PEAK RUNOFF ESTIMATION OF THE UNGUAGED AREA IN NAIVASHA BASIN USING THE SLOPE AREA METHOD AND EMPIRICAL FORMULAS

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By

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DISCLAIMER

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Abstract

In areas where water dependency is remarkable a proper management of the natural resource must be completed. For this purpose hydrological information of the hydrological systems, quantitative and functional, is needed. The information collection is complex when dealing with ungauged areas.

This study addresses this issue, focussing in the estimation of the surface peak runoff in the Ungauged Area of Naivasha Basin. The sporadic hydrological rhythm in the area adds more difficulty to the research

Three classic hydrological methods for the runoff estimation were used, relating them to synthetic landscape units.

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1.1 The Study Area

1.1.1. Location

The study area, also known as the Ungauged Area, is located in the Southern part of the Lake Naivasha Basin, Kenya. It represents the only fresh water lake of the Eastern Rift Valley or Gregory Rift. This endorreic basin is located at the highest point of the rifted valley floor.

Its geographical location is between 0° 00' to 1° 00' South and 36°00' to 36°45' East; altitude varies from 1800 m to 3200 m. The Ungauged drainage basin has an area of 1100 km^2.

The basin is located between Nakuru (65 km) and Nairobi (80 km), and is linked with these cities by the important A-104 Eastern truck road and a railroad, which connect the Western part of the country with the capital and Mombassa.

Due to its exceptional water quality, this lake confers a paramount strategic value to this area; powerful extensive horticulture farms are located around the lake, producing nearly 75% of Kenya's horticultural exports.

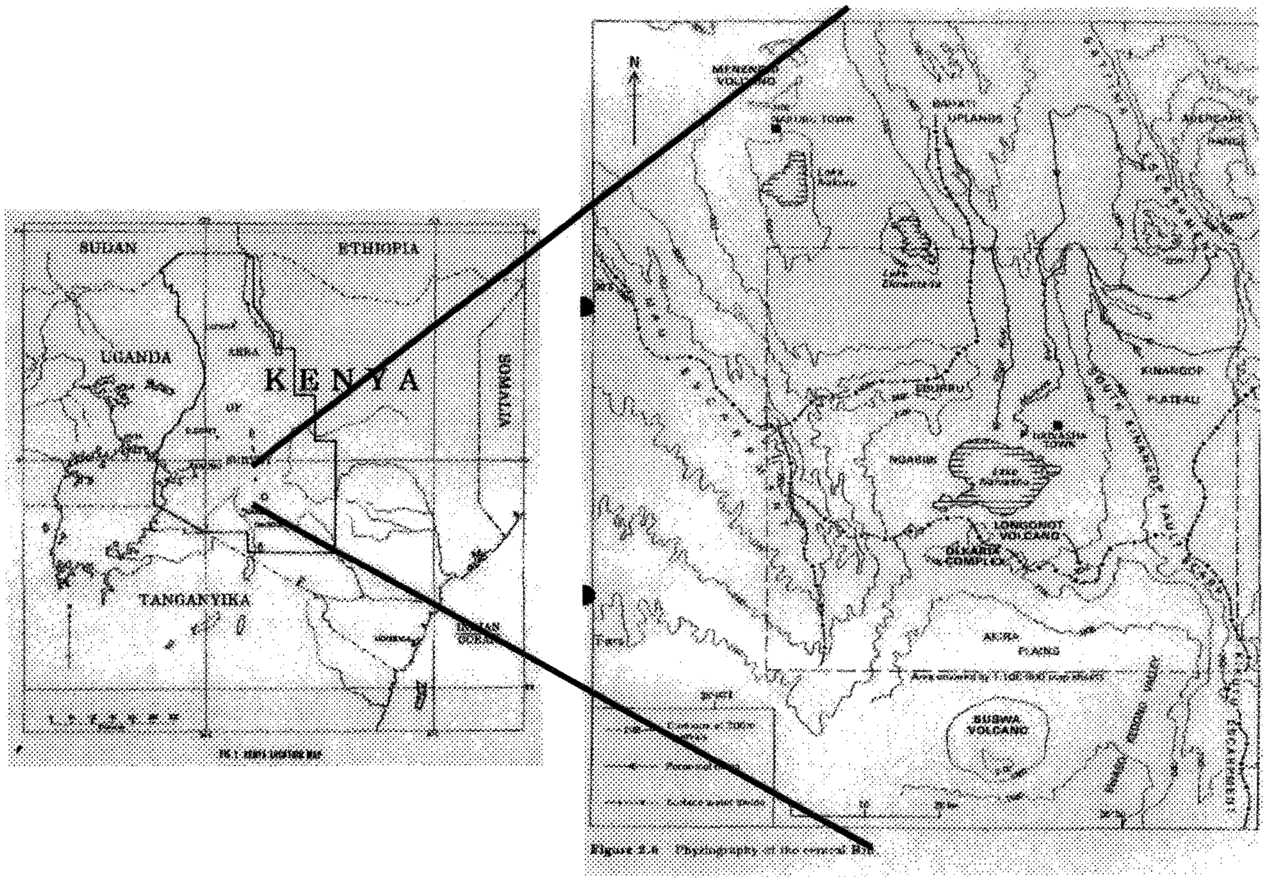


Figure 1.1 The regional location of the study area

1.1.2 Relief and topography

The effects of rift faulting and volcanic activity are responsible for the relief configuration of the area. The altitude goes from 1800 m a.s.l. around the lake to 3100 m. a.s.l. at the top of the Maumau escarpment.

The Ungauged area of Lake Naivasha is a topographically depressed rift floor surrounded by higher landforms namely the Kinangop Plateau at East, the Maumau Escarpment at West, the Olkaria Volcanic Complex and the Longonot volcano at South. The floor of the Gregory Rift valley crosses the basin from its central part in a North-South direction.

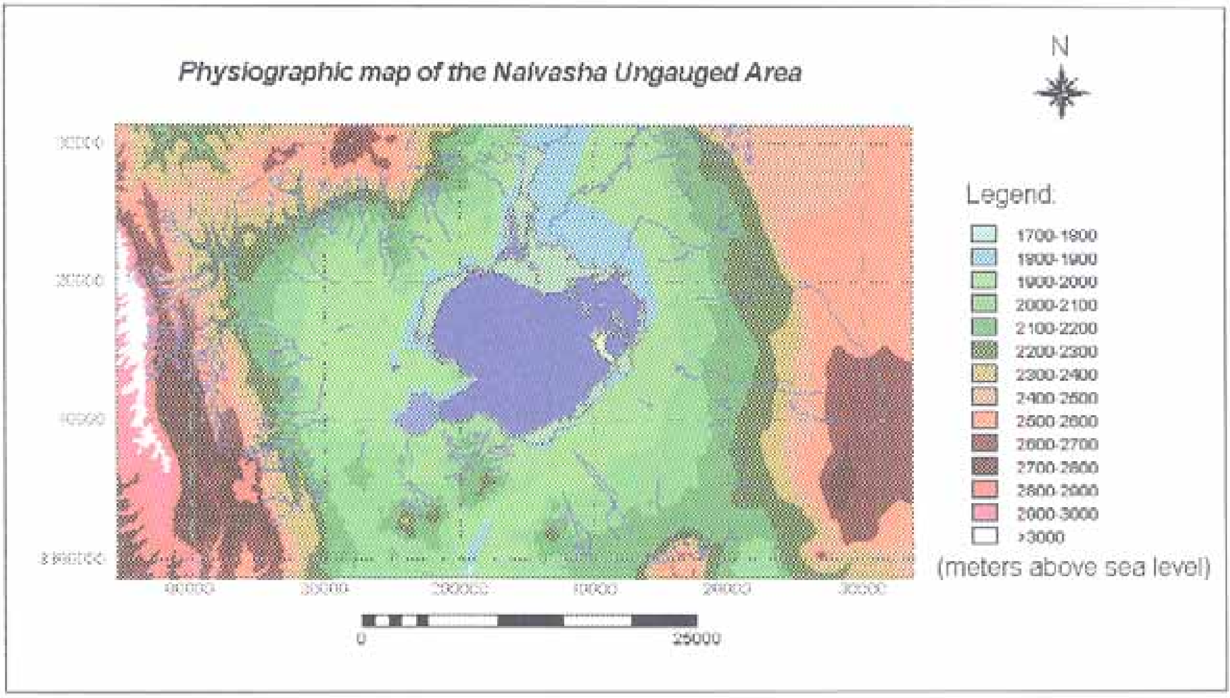
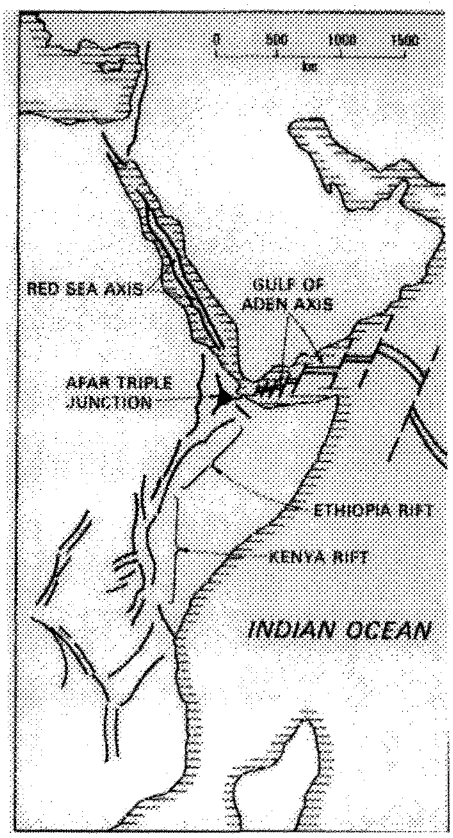


Figure 1.2. Physiographic map of the Ungauged area.

1.1.3. Geology

The study area is located in a geologically dynamic area, the Rift Valley, which is in continuous evolution. This geo-tectonic structure crosses the East Africa in a North-South Axis from Ethiopia to Tanzania.



The geological structure is clearly related to the regional tectonic setting.

Tectonic and volcanic regimes commenced in the early to mid Miocene (25-30 Ma), but only since 4 Ma has there been a graben. From about 1.7 Ma an inner narrow trough appeared within which the best-preserved and still-active central volcanoes are located.

Combination of intrarift faulting and volcanic activity has resulted in localised drainage basin development (the difference between lake and the Playa Lake, by a divisory line, volcanic wall, and limiting alignment).

The volcanic rocks in the area consist of tuffs, pumice, tephrites, agglomerates, tephrites, trachytes phonolites and acid lavas rhyolite, comendite and obsidian.

The lacustrine deposits are composed by reworked volcanic material and sub-aqueosly deposited pyroclastics.

Figure 1-3 Geostructural Map of Eastern Africa

MAJOR VOLCANIC AND DEFORMATION EPISODES			
Episode	**Activity**	**Units**	**Age Range**
V4	Late Quaternary to Recent Salic	*Longonot, Eburru, Ol-*	0.4-0 Ma
D4	Volcanoes	*karia* and *Ndabibi* vol-	0.8-0.4 Ma
	Extensive minor faulting of Rift	canic groups	
	floor		1.65-0.9 Ma
V3			1.7 Ma
D3		*Kijabe Hill* formation	
	Quaternary flood lavas of Rift		
	Floor		
V2	Renewed faulting of Rift margins		2.0-1.8 Ma
D2		*Karati* and *Ol Mogogo*	3-2 Ma
		Basalt Formation	
	Early Quaternary flood trachytes		
V1	Formation of step faults (narrow-		3.7-3.4 Ma
D1	ing of graben)	*Kinangop Tuff* Formation	4-3 Ma
		Mau Tuff Formation	
	Pliocene ash flows		
	Major faulting of Eastern Rift		
	margin		

Table 1.1. The latest volcanic activity episodes in the study area (Source, MCG Clarke, 1990)

The tectonic activity has produced a big number of faults. Their azimuths are normally northwest-southwest, following the axis of the rift valley. Most of the faulting has probably occurred prior to the development of the volcanic center on the rift floor.

1.1.4. Soils

Soils are a product of the geological, topographical and land cover factors and can be considered as the meeting point between the biotic and abiotic systems.

The soils of the study area are young and poorly developed, and show a high degree of porosity.
The Kinangop plateau is covered by Andoluviak phaeozem (well drained, deep to very deep, consisting of clay loam and clay). This soil has a high agricultural fertility, good workability and good water holding capacity (Jaetzold and Schmidt, 1983).
In the Mau and Eburru mountains Regosols and Andosols are found. They are developed on ashes and other pyroclastic materials of recent volcanoes. Regosols appear as excessively drained, deep, slightly smeary by strong calcareous, stony go gravel clay loam. Andosols are well drained as they are developed on older volcanic ashes; they have humic topsoils.

1.1.5. Climatology

Africa constitutes the largest landmass between the tropics; such strong continental character expressed in these particular geographical zone makes the climatic dynamics very complex.

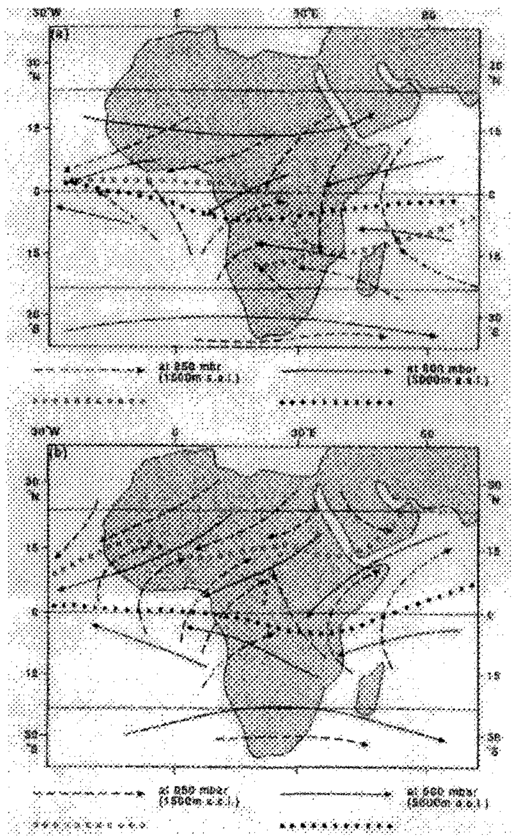


Figure 1-4 Map showing the ITCZ variation in Africa

The basin lies within the semi-arid belt of Kenya, with an average precipitation of 700 mm. The rainfall pattern is bimodal due to the movement of the Inter Tropical Convergence Zone (ITCZ), with two rainy periods followed by other two dry periods:

- "*Long Rains*", from March to May (when the ITCZ is going northwards and slowly)
- "*Short Rains*", from October to November (the ITCZ travels faster to the South)

The precipitation distribution is governed by the orographic character of the area, therefore the maximums occurs along the Mau and Eburru escarpments and Kinangop Plateau with averages of 1250-1500 mm annually. In the floor of the Rift Valley precipitation averages around 650 mm.

In the lacustrine area, the estimated annual potential evapotranspiration is about 1700 mm (McCann, 1974). Monthly averaged evaporation of the floor of the basin exceeds rainfall by a factor of 2 to 8, except in April. However during this month the potential evaporation is still greater than rainfall.

Although the basin is located in an equatorial position (having more or less a constant number of daylight hours during the year), it generally experiences relatively cool conditions determined by the altitude. Besides there is a large diurnal temperature variation, or thermal amplitude, but small variation temperature throughout the year.

So instead of having the typical tropical semi-arid climate, the study area expresses almost a wet or semi-wet tropical climate.

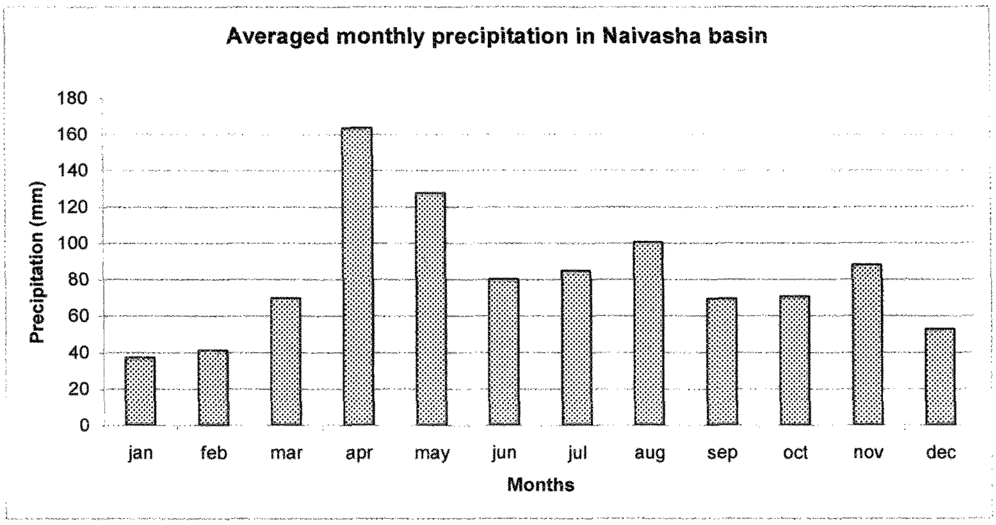


Figure 1.5: Graph of the mean yearly precipitation at Naivasha basin

1.1.4.Hydrology

The endorreic Naivasha basin has a centripetal shape, due to the relief configuration of the area. The lake has underground water inflows and outflows, showing an important hydro-geological activity.

The surface water is affected by the morphology of the rift valley, where most of the surface drainage occurs. The lake is continuously recharged by the Malewa and Gilgil, that drain extensive and far basins. These rivers take water from the surrounding highlands. The drainage network around the lake is intermittent or periodic.

The rivers of the study area which are closer to the lake show a seasonal regime, carrying water in rainy seasons.

The only intermittent rivers that reach the lake are coming from the Kinangop Plateau, namely the Karati and the Nyamamathi; some gullies reach the lake zone from the Olkaria volcanic complex.

Some ephemeral channels reach the western dried part of the lake, being the Marmanet and the Ngathi the most important fluvial systems. These streams drain the Mau and Eburru escarpments hill-slopes.

1.1.5. Man and Land Use

The first settling of human beings in this area is rooted in prehistorical times (as many stone aged tools evidence). In fact the Rift Valley is the first land that people walked. The favourable conditions of the developed ecosystem around the lake (fresh water, vegetation, big mammal presence) converted this area a desirable one for hunting and gathering.

The *Masaai* give origin to name of the lake (with the root term *Nai-*, as *Nairobi*); this tells about the very ancient presence of these cattle-based nomad people in this area. Until the arrival of the Europeans in the XIX century this area was mainly used for grazing and hunting. Changes in the land use were induced by the burning practices, which were aiming to produce adequate pasture lands. As a consequence the reduction of space of a potential Acacia forest formation took place.

The colonial stage carried deep structural changes. A new land property system was established, focusing the new tenures along the lake perimeter. Big scale and irrigated agriculture and rangeland activities started, introducing new forms of production and exogenous crops. In the middle of the XX century the floricultural activity started and became the strongest economical issue, taking advantage of the global scale economy.

During the european presence a change was made concerning the indigenous people spatial and functional distribution. The *Kikuyu,* small farmers, started to occupy the basin from west to east. The *Masaai* population was forced to move eastwards, to the savannah open fields of the South and East.

With the uprising of the political independence in the 1960's a strong campaign of small farmers settlement took place in the East part of the Basin. The Kinangop Plateau and the Kijabe mountain area were occupied by rainfed agriculture (potato, maize, cabbage, etc...). The same process was developed in the western side, where these same farmers settled in the eastern Mau's hillslopes, even if in a less dense and intense way (due to the scarcity of rain water). The last stage of this new occupation and changes of land use took place in the Ndabibi planes, the western dried part of the Lake in the middle 1980's.

This process carried the reduction of the woodland areas (forest and shrubland).
During the last years an increasing land use pressure restarted around the lake. Beside the floriculture farms spreading/resizing, new horticultural techniques were introduced (new types of irrigation like the pivot systems, resulting in big space and water consuming). This spatial and productive agricultural increment carries attached consequences. The labour population has been concentrated around the horticultural farms and mainly around Naivasha City, where some spontaneous settlements appeared.

There is a clear land use gradient starting from the main economical and environmental source, the Naivasha Lake:

- In the closest zone to the water some natural vegetation still remains (papyrus swamp and acacia woodland, Acacia Xantophlea)

- In a intermediate zone, horticulture and floriculture farms own all the available fertile space around the lake, except the deltoid formation formed by Gilgil and Malewa rivers. This area produces the 75% of the country's horitcultural yield.

- Further away from the lake the small scale agriculture starts, mainly in the Kinangop plateau, taking advantage of the high rainfall. In the Rift Valley wooded savanna type sparse vegetation appears in the more arid zones. The shrubs occupy more elevated areas and play a transitional role before the mountainous forest starts.

Land Use	Area	
	km²	% area
Mountainous forest	116	9.87
Acacia woodland	15	1.27
Papyrus swamp	10	0.85
Shrubs	278	23.66
Bare soil and sparse vegetation	260	22.13
Agriculture	345	29.4
Greenhouse	17	1.45
Urban areas	3	0.25
Water	131	11.15
	1175	

Table 1: Main Land Uses in the Ungauged area and its areal percentage.

As it can be seen in table 1 the agricultural land use is the most extended one. In this category both small scale and big scale agricultural types are counted.
This table shows the results of the strong land cover changes that had taken place in the Naivasha basin in the past.

1.2. Problem definition

There is an increasing need of hydrological information to quantify the amount and spatial distribution of water resources as well as the temporal and spatial variability of processes influencing them (Wolski 1999), especially in areas where the dependence on water is crucial for socio-economic development.

Obtaining geo-information on processes and factors influencing the water balance of a region is a basic issue in this context. The complexity of the environment and the availability of hydrological data condition this methodological approach.

make use of the data collected by the gauge stations of the rivers of the basin that present a discharge during the whole year.

Intermittent rivers are usually not gauged due to their little or no runoff during the year, therefore there is a lack of knowledge on their surface runoff behaviour. Nevertheless it seems important to study the magnitude and occurrence of flash events and floods of these rivers, considering that in the past they produced several damages with serious socio-economical consequences. Such kind of study has to be incorporated in a holistic under-standing of hydro-environmental system in order to generate a suitable management of the water resources.

1.3 Applied Methodology

For rainfall runoff interaction the hydrological conditions can be related to natural associa-tions of lithology, geomorphology, soils and vegetation. The interpretation of remote sensing images can supply qualitative information on heterogeneity of hydrological processes.
The mentioned associations can be identified by the Terrain Main Units, which are deter-mined by analytical interpretation of remotely sensed images.

Qualitative description of hydrological processes within TMUs can be obtained from fieldwork and relational hydrologic reasoning.

1.4. Thesis objectives

The general objective is to develop a procedure by which interpreting remotely sensed im-agery hydrologic processes can be represented and approximately estimated in an un-gauged basin. .

The hypothesis that refers to the convenience of the adopted method to estimate the runoff of an ungauged area using remote sensing qualitative interpretation and GIS. Trying to prove the method applicability for runoff estimations based on indirect measurements.

Our study aims to get an approximation to the hydrological response of this landscape unit of the southern Naivasha basin. It is considered as a first step of hydrological characterization of the area

1.5 Literature Review of distributed hydrological methods

One problem in hydrology is that model parameterisation of surface hydrology are usually unsuitable representation of complex, spatially variable processes of land-atmosphere interactions.

One of the simplest solutions for analysing the hydrological behaviour of a water body is to use ***lumped models***, which consider average parameters assumed to be constant for a certain area of interest, e.g. a river catchment. They may produce reasonable results but over simplify the land heterogeneity, e.g. *simple lumped reservoir parametric, SLURP* (Kite, 1989). In the other hand, physically based ***distributed models***, such as the *Systeme Hydrologique European, SHE*, (Bathurst, 1986), assume constant parameters for a grid cell, which area has to be set according to the particular needs of a study. They take more in consideration the spatial variability of the parameters but they are operationally limited due to computational constraints.

Alternatives of grid-based models are ***zone-based methods***, which divide the system under investigation, e.g. a river catchment, into a certain number of zones or sub-catchments. Each zone is assumed to express a homogeneous hydrologic behaviour and therefore can be consider as a reference system where a lumped model is applied.

Lavesley and Stannard (1986) defined a zoned approach that divides a watershed into sub-areas that should be characterised by similar hydrologic response. These areas are called ***Hydrologic Response Units*** (HRUs) and can be characterised using topographic (elevation, slope and aspect) and geographic (soil type, vegetation type, precipitation distribution, etc...) variables. Therefore, for this method, the criteria for the differentiation and consequently the delineation of these sub-areas is by matching similar characteristics of the catchment under study.

Hence, while the physically based models attempt to represent the spatial variability of the hydrologic parameters for each location or grid cell, the HRU method assumes the existence of hydrologically homogeneous sub-areas.

Kite and Kouwen (1992) made the following statements concerning the HRU approach:
- the size of each hydrologic response unit is arbitrary
- the number of the units is limited by computer capacity
- the model calibration is limited

In order to overcome these limitations they recommended to use the ***Group Response Units*** concept (GRUs), which are groups of HRUs with similar hydrological response and that are differentiated only by land cover.

Wood et al. (1988, 1990) proposed the concept of ***Representative Element Area*** (REA). It considers a fundamental scale for catchment modelling at which the intra-element statistics can be considered significant for modelling purposes, and the spatial patterns no longer have to be considered explicitly. The principle is that if the variability is integrated over a large enough area, the effects at the point scale may be attenuated or submerged.

The ***Terrain Mapping Units*** concept (TMUs) developed by Meijerink (1988) is based in landscape units that group natural associations of geology, geomorphology, morphometry and soil distributions derived usually by aerial photo interpretation. Satellite images, existing thematic maps and field data represent other sources of information for units delineation. The classification procedure is functional, open ended, independent of scale and accepts user-defined alternatives to make it universally applicable.

1.6 Qualitative interpretation vs. GIS overlay analysis

TMUs should be based mainly on the qualitative interpretation of remotely sensed data. During the last decade computerised procedures, such as overlay analysis in a GIS environment, are used to delineate these terrain units, giving excessive confidence to this computational and deterministic approach. To my opinion, the hydrologist or earth scientist better delineates TMUs since he can express a more flexible analysis and adapt his subjective interpretation to the natural complexity of the landscape.

Manually interpreted TMUs in this sense are closer to reality and therefore more accurate; units are derived as a result of visual and mental processing, which is free of computational limitations. Of course it is time consuming, but this is necessary in order to obtain an accurate analysis of the terrain.
A computer doesn't think; it defines sharp boundaries and can generate several units that result to be difficult to explain in a scientific relational way.

This is an attempt to emphasise the importance of the use of aerial photography in this technological era. Software development represents an important tool for hydrologic systems simulations and analysis, but cannot totally replace the expert knowledge of an environmental scientist. In the case of the TMUs approach, interpretation of aerial photography represents cheapest and more accurate way to obtain detailed terrain information, especially in areas where there is scarce availability of geographical data.

2. APPLIED METHODOLOGY

2.1. Presentation

In this chapter a description of the selected and applied methodology is presented. As it has already been observed this research is conditioned by the lack of hydrological data, as no gauged data are available for the study area. Another research difficulty lies when dealing with ephemeral hydrology analysis.

2.2 General framework

For rainfall runoff interaction the hydrological conditions can be related to natural associations of lithology, geomorphology, soils and vegetation. The interpretation of remote sensing images can supply qualitative information on heterogeneity of hydrological processes.

The mentioned associations can be identified by the Terrain Main Units, which are determined by analytical interpretation of remotely sensed images, fieldwork observations and digital cartography interpretation.

Three clasical methods were used to try to estimate peak discharges of the ephemeral rivers of the ungauged area:

-slope-area method
-the rational formula
-curve number method

The data required for the slope area method were measured in the field. For the empiriical methods field work landscape interpretation, remote sensed image qualitative interpretation, GIS operations and estatistical analysis were developed.

2.2.1. Slope Area Method

The slope-area method is necessary to determine the peak discharge of a river that remains dry for most part of the year and ungauged.

It consists of using the slope of the water surface in a uniform reach of channel and the average cross-sectional area of that reach to give a rate of discharge. The discharge may be computed from the Manning formula:

$$Q = (1.486/n)\ A\ R_h^{2/3}\ S^{1/2}$$

where:

Q = discharge (ft^3/s)
A = mean area of the channel cross section (ft^2)
R_h = mean hydraulic radius of the channel (ft)
S= energy slope of the flow
n = a roughness factor depending on the character of the channel lining

In order to apply this method it is necessary to determine the slope, the channel dimensions and the roughness coefficient in the field. The mean area of the channel cross section depends on the elevation of high water marks and on the channel depth along the cross section. These measurements constituted basic hydrological skills that were performed during fieldwork .

It was difficult to determine the peak discharge water marks. The long period of droughts and the dense vegetative cover in the channel have deleted any material reference. For solving this problem the local knowledge was used as a main information source, knowing that implies uncertainty in the precise determination of water depths.

The measured data were prepared in excell spreadshets. The runoff estimations were generated by the CROSECT MS-DOS programme (Donker, 1990).

2.2 2 The Rational Formula

The rational formula represents a simple way of assessing the peak runoff of a watershed. It considers the entire basin area as a single unit (*lumped model*), estimates the flow at the most downstream point and makes the assumption that the rainfall is uniformly distributed over the drainage area.

Q=0.002778*C.I.A

Where

C = the Runoff Coefficient
I=the rainfall intensity (mm/hr)
A = the Area of the contributing catchment (m^2).
Q = Peak runoff rate (m^3/sec)
0.002778 = the conversion factor.

This empirical formulae assums that the rainfall intensity generating the peak flow is mantained tor a time equal to the period of concentration of flow at the point of consideration. This is known as the ***time of concentration*** (the time required for the surface runoff from the remotest part of the catchment to that point). This would be the time of equilibrium at which the rate of runoff equals the rate of rain precipitation.

The peak discharge frequency is assumed to be the same as the rainfall intensity one for the time of concentration.

The hourly rainfall intensity data for the Naivasha basin is only available for one year (1997). This is the only source of hourly precipitation in the basin. This lack of long term rainfall intensity data made necessary to adopt an alternative source of information. The intensity data of Nairobi (27 years of observations) were used to approximately design a long term intensity scenario for Naivasha basin.

Because the available intensities were gauged hourly, Bell's ratio's were used. He reports that the t-minute rainfall has a consistent ratio to the 1 hour rainfall of the same frequency. The ratio of Australia was selected:

Rainfall Intensities for different Return Periods			
time (min)	2 years	10 years	100 years
5	108	172.8	252
10	81	129.6	189
15	68.4	109.44	159.6
30	47.5	75.84	110.6
60	30	48	70
120	18.75	30	43.75

Table 2.1. Different Rainfall Intensity frequencies derived from Nairobi metereological data.

2.2.2.1.Runoff Coefficient estimation

This was carried by using the created land cover map from the Landsat TM (25-V-OO) RGB 453 False Colour Compostit image supervised classification. Runoff coefficients were assigned for the different land cover types.

Due to the tendence of this area to high infiltration levels the selected runoff coefficients difered from those of manual´s tables. Those manual standard coefficients were taken as a reference and smaller values were assigned.

The Rational Method can provide acceptable estimates of peak flow rates in small non-retentive rural watersheds. It is mostly applied to an urban catchment as a design tool to size storm sewers.

The present practical use of this formula is limited generally to rural watershed drainage areas less than 1 km^2

The obtained results have to be handled with particular care considering that many catchment under study are much bigger.

Land cover LC	Runoff Coefficient C
agriculture	0.12
forest	0.07
acacia	0.08
papyrus	0.4
shrubs	0.09
bare soil and sparse vegetation	0.1
urban	0.85
greenhouse	0.78
rural settlement	0.75

Table 2.2. The selected Runoff Coefficient.

Although the formula is based in assumptions difficult to be satisfied under actual conditions, its symplicity has converted in a popular one. It is considered as a firstable approximation for estimating the peak runoff of ungauged catchments.

The origin of the is rooted on the 2nd half of the XIXth century.

2.3. The SCS Curve Number Method

The SCS Curve Number Method was developed for the estimation of runoff volume from one day precipitation.

The SCS method is used for estimating floods on small to medium sized ungauged drainage basins. Physical characteristics of of the basin are considered in the method.
It was originally developed as a procedure to estimate runoff volume and peak discharge for design of soil conservation works and flood control projects.

While there is quite information about the method, little quantitative information is available on the data base from which it was developed and the way those data were used in the development. The method was originally derived from infiltrometer tests and measured rainfall and runoff on small basins.

The technique is considered as a reliable one. It has been used for many years as it was adopted as an alternative to the Rational Method. It can be considered computationally efficient. The required inputs are generally available, and it relates runoff to soil type, land use, and management practices.

The use of readily available daily rainfall data is a particularly important attribute of the curve number technique because for many locations, rainfall data with time increments of less than 1 day are not available. Also, rainfall data manipulations and runoff computations are more efficient for data taken daily than at shorter intervals.

The method is based in the fact that no runoff occurs until rainfall equals an initial abstraction I_a.
After allowing for I_a the depth of runoff Q is the residual after substracting the infiltration, F. The potential retention S, is the value that ($F + I_a$).

The Initial abstraction I_a consists of all the storm rainfall occurred before surface flow starts.

$$F / S = Q / P_e$$

where
F= actual infiltration excluding the initial abstracion (in)
S= potential infiltration (in)
Q=actual direct runoff (in)
P_e= Potential runoff (effetive storm rainfall) (in)

$$Q = P_e^{\,2} / P_e + S$$

The initial abstracition for small watersheds is consideres as

$$I_a = 0.2 * S$$

So the actual direct runoff is calculated as follows

$$Q = (P-0.2*S) / P + 0.8 *S$$

The S is related with the Runoff Curve Numbers as

$$S = (1000/CN) - 10$$

2.3.1. Determination of peak runoff rate using the SCS Dimensionless Unit Hydrograph

Because the most frequent storm type occurring in Naivasha is convective, it can be considered as an advanced type of hyetograph. It has a rapid increase to the maximum intensity value during the first half on the storm duration then it decreases exponentially.

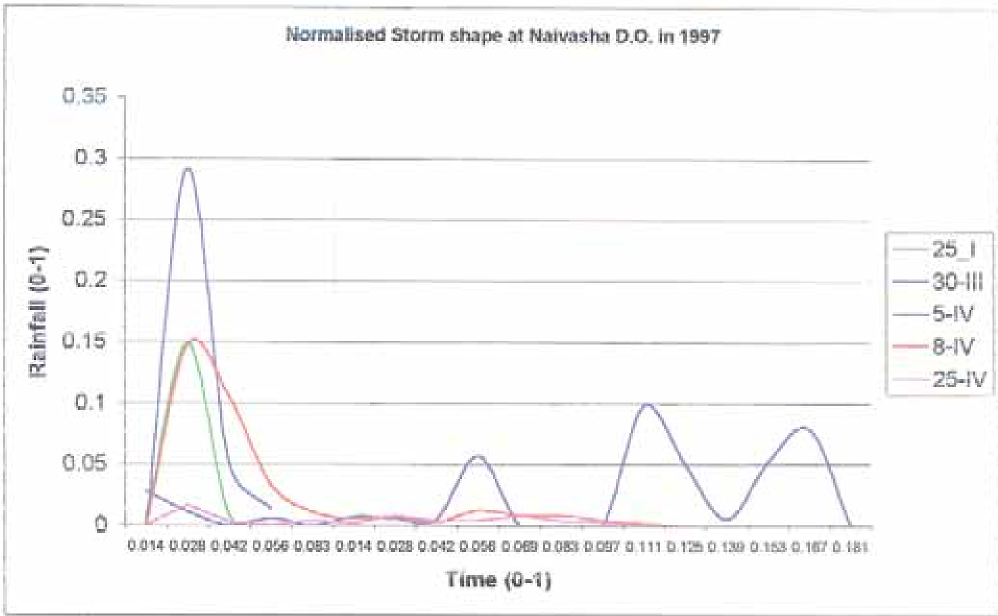


Figure 2.1: Normalised storm types in Naivasha D.O. in 1997.

The SCS Dimensionless Unit Hydrograph (U.S. Soil Conservation Service, 1964) is an important empirical formula for determinig the quantity of runoff. It is one of the isochronical methods for determining peak runoff rates. The method is based on the theory of Sherman (1932). In order to apply the method, the time to peak t_{peak} and the peak discharge q_{peak} are estimated.

The method makes the following assumptions:

The peak discharge is given by

$$Q_p = 0.208 * A Q / 0.5 * D + 0.6 * t_c$$

where

A = Basin size km^2
Q = runoff volume in mm

The estimation of *Time of concentration* was carried using the California Method..

$$Tc = (11.9 * L^3 / H)^{0.385}$$

Where

Tc in hours
L=in miles
H =in feet

For the change of dimensions the *Dimcalc* Software resulted very helpful.

2.3.2 GIS procedure for CN calculation

The CN values were designed from average watershed soil-cover and soil moisture conditions in a GIS environment.

At first the available soil map of the study area was correctly georeferenced. Further editing concerning the delineation of the soil unit boundaries was made based on the information of a more detailed geological map, satellite imagery and aerial photography. Such editing operations can be justified considering that soils result from the combination of topography, geology and weathering processes that take part on it.

Then the soil map was classified into hydrological soil groups map A, B, C, D according to the SCS system (see table...). A new hydrological soil group *A/B* was introduced for a better representation of the particular soil conditions existing in the study area.
Group A/B stands for high infiltration and low runoff potential for soils that are not constituted by sand or gravel.

The delineation of the hydrologic soil-cover complexes is required by the method. This was performed using two dimensional table operations in ILWIS.

1-The soil map was reclassified to HYDROLOGICAL SOIL MAP by Table operations.
2- A two dimensional table was created with the Hydrologic Group Soil Map and the Land Cover map The Curve numbers were assigned by linking the different values.

With this map we were able to calculate the area occupied by each CN value for the selected drainage basins. Because many cover types were not found in the standard tables and values were selected according to close vegetation types and knowledge acquired during the fieldwork.

-(See the attached CN map of the Study area, Map 1)

2.4. Fieldwork data collection

The fieldwork (carried from 6-IX-00 to 28-IX-00) was mainly dedicated to measure the cross sections areas of the more representative ephemeral streams of the study area, in order to be able to apply the slope-area method and thus to assess the hydrologic response.

For this purpose some steps were followed:

- global knowledge of the area and its landscape by visual interpretation during a general visit of the study area
- use of topographic maps and satellite images poster as information sources to better understand the area and its natural associations
- first recognition and relative discretization of the main terrain units existing in the study area
- after this first insight on the spatial distribution of the natural processes and characteristics of the area, a plan of the cross-section measurements of the intermittent rivers was set in order to get the most interesting distribution of this information in the area, and according to the different main terrain units that had been recognised

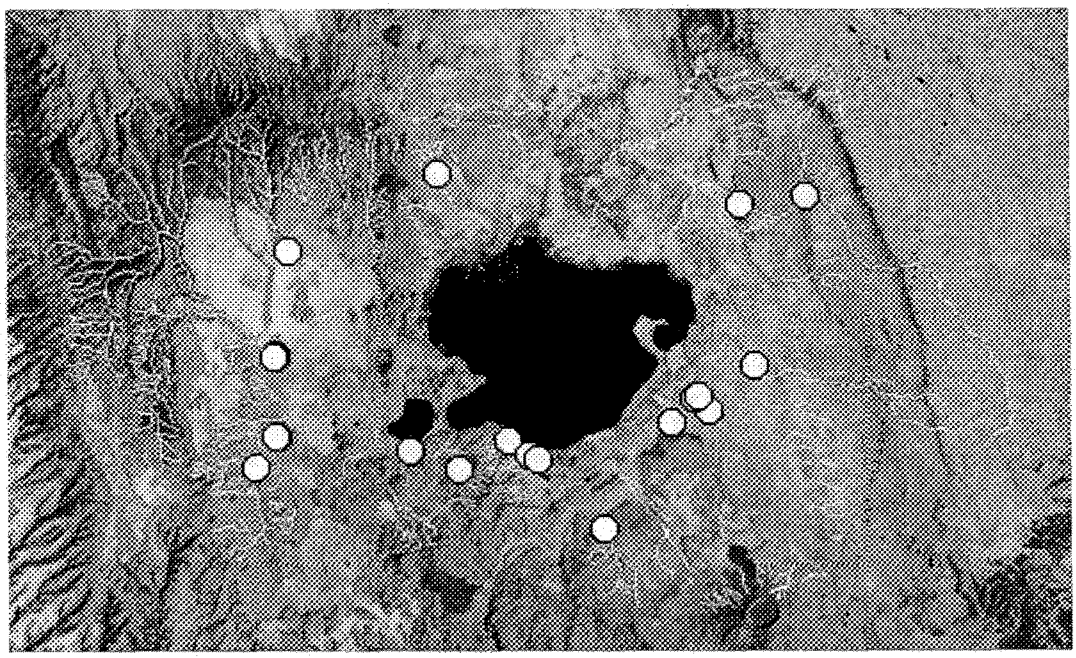


Figure 2.2: Landsat TM image showing the spatial distribution of the river channel measurements.

When no water height marks could be identified the information was obtained from local knowledge by semi-structural interviews. This source of information resulted very helpful for assessing the magnitude of extreme hydrological events and their spatial and temporal distribution.

In order to work with georeferenced information, all cross sections were located with at least 10 m accuracy using Global Positional Systems.

Land cover observations were carried out as well in the field, and constitute an important input for the determination of the land cover map.

More specific information about the riverbed cover was used for the estimation of the roughness coefficient for each channel, input parameter of the slope-area method. An overall description of the vegetative cover was considered for selecting a reliable coefficient.

Moreover the land cover type and distribution were found to be of paramount importance to understand the hydrologic conditions governing the area. Local knowledge was also necessary for defining specific cover types.

Such interpretation gave some information about the landscape evolution in the area.
Photography pictures (slides) of the channel cross-sections, vegetative cover and geomorphology were taken as an alternative remote sensing source.

Fieldwork included a visit to the Ministry of Water Resources at Nairobi for the collection of Karati's discharge data.

2.5. Remote sensing data

The used remote sensing data were aerial photographs of 1966 and a Landsat TM Image of May 2000.

The use of aerial photographs has been pointed as the best way for deriving information on the timing characteristics of runoff (Mannaerts, 1990). In this sense the existing flow types, the surface roughness and resistance and evaluation of temporary storage effects were assessed.

The qualitative interpretation of this remote sensing data represented a primary source for the TMUs delineation.

During the last years the use of aerial photographs has apparently become less important in the environmental research while digital imagery and processing are representing the main source of optical information. In this work aerial photography is of primary importance for the collection of terrain information.

A false colour composite RGB453 false colour composite was obtained from the Landsat TM 2000 image in order to enhance the differentiation of land cover reflective characteristics. Afterwards a land cover thematic map was carried out using supervised image classification (by maximum likelihood algorithm application).

(See the attached land cover map, Map 2)

2.6. Preparing GIS data

Hydrologic processes are distributed in space and time. Digital maps of soils, geology, land use, topography, and rainfall rates are often used in hydrological models as input data to simulate flash floods and other hydrologic phenomena. The determination of the several spatially distributed parameters affecting such hydrological events is greatly facilitated by the use of Geographic Information System (GIS). Such computer system gives the necessary tools to store, manipulate and analyse maps of model parameters.

2.6.1.Editing and correction

The first step of any research work based on geo-information is the need proper database layers. These layers were selected, constructed, edited or corrected according to the study objectives, i.e. the main terrain factors controlling runoff generation.

2.6.2. Editing of topographic information

The editing of the digital topographic map was realised by screen-digitising of scanned and georeferenced topo-sheets. Small-scale relief features were added to the topographic database, especially where several volcanoes crater of the Ndabibi plane are found.

The upper part of the Karati's basin was missing in the 1:50.000 map therefore another map covering a wider area was used in order to add the topographic information of this important part. For this purpose the Kenyan government (1981) NYERI SA-37-1 1:250.000 scale map was scanned and georeferenced; screen digitising of the main contour lines was performed.

2.6.3.Other GIS operations

- soil map reclassification into hydrologic soil group map
- land cover reclassification into runoff coefficients
- crossing table operations of the hydrological soil group map and of the land cover map for curve number map generation

2.7. Delineating Terrain Main Units (TMU)

These landscape units group natural associations of geology, geomorphology, morphometry, soil distribution and land cover (Meijerink, 1988). They operate as ecological units where water is the dynamic factor, landscape modeller and sediment transport and deposition main agent.

The Terrain Mapping Units were derived by qualitative interpretation using the following material:

- Geological Map of Naivasha, scale 1:50.000
- Soil Map of Kenya, scale 1:1.000.000
- Aerial Photographs, 1966, scale 1:50.000
- Landsat TM images of 1996 and 2000, 7 bands, 30 m pixel resolution
- Slides of the study area, notes, semi-structural interviews

All these sources of information were compiled, analysed and inter-linked in order to define the TMUs. Soil and geological maps were combined with the land cover map. As a result the obtained units are shown in the map of the Terrain Mapping Units.

Further differentiation and delineation of sub-units could have been performed, but the reached degree of detail was judge sufficient for the scope of this study. In fact the size of the interpreted terrain units allow to include different drainage basins under investigation in one unit. Therefore the hydrological relationships existing between basins falling within the same unit can be analysed and finally the TMUs could be hydrologically characterised.

2.8. Drainage basin characteristics

We tried to make a brief geomorphic description of the drainage basins by appliying some basin measurements.
The drainage density was selected to perform this task., as is considered as a valuable index.

TMUs	Drainage basins	Area (Km^2)	Length (Km)	Drainage Density
Kinangop Plateau	*Karati*	154.00	38.40	0.25
	Nyamamiti	86.00	19.70	0.23
Mountains	*CEburru*	15.00	29.85	1.98
	marmanet	150.00	151.40	1.01
	ngathi	33.20	44.00	1.33
	WEburru	25.00	14.67	0.59
Volcanic Complex	*oserian*	6.50	7.40	1.14
	kongoni	3.80	7.60	1.96
	kongoni2	0.80	1.20	1.55
	kongoni3	1.90	1.83	0.93
Rift Valley	*marula*	2.80	1.65	0.59
	NWLongonot	20.80	14.50	0.70

Table 2.5. The basic physical data of the studied sub-basins.

With the drainage density, a short descriptive value of the involved drainage basins is developed. This value can offer a relatively rapid indication of the geomorpholigal character of the area. It is considered as a first and quite good information on type and distribution of the rocks encountered as well as of their erodibility and tectonic estructure.

The extent and density of the network reflect topographic, lithological, pedological, and vegetational controls.

(See the attached Satellite image with the measured basins, Map 3)

3. Rainfall analysis

Rainfall characteristics determine the type of runoff generation. In this sense, it is necessary to understand the precipitation distribution, both in space and time.

The East African tropical climate zone is characterised by a relatively low rainfall. This is exceptional if we consider the equatorial location of the area. The reason for this aridity is the monsoonal system that prevails over this region during large part of the year, which carries dry air masses.

As it has already been explained precipitation is generated by the latitudinal variability of the ITCZ, which imposes a dual moisture regime.

As a consequence precipitation in the study area is characterised by high variability in time and space, of the individual storms, seasonal rainfall and annual and cyclical totals. Furthermore there is a diurnal variation, with a peak precipitation during the late afternoon induced by local convective storms.

3.1. Yearly rainfall variability

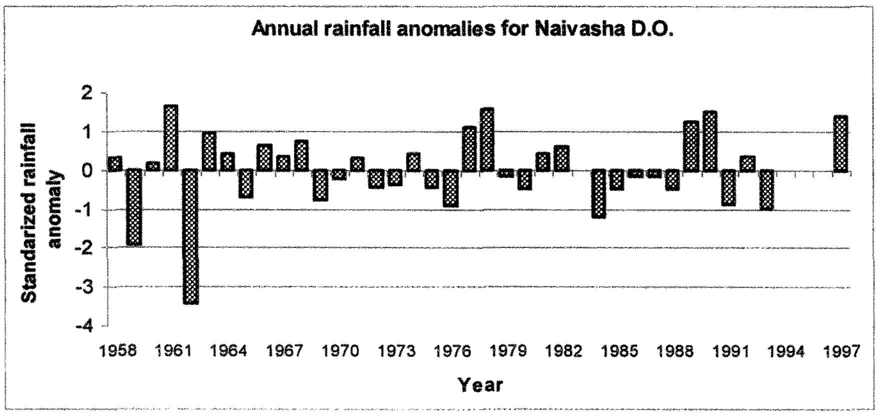


Table 3.1. Table showing year by year rainfall anomalies

As it can be observed in the graph there are substantial differences of annual precipitation during the last 40 years. Most of the anomalies vary around one standard deviation, while major anomalies can exceptionally reach 3 standard deviations.

3.2. Seasonal rainfall variability

From the following graph an important seasonal variation of precipitation can be noticed as well. Precipitation is concentrated mainly during the two rainy seasons, from April to May and from October to November.

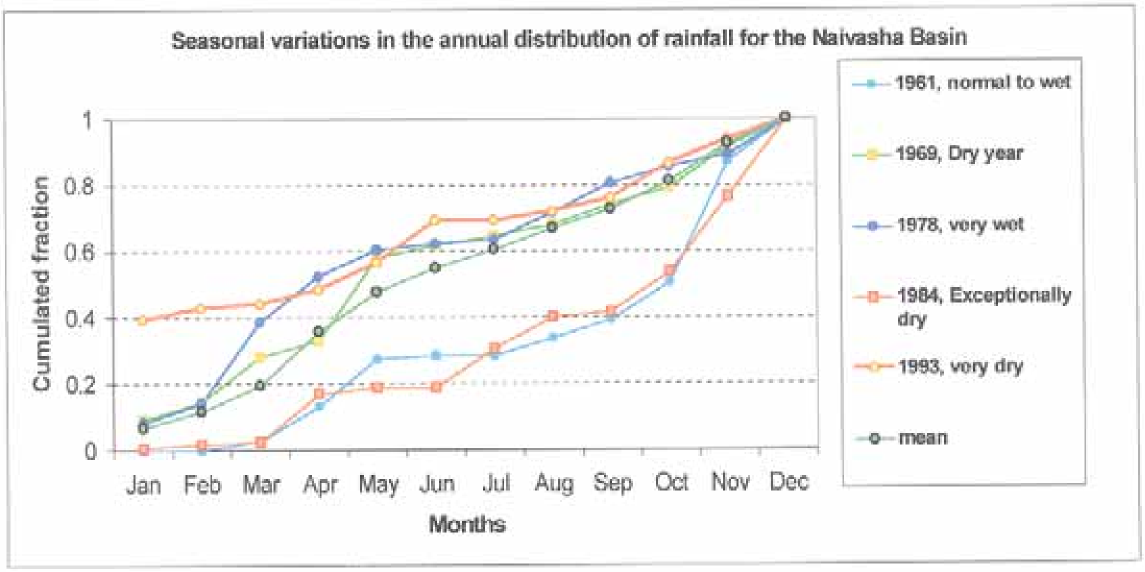


Table 3.2. Seasonal variation of the rain during different moisture regime years

Monthly variation of precipitation for different years

In the graph five typical rainfall years were selected: two wet years, two dry years and one reference year close to the mean annual precipitation.

The variation of the cumulative fraction shows that there is a seasonal rainfall variability independently from the type of year. The two dry years 1984 and 1993 present completely different rainfall distribution throughout the year, while a dry year (1984) and a wet year (1961) have a very similar distribution.

Precipitation in arid and semi-arid zones results mainly from convective mechanisms, which typically produce storms of short duration, relatively high intensity and limited areal extent.

3.3.Rainfall Intensity

Rainfall intensity is an essential parameter that has to considered for tropical areas. Hudson (1981) stated that 60% of tropical rainfall have intensity lower than 25 mm/hour and that 40% of it expresses higher values.

Intensity controls runoff generation when it exceeds the maximum infiltration rate of the soil. In this section daily and hourly intensities are studied.

3.3.1.Daily rainfall

Daily maximum precipitation is considered a main parameter regulating runoff generation, in particular when using the SCS curve number method.

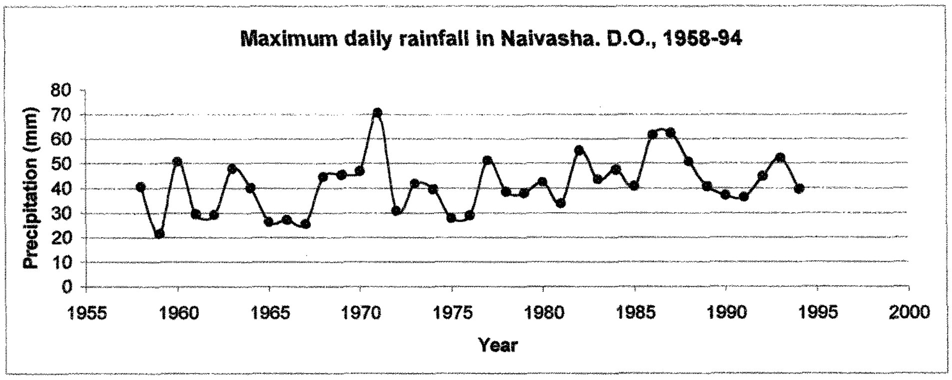


Table 3.3. The variation of daily rainfall at Naivasha D.O.

The values of the maximum daily rainfall of Naivasha show a cyclic pattern, varying within a defined umbral range between 20 mm and 60-70 mm per day. From the graph there is apparently no important change of regime, with a random variation around a mean value of 40-45 mm/day. This is maybe due of the relatively short period of observation.

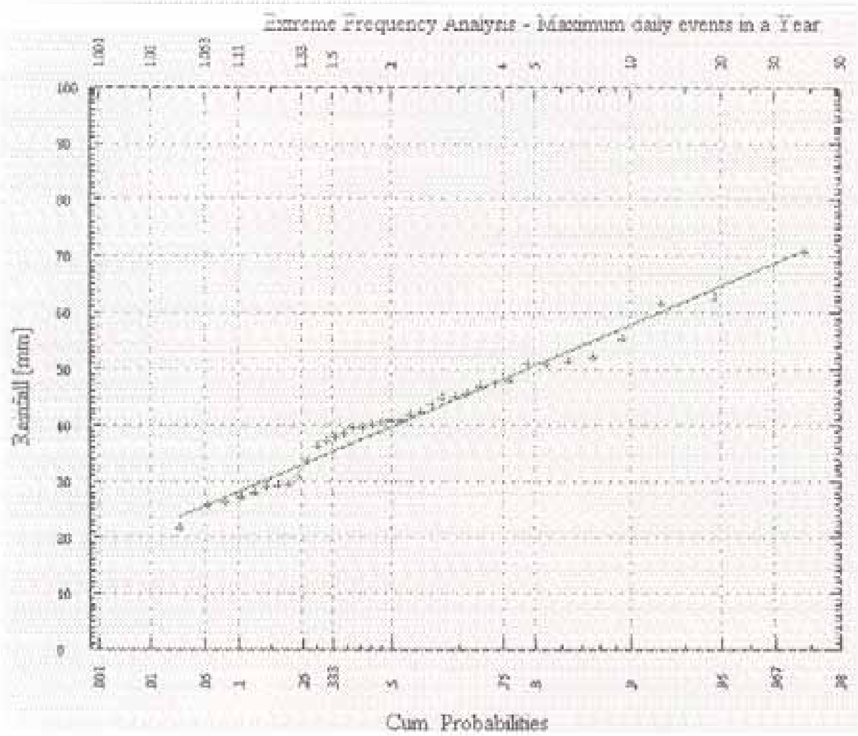


Figure 3.3 Maximum daily events frequency table for 50 years.

Mean: 41.75 mm/day
Standard Deviation: 11.10 mm/day
Maximum value: 70.7 mm/day in 1971

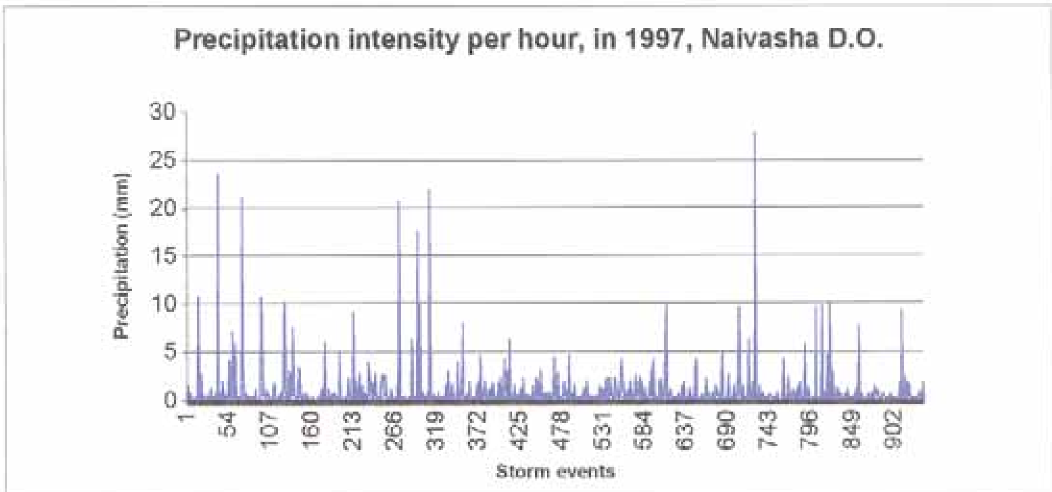


Figure 3.4, Hourly precipitation intensities of Naivasha D.O. in 1997

The graph shows that for a relatively dry year (1997) hourly precipitation was 5 times greater than 20 mm/day, and only once exceeded 25 mm/day, exactly 27mm/day.

3.3.2. Hourly rainfall intensity

Hourly rainfall intensity data for the Naivasha basin are only available for 1997. Considering this lack of long term rainfall intensity data it was necessary to use an alternative source of information. The intensity data of Nairobi (27 years of observations) were analysed in order to approximately design a long-term intensity scenario for Naivasha basin.

In this context Bell's ratio's have been applied. This author reports that t-minutes rainfall has a consistent ratio compared to 1 hour rainfall of the same frequency. For Naivasha area the ratio for Australia was selected.

Rainfall duration	5 min	10 min	15 min	30 min	1 hr	2 hr
Ratio	0.3	0.45	0.57	0.78	1	1.24

Rainfall Intensities for different Return Periods			
time (min)	2 years	10 years	100 years
5	108	172.8	252
10	81	129.6	189
15	68.4	109.44	159.6
30	47.5	75.84	110.6
60	30	48	70
120	18.75	30	43.75

Table 3.1. Tables showing the utilised Bell's ratios and the latter dissection of the hour precipitation intensity in minutes

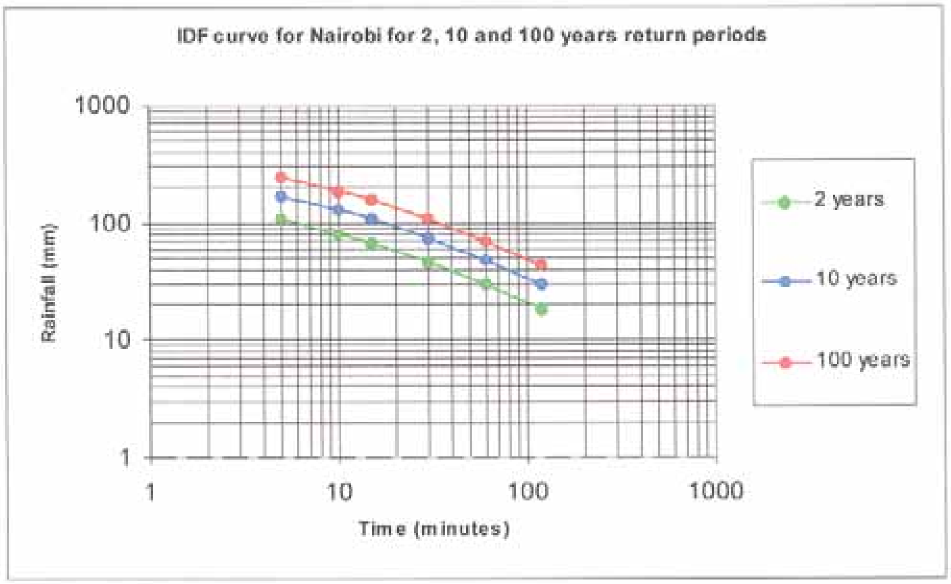


Figure 3.5: The calculated IDF curves for Naivasha basin

3.4. Rainfall spatial Distribution

Rainfall is distributed according to its convective nature. Nevertheless the area presents an important orographic effect therefore the rain is not associated with discrete convective cells. The central part of the study area is depressed, surrounded by elevated morphological units. For assessing the annual spatial distribution of the rain the DEM information was used and a linear regression equation was derived from the data of 30 rain gauge stations and their relative altitude.

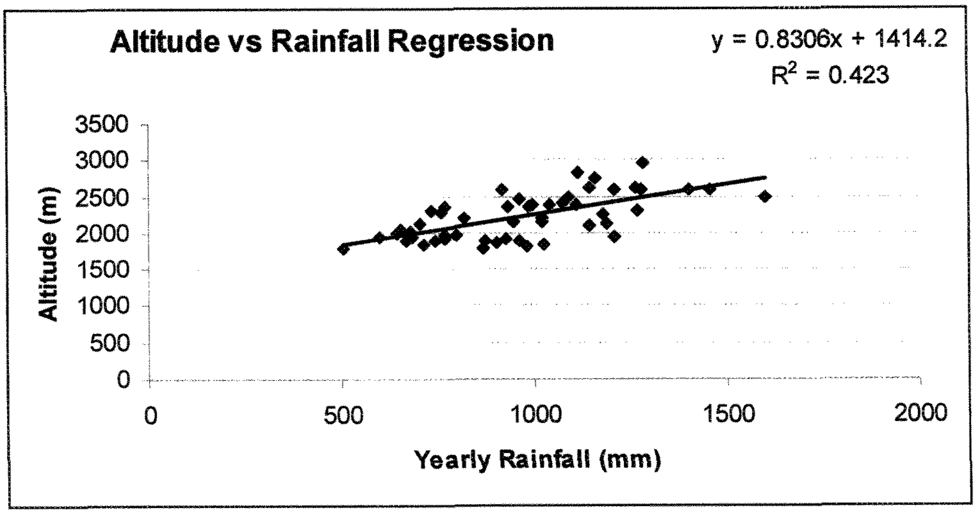


Figure 3.6. Graph showing the relation between rain and orography.

Four major factors affecting rainfall distribution in mountainous areas are the velocity 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 rather than its distribution

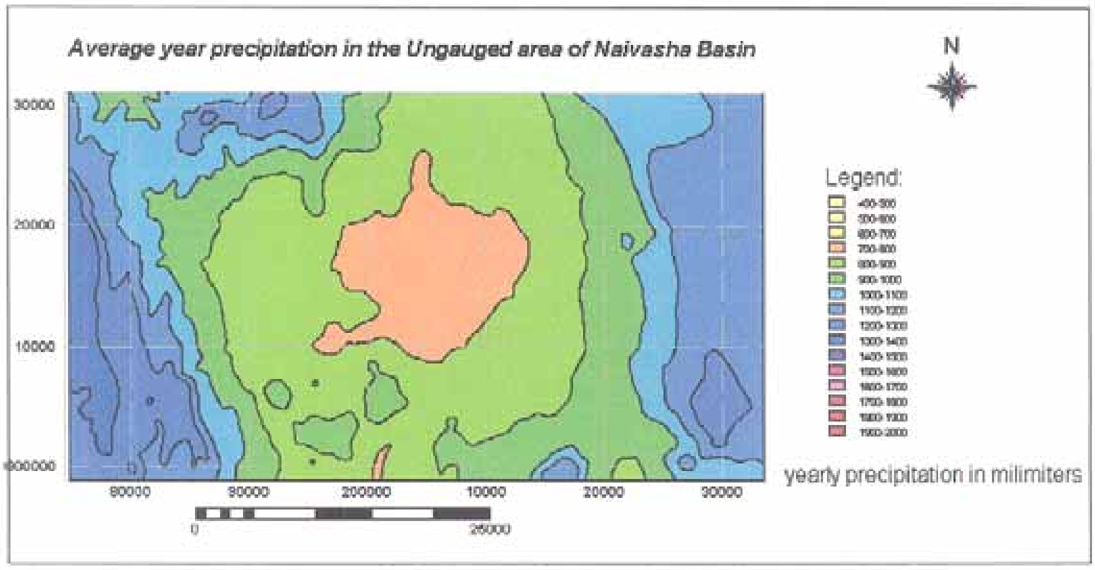


Figure 3.7: Rainfall map of the Ungauged area.

This map shows the yearly average precipitation in Naivasha basin. This information gives the general pattern of the rainfall distribution in Naivasha. The relieve is the major factor controlling its occurrence. The elevated areas present values for more than 1000 mm per year, while the rift valley recieves around 700 mm. There is a big precipitation gradient in the area. This fact gives more complexity to the area, where semiarid and moisture climates meet. The hydrology is also affected by this characteristic, being the Karatis dual regime (perennial upstream, and ephemeral downstream) the best example.

4. The TMUs of the study area

4.1. Introduction

The Terrain Mapping Units delineated for the research area are based on geological processes and lithological features. Each landscape unit shows slight differences in the elements structure and distribution; they are strongly dependent on the rifting and volcanic activity. Denudational processes model the landscape features in close conformity with the patterns of bedrock composition.

The terrain units act as an integrated system that defines the hydrological relations between them. The highlands represent the main groundwater recharge areas for the lake and aquifers that are exploited by men activities. A centripetal drainage pattern centred in the lacustrine area characterises the Naivasha basin. The lacustrine depression is formed by a western dry area or playa (which represents the ancient western limit of the lake) and a wet central part.

The surrounding highlands units, resulting in a strong negative hydrologic balance for the lake basin intercept most of the monsoonal rainfall directed to the central Rift valley.

As it has already been explained, the units cover large areas in order to fulfil the objectives of this research. In fact each terrain unit should include one or more sub-basins under investigation that present similar hydrologic characteristics.

(See the attached TMU map of the study area, Map 4)

4.2. Presentation of the Units

4.2.1. Mountainous area, Eburru and Mau escarpments

This unit is composed by the Mau escarpment at the western edge of the study area and the Eburru volcanic complex at the north-west of Lake Naivasha.

The Mau escarpment belongs to the western Rift margin. Its maximum elevation is about 3080 m, and it is over 3000 m for 36 km of its length, showing a decrease in height at north and at south. The escarpment is 1000 m higher than the rift floor at Ndabibi, the playa at the western border of the lake. This orographic unit is separated by down-faulted platforms from the rift floor.

The western Eburru escarpment forms the drainage divide between the basins of lake Naivasha and of Nakuru-Elmentetia. This complex has an area of 470 km^2 and forms a 23 km long ridge perpendicularly to the western rift margin. It has a maximum width of 18 km from North to South and a maximum elevation of 980 m above the adjacent rift floor. It extends onto the down-faulted platforms along the western rift margin, having a maximum altitude of 2820 m. The upper flanks exhibit a radial pattern of intermittent rivers with gullies less than 200 m deep. It may be an older volcanic pile, actually completely blanketed with thick pumice and ash beds from the younger centres comprising Eastern Eburru.

From a lithological point of view, this unit shows an older sequence of trachytic and pyroclastics.

The main catchments belonging to this terrain unit are the Marmanet and the Ngathi. Both descend from the Mau Escarpment to the Ndabibi plain. They have a composite drainage pattern, dendritic in the upper zones, and trellis or angulated in the lower part due to the presence of fault lines. Between these two basins there are small gullies and paleorivers.
The drainage descending from the Eburru has a fine rectangular dendritic pattern.
Those physical attributes were detected by aerial photo interpretation.

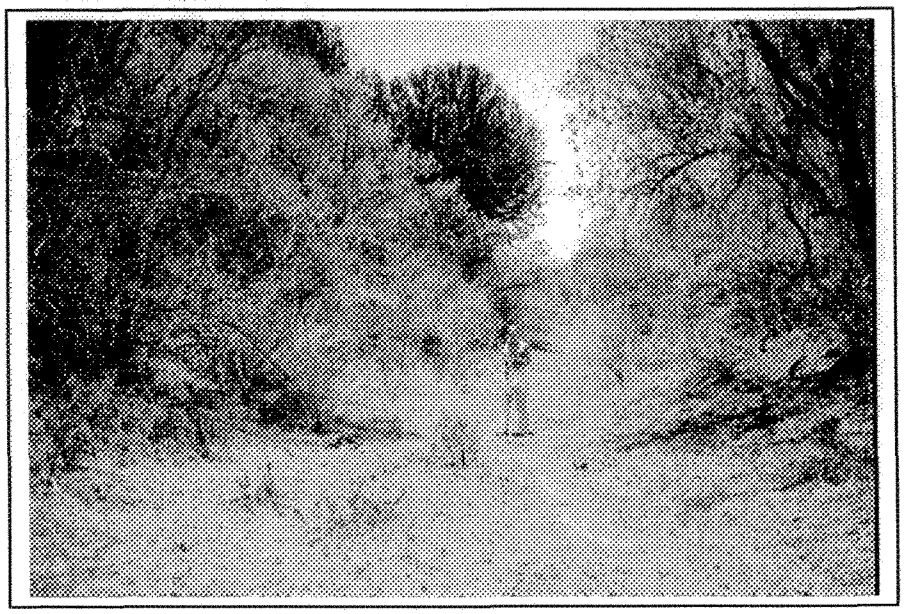


Figure 4.1: Ephemeral Channel of West Eburru. The photography shows the esporadic runoff occurrence in the channel and the high surface roughness.

4.2.2. Volcanic Complex, Olkaria and Eastern Eburru

A field of 80 scattered craters forms the Olkaria volcanic complex. It has an extension of 240 km^2 and lies at south of the lake and at west of the Longonot volcano. In this area is located the Olkaria geothermal field.
A 16 km long and narrow valley, called Njorowa Gorge Hells Gate, is meandering southward across the unit. This valley is the geomorphological remain of the ancient outlet of the lake.

The main lithological formation is comendite (or Peralkaline rhyolite); lava and pyroclastic rocks are also present.

Concerning the cover, there is a clear dominance of the scrub grassland. Euphorbia trees (cactus shape) are located in the valley bottom where higher moisture is available.

Due to the short distance between this unit and the lake, the drainage basins are small and steep. These streams are flashy and their erosional activity can be important; they represent a danger for the flower farm settlements that are located in their way to the lake.

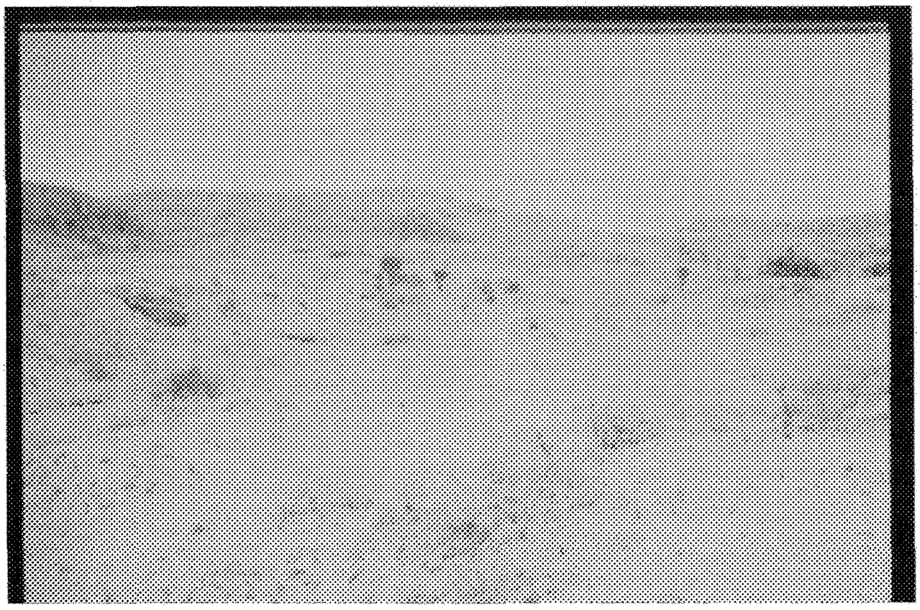


Photo 1 The Olkaria Volcanic Complex Northern Hills

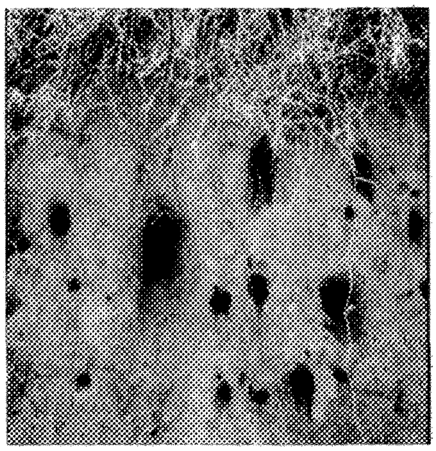
4.2.3. Rift Valley, North Longonot

The Rift valley unit is formed by the northern Longonot volcano and the volcanic sediment plane. This area is the most arid one.

The area is covered by savannah woodland of scattered Acacia and Euphorbia trees. Close to the lake some rangelands cover the surface. The Masai have chosen this area for temporal staying. Wind is the major erosional factor in this north-south open space.

The ephemeral rivers belonging to this unit cannot reach the actual lake as they infiltrate in the dry and porous savannah soils. Such high infiltration produces subsurface runoff from the adjacent and more permeable volcanic highlands, leading to see page gully formation due to seepage.

Photo 2, Photo showing the seepage micro-holes.



4.2.4. Rifted Plateau, Kinangop Platform

This unit, part of the Eastern Rift margin, is a plateau elevated 500-600 m from the Rift floor and presents a composite fault line scarp.
Drainage shows a linear pattern without contributing branches. The low drainage density is due to the particular lithological composition and the flatness of the unit.

The main rivers are the Karati and the Nyamamathi. The first one has a dual runoff regime, being perennial in the upper part (where annual precipitation reaches 1250 mm), and ephemeral in the lower part where porous welded tuffs and fault lines are found. This is a clear example of water transmission losses through the stream bed.

Small-scale rainfed agriculture is the main land use in this area, taking advantage of the favourable atmospheric conditions.

4.2.5. The lacustrine area

This unit incorporates the Lake Naivasha, its surroundings and the Ndabibi plains.

It presents a sedimentary lithology composed of lacustrine depositions such as pumiceous granule, pebble gravel, coarse sand, silt and clay. This particular depositional environment is originated from the reworking of pyroclastic material.

The following two sub-areas can be identified within this unit.

4.2.5.1. The lake and its lacustrine plain

The bottom of the lake is smooth and has a mean depth of 4.7 m. The deepest parts are located within Oloiden Bay (9m) and close to Crescent Island (17m).

Around the lake develops, as a buffer pattern, a gradual zone of papyrus and Acacia forest. Floriculture and horticulture farms have occupied many areas corresponding to the natural forest. The more important extensions of Acacia exist in protected areas situated at north and west of the lake.

This area is the most densely occupied by humans, with Naivasha city, its peripheral settlements and the highly productive flower farms.

Some rare gullies coming from the Olkaria volcanic complex reach this area and can occasionally show flashy discharges. There is lack of planning for predicting and zoning the potentially flooded areas.

4.2.5.2. The western Ndabibi plains

Within the last 12.000 years the Ndabibi plains have been submerged during more humid climatic conditions and were part of the lake. This unit extends up to 9 km west of the lake, and separates the Eburru and Olkaria volcanic complexes. Intermittent rivers from western Eburru and Mau escarpments reach this area and form some alluvial fans that enter the plains till a maximum length of 1.5 km.

The Marmonet and the Ngathi rivers, which descend from the western rift margin, are the most important runoff contributors to this area and wide alluvial fans. The latter are possibly interbedded with lacustrine sediments.

From these geomorphological and hydrological characteristics the Ndabibi plains can be described as a playa lake, which acts as an ephemeral collector of the surrounding gullies. Thus under extreme hydrological events this area is inundated.

This area is covered by a combination of rainfed agriculture (mainly maize and potatoes) and big scale agriculture (wheat) in the south. Open savannah with scattered shrubs develops in the north, and in the extreme part of Marmonet´s mouth a little Acacia forest is located, indicating the existence of subsurface humidity.

Local people and nomads depend on the water extracted from the three wells located in the plain.

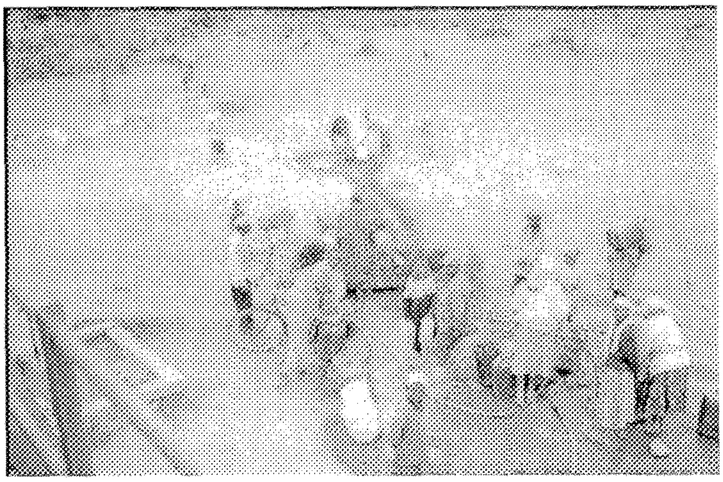


Photo 3 Southern Ndabibi Plain borehole

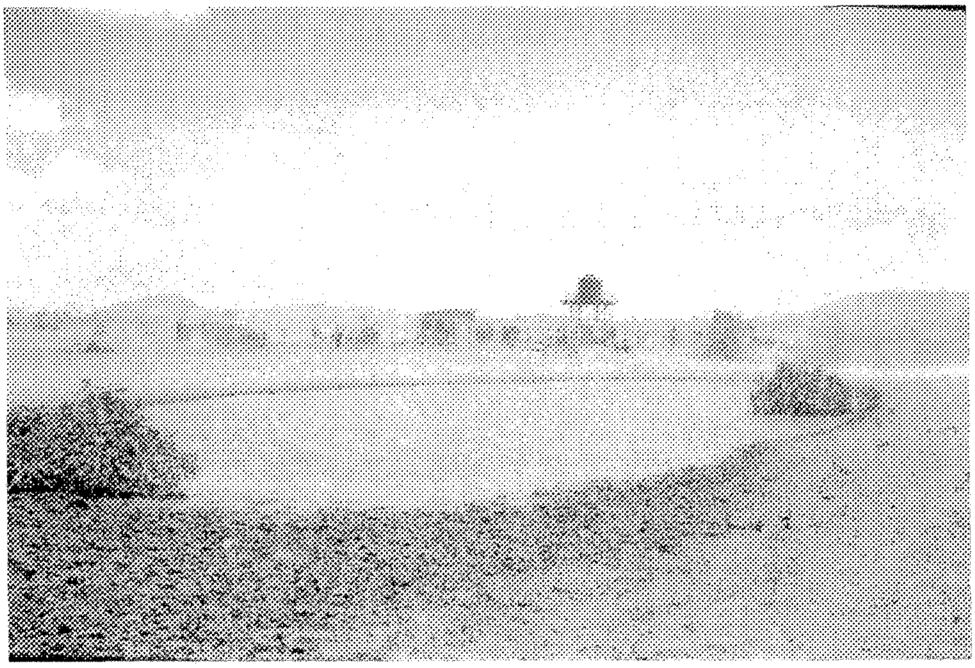


Photo 4 The Ndabibi Plain depression with ephemeral water storage.

Photo 5 The Central Ngathi, the river incises the relieve by a sequence of terraces, showing the different hydroclimatic rhythms occurred in the area.

Mapping Terrain Units		Morphometry	Geology	Soils	Vegetation	Drainage
1) Eburru and Maumau scarpment		Steepy Hilly scarpments Sharp, knife-edged ridges within a highly dissected topography Steepy sideslopes	Volcanic ash, tryachite pumice and tuff cones Pantallerite, Lava flows Pyroclastic cones	Clay loam Stony loam	Montainous forest, transitional shrubland	Dendritic, Angulated .Angular denttritic
2) Lacustrine sediments	***2B)***	Buffer plane of the Naivasha lake.	Lacustrine sediments, volcanic and weathered/deposited river sediments	Silt loam to clay Clay	Sparse vegetation, rangeland, intensive agriculture/horticulture	Terminal drainage of the surrounding baisns. Meandering, narrow incised.
	2A)	Natural depression Flat basin topography Western dried Naivasha lake Gentle depression SW.	Lacustrine sediments, volcanic and weathered/deposited river sediments	Loose fine sand to very friable sandy loam, stratiified and calcareous	Bare soil, sparse vegetation, rainfed agriculture, extensive agriculture	Terminal drainage of surrounding highlands **Unit 1** discharges in this area
3) Olkaria volcanic complex		Massive domelike rounded hills	ComenditePantallerite, lava flows, pyroclastic cones and material	Loam-clay loam Friable, stony and calcareous	Bushland and Shrubland	Dendritic little ephemeral streams
4) Rift Valley and the Longonot volcano		Flat basin topography	Volcanic ash, pumice, tuff cones Mixed basalt/tryachite lava flows, pyroclastic cones	Loose fine sand to very friable fine sandy loam	Wooded savanna, sparse vegetetation and bare soil	Semi Linear channels Seepage gully formation
5) Kinangop plateau		Elevated Gentle uniform slope	Tuff, volcanic ash,pumice,	Loam to clay loam, with clay loam to clay	Small rainfed agriculture and scattered vegetation.	Longitudinal, linear channels. Little drainage density

Table 4.1. Esquematic table showing the TMUs and their environmental characteristics

5. Analysis of the Results

The experimental results obtained from the applied methods are graphically presented and latterly discussed. As an introduction to the hydrological units, a physical presentation of the measured channels is given. Afterwards the applied methods result are presented, evaluating their results and comparing them.

5.1. Drainage density

This value is considered as a indirect explanatory factor for differentiate hydrological units in ungauged and remote areas.

This parameter synthesises the spatial relation existing between the drainage area and the river length. It represents a first descriptive data of the studied basins.

TMUs	Drainage basins	Area (Km^2)	Length (Km)	Drainage Density
Kinangop	*Karati*	154.00	38.40	**0.25**
Plateau	*Nyamamiti*	86.00	19.70	**0.23**
	CEburru	15.00	29.85	**1.98**
Mountains	*Marmanet*	150.00	151.40	**1.01**
	Ngathi	33.20	44.00	**1.33**
	WEburru	25.00	14.67	**0.59**
Volcanic	*oserian*	6.50	7.40	**1.14**
Complex	*kongoni*	3.80	7.60	**1.96**
	kongoni2	0.80	1.20	**1.55**
	kongoni3	1.90	1.83	**0.93**
Rift	*marula*	2.80	1.65	**0.59**
Valley	*NWLongonot*	20.80	14.50	**0.70**

Table 5.1. Showing the basic physical characteristics of the estudied basin.

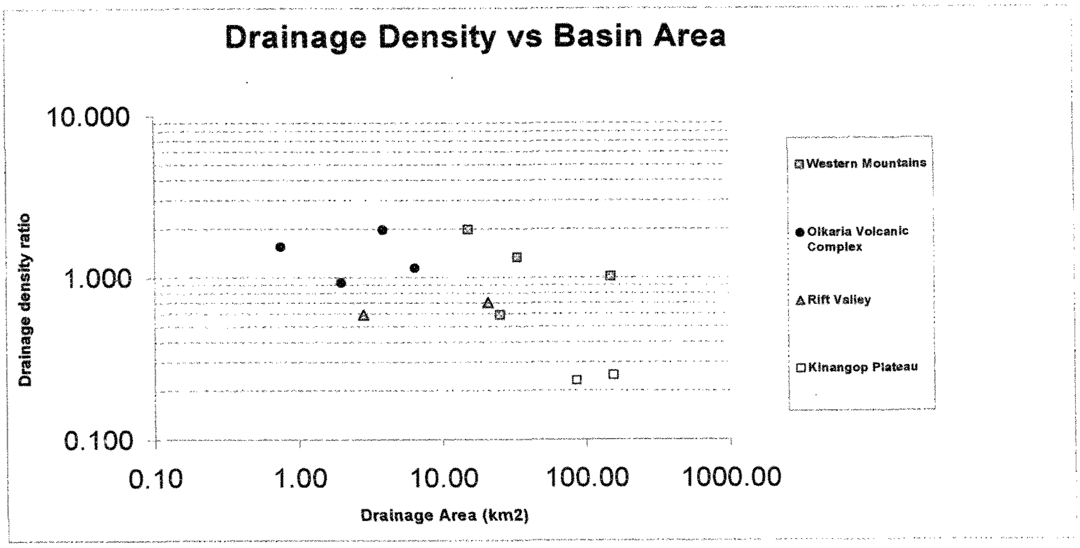


Figure 5.1 Relation between basin areas and drainage density

From the graph a correlation line could be plotted with a gentle negative slope. From small areas with high density the trend decreases to bigger basins with lower drainage densities. The Olkaria volcanic complex unit shows the highest drainage density of the study area. This means that compared with the other areas this unit is interested by a lot of runoff.

Although the Marmonet catchment occupies a relatively huge area, its drainage density value is quite important. This river flows through deposited and fine volcanic materials (mainly Eburru and Akira Pumices). In this unit the smallest catchment show the highest densities. In the other hand the Rift valley and the Kinangop basins show a low drainage density, while it decreases with big drainage areas. In the Kinangop plateau the tendency is different: small area-low density, big area-higher density.

Western Mountains and the Kinangop Plateau, both Rift margins, have a clear different hydrological behaviour. The geopedological composition marks the difference. While the western mountains erode porous and soft volcanic ash depostion (pumice), the Kinangop Platform is compossed by welded tuff, more strong and less erodible than the previous one. The relieve distribution insert a different response between the unit. While the Mountains are compossed by steepy hillsides coming from the Mau escarpment, the Kinangop plateau, as its name expresses, is gently inclined to the north. Only the fault line scarps save the altitudinal gradient from the rift valley to this elevated area.

It can be stated that this simple parameter clearly differentiates the units from an hydrological point of view, despite the reduced number of the studied dentities.

5.2. Peak discharge vs. drainage area

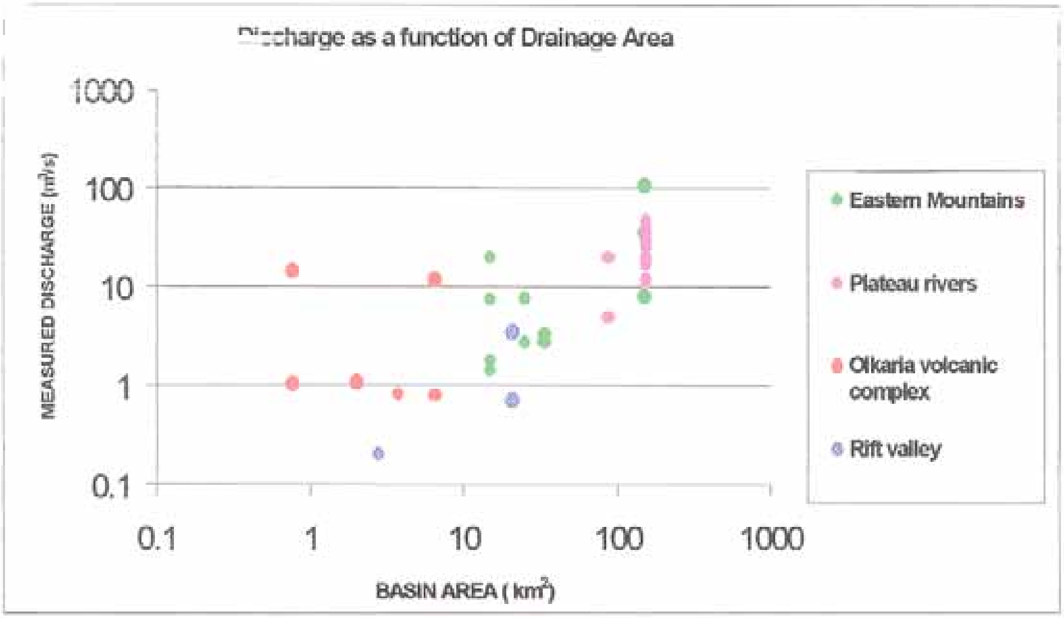


Figure 5.2 Peak discharge Vs drainage basin area

Each unit is distributed following a certain trendline. The Olkaria rivers are grouped in a semy horizontal trendline. The other groups show a higher angle in the trend but are located and distributed differently.

The rivers of the Olkaria volcanic complex that flow in steep and relatively more impervious terrain express higher discharge values compared to the other units. Furthermore their channel length is relatively short.

Kinangop Plateau and Western Mountain values appear very close to each other, but the angle drown between the discharge values seem to be a little different. For a more wide differentiation and interpretation more measurements should be done.

The Rift Valley basins, located in lacustrine and volcanic sediments, show the smallest peak discharges. There exists a high infiltration rate produced by the combined action of soils and vegetation (mainly shrubs).

Some points are vertically distributed because for the same catchment the discharges vary from their seasonal magnitude to their maximal peak discharge.

It can be outlined that the measured discharges don't correspond with the areas that are related

5.3. Rational formula

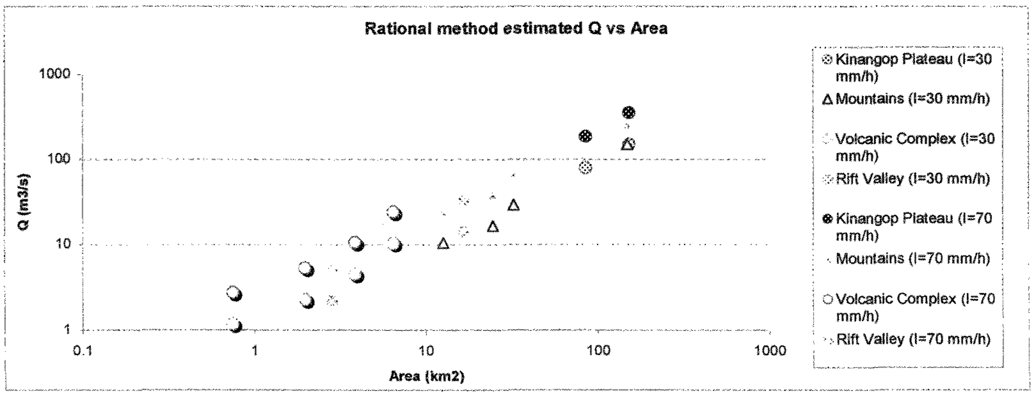
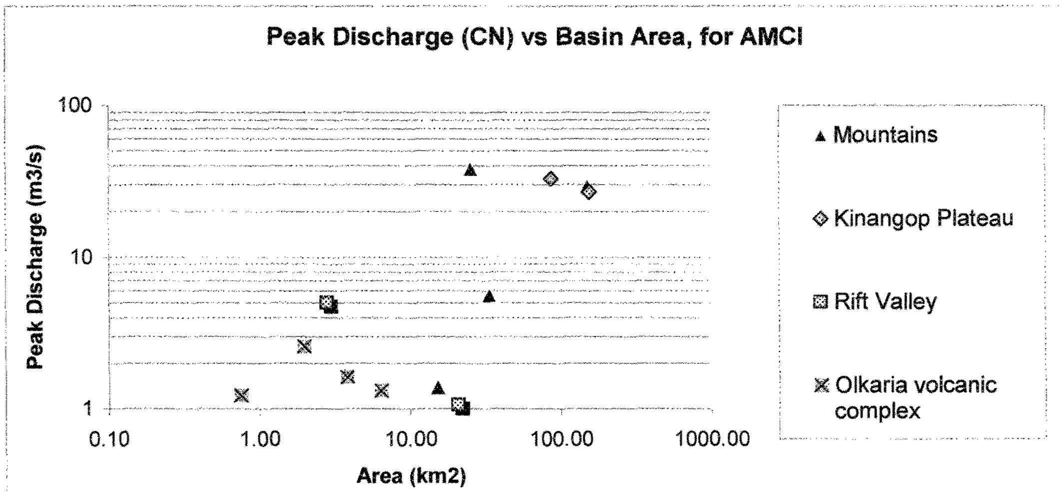


Figure 5.3 Drainage Basin Area vs estimated peak discharge.

As can be appreciate in the graph, the rational method shows a linear relation between the discharge and the basin area. No possible relationship can be concluding from those data with the Terrain Units. The linearity clearly shows the dependency of the estimations in the size of the basins. The discharges seem to group based on the area of the basin. Three major groups and an issolated basin can be differentiated.

The assumptions of this formula (the same rainfall intensity for all the catchment, and rainfall duration equal to the time of concentration) can only be fulfilled by the small basins of the Olkaria and the Rift Valley units. The estimations in those areas are more reliable. There is a clear difference between the estimation of the smallest basin and the other rivers.

5.4.The SCS Curve Number Method



Some kind of relationships between the TMUs and the peak discharges estimeted with the method can be considered. Each unit behave relatively in the same way. The influence of the CN distributed value seems to be very high.

The highest values correspond with the Kinangop Plateau, where less permeable soil exist (especially in the upper Karati area) and more agriculture areas exist. The method considers this cover type as a very impermeable one. This condition may be correct for US rural fields, but in the research area it may overestimate the surface runoff.

By the other hand the method can explain the high infiltration rates that govern the Naivasha basin. The lowest estimations are reflected in the Rift Valley area, were the infiltration it may be the highest and where the subsurface runoff is a principal hydrological process.

In the mountainous area there exist an overestimation of the runoff values for the W_Eburru basin, with more discharge than the Marmanet one. Again the land cover influence is quite big. The Marmanet basin has a dense and extense forest . The method considers this cover as a very permeable one.

The method can demonstrate the especial combination of land cover and soil types in the study area, where a big rate of infiltration exists.

It has to be considered the possibility of taking into account the Antecedent Moisture Conditions of the soils. The AMC I condition is the more usual one in the area. By the other hand the AMC II and III conditions can happen with long rain extreme conditions.

The estimations for the AMC II condition can be considered as the maximum peak flows of the area, despite some values are overestimated. The AMC III condition gives a very big overestimation of the runoff.

This method gives relatively good estimations. By its application the high infiltration governing the hydrological cycle can be described.

5.4.2. Synthetic Triangular Hydrograph

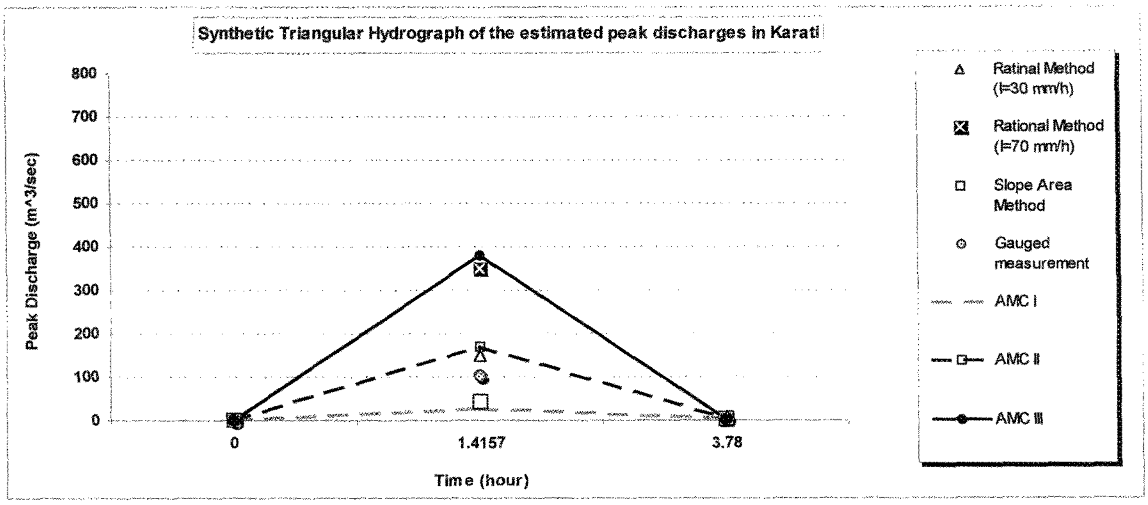


Figure 5.5. Synthetic Triangular Hydrograph showing the different calculated peak discharges.

This graph summarizes all the applied methods to estimate the peak runoff in the Naivasha area. The Karati river was selected because is the only one with some gauged data (discontinuous series). Therefore we can compare the empirical method estimations, the field measurements and the gauged data.

The gauged data was the maximum of a serie of 40 years. In November of 1961 the Karati gauge station measured 102 m^3 /s. This data coincide with planetary climatic variations, given by the Southern Oscillation, best known as "El Niño". This data cannot be considered as an absolute one because it only depends in the years of measurements.
The slope area estimation gives a value of 40 m^3 /s.

The slope area method estimation and the AMC I seem to be in the same trend, while the AMC II and the rational method values are close to the gauged data. In this sense we can conclude that the slope are method gives the usual value of the rainny season discharge. This is quite well correlated with the CN AMC I estimation. The other estimations are suitable for estimating extreme runoff events.

Terrain Mapping Units	Rivers	Basin Area Km²	Slope Area Q m³/s	Rational Q=C*I*A	SCS CN method AMC I Q peak	AMC III Q peak	AMC II Q peak
Western Mountains	Marmanet	150.16	98	112.00	29	228	34
	ngunyumu	33.2	3.19	29.3	6	220	86
	Weburru	25	7.53	15.7	38	57	2
	EastEburru	15.08	11	10.456	1	203	72
Rifted Plateau	Karati-61	154.45	***102***	118.47	27	380	171
	Nyamamithi	85.9	19.24	82.6	33	648	287
Rift Valley	Marula	2.8	0.2	2.21	5	196	83
	NWLongonot	20.7	3.47	19.4	1	155	55
Olkaria Volcanic Complex	Oserian	6.4	11.8	9.87	1	108	38
	Kongoni	3.8	0.8	4.46	2	91	33
	Kongoni2	0.754	1.23	1.12	1	39	16
	kongoni3	1.97	1.06	2.3	3	12	2

Table 2 Summarising the estimated peak discharges of the ungauged area. The Karati value is gauged one (Nov. 1961)

The slope area method gives the lowest estimation values except the SCS ones for a AMC I.

The Karati extreme peak discharge allow us to compare all the methods with the real events. It seems that the empirical methods estimate the discharge for the eventual runoff rates.

The relation of the estimations can be appreciated. The estimations coincide relatively for the small catchment. It is obvious that is simpler to model the processes and conditions for small catchment than for extense ones. In bigger areas, there is higher heterogeneity of the factors affecting the runoff. Complexity for runoff estimations increases with the spatial adition of elements. .

Each method uses different approaches for estimating the peak runoff. It resulted interesting to see the relation between the slope area and the CN SCS methods' estimations with the TMUs. This proves the correctness of the Hydrological units delimitation. The Rational method didn't offer any kind of relation with the units.

CONCLUSIONS

The selected approach has resulted in meaningful results when characterising the hydrological response of the Terrain Units. Although the slope area method gives approximate estimations, it represents a valid scientific approach to relate landscape units with peak flow values. Despite the reduced amount of measured basin the method still gave meaningful information for the hydrological characterisation of the TMUs.

The qualitative interpretation of remote sensing data is certainly one of the best approaches for defining terrain units. This technique results suitable for facing the problem of geographical data scarcity at a regional scale. The information quality obtained with aerial photography interpretation cannot be derived by any satellite image analysis procedure.

Concerning the peak discharge estimations, it is clear that the coefficient values and parameters used in empirical formulas such as the *rational method* should be calibrated to the particular environment under investigation. Most of these hydrological formulas were derived in a different or aloctone environment, mainly in the U.S., therefore their application to a peculiar area such as Lake Naivasha produces results that cannot be completely trusted and should be interpreted with duly care.

The rational formula seems to be proper for the peak estimation of small catchments, as those of the Olkaria Volcanic Complex. The assumptions of the method can be fulfilled in those basins. The bigger the drainage area sizes the more inaccurate results we get.

Moreover some numerical methods applied in this study were set for small watersheds ($<1 km^2$).
In this sense it can be stated that the estimated discharge data for small basins located in the northern part of the Olkaria volcanic complex and inside the Rift valley are more reasonable.

For bigger drainage basins part of the runoff reaches the outlet too late to contribute to the peak flow, therefore the time of concentration will be greater than the lag time of the peak flow.

It has to be noted that the rational formula has been used in hydrology for more than a century. This explains the validity of old procedures for relating precipitation to runoff and thus the clear difficulty of quantitatively describe this complex process.

The *Curve Number method* resulted in fair runoff estimations for dry moisture condition, which apply for the study area. The predicted values increase consistently when higher moisture is considered.

The results of the applied empirical methods are based on the physiographic characteristics of the drainage basins such as area, channel length, average slope, etc.... However by carefully analysing particular morphological features, e.g. the width of inactive riverbeds, it seems to be fair to assume that they were generated during a different climatic context, when much more precipitation was occurring. Therefore it can be concluded that the hydrological response of the area at present doesn't correspond to the potential runoff that is related to its morphological characteristics.

A deeper historical analysis leads to the following facts. Due to late Quaternary hydro-climatic oscillations the lake experienced a succession of distinct phases. During late Pleistocene and early Holocene (between 11,000-10,000 years BC and 8,000-7,000 years BC) there were high water levels. The recent period represents the arid phase of this cyclic climatic. Many signs strength the thesis that lake Naivasha represents a fossil hydrological system:

- the western lacustrine area is now dry and act as a sporadic water storage
- large alluvial fans and gullies are covered by vegetation and thus are inactive
- there is a paleo-outlet in the southern part of the lake
- the location and paths of the ephemeral rivers are identical of those followed by important rivers in the past; they end in the lacustrine dried areas namely the Ndabibi plain and in the Rift valley area close to the lake; only the Karati river and some few other channels reach the actual lake

The interesting observation that can be derived from this work is the awareness that these intermittent rivers can show sudden flashy behaviour and become active again, serving as preferential paths for flood transmission. The estimated peak discharges for these rivers using empirical formulas correspond to a return time of 40 years (e.g. in 1961 the Karati river had a peak of 102 m^3/s). Therefore this fossil hydrological system is not completely inactive and it has to be carefully analysed and studied when decisions for future territorial planning will be made.

It can be admitted that here is a dearth of information about the processes concerning ephemeral rivers, therefore the adoption of stochastic methods or other analytical methods is difficult for this type of rivers. It is rare that planned and structured measurements are made in this context; ephemeral hydrology is still remains a pioneering territory.

The multidisciplinary approach is considered a proper way for dealing with this kind of environmental conditions, where climate, hydrology and geomorphology interact in such a close (intense) relation, despite being esporadically.

There is a lack of hydrological processes information that take place in Africa. The available are scarce and therefore the documental information is very little. The applied method can be considered as proper one for handling this difficulties in such conditions.

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Appendix

APPENDIX 1

Hydrologic Soil Groups

Soil Group A	Represents soils having a low runoff potential due to high infiltration rates. These soils consist primarily of deep, well-drained sands and gravels.
Soil Group B	Represents soils having a moderately low runoff potential due to moderate infiltration rates. These soils consist primarily of moderately deep to deep, moderately well-drained to well-drained soils with moderately fine to moderately coarse textures.
Soil Group C	Represents soils having a moderately high runoff potential due to slow infiltration rates. These soils consist primarily of soils in which a layer exists near the surface that impedes the downward movement of water, or soils with moderately fine to fine texture.
Soil Group D	Represents soils having a high runoff potential due to very slow infiltration rates. These soils consist primarily of clays with high water tables, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious parent material.

Table 2.3. The hydrological soil grups.

Appendix 2, roughness coefficients

Values of Runoff Coefficient (C) for Rational Formula

Land Use	C	Land Use	C
Business: Downtown areas Neighborhood areas	0.70 - 0.95 0.50 - 0.70	Lawns: Sandy soil, flat, 2% Sandy soil, avg., 2-7% Sandy soil, steep, 7% Heavy soil, flat, 2% Heavy soil, avg., 2-7% Heavy soil, steep, 7%	0.05 - 0.10 0.10 - 0.15 0.15 - 0.20 0.13 - 0.17 0.18 - 0.22 0.25 - 0.35
Residential: Single-family areas Multi units, detached Munti units, attached Suburban	0.30 - 0.50 0.40 - 0.60 0.60 - 0.75 0.25 - 0.40	Agricultural land: Bare packed soil *Smooth *Rough Cultivated rows *Heavy soil, no crop *Heavy soil, with crop *Sandy soil, no crop *Sandy soil, with crop Pasture *Heavy soil *Sandy soil Woodlands	0.30 - 0.60 0.20 - 0.50 0.30 - 0.60 0.20 - 0.50 0.20 - 0.40 0.10 - 0.25 0.15 - 0.45 0.05 - 0.25 0.05 - 0.25
Industrial: Light areas Heavy areas	0.50 - 0.80 0.60 - 0.90	Streets: Asphaltic Concrete Brick	0.70 - 0.95 0.80 - 0.95 0.70 - 0.85
Parks, cemeteries	0.10 - 0.25	Unimproved areas	0.10 - 0.30
Playgrounds	0.20 - 0.35	Drives and walks	0.75 - 0.85
Railroad yard areas	0.20 - 0.40	Roofs	0.75 - 0.95

APPENDIX 3: Rational Method Runoff Coefficients

Drainage basin	Land cover LC	RunoffCoef C	Area Km2 A	Discharge in m^3/s Q I = 30 mm/h	Q I= 48 mm/h	Q I=70 mm/h
Karati	agriculture	0.12	98.72	98.73	157.96	230.37
Karati	forest	0.07	8.52	4.97	7.95	11.60
Karati	acacia	0.08	0.45	0.30	0.48	0.70
Karati	papyrus	0.4	0.02	0.07	0.11	0.16
Karati	shrubs	0.09	15.96	11.97	19.15	27.93
Karati	bare soil and sparse vegetation	0.1	26.3	21.92	35.07	51.14
Karati	urban	0.85	1.29	9.14	14.62	21.32
Karati	greenhouse	0.78	0.49	3.19	5.10	7.43
Karati	rural settlement	0.75	0.01	0.06	0.10	0.15
			151.76	**150.34**	**240.54**	**350.79**
Marmanet	agriculture	0.12	30.49	30.49	48.79	71.15
Marmanet	forest	0.07	63.8	37.22	59.55	86.85
Marmanet	acacia	0.08	0.03	0.02	0.03	0.05
Marmanet	papyrus	0.07	0	0.00	0.00	0.00
Marmanet	shrubs	0.09	47.73	35.80	57.28	83.53
Marmanet	bare soil and sparse vegetation	0.1	6.09	5.08	8.12	11.84
Marmanet	greenhouse	0.78	0.02	0.13	0.21	0.30
Marmanet	lava	0.2	0.06	0.10	0.16	0.23
			148.22	**150.34**	**174.14**	**253.96**
WEburru	agriculture	0.12	1.98	2.00	3.19	4.66
WEburru	forest	0.07	15.7	9.23	14.77	21.54
WEburru	shrubs	0.09	4.75	3.59	5.75	8.38
WEburru	bare soil and sparse vegetation	0.1	2.06	1.73	2.77	4.04
WEburru	lava	0.1	0	0.00	0.00	0.00
			24.49	**16.55**	**26.48**	**38.61**
CEburru	agriculture	0.12	2.45	2.47	3.95	5.76
CEburru	forest	0.07	0.14	0.08	0.13	0.19
CEburru	papyrus	0.05	0	0.00	0.00	0.00
CEburru	shrubs	0.09	6.14	4.64	7.43	10.83
CEburru	bare soil and sparse vegetation	0.1	3.93	3.30	5.28	7.70
			12.66	**10.49**	**16.79**	**24.49**
Ngathi	agriculture	0.12	11.36	11.45	18.32	26.72
Ngathi	forest	0.07	1.54	0.91	1.45	2.11
Ngathi	shrubs	0.09	7.91	5.98	9.57	13.95
Ngathi	bare soil and sparse vegetation	0.1	11.57	9.72	15.55	22.68

Ngathi	rural settlement	0.75	0.16	1.01	1.61	2.35
			32.54	**29.06**	**46.50**	**67.81**
Nyamamiti	agriculture	0.12	48.51	48.90	78.24	114.10
Nyamamiti	forest	0.07	1.77	1.04	1.67	2.43
Nyamamiti	shrubs	0.09	6.23	4.71	7.54	10.99
Nyamamiti	bare soil and sparse vegetation	0.1	28.98	24.34	38.95	56.80
Nyamamiti	rural settlement	0.75	0	78.99	126.39	184.31
			85.49	**78.99**	**126.39**	**184.31**
Oserian	agriculture	0.12	1.01	1.02	1.63	2.38
Oserian	forest	0.07	0.05	0.03	0.05	0.07
Oserian	acacia	0.08	0.09	0.06	0.10	0.14
Oserian	papyrus	0.05	0.05	0.02	0.03	0.05
Oserian	shrubs	0.09	4.23	3.20	5.12	7.46
Oserian	bare soil and sparse vegetation	0.1	0.14	0.12	0.19	0.27
Oserian	greenhouse	0.78	0.9	5.90	9.43	13.76
Oserian	lava	0.2	0.01	0.02	0.03	0.04
			6.48	**10.36**	**16.57**	**24.17**
Kongoni	agriculture	0.12	1.25	1.26	2.02	2.94
Kongoni	forest	0.07	0.01	0.01	0.01	0.01
Kongoni	shrubs	0.09	1.64	1.24	1.98	2.89
Kongoni	bare soil and sparse vegetation	0.1	0.75	0.63	1.01	1.47
Kongoni	greenhouse	0.78	0.21	1.38	2.20	3.21
			3.86	**4.51**	**7.22**	**10.53**
NWLongonot	agriculture	0.12	0.23	0.23	0.37	0.54
NWLongonot	forest	0.07	0	0.00	0.00	0.00
NWLongonot	shrubs	0.09	13.96	10.55	16.89	24.63
NWLongonot	bare soil and sparse vegetation	0.1	2.08	1.75	2.80	4.08
NWLongonot	greenhouse	0.78	0.26	1.70	2.73	3.97
			16.53	**14.24**	**22.78**	**33.22**
Marula	agriculture	0.12	0.07	0.07	0.11	0.16
Marula	shrubs	0.09	0.01	0.01	0.01	0.02
Marula	bare soil and sparse vegetation	0.09	2.73	2.06	3.30	4.82
Marula	greenhouse	0.78	0.01	0.07	0.10	0.15
			2.82	**2.21**	**3.53**	**5.15**
Kongoni2	agriculture	0.12	0.24	0.24	0.39	0.56
Kongoni2	shrubs	0.09	0.06	0.05	0.07	0.11
Kongoni2	bare soil and sparse vegetation	0.1	0.36	0.30	0.48	0.71
Kongoni2	greenhouse	0.78	0.09	0.59	0.94	1.38

			0.75	**1.18**	**1.89**	**2.75**
kongoni3	agriculture	0.12	0.86	0.87	1.39	2.02
kongoni3	acacia	0.08	0	0.00	0.00	0.00
kongoni3	shrubs	0.09	0.5	0.38	0.60	0.88
kongoni3	bare soil and sparse vegetation	0.15	0.56	0.71	1.13	1.65
kongoni3	greenhouse	0.78	0.05	0.33	0.52	0.76
			1.97	**2.28**	**3.64**	**5.32**

Appendix 4: Curve Number designation for different basins

		AMC II	AMC I	AMC III			AMC II	AMC I	AMC III
	hydrobas	**cn**	**cn**	**cn**	**CN % area**	**Area km2**	**CN x Area**	**CN x Area**	**CN x Area**
Kr * 35	**Karati**	35	18	55	3.93391	5.9571	208.499	107.228	327.6
Kr * 55	**Karati**	55	35	74	0.28528	0.432	23.76	15.12	31.97
Kr * 58	**Karati**	58	38	76	0.29776	0.4509	26.1522	17.1342	34.27
Kr * 61	**Karati**	61	41	77	7.70259	11.664	711.504	478.224	898.1
Kr * 66	**Karati**	66	46	82	6.25836	9.477	625.482	435.942	777.1
Kr * 70	**Karati**	70	51	85	12.5637	19.0251	1331.76	970.28	1617
Kr * 71	**Karati**	71	52	85	43.2843	65.5452	4653.71	3408.35	5571
Kr * 72	**Karati**	72	53	86	2.78744	4.221	303.912	223.713	363
Kr * 74	**Karati**	74	55	88	0.32035	0.4851	35.8974	26.6805	42.69
Kr * 79	**Karati**	79	61	90	6.63398	10.0458	793.618	612.794	904.1
Kr * 80	**Karati**	80	63	91	0.00297	0.0045	0.36	0.2835	0.41
Kr * 81	**Karati**	81	65	91	0.04458	0.0675	5.4675	4.3875	6.143
Kr * 85	**Karati**	85	71	93	15.4682	23.4234	1990.99	1663.06	2178
Kr * 86	**Karati**	86	72	94	0.41544	0.6291	54.1026	45.2952	59.14
Kr * 91	**Karati**	91	79	96	0.00119	0.0018	0.1638	0.1422	0.173
					100	**151.43**	**10765.4**	**8008.64**	**12812**
							71.0917	**52.8869**	**84.6**
mar * 25	**marmanet**	25	12	43	0.04193	0.0621	1.5525	0.7452	2.67
mar * 35	**marmanet**	35	18	55	43.0522	63.7686	2231.9	1147.83	3507
mar * 40	**marmanet**	40	22	60	0.00061	0.0009	0.036	0.0198	0.054
mar * 42	**marmanet**	42	24	62	0.01823	0.027	1.134	0.648	1.674
mar * 61	**marmanet**	61	41	77	32.2129	47.7135	2910.52	1956.25	3674
mar * 63	**marmanet**	63	43	80	0.0158	0.0234	1.4742	1.0062	1.872
mar * 70	**marmanet**	70	51	85	4.10385	6.0786	425.502	310.009	516.7
mar * 71	**marmanet**	71	52	85	20.5545	30.4452	2161.61	1583.15	2588
					100	**148.119**	**7733.73**	**4999.67**	**10292**
							52.2129	33.7543	69.48

web * 25	**WEburru**	25	12	43	0.00368	0.0009	0.0225	0.0108	0.039
web * 35	**WEburru**	35	18	55	64.1045	15.6951	549.329	282.512	863.2
web * 61	**WEburru**	61	41	77	19.3832	4.7457	289.488	194.574	365.4
web * 70	**WEburru**	70	51	85	8.4142	2.0601	144.207	105.065	175.1
web * 71	**WEburru**	71	52	85	8.0944	1.9818	140.708	103.054	168.5
					100	**24.4836**	**1123.75**	**685.215**	**1572**
							45.8982	27.9867	64.22
ceb * 35	**CEburru**	35	18	55	1.12456	0.1422	4.977	2.5596	7.821
ceb * 40	**CEburru**	40	22	60	0.02847	0.0036	0.144	0.0792	0.216
ceb * 55	**CEburru**	55	35	74	13.7367	1.737	95.535	60.795	128.5
ceb * 61	**CEburru**	61	41	77	32.4698	4.1058	250.454	168.338	316.1
ceb * 66	**CEburru**	66	46	82	9.82918	1.2429	82.0314	57.1734	101.9
ceb * 68	**CEburru**	68	48	84	20.4057	2.5803	175.46	123.854	216.7
ceb * 70	**CEburru**	70	51	85	1.64413	0.2079	14.553	10.6029	17.67
ceb * 71	**CEburru**	71	52	85	3.93594	0.4977	35.3367	25.8804	42.3
ceb * 72	**CEburru**	72	53	86	2.24199	0.2835	20.412	15.0255	24.38
ceb * 77	**CEburru**	77	59	89	5.53025	0.6993	53.8461	41.2587	62.24
ceb * 79	**CEburru**	79	61	90	9.05338	1.1448	90.4392	69.8328	103
						12.645	**823.189**	**575.4**	**1021**
							65.0999	45.5041	80.74
Ngun * 35	**ngunyumu**	35	18	55	4.74463	1.5417	53.9595	27.7506	84.79
Ngun * 55	**ngunyumu**	55	35	74	0.03047	0.0099	0.5445	0.3465	0.733
Ngun * 61	**ngunyumu**	61	41	77	23.5625	7.6563	467.034	313.908	589.5
Ngun * 66	**ngunyumu**	66	46	82	0.34622	0.1125	7.425	5.175	9.225
Ngun * 68	**ngunyumu**	68	48	84	0.29637	0.0963	6.5484	4.6224	8.089
Ngun * 70	**ngunyumu**	70	51	85	35.1983	11.4372	800.604	583.297	972.2
Ngun * 71	**ngunyumu**	71	52	85	30.0493	9.7641	693.251	507.733	829.9
Ngun * 72	**ngunyumu**	72	53	86	0.65644	0.2133	15.3576	11.3049	18.34
Ngun * 77	**ngunyumu**	77	59	89	5.00776	1.6272	125.294	96.0048	144.8
Ngun * 79	**ngunyumu**	79	61	90	0.05263	0.0171	1.3509	1.0431	1.539
Ngun * 80	**ngunyumu**	80	63	91	0.0554	0.018	1.44	1.134	1.638
						32.4936	**2172.81**	**1552.32**	**2661**
							66.8689	47.7731	81.89
Nyamamiti * 35	**Nyamamiti**	35	18	55	2.07061	1.7694	61.929	31.8492	97.32
Nyamamiti * 61	**Nyamamiti**	61	41	77	6.95644	5.9445	362.615	243.725	457.7
Nyamamiti * 66	**Nyamamiti**	66	46	82	1.79993	1.5381	101.515	70.7526	126.1
Nyamamiti * 70	**Nyamamiti**	70	51	85	24.1037	20.5974	1441.82	1050.47	1751
Nyamamiti * 71	**Nyamamiti**	71	52	85	54.9374	46.9458	3333.15	2441.18	3990
Nyamamiti * 72	**Nyamamiti**	72	53	86	0.31807	0.2718	19.5696	14.4054	23.37
Nyamamiti * 79	**Nyamamiti**	79	61	90	9.81063	8.3835	662.297	511.394	754.5
Nyamamiti * 80	**Nyamamiti**	80	63	91	0.00316	0.0027	0.216	0.1701	0.246
						85.4532	**5983.11**	**4363.94**	**7200**
							70.0162	51.0682	84.26

oserian * 25	**oserian**	25	12	43	0.22247	0.0144	0.36	0.1728	0.619
oserian * 40	**oserian**	40	22	60	0.04171	0.0027	0.108	0.0594	0.162
oserian * 42	**oserian**	42	24	62	0.16685	0.0108	0.4536	0.2592	0.67
oserian * 55	**oserian**	55	35	73	1.41824	0.0918	5.049	3.213	6.701
oserian * 58	**oserian**	58	38	76	1.16796	0.0756	4.3848	2.8728	5.746
oserian * 61	**oserian**	61	41	78	53.0729	3.4353	209.553	140.847	268
oserian * 63	**oserian**	63	43	80	1.00111	0.0648	4.0824	2.7864	5.184
oserian * 66	**oserian**	66	46	82	5.92325	0.3834	25.3044	17.6364	31.44
oserian * 70	**oserian**	70	51	85	1.19577	0.0774	5.418	3.9474	6.579
oserian * 71	**oserian**	71	52	85	9.73304	0.63	44.73	32.76	53.55
oserian * 72	**oserian**	72	53	86	12.2219	0.7911	56.9592	41.9283	68.03
oserian * 74	**oserian**	74	55	88	12.8476	0.8316	61.5384	45.738	73.18
oserian * 77	**oserian**	77	59	89	0.0139	0.0009	0.0693	0.0531	0.08
oserian * 79	**oserian**	79	61	90	0.9733	0.063	4.977	3.843	5.67
						6.4728	**422.987**	**296.117**	**525.6**
							65.3484	45.7479	81.2
kongoni * 35	**kongoni**	35	18	55	0.25617	0.0099	0.3465	0.1782	0.545
kongoni * 61	**kongoni**	61	41	78	42.3381	1.6362	99.8082	67.0842	127.6
kongoni * 63	**kongoni**	63	43	80	5.44946	0.2106	13.2678	9.0558	16.85
kongoni * 70	**kongoni**	70	51	85	19.5156	0.7542	52.794	38.4642	64.11
kongoni * 71	**kongoni**	71	52	85	32.4406	1.2537	89.0127	65.1924	106.6
						3.8646	**255.229**	**179.975**	315.7
							66.0429	46.5701	81.69
NWLongonot * 25	**NWLongonot**	25	12	43	0.00546	0.0009	0.0225	0.0108	0.039
NWLongonot * 55	**NWLongonot**	55	35	73	27.856	4.5954	252.747	160.839	335.5
NWLongonot * 61	**NWLongonot**	61	41	78	19.7709	3.2616	198.958	133.726	254.4
NWLongonot * 63	**NWLongonot**	63	43	80	1.55483	0.2565	16.1595	11.0295	20.52
NWLongonot * 70	**NWLongonot**	70	51	85	9.37261	1.5462	108.234	78.8562	131.4
NWLongonot * 71	**NWLongonot**	71	52	85	1.39116	0.2295	16.2945	11.934	19.51
NWLongo	**NWLongonot**	72	53	86	36.8303	6.0759	437.465	322.023	522.5

not * 72									
NWLongo not * 79	**NWLongonot**	79	61	90	3.21877	0.531	41.949	32.391	47.79
					100	**16.497**	**1071.83**	**750.809**	1332
							64.9711	45.5118	80.72
marula * 66	**marula**	66	46	82	2.56082	0.072	4.752	3.312	5.904
marula * 72	**marula**	72	53	86	0.22407	0.0063	0.4536	0.3339	0.542
marula * 74	**marula**	74	55	88	0.28809	0.0081	0.5994	0.4455	0.713
marula * 79	**marula**	79	61	90	96.927	2.7252	215.291	166.237	245.3
					100	**2.8116**	**221.096**	**170.329**	252.4
							78.637	60.5807	89.78
kongoni2 * 61	**kongoni2**	61	41	78	2.31176	0.063	3.843	2.583	4.914
kongoni2 * 63	**kongoni2**	63	43	80	3.43461	0.0936	5.8968	4.0248	7.488
kongoni2 * 70	**kongoni2**	70	51	85	13.2431	0.3609	25.263	18.4059	30.68
kongoni2 * 71	**kongoni2**	71	52	85	8.6856	0.2367	16.8057	12.3084	20.12
						0.7542	**51.8085**	37.3221	63.2
							68.6933	49.4857	83.79
kongoni3 * 42	**kongoni3**	42	24	62	0.03303	0.0009	0.0378	0.0216	0.056
kongoni3 * 61	**kongoni3**	61	41	78	18.2959	0.4986	30.4146	20.4426	38.89
kongoni3 * 63	**kongoni3**	63	43	80	1.84941	0.0504	3.1752	2.1672	4.032
kongoni3 * 70	**kongoni3**	70	51	85	20.4095	0.5562	38.934	28.3662	47.28
kongoni3 * 71	**kongoni3**	71	52	85	31.7371	0.8649	61.4079	44.9748	73.52
					100	**2.7252**	**133.97**	**95.9724**	163.8
							49.1595	35.2166	60.1

Appendix 5, Rational method estimations

Terrain Mapping Units	Rivers	AREA Km^2	RATIONAL METHOD I = 30 mm/h	I= 48 mm/h	I = 70 mm/h
Kinangop Plateau	*KARATI*	151.76	150	241	351
	NYAMAMATHI	85.49	79	126	184
Western Mountains	*MARMONET*	148.22	150	174	254
	W-EBURRU	24.49	17	26	39
	E-EBURRU	12.66	10	17	24
	NGATHI	32.54	29	47	68
Olkaria Volcanic Complex	*OSERIAN*	6.48	10	17	24
	KONGONI	3.86	5	7	11
	KONGONI2	0.75	1	2	3
	KONGONI3	1.97	2	4	5
Rift Valley	*MARULA*	2.82	2	4	5
	NW_LONG	16.53	14	23	33

Table 3, Peak discharges for the Rational Method, with different Rain Intensities.

Appendix 6

Terrain Mapping Units		P= 70 mm AMC I Qp (m^3 /s)	AMC III Qp (m^3 /s)	AMC II Qp (m^3 /s)
Kinangop Plateau	*Karati*	27	380	171
	Nyamamithi	33	648	287
Western Mountains	*Marmonet*	29	228	34
	Ngathi	6	220	86
	Weburru	2	57	38
	C_E_Eburru	1	203	72
Olkaria Volcanic Complex	*Oserian*	1	108	38
	Kongoni	2	91	33
	Kongoni2	1	39	16
	Kongoni3	3	12	2
Rift Valley	*NW_Longonot*	1	155	55
	Marula	5	196	83

Tabl 4Peak discharges using the SCS CN method and the unit hydrograph.

Terrain Mapping Units	P= 40 mm			
		AMC I Qp (m^3 /s)	AMC III Qp (m^3 /s)	AMC II Qp (m^3 /s)
Rifted Plateau	***Karati***	26.53	136.93	32.49
	Nyamamithi	6.39	226.30	50.64
Western Mountains	***Marmonet***	130.87	37.19	3.45
	Ngathi	6.32	71.50	11.64
	Weburru	89.85	5.21	8.52
	C_E_Eburru	11.96	63.60	7.57
Olkaria Volcanic Complex	***Oserian***	5.23	34.00	4.04
	Kongoni	3.34	29.56	3.97
	Kongoni2	0.77	13.72	2.64
	Kongoni3	13.76	0.42	1.28
Rift Valley	***NW_Longonot***	9.15	48.64	5.79
	Marula	5.62	63.67	12.36

Terrain Mapping Units	P= 70 mm			
		AMC I Qp (m^3 /s)	AMC III Qp (m^3 /s)	AMC II Qp (m^3 /s)
Kinangop Plateau	***Karati***	27	380	171
	Nyamamithi	33	648	287
Western Mountains	***Marmonet***	29	228	34
	Ngathi	6	220	86
	Weburru	2	57	38
	C_E_Eburru	1	203	72
Olkaria Volcanic Complex	***Oserian***	1	108	38
	Kongoni	2	91	33
	Kongoni2	1	39	16
	Kongoni3	3	12	2
Rift Valley	***NW_Longonot***	1	155	55
	Marula	5	196	83

Tabl 4Peak discharges using the SCS CN method and the unit hydrograph.

Appendix7, Times of concentration (rational method and SCS)

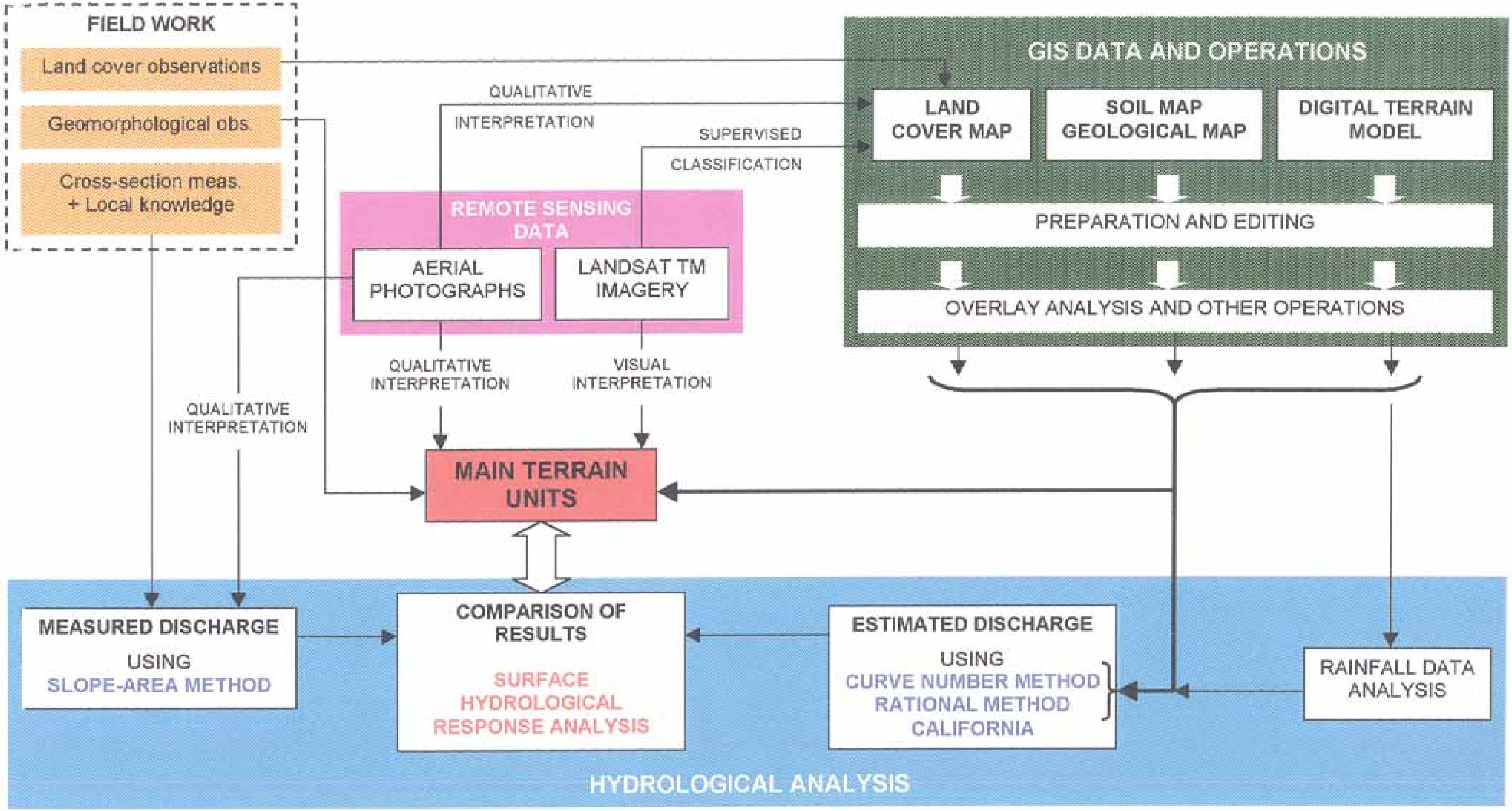
		California M.	SCS M.
	Area Km2	Tc hr	Tc
Karati	154.45	4.47	3.87
Nyamamithi	85.90	1.38	1.20
Marmanet	150.16	2.83	2.45
ngunyumu	33.20	1.43	1.24
Weburru	25.00	1.27	1.10
EastEburru	15.08	0.67	0.58
Oserian	6.40	0.53	0.46
Kongoni	3.80	0.39	0.35
Kongoni2	0.75	0.20	0.18
Kongoni3	1.97	0.32	0.28
NWLongonot	20.70	1.19	1.04
Marula	2.80	0.31	0.27

Appendix 8, Marmanet Cross section data

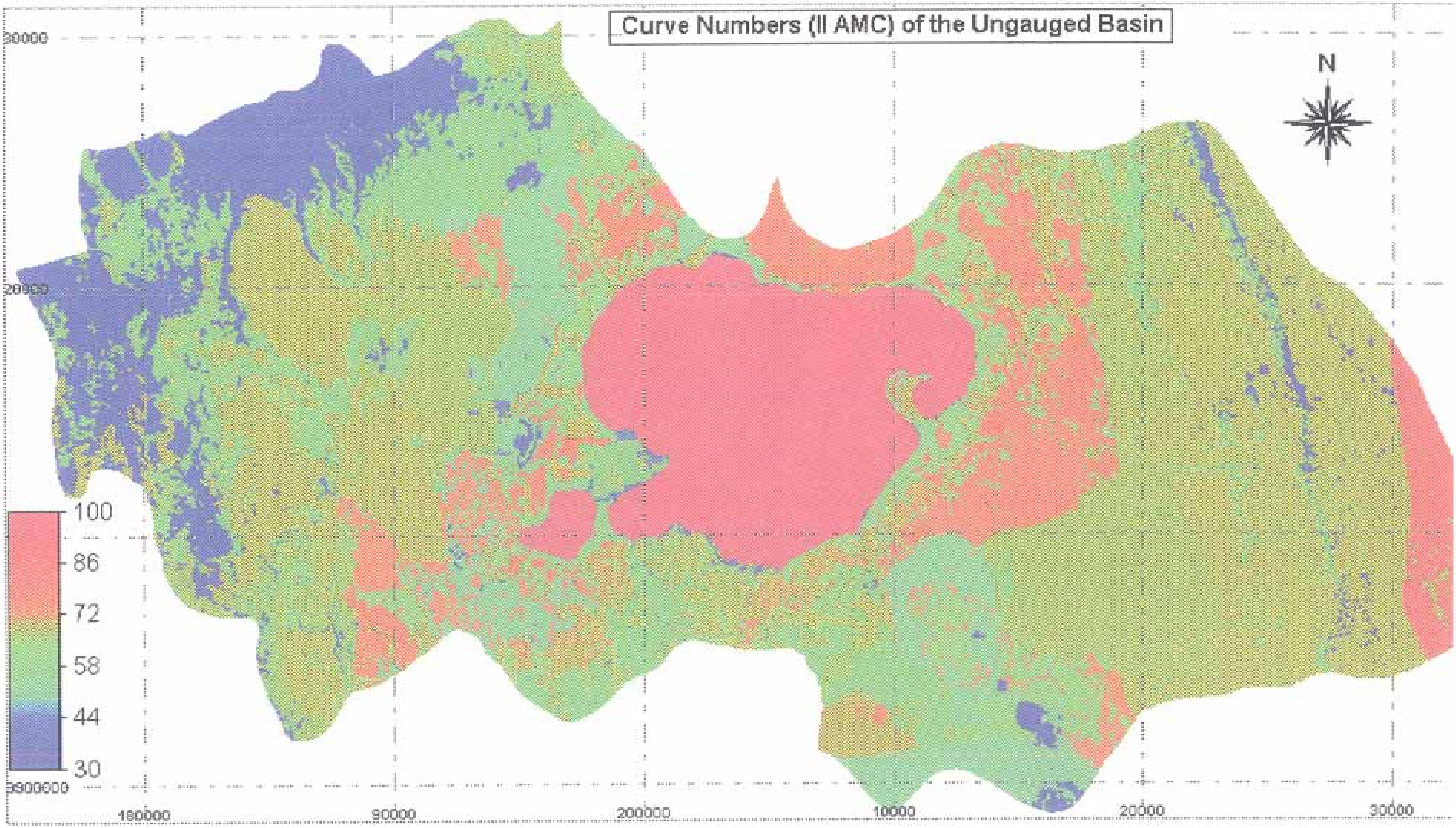
MARMANET
RIVER
188690-9914252
Measurements taken from the Marmonet mouth, evergreen ephimeral wetland vegetation in the rive
bed
Cutting the trees for CHAKO, vegetable carbon production

1981 m			1982			31.8 m	1982.6
Depth	Distance		Depth	Distance		Depth	Distance
0.431	0		0.37	0		0.109	0
2.47	30.5		0.58	9		0.65	14
2.95	41	0.2	0.62	17.1		1.71	17.5
3.49	43		1.982	23		4.21	24
3.55	44.5		2.34	27.99		4.49	26
3.45	46.9		2.94	29.9		0.07	
3.26	48.5		3.14	36		0.52	3.5
3.211	49.3		2.98	38		2.17	7
2.82	51.5	0.15	2.6	41.7		2.3	9
2.7	54.5		2.2	45		2.79	9.5
3.01	61		2.15	53.1		3	11
3.06	74		1.93	67		3.67	13
3.17	92		0.6	80		3.55	
3.13	102					3.26	
2.96	122	0.2	Measurement taken on the terrace of the river, first one.			2.435	
2.83	145		Bed river coord.: 1887429914296			2.2	
2.82	154					0.27	
2.27	158						
0.8	162						
0.62	172						

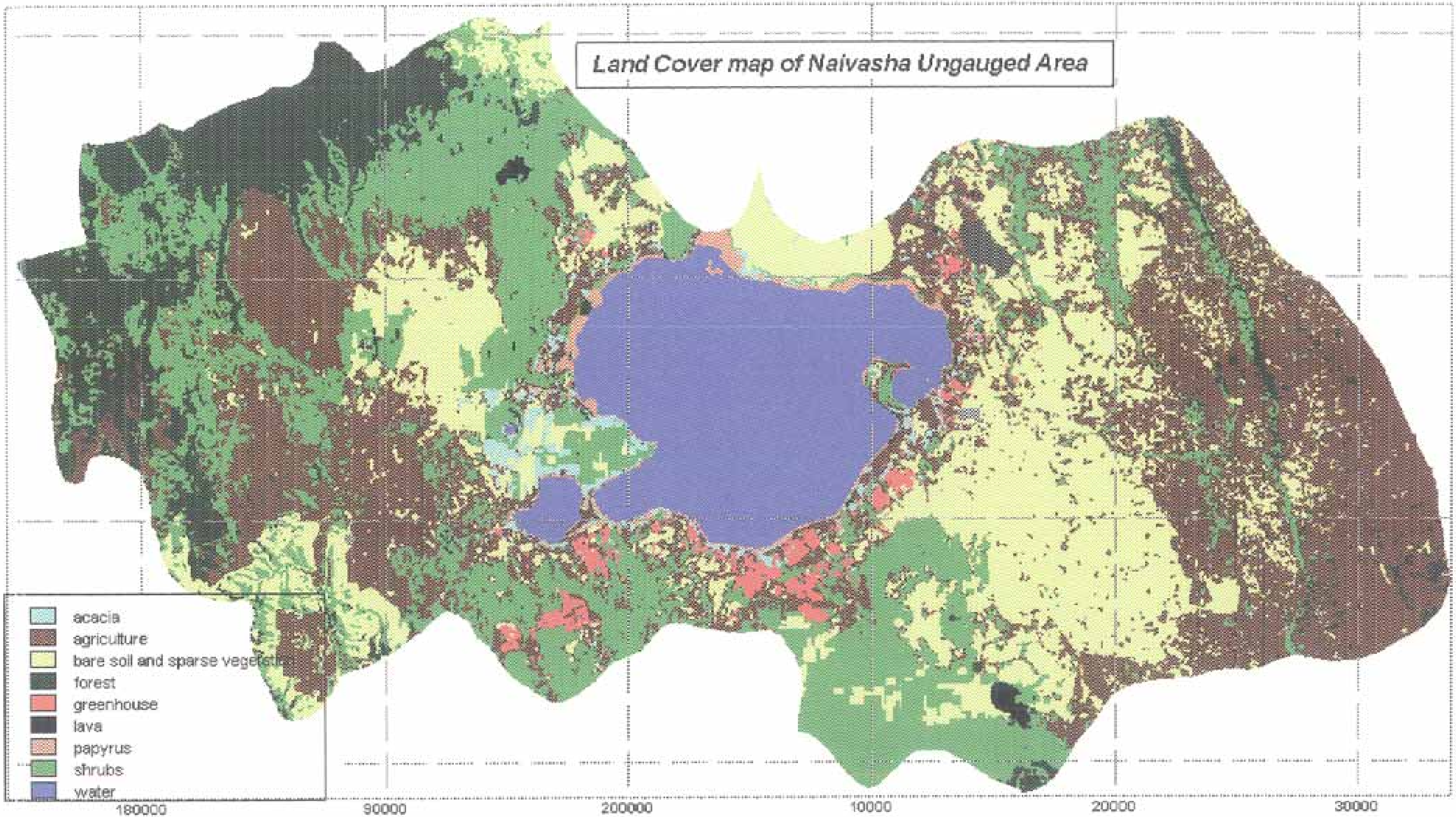
From right side of the river to the left is the measurement direction.


FIELD WORK
Land cover observations
Geomorphological obs.
Cross-section meas.
+ Local knowledge
QUALITATIVE
INTERPRETATION
SUPERVISED
CLASSIFICATION
REMOTE SENSING
DATA
AERIAL
PHOTOGRAPHS
LANDSAT TM
IMAGERY
QUALITATIVE
INTERPRETATION
VISUAL
INTERPRETATION
QUALITATIVE
INTERPRETATION
MAIN TERRAIN
UNITS
GIS DATA AND OPERATIONS
LAND
COVER MAP
SOIL MAP
GEOLOGICAL MAP
DIGITAL TERRAIN
MODEL
PREPARATION AND EDITING
OVERLAY ANALYSIS AND OTHER OPERATIONS
MEASURED DISCHARGE
USING
SLOPE-AREA METHOD
COMPARISON OF
RESULTS
SURFACE
HYDROLOGICAL
RESPONSE ANALYSIS
ESTIMATED DISCHARGE
USING
CURVE NUMBER METHOD
RATIONAL METHOD
CALIFORNIA
RAINFALL DATA
ANALYSIS
HYDROLOGICAL ANALYSIS

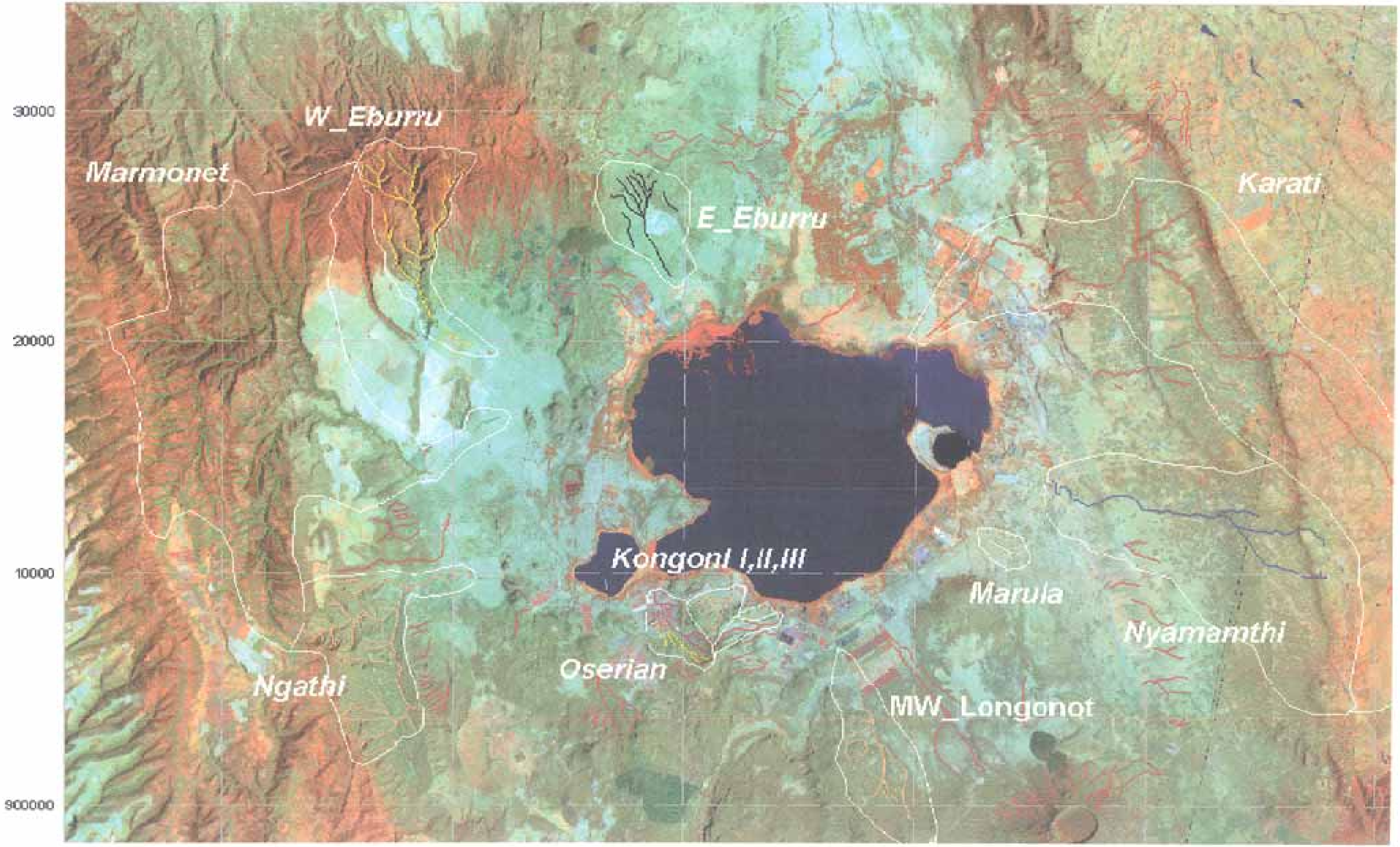
a.


Curve Numbers (II AMC) of the Ungauged Basin
N
100
86
72
58
44
30
30000
20000
9900000
180000
90000
200000
10000
20000
30000

b.

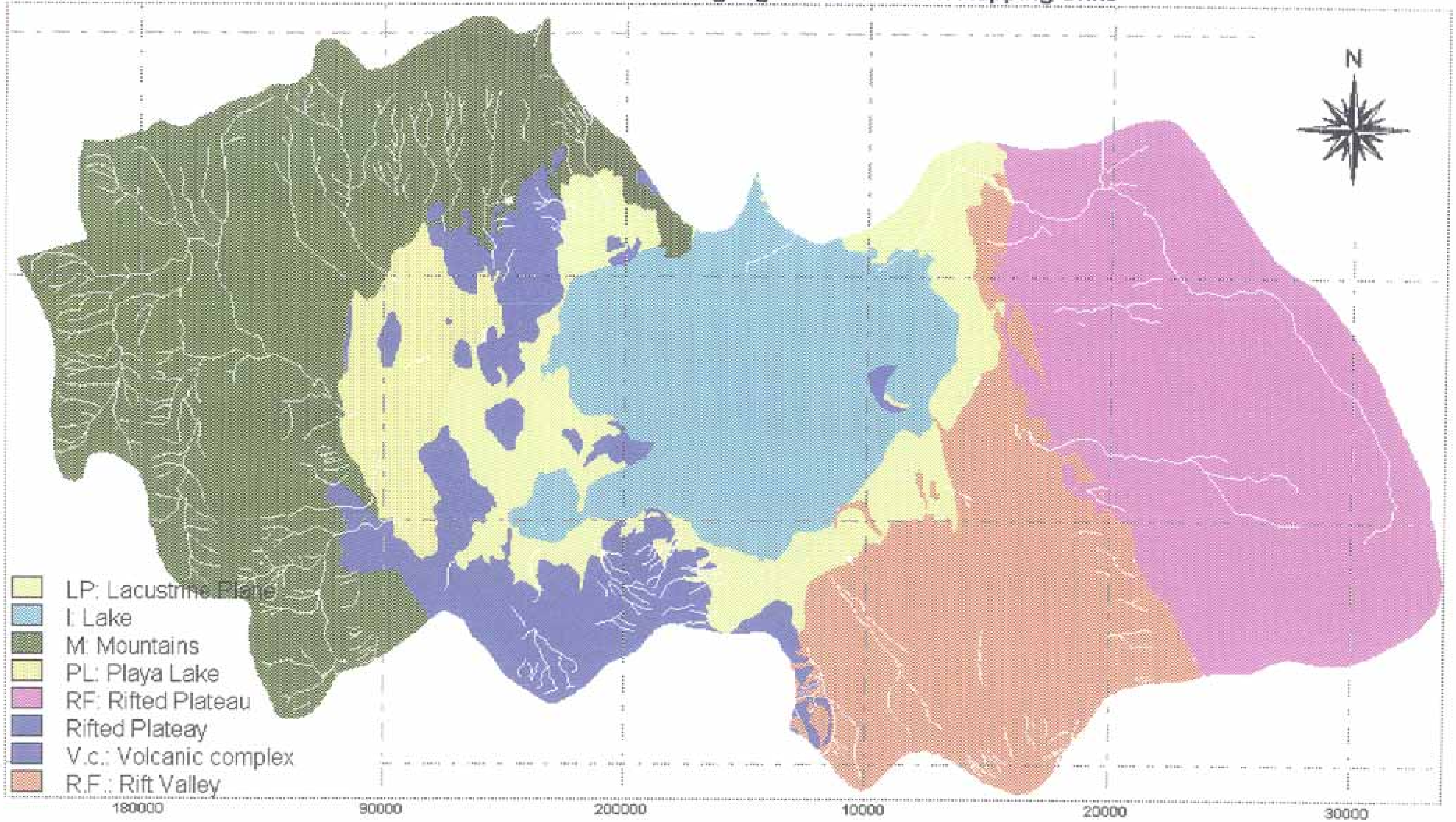

Land Cover map of Naivasha Ungauged Area
acacia
agriculture
bare soil and sparse vegetation
forest
greenhouse
lava
papyrus
shrubs
water
180000
90000
200000
10000
20000
30000

Measured drainage basins



d.

The Ungauged Basin Terrain Mapping Units



e.