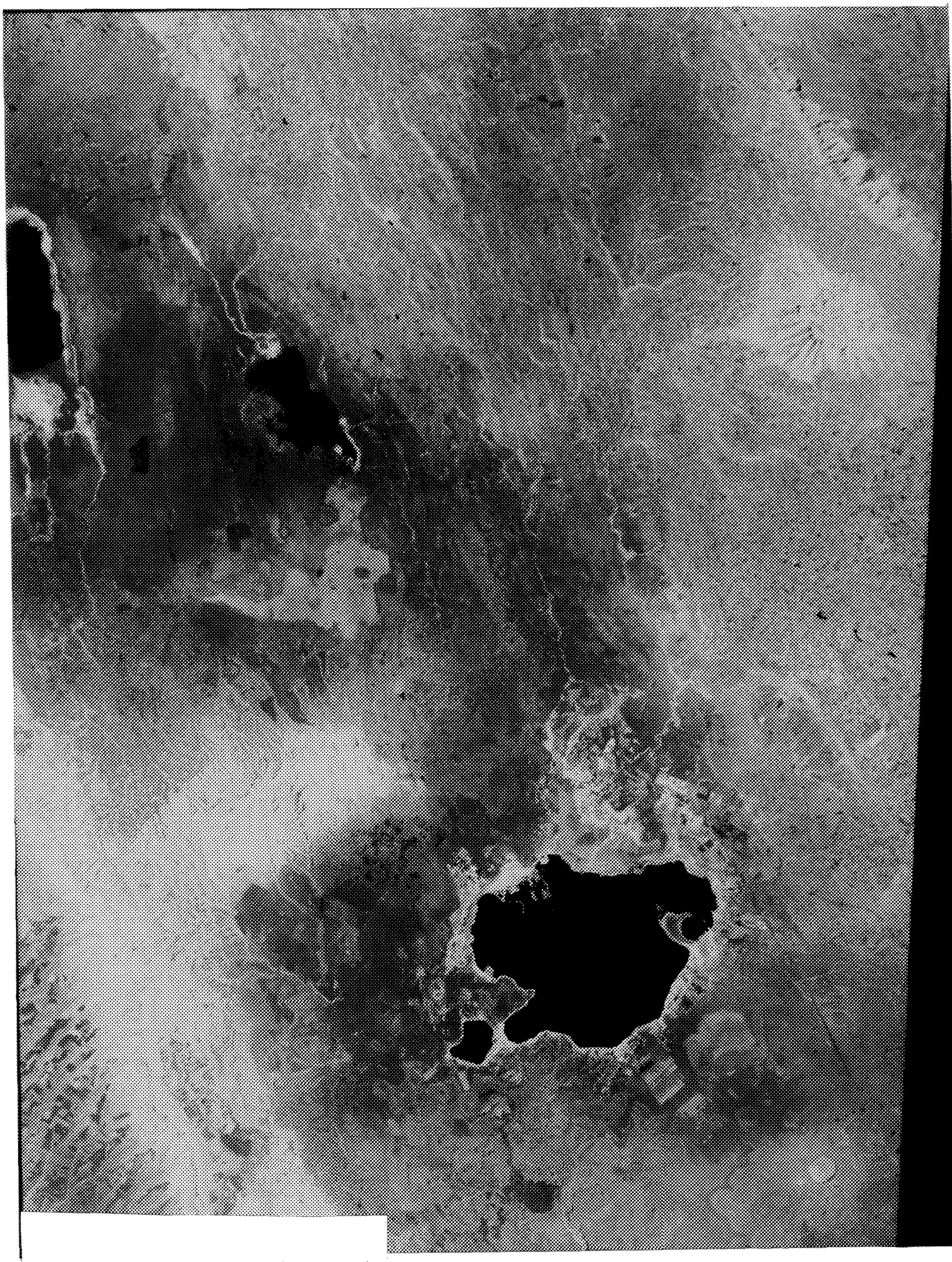


Figure 6.8 NDVI image (Band 3, 4)

6.7 Normalised Difference Vegetative Index

The vegetative indices give the variations in density of cover. Though the indices are complex, due to other factors like the leaf area, the NDVI is used, most often, they to deduce the cover differences of the earth's surface. The NDVI was calculated from band 4 and 3, taking band 4 as band in the near Infra red and band 3 as the band in red.

$$NDVI = \left(\frac{Band4 - Band3}{Band4 + Band3}\right)$$ plus an offset of (*90+127)

6.8 Classification by Feature Space

In order to derive the land cover classes that are related to erosion, only a few classes were chosen; Forest, Scrub land, Agricultural crops, Bare soil and Water. This made the classification to be rather difficult due to the small number of classes. The classification was done on the NDVI with training samples of the above classes taken with the aid of aerial photos where they are still valid. In addition to this, a large part of the study area is agricultural land with very small plots that is mixed with natural vegetation, and this, too, complicates the classification. In the figures below 'naivas' is used in place of 'band'

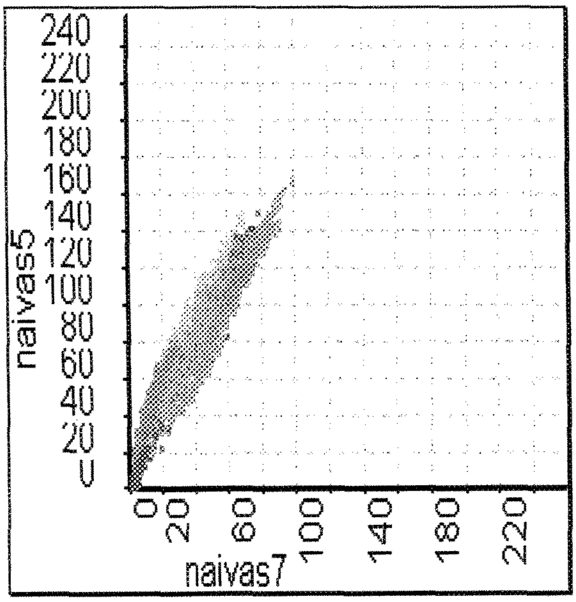


Figure 6.9a Feature Space for Band 7 & 5

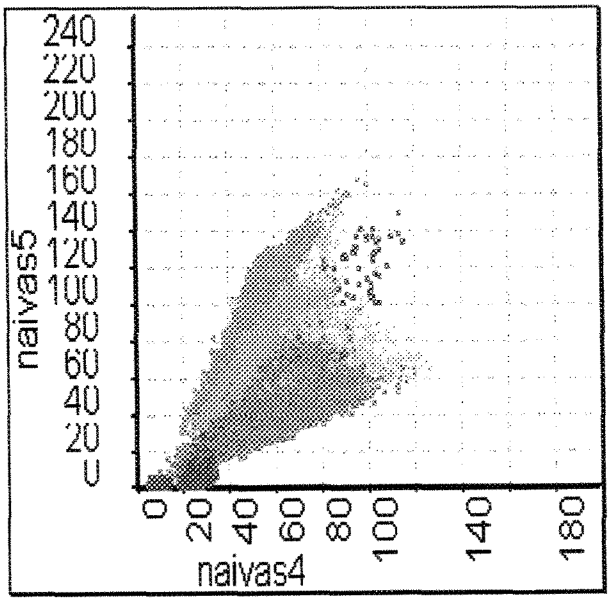


Figure 6.9b Feature Space for Band 4 & 5

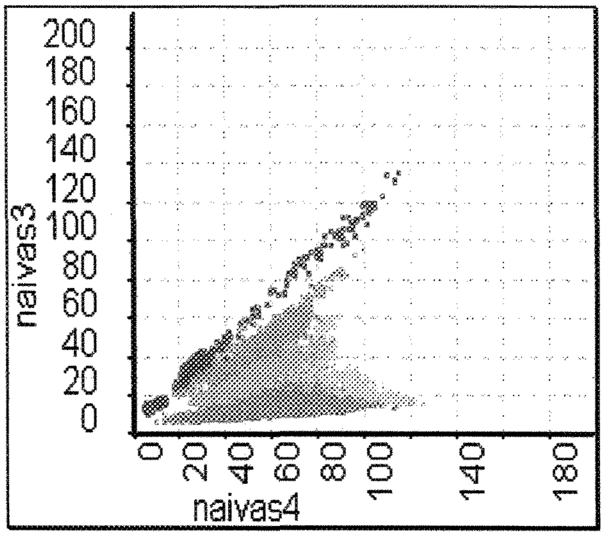


Figure 6.9c Feature Space for Band 4 & 3

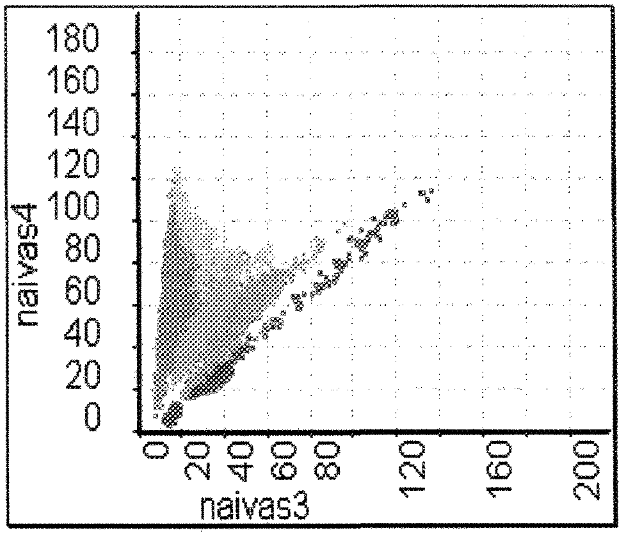


Figure 6.9d Feature Space for Band 3 & 4

Water pixels Agriculture Forest pixels Scrub land

Bare soil

A confusion matrix was calculated by making another test sample with pure and known pixels. The rows in the table are classes from the sample set used for classification. The column are the pure and known class pixels for test. The over all accuracy of the classification was 81.42 %. In order to improve the classification of the image, further classification was done in every TMU separately. For example, in the Mountain unit, all the unclassified pixels were reclassified as scrubs while all the water classified pixels within the unit were reclassified as forest using map calculations within the ILWIS - GIS.

***Table** 6.7* Confusion matrix for the 21 st Jan 1995

	Water	Forest	Bare Soil	Scrub	Agriculture	Unclassified	*Accuracy*
Water	4635	0	0	0	0	1536	0.75
Forest	0	5075	0	0	35	303	0.94
Bare Soil	0	0	1065	0	0	89	0.92
Scrub land	0	0	13	1068	314	0	0.92
Agriculture	0	0	273	1	331	215	0.77
Unclassified	21	5	0	0	0	0	0.40
Reliability	1.00	1.00	0.79	1.00	0.49	0	

Average accuracy = 75.62 %
Average reliability = 85.48 %
Overall accuracy = 81.42 %

6.9 Classification by Ratios

With the results of the above classifcation, another method of classification by rationing was opted for. The feature space above provided the ratios between band 3 and band 4 (figure 6.9 c). This classification has been recommended by Meijerink et al, 1994 for mountainous regions. The ratio betweeen band 4 and 3 was used as it provided good separability. The table below shows the ranges of ratios used for this classification. The results when compared with above method gave satisfictory result except for the scrubs which could not differentiated from Agriculture, Forest and Bare soil. However, this was improved by conditional statements. The cover class in the table below could be distinguished from the ratios. Other classes like lava flows, etc could not be easily classified with this method.

Table 6.8 Classification by Ratios

Cover	Ratio	Comments
Water	< 1.00	
Bare Soil	1.00 - 1.33	
Agriculture	1.33 - 3.00	Band 4 < 60, band 3 < 40
Forest	3.00 - 9.00	Band 3 < 20
Scrub	1.33 - 6.00	60<Band 4<120, 10<Band 3<60

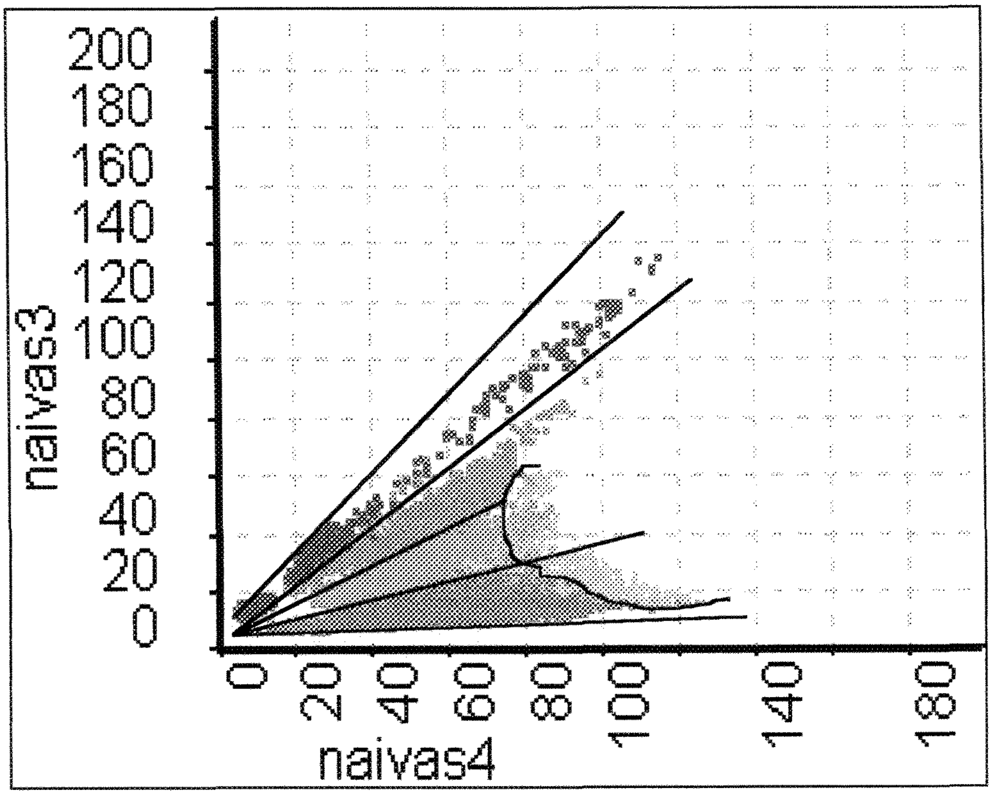
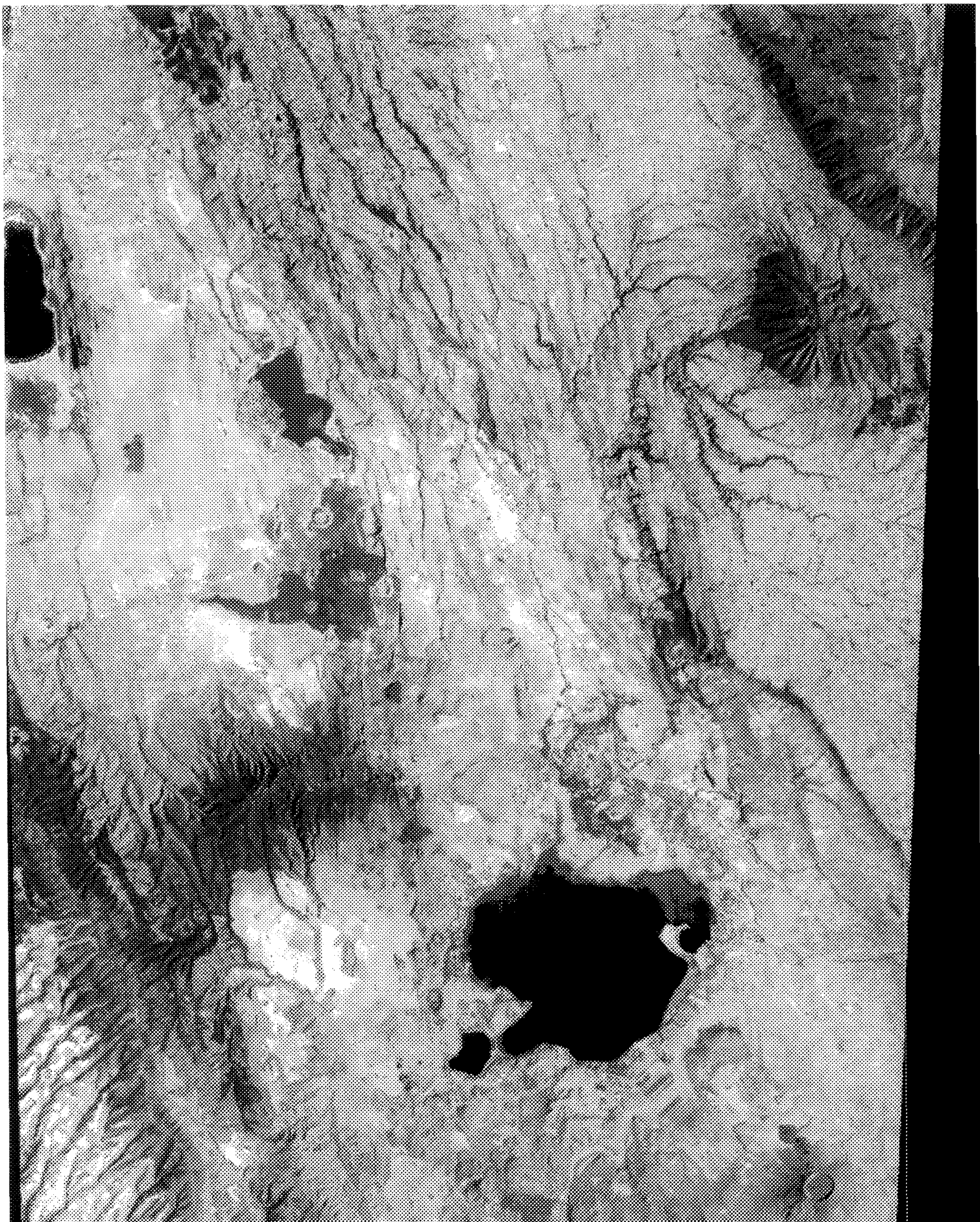


Figure 6.10 Feature Space for Ratio between band 4 and band 3



6.10 Transformation the Rainfall, TMU and Cover data into Erosion Map

The three data layers were prepared as explained in the previous sections. The TMU was from aerial photo interpretation, the Rainfall from the rainfall stations within and around the catchment and the cover from the classification of the satellite image. This transformation utilises the data or experience obtained while in the field regarding the processes of erosion. The derived relationships are then used to simulate other areas without any data.

Using the GIS, the relationships between the TMU and cover, and the TMU and rainfall were implemented by using the 2 dimensional tables. Using the domain of the TMU and the cover, one 2 dimensional table was created and another between the TMU and rainfall. The rainfall data was classified from very low (< 600 mm) to Very high (> 1200 mm).

Rules pertaining to attribution of numbers within the 2-D tables (look up) were:

1 Under forest on any unit of any topography, there is no overland flow occurs. This is mainly due to thick litter consequently minimal detachment by splash and sheet erosion.

2 On dissected Scarps and foot slopes, there is splash detachment and transport by overland flow due to poor cover at times. Agricultural changes during the year also contribute to cover changes.

3 On the plains little overland flow occurs due the type of soils of fine textures but is further reduced due to low slopes. Sheet wash may be high at times.

4 On the lava flows, there is neither sheet wash nor detachment due the bare rock that cannot be eroded.

5 In the river valleys, there is deposition and stream bank erosion occurs.

6 In Agricultural lands, plateau and plains, there is sheet wash and detachment especially during beginning of the rain season in April, when the land is bare and the rains are heavy.

With this knowledge, coupled with field work experience, the 2-D tables were developed. The results of the above tables are were formulated to map reclassification. The resulting maps as shown are maps of showing the areas that are eroded qualitatively. This means that it only the ratings from one area to another.

Table 6.9 2-D table for Rainfall and Cover

COVER	RAINFALL Very low < 600	Low 600 - 800	Moderate 800 -1000	High 1000 - 1200	Very high > 1200
Agricultural crops	0	1	2	3	4
Bare soil	1	2	3	4	5
Forest	0	0	1	1	2
Grass	0	0	1	2	3
Scrub	1	2	3	4	5
Lava	0	0	0	0	1
Water	0	0	0	0	0

Table 6.10 2-D table for Rainfall/cover and TMU

TMU	RAINFALL and COVER				
	0	**1**	**2**	**3**	**4**
Foot Slope	0	0	1	2	3
Lava	0	0	0	0	0
Lower Lucastrine plain	0	0	0	1	2
Mountain	0	1	2	3	4
River valley	0	1	2	3	4
Scarp	0	1	2	3	4
Upper Lucastrine plain	0	0	1	2	2
Volcanic complex	0	1	1	2	3
Volcanic plain	0	0	1	2	3
Volcanic Plateau	0	1	2	3	4
Water	0	0	0	0	0

Table 6.11 2D table for TMU and Rainfall

	Rainfall				
	Very low < 600	Low 600 - 800	Moderate 800 -1000	High 1000 - 1200	Very high > 1200
Foot Slope	0	1	2	3	4
Lava	0	0	0	0	0
Lower Lucastrine plain	0	0	0	1	2
Mountain	0	1	2	3	4
River valley	1	2	3	4	5
Scarp	2	3	4	5	5
Upper Lucastrine plain	0	0	1	2	2
Volcanic complex	0	1	1	2	3
Volcanic plain	0	0	1	2	3
Volcanic Plateau	0	1	2	3	4
Water	0	0	0	0	0

0 = No erosion, 1 = Very low, 2 = Low, 3 = Moderate, 4 = High, 5 = Very High

Table 6.12 2-D table for TMU and Cover

	Land cover	Land use			
	Agriculture	Bare soil	Forest	Scrub land	Water
Foot Slope	2	3	0	2	0
Lava	0	0	0	0	0
Lower Lucastrine plain	1	4	0	1	0
Mountain	4	4	0	3	0
River valley	4	3	0	2	0
Scarp	5	5	2	4	0
Upper Lucastrine plain	2	3	0	1	0
Volcanic complex	3	4	1	2	0
Volcanic plain	2	3	0	1	0
Volcanic Plateau	3	3	0	2	0
Water	0	0	0	0	0

The above tables were used to classify the TMU maps. The values within the table were assigned with knowledge of field experience. The number 0 stands for no erosion while 5 indicate very high erosion within the unit. This is some sort of conditional statements applied on the three data layers. The resulting data maps were again used to come up with one final map.

Table 6.13 2-D table for TMU/Rainfall and TMU /Cover

Terrain Mapping Units	Terrain Mapping Units / Rainfall					
Land Cover	0	1	2	3	4	5
0	0	0	0	1	1	2
1	0	0	1	1	2	2
2	0	0	1	2	3	3
3	0	1	2	2	4	4
4	0	1	2	3	4	5
5	0	1	2	3	4	5

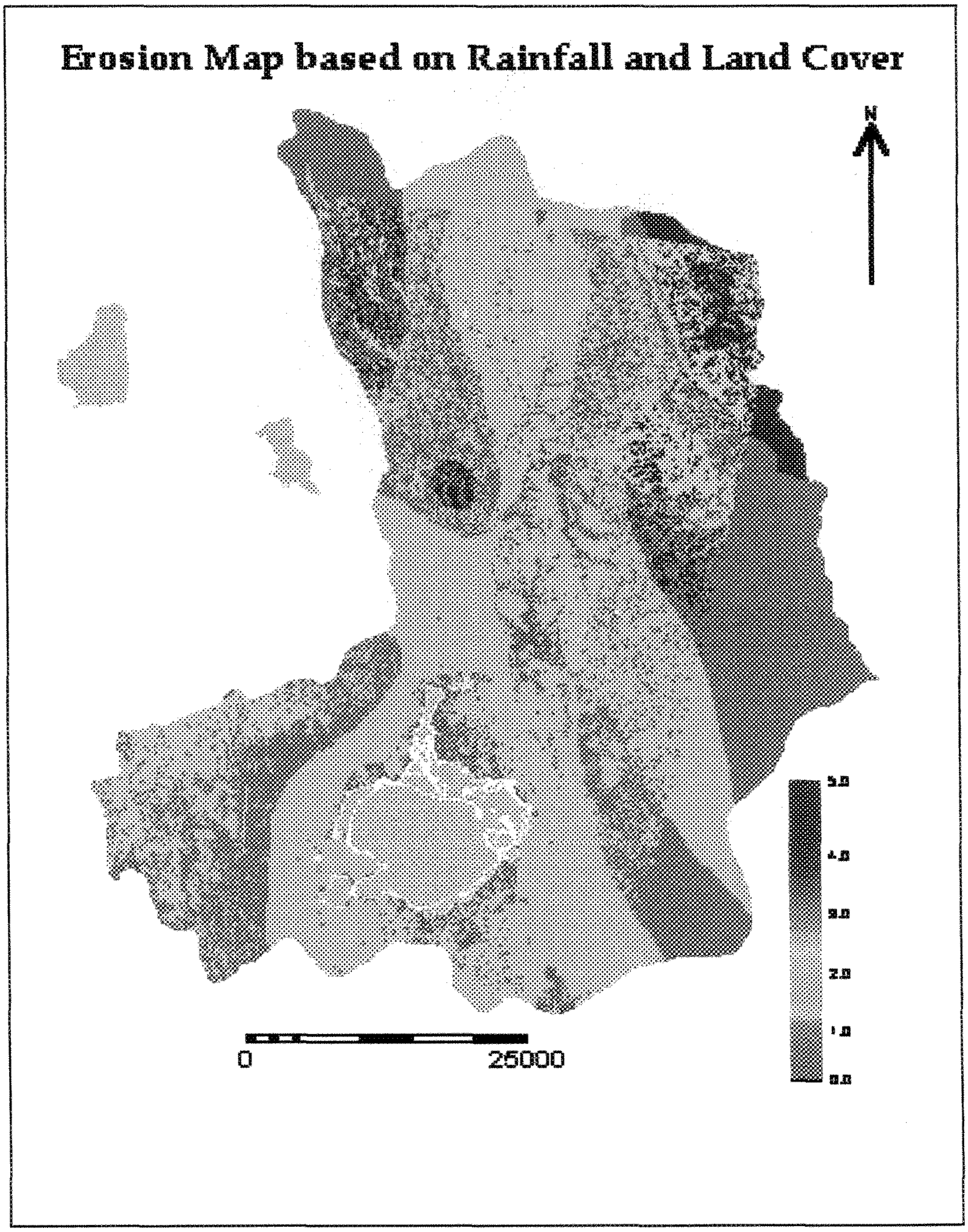


Figure 6.12 Erosion Map based on Rainfall and Land Cover

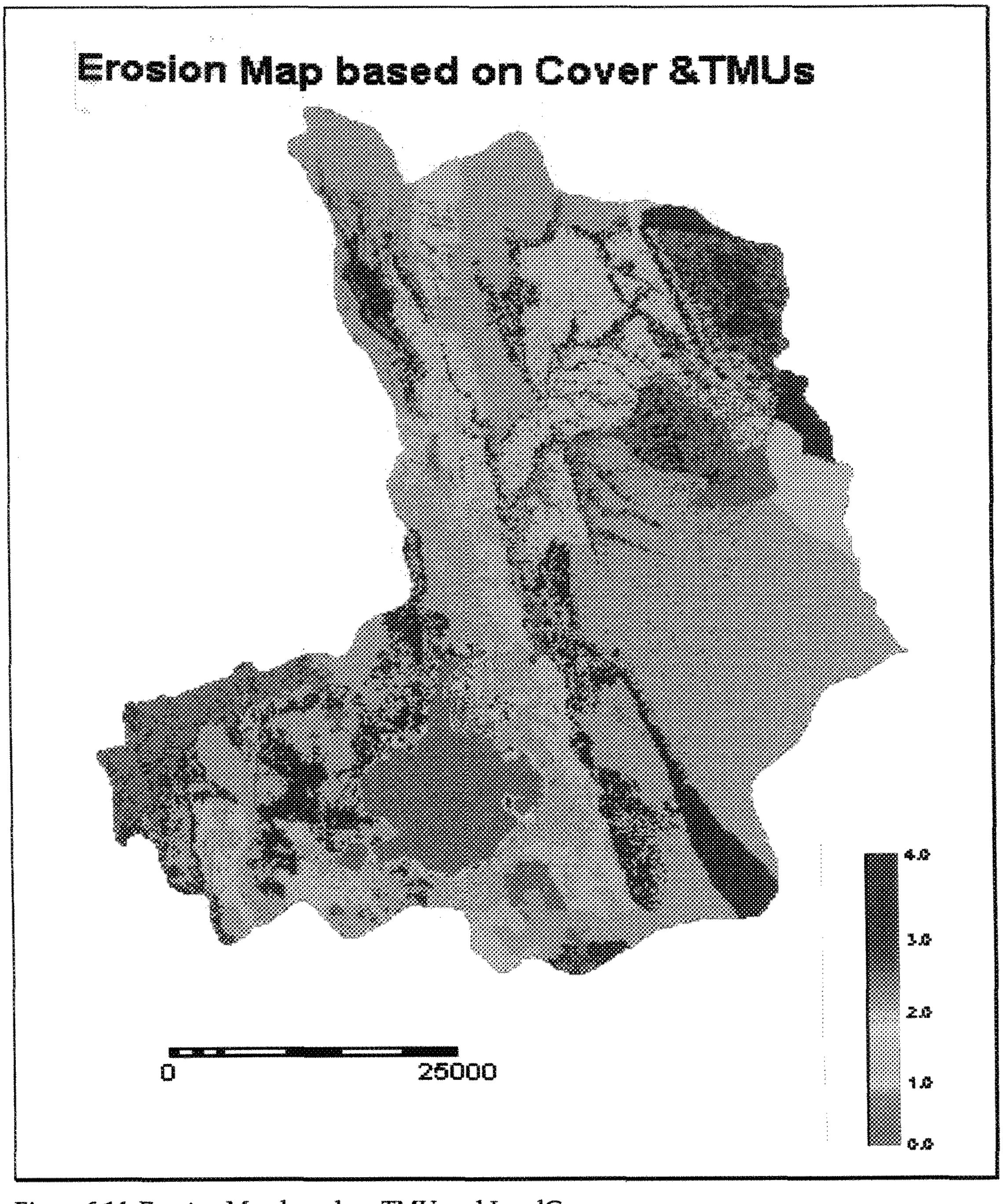
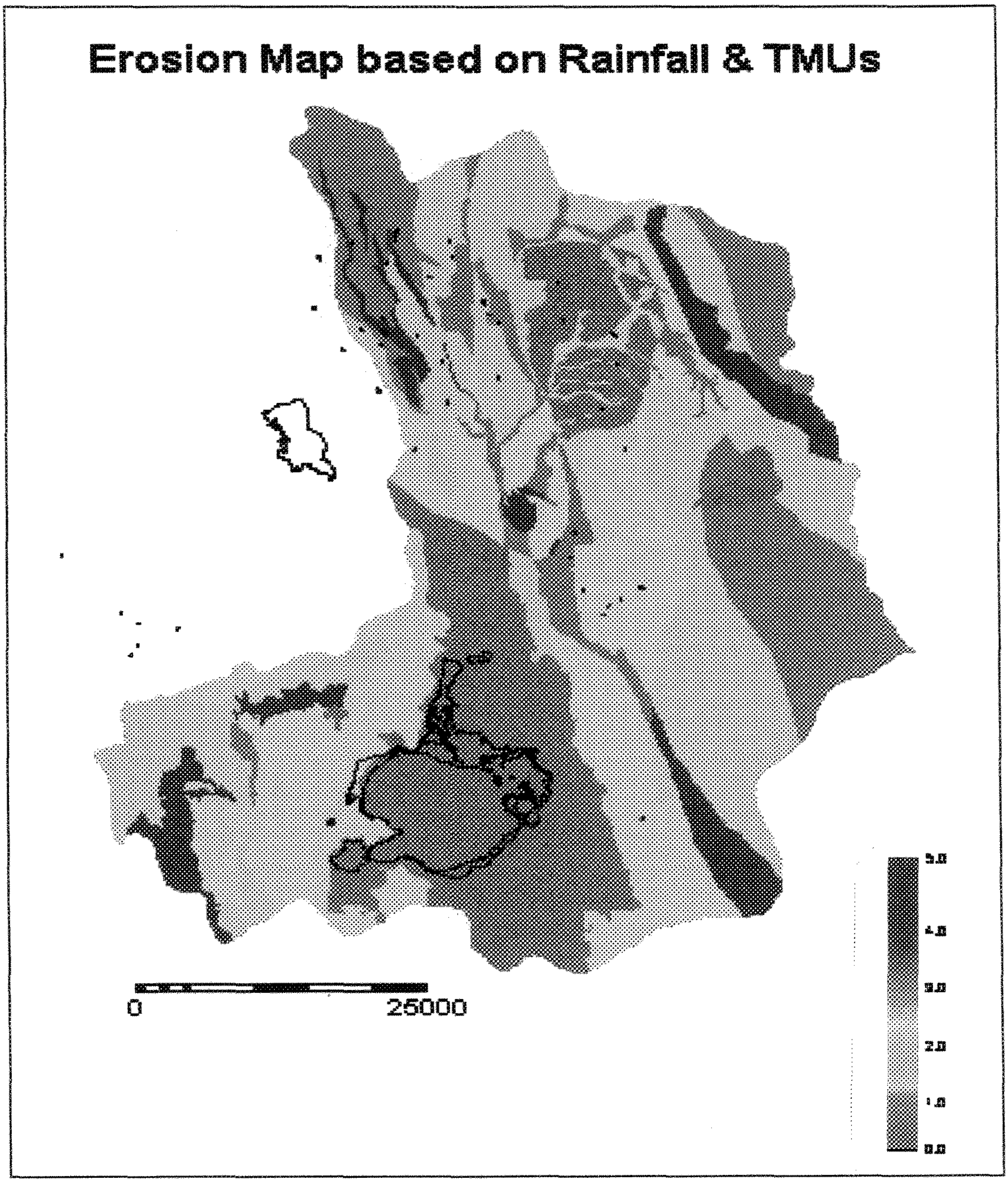
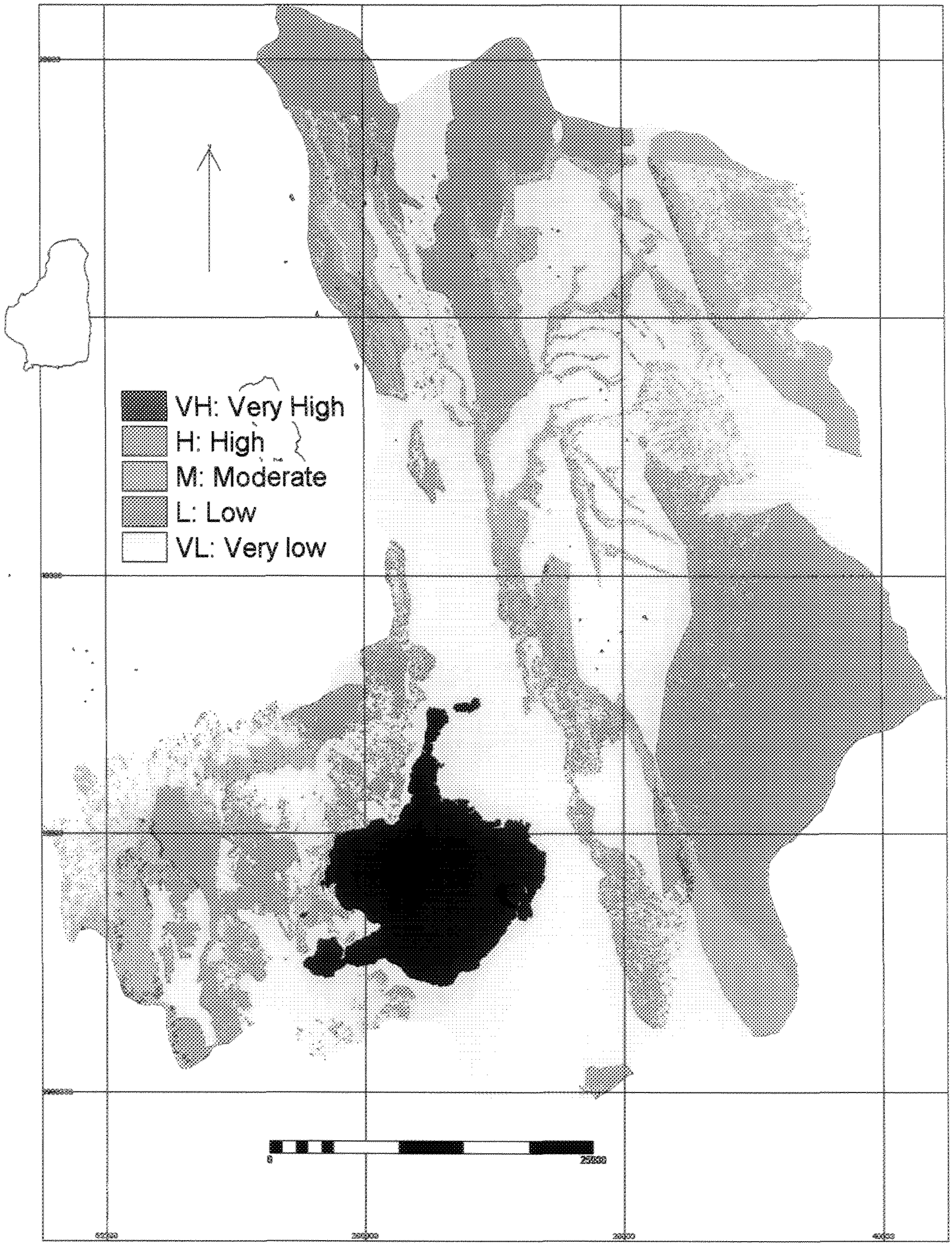


Figure 6.14 Erosion Map based on TMU and LandCover

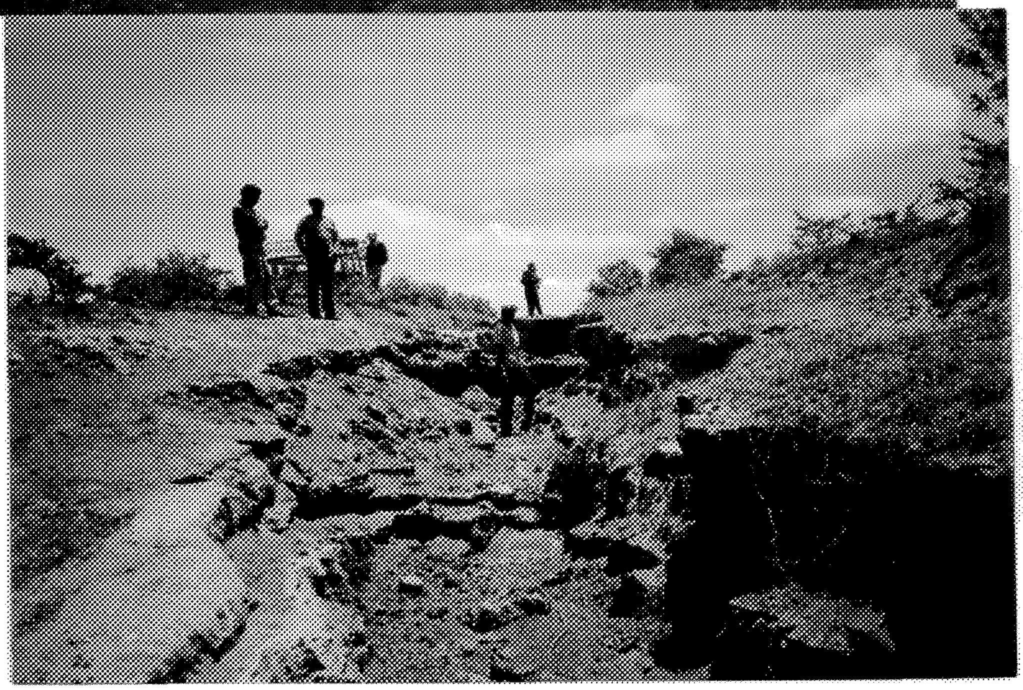

Erosion Map based on Rainfall & TMUs
0
25000
5.0
4.0
3.0
2.0
1.0
0.0

Erosion Map based on TMU, Rainfall & LandCover

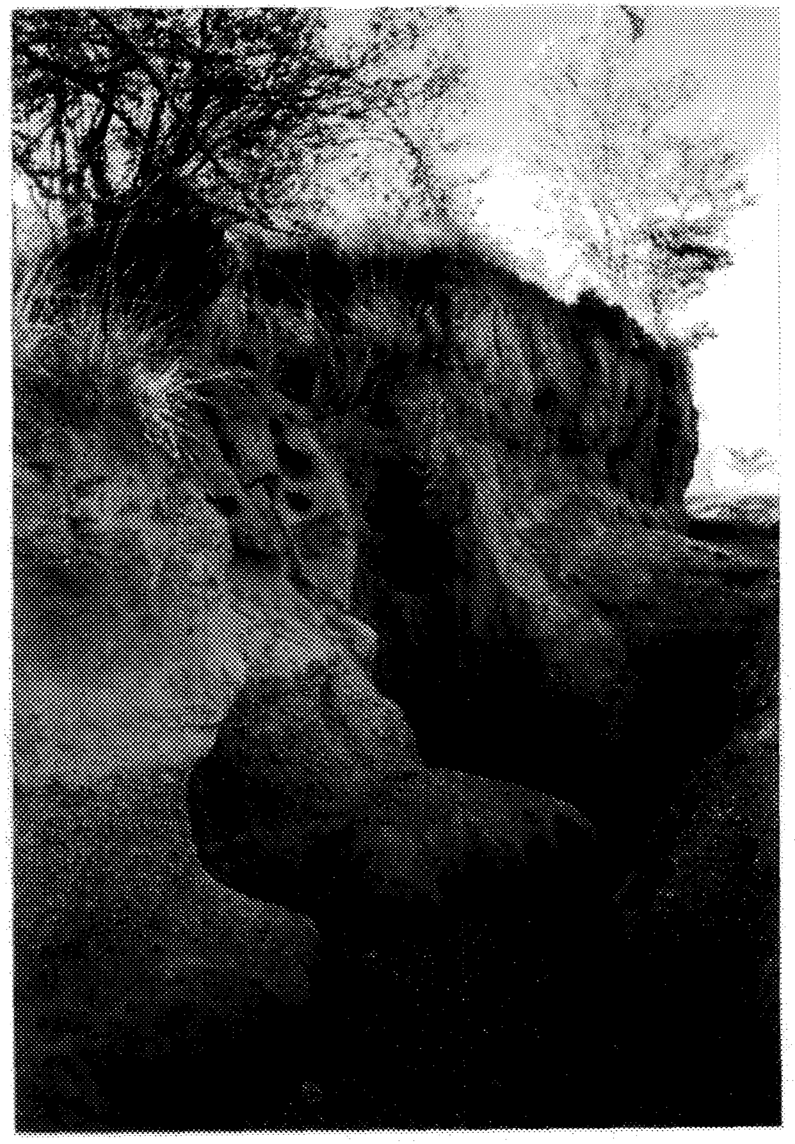


A

B



C



D

E

7 REGIONAL SCALE ASSESSMENT

There is no sense in using the "refined" models like the ones that work on rainstorm basis or for segment of slopes, when much of the information needed must be generated by the model itself (Engelen, 1995).

7.1 Introduction

There is little research done on erosion hazard at regional level. The little that has been done at that level is qualitative and in most cases the models used in hazard assessment are not validated. The SOTER provides a unique opportunity to try and make a validation of some of these models used.

7.2 SOTER (SWEAP Program)

SWEAP (Soter, Water Erosion Assessment Program) is a computer program based on the SOTER database developed at ISRIC. SWEAP was developed to make use of the digital database of SOTER that is a methodology for world Soils and Terrain digital database at a scale of 1:1 000 000. The objective of SWEAP is not present another model for erosion hazard assessment but to take advantage of the existing models as a tool for assessment of erosion risks to be used with the SOTER, that is at small scale (Van Engelen *et al.* 1993). The aim was optimise the balance between the refinement of the equations and the available data. 'There is no sense in using the "refined" models like the ones that work on rainstorm basis or for segment of slopes, when much of the information needed must be generated by the model itself'(Engelen, 1995).

ISRIC is an abbreviation for International Soil Reference Information Centre in Wageningen, in the Netherlands. SOTER is a comprehensive set of digitised map units and their attributes. The SWEAP therefore uses this automatically accessible database of transfer functions and conversion tables that relate parameters that are relevant to erosion assessment to conditions of soil, terrain, climate, land use and vegetation.

7.3 Methodology

The SWEAP uses the modified USLE (Universal Soil Loss Equation) and SLEMSA Soil Loss Estimation for Southern Africa) models. USLE is the widely used models for erosion assessment over the world while SLEMSA model is indicated as the most promising and better applicability for the tropical areas. Any of the two models can be selected for use within the program.

The USLE mode employs the Wischmeier and Smith's K-nomograph for the soil erodibility. The rainfall erosivity is calculated on the monthly basis as the available data was on monthly averages. The rainfall data used was obtained from the climatic data base (CLIMDATA) of Food and Agriculture Organisation. The rainfall erosivity was calculated using the Modified Fournier Index (MFI) for 60 rainfall station over the entire country. The MFI was assigned to the Agro-Climatic zones resulting in rainfall erosivity. In each unit, erosivity is calculated based on the rainfall station within the unit. The soils and terrain data, land use were all extracted from the SOTER units. These units are stored in database (Dbase format) in which all attributes for the units are stored. Some files used to extract specific data (climatic, soils, slope, land use, vegetation, etc.) from this database necessary to run SWEAP program.

SLEMSA model is sub model of the original equation for slope factor expression of the USLE using the slope gradient and slope length. The model uses the seasonal rainfall energy, and percentage rainfall interception. The only limitation is that the model was developed for Zimbabwe conditions. This means that most of the parameters that are given for the Zimbabwe region only. This may cause erroneous values when applied to another region. However in the SLEMSA mode, the F-ratings tabulated according to the soil type, texture class, internal drainage, surface sealing, horizon boundaries, shallow soils, salinity, etc. All these are taken from the database of SOTER. The slope length LS, factor has also been modified to allow for longer slope lengths more than 22 metres. The program uses the equations proposed by Mulchler & Mulphree (1978) for the LS factor. The equations give similar results to the Wischmeier & Smith, (1978) but is preferred for better data handling to the Wischmeier & Smith. Figure 7.1 shows the flow chart of SLEMSA model. With the SWEAP program all these attributes are derived from the huge data base of KENSOTER.

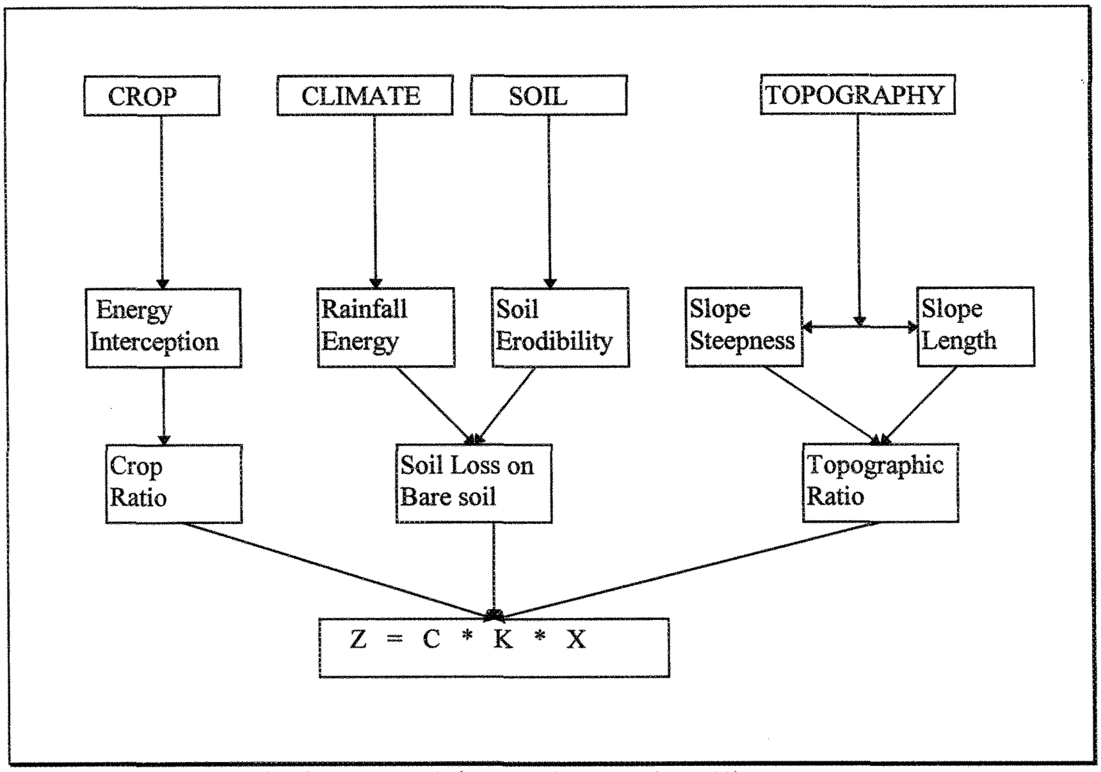


Figure 7.1 Frame Work of SLEMSA (after Stocking et al., 1988)

For the C factor, two options are available; the natural vegetation whose variation does not change so much and the perennial crops in which other details is requested; like the planting date growing period, etc. If the type of land use is permanent (for example forest or any natural vegetation), the C factor is then assumed constant for the rest of the months in the year. Otherwise if it is crops, the three sub factors come are requested. The P factor is assumed to be constant through the entire year.

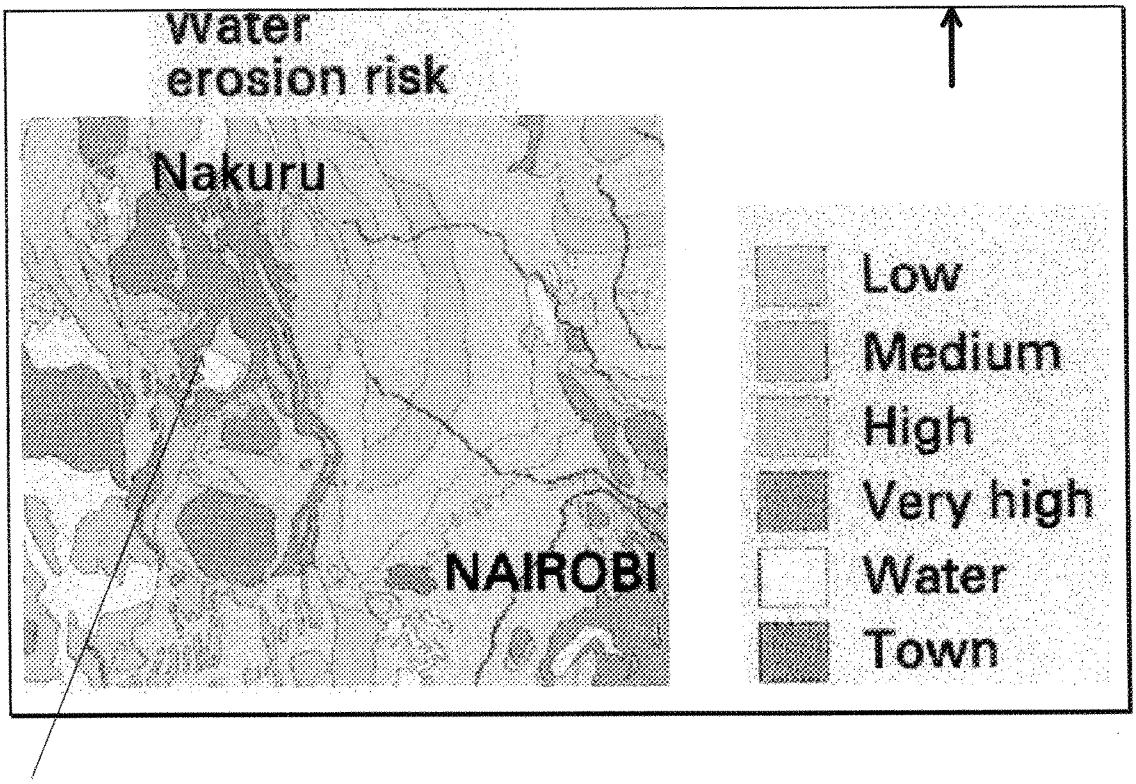
A time step used in the program is one month. This means that seasonal changes can be accounted for within the program. With this time step various factors can be changed to accommodate the growing periods when required for example. Crop residues are also accounted with a decay function after harvest.

Using the above program and the database for Kenya (Kenya Soil Survey), a soil erosion risk map was prepared for the country of Kenya. The slope map was prepared from the Digital Elevation model, while the land use, soil, map was prepared from the same database. The erosivity map was derived from the agro-ecological zone map. The USLE model was used and the result was a map showing the areas that are at risk to erosion. The rainfall erosivity units and the SOTER units were overlaid to result in the Erosion risk mapping units. The erosion risk was calculated for every combination of rainfall erosivity and SOTER unit by means of modified version of Universal Soil Loss Equation.

7.4 Results

The results of the SWEAP are satisfactory on the basis of USLE. With the SOTER database a lot of erosion risk map for various countries can be prepared. However, soil erosion modelling, it must be remembered, is not yet 'office work'. The field visit to the Naivasha area, in the Rift Valley province of Kenya revealed that most of the areas that classified as high erosion risk, actually do not have any erosion at all. One of the most likely reasons is that the units used in SOTER database are very big, judging it from the scale of the database itself. Secondly the rainfall pattern within Naivasha area varies both in time and space. Lack of rainfall data may lead to over estimation of the erosivity indices. The soils, too, are well drained with very high infiltration capacities.

Even to make comparisons is difficult as the scale of the two maps are different and the units under considerations are generalised. In fact, Naivasha basin according to SOTER methodology is divided into three units only.



Lake Naivasha

Figure 7.2 A small part of the Water Erosion Risk Map of Kenya, from SOTER.

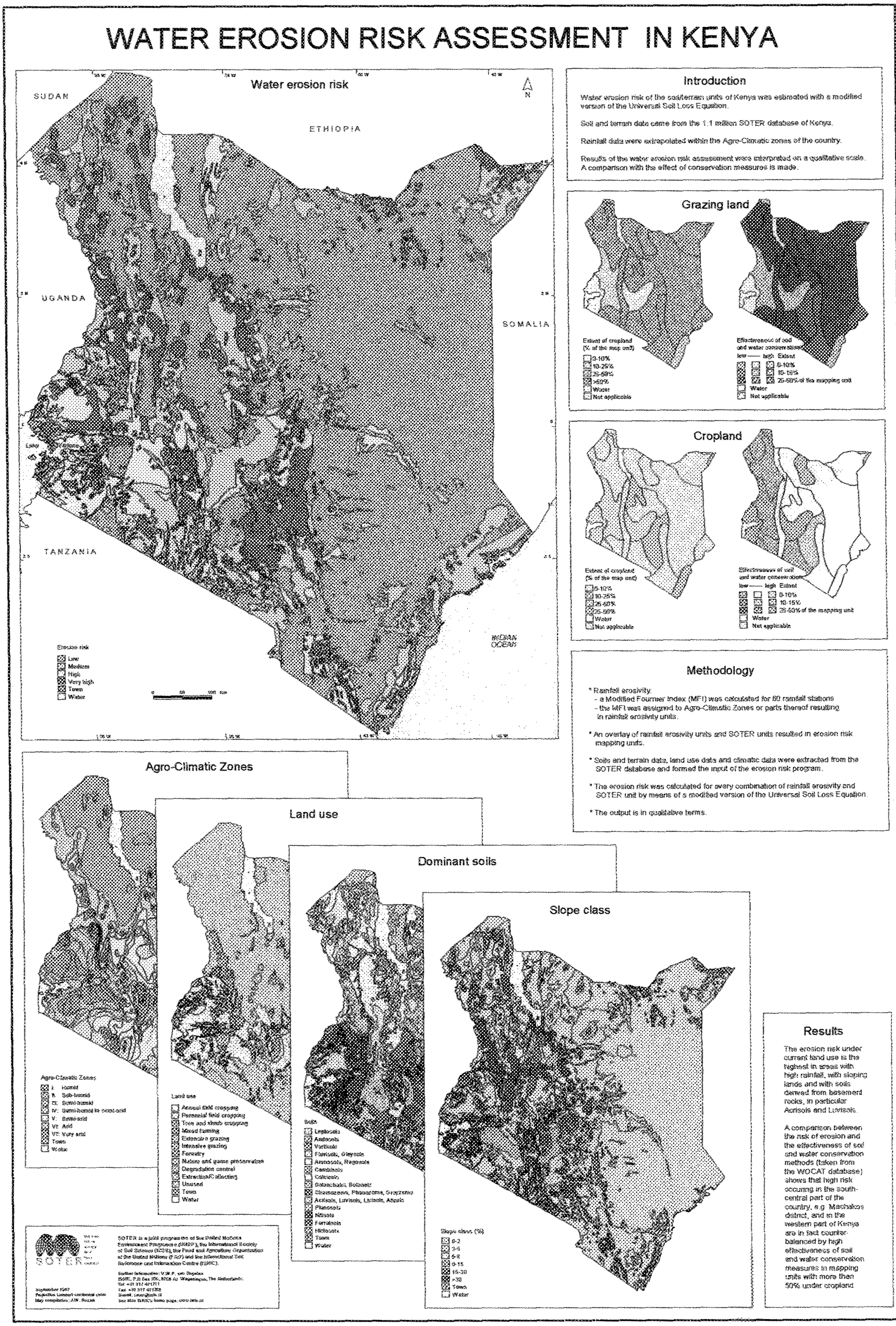


Figure 3 Water Erosion Risk Map of Kenya (after SOTER)

8 MORGAN METHODOLOGY

8.1 Introduction

The Morgan model was developed (Silsoe, UK) for determining mean annual soil loss by overland flow and rain splash erosion from field sized plots on hill side slopes. The model is composed of water phase and sediment phase. In the sediment phase, erosion is taken to result from the detachment of soil particles by rainsplash and their transport by overland flow. Splash is related to the rainfall energy and rainfall interception; runoff transport capacity depends on the volume of runoff, slope steepness and crop management. The method uses the probability distribution of daily rainfall events generating overland flow when the soil moisture storage capacity is surpassed. The model considers soil loss to be a result of splash detachment and overland flow as means of transport. The model is empirical but has more physical base than the Wischmeier's USLE in that it is possible to determine whether the erosion is detachment or transport limited. However, the model does not consider splash transport, which at times, is significant (Quansah, 1981).

The structure of the sediment phase is a simplification of the USLE by Wischmeier *et al.* It considers soil loss to result from detachment of soil particles by rain drop impact and the transport of these particles by overland flow. The operating equations were selected from the engineering and geomorphologic point of view. There are simple and input parameters are easy to determine.

8.2 Structure of the Model

8.2.1 *The water phase*

In the water phase, annual rainfall is used to determine the energy of rainfall for splash detachment and volume of runoff. The rainfall energy is modelled by extending the relationship between kinetic energy and intensity as described by Wischmeier & Smith using the annual rainfall and the rainfall intensity.

$$KE = R(11.9 + 8.7\log_{10} I)$$

Where

E = Rainfall energy (kJ/m².yr)
I = rainfall intensity (mm/hr)
R= Mean annual rainfall (mm).

The runoff volume is calculated with the assumption that runoff occurs when the daily rainfall exceeds a certain limit; moisture storage capacity of the soil with crop. Therefore it follows that the moisture storage capacity depends on the moisture storage at field capacity, the bulk density and rooting depth of topsoil.

In the absence of Intensity Duration Frequency Curves (I-D-F) and the detailed rainfall data (daily or hourly), the intensity was estimated by the formula below:

$$I = \frac{P}{24}\left(\frac{24}{t}\right)^{0.6}$$

where

I = rainfall intensity (mm/hr)
P = maximum 24-hour storm rainfall of a 10 year period (mm)
t = Design duration (hr)

From the National Water Master plan, 1992, the tables of probable rainfall, a value for this maximum was read as 62 mm in one day with a return period of 10 years. While the mean annual rainfall was calculated from the Isohyetal map. This was prepared from interpolation of rainfall stations support by the vegetation density on the satellite image of January 1995. The map was a value map in millimetres. An average values could be used as the area was very large an average value would not a good value to use.

The overland flow, Q, is calculated from:

$$Q = \mathrm{Re}\,xp\left(-\frac{R_c}{R_o}\right)$$

where

Q = overland flow (mm)
R = mean annual rainfall (mm)
R_c = soil moisture storage (mm)

It is evaluated from

$$R_c = 1000 \times M \times \gamma \times D_r \left(\frac{E_t}{E_o}\right)^{0.5} \quad \text{and} \quad R_o = \frac{R}{R_n}$$

where;

M = Soil moisture content at field capacity (%)
γ = Bulk density of the top soil layer (g/m^3)
D_r = Top soil rooting depth (m)
E_t = Actual evapo-transipration (mm)
E_o = Potential evapo- transipration (mm)
R_n= Number of rain days in a year (days)
R = Annual rainfall (mm)

8.2.2 The sediment Phase

The sediment phase has two components; splash detachment and runoff transport. Splash is determined using the power relationship of with rainfall energy coupled with interception of the cover. The energy decreases with the increase in the interception.

$$F = K\left(Ee^{-aP}\right)^{b} \times 10^{-3}$$

The transport carrying capacity of the overland flow is estimated from the volume of the overland flow, cover and the slope steepness.

$$G = CQ^{d}(\sin S) \times 10^{-3}$$

Kirby used the tangent of the slope angle. This results in high soil loss estimation at high slope angles. Normally, the sine of the angle is used in place of the tangent. The differences at low angles are minimal between sine and tangent and the estimation at high angles is reduced. The cover factor is assumed as in USLE. In this case it was determined from the three sub factors (Kooiman, 1987) The values of the empirical constants are given as; $a = 0.05$, $b = 1.0$, $d = 2.0$.

8.3 Input Parameters

Most of the soil input parameters were derived from the SOTER database obtained from the Kenya Soil Survey (KSS) through ISRIC. The data is in digital format (Dbase) and is therefore easy to couple it into this methodology. However, due to the size of pixel in the cover map, the cell size was made to be 28.455 m as well. This was for easy manipulation in GIS.

8.3.1 Climatic Data

This data was obtained from the climatic data collected before and during field work in Kenya. As the data was not detailed enough some calculation were performed to obtain some average figures. For example the maximum annual intensity in day was derived through a formula as indicated. Others were calculated from the Isohyetal map prepared from the available rainfall stations.

8.3.2 Soil Data

The soil data was obtained from this database in which a lot soil characteristic were found. Some parameters were determined whilst in the field like the top soil rooting depth, soil texture, permeability, etc. The other factors (bulk density, Organic matter content) were done at the Kenya Soil Survey laboratory in Nairobi, Kenya.

8.3.3 Cover data

The vegetation cover and interception were observed in the field, though not directly measured. In each unit of land cover, this was observed and noted. The sub factors were then calculated according to the methodology proposed by Kooiman, 1987. The splash detachment index was taken from tables (Quansah, 1981)

R	Mean annual rainfall (mm)
E	Kinetic energy of rainfall (J/m^2)
H	Soil moisture capacity under dense forest (mm)
R_c	Soil moisture capacity under actual vegetation (mm)
R_d	Root depth (m)
M_s	Moisture content at field capacity
Bd	Bulk density (g/m^3)
R_n	Mean number of rain days in a year
R_o	Mean rainfall depth per rain day (mm)
E_t	Actual evapotranspiration (mm)
E_o	Potential evapotranspiration (mm)
Int	Percent of rainfall intercepted
k	Soil detachability (g/Jm^2)
a	Interception index
b	Splash detachment index
C	Crop cover and management factor
S	slope of the land (degrees)

8.4 The Results

The results of this method shows clearly that the limiting factor is transport of the soil particles. From the figure 8.1, the map shows that the detachment map varies a lot over the entire basin. The transport map has only few places where there is enough transportation capacity of the overland flow. The overland flow is limiting in this case. The model therefore compares the predicted rate from the splash detachment to the transport capacity of the overland flow. The lower (limiting) of the two is taken to be rate at that site. The values in the figure are averages in each TMU but they vary from pixel to pixel. The pixel size is 28.445 metres.

TMU	AREA (ha)	LANDCOVER	SLOPE (deg.)	RAINFALL (mm)	Et/Eto	H (mm)	G (g/m^2)	F (g/m^2)	Gross Erosion (g/m^2)
MOUNTAIN	27228	Forest	35	1055	1	40.3	0	4835	0
VOLCANIC COMPLEX	34709	Agric, Scrubs	12	781	0.6	30.3	0	4634	0
SCARP	13867	Agric scrubs	45	961	0.6	31.2	0	6192	0
VOLCANIC PLATEAU	65138	Agric,	4	972	0.6	3.73	0	8742	45.76
FOOT SLOPE	7157	Agric scrubs	6	925	0.75	31	0	1831	0
VOLCANIC PLAIN	327392	Agric Crops	2	879	0.8	19.4	0	6352	0
UPPER LACUSTRINE PLAIN	9954	Agric, bare soils	2	659	0.8	19.7	0	2561	0
LOWER LACUSTRINE PLAIN	6345	Natural grass	2	620	1.2	19.1	0	2860	0
LAVA FLOW	4467	Bare rock	4	871	0.4	0	0	2523	0
RIVER VALLEY	21315	Agric. Crop, grass	15	861	0.8	18.5	0	5024	0

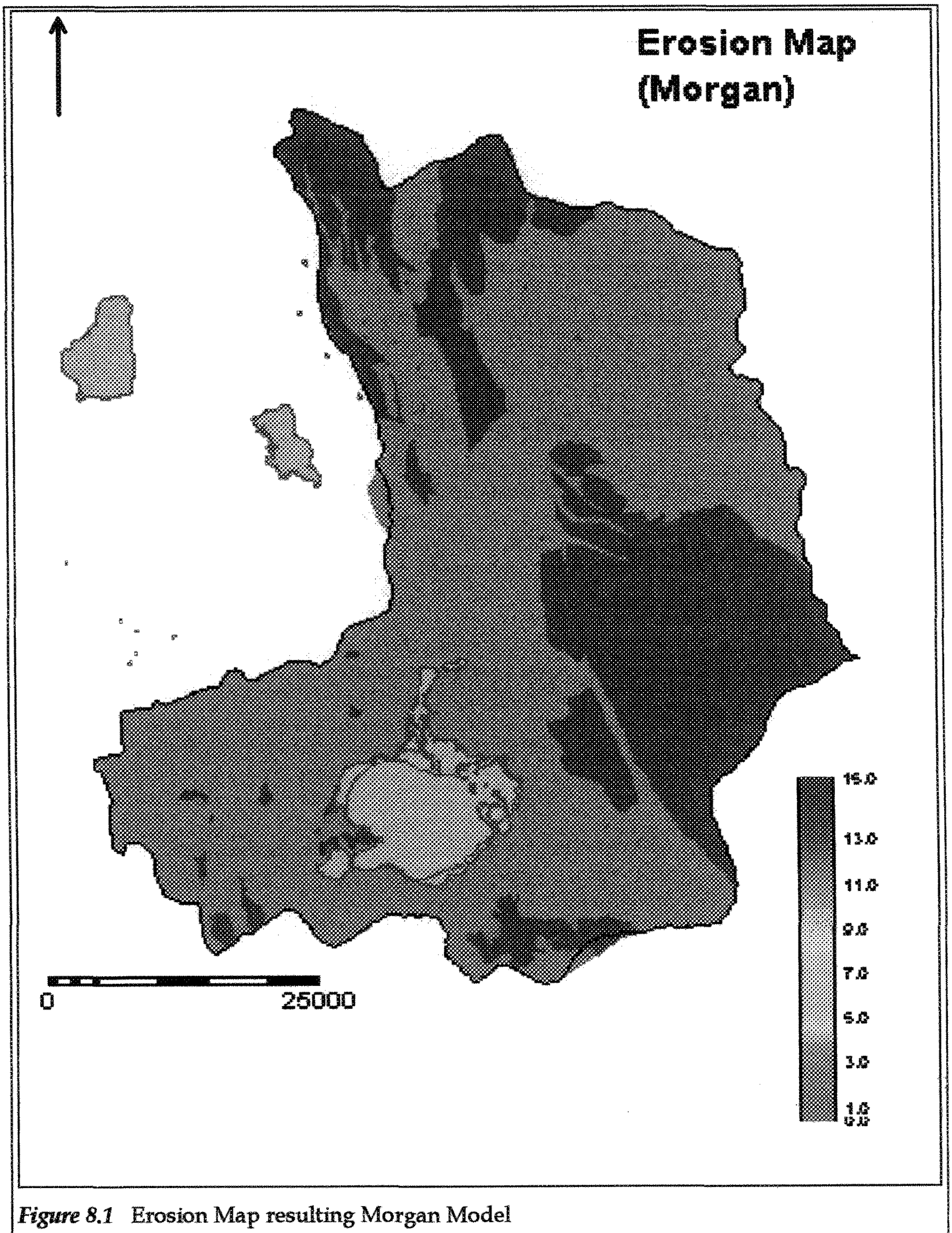


Figure 8.1 Erosion Map resulting Morgan Model

9 DISCUSSION OF RESULTS

9.1 Land cover from Remote Sensing

Remote sensing has been used to extract the land cover for use in the assessment. The NDVI, and PCII showed the vegetation very distinctively. The classification was originally done using the NDVI. After close examination, the PCII revealed the same spectral pattern like the NDVI. However, on PCII, the relief effect was completely absent in the image, making easier to interpret than the NDVI.

When compared to the erosion map prepared using the look up tables, there is no direct relationship. However the drainage appeared sharper on the PCII. The area is not highly eroded implying that there are no specific areas where a relationship would be obtained. Some gullies can be seen clearly from the second principal component. The bare soils appear in light tone while the forest appear very dark. The NDVI and PCII appeared similar except that the light tone areas on NDVI image are the dark tone areas on the PCII, i.e. the reverse of the other.

9.2 Terrain Mapping Units (Relational Modeling)

The qualitative erosion map prepared using the relational modelling together with TMUs is more accurate than the other methods. This may be attributed to fact that this methodology is knowledge driven and in this case the knowledge used was obtained through field observance and aerial photos. With this knowledge other areas with similar characteristics were assigned similar ratings. This represented the actual status of the erosion in the area. With other models, verification of the predicted rates is necessary but difficult. Using the rule based assessment relative rates can be evaluated and assigned appropriately.

The advantage of this methodology is that the complicated soil erosion processes are not simplified by equations but are instead avoided. In other methods of modelling these complicated processes are simplified and the result of this simplification affects the prediction of these models. In this methodology these processes are never attempted to be simplified but the result of the process is obtained from the ground truth.

The result of this method shows that most areas, some of which are rated as erosion risk from the SOTER methodology, are in fact not eroded at all. However clearly the rainfall erosivity together with land cover are the limiting factors. In the Rift valley floor the rainfall erosivity is quite low (500 mm per annum) while the land cover is quite poor (bare and savannah shrubs). In the margins, the rainfall increases but so does the land cover. However most of the sediments originate from these areas. Most of the land in this part is cultivated. This exposes it to high erosive storms at times with little or no cover. From the analysis of the sediment yield it clear the first storms always erodes more than the rest of the storms as the land cover is poor.

The result of this methodology (TMUs with rule base modelling) would have been further improved by coupling the sediment yield from different TMUs drained by rivers. The quantification of the qualitative rates would have done through sediment yield from two rivers. The two rivers with sediment load data were used to quantify the amount sediment production in each TMU. The result of this quantification would not have been accurate as the most of the other rivers did not have enough sediment data to be used for this purpose.

9.3 SOTER (SWEAP)

The initial aim of this methodology was to validate objectively, through pilot areas and available data and improve the qualitative erosion maps into actual erosion rates. The data used was gathered by independent experts in respective countries and therefore provided a nice opportunity for extension qualitative terms into actual rates. The method is good in that erosion assessment can now be done at a very large scale, for example, the entire country of Kenya. This has been, for a long time now, the major problem of erosion modeling.

However, this was not achieved as some of the parameters are still missing and had to be estimated or determined empirically. The resulting map was still a qualitative risk (potential) map. Some of the doubts that are cast on the structure of the this program were;

Should more relations be expressed as external input tables or coefficients of transfer functions?

Which would be the best way to account for erosion control practices at the SOTER Scale?

How best can the seasonal dynamics (perennial crops) be included into the program? (SWEAP manual, 1995)

Without addressing the above questions the methodology still gives the same result as the USLE. The weaknesses of the USLE are well known and this methodology suffers the similar weakness unless further modifications are done.

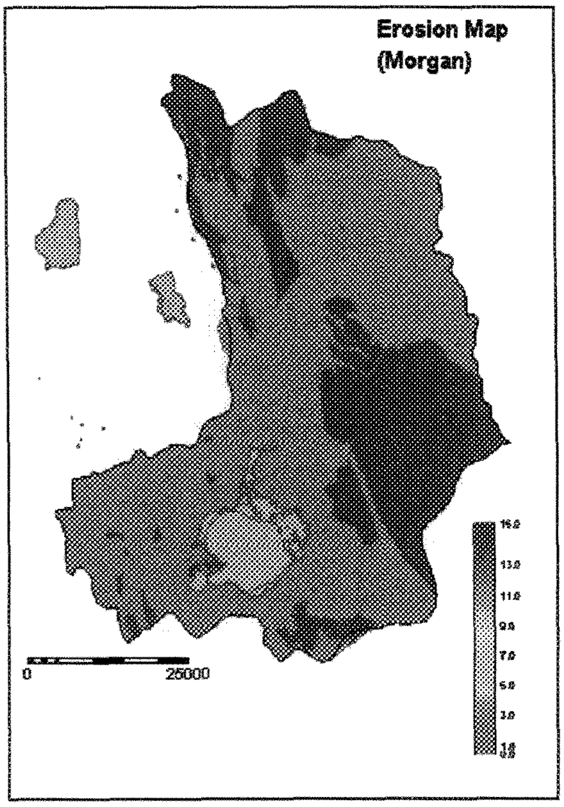
The results of the methodology are shown in the previous chapter. The areas close to the lake are rated as high risk areas. From the field observance, this is not so. This is one of areas that unfortunately show the weakness of this methodology. This may be attributed to the size of the SOTER units (>2.5 km^2). The measurement points these are still point measurement. The application of these attributes over the entire area of greater than the minimum size makes it more general.

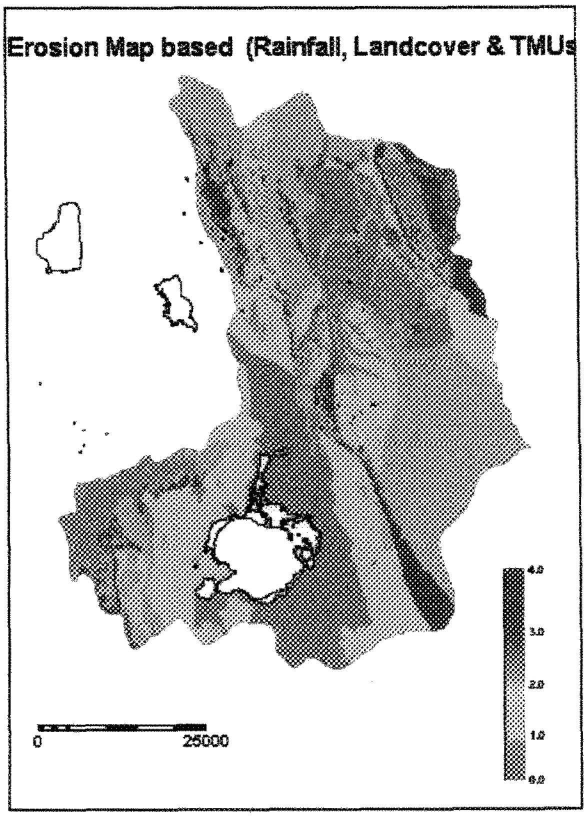
9.4 Morgan Method

The Morgan methodology somehow showed results that were similar to the relational modelling. It also clearly shows that the erosion process in the area is transport limited. Due to little overland flow, sediments though detached are not transported. In all the TMU the overland is less than 15 % of the total rainfall, as estimated by the water phase of this method. This infers that the area has high infiltration rates with very low curve numbers (CN 5 - 10).

This methodology of sediment transport capacity is highly dependent on overland flow. Since overland flow is estimated by a series of parameters whose determinations have no clear guidelines, they are generalized. The use of this method should be done with this caution, especially in the determination of the parameters. Even then some parameters remain complicated to determine. For example, the splash detachment factor exponent (b), the interception exponent (a) and the soil detachability index (k) are given as constants. These parameters make the use of this method difficult or otherwise it is generalized since these values may have to be assumed to remain the same irrespective of the region.

This method does present some results that are similar to the field observance though rates may not be accurate. It can be used together with SWEAP or Relational modeling for the quantification of erosion rates.





10 Summary and Conclusion

Rainfall analysis has revealed that rainfall in the basin varies spatially due to topography. The temporal variations are due to the seasonal changes. The seasons are are identified as; main rainy season (April - June), dry period (July-September and January - March) and short rainy season (October - December). On a monthly basis, the correlation between rainfall depth and the distance between stations was poor. The relation between the elevation and rainfall depth was positive though not very strong. The correlation is poor due, possibly to the low density of rainfall stations within the catchment. This has the effect of not having the full coverage of rainfall measurement over the entire area.

Rainfall erosivity was calculated from the available data for the rainfall stations within the area. Monthly data was used as the daily data had a lot gaps with missing data. An isohyetal map was generated using this data coupled with the vegetation pattern on the color composite of the Landsat image. The vegetation pattern on the image appeared to be influenced by the rainfall pattern in the area. The rainfall stations were overlaid on the color composite and isohyets were drawn. This improved isohyets for places where there are no rainfall stations. Furthermore, the isohyets could now be assigned values.

The isohyetal map reveals that most parts of the lower floor of the rift valley receive low rainfall. The area around Lake Naivasha and the south of the lake receive less than 500 mm per year (except Longonot volcano). The northern part of the basin generally receives more rainfall due to the higher elevation. The central part receives on average between 700 and 900 mm annually. The western and eastern part of the valley margins receive more that 1000 mm per year. To the east, the Kinangop plateau receives above 1100 mm although it is close to the lake (15 km). On the western side the Mau escarpment was rated as receiving as much as the Aberdares Range (above 1300 mm per year). There were no rainfall stations on the Mau escarpment. The vegetation density pattern was used to estimate rainfall amounts.

The correlation between the daily rainfall and daily runoff was poor. This was thought to be the result of the large size of the catchment and the influence of large ground water component. These factors influence the reaction of the river to any storms that occur in the catchment. This is further compounded by the high infiltration rates of the soils developed on ashes of volcanoes. In addition to this the rainfall in Naivasha area is of low intensity. For example in 1997, only 45 % of the storms were above 10 mm depth. In the whole period of 12 months only 4 four storms had intensities above 12 mm/h.

TMUs were established through the interpretation of aerial photos at scales of 1: 50 000 and 1: 12 500 and the Landsat TM image supported by the topographic maps. The essential idea associated with the generation of TMUs was the integration of relief, general soil constituents and the genesis of the landforms.

The first step in the identification of TMUs was the delineatation of areas of similar relief, soils and geology using the image interpretation (under stereo) and topographic maps to establish the boundaries. The variation in morphometry, lithology, geology and the dominant land cover and land use within the area, with their distinctive patterns on the image could be easily related to the TMUs. The means that each TMU could be considered to be uniform almost in all aspects. The same could be said about soil erosion process in each TMU. The erosion was checked and finalised during the field visit.

The NDVI image (created from Landsat TM image Jan 1995) was classified in order to obtain a more recent land cover thematic map of the area. The second principal component from the principal component analysis proved to contain the same spectral information as the NDVI. The advantage of the PCII was that relief effect was completely eliminated from the image. This too was used in the land cover classification.

Where as TMUs do not change with time, the land cover changes from year to year and even within a year. The classification was done using ILWIS package. Supervised classification was carried out and training samples were made for the different land cover classes that were seen to be related to erosion. The main classes identified were forest, scrub (natural, stunted) agriculture, bare soil and water.

With the above layers, the GIS was then used to generate the erosion map using the look up tables (here referred to as 2 D tables). It is thought that the soils, land cover and rainfall are the main controlling factors in the process of erosion. With each class in the three maps given a rating, from field experience, a combination of either two resulted in another map. For example, a combination of rainfall and land cover resulted in one map which showed areas with ratings of rainfall and land cover. With these factors the major component of erosion process is already determined. This is the interaction of rainfall (eroding force) and the ground (eroded). If there is no land cover and there is high rainfall, irrespective of the TMUs, erosion occurs, except in lava (rocky) areas. This map was then combined with the TMUs to account for slopes, permeability and deposition which resulted a final erosion assessment map. Other combinations were made as well. The TMUs were combined with the rainfall map and another map from a combination of TMUs and cover. The resulting erosion maps were qualitative and quantification of these map was not possible as the suspended load data available was not adequate for computation of sediment yield in each TMU. The large size of the basin, coupled with varying land cover was the limiting factor for this process.

According to this method of rule-based modeling, the areas with high erosion are those on the scarps and other steep slopes. To the north, the scarp just below the Aberdare's Range showed high erosion rates. The slopes south east of Lake Naivasha and east of Longonot Volcano also had high erosion rates. Here some gullies could be seen from photographs taken from the air. The same area is highly eroded by wind. The winds along the rift valley sometimes are very strong. The area too is overgrazed by goats whose habit is to completely up root the grass. During the dry seasons, the loose soils have no cover and the strong winds easily sweeps the soil particles away. The beginning of the rain season is still a problem as there is no cover and the month of April is characterized by high intensity erosive storms which can cause this erosion. Some gullies are seen on the steep slopes where there are agriculture plots. These slopes (> 8 %) are not suitable for agriculture.

The SOTER method shows that the area close to the lake is rated as a high risk area. Field visits revealed however that there is very little erosion here and in some places none at all. This discrepancy may be attributed to the large size of the SOTER units (the smallest unit size is 2.5 km^2). When such a large unit is used a lot of attributes are generalised. Another reason is that the database is still being updated, some attributes may not be correct. Moreover, most of these attributes are point observations and measurements. This indicates that in order to model erosion, field visits are a very important component, without which the result are without substance.

The sediment yield of catchment is not very high (Malewa catchment yields 142 tons per year) with respect to its size. The average sediment yield is 6 tons/km^2/year. The sediment yield in the long rainy season is 12.4 tons/km^2/yr while in the dry months it is 3.6 tons/km^2/yr. and the short rainy season it is 0.8 tons/km^2/yr. This based on the Malewa catchemnt which is about half of the whole basin in size. The lake sedimentation is therefore very low. However it must be remembered Lake Naivasha is a shallow lake, an increase of of about 1 mm per year increases the surface and eventually the lake evaporation. The eveporation rates are quite high (1300 mm per year).

In general the area has little to no erosion except for localised places, like the mentioned above. The type of erosion in the area is mainly sheet and wind erosion.

The TMUs were found to be a very useful way of describing the terrain characteristics in a GIS environment. These attributes were used in the assessment of erosion. The repeatability of boundaries as well as the thematic attributes were used to evaluate the erosion process in each TMU.

The rule based modeling is knowledge based. Oftentimes data driven models are either lacking data, or the data is neither reliable nor accurate. With knowledge driven models, such problems may be eliminated. However the drawback is that the method does not quantify erosion rates.

Finally it must be stated here that with normal rainfall, no accelerated erosion can be noticed in this area. As the rainfall years are not always the same, a very wet year would result in very high erosion in this area. The erosion potential rates are very high but the actual erosion rates are very low.

The unit which requires attention immediately is area east of Longonot volcano. The conservation measures must be directed to area. Terraces should be constructed on the agriculture plots as a means of reducing the slope length and steepness. In places where there are channels, check dams must be constructed to trap the sediments and reduce the flow velocities of flowing water within theses channels. For areas which are eroded by wind, hedges of trees, across the direction should planted. These would reduce the wind velocities. Although this area does not contribute to lake sedimentation, the erosion is degrading the soil. The productivity of the soils will reduce eventually if nothing is done.

Recommendations

The use of models in erosion assessment is the order the day in this computer age. However, care should be taken on the selection of the model to use, as it influences the results. It is the quick way of erosion assessment but at times it may be very inaccurate.

Soil erosion is very difficult to model. Careful field observations and measurements should be carried out before modeling is done.

Use of remote sensing and GIS should be seen as one of the promising aspects in modeling. The land cover factor that is always dynamic can only be assessed qualitatively through remote sensing.

The following are recommendations that should be considered in the Naivasha basin.

- Cultivation on slopes steeper than 8 % should not be allowed as these are the most vulnerable areas of severe erosion.

- If cultivation is allowed on these slopes (>8 %), conservation measures must be taken. Terraces and cut off drains must be constructed prior to allocation as farmers may not have the capacity to construct them.

- Under no circumstances should very steep slopes (especially those on river banks) be put under cultivation as is now happening.

- Reaforestation should be introduced in the basin. Replanting the natural vegetation may serve best for this purpose.

- Grazing was found to be one of the main causes of erosion in the area. It is proposed that areas overgrazed by animals be isolated. Grazing should be controlled and restricted only to suitable areas.

- Farmers need to understand the effect of overgrazing, cultivation on steep slopes and removal of crop residuals from the fields. This can only done if they are made aware through extension workers.

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KENYA AGRICULTURAL RESEARCH INSTITUTE
SOIL TEST REPORT

18/11/9

INWARD REF.:

1st LOT

OUR REF.: Ex-SIDERIUS

SOILS AND AGRICULTURAL CHEMISTRY SECTION
NATIONAL AGRICULTURAL RESEARCH LABORATORIE
P.O. BOX 14733,
NAIROBI.

DATE SAMPLE RECEIVED:

DATE SAMPLE REPORTED:

FROM (PLACE)

NB: requested C% and texture only

SAMPLE/S SENT BY: ....

....

Field Designation	GB1	GB2	LG1	LG2	E1	E2	M1	M2	M3
Lab No.	A	B	C	D	E	F	G	H	I
Depth									
Colour									
Chemical Test Results									
pH									
K m.e.%									
Ca m.e.%									
Mg m.e.%									
Mn m.e.%									
P. p.p.m									
N%									
C%	1.70	0.93	1.04	0.33	0.99	1.28	0.39	1.46	0.93
Hp m.e%									
E.C.									
Fe p.p.m									
Cu p.p.m									
Zn p.m.m									

(Toxicities Brackected) Deficiencies Underlined

Remarks:

MECHANICAL ANALYSIS (HYDROMETER METHOD)

Sampled by: Dr.Siderius

Location ______________________________

Analysed by Mr. Michael

Date: 19/11/97

Lab No.		% Sand	% Silt	%Clay	Texture Grade
Gilgil	1	14	26	60	C
	2	22	22	56	C
Longonot	1	34	26	40	SL/C
	2	76	16	8	SL
Eburu	1	36	32	32	CL
	2	28	30	42	C
Maela	1	80	12	8	LS
	2	62	22	16	SL
	3	60	24	16	SL
Middle		26	16	58	C

KENYA AGRICULTURAL RESEARCH INSTITUTE
SOIL TEST REPORT

18/11/9'

INWARD REF.:

1st LOT

OUR REF.: Ex-SIDERIUS

SOILS AND AGRICULTURAL CHEMISTRY SECTION
NATIONAL AGRICULTURAL RESEARCH LABORATORIE
P.O. BOX 14733,
NAIROBI.

DATE SAMPLE RECEIVED:

DATE SAMPLE REPORTED:

FROM (PLACE)

SAMPLE/S SENT BY: ....

....

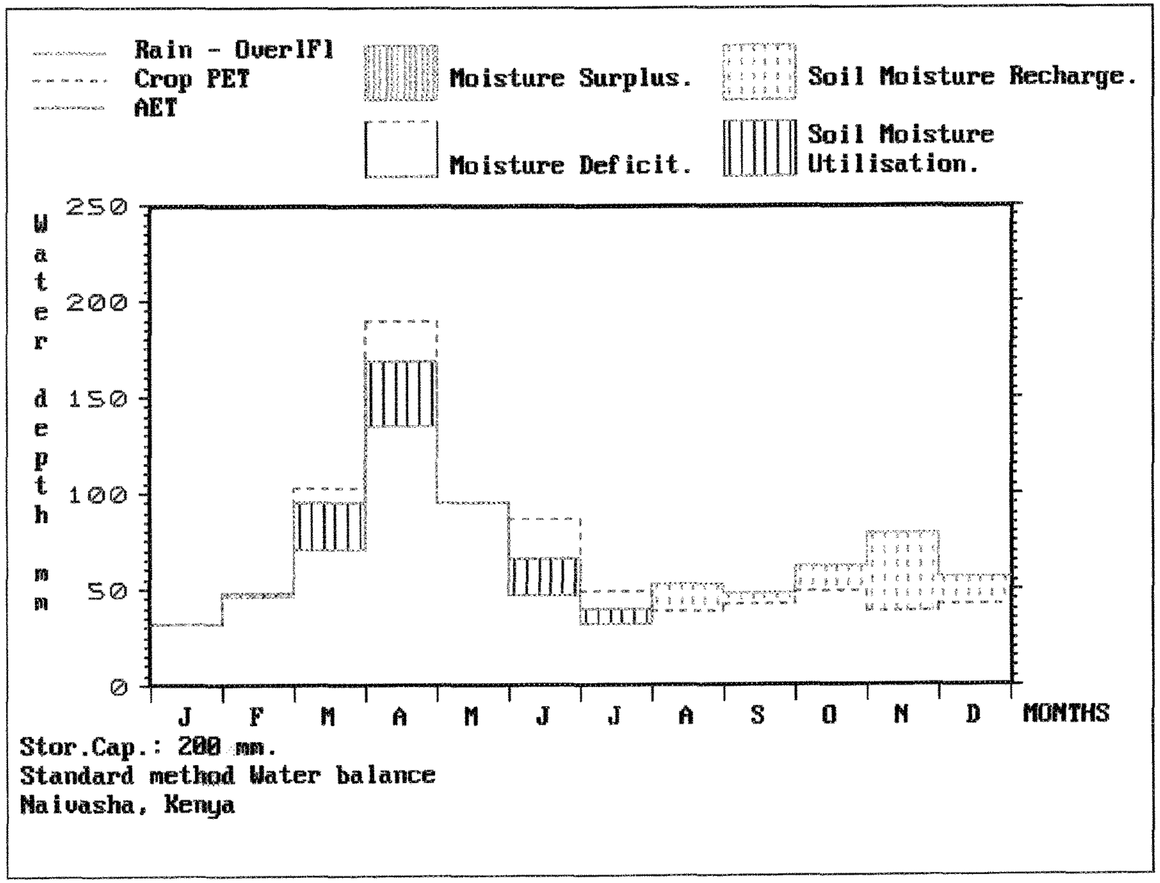
Field Designation	MM1								
Lab No.	J								
Depth									
Colour									
Chemical Test Results									
pH									
K m.e.%									
Ca m.e.%									
Mg m.e.%									
Mn m.e.%									
P. p.p.m									
N%									
C%	1.82								
Hp m.e%									
E.C.									
Fe p.p.m									
Cu p.p.m									
Zn p.m.m									

(Toxicities Brackected) Deficiencies Underlined

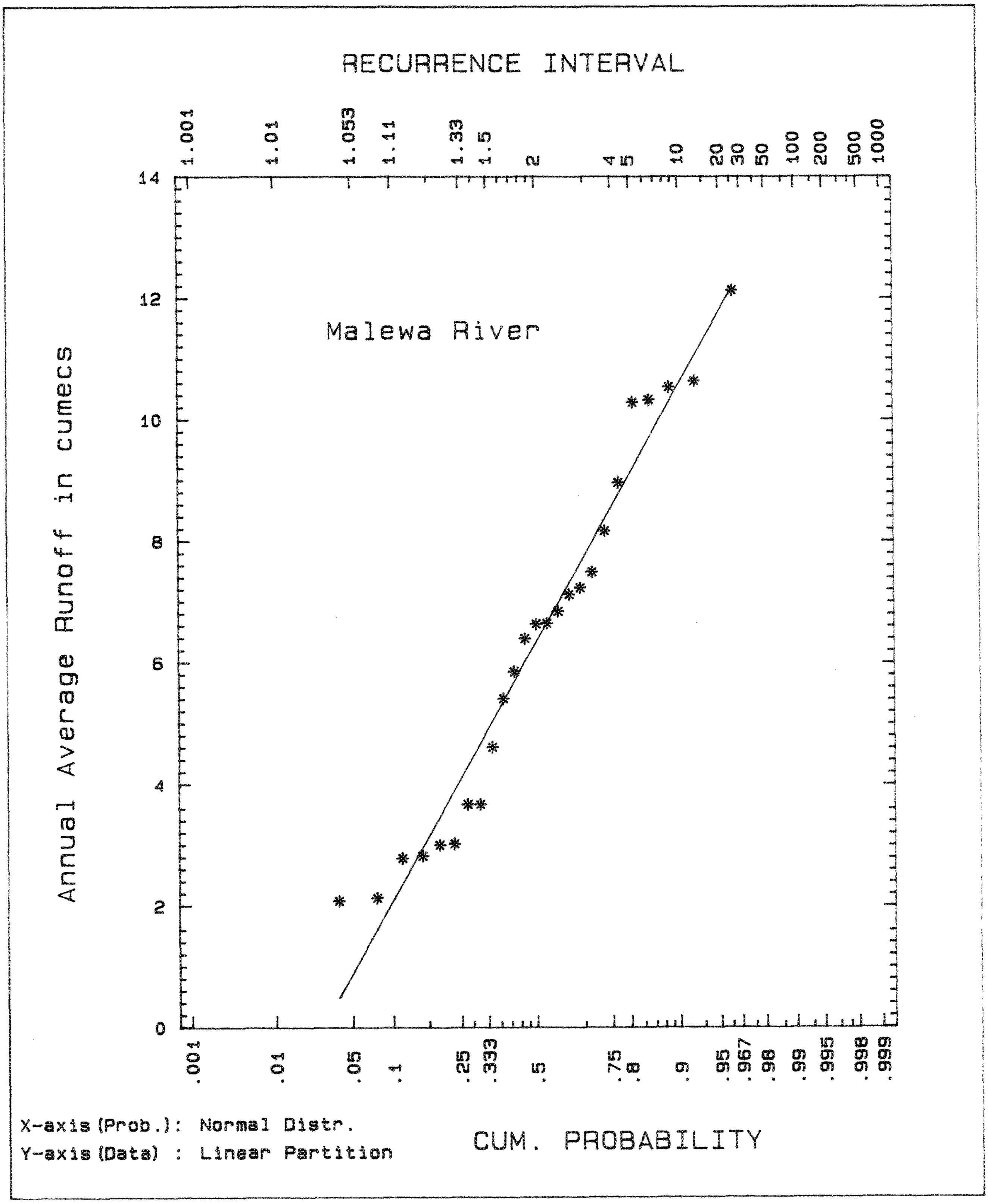
Remarks:

Appendix 1

WATER BALANCE FOR NAIVASHA BASIN



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yr
Rain:	32	46	71	142	100	47	32	53	48	62	79	57	**769**
Overland Flow:	0	0	0	7	5	0	0	0	0	0	0	0	**12**
Effective Rain:	32	46	71	135	95	47	32	53	48	62	79	57	**757**
Ref.Pot.Evp.:	106	160	171	152	119	108	123	128	142	165	129	142	**1645**
Kc values :	0.3	0.3	0.6	1.3	0.8	0.8	0.4	0.3	0.3	0.3	0.3	0.3	
Crop Pot.Evp.:	32	48	103	190	95	86	49	38	43	50	39	43	**815**
Rain - Evpt.:	0	-2	-32	-55	-0	-39	-17	15	5	12	40	14	**-58**
Ac. Pot. Water Loss:	-34	-36	-68	-123	-123	-162	-179	0	0	0	0	0	
Soil Moisure:	169	167	143	108	108	89	82	96	102	114	154	169	
Difference in Soil Moisture:	-0	-2	-24	-34	-0	-19	-7	15	5	13	40	14	
Actual Evapotranspiration:	32	48	95	169	95	66	39	38	43	50	39	43	**757**
Moisture Deficite:	0	0	7	21	0	20	10	0	0	0	0	0	**58**
Moisture Surplus:	0	0	0	0	0	0	0	0	0	0	0	0	**0**



RECURRENCE INTERVAL
1.001
1.01
1.053
1.11
1.33
1.5
2
4
5
10
20
30
50
100
200
500
1000
Malewa River
Annual Average Runoff in cumecs
0
2
4
6
8
10
12
14
.001
.01
.05
.1
.25
.333
.5
.75
.8
.9
.95
.967
.98
.99
.995
.998
.999
CUM. PROBABILITY
X-axis (Prob.): Normal Distr.
Y-axis (Data) : Linear Partition

Appendix 2

Sediment Yield data

Sation ID	River	Date	Discharge	Suspended load
2GA01	Gilgil	19-Apr-50		913
2GA01	Gilgil	19-Apr-50	11	775
2GA01	Gilgil	20-Apr-50	3	413
2GA01	Gilgil	20-Apr-50		413
2GA01	Gilgil	24-Apr-50	2	299
2GA01	Gilgil	24-Apr-50		299
2GA01	Gilgil	02-May-50		1484
2GA01	Gilgil	02-May-50	4	1484
2GA01	Gilgil	11-May-50		370
2GA01	Gilgil	11-May-50	4	370
2GA01	Gilgil	12-May-50	6	211
2GA01	Gilgil	13-May-50		930
2GA01	Gilgil	13-May-50	12	930
2GA01	Gilgil	15-May-50		248
2GA01	Gilgil	23-May-50		456
2GA01	Gilgil	02-Jun-50	15	190
2GA01	Gilgil	02-Jun-50		190
2GA01	Gilgil	07-Jun-50		573
2GA01	Gilgil	26-Jun-50		552
2GA01	Gilgil	08-Jul-50		262
2GA01	Gilgil	08-Jul-50	17	262
2GA01	Gilgil	15-Jul-50		457
2GA01	Gilgil	09-Jul-50		5
2GA01	Gilgil	09-Jul-50		200
2GA01	Gilgil	12-Aug-50		192
2GA01	Gilgil	13-Aug-50		181
2GA01	Gilgil	17-Aug-50		137
2GA01	Gilgil	18-Aug-50		594
2GA01	Gilgil	19-Aug-50		359

Sation ID	River	Date		Discharge	Suspended load
2GA03	Gilgil	21-Apr-81		1	162
2GA03	Gilgil	24-May-82		1	112
Sation ID	**River**	**Date**		**Discharge**	**Suspended load**
2GA06	Little Gilgil	21-Apr-81		1	173
2GA06	Little Gilgil	09-Feb-82		1	575
2GA06	Little Gilgil	02-Jun-82		1	253

Sation ID	River	Date		Discharge	Suspended load
2GB03	Malewa	28-Sep-53		39	20
2GB03	Malewa	02-Nov-53		15	11
2GB03	Malewa	09-Nov-53		10	17
2GB03	Malewa	16-Nov-53		15	16
2GB03	Malewa	23-Nov-53		8	17
2GB03	Malewa	10-May-54		15	24
2GB03	Malewa	17-May-54		32	14
2GB03	Malewa	25-May-54		20	7
2GB03	Malewa	25-May-54		20	7
2GB03	Malewa	31-May-54		7	6
2GB03	Malewa	31-May-54		7	6
2GB03	Malewa	07-Jun-54		8	5
2GB03	Malewa	07-May-54		8	20
2GB03	Malewa	14-Jun-54		43	8
2GB03	Malewa	14-Jun-54		43	8

Sation ID	River	Date		Discharg e	Suspended load	
2GB04	Wanjohi	28-Sep-53		13	6	
2GB04	Wanjohi	05-Oct-53		14	20	
2GB04	Wanjohi	19-Oct-53		23	20	
2GB04	Wanjohi	26-Oct-53		31	24	
2GB04	Wanjohi	02-Nov-53		58	19	
2GB04	Wanjohi	09-Nov-53		24	15	
2GB04	Wanjohi	16-Nov-53		35	22	
2GB04	Wanjohi	23-Nov-53		23	15	

	Long rains					
2GB04	Wanjohi	10-May-54		20	37	
2GB04	Wanjohi	17-May-54		136	31	
2GB04	Wanjohi	25-May-54		119	17	
2GB04	Wanjohi	31-May-54		32	9	
2GB04	Wanjohi	07-Jun-54		99	46	
2GB04	Wanjohi	14-Jun-54		200	38	
2GB04	Wanjohi	21-Jun-54		39	15	
2GB04	Wanjohi	17-Jul-54		135	58	

Sation ID	River	Date		Discharge	Suspended load	
2GC01	Nandarasi	15-Feb-53		3	14	
2GC01	Nandarasi	30-Jul-53		4	14	
2GC01	Nandarasi	04-Aug-53		4	15	
2GC01	Nandarasi	06-Aug-53		4	12	
2GC01	Nandarasi	21-Aug-53		4	13	
2GC01	Nandarasi	02-Jan-54		4	14	
2GC01	Nandarasi	12-Jul-54		7	17	
2GC01	Nandarasi	26-Jul-54		13	19	
2GC01	Nandarasi	16-Aug-54		7	10	
2GC01	Nandarasi	27-Sep-54		6	8	
2GC01	Nandarasi	06-Dec-54		5	9	
2GC01	Nandarasi	24-Jan-55		4	30	
2GC01	Nandarasi	07-Feb-55		4	38	
2GC01	Nandarasi	20-Feb-55		5	33	

	long rains				
2GC01	Nandarasi	29-Jun-53		4	22
2GC01	Nandarasi	28-Jun-54		6	14
2GC01	Nandarasi	07-Mar-55		3	32
2GC01	Nandarasi	09-May-55		4	28
2GC01	Nandarasi	23-May-55		4	42
2GC01	Nandarasi	06-Jun-55		4	28
	short rains				
2GC01	Nandarasi	08-Nov-54		5	12
2GC01	Nandarasi	16-Nov-53		5	29

Sation ID	River	Date		Discharge	Suspended load	
2GB04	Wanjohi	28-Sep-53		13	6	
2GB04	Wanjohi	05-Oct-53		14	20	
2GB04	Wanjohi	19-Oct-53		23	20	
2GB04	Wanjohi	26-Oct-53		31	24	
2GB04	Wanjohi	02-Nov-53		58	19	
2GB04	Wanjohi	09-Nov-53		24	15	
2GB04	Wanjohi	16-Nov-53		35	22	
2GB04	Wanjohi	23-Nov-53		23	15	

2GB04	Wanjohi	10-May-54		20	37	
2GB04	Wanjohi	17-May-54		136	31	
2GB04	Wanjohi	25-May-54		119	17	
2GB04	Wanjohi	31-May-54		32	9	
2GB04	Wanjohi	07-Jun-54		99	46	
2GB04	Wanjohi	14-Jun-54		200	38	
2GB04	Wanjohi	21-Jun-54		39	15	
2GB04	Wanjohi	17-Jul-54		139	58	

Sation ID	River	Date		Discharg e	Suspend ed load
2GB03	Malewa	28-Sep-53		39	20
2GB03	Malewa	02-Nov-53		152	11
2GB03	Malewa	09-Nov-53		10	17
2GB03	Malewa	16-Nov-53		15	16
2GB03	Malewa	23-Nov-53		8	17
2GB03	Malewa	10-May-54		15	24
2GB03	Malewa	17-May-54		32	14
2GB03	Malewa	25-May-54		20	7
2GB03	Malewa	25-May-54		20	7
2GB03	Malewa	31-May-54		7	6
2GB03	Malewa	31-May-54		7	6
2GB03	Malewa	07-Jun-54		8	5
2GB03	Malewa	07-Jun-54		8	20
2GB03	Malewa	14-Jun-54		43	8
2GB03	Malewa	14-Jun-54		43	8

Apendix 2

Sediment yield data

	Long Rains		March - June	
		Malewa River		
		Station ID:2GB01		
ID	Date	Discharge		Suspended load
2GB01	26-Mar-51	41		16
2GB01	02-Apr-51	89		16
2GB01	05-Apr-51	168		29
2GB01	09-Apr-51	720		260
2GB01	11-Apr-51	496		74
2GB01	13-Apr-51	895		210
2GB01	14-Apr-51	133		38
2GB01	16-Apr-51	2200		1610
2GB01	19-Apr-51	1598		219
2GB01	24-Apr-51	3921		603
2GB01	25-Apr-51	2458		290
2GB01	25-Apr-51	2802		268
2GB01	27-Apr-51	1985		275
2GB01	02-May-51	890		197
2GB01	03-May-51	597		187
2GB01	23-Jun-51	168		42
2GB01	02-May-52	181		212
2GB01	05-May-52	368		205
2GB01	06-May-52	609		316
2GB01	12-May-52	978		294
2GB01	14-May-52	613		137
2GB01	14-May-52	556		145
2GB01	15-May-52	940		159
2GB01	15-May-52	916		121
2GB01	15-May-52	508		318
2GB01	16-May-52	855		184
2GB01	16-May-52	780		166
2GB01	23-May-52	277		180
2GB01	23-May-52	275		170
2GB01	23-May-52	319		166
2GB01	24-May-52	236		109
2GB01	26-May-52	177		36
2GB01	26-May-52	137		68
2GB01	27-May-52	139		76
2GB01	27-May-52	356		112
2GB01	27-May-52	277		110
2GB01	26-Jun-53	73		68
2GB01	13-Apr-50	96		20

2GB01	14-Apr-50	130		60
2GB01	15-Apr-50	109		74
2GB01	18-Apr-50	192		280
2GB01	20-Apr-50	156		34
2GB01	22-Apr-50	105		58
2GB01	25-Apr-50	73		5
2GB01	27-Apr-50	56		6
2GB01	01-May-50	59		45
2GB01	03-May-50	64		59
2GB01	05-May-50	49		35
2GB01	11-May-50	68		63
2GB01	12-May-50	58		44
2GB01	16-May-50	62		20
2GB01	19-May-50	67		37
2GB01	02-Jun-50	53		65
2GB01	08-Jun-50	59		56
2GB01	14-Jun-50	79		61
2GB01	17-Jun-50	135		134
2GB01	23-Jun-50	107		151
2GB01	27-Jun-50	78		121
2GB01	05-Apr-54	36		54
2GB01	12-Apr-54	98		45
2GB01	26-Apr-54	51		18
2GB01	29-Apr-54	20		5
2GB01	03-May-54	255		75
2GB01	08-May-54	20		5
2GB01	10-May-54	377		188
2GB01	17-May-54	1598		774
2GB01	24-May-54	1120		113
2GB01	31-May-54	365		71
2GB01	07-Jun-54	577		304
2GB01	21-Jun-54	425		60
2GB01	28-Jun-54	425		44
2GB01	28-Jun-54	164		35
2GB01	04-Apr-55	32		33
2GB01	11-Apr-55	53		33
2GB01	18-Apr-55	75		69
2GB01	25-Apr-55	124		50
2GB01	16-May-55	86		76
2GB01	30-May-55	56		44
2GB01	13-Jun-55	33		27
2GB01	20-Jun-55	38		25
2GB01	09-Apr-56	58		21
2GB01	16-Apr-56	86		19
2GB01	07-May-56	1034		280
2GB01	14-May-56	365		84
2GB01	21-May-56	536		164
2GB01	28-May-56	356		93
2GB01	04-Jun-56	203		92

2GB01	11-Jun-56	128		64
2GB01	18-Jun-56	91		36
2GB01	25-Jun-56	272		79

Short Rains		Oct-Nov		
	Malewa River			
	Station ID:2GB01			
Date	Discharge		Suspended load	
03-Oct-50	135		62	
12-Oct-50	116		75	
14-Nov-50	71		41	
18-Nov-50	102		30	
05-Oct-53	35		8	
12-Oct-53	33		37	
19-Oct-53	98		31	
26-Oct-53	86		24	
02-Nov-53	139		27	
09-Nov-53	59		13	
16-Nov-53	81		22	
04-Oct-54	433		113	
11-Oct-54	147		25	
18-Oct-54	109		21	
25-Oct-54	135		39	
01-Nov-54	162		45	
08-Nov-54	105		26	
15-Nov-54	85		25	
22-Nov-54	70		16	
29-Nov-54	71		13	

Dry Months		Dec Jan Feb Aug Sept	
	Malewa River		
	Station ID:2GB01		
Date	Discharge		Suspended load

01-Dec-49	49		17
12-Dec-49	48		24
28-Dec-49	70		21
26-Jan-50	44		8
18-Feb-50	30		19
23-Feb-50	30		17
03-Mar-50	24		10
10-Mar-50	44		3
11-Mar-50	41		8
24-Mar-50	61		3
29-Mar-50	45		6
12-Feb-50	52		26
15-Jul-50	345		289
20-Jul-50	395		166
02-Aug-50	433		250
18-Aug-50	425		1168
28-Aug-50	536		152
29-Aug-50	1060		429
06-Sep-50	13		1503
13-Sep-50	116		98
18-Sep-50	460		150
22-Sep-50	544		120
05-Dec-50	58		28
14-Dec-50	48		20
08-Jan-51	30		34
16-Jan-51	32		7
07-Feb-51	27		37
13-Feb-51	24		26
20-Feb-51	26		43
27-Feb-51	23		54
12-Mar-51	29		34
13-Mar-51	33		34
15-Mar-51	40		1
14-Dec-53	100		18
11-Jan-54	26		10
18-Jan-54	25		7
25-Jan-54	25		7
01-Feb-54	23		6
02-Feb-54	22		7
08-Feb-54	20		5
15-Feb-54	22		10
01-Mar-54	22		9
08-Mar-54	20		8
15-Mar-54	22		6
22-Mar-54	18		5
25-Jul-53	41		17
27-Jul-53	36		13
21-Sep-53	53		21
28-Sep-53	35		18

05-Jul-54	311		60
12-Jul-54	337		78
19-Jul-54	194		51
26-Jul-54	496		260
02-Aug-54	820		178
09-Aug-54	205		38
16-Aug-54	321		59
23-Aug-54	1034		360
30-Aug-54	416		47
06-Sep-54	260		81
13-Sep-54	658		165
20-Sep-54	243		35
27-Sep-54	240		55
06-Dec-54	162		22
13-Dec-54	83		25
14-Dec-54	100		18
20-Dec-54	70		11
21-Dec-54	58		8
03-Jan-55	58		31
10-Jan-55	41		36
17-Jan-55	38		29
24-Jan-55	37		37
31-Jan-55	33		26
07-Feb-55	58		41
14-Feb-55	51		51
21-Feb-55	32		31
28-Feb-55	64		34
02-Mar-55	26		41
07-Mar-55	37		43
14-Mar-55	29		34
28-Mar-55	30		33
16-Jul-56	137		64
03-Sep-56	922		125
10-Sep-56	820		96
17-Sep-56	365		83
24-Sep-56	226		58
01-Oct-56	623		174
08-Oct-56	670		113
15-Oct-56	67		568
22-Oct-56	260		54
28-Jan-57	51		51
04-Feb-57	116		24
11-Feb-57	71		23
18-Feb-57	41		20
11-Jul-57	536		281
07-Sep-57	337		77

Appendix 3

Monthly Rainfall Variations

	Mean	Std	Coefficient of Variation	Variance
Jan	46	50	1.1	2636
Feb	39	37	1.0	1492
Mar	70	53	0.8	3175
Apr	170	101	0.6	16155
May	119	45	0.4	2580
Jun	84	47	0.6	2401
Jul	64	37	0.6	1540
Aug	71	38	0.6	1694
Sep	53	33	0.7	1288
Oct	66	39	0.6	1631
Nov	78	38	0.5	1908
Dec	53	39	0.8	1668

Appendix 4

Correlation between Stations

Correlation	9036025	9036029	9036032	9036034	9036055	9036062	9036073	9036081	9036109	9036147	9036150	9036152	9036162	9036164	9036188	9036236	9036241	9036243	9036250	9036253	9036257	9036262	9036264	9036289	9036290	9036312	9036322	9036333	9036334	9036335
9036002	0.79	0.5	0.34	0.54	0.16	0.71	0.83	0.8	0.76	0.5	0.67	0.69	0.66	0.61	0.73	0.72	0.31	0.47	0.46	0.66	0.64	0.63	0.81	0.35	0.59	0.31	0.7	0.67	0.86	0.57
9036025	1	0.79	0.68	0.7	0.4	0.5	0.82	0.86	0.79	0.79	0.65	0.64	0.51	0.67	0.67	0.77	0.89	0.78	0.81	0.64	0.53	0.71	0.84	0.63	0.81	0.47	0.56	0.64	0.8	0.63
9036029		1	0.85	0.81	0.77	0.09	0.65	0.61	0.7	0.91	0.67	0.32	0.32	0.38	0.41	0.84	0.85	0.94	0.36	0.6	0.28	0.35	0.79	0.9	0.88	0.84	0.48	0.68	0.66	0.66
9036032			1	0.13	0.84	0.56	0.2	0.11	0.17	0.43	0.3	0.19	0.14	0.01	0.11	0.49	0.79	0.91	0.11	0.14	0.08	0.12	0.87	0.93	0.89	0.73	0.16	0.41	0.38	0.35
9036034				1	0.51	0.53	0.82	0.8	0.81	0.92	0.77	0.62	0.44	0.6	0.57	0.73	0.66	0.71	0.53	0.73	0.5	0.46	0.59	0.6	0.67	0.66	0.64	0.85	0.83	0.67
9036055					1	0.99	0.19	0.44	0.16	0.17	0.04	0.69	0.11	0.42	0.3	0.03	0.29	0.69	0.25	0.13	0.41	0.78	0.62	0.89	0.75	0.84	0.11	0.41	0.27	0.27
9036062						1	0.77	0.74	0.75	0.44	0.41	0.83	0.88	0.82	0.79	0.27	0.26	0.17	0.79	0.58	0.87	0.44	0.3	0.08	0.27	0.11	0.74	0.61	0.78	0.56
9036073							1	0.95	0.97	0.76	0.79	0.81	0.83	0.84	0.58	0.58	0.61	0.55	0.81	0.78	0.78	0.51	0.68	0.42	0.65	0.43	0.66	0.74	0.91	0.73
9036081								1	0.92	0.73	0.74	0.89	0.79	0.91	0.59	0.61	0.55	0.79	0.8	0.8	0.75	0.53	0.66	0.41	0.61	0.37	0.67	0.65	0.89	0.78
9036109									1	0.81	0.74	0.79	0.67	0.78	0.8	0.62	0.61	0.51	0.79	0.84	0.76	0.57	0.64	0.46	0.64	0.51	0.69	0.75	0.94	0.79
9036147										1	0.89	0.5	0.44	0.5	0.5	0.81	0.82	0.82	0.48	0.71	0.42	0.64	0.71	0.76	0.8	0.76	0.58	0.77	0.8	0.76
9036150											1	0.51	0.4	0.53	0.52	0.79	0.69	0.77	0.47	0.68	0.41	0.63	0.63	0.7	0.74	0.77	0.44	0.71	0.71	0.77
9036152												1	0.83	0.96	0.96	0.41	0.37	0.28	0.97	0.72	0.49	0.37	0.37	0.14	0.3	0.15	0.69	0.51	0.78	0.75
9036162													1	0.84	0.87	0.25	0.34	0.22	0.86	0.6	0.88	0.4	0.46	0.13	0.35	0.13	0.61	0.5	0.75	0.5
9036164														1	0.99	0.44	0.4	0.31	0.79	0.66	0.95	0.49	0.44	0.16	0.37	0.13	0.62	0.55	0.8	0.65
9036188															1	0.45	0.43	0.3	0.98	0.67	0.94	0.48	0.7	0.42	0.62	0.38	0.76	0.71	0.87	0.8
9036236																1	0.84	0.9	0.43	0.62	0.31	0.58	0.84	0.9	0.86	0.81	0.58	0.71	0.77	0.79
9036241																	1	0.93	0.39	0.46	0.28	0.63	0.95	0.92	0.95	0.78	0.6	0.74	0.77	0.7
9036243																		1	0.29	0.45	0.19	0.46	0.92	0.96	0.95	0.86	0.55	0.75	0.73	0.7
9036250																			1	0.72	0.97	0.5	0.66	0.39	0.57	0.36	0.79	0.69	0.89	0.81
9036253																				1	0.67	0.54	0.66	0.62	0.63	0.69	0.8	0.7	0.9	0.91
9036257																					1	0.47	0.57	0.29	0.5	0.29	0.79	0.69	0.88	0.77
9036262																						1	0.68	0.62	0.68	0.52	0.71	0.66	0.81	0.7
9036264																							1	0.87	0.96	0.72	0.57	0.72	0.77	0.61
9036289																								1	0.93	0.92	0.44	0.65	0.63	0.62
9036290																									1	0.81	0.57	0.79	0.77	0.63
9036312																										1	0.48	0.65	0.63	0.71
9036322																											1	0.84	0.89	0.84
9036333																												1	0.88	0.8
9036334																													1	0.86
9036335																														1

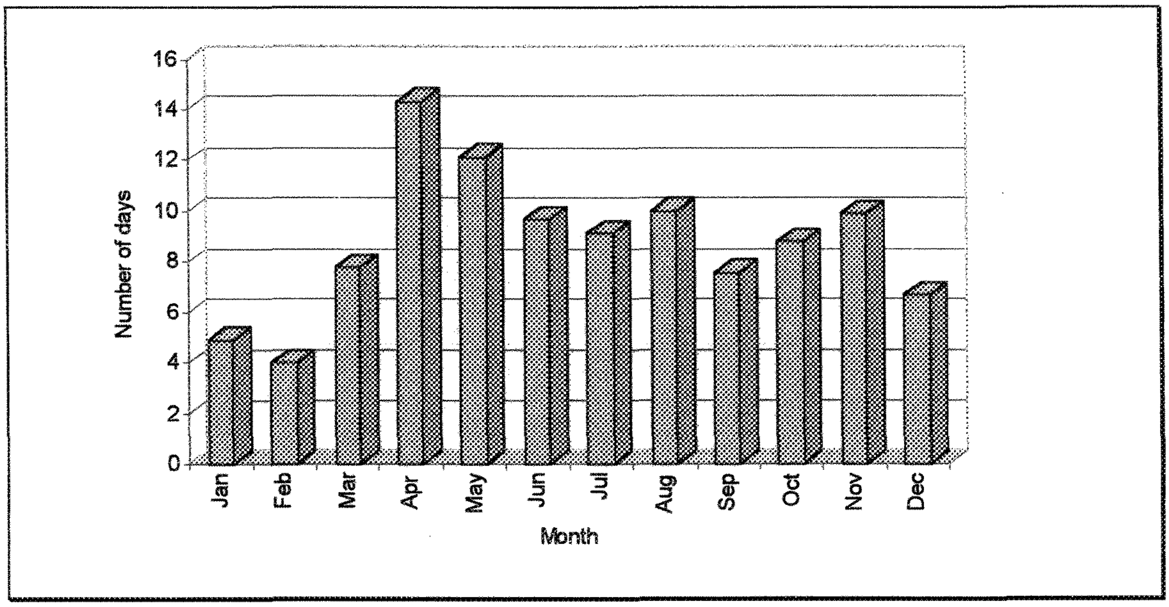
Average Rainfall (mm) from Different Station in and around the Basin

X-coord	Y-Coord	Station ID	Station Name	Height	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Reords
214315	9920714	9036002	Naivash D.O."	1900	25	36	58	113	84	82	34	45	43	49	61	40	77
236582	9935474	9036025	North Kinangop Forest Station"	2630	43	51	87	174	154	107	75	94	103	99	98	59	72
199446	9961275	9036029	Gilgil Kwetu Farm"	2347	30	30	61	149	125	88	98	117	75	77	88	47	68
186444	9981558	9036032	Bahati Forest Station"	2316	26	32	57	163	210	126	134	164	120	104	92	38	59
218635	9944686	9036034	Gilgil Station (Railway)"	2006	24	30	52	101	70	53	62	62	39	50	60	42	51
206870	9970497	9036055	Ol Kalou Station"	2367	20	18	31	99	105	86	106	128	54	47	53	20	50
195758	9909639	9036062	Naivasha Kongoni Farm"	2012	39	51	71	123	80	53	37	35	37	39	54	58	23
208743	9926243	9036073	Naivasha K.C.C Ltd"	1951	28	35	48	102	83	51	40	50	31	39	53	38	57
212455	9928088	9036081	Naivasha Vet. Experimental Stn."	1829	33	39	55	117	96	55	43	55	42	62	68	46	54
208742	9928088	9036109	Naivasha Marula"	2042	32	33	51	113	84	50	47	59	38	40	62	44	50
194994	9948365	9036147	Elementaita, Soysambu Estate"	1849	28	29	50	112	81	57	66	75	59	50	62	44	54
184596	9948360	9036150	Gilgil, Kikopey Ranch"	2134	22	28	53	85	72	53	55	69	37	47	59	39	59
238446	9920727	9036152	South Kinangop Njabini Farmers Tr Ctr"	2591	65	67	117	232	174	74	64	65	64	119	133	106	38
231034	9898599	9036162	Kijabe Railway Station"	2203	55	51	66	198	163	48	26	26	25	34	62	64	34
242157	9920729	9036164	South Kinangop Forest Station"	2591	70	79	148	278	219	89	68	64	64	130	160	85	35
240304	9917041	9036188	Kinangop Sasumua Dam"	2481	79	81	149	310	267	97	66	69	66	140	179	94	40
182733	9966803	9036236	Nakuru Lanet Police Post"	1890	30	37	53	116	102	72	73	92	75	86	93	41	29
207248	9948369	9036241	Geta Forest Station"	2591	41	45	75	168	169	110	106	117	125	106	91	55	32
192016	9972338	9036243	Dundori Forest Station"	2256	29	29	65	165	161	121	122	132	106	105	105	39	30
236598	9905977	9036250	Kamae Forest Station"	2591	71	67	113	303	235	70	50	47	57	125	172	93	32
197602	9929925	9036253	Thome Farmers No.2"	2350	28	51	44	170	112	68	55	86	53	64	118	83	22
244026	9898608	9036257	Eastern Rift Sawmill Ltd."	2591	54	60	89	201	137	42	33	29	36	67	110	62	25
216168	9928090	9036262	Olarogwai Farm Naivasha"	1981	31	47	57	124	80	51	45	60	98	61	71	45	26
223586	9944688	9036264	North Kanangop Mawingo Scheme"	2484	52	41	56	162	185	113	90	104	96	81	77	31	9
225436	9961282	9036289	Wanjohi Chief's	2469	36	32	47	123	119	94	94	130	91	78	78	40	19

			Office"														
216155	9959436	9036290	Malewa Scheme"	2316	30	26	50	111	107	77	64	86	63	53	48	16	14
225433	9977875	9036312	Chamate Gate"	2835	35	34	63	145	123	104	112	165	85	69	98	83	11
201338	9894890	9036322	Akira Ranch Hell's P. Post"	1798	25	21	35	112	45	50	36	26	31	43	37	47	8
184600	9939139	9036333	A.D.C. Ol Jorrai (Main House)"	1920	17	28	76	173	86	77	94	59	37	46	48	27	1
188315	9937297	9036334	A.D.C. Ol Jorrai (Primary Sch.)"	1981	24	22	56	201	110	73	46	55	46	40	89	35	5
184603	9933606	9036335	A.D.C. Ol Jorrai (Hill House)"	2286	9	21	56	146	86	44	63	70	36	72	79	74	6

Average Number of rainfall Days per Month (1985 - 1993)

	1985	1986	1987	1988	1989	1990	1991	1992	1993	Ave.
Jan	2	2	4	7	6	5	3	2	13	5
Feb	4	2	3	2	5	8	1	3	8	4
Mar	9	7	6	9	8	16	7	4	4	8
Apr	17	16	12	19	14	17	12	14	8	14
May	14	12	13	13	11	11	12	11	12	12
Jun	9	12	12	8	5	6	11	12	12	10
Jul	10	9	5	11	12	8	9	11	7	9
Aug	9	8	8	13	11	10	13	12	6	10
Sep	7	7	5	12	10	5	7	9	6	8
Oct	6	8	5	9	13	11	9	13	5	9
Nov	9	10	13	10	13	9	7	8	10	10
Dec	3	8	2	7	11	8	5	10	6	7

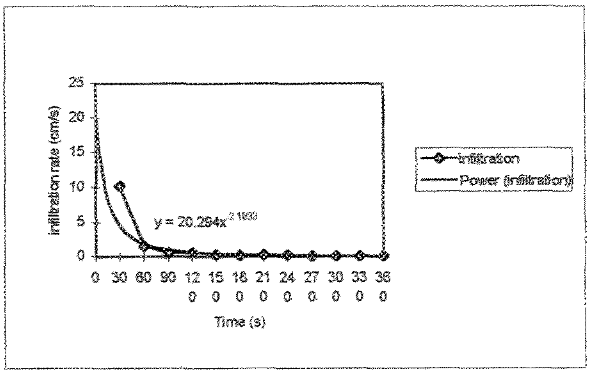


Appendix 5

Infiltration Rates of sample areas

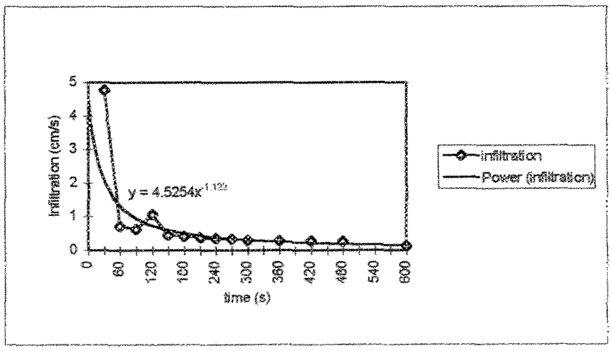
Maiella village natural veg **X=190626 Y=9908940**

time	depth	k cm/s	Q cm^3/s
0	0		
30	170	10.3	6284.8
60	240	1.5	1275.4
90	270	0.5	496.4
120	310	0.6	668.4
150	330	0.3	323.0
180	340	0.1	159.1
210	360	0.3	322.3
240	380	0.3	321.8
270	390	0.1	158.8
300	400	0.1	158.8
330	410	0.1	158.7
360	420	0.1	158.7



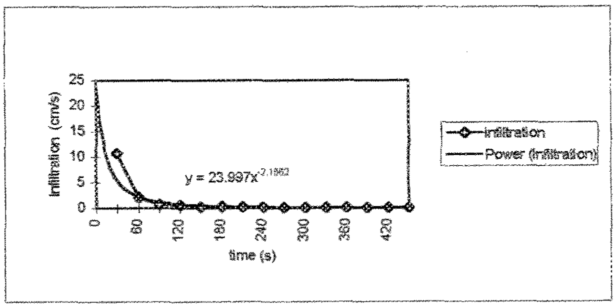
Maiella Village Maize field **X=190783 Y=9909837**

time	depth	k cm/s	Q cm^3/s
0	0		
30	40	4.8	974.5
60	50	0.7	168.4
90	60	0.6	166.9
120	80	1.1	348.1
150	90	0.5	164.1
180	100	0.4	163.5
210	110	0.4	163.0
240	120	0.4	162.6
270	130	0.3	162.2
300	140	0.3	161.9
330	140		
360	150	0.3	161.6
390	150		
420	160	0.3	161.3
450	160		
480	170	0.3	161.1
510	170		
540	170		
570	170		
600	175	0.1	79.4



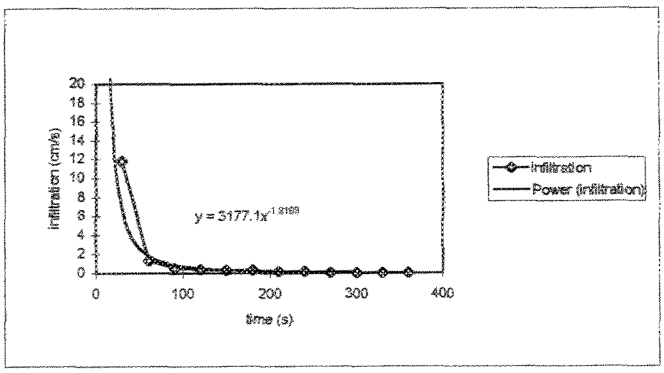
Maiella Village Grassland **X=190830 Y=9910089**

time	depth	k cm/s	Q cm^3/s
0			
30	190	10.7	7258.8
60	300	2.1	2107.0
90	350	0.7	842.0
120	400	0.6	834.6
150	420	0.2	321.1
180	460	0.4	655.0
210	490	0.3	485.0
240	520	0.3	484.2
270	540	0.2	319.5
300	560	0.2	319.3
330	570	0.1	158.2
360	580	0.1	158.2
390	590	0.1	158.2
420	600	0.1	158.2
450	610	0.1	158.2



Maiella Village Grazing land

time	depth	k cm/s	Q cm^3/s
0			
30	240	11.8	9816.3
60	320	1.3	1428.1
90	360	0.5	662.7
120	390	0.4	488.6
150	420	0.3	487.3
180	450	0.3	486.2
210	470	0.2	320.3
240	490	0.2	320.1
270	500	0.1	158.4
300	510	0.1	158.4
330	520	0.1	158.4
360	530	0.1	158.3



Appendix 6

Soil Properties

soil	tmu	texture	Bd	Moist	Clay	Silt	Sand	Fss	OMC	Perm	Structure	Permc	M	K	Kt
H4	Mountain	Sand clay	1.2	0.25	22	27	50	0.025	0.92	0.78	4	3	2107.9	0.30789	0.828
H4	Scarp	Sand clay	1.2	0.25	22	27	50	0.025	0.92	0.78	4	3	2107.9	0.30789	0.828
H4	Volcanic P	Sand clay	1.2	0.25	22	27	50	0.025	0.92	0.78	4	3	2107.9	0.30789	0.828
H4	Lake wate	Sand clay	1.2	0.25	22	27	50	0.025	0.92	0.78	4	3	2107.9	0.30789	0.828
H4	Lucastrine	Sand clay	1.2	0.25	22	27	50	0.025	0.92	0.78	4	3	2107.9	0.30789	0.828
H4	Lower Luc	Sand clay	1.2	0.25	22	27	50	0.025	0.92	0.78	4	3	2107.9	0.30789	0.828
H6	Mountain	Clay	1.3	0.35	70	12	17	0.0085	0.19	0.56	2	6	360.3	-0.03913	0.03
H6	Scarp	Clay	1.3	0.35	70	12	17	0.0085	0.19	0.56	2	6	360.3	-0.03913	0.03
H6	Volcanic C	Clay	1.3	0.35	70	12	17	0.0085	0.19	0.56	2	6	360.3	-0.03913	0.03
H6	Volcanic P	Clay	1.3	0.35	70	12	17	0.0085	0.19	0.56	2	6	360.3	-0.03913	0.03
H6	Lake wate	Clay	1.3	0.35	70	12	17	0.0085	0.19	0.56	2	6	360.3	-0.03913	0.03
H6	Lucastrine	Clay	1.3	0.35	70	12	17	0.0085	0.19	0.56	2	6	360.3	-0.03913	0.03
H6	Lower Luc	Clay	1.3	0.35	70	12	17	0.0085	0.19	0.56	2	6	360.3	-0.03913	0.03
H9	Mountain	Clay	1.3	0.35	70	12	17	0.0085	0.19	0.56	2	6	360.3	-0.03913	0.03
H9	Scarp	Clay	1.3	0.35	70	12	17	0.0085	0.19	0.56	2	6	360.3	-0.03913	0.03
H9	Volcanic C	Clay	1.3	0.35	70	12	17	0.0085	0.19	0.56	2	6	360.3	-0.03913	0.03
H9	Volcanic P	Clay	1.3	0.35	70	12	17	0.0085	0.19	0.56	2	6	360.3	-0.03913	0.03
H9	Lake wate	Clay	1.3	0.35	70	12	17	0.0085	0.19	0.56	2	6	360.3	-0.03913	0.03
H9	Lava	Clay	1.3	0.35	70	12	17	0.0085	0.19	0.56	2	6	360.3	-0.03913	0.03
H9	Lucastrine	Clay	1.3	0.35	70	12	17	0.0085	0.19	0.56	2	6	360.3	-0.03913	0.03
H9	Lower Luc	Clay	1.3	0.35	70	12	17	0.0085	0.19	0.56	2	6	360.3	-0.03913	0.03
Lava	Scarp	Sand loam	1.5	0.18	10	25	65	0.0325	0.86	4.68	3	2	2252.9	0.31388	0.842
Lava	Volcanic P	Sand loam	1.5	0.18	10	25	65	0.0325	0.86	4.68	3	2	2252.9	0.31388	0.842
Lu2	Mountain	Clay	1.3	0.35	50	25	25	0.0125	0.19	0.56	2	6	1250.6	0.04503	0.224
Lu2	Scarp	Clay	1.3	0.35	50	25	25	0.0125	0.19	0.56	2	6	1250.6	0.04503	0.224
Lu2	Volcanic P	Clay	1.3	0.35	50	25	25	0.0125	0.19	0.56	2	6	1250.6	0.04503	0.224
Lu2	Lucastrine	Clay	1.3	0.35	50	25	25	0.0125	0.19	0.56	2	6	1250.6	0.04503	0.224
Lu2	Foot slope	Clay	1.3	0.35	50	25	25	0.0125	0.19	0.56	2	6	1250.6	0.04503	0.224
M1	Mountain	Clay loam	1.3	0.3	30	25	45	0.0225	2	0.78	4	5	1751.6	0.19104	0.559
M1	Scarp	Clay loam	1.3	0.3	30	25	45	0.0225	2	0.78	4	5	1751.6	0.19104	0.559
M1	Volcanic P	Clay loam	1.3	0.3	30	25	45	0.0225	2	0.78	4	5	1751.6	0.19104	0.559
M1	Foot slope	Clay loam	1.3	0.3	30	25	45	0.0225	2	0.78	4	5	1751.6	0.19104	0.559
Pi11	Scarp	Silty clay l	1.4	0.2	35	55	10	0.005	0.98	3.45	4	6	3575.3	0.36311	0.955
Pi11	Volcanic C	Silty clay l	1.4	0.2	35	55	10	0.005	0.98	3.45	4	6	3575.3	0.36311	0.955
Pi11	Volcanic P	Silty clay l	1.4	0.2	35	55	10	0.005	0.98	3.45	4	6	3575.3	0.36311	0.955
Pi11	Lake wate	Silty clay l	1.4	0.2	35	55	10	0.005	0.98	3.45	4	6	3575.3	0.36311	0.955
Pi11	Lucastrine	Silty clay l	1.4	0.2	35	55	10	0.005	0.98	3.45	4	6	3575.3	0.36311	0.955
Pi11	Foot slope	Silty clay l	1.4	0.2	35	55	10	0.005	0.98	3.45	4	6	3575.3	0.36311	0.955
Pi11	Lower Luc	Silty clay l	1.4	0.2	35	55	10	0.005	0.98	3.45	4	6	3575.3	0.36311	0.955
Pl7	Scarp	Clay loam	1.3	0.3	30	25	45	0.0225	2	0.78	4	5	1751.6	0.19104	0.559
Pl7	Volcanic C	Clay loam	1.3	0.3	30	25	45	0.0225	2	0.78	4	5	1751.6	0.19104	0.559
Pl7	Volcanic P	Clay loam	1.3	0.3	30	25	45	0.0225	2	0.78	4	5	1751.6	0.19104	0.559
Pl7	Lake wate	Clay loam	1.3	0.3	30	25	45	0.0225	2	0.78	4	5	1751.6	0.19104	0.559
Pl7	Lucastrine	Clay loam	1.3	0.3	30	25	45	0.0225	2	0.78	4	5	1751.6	0.19104	0.559
Pl7	Foot slope	Clay loam	1.3	0.3	30	25	45	0.0225	2	0.78	4	5	1751.6	0.19104	0.559
Pl7	Lower Luc	Clay loam	1.3	0.3	30	25	45	0.0225	2	0.78	4	5	1751.6	0.19104	0.559
Pv10	Mountain	Clay	1.3	0.35	50	25	25	0.0125	0.19	0.56	2	6	1250.6	0.04503	0.224
Pv10	Volcanic C	Clay	1.3	0.35	50	25	25	0.0125	0.19	0.56	2	6	1250.6	0.04503	0.224
Pv10	Volcanic P	Clay	1.3	0.35	50	25	25	0.0125	0.19	0.56	2	6	1250.6	0.04503	0.224
Pv10	Lava	Clay	1.3	0.35	50	25	25	0.0125	0.19	0.56	2	6	1250.6	0.04503	0.224
Pv10	Lucastrine	Clay	1.3	0.35	50	25	25	0.0125	0.19	0.56	2	6	1250.6	0.04503	0.224
Pv6	Mountain	Clay loam	1.3	0.3	35	30	35	0.0175	2	0.78	4	5	1951.1	0.2091	0.601
Pv6	Scarp	Clay loam	1.3	0.3	35	30	35	0.0175	2	0.78	4	5	1951.1	0.2091	0.601
Pv6	Volcanic C	Clay loam	1.3	0.3	35	30	35	0.0175	2	0.78	4	5	1951.1	0.2091	0.601
Pv6	Volcanic P	Clay loam	1.3	0.3	35	30	35	0.0175	2	0.78	4	5	1951.1	0.2091	0.601
Pv6	Lake wate	Clay loam	1.3	0.3	35	30	35	0.0175	2	0.78	4	5	1951.1	0.2091	0.601
Pv6	Lucastrine	Clay loam	1.3	0.3	35	30	35	0.0175	2	0.78	4	5	1951.1	0.2091	0.601
Pv6	Foot slope	Clay loam	1.3	0.3	35	30	35	0.0175	2	0.78	4	5	1951.1	0.2091	0.601
Pv6	Lower Luc	Clay loam	1.3	0.3	35	30	35	0.0175	2	0.78	4	5	1951.1	0.2091	0.601
Um4	Mountain	Clay	1.3	0.35	70	12	17	0.0085	0.19	0.56	2	6	360.3	-0.03913	0.03
Ux7	Mountain	Clay loam	1.3	0.3	30	25	45	0.0225	2	0.78	4	5	1751.6	0.19104	0.559
Ux7	Scarp	Clay loam	1.3	0.3	30	25	45	0.0225	2	0.78	4	5	1751.6	0.19104	0.559
Ux7	Volcanic C	Clay loam	1.3	0.3	30	25	45	0.0225	2	0.78	4	5	1751.6	0.19104	0.559
Ux7	Volcanic P	Clay loam	1.3	0.3	30	25	45	0.0225	2	0.78	4	5	1751.6	0.19104	0.559
Ux7	Lava	Clay loam	1.3	0.3	30	25	45	0.0225	2	0.78	4	5	1751.6	0.19104	0.559
Ux7	Lucastrine	Clay loam	1.3	0.3	30	25	45	0.0225	2	0.78	4	5	1751.6	0.19104	0.559
Ux7	Foot slope	Clay loam	1.3	0.3	30	25	45	0.0225	2	0.78	4	5	1751.6	0.19104	0.559
Ux7	Crater	Clay loam	1.3	0.3	30	25	45	0.0225	2	0.78	4	5	1751.6	0.19104	0.559
Ux7	Lower Luc	Clay loam	1.3	0.3	30	25	45	0.0225	2	0.78	4	5	1751.6	0.19104	0.559

Appendix 6

Soil Properties

	Bd	Moist	OMC	Perm	Struc	Permc	Detach	b
Clay	1.3	0.35	0.19	0.56	2	6	0.02	1.2
Sand clay loam	1.2	0.25	0.92	0.78	4	3	0.3	0.9
Clay loam	1.3	0.3	2	0.78	4	5	0.25	1.3
Sand silty loam	1.5	0.15	0.84	1.24	4	3	0.2	0.9
Sand clay	1.2	0.1	1.06	3.58	4	3	0.25	0.8
Sand loam	1.5	0.18	0.86	4.68	3	2	0.3	0.9
Silty clay loam	1.4	0.2	0.98	3.45	4	6	0.4	1.3
Sandy loam	1.4	0.18	0.86	4.68	4	2	0.3	0.9

APPENDIX 8

Morgan Model, major parameters.

TMU	AREA	LANDCOVER	SL	RAIN	Et/Et	H	Rc	Ro	E	Q	Cf	F	G	Er
Mountain	12020616.6	Forest	35	1055	1	45.5	455	8.79	158.29	0	0.5	29.4	0	0
Mountain	6581137.8	Forest	35	1055	1	30	300	8.79	158.29	0	0.5	22.5	0	0
Mountain	35179290.7	Forest	35	1055	1	45.5	455	8.79	158.29	0	0.5	29.4	0	0
Mountain	51653996.7	Forest	35	1055	1	45.5	455	8.79	158.29	0	0.5	29.4	0	0
Mountain	635604.5	Forest	35	1055	1	39	390	8.79	158.29	0	0.5	990	0	0
Mountain	5683194.6	Forest	35	1055	1	45.5	455	8.79	158.29	0	0.5	29.4	0	0
Mountain	70793383.4	Forest	35	1055	1	45.5	455	8.79	158.29	0	0.5	29.4	0	0
Mountain	45559480.9	Forest	35	1055	1	45.5	455	8.79	158.29	0	0.5	29.4	0	0
Mountain	4150456.7	Forest	35	1055	1	39	390	8.79	158.29	0	0.5	990	0	0
Mountain	3369918.2	Forest	35	1055	1	45.5	455	8.79	158.29	0	0.5	29.4	0	0
Mountain	12744477	Forest	35	1055	1	28	280	8.79	158.29	0	0.5	1584	0	0
Mountain	526296.7	Forest	35	1055	1	45.5	455	8.79	158.29	0	0.5	29.4	0	0
Mountain	13461050.2	Forest	35	1055	1	25.2	252	8.79	158.29	0	0.5	22.5	0	0
Mountain	9922717	Forest	35	1055	1	39	390	8.79	158.29	0	0.5	990	0	0
Volcanic Complex	26588509.2	Scrubs, agric crops	12	781	0.6	24	185.9	6.51	117.18	0	0.05	17.5	0	0
Volcanic Complex	121771291	Scrubs, agric crops	12	781	0.6	36.4	282	6.51	117.18	0	0.05	21	0	0
Volcanic Complex	9082261.6	Scrubs, agric crops	12	781	0.6	36.4	282	6.51	117.18	0	0.05	21	0	0
Volcanic Complex	19285940.1	Scrubs, agric crops	12	781	0.6	31.2	241.7	6.51	117.18	0	0.05	687	0	0
Volcanic Complex	18413906.9	Scrubs, agric crops	12	781	0.6	21.6	167.3	6.51	117.18	0	0.05	17.5	0	0
Volcanic Complex	4050865.2	Scrubs, agric crops	12	781	0.6	36.4	282	6.51	117.18	0	0.05	21	0	0
Volcanic Complex	17979104.9	Scrubs, agric crops	12	781	0.6	31.2	241.7	6.51	117.18	0	0.05	687	0	0
Volcanic Complex	16539481	Scrubs, agric crops	12	781	0.6	22.4	173.5	6.51	117.18	0	0.05	1100	0	0
Volcanic Complex	34074067.6	Scrubs, agric crops	12	781	0.6	31.2	241.7	6.51	117.18	0	0.05	687	0	0
Volcanic Complex	23732742.3	Scrubs, agric crops	12	781	0.6	31.2	241.7	6.51	117.18	0	0.05	687	0	0
Volcanic Complex	55577741	Scrubs, agric crops	12	781	0.6	31.2	241.7	6.51	117.18	0	0.05	687	0	0
Scarp	6006259.9	Scrub, agric. crops	45	961	0.6	36.4	282	8.01	144.19	0	0.05	26.9	0	0
Scarp	2736742.8	Scrub, agric. crops	45	961	0.6	24	185.9	8.01	144.19	0	0.05	21.1	0	0
Scarp	11731558.2	Scrub, agric. crops	45	961	0.6	36.4	282	8.01	144.19	0	0.05	26.9	0	0
Scarp	13491008.6	Scrub, agric. crops	45	961	0.6	36.4	282	8.01	144.19	0	0.05	26.9	0	0
Scarp	5663762.2	Scrub, agric. crops	45	961	0.6	36.4	282	8.01	144.19	0	0.05	26.9	0	0
Scarp	25914039.7	Scrub, agric. crops	45	961	0.6	36.4	282	8.01	144.19	0	0.05	26.9	0	0
Scarp	80159	Scrub, agric. crops	45	961	0.6	31.2	241.7	8.01	144.19	0	0.05	900	0	0
Scarp	1294689.9	Scrub, agric. crops	45	961	0.6	21.6	167.3	8.01	144.19	0	0.05	21.1	0	0
Scarp	7019178.6	Scrub, agric. crops	45	961	0.6	36.4	282	8.01	144.19	0	0.05	26.9	0	0
Scarp	877701	Scrub, agric. crops	45	961	0.6	31.2	241.7	8.01	144.19	0	0.05	900	0	0
Scarp	4734241.2	Scrub, agric. crops	45	961	0.6	36.4	282	8.01	144.19	0	0.05	26.9	0	0
Scarp	23248549.4	Scrub, agric.	45	961	0.6	22.4	173.5	8.01	144.19	0	0.05	1440	0	0

		crops												
Scarp	12733141.3	Scrub, agric. crops	45	961	0.6	31.2	241.7	8.01	144.19	0	0.05	900	0	0
Scarp	13797880	Scrub, agric. crops	45	961	0.6	31.2	241.7	8.01	144.19	0	0.05	900	0	0
Scarp	6130142	Scrub, agric. crops	45	961	0.6	20.2	156.2	8.01	144.19	0	0.05	21.1	0	0
Scarp	3212838.9	Scrub, agric. crops	45	961	0.6	31.2	241.7	8.01	144.19	0	0.05	900	0	0
Volcanic Plateau	846123.2	Agric, Bare	4	972	0.6	3	23.24	8.1	145.84	55.17	0.02	21.4	4.3	4.3
Volcanic Plateau	9292780.3	Agric, Bare	4	972	0.6	4.55	35.24	8.1	145.84	12.53	0.02	27.4	0.2	0.2
Volcanic Plateau	212820620	Agric, Bare	4	972	0.6	4.55	35.24	8.1	145.84	12.53	0.02	27.4	0.2	0.2
Volcanic Plateau	25910	Agric, Bare	4	972	0.6	4.55	35.24	8.1	145.84	12.53	0.02	27.4	0.2	0.2
Volcanic Plateau	72914763.9	Agric, Bare	4	972	0.6	3.9	30.21	8.1	145.84	23.33	0.02	919	0.8	0.8
Volcanic Plateau	25747244.1	Agric, Bare	4	972	0.6	4.55	35.24	8.1	145.84	12.53	0.02	27.4	0.2	0.2
Volcanic Plateau	2058224.9	Agric, Bare	4	972	0.6	4.55	35.24	8.1	145.84	12.53	0.02	27.4	0.2	0.2
Volcanic Plateau	4758531.8	Agric, Bare	4	972	0.6	2.25	17.43	8.1	145.84	113	0.02	14.3	18	14.2603
Volcanic Plateau	14556557	Agric, Bare	4	972	0.6	3.9	30.21	8.1	145.84	23.33	0.02	919	0.8	0.8
Volcanic Plateau	87446.2	Agric, Bare	4	972	0.6	2.7	20.91	8.1	145.84	73.51	0.02	21.4	7.6	7.6
Volcanic Plateau	1138420.2	Agric, Bare	4	972	0.6	4.55	35.24	8.1	145.84	12.53	0.02	27.4	0.2	0.2
Volcanic Plateau	15651254.1	Agric, Bare	4	972	0.6	3.9	30.21	8.1	145.84	23.33	0.02	919	0.8	0.8
Volcanic Plateau	128913542	Agric, Bare	4	972	0.6	2.8	21.69	8.1	145.84	66.8	0.02	1471	6.2	6.2
Volcanic Plateau	41294048.6	Agric, Bare	4	972	0.6	3.9	30.21	8.1	145.84	23.33	0.02	919	0.8	0.8
Volcanic Plateau	8286339.1	Agric, Bare	4	972	0.6	4.55	35.24	8.1	145.84	12.53	0.02	27.4	0.2	0.2
Volcanic Plateau	1427478.6	Agric, Bare	4	972	0.6	3.9	30.21	8.1	145.84	23.33	0.02	919	0.8	0.8
Volcanic Plateau	3830630.3	Agric, Bare	4	972	0.6	2.8	21.69	8.1	145.84	66.8	0.02	1471	6.2	6.2
Volcanic Plateau	22883380.4	Agric, Bare	4	972	0.6	4.55	35.24	8.1	145.84	12.53	0.02	27.4	0.2	0.2
Volcanic Plateau	65068085	Agric, Bare	4	972	0.6	1.2	9.295	8.1	145.84	308.5	0.02	6.65	0.8	0.8
Volcanic Plateau	19786326.8	Agric, Bare	4	972	0.6	3.9	30.21	8.1	145.84	23.33	0.02	919	0.8	0.8
Foot slope	20917459.8	Scrubs, Agric	5	925	0.75	24	207.8	7.71	138.78	0	0.05	20.4	0	0
Foot slope	1672813.8	Scrubs, Agric	5	925	0.75	36.4	315.2	7.71	138.78	0	0.05	25.7	0	0
Foot slope	11996326	Scrubs, Agric	5	925	0.75	36.4	315.2	7.71	138.78	0	0.05	25.7	0	0
Foot slope	7845869.2	Scrubs, Agric	5	925	0.75	31.2	270.2	7.71	138.78	0	0.05	856	0	0
Foot slope	53439.4	Scrubs, Agric	5	925	0.75	21.6	187.1	7.71	138.78	0	0.05	20.4	0	0
Foot slope	27458922.9	Scrubs, Agric	5	925	0.75	36.4	315.2	7.71	138.78	0	0.05	25.7	0	0
Foot slope	1629900.4	Scrubs, Agric	5	925	0.75	31.2	270.2	7.71	138.78	0	0.05	856	0	0
Volcanic Plain	6268598.5	Agric.	2	879	0.8	22.8	203.5	7.33	131.88	0	0.05	24.1	0	0
Volcanic Plain	35910438.2	Agric.	2	879	0.8	22.8	203.5	7.33	131.88	0	0.05	24.1	0	0
Volcanic Plain	210656326	Agric.	2	879	0.8	22.8	203.5	7.33	131.88	0	0.05	24.1	0	0
Volcanic Plain	6477.5	Agric.	2	879	0.8	22.8	203.5	7.33	131.88	0	0.05	24.1	0	0
Volcanic Plain	48907537.6	Agric.	2	879	0.8	19.5	174.4	7.33	131.88	0	0.05	799	0	0
Volcanic Plain	18918342.1	Agric.	2	879	0.8	22.8	203.5	7.33	131.88	0	0.05	24.1	0	0
Volcanic Plain	40073040.3	Agric.	2	879	0.8	22.8	203.5	7.33	131.88	0	0.05	24.1	0	0
Volcanic Plain	13350932.7	Agric.	2	879	0.8	11.2	100.6	7.33	131.88	0.001	0.05	12.9	0	0
Volcanic Plain	19288369.1	Agric.	2	879	0.8	19.5	174.4	7.33	131.88	0	0.05	799	0	0

Volcanic Plain	4386075.7	Agric.	2	879	0.8	22.8	203.5	7.33	131.88	0	0.05	24.1	0	0
Volcanic Plain	465570.2	Agric.	2	879	0.8	19.5	174.4	7.33	131.88	0	0.05	799	0	0
Volcanic Plain	2243643.3	Agric.	2	879	0.8	22.8	203.5	7.33	131.88	0	0.05	24.1	0	0
Volcanic Plain	84527298.1	Agric.	2	879	0.8	14	125.2	7.33	131.88	0	0.05	1278	0	0
Volcanic Plain	14288550.5	Agric.	2	879	0.8	19.5	174.4	7.33	131.88	0	0.05	799	0	0
Volcanic Plain	2612860.7	Agric.	2	879	0.8	22.8	203.5	7.33	131.88	0	0.05	24.1	0	0
Volcanic Plain	15164632.1	Agric.	2	879	0.8	19.5	174.4	7.33	131.88	0	0.05	799	0	0
Volcanic Plain	12784151.6	Agric.	2	879	0.8	22.8	203.5	7.33	131.88	0	0.05	24.1	0	0
Volcanic Plain	35241636.6	Agric.	2	879	0.8	6	53.67	7.33	131.88	0.581	0.05	6.1	0	0
Volcanic Plain	8712234.6	Agric.	2	879	0.8	12.6	112.7	7.33	131.88	0	0.05	19.4	0	0
Volcanic Plain	24352153.1	Agric.	2	879	0.8	19.5	174.4	7.33	131.88	0	0.05	799	0	0
Upper Lucastrine Plain	9124365.4	Agric. crops	2	659	0.8	22.8	203.5	5.49	98.874	0	0.05	17.1	0	0
Upper Lucastrine Plain	28326907.7	Agric. crops	2	659	0.8	22.8	203.5	5.49	98.874	0	0.05	17.1	0	0
Upper Lucastrine Plain	30308212.3	Agric. crops	2	659	0.8	19.5	174.4	5.49	98.874	0	0.05	549	0	0
Upper Lucastrine Plain	7902547.3	Agric. crops	2	659	0.8	14	125.2	5.49	98.874	0	0.05	879	0	0
Upper Lucastrine Plain	10563989.3	Agric. crops	2	659	0.8	19.5	174.4	5.49	98.874	0	0.05	549	0	0
Upper Lucastrine Plain	13320164.6	Agric. crops	2	659	0.8	19.5	174.4	5.49	98.874	0	0.05	549	0	0
Lower Lucastrine Plain	5246773.2	Natural grass	2	620	1.2	15	164.3	5.17	93.023	0	0.08	14.1	0	0
Lower Lucastrine Plain	9106552.2	Natural grass	2	620	1.2	22.8	249.2	5.17	93.023	0	0.08	15.7	0	0
Lower Lucastrine Plain	13413278.6	Natural grass	2	620	1.2	22.8	249.2	5.17	93.023	0	0.08	15.7	0	0
Lower Lucastrine Plain	8058007.3	Natural grass	2	620	1.2	19.5	213.6	5.17	93.023	0	0.08	503	0	0
Lower Lucastrine Plain	6168197.3	Natural grass	2	620	1.2	14	153.4	5.17	93.023	0	0.08	804	0	0
Lower Lucastrine Plain	2733504.1	Natural grass	2	620	1.2	19.5	213.6	5.17	93.023	0	0.08	503	0	0
Lower Lucastrine Plain	4017668	Natural grass	2	620	1.2	19.5	213.6	5.17	93.023	0	0.08	503	0	0
Lower Lucastrine Plain	14715255.7	Natural grass	2	620	1.2	19.5	213.6	5.17	93.023	0	0.08	503	0	0
Lava	1285783.3	Bare rock	4	871	0.4	0	0	7.26	130.68	871	0	24.2	0	0
Lava	19424396.6	Bare rock	4	871	0.4	0	0	7.26	130.68	871	0	24.2	0	0
Lava	1033970.6	Bare rock	4	871	0.4	0	0	7.26	130.68	871	0	802	0	0
Lava	14512833.9	Bare rock	4	871	0.4	0	0	7.26	130.68	871	0	24.2	0	0
Lava	26719.7	Bare rock	4	871	0.4	0	0	7.26	130.68	871	0	19.5	0	0
Lava	2361857.6	Bare rock	4	871	0.4	0	0	7.26	130.68	871	0	24.2	0	0
Lava	104449.7	Bare rock	4	871	0.4	0	0	7.26	130.68	871	0	802	0	0
Lava	5920433	Bare rock	4	871	0.4	0	0	7.26	130.68	871	0	802	0	0
River valley	6000592	Agric crops	15	861	0.8	22.8	203.5	7.18	129.18	0	0.05	23.5	0	0
River valley	80183326.1	Agric crops	15	861	0.8	22.8	203.5	7.18	129.18	0	0.05	23.5	0	0
River valley	15384.1	Agric crops	15	861	0.8	22.8	203.5	7.18	129.18	0	0.05	23.5	0	0
River valley	26033063.7	Agric crops	15	861	0.8	19.5	174.4	7.18	129.18	0	0.05	778	0	0
River valley	187037.7	Agric crops	15	861	0.8	22.8	203.5	7.18	129.18	0	0.05	23.5	0	0
River valley	19998464.8	Agric crops	15	861	0.8	22.8	203.5	7.18	129.18	0	0.05	23.5	0	0
River valley	882559.1	Agric crops	15	861	0.8	11.2	100.6	7.18	129.18	0.001	0.05	12.7	0	0
River valley	53439.4	Agric crops	15	861	0.8	13.5	120.7	7.18	129.18	0	0.05	19	0	0
River valley	1112510.3	Agric crops	15	861	0.8	22.8	203.5	7.18	129.18	0	0.05	23.5	0	0
River valley	41392020.8	Agric crops	15	861	0.8	14	125.2	7.18	129.18	0	0.05	1244	0	0
River valley	177321.5	Agric crops	15	861	0.8	19.5	174.4	7.18	129.18	0	0.05	778	0	0
River valley	1208863	Agric crops	15	861	0.8	14	125.2	7.18	129.18	0	0.05	1244	0	0
River valley	2674396.9	Agric crops	15	861	0.8	22.8	203.5	7.18	129.18	0	0.05	23.5	0	0
River valley	31661199.7	Agric crops	15	861	0.8	6	53.67	7.18	129.18	0.489	0.05	6	0	0
River valley	1578890.1	Agric crops	15	861	0.8	19.5	174.4	7.18	129.18	0	0.05	778	0	0
Volcanic plain1	7071808.2	Agric.	2	750	0.8	15	134.2	6.25	112.53	0	0.05	16.8	0	0
Volcanic plain1	46637984.3	Agric.	2	750	0.8	22.8	203.5	6.25	112.53	0	0.05	19.9	0	0
Volcanic plain1	27495358.9	Agric.	2	750	0.8	14	125.2	6.25	112.53	0	0.05	1040	0	0

Determination of Parameters often used in Erosion Studies

Rainfall Erosivity

This factor was derived from rainfall characteristic as it is correlated to the soil loss on the surface (splash). Wischmeier studied this relationship proved that erosivity is the product of rainfall energy and the intensity. Bergsma, 1981 defines the rainfall erosivity index of a storm as the kinetic energy of the storm times the 30 minute maximum rainfall intensity.

See rainfall section!

Erodibility Factor, K

This indicates the soil's susceptibility to the erosive forces and gives the soil loss per unit erosivity as measured on a unit plot (with original dimensions of Wischmeier). If slope steepness and length factor, Crop management factor and Support factor are all unit, then the soil erodibility is Soil loss divided by erosivity. It is a quantitative value experimentally determined for each location. It differs from region to region as it depends on many factors which vary in space and time.

The main factors which influence erodibility are Soil texture, Soil structure, Organic matter and permeability.

$$K = 2.77 \times 10^{-6} \times M^{1.14} \times (12 - OM) + 0.043 \times (SC - 2) + 0.033 \times (4 - PC)$$

while

$$M = (Si + ffS) \times (100 - Cl)$$

K= Soil erodibility (ton*hr/N*ha)
OM = Organic matter (%), in this case 1.72 multiplied by the carbon content.
SC = Structure class
PC = Permeability Class
Si = Silt content (%) 50 - 2 μm diameter
ffS = Very fine sand (%) 100 - 50 μm diameter
Cl = Clay content (%) ≤ 2 μm in diameter particle size.

The coarse particles in soil lowers down the erodibility. However the cohesion between these particles is much less than the fine particles but cannot be easily be transported. The presence of organic matter increases the infiltration capacity of the soil, thereby reducing the amount of runoff potential. This reduces the erodibility as well.

These parameters were determined in the field of study for a selected points. The texture and organic matter content (carbon) were got from the from the samples sent to and analysed by Kenya Soil Survey laboratory. The permeability was determined in the field for selected points by the inverse auger method, depth of about 50 cm. Most of the soils in the area are of high permeability class. The textural class varied but generally most of the soils are Sand clay loam. This is attributed to lucastrine sediments which are the main part of the area studied. Other factors like the chemical compositions for these sites were not done. A few areas showed some signs of sealing, close to mount Longonot.

Table xx1Organic Matter Ratings

Organic Matter Content %	Total Organic Matter levels	Ratings
< 1	Very low	0
1 - 2	Low	1
2 - 3	Moderate	2
3 - 4	High	3
> 4	Very high	4

Table xx 2 Soil Structure Ratings

Soil Structure	Rating
Very fine granular	1
Fine single granular	2
Medium sub angular blocky	3
Angular to medium angular	4

Table xx 3Soil Permeability Ratings

Permeability Class	Class cm hr^{-1}	Rating
Very rapid	> 12.5	1
Rapid	8.0 - 12.5	2
Moderate rapid	6.0 - 8.0	3
Moderate	2.0 - 6.0	4
slow	0.8 - 2	5
very slow	< 0.8	6

Slope Length and Steepness

It is clearly understood by everyone that soil loss is favoured with increasing slope steepness and length i.e. the steeper and longer the slope, the more soil loss expected, all other factors remaining constant. The length of slope gives, *L*, gives soil loss on a given slope length relative to the soil loss on the 'USLE' unit plot. The gradient gives the ratio of the soil loss on any given slope to that of a 9 % slope in the USLE standard unit slope.

The two factors are normally combined to make what is commonly known as topographic factor, *LS*. This allows to adjust soil loss on a given slope length, gradient and form to that of the unit plot in the USLE. The topographic factor was estimated from the Wischmeier & Smith, 1978, formula:

$$LS = \left(\frac{l}{22.13}\right)^m \times \left(65.41 \times \sin^2 \alpha + 4.56 \sin \alpha + 0.065\right)$$

where;

l = slope length (m)
m = slope length exponent
α = slope angle (deg.)

Gradient (%)	*m*
≤ 0.5	0.15
0.5 - 1.0	0.20
1.1 - 3.4	0.30
3.5 - 4.9	0.40
> 5	0.5

The slope length exponent, *m*, depends on the gradient. It is smaller for low angles. On low angles, m, becomes smaller as low obstacles such as clods, produced by tillage slow down the overland flow. An exponent, m < 1, shows that soil loss increases to a lesser extent than the slope length.

In the field, the gradient was measured using the clinometer while the lengths were measured by tape and estimated from aerial photos where it was not feasible to measure. Most of the slope lengths were long and this lead to the slopes being divided into a number of segments. The calculation was done on each of these segments and the weighted sum of the segment values was taken. This was done for each TMU within the study area.

The Land Cover factor

The C factor as it is normally called gives the ratio of the soil loss on bare soil (furrow) with similar characteristics. The soil loss on a cropped plot changes with time as it depends on crop growth stage and the management. The changes in canopy cover through time is quite laborious and expensive to determine in the field. The C factor forms the protection of the soil surface and it means that it reduces the rainfall impact but still an uncovered soil surface is only endangered if erosive storms occur. However it also depends on the amount and quality of the coverage.

Wischmeier & Smith, 1978, proposed and divide the C factor (cropping system) into sub factors of influence;

C1 = the influence of canopy cover
C2 = the influence of mulch or vegetation close to the soil surface
C3 = tillage and residual effects of the former vegetation.

Nill *et al* suggested that the sub factor method is helpful because for many crops no experimentally determined data exist. The problem is further complicated by the fact that in Africa there exists a large variety of small holder system which are difficult to compare to the American standards (e.g. hand tillage, mixed cropping, heaping, bedding, etc.) In the field, the ground cover percentages were visually estimated by in all units. These were later used in the calculations that follow below. As these were rough estimated some of the values appear to be outside the limits. In such cases Koiman, 1987 was used to supplement and adjust the unacceptable values from the field.

Sub factor 1

$$C1 = 1 - CC_e \times e^{-0.34 \times He}$$

CC_e = effective canopy cover
H_e = effective canopy height

The height of the canopy reduces the velocity of falling rain drops and thereby the energy, erosivity onto the soil surface. The height is approximated by;

H_e= 0.6 H_{max}; H_{max}= mean height of the upper most horizontal leaf of the crops.

The effective canopy cover of the mulch, CC_e, is more protective than the canopy itself and the mulch is taken into consideration. CC_e is estimated by;

CC_e= CC x (1 - MC)

CC = Canopy cover (%), and MC = Mulch cover (%)

Sub factor 2

The influence of mulch is here determined by formula (Yoder *et al*, 1992);

$$C2 = e^{-0.035 \times MC}$$

Measurements by several authors (Dumas, 1965; Kainz, 1989; Nill, 1993) agreed with formula and revealed a higher efficiency of this formula.

Sub factor 3

Residual effect of previous vegetation:

This factor is very difficult to determine. In addition not a lot of data is available especially for the tropical environment. The agro system which is varying and different makes it difficult to determine this factor.

Finally the C factor is calculated from the product of the three sub factors determined from above.

$$C = C1 \times C2 \times C3$$

Table 4 Different land cover units and their C factors

	H_e	CC	MC	CC_e	C1	C2	C
Agriculture Ord.	0.5	0.6	0.2	0.48	0.567	0.50	0.06
Bare	0.01	0.01	0.001	0.01	0.99	1.00	0.99
Forest	3	0.4	0.35	0.26	0.859	0.29	0.20
Grass	0.5	0.95	0.2	0.76	0.314	0.50	0.08
Large Scale Agric	0.5	0.8	0.3	0.56	0.494	0.35	0.05
Savannah Shrubs	0.8	0.4	0.15	0.34	0.711	0.59	0.04
Thick Forest	4	0.9	0.7	0.27	0.881	0.09	0.07
Urban	0.01	0.01	0.001	0.01	0.99	1.00	0.99
Water	0.01	0.01	0.001	0.01	0.99	1.00	0.99

The Support Practice Factor, P

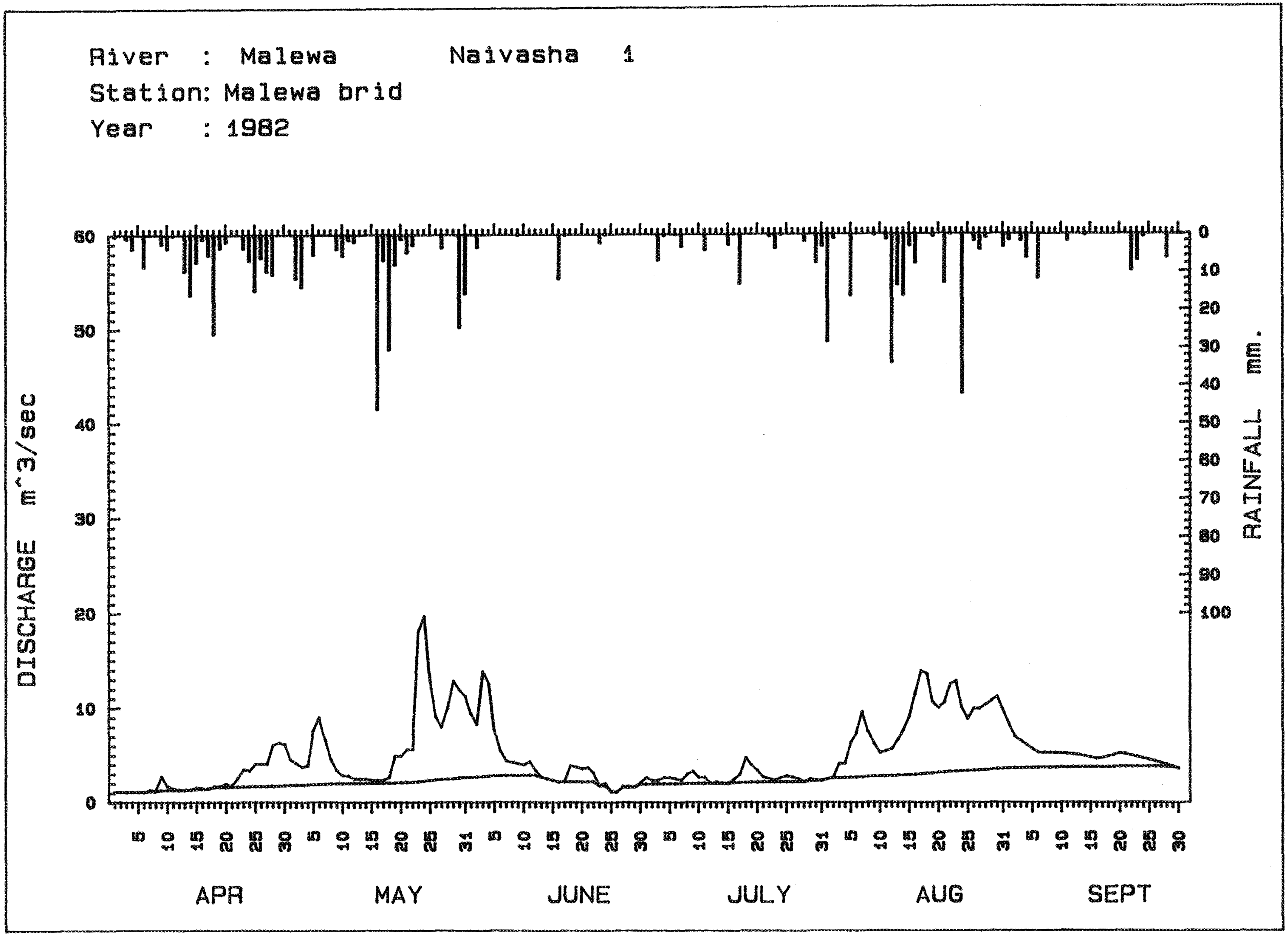
The factor is defined as the ratio of soil loss with a specific support practice to the corresponding soil loss with up down slope cultivation. The P factor depended on the land use and topographic position of the units under consideration. The values for the low areas, close to the Lake, were much lower than those high elevation with steep slopes, where there was almost practices at all.

Results

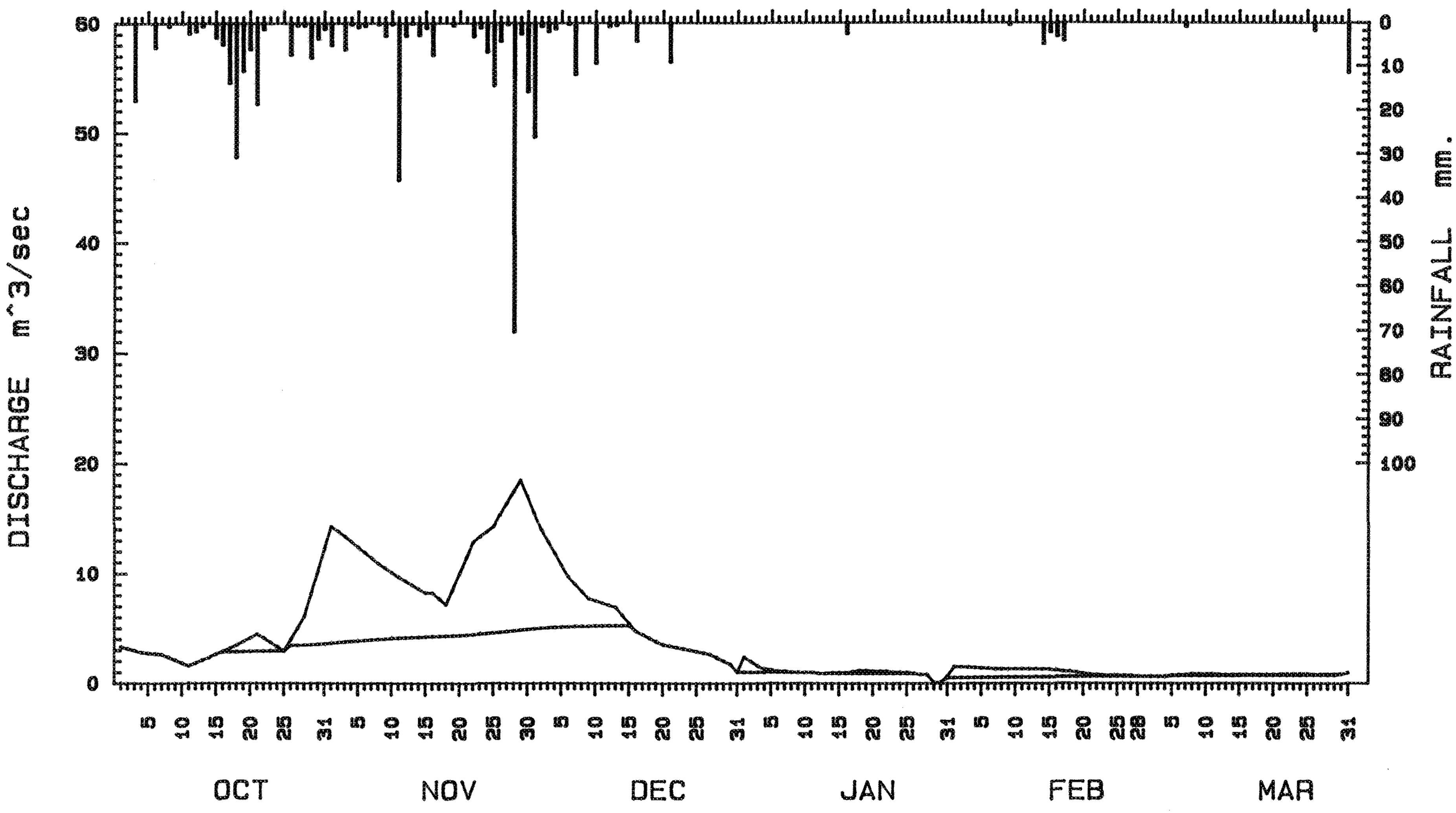
The result of the prediction of soil loss using the USLE are presented below. The area has low erosion rates as can be seen from the table. The highest soil loss rates was 163 N/ha (0.0166 t/ha/yr). The larger part of the area, about 90 % is still below 9.0 N/ha (0.00092 ton/ha/yr) and only 10 % is above the value. The classes below were just put to differentiate the area in to different ratings, otherwise the whole area would be under low erosion risk.

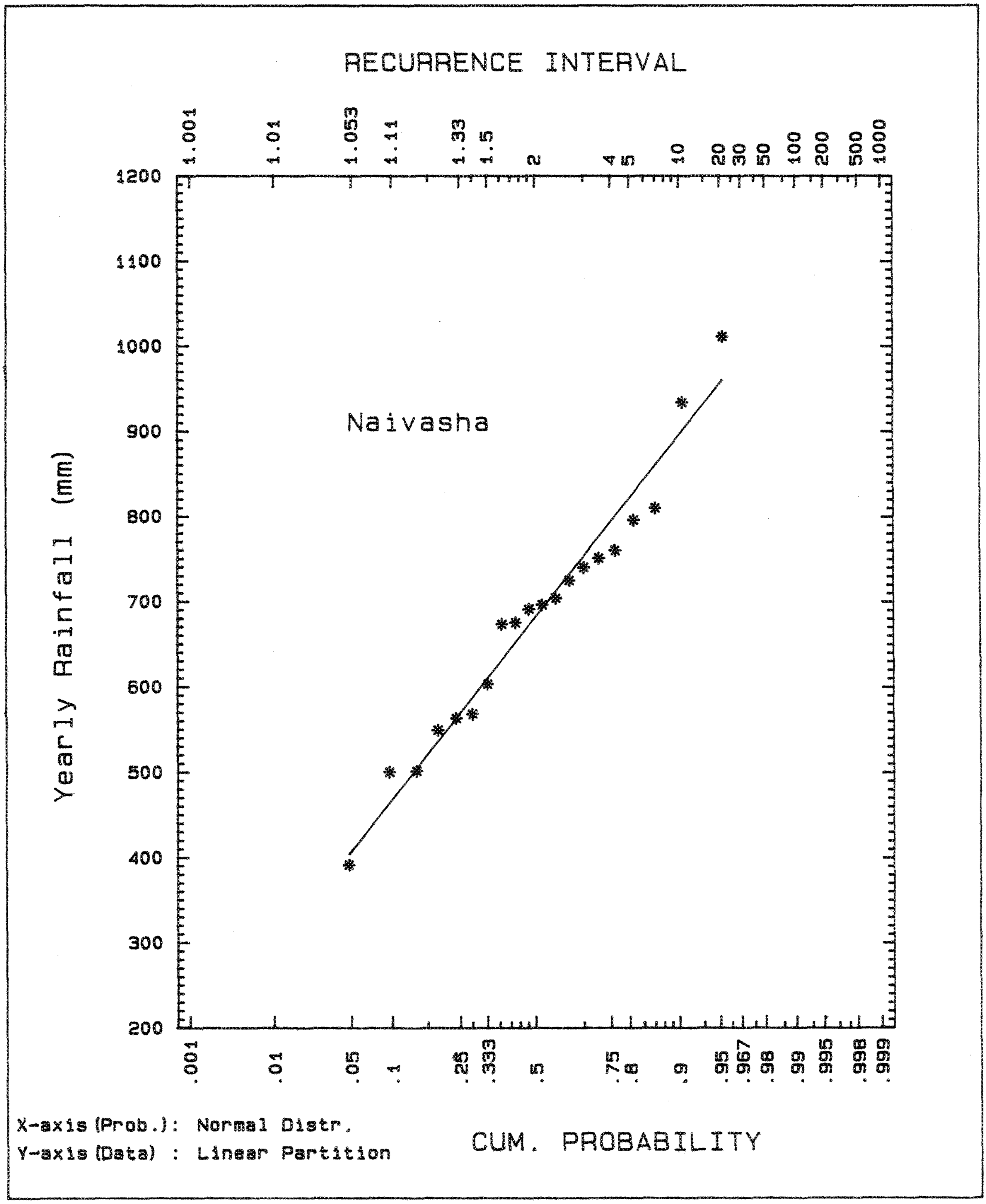
Erosion Rates from USLE

Class	Rate (N/ha)*	% Area
Very Low	< 0.6	34.9
Low	0.61 - 3.0	14.1
Moderate	3.1 - 9.0	41.2
High	9.1 - 15.0	3.2
Very High	> 15.0	6.5
* Divide by	9806 to t/ha	100.0


River : Malewa
Naivasha 1
Station: Malewa brid
Year : 1982
DISCHARGE m^3/sec
RAINFALL mm.
APR
MAY
JUNE
JULY
AUG
SEPT

River : Malewa Naivasha 1
Station: Malewa brid
Year : 1982




RECURRENCE INTERVAL
1.001
1.01
1.053
1.11
1.33
1.5
2
4
5
10
20
30
50
100
200
500
1000
1200
1100
1000
900
800
700
600
500
400
300
200
Yearly Rainfall (mm)
Naivasha
.001
.01
.05
.1
.25
.333
.5
.75
.8
.9
.95
.967
.98
.99
.995
.998
.999
X-axis (Prob.): Normal Distr.
Y-axis (Data) : Linear Partition
CUM. PROBABILITY