Surface runoff modelling using GIS and remote sensing

Case study in Malewa catchment, Naivasha, Kenya

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By

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Dedicated to
My wife Lina , My lovely daughters Zena, and Bana

ABSTRACT

Malewa Catchment is the main sub-catchment of Naivasha Basin, its area is 1700 km^2, in general it comprises dense drainage system and particularly two main river Malewa and Turasha, therefore, it is consider the main source of water for Naivasha lake.

The relationship rainfall-runoff in a catchment is a function to the hydrologic and physiographic characteristics of it. The natural features (land-cover) and human-made features (land-use)play important role in the runoff process as well.

The study tries to analyse rainfall-runoff relationship in Malewa catchment through applying semi distributed hydrologic model SLURP in order to detect the hydrologic behaviour and response of it towards the precipitation events.

The model uses three types of data, daily time series, physiographic data, and model parameters. Daily time series comprise (rainfall, discharge, temperature, relative humidity, global radiation, and wind speed). Physiographic data have been created by TOPAZ. Some model parameters have been measured, estimated, or calibrated.

Calibration of the model was stopped after many trial and error steps because of limitation of time, result of the simulation was over estimated, may be due to calculations of evapotranspiration which were under estimated, therefore, it was impossible to compare the observed discharge for each ASA (sub catchment) with the computed one. But an attempt was done to compare the percentages of total discharges for both computed and observed regardless the clear difference between their extreme values,
In that case, Wanjohi, Upper Turasha, Kitiri, and Makungi play impotant role in generating of Malewa discharge. And for the land cover, Mixed area (3), Moor land, and Mixed forest generate more discharge than the other land cover. But of course, as further work, calibration of the model should be repeated for more accurate results.

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CHAPTER 1

INTRODUCTION

1.1 Generalities

Lake Naivasha is the only freshwater resource among many saline Lakes in the Kenyan rift valley. Two perennial (Malewa and Gilgil) and one ephermal (karati) rivers drain into it but it has no surface outlet. The water of the lake is very heavily used for agricultural irrigation, domestic, municipal, wildlife and geothermal projects. However, Recent drop in the lake water level poses a treat to its sustainability.

The relationship rainfall-runoff in a catchment is a function of the hydrologic and physiographic characteristics of it. The natural features (land-cover) and human-made features (land-use)are very important elements in runoff process.

Understanding of the behaviour of Malewa catchment through applying rainfall- runoff model will be helpful for future analysis of lake Naivasha sustainability, as the Model will be able to realise of the influence of land use change on runoff.

1.2 Objectives

The main objectives of the study can be summarised as follow:

- analysing of the rainfall-runoff relationship in Malewa catchment using semi-distributed hydrological model.
- Studying of the influence of land-use change on the runoff.

1.3 Applied method

In order to achieve this research with scientific way and to arrive at a satisfied result, the following steps have been done:

1.3.1 Literature review of the following topics

- The statistical methods for analysing of hydrologic data.
- Remote sensing for hydrologic models.
- Computer-based hydrological models.
- Characteristics of SLURP Model.

1.3.2 Data collection

Collecting of the required data for the study can be divided into two stages, before and during the field work,. In general, the input data which have been used for achieving of the study can be categorised as the following:

- Daily rainfall records for many stations inside and around the catchment
- Daily streamflow records for many gauging stations on Malewa river and its tributaries.
- Daily other meteorological data as (air temperature, relative humidity, dew point temperature, global radiation, wind speed).

- Topographic maps.
- Geological map
- TM 2000 Satellite images
- Areal photographs

1.3.3 Data analysis and interpretation

- Analysis of rainfall data to extract the reliable periods for SLURP.
- Analysis of discharge data to extract the reliable periods for SLURP.
- Rainfall runoff relationship.
- Digitising of contour map.
- Derivation of DEM from digitised contour map
- Image processing of the TM satellite images, and derivation of parameters of the images as (land cover classification, leaf area index, surface albedo).

1.3.4 Field work activities

The fieldwork aimed at collecting of the missing data needed for the research, and characterising of Malewa catchment. As the satellite images and areal photographs can not be interpreted correctly without checking of the ground truth. The following activities have been done :

Collection of the following meteorological data

1. Daily rainfall data for (Naivasha D.O 9036002, N.Kinangop forest station 9036025, Geta forest station 9036241, N. Kinangop Mawingo Scheme 9036264, Malewa Farmer'Coop. Soc. 9036290, N. Getcha New Farmers Co-op 9036294, Tumaini N. Y. S Camp 9036336)
2. Daily discharge data for the following gauging stations(2GB1, 2GB5, 2GB4, 2GC4, 2GC5, and 2GC7)
3. Additional meteorological data as(Daily mean air temperature, Daily dewpoint temperature or relative humidity, Daily global radiation or hours of bright sunshine)

Maps collection

- Collection of the following topographic sheets: (Naivasha 133/2, Kinangop 134/1, Gilgil 119/4, Kipipiri 120/3, Ol joro orok 119/2, and Ndaragwa 120/1) with the following parameters:

Grid:	U.T.M. Zone 37
Projection:	Transverse Mercator
Spheriod:	Clark 1880 (modified)
Unit of measurement:	Meter
Datum	New (1960)Arc

- Collection of Contour map related to the right upper part of the catchment.

Identification of the catchment with different land cover/land use

Comparing of the satellite image(TM 2000) with the ground truth to identify correctly the land cover/land use units.

Performing of many field tests to estimate required parameters for SLURP

1. measuring of the discharge for different channels inside the catchment using slope area method, and estimating of roughness coefficients for different channels for routing.

2. Measurements of conductivity for different land cover
3. Measurements of saturated infiltration rate for different land covers

1.4 Thesis lay-out

Chapter 1 introduction
Chapter 2 general features of the study area
Chapter 3 literature review
Chapter 4 rainfall analysis
Chapter 5 streamflow analysis
Chapter 6 runoff simulation
Chapter 7 Summary and conclusion
Recommendation
References
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1.5 Key words

Catchment is used synonymously with " watershed "and "drainage basin" to indicate the area that topographically appears to contribute all the water that passes through a given cross section of a stream

Streamflow is used synonymously with flow rate, discharge, and runoff to refer into the sum of quickflow(the rapid runoff during and after rainfall of new water) and baseflow (return flow from groundwater).

Rainfall is the form of precipitation which is observed in the rainfall station.

Gauging station is used to refer into the streamflow measurement station.

CHAPTER 2

GENERAL FEATURES OF THE STUDY AREA

2.1 Location of the study area

Naivasha basin is situated in the highest part of the Rift Valley of about area of 3184 $km^{2.}$ This basin has its internal drainage system and no outlet yet to be visible. Malewa river drains into the Lake which is the main source of surface water. The main purpose of the Lake are:

- Water supply for irrigation
- Water supply for generation of electricity
- Fish cultivation
- Drinking water & heritage of some wildlife
- Recreation
- Tourism

Malewa catchment is the main sub-catchment within the upper part of Naivasha basin, situated in the Kenyan Rift Valley almost 70 km from Nairobi (figure 2.1). It is located between latitude 0° 09to 0° 55 south and longitude 36° 09to 36° 24 east. The maximum altitude is about 3935 meter and minimum altitude 1900 meter above the mean sea level. The area of the catchment is 1700 km^2

2.2 Climate

The climatic conditions in the study area are quite divers due to considerable differences in the altitude and the land forms. Although the Lake is located within one degree of the equator and is thus "tropical", the annual temperature range is approximately from 8 °C to 30 °C (Kenya government, 1967). The rainfall regime within the Lake catchment is influenced by the rainshadow from the surrounding highlands of the Nyandarua rang (Aberdare) to the east, and the Mau Escarpment to the west. Two rainy seasons observed in the region. The "long rain" occurs in March, April and May and the "short rain" in October and November. The rainfall pattern is controlled by the relief, with much more rainfall in the higher altitudes than the lower altitudes.

Naivasha experiences an average rainfall of 610 mm, and the wettest slopes of the Nyandarua mountains within the Lake's catchment receives as much as 1525 mm. The evaporation experienced by Naivasha is some 1360 mm, so, the runoff from the non-immediate catchment would seem to be broadly sufficient to maintain Lake level (East african Meteorological Department, 1963).

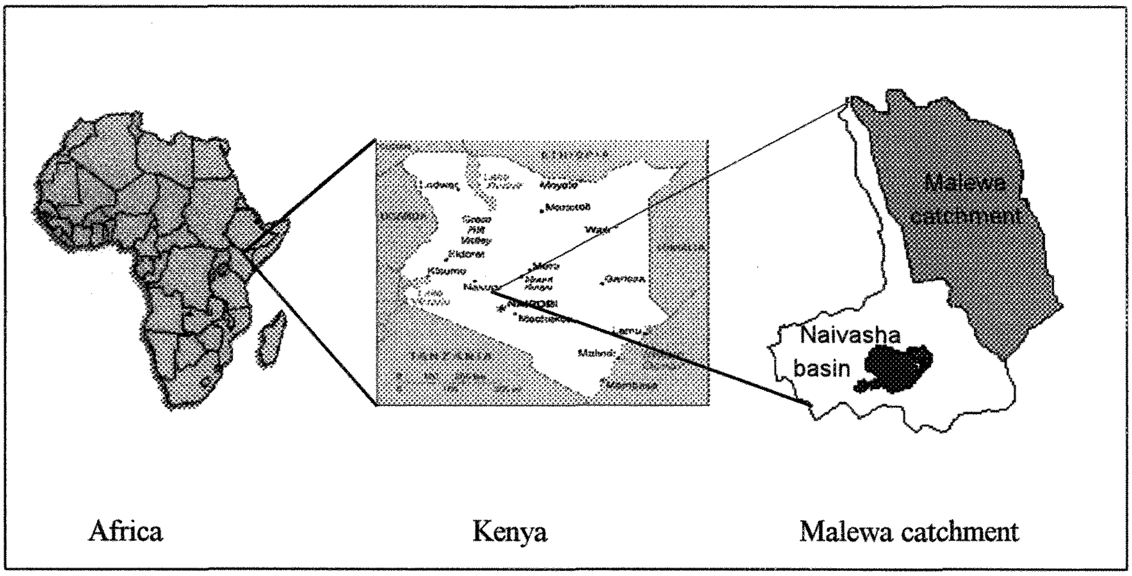


Figure 2.1 General location of the study area

2.3 Geology

The African Rift Valley is the most prominent morphologic and structural phenomenon in east Africa, In simple terms it is a deep Garben divided into two clearly defined branches, The geological formations of the area is characterised by volcanic tuff and quaternary lacustrine deposits and in a few locations with volcanic rocks as Basalt(Cole, 1950), Volcanic eruption have occurred intermittently since Miocene to recent times, but there is currently no major volcanic activity. Kamasian deposits of the Middle Pleistocene found in the study area have fluvial and lacustrine origin.

2.4 Topography

Naivasha area of the Rift Valley is confined by the Nyandarua mountains (formerly the Aberdares mountain) to the east, (the elevation exceeds 3990 m), and the Mau Escarpment to the west (the elevation exceeds 3000 m). The Kinangop Plateau forms a broad step between the Nyandarua range and the valley floor, east of Naivasha. The mount Longonot stands on the South of the Lake.

2.5 Rivers

Malewa catchment has a number of rivers and its tributaries. The main river is Malewa., Turasha, Nandarasi, Engare Mugutyu, and Wanjohi are the tributaries of this river. Gilgil and Karati are the other rivers of the Naivasha basin.

2.6 land use

The semi-arid climate and the topography are greatly influenced the vegetation of the area. The vegetation of the catchment can broadly be grouped into:

- Forest
- Bushland
- Grassland
- Agricultural land

The natural forest within the study area comprises indigenous hardwood trees and grasses such as bamboo's. Menegai crater, the Eburru hills, Mau escarpment, Mount longonot and the Nyandarua escaroment are all host of hardwood forest, whereas bamboo is confined to the Nyandarua and Mau escarpment. These form the main watershed of the lakes.
The greatest proportions of the low lying central part of the catchment are range land. Range land are land carrying natural or semi-natural vegetation that provide a habitat suitable for wild or domestic ungulates and varies from shrubland to grassland to bushland (Pratt and Gweynne, 1977). Naivasha shores are often encircled by ephemeral Papyrus colonies, and the surface covered by raft of Salvinia molesta (sometimes up to 25 % of the total surface area)

The main farming system in this area would commonly be referred to as mixed farming. Rainfed crop production is the most important activity within the catchment. Slope of the Nyandarua, Mau mountains are the most common farming areas. Common crops include wheat, maize, potato, beans and sunflowers.

Irrigated crop farming is common near Lake Naivasha where large quantities of wheat, barley, french bean and fodder crops are grown. Another important horticulture products are flowers.

The livestock production by some dairy farms and by the Masai people is also common practice.

2.7 Communication links

The road from Nairobi to Uganda and Sudan crosses this region. The main road in this region forms part of the Trans-african Highway and the Great North Road. The main line of the East African Railway also passes through the eastern part of the area and is followed closely by the main road from Nairobi to Nakuru. The region is thus the focus of important communication links.

CHAPTER 3

LITERATURE REVIEW

3.1 Introduction

Statistics for hydrology, hydrologic models and remote sensing for hydrologic models are the main topics which have been reviewed in order to extract the most convenient methods which fit the diverse climatic and physiographic conditions of the study area from one hand and quantity and quality of the available data on another hand.

- Data availability
- Hydrologic data analysis
- Remote sensing for hydrologic models
- SLURP model

3.2 Data availability

The main requirements for any hydrological model, especially for distributed and semi distributed models, are the huge amount of data needed to develop it, for this study, the following time series and parameters are available:

3.2.1 Time series data

- Daily rainfall records for 7 rainfall stations (Naivasha D.O, N.Kinangop Forest Station, Geta Forest Station, N. kinangop Mawingo Scheme, Malewa Farmer Coop.Soc., Ngecha New Farmers Co-op, Tumaini N.Y.S. Camp).
- Daily discharge records for 6 gauging stations (2GB1, 2GB5, 2GB4, 2GC4, 2GC5, and 2GC7)
- Daily mean air temperature record, only for one station (Oserian)
- Daily dew point temperature or relative humidity record, only for one station (Oserian)
- Global radiation or hours of bright sunshine record, only for one station (Oserian)

3.2.2 Model parameters

The following parameters have to be estimated for SLURP:

- Maximum capacities for the canopy, detention storage and slow store.
- Interception coefficients, and maximum and minimum LAI.
- Surface albedo and maximum soil heat flux.
- Hydraulic conductivity
- Saturated infiltration rate
- Roughness coefficient for each land cover and for channel within the ASA
- Lapse rate for temperature and precipitation / elevation adjustment rate.
- Parameters for specific evapotranspiration methods such as wind speed, wilting point, field capacity.

3.2.3 Satellite images

Landsat 2000 images were available for 8 bands(TM1, TM2, TM3, TM4, TM5, TM6, TM7, and TM8), but the area was covered through two images of different time, the western image was taken in may(wet season) while the eastern image was taken in February(dry season).

3.2.4 Maps

Topographic map of scale 1:50,000 for most of the catchment, and topographic map of scale 1:250000 for the upper part of the catchment.

3.3 Hydrologic data analysis

Before using of the hydrologic data in any further applications, many kinds of analysis have to be done, for instance, detecting the systematic errors (bias), correlation between the measuring stations or gauge stations, frequency analysis etc.

3.3.1 Rainfall data analysis

3.3.1.1 Degree of consistancy

There are many cases where the hydrological data show kind of inconsistency or non homogeneity (systematic error, bias) because for example changing in the observational technique, changing of the environment around the precipitation gauges. Change in time, as tree growing slowly around the precipitation gauge, so that the rain measurements show downward systematic error (or upward) doesn't exist in the true value.

Detecting of the magnitude of the systematic errors (inconsistency, non-stationarity) in the hydrological data is of great practical interest, because any projection into the future based on past properties of hydrological variables requires that the conclusions are derived from data free of significant systematic error. Many methods are used to detect the errors in the measured data as:

- **Mass curve**

By plotting the annual accumulating rainfall data against the time, different possibilities can be noticed, if the line is approximately straight, the data are correct. if the line shows kind of trend, something has changed gradually in the near vicinity of the gauge. If the line shows a distinct break point, this indicates a sudden change or discontinuity. This method has been used in this study for rainfall and streamflow analysis.

- **Double mass curve**

A Plot of the accumulated rainfall data against the accumulated average of the surrounding stations, is generally used to check the consistency of the rainfall record. Again a deviation means a change. To make the record comparable before and after the change, the slopes of the line fitted to the points are determined, a part of the line should be adjusted. For this study, this method was used for rainfall analysis.

- **Isohyetal mapping**

By plotting the data on a map and drawing isohyets, faulty stations may be discovered.

3.3.1.2 Correlation between the stations

One of the methods to estimate the degree of correlation between the stations is developing a linear regression model between two data sets after plotting them in a graph, and then the correlation coefficient can be estimated. As another kind of association can be detected, according to the altitude of the stations. This work was not done because of non availability of complete rainfall series for the whole stations and also it does not serve too much the main line of the thesis.

3.3.1.3 Filling in missing data

It is very often in hydrology that some rainfall data are missing from the observed records due to different reasons, the records might not be measured at all because the gauging station was installed after the period of interest or the station was closed down for a certain period, etc. in most cases it is preferable to fill in the missing data than to analyse the series without them.

There are many methods to fill in the missing data as station- year method, weighted average method, weighted distance method and Isohyetal method. The most common method is to develop a mathematical equation (regression) between the data of interest and another data Seri completed and correlatively related to it, for this purpose, linear or non-linear regression (simple or multiple) can be used. Because of limitation of time, filling data did not done, but it was preferable to fill the gaps in the time series in order to be closer to the reality.

3.3.1.4 Frequency analysis

The objective of frequency analysis for the hydrologic data is to relate the magnitude of extreme events to their frequency of occurrence through the use of probability distributions. Using program as RANK-PLOT(Donker, 1996) will be useful for this kind of analysis. These calculations have not been done because of limitation of time from one hand and because are not related to the core target of the thesis on another hand.

3.3.2 Streamflow data analysis

3.3.2.1 Degree of consistency

As for the rainfall data, the Mass curve and Double mass curve are useful tools to reveal the systematic error (inconsistency) in the discharge time series. For this study, Mass curve method was used for consistency check.

3.3.2.2 Flow duration curve

The flow duration curve plots cumulative frequency of discharge, that is, discharge as function of the percentage of time that the discharge is exceeded. It is not probability curve, because discharge is correlated between successive time intervals, and discharge characteristics are dependent on season of the year. Flow duration curve provide a compact graphical summary of streamflow variability (Maidment,199). So, by using this technique the variability of the streamflow data can be detected. Also these kind of calculations have not been done because of limitation of time.

3.3.2.3 Frequency analysis

In order to understand the relationship between the extreme values of the discharge data and the probability of their occurrence in the future. Frequency analysis should be done. Using program as RANK-

PLOT(Donker, 1996) will be useful for this kind of analysis. But because of limitation of time this analysis has not been used.

3.3.3 Baseflow separation

Programme TIME PLOT was used for baseflow separation. It adopts recursive filter technique for baseflow separation.
Recursive filter technique is commonly used for signal analysis, the filter has been described by Nathan and MacMahon(1990) and Lyne and Hollick(1979).the filter has the following form:

$$F_k = \alpha F_{k-1} + \frac{(1+\alpha)}{2}(Y_k - Y_{k-1}) \qquad (3\text{-}1)$$

Where,
F_k = filtered quick response at sampling instant K
Y_k = original streamflow
α = filter parameter (approx. 0.9-0.99)
Thus, the base flow is Y_k - F_k

In program TIMESPLOT the filter passes three times over the data; forward, backward and forward again. The parameter α effects the degree of attenuation and the number of passes determines the degree of smoothing. For the study, this technique was used twice, for Malewa and Turasha catchments.

3.4 Remote sensing for hydrologic models

Many data can be derived from Satellite Imagery to be applied in the hydrologic model, for SLURP model the following data should be derived:

3.4.1 Leaf area index - LAI

The leaf area index (LAI) is ratio of the total area of all leaves on a plant to the area of ground covered by the plant. It represents the total biomass and is indicative of crop yield, canopy resistence, and heat flux.

There have been many attempts to relate LAI to NDVI, SAVI, TSAVI, and WDVI. Most relationships between vegetation indices and LAI are perturbed by solar zenith and azimuth angles, viewing angles, ratio of diffuse to total shortwave radiation, leaf angle distribution, leaf chlorophill content, mesophyll structure, and canopy geometry. the derived relationship between LAI and SAVI (soil adjusted vegetation index)shown in the following formula:

$$LAI = -\frac{1}{c_3}.\ln\left(\frac{c_1 - SAVI}{c_2}\right) \qquad (3\text{-}2)$$

where:
c_1, c_2, and c_3 are regression coefficients related to the crop, many experiences show average values (c_1=0.69, c_2=0.59, and c_3=0.91).
SAVI is given by the following formula:

$$SAVI = \frac{(1+L).(CH4_{SUR} - CH3_{SUR})}{(CH4_{SUR} + CH3_{SUR} + L)} \qquad (3\text{-}3)$$

Where:
L is a non-dimensional correction factor (0 for very high vegetation cover, 1 for very low vegetation cover)
$CH4_{SUR}$ and $CH3_{SUR}$ are the atmospherically corrected ground reflectance in channel 4 and 3, expressed in decimals.

NDVI is given by the following formula:

$$NDVI = \frac{CH4_{SUR} - CH3_{SUR}}{CH4_{SUR} + CH3_{SUR}} \quad (3\text{-}4)$$

3.4.2 Surface albedo

3.4.2.1 Radiometric correction

To be able to extract physical parameters from the satellite it is necessary to convert the raw digital numbers in the different channels to radiance values. The Earth Observation Satellite Company (EOSAT), distributes so called Technical Notes for Landsat technology and processing, The conversion of these digital numbers back to spectral radiance again is done by using the following equation and by knowing the upper and lower limit of so called dynamic ranges for any band:

$$L_i = L_{\min,i} + \frac{L_{\max,i} - L_{\min,i}}{DN_{\max}} DN \quad (3\text{-}5)$$

where:
Li = spectral radiance in band i [$mW/cm^2/str/\mu m$]
$Lmin,i$ = spectral radiance at DN = min [$mW/cm^2/str/\mu m$]
$Lmax,i$ = spectral radiance at DN = max [$mW/cm^2/str/\mu m$]
DN = digital number [-]
DN_{max} = maximum digital number [-]

Because the data is provide in 8-bit format, the maximum digital number is always equal to 255. Table (3.4.2.1) in Appendix B provides the minimum and maximum spectral radiances that were used to convert the digital number into atmospherically corrected ground reflectance .

3.4.2.2 Atmospheric albedo

Before the reflection at the earth's surface can be determined, first the reflection coefficient, ρ_p, for the entire spectrum is calculated for the top of the atmosphere. This ρ_p, value is based upon the amount of reflected radiation in the visible range of the spectrum, which is approximately from 0.4 to 3.0 µm. for Land sat-TM data this means bands 1 to 5 and 7. The spectral range of band 6 is in the thermal infrared part of the electromagnetic spectrum.
For deriving of the reflection of a Lambertian reflector, in this case the following formulas is used:

$$\rho_{p,i} = \frac{\pi.L_i.d^2}{S_{sun,i}.\cos(\theta_z)} \qquad (3\text{-}6)$$

Where:

$\rho_{p,i}$ = reflection at the top of the atmosphere in band I [-]

L_i = radiation reflected in band i [$mW/cm^2/str/\mu m$]

d = sun-earth distance in astronomical units[AU]

$S_{sun,I}$ = incoming solar radiation in band i [$mW/cm^2/str/\mu m$]

θ_z = solar zenith angle [°]

Li is calculated following the procedure as explained in paragraph 3.4.2.1, the sun-earth distance is derived using the expression from another hand out called " solar radiation", where also the calculation of the solar zenith angle is explained. The incoming solar radiation in the wavelength ranges of the different bands is taken from "eosat, 1986, table(3.4.2.2) in appendix B.

The albedo values obtained in this way are in fact narrow band albedos for the different channels. To determine the broad band albedo the following formula has to be used:

$$\rho_p = \Sigma w_i.\rho_{p,i} \qquad (3\text{-}7)$$

Where:

ρ_p = broad band reflection at the top of the atmosphere[-]

W_i = weight factor in band I [-]

$\rho_{p,i}$ = narrow band reflection, from equation (3-6)the weight factor depends on the ratio between the incoming shortwave radiation in any channel and the total incoming shortwave radiation summed for all the channels following:

$$W_i = \frac{S_{sun,i}}{\Sigma S_{sun,i}} \qquad (3\text{-}8)$$

The values produced in this way are only valid for the top of the atmosphere. To be able to extract a surface reflectance from this atmospheric reflection an atmospheric correction is necessary.

3.4.2.3 Surface reflection

Numerous methods exist to derive a surface reflection, or surface albedo, ρ_0, from the atmospheric or planetary reflection ρ_p, these methods depend on the type of the satellite and the company, for TM-imagery, one very simple method will be used, it assumes a more or less linear relationship between the planetary and surface albedo for the case of so called clear skies. This relationship enables one to estimate the surface albedo given only the planetary albedo and vice versa.

The method follows the procedure proposed by Chen and Ohring, 1984. The derived relationship is of the form:

$$\rho_o = \frac{\rho_p - a}{b} \qquad (3\text{-}9)$$

Where:

ρ_p = planetary albedo

ρ_o = surface albedo

a,b = parameters depending on the solar zenith angle, see table (3.4.2.3) in appendix B.

In this relationship 'a' can be seen as the mean planetary albedo of a clear atmosphere above a non reflecting surface while 'b' is an indicator for the so-called two-way transmittance of the clear atmosphere.

3.5 SLURP model

3.5.1 Introduction

A hydrological model is an attempt to describe the physically processes controlling the transformation of precipitation to runoff. There are many types of hydrologic simulation models but the main categories are:

Event vs. continuos models, lumped vs. distributed models, calipratedparameters vs. measured parameters models

SLURP is a conceptual model which, although normally used in semi-distributed form, is capable of use as a fully distributed hydrological model.

The SLURP model (Kite, 1995a) divide a watershed into a number of units known as aggregated simulation areas (ASA). An ASA is not a homogenous area but is a group of smaller areas each of which has known properties. For example, land cover may be measured from satellite for pixels as small as 10 m but it would be impracticable for a hydrological model to operate at such a pixel dimension for a macro-scale basin. Instead, the pixels are aggregated into areas which are more convenient for modeling. Such ASAs do not need to be squres, rectangles or any other regularly shaped areas (although such forms are possible subsets of the ASA) and may more usually be based on stream network shapes.

The basic requirements for an ASA are that the distributions of land covers and elevations for elements within the ASA are known and that the ASA contribute runoff to a definable stream channel. The latter requirement is also an operational consideration since it means that the stream system within the watershed must be at a level of detail such that each ASA contains a defined stream connected to the watershed outlet. The number of ASAs used in modelling a basin will depend on the size of the basin and the scale of data available. It is better if the number of ASAs equals or exceeds the number of land cover classes. Land cover data may be derived from satellite images, SLURP has the ability to work with land covers that may change any number of times throughout a model run. Applications of SLURP were tested for different sizes of watershed varying in size from few hectares till 1.8 million square kilometres.

3.5.2 The vertical water balance

At each time increment the model is applied sequentially to a matrix of ASAs and land covers. Each element of the (ASA x land cover) matrix is simulated by four nonlinear reservoirs representing canopy interception, snowpack, rapid runoff(may be considered as a combined surface storage and top soil layer storage)and slow runoff (may be considered as groundwater). The model routes precipitation through the appropriate processes and generates outputs (evaporation, transpiration, surface runoff, interflow and groundwater discharge) and changes in storages (canopy interception, snowpack, fast flow and slow store). Runoffs are accumulated from each land cover within an ASA using a time/contributing area relationship for each land class and the combined runoff is converted to streamflow and routed between each ASA. The figure (3.5.2) shows the vertical water balance process applied for each land class within each ASA.

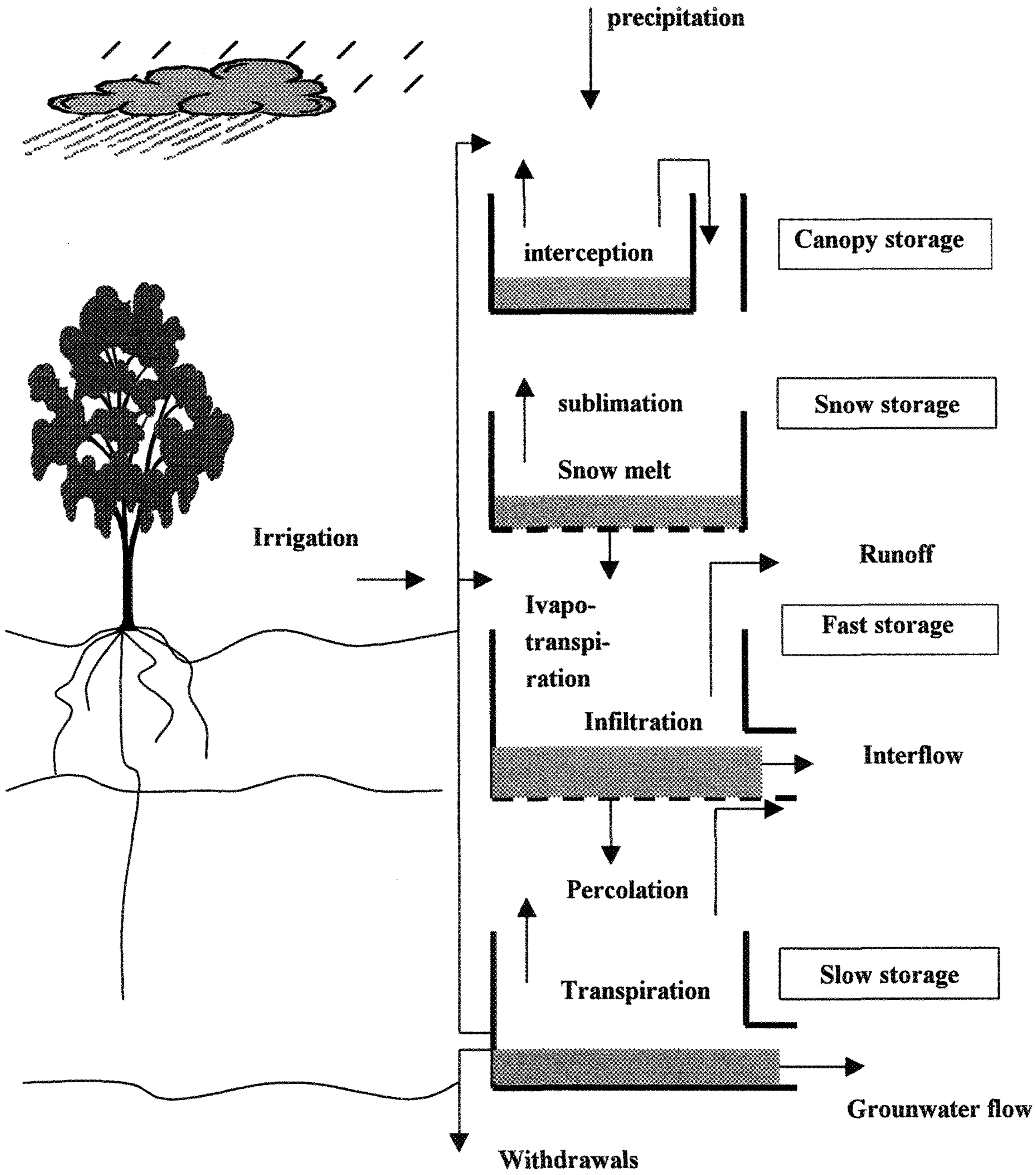


Figure 3.5.2 Simplified flow chart of the vertical water balance applied to each land class within each ASA

Using of SLURP in a semi distributed form for Malewa catchment, the model is able to simulate the behaviour of the basin at many points and in many variables while avoiding the data and computation hungry excesses of the fully distributed models. Table (3.5) shows the total data required for SLURP model and how are derived.

Table 3.5 Total Data required for SLURP

Parameters required for each ASA	UNIT	Availability	How Derived
Physiographic Data			
ASA area		AV.	GIS
Percentages of ASA are occupied by different land cover	Perc.	AV.	GIS
Differences in the mean elevations of each land cover, differences in the mean elevation along the stream to the ASA outlet.	m	AV.	GIS
Mini and max distances to the nearest point on a stream and max and mini distances along the stream to the ASA outlet.	km	AV.	GIS
Mean latitude and altitude of each ASA.		AV.	GIS
Time Series Data			
daily total precipitation	mm	AV.	Measuring records
daily mean air temperature	C°	N/A*	Measuring records
daily dew point temperature or relative humidity	C°	N/A*	Measuring records
daily global radiation or hours of bright sunshine	$W/m^2/d$	N/A*	Measuring records
daily discharge record for calibration purpose	m^3/sec	AV.	Measuring records
Model Parameters			
Maximum capacities for the canopy, detention storage and slow store.	---	AV.	Tables
Interception coefficients, and maximum and minimum LAI		AV.	Tables, Image Processing
Surface albedo and maximum soil heat flux.	---	AV.	Image Processing
Conductivity		AV.	Field measurement
Saturated infiltration rate	mm/day	AV.	Field measurement
Roughness coefficient for each land cover and for channel within the ASA	---	AV.	Manning Table
Lapse rate for temperature and precipitation / elevation adjustment rate		AV.	Estimated
Parameters for specific evapotranspiration methods such as wind speed, wilting point, field capacity	various	AV.	Estimated

* indicator of non availability of the data for exact date of simulation.

The input data of SLURP leads to the following conclusions :

- The model strongly incorporate with GIS and Satellite Imagery derived data
- Being the model depend on ASA simulating environment, it deals with the catchment naturally more than artificially as in the grid-base model.

3.5.3 TOPAZ and SLURPAZ

Two softwares TOPAZ and SLURPAZ are required to build SLURP command and weight files. TOPAZ processes a raster digital elevation model (DEM) to derive a wide range of topographic and topologic variables that may be used in basin runoff processes such as:

- ASA areas.
- Mean UTM northing and elevation for each ASA.
- Areas occupied by each land cover within each ASA.
- Channel length and change in elevation along the channel within each ASA.
- Mean distances to stream and average change in elevation to stream for each land cover within each ASA.
- Mean distances downstream and average change in elevation downstream for each land cover within each ASA.
- Number of next ASA downstream.
- Areas of influence for climate stations.
- Mean annual precipitation for each ASA (needed for the Morton evapotranspiration option).

The SLURPAZ interface processes the physiographic outputs from TOPAZ together with a raster of land cover data and routing data to generate a SLURP command file (.CMD). It also processes climate stations coordinates in order to generate a SLURP weights file (.WTS) and SLURP evaporation files (.MOR, .GRA, .SB and .PM). See (Figure 3.5.3).

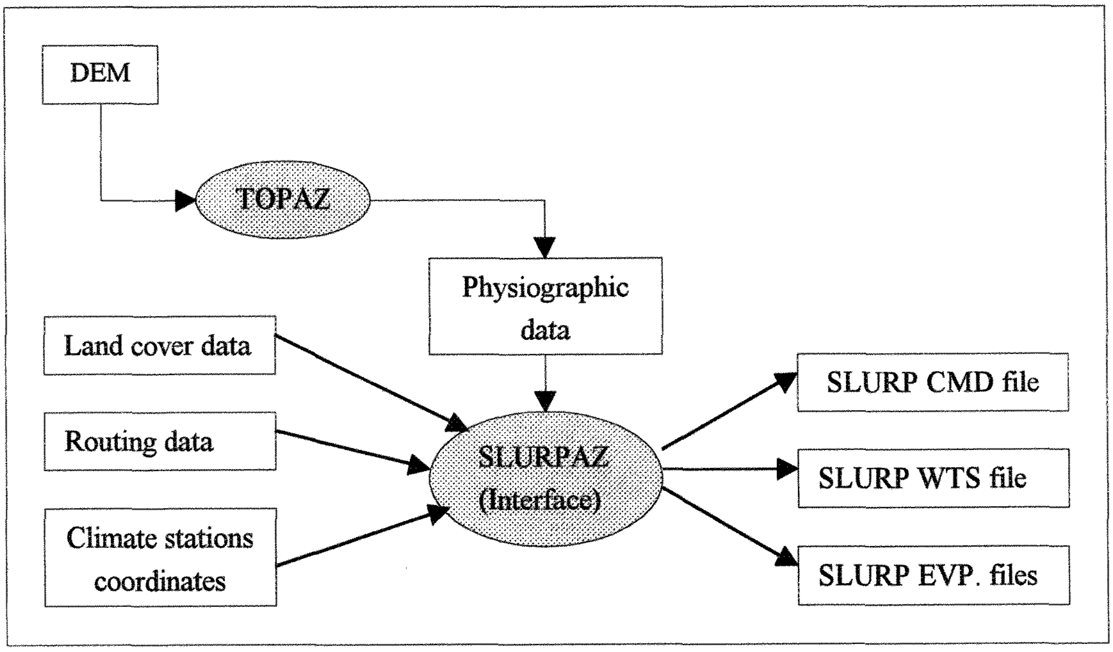


Figure 3.5.3 Schematic of TOPAZ and SLURPAZ links

CHAPTER 4

RAINFALL ANALYSIS

4.1 Introduction

Precipitation occurring in Malewa catchment plays the most important role in the runoff process. There are two rainy seasons can be distinguished, short season (October and November) and long season (March, April and May). There are many stations inside the catchment but the data for most of them are not available. Table 4.1.1 shows the characteristics of the rainfall stations which had been used in the study. Figure 4.1 shows the distribution of the rainfall stations and the gauge stations in the catchment,.

Daily rainfall data for the previous stations were available for different time series, Figure 4.1.1 shows the average monthly rainfall of the stations, Table 4.1 in the Appendix C shows the average monthly rainfall data for the stations.

The reliable situation of the catchment considers two raining periods, long rain (March, April and May) and short rain (October and November), Figure 4.1.1 shows that whole stations have reliable rainfall for the long rain period, but their short rain period differs from one station to another, except 9036025 which has reliable rainfall for both periods, 9036002 shows additional smooth peak in August while 9036241 shows additional high peak in August, 9036264 shows smooth peak in August and very high peak in October, 9036290 has a peak in August as well, 9036294 has additional peak in August and smooth peak in November, and the short rain period for 9036336 shifted to July and August.

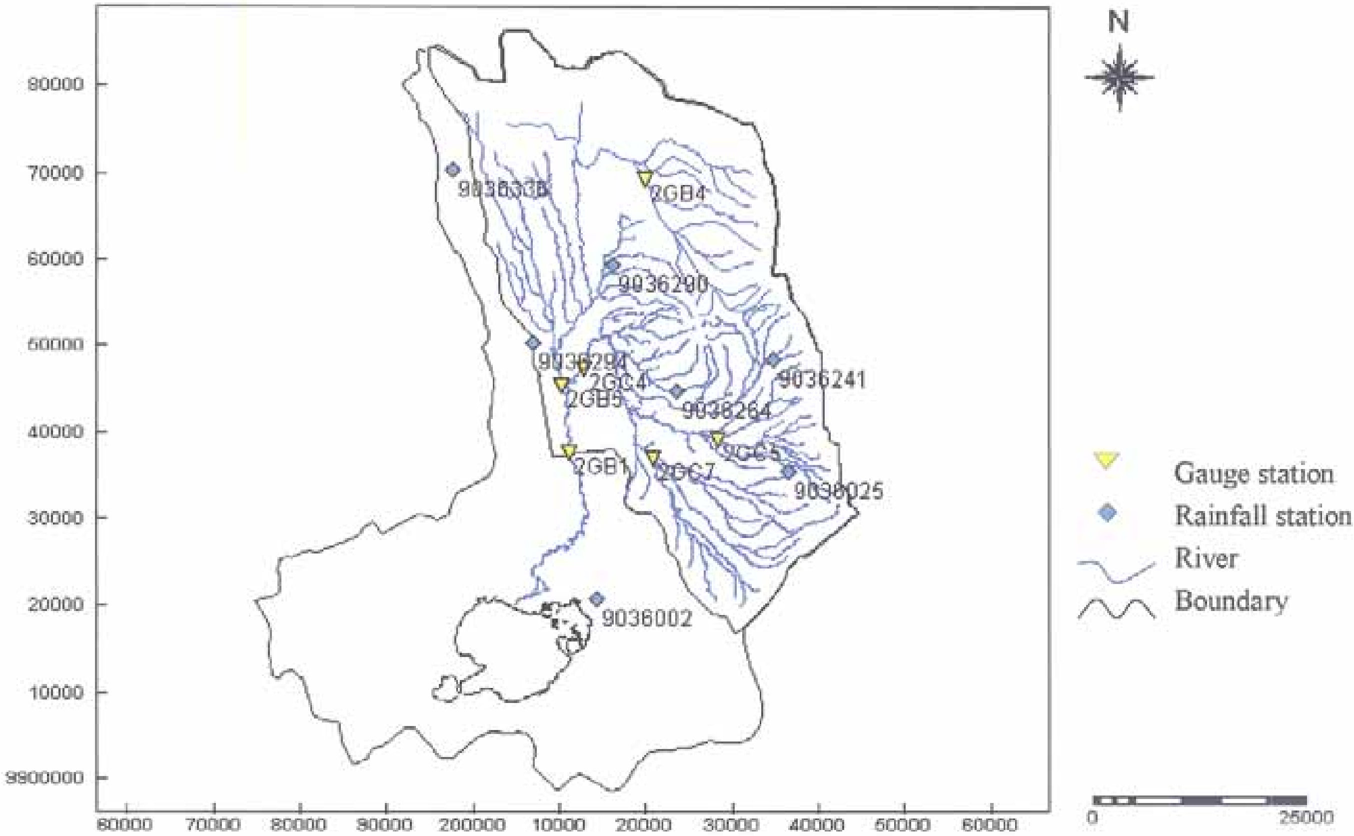


Figure 4.1 Rainfall and gauging stations map

Table 4.1.1 Characteristics of the rainfall stations

Station	ID	Altitude	Latitude	Longitude	Records	Location
		m.a.s.l			years	*
NAIVASHA D.O.	9036002	1907	36.433333	-0.716667	64	O
N. KINANGOP FOREST STATION	9036025	2635	36.63333	-0.583333	42	I
GETA FOREST STATION	9036241	2605	36.61667	-0.466667	38	I
N. KINANGOP MAWINGO SCHEME	9036264	2418	36.516667	-0.5	31	I
MALEWA FARMER'COOP. SOC.	9036290	2315	36.45	-0.366667	24	I
NGECHA NEW FARMERS CO-OP.	9036294	2175	36.36667	-0.45	10	O
TUMAINI N.Y.S. CAMP	9036336	2510	36.283333	-0.266667	18	O

*** (I) Inside the catchment (O) Outside the catchment**

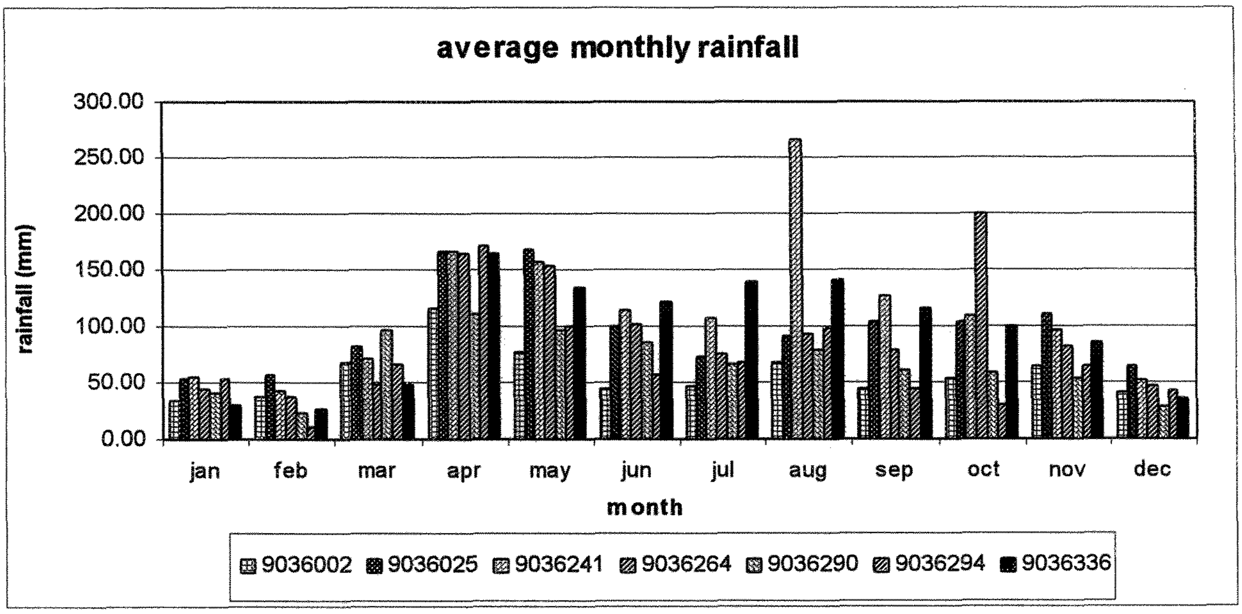


Figure 4.1.1 the average monthly rainfall

4.2 Reliability of the rainfall data

Before using the Rainfall data in the Hydrological Model SLURP for simulation purpose, the outliers or the typing errors values should be removed and the reliable periods for each station should be detected. Mass curve and Double mass curve are good tools for checking the consistency and the continuity of the data.

4.2.1 Mass curve and Double mass curve

The accumulated yearly rainfall values for each station were plotted against time for the Mass curve and against the other stations for the Double mass curve, all stations except 9036025 showed outliers or typing errors with high and low values, either because of the high typing errors or because of the missing measurements for many months. The typing errors were corrected and the graphs showed improving in their trend. Table 4.2.1 shows the Years and the Months outliers for each Rainfall station. Figures 4.2.1.a, 4.2.1.1.b, 4.2.1.2.b show respectively examples of the Mass curves and Double mass curves graphs for many stations before and after correcting the outliers.

Table 4.2.1 Outliers of the rainfall stations

Rainfall station	Outliers Year (month)
9036002	1946 (Mar), 1952 (Aug), 1955(Jul), 1956(Jan, Apr, and May), 1957(measurement only for Jan), 1961(Nov), 1962(Jan, Apr, May, Jun and Aug)
9036025	No outliers
9036241	1976(Aug), 1995(measurement only for Sep.)
9036264	1964(measurements only for Jan, Oct, Nov. and Dec.), 1976(measurements only for Oct., Nov., and Dec.), 1980(Oct., no measurements for Feb., Mar., Apr., May, Jun.), 1984(Mar., May, Aug., and Oct.), 1991(Jun, Nov., no measurements for Jan., Feb., and Apr.), 1995(no measurements for Feb., Jul, Aug., Sep., and Oct.)
9036290	1976(Apr), 1981(Mar), 1983(measurements only for Feb. and Mar.), 1984(measurement only for Aug.), 1987(measurement only for May), 1988(measurements only for Sep., Oct., Nov., and Dec.)
9036294	1973(measurement only for Jul.), 1986(measurement only for Jan.)
9036336	1989(measurements only for., Aug., and Sep.), 1994(measurements only for Jan., Feb., Mar., Apr., May, and Jun.), 1995(measurements only for Jul. and Nov.), 1998(Jan., Jun., Jul., Aug., Sep)

Before the correction

After the correction

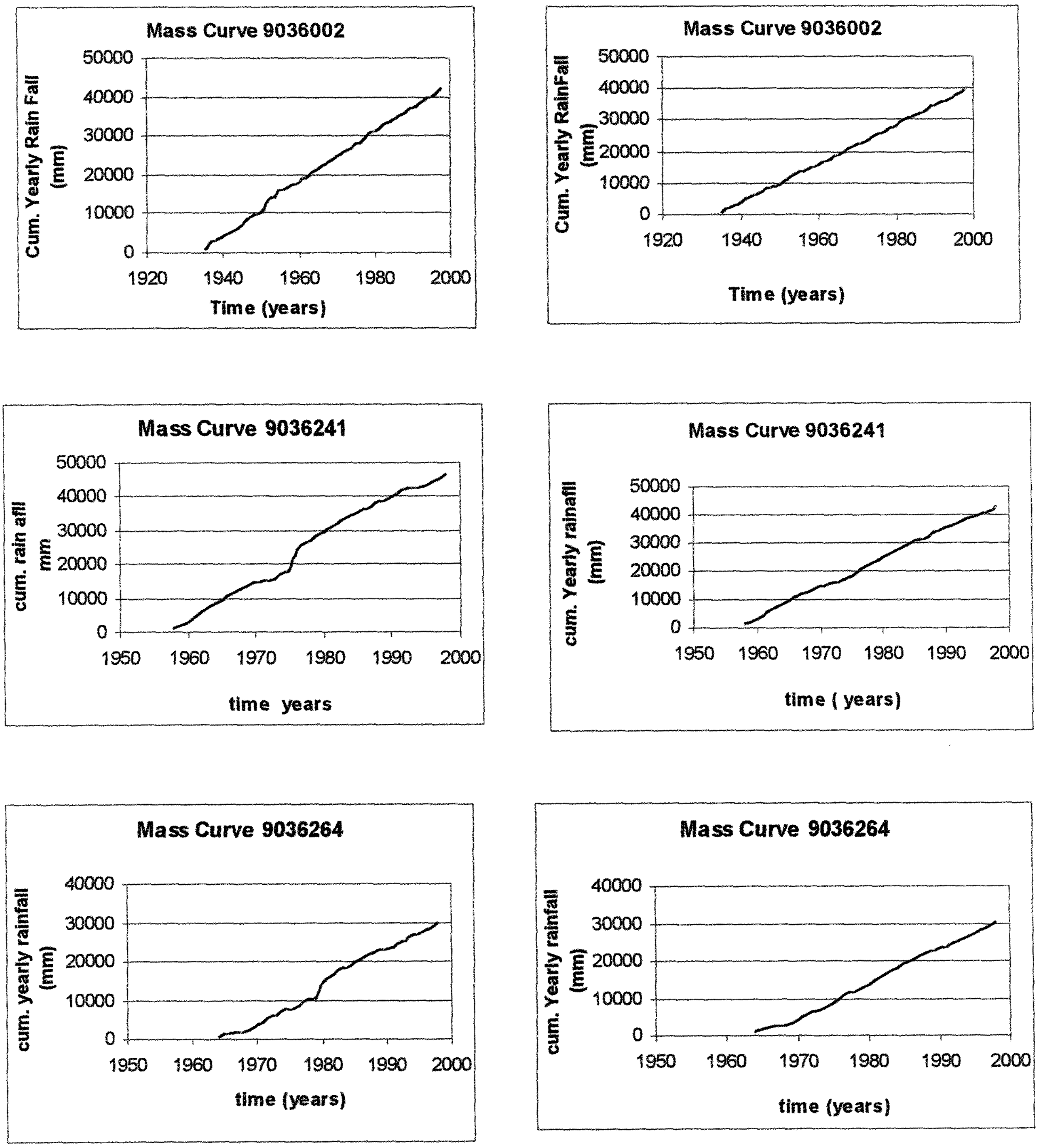


Figure 4.2.1.a Mass curves before and after correcting of the Outliers

Before the correction After the correction

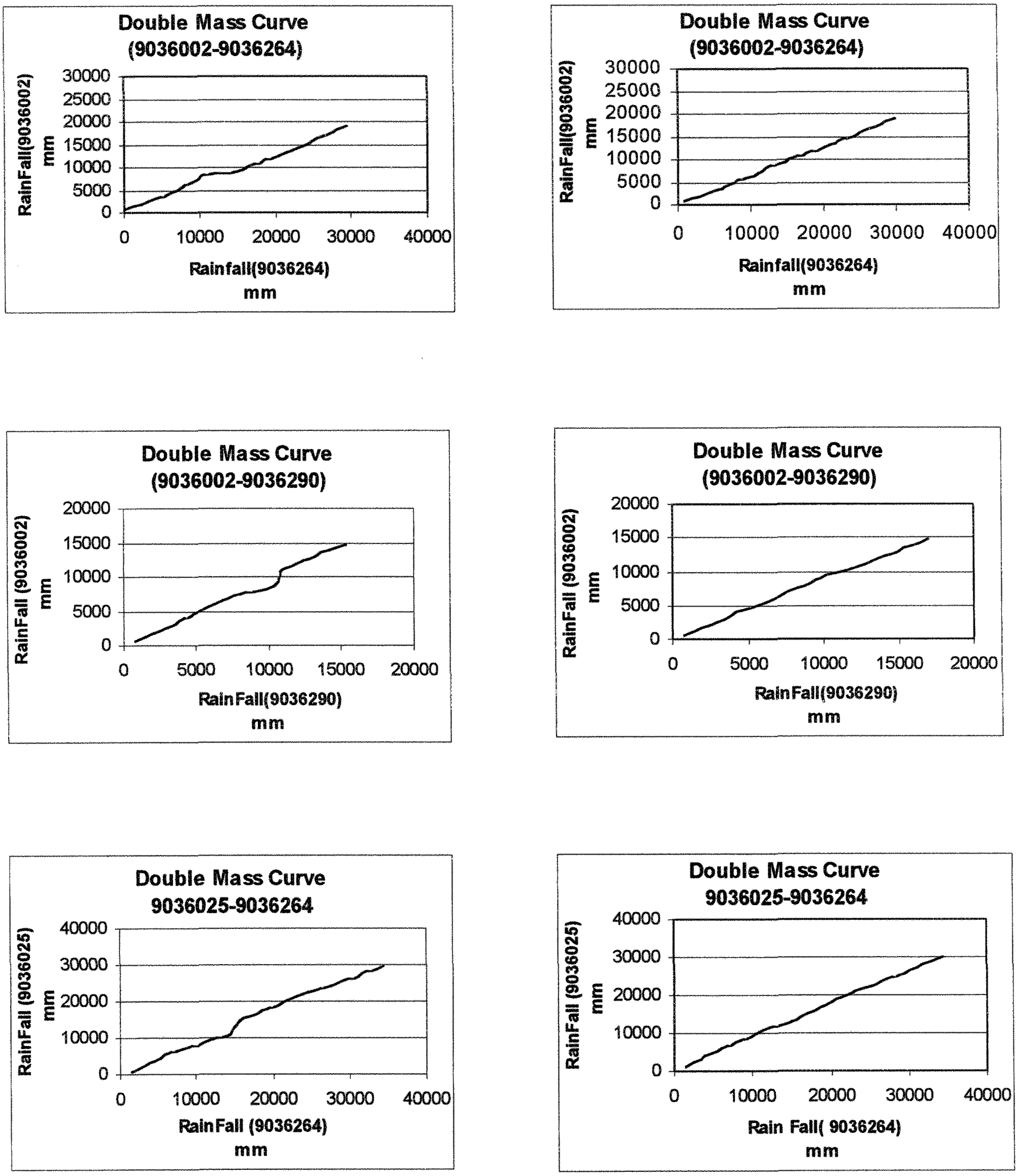


Figure 4.2.1.1.b Examples of Double mass curves before and after correcting of the Outliers

Before the correction After the correction

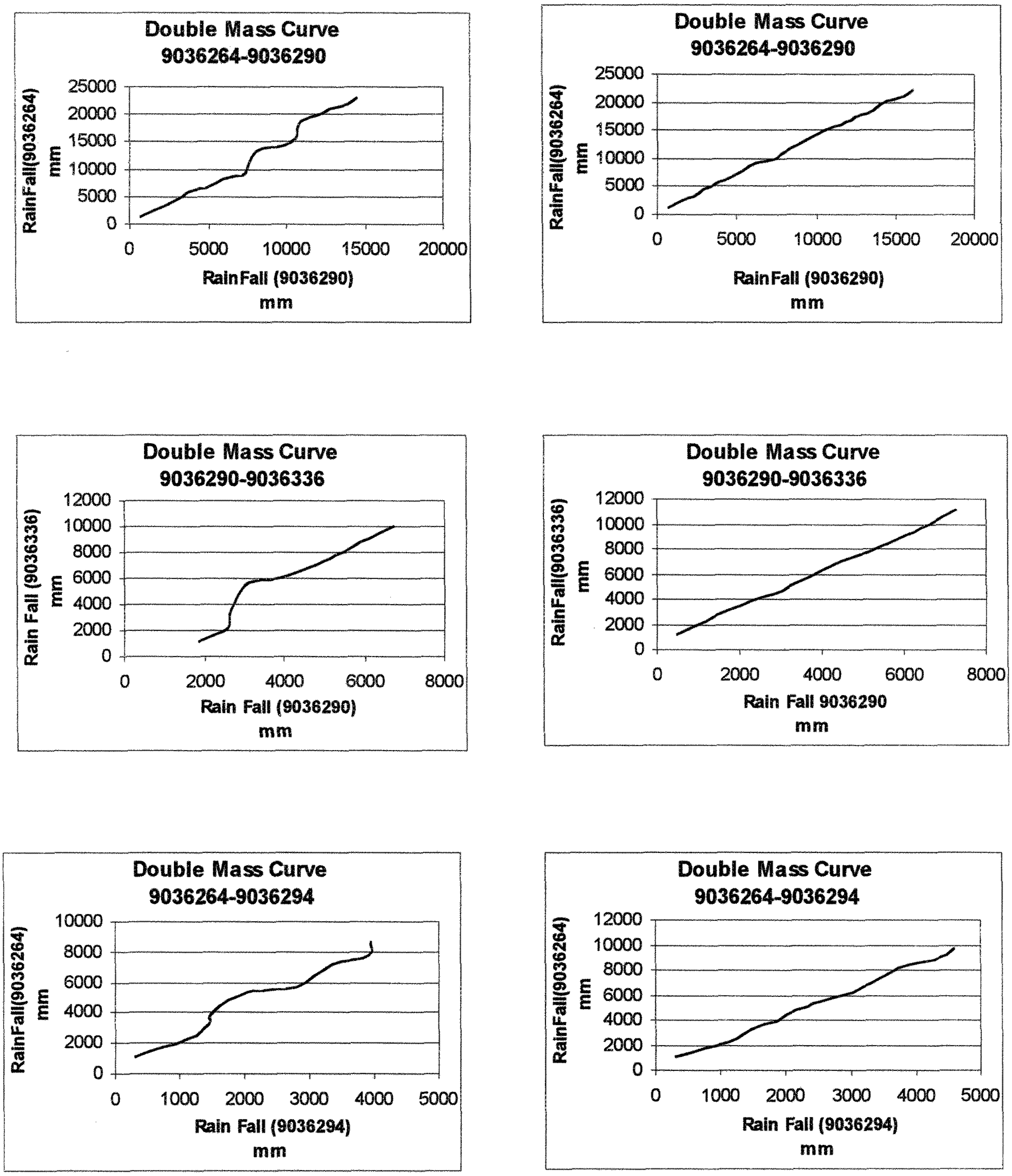


Figure 4.2.1.2.b Examples of Double mass curves before and after correcting of the Outliers

4.3 Areal rainfall

In order to convert the point measurements of the rainfall in each station into average values over the whole catchment, many methods are available, Thiessen polygons, Isohyetal method, arithmetic mean and the Orthographic relationship.

The rainfall stations are not uniformly distributed over the catchment and the individual measurements significantly vary, the arithmetic mean method is not analysed, As the number of rainfall stations is limited, Isohyetal method was not satisfied method for applying as well, Two methods were checked, Orthographic relationship and Thiessen polygon.

To detect the relationship between the rainfall and the altitude, the average annual rainfall was plotted against the altitude of the stations, the figure 4.3.1 shows reasonable correlation between the rainfall and the elevation, the correlation coefficient equal to 0.65.

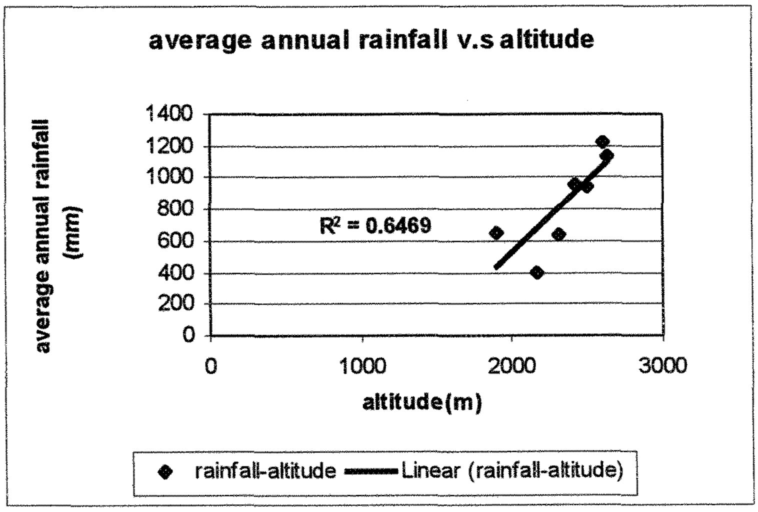


Figure 4.3.1 Relationship between the rainfall and the elevation

Thiessen polygon method was applied to calculate the average rainfall over the catchment, because the rainfall data are not continuous records for whole stations, the weight of the stations is different for 1975,1977 than the weight for 1992,1993. For the years 1975 and 1977 the stations which have data are (9036002, 90362025, 9036241, 9036264, 9036290, and 9036294) while for the years 1992, 1993 the stations which have data are (9036002, 90362025, 9036241, 9036264, 9036290, and 9036336). It is clear from the result that 1975 and 1993 are drought years while 1977 and 1992 are rainy years. Table 4.3.1 shows Thiessen average rainfall for the years of simulation.

It should be mentioned here that SLURP will use Thiessen polygon method to convert the point meteorological data into average areal data over each ASA of the catchment.

Table 4.3.1 Average annual rainfall calculated by Thiessen polygon method

Station code	Years of simulation			
	1975	1977	1992	1993
	Average annual rainfall (mm)			
9036002	22.9	35.0	28.2	18.9
9036025	170.1	285.5	209.1	143.8
9036241	130.9	197.3	170.5	80.9
9036264	116.9	252.3	184.8	137.2
9036290	329.4	358.6	262.9	226.9
9036294	35.4	48.7	-	-
9036336	-	-	150.0	143.7
Average rainfall	805.7	1177.3	1005.4	751.5

4.4 Selection of the reliable periods for SLURP

Analysis of the Mass curves and Double mass curves showed that the stations are not well consistent. The reliable periods were extracted, and for input data for SLURP, a Rainy and dry years were selected from the reliable periods. Figure 4.4 shows the total, reliable, and selected periods for each rainfall station and Gauging Station.

4.4 Conclusion

- Missing years are available in the rainfall records.
- The rainfall data are not well consistent for all rainfall stations.
- Relationship between the rainfall and the elevation was found.
- Reliable dry and rainy years have been selected for SLURP.

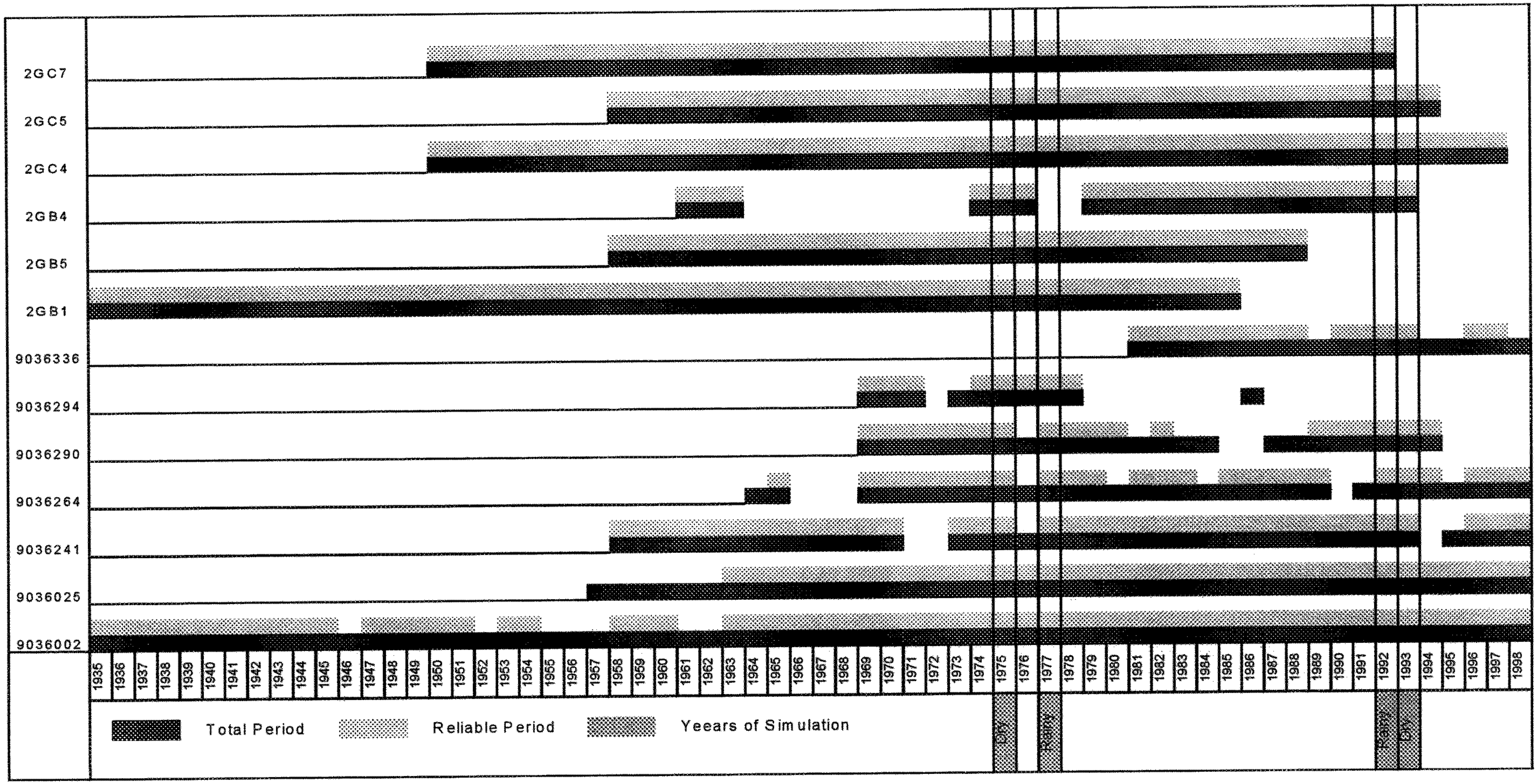


Figure 4.4 Total, reliable, and selected periods of the rainfall and gauging stations

CHAPTER 5

STREAMFLOW ANALYSIS

5.1 Introduction

Streamflow is generated by combination of baseflow (return flow from the ground water), inter-flow(rapid subsurface flow through pipes, macro-pores, and seepage zones in the soil), and saturated overland flow (from the surface of poorly permeable or temporarily saturated soil, or from permanently saturated zones near the channel system. Interflow and saturated overland flow together comprise quickflow(the rapid runoff during and after rainfall of new water.

Baseflow and quickflow are conventionally separated on streamflow hydrograph by a line extended from the foot of the rising limb of the hydrograph to the falling limb, or recession.

Choosing of the gauging stations for the analysis and SLURP was controlled by two factors: firstly, the availability of the gauging stations inside the catchment, secondly, the reliability of the discharge measurements for the selected gauging stations.

The gauging stations which have been selected for the analysis were 2GB1, 2GB5 and 2GB4 on Malewa river, and 2GC4, 2GC5, and 2GC7 on Turasha river, figure(4.1) shows the locations of the Gauging stations. Table(5.1.1) shows the characteristics of the Gauging Stations

Daily discharge records for the selected gauging stations were obtained from the Meteorological Department in Nairobi, Kenya. figure 5.1 shows the average monthly, whole stations have peak in May but their behaviour differ for the second peak, GB1 and GB5 show peak in August, GC4 seems to be more reliable in its response. See table 5.1.2 for the average monthly discharge in Appendix C.

Table 5.1.1 Characteristics of the gauging stations

Gauging station	River	X_UTM	Y_UTM	Records (years)
2GB1	Malewa	0210988	9937654	55
2GB5	Malewa	0210217	9945348	31
2GB4	Malewa	0219913	9969390	22
2GC4	Turasha	0212797	9947266	48
2GC5	Turasha	0228256	9939082	37
2GC7	Turasha	0220737	9936910	43

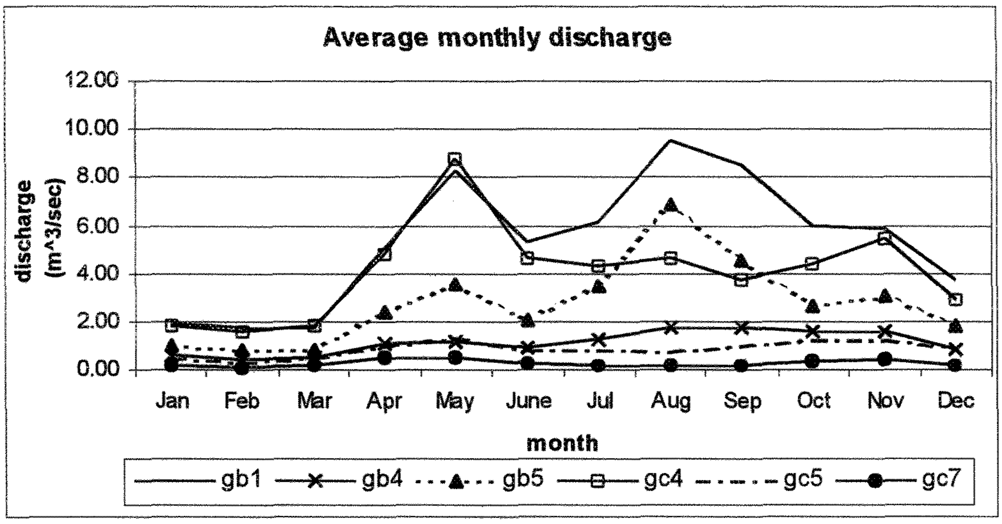


Figure 5.1 Average monthly discharge of the selected gauging stations

5.2 Consistency of the data

Mass curve has been used as a indicator for consistency check of the discharge series, in general, most of the stations seem to be consistent more or less, 2GB1 shows trend between 1938 and 1965, and 2GC4 shows trend starting at 1994 forwards. Figure 5.2 shows Mass curves for the six gauging stations.

5.3 Base flow separarion

Before separating hydrograph components, it is necessary to identify the start and the end of surface runoff and the shape of the line between these two points. The starting point is usually easily identified where the hydrograph diverges from constant or steadily declining baseflow, which prevailed previously. The other two components are more difficult to define.

For the years of simulation 1975, 1977 programme TIME PLOT was used to analyse the rainfall-runoff relationship through separating the base flow of the daily discharge over a year. Discharge data of 2GB1and 2GC4 Gauging Stations and Theissen average of Rainfall have been used as input data. Coefficient α which determines the shape of the separating line was taken 0.985. Table 5.3 summarises the results of baseflow separation, figures 5.3a,b,c,d show the graphs of baseflow separation.

Analysing of the graphs shows that there are not always response of the catchment to the rainfall event, this phenomenon can be interpreted by many reasons, errors or missing values in the rainfall and discharge measurement, inconvenience of the distribution of rainfall stations over the catchment, and other factors due to special hydrological or physiographical symptoms of the catchment. From another hand Turasha sub-catchment reflects more response to the rainfall events than Malewa, usually.

Table 5.3 Base flow separation results

year	Catchment	Base flow m^3/sec	Storm runoff m^3/sec	Total flow m^3/sec	Thiessin avg. rain mm
1975	Malewa	1508.2	816.0	2324.3	805.7
1977	Malewa	1002.1	1184.8	2187.0	1177.3
1975	Turasha	560.4	372.4	932.9	728.3
1977	Turasha	1085.5	1008.7	2094.2	1292.1

5.4 Runoff coefficient

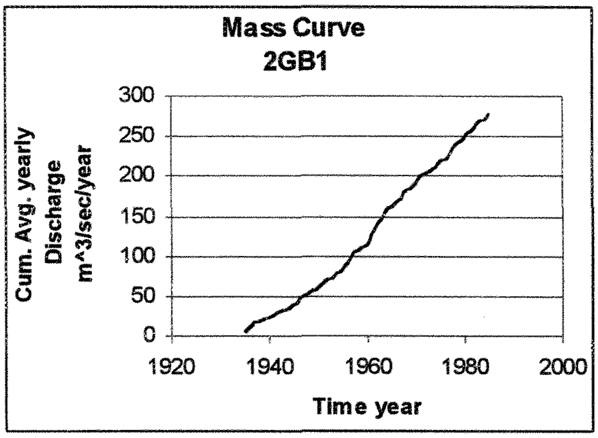
On the basis of TIMEPLOT results, runoff coefficients have been calculated for the years of simulation and for Malewa and Turasha basins, table 5.4 summarises the results of calculation. Three things can be noticed from the table, firstly, runoff coefficient is between (5.7 - 6.0) % and (5.5 - 8.4)%for Malewa and Turasha respectively depending on the rainfall amount, secondly, increasing the rainfall will be accompanied by slightly increasing in the runoff coefficient and vice versa, thirdly, runoff coefficient didn't change when the area of the catchment doubled.

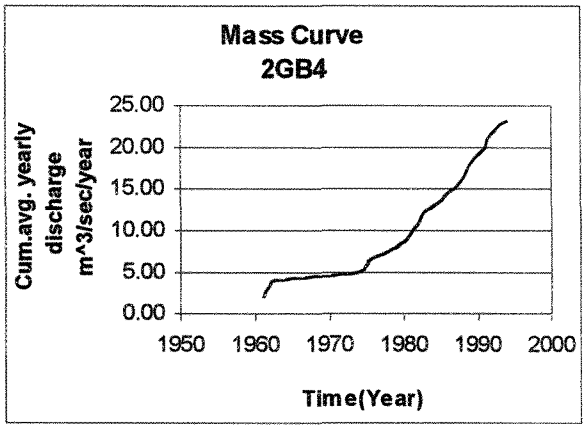
Table 5.4 Runoff coefficient results

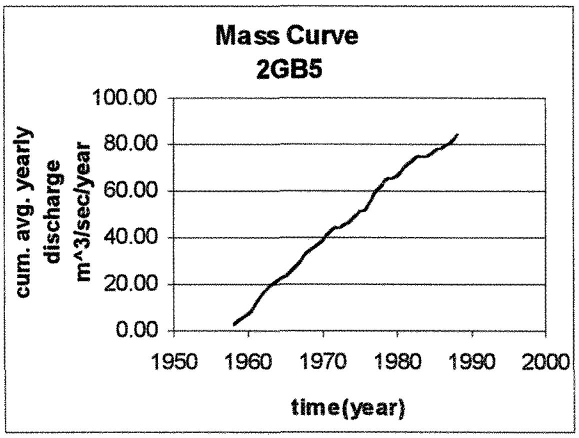
year	Catchment	Thiessen avg. rain mm	Baseflow coef. %	Storm runoff coef %	Total flow coef. %
1975	Malewa	805.7	10.5	5.7	16.1
1977	Malewa	1177.3	5.0	6.0	11.0
1975	Turasha	728.3	8.3	5.5	13.8
1977	Turasha	1292.1	9.0	8.4	17.4

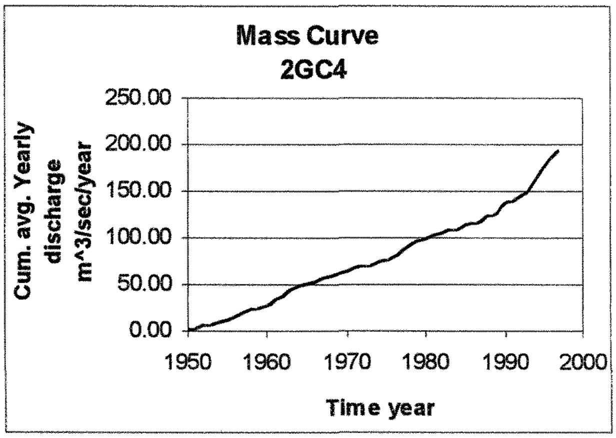
5.5 Conclusion

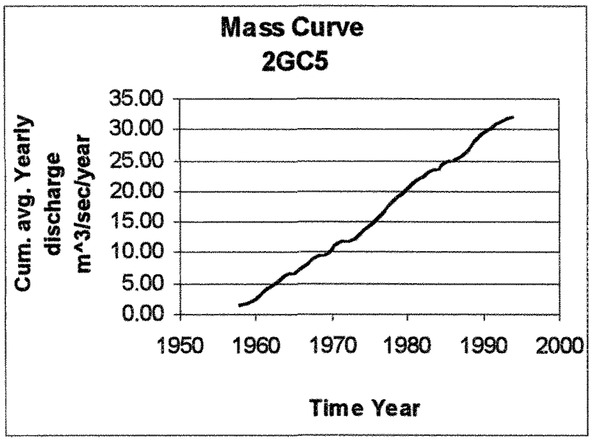
- Discharge records are more or less consistent.
- Missing values are present and vary from days to months
- Non response of the catchment to the rainfall events doesn't prove errors in rainfall or discharge measurements because of the complexity of the rainfall runoff process.











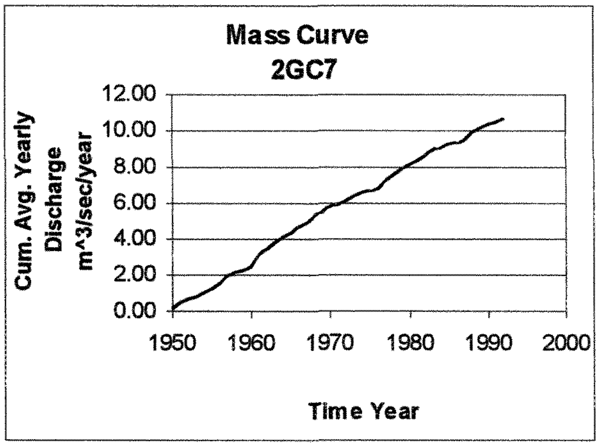
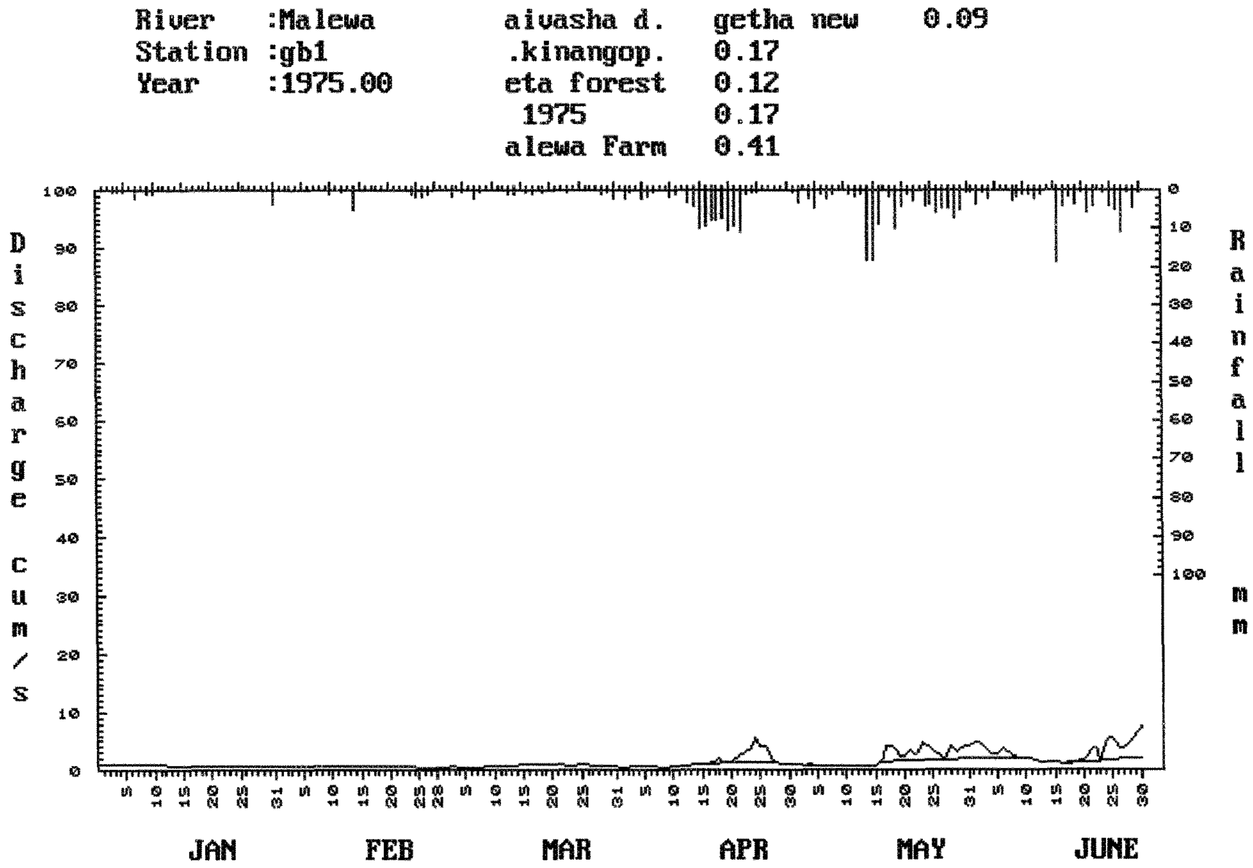


Figure 5.2 Mass Curve of the gauging stations



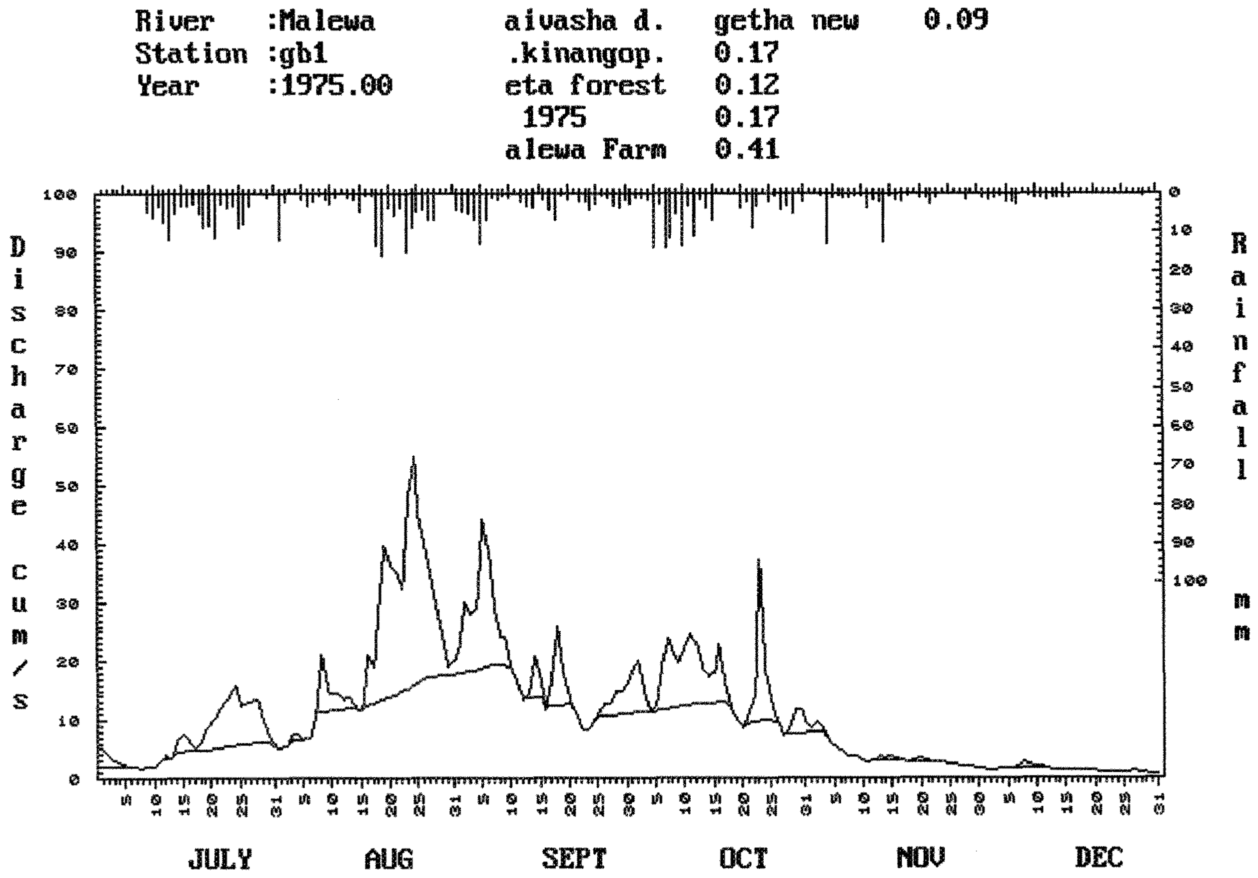
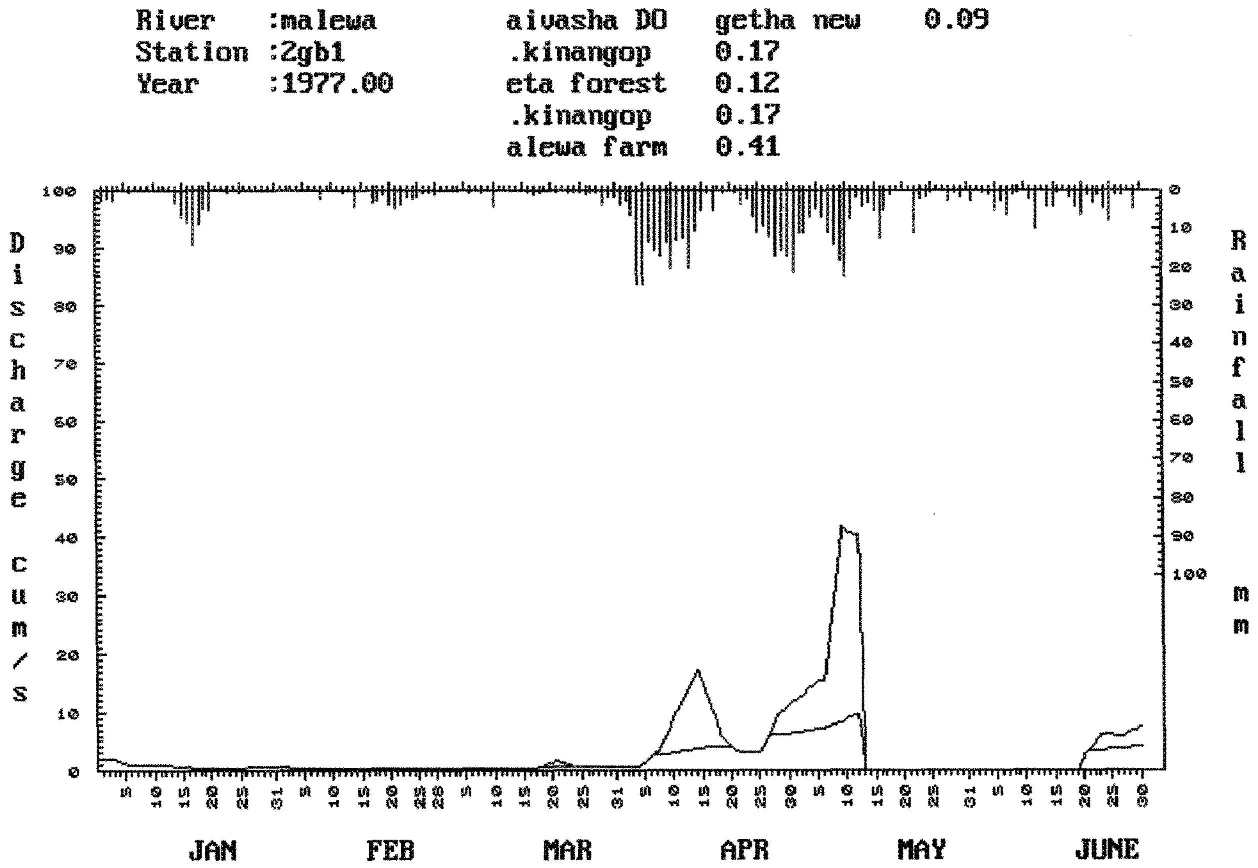


Figure 5.3.a Baseflow separation for Malewa catchment, year 1975



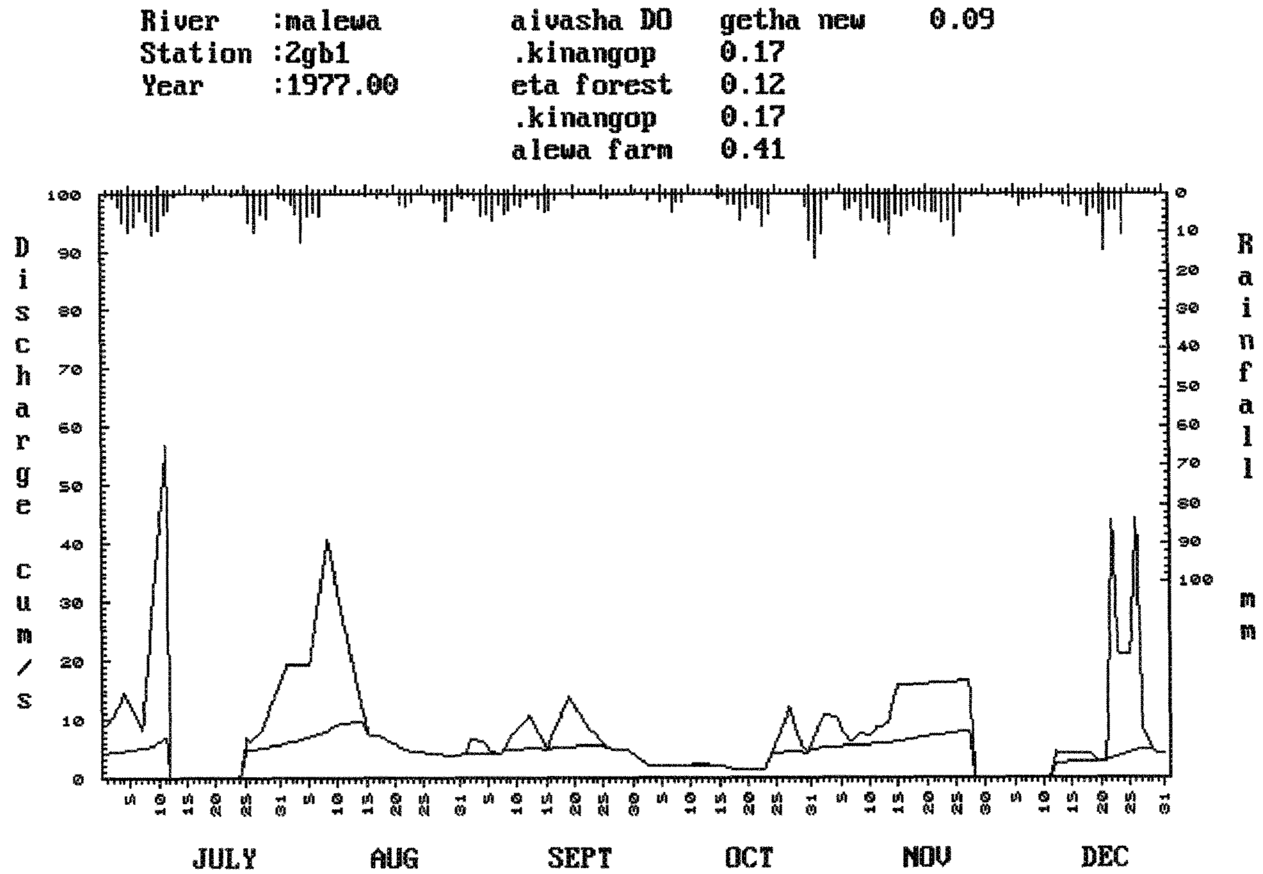
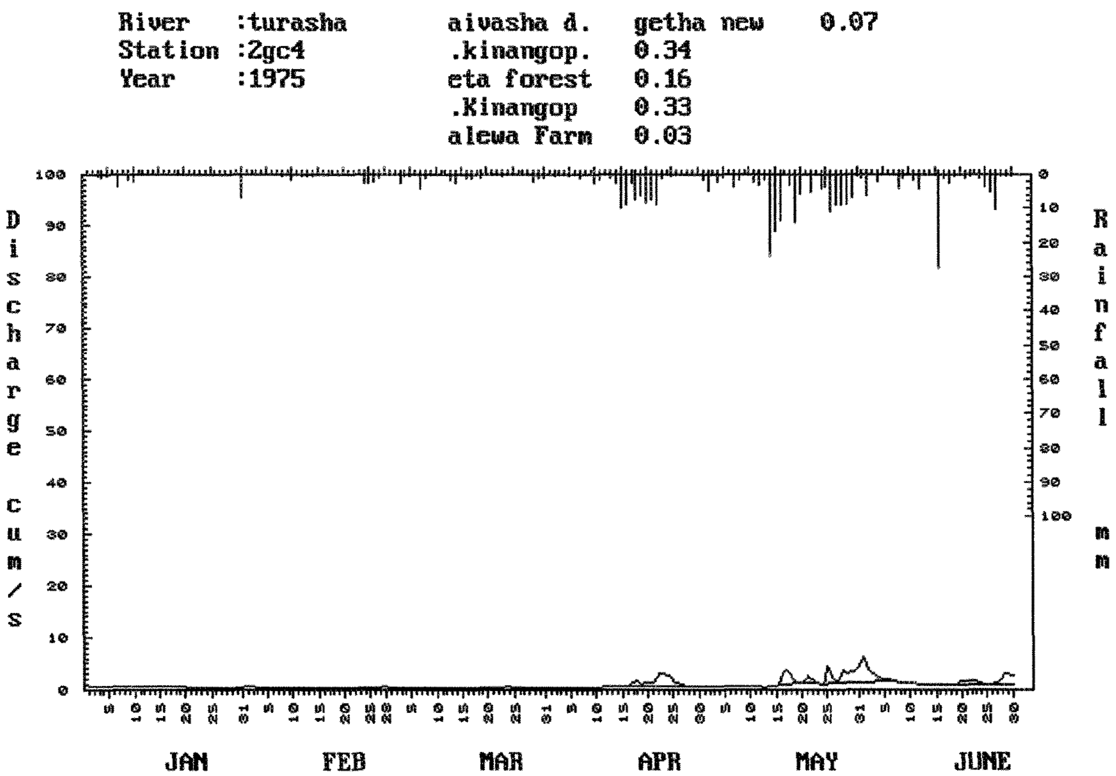


Figure 5.3.b Baseflow separation for Malewa catchment, year 1977



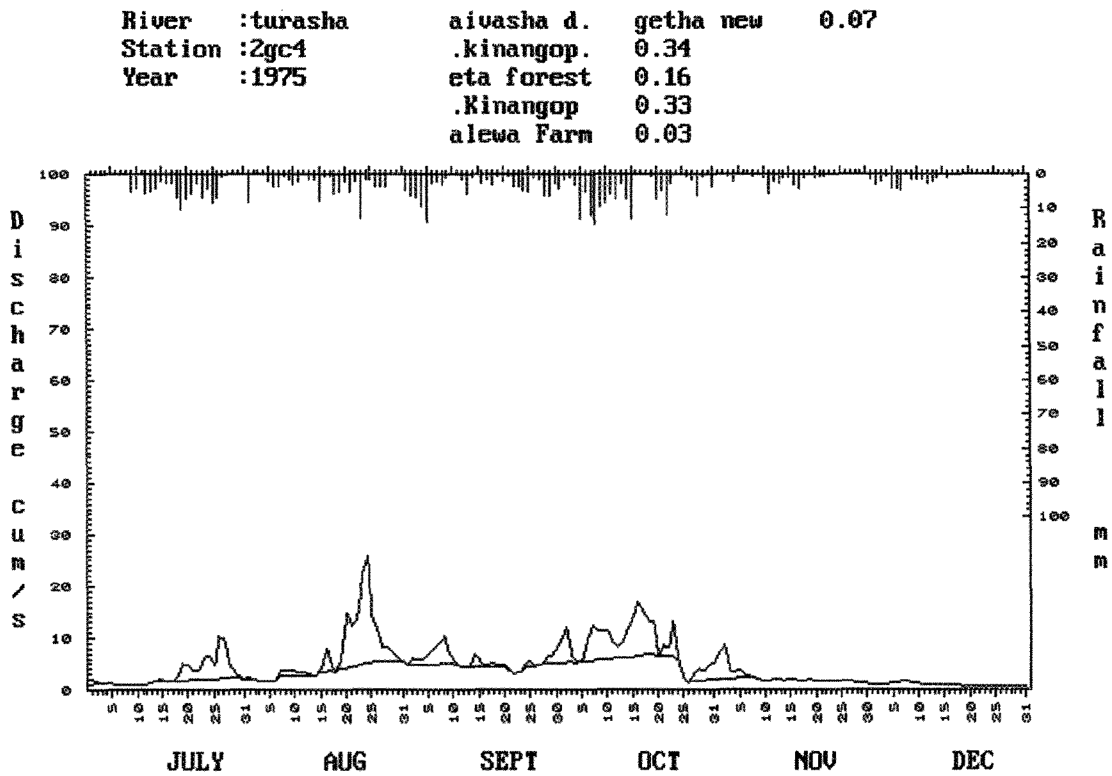
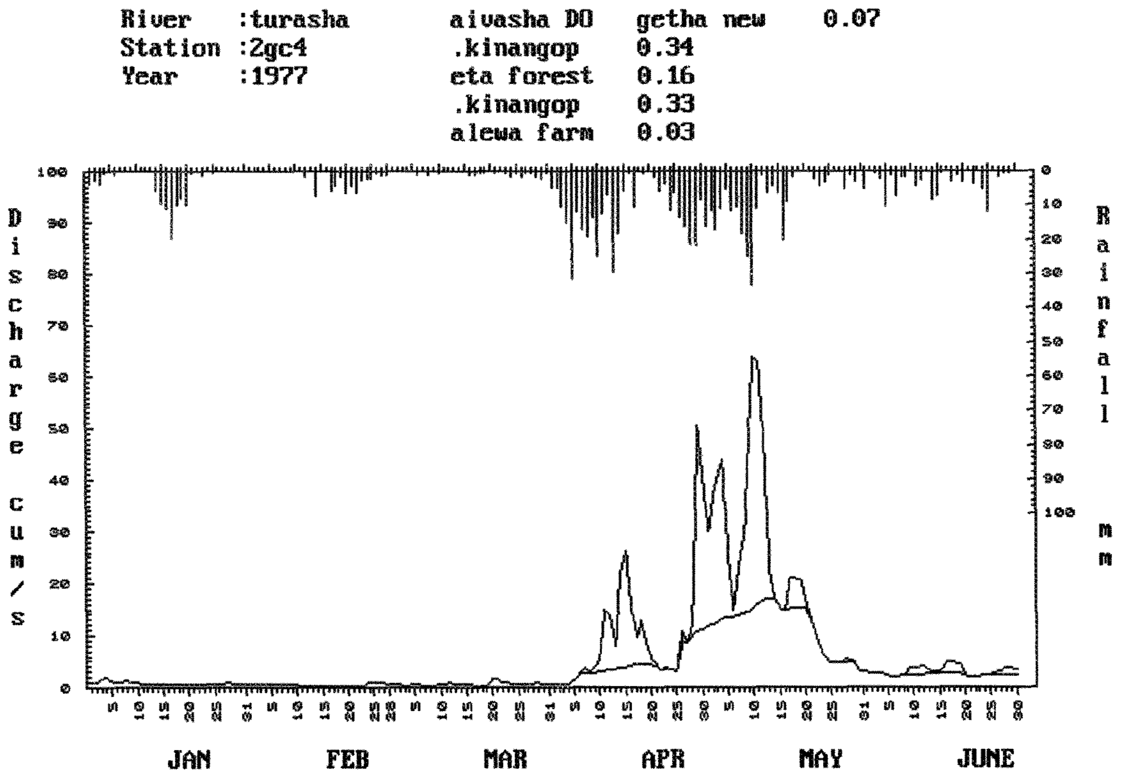


Figure 5.3.c Base flow separation for Turasha sub-catchment, year 1975



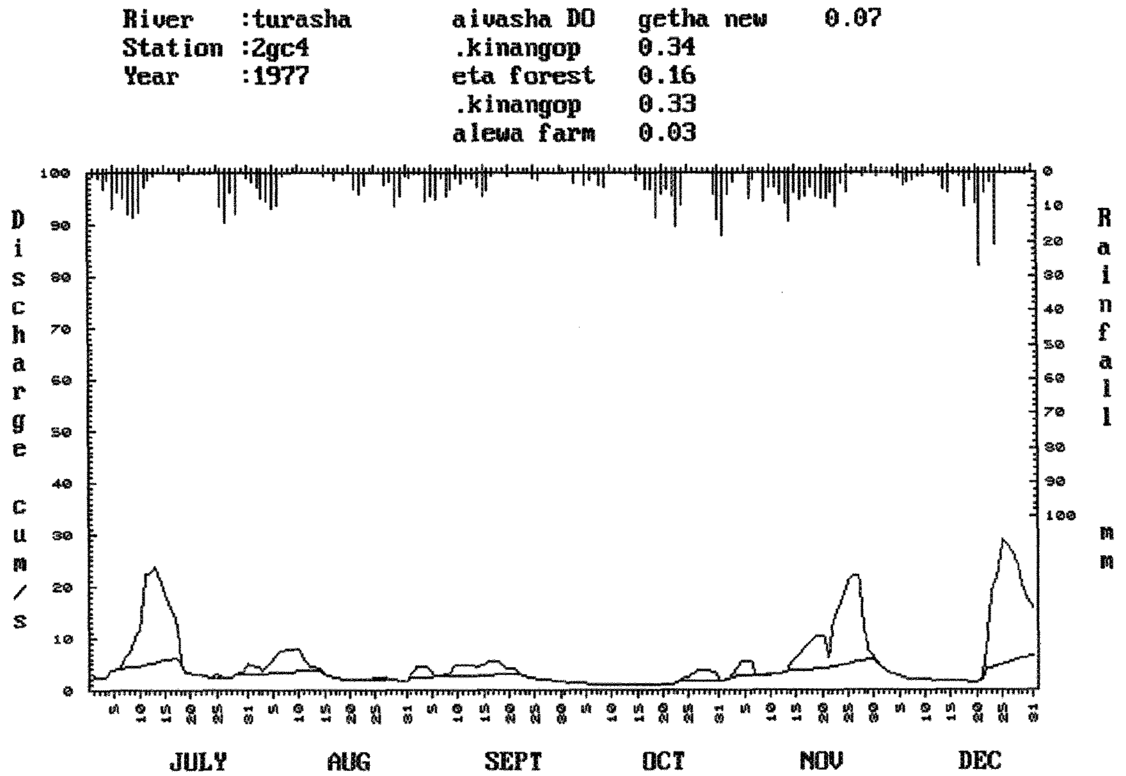


Figure 5.3.d Baseflow separation for Turasha sub-catchment, year 1977

CHAPTER 6

RUNOFF SIMULATION

6.1 Introduction

In order to simulate the runoff using SLURP, Three types of input data have been prepared: time series, physiographic data, and model parameters.

Daily series as (rainfall, discharge, air temperature, wind speed, relative humidity, and global radiation) were rearranged in a certain format to be readable by SLURP. The physiographic data of the catchment were calculated by TOPAZ starting from DEM. Some of model parameters have been measured or estimated and the others have been calibrated.

Model calibration is a complicated and time consumed process, because of limitation of time of this study, calibration of SLURP was stopped after many attempts. Therefore, the results were not accurate enough from one hand and overestimated from another hand.

Lacking of many meteorological data for the exact years of simulation as (wind speed, global radiation, relative humidity and temperature), missing measurements in the meteorological records, and non availability of satellite images on monthly basis also affected accuracy of the results.

6.2 Parameters of sattelite images

LAI and surface albedo have been derived from satellite images, in addition to land cover classification. Landsat7 (TM) 2000 series have been used.

6.2.1 Available data

Two series of the satellite images with different dates have been used in this study:
Landsat 7, Thematic Mapper, TM1, TM2, TM3, TM4, TM5, TM6, TM7, and TM8
Date: 21of February 2000 for the right side of the catchment and 18 of May 2000 for the left side of it.
Spatial resolution: 30m for visible range images(TM1-5,7), 60m for thermal infrared images(TM6), and 15m for panchromatic images (TM8).
Pass times of LandSat –7 in February and May are 10:37 AM and 10:40 AM respectively.
Solar zenith angles of February and May images are 34.167 degree and 33.45 degree respectively.

6.2.2 Geometric correction

Remote sensing data is affected by geometric distortions due to sensor geometry, scanner and platform instabilities, earth rotation, earth curvature, etc. some of these distortions are corrected by the image supplier and others can be corrected by referencing the images to existing maps. By applying affine transformation (first order transformation) the correction of all distortion is done at once.

In order to define the relationship between rows and columns in the image and XY coordinates, Geo-referencing was done by selecting 25 well distributed tie points (reference points) on the topographic map of scale 1:50000 which well distinguished on the images as well. RMSE error or Sigma was 0.79. The images then were resampled using the nearest neighbour technique. The images resampled again with pixel size 500 m In order to coincide with the digital elevation model.

6.2.3 Land cover classification

For land cover classification, numbers of bands combination were used to produce false colour composite (Red, Green, Blue), because different cover types has its unique spectral response in the electro

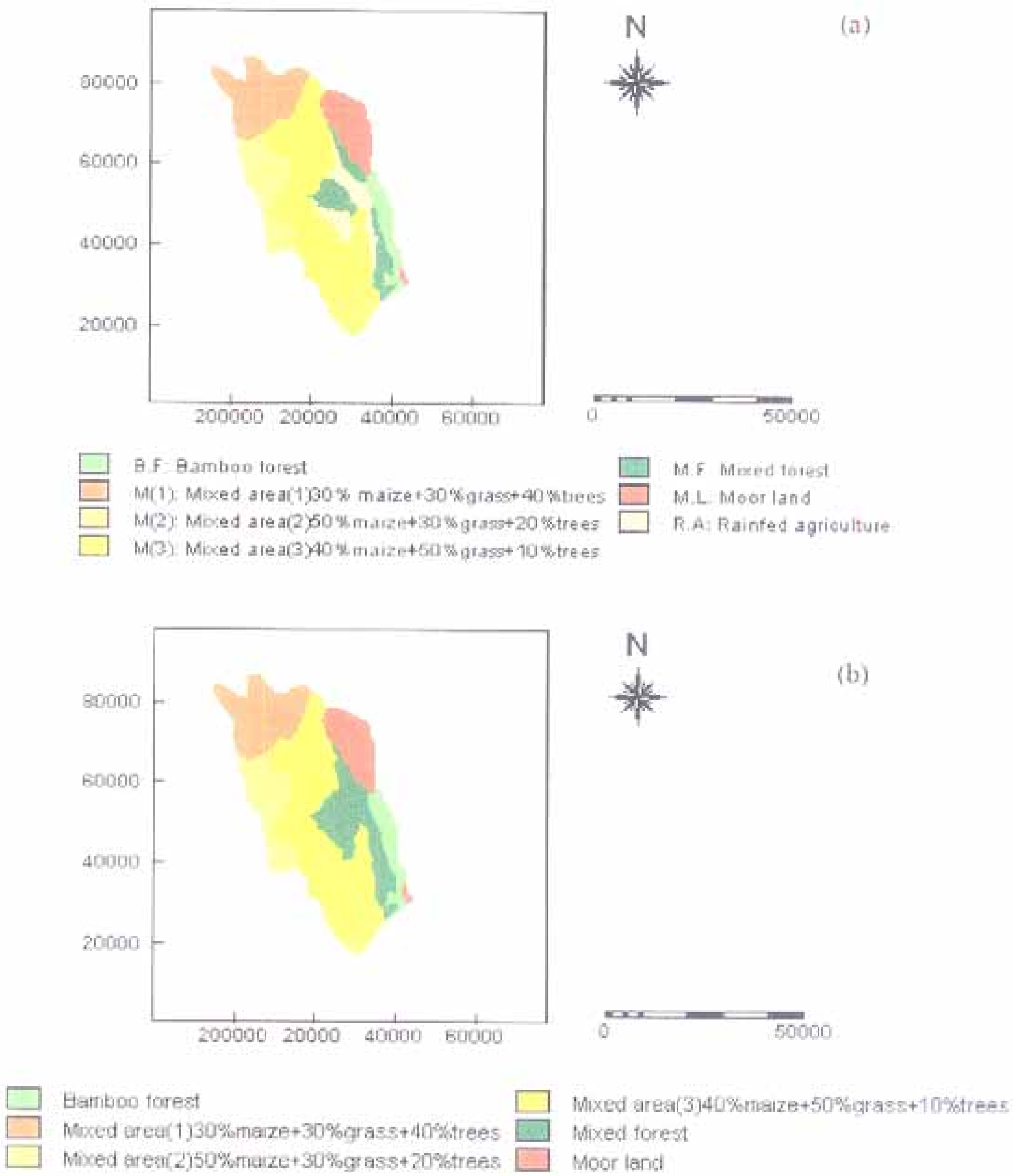


Figure 6.2.3 Land cover maps (a) and (b) for years of simulation 1992-1993 and 1975-1977 respectively.

magnetic spectrum. The best result yielded by combining the following bands:
TM4(Red), TM5(Green), TM3(Blue).
The classified map using supervised classification method was not satisfied because of the widely mixing areas in the catchment, especially for the agricultural and natural vegetation areas. A correction had been done according to what have seen during the field work using segment digitising of the catchment to many classes with percentages of different land cover.
Two land use maps have been created to fit 1992/1993 and 1975/1977 dates. The main class which have been changed with the time was Mixed forest which converted in some parts into rainfed agricultural. These two maps have been transferred into SLURPAZ as ASCII file,Figure 6.2.3 shows two land use maps.

6.2.4 Leaf area index

SLURP uses LAI to calculate interception from canopy and to estimate evaporation and transpiration from fast storage(Jeoff Kite, SLURP manual).
Because area of the catchment is quite big (1700 km^2),it was covered by two satellite images with different dates as mentioned before, but because calibration factors of Land sat –7, 2000 don't differ from May to February and no information about the growing season of the crops (essentially for the Maize), therefore the calculations have done only once after gluing the two images , the left and the right ones. Although the southern part of the catchment which represent almost 2% of the total area was out of the images.

Firstly, digital number of bands 3 and 4 was converted into spectral radiances by applying the formula (3-5), calibration factors have been downloaded from the Internet through U.S. Geological Survey web site (see references), table 3.4.2.1 in the appendix A shows calibration factors for May and February 2000.Secondly, NDVI, SAVI, and LAI maps have been generated by applying the formulas (3-4), (3-3), and (3-2) respectively.

Values of average LAI varied between 0.25 for the mixed areas (2) and 6.5 for the Bamboo forest . LAI of the mixed areas was considered stable over the year as the forested areas because of the reason mentioned previously . See table 6.2.4.

Values of LAI related to different land covers seem to be reasonable according to the table available in (AHVRR hydrological analysis system, algorithm and theory, version 1.0 ,page 9, by Ir. Gabriel N. Parodi). For the very dense Bamboo forest and mixed forest, LAI are so high 6.5 and 5.2 respectively, both land covers have almost the maximum values of this parameter, while rest of the land covers which show less vegetation have smaller values.

Table 6.2.4 average LAI for different land cover

Land cover type	Average LAI
Moor land	2.75
Mixed forest	5.20
Bamboo forest	6.50
Rainfed agriculture	2.50
Mixed area(1)	0.35
Mixed area(2)	0.25
Mixed area(3)	0.29

6.2.5 Surface albedo

SLURP needs average value of surface albedo for each land cover. Because two images have been used in this study of different dates February and May, different pass time and subsequently different solar zenith angles , the calculations of surface albedo have been done twice. In order to extract this parameter from the images, digital number has been converted into spectral radiance at the top of the atmosphere for the rest of the bands(1, 2, 5, 7) by applying the formula (3-5). Shortwave hemispherical planetary reflectance was calculated by applying the formula (3-6), the integrated broad band reflectance at the top of the atmosphere was calculated by applying the formula (3-7) and subsequently surface albedo have been derived using the formula (3-9) which propose a linear relationship between the planetary albedo and the surface albedo. Table 6.2.5 shows average values of surface albedo.

The highest values of surface albedo were related to the mixed area (2) and mixed area (3), while the lowest values were related to the very dense vegetated areas, moor land, mixed forest, and bamboo forest. Comparing of these values with literature relevant to the area (estimation of regional evaporation under different weather conditions from satellite and meteorological data, phd. thesis, H.O. Farah, 48.pp) indicated at acceptable numbers.

Table 6.2.5 Average surface albedo for different land covers

Land cover type	Average surface albedo
Moor land	0.05
Mixed forest	0.07
Bamboo forest	0.07
Rainfed agriculture	0.10
Mixed area(1)	0.07
Mixed area(2)	0.15
Mixed area(3)	0.13

6.3 Measured parameters

Infiltration rate and hydraulic conductivity are used by SLURP for simulating the subsurface flow processing through two linear reservoir, fast storage (aerated soil zone) and slow storage (ground water zone).

Infiltration rate and hydraulic conductivity have been measured during the field work period for many land cover and different soil types.
Different methods of infiltration measurement exist, as ring infiltrometer, double ring infiltrometer, rainfall simulator, and pond test. The most important and popular one is double ring infiltration test, see(Basic hydrology, subsurface water, 1996, by Ir. Hans de Brouwer).

In general, the tests gave too high values between (432-2880) mm/day, the highest value was in the mixed forest, although most of the soils of the catchment were classified using feeling test as clay or clay loam , for one location it was sandy loam. That matter may be interpreted that origin of clay of the catchment are different than the impermeable popular one. It is advise for future works to repeat the test for selected dense net of points associated with laboratory soil tests. Table 6.3 shows the results of infiltration test, for more details about the used method see appendix A.

Inverse auger method was used for measuring the hydraulic conductivity for different land covers inside the catchment, the tests have been done associated with the infiltration tests for each place. Values of the hydraulic conductivity vary between (0.7-104)cm/day, also these values are high. So, it looks there is compatibility between the infiltration rate and the hydraulic conductivity of the catchment. See table 6.3 for the results and appendix A for detailed method.

Table 6.3 results of infiltration rate test and inverse auger test

Point	X Coordinate	Y Coordinate	Land cover	Soil type	Lithological formation	Infiltration rate mm/day	Hydraulic conductivity Cm/day
1	0221728	9930362	Natural vegetation	Clay loam	Volcanic tuff	576	2.1
2	0207473	9964142	Maize field	Clay loam	Volcanic tuff	864	2.4
3	0213162	9964552	Mixed area	Loam	Volcanic tuff	576	0.7
4	0211754	9964696	Grass land	Clay	Volcanic tuff	432	3.1
5	0236666	9946298	Bamboo forest	Loam	Volcanic tuff	-	69.6
6	0231097	994232	Cabbage field	Sandy loam	Volcanic tuff	-	104
7	0222277	9949536	Mixed forest	Silt loam	Volcanic tuff	2880	34.8

6.4 Estimated parameters

Manning's roughness coefficient have been estimated for many channels inside the catchment for routing calculations, many factors usually affect "n" coefficient as bed material, surface irregularities, obstructions, vegetation, and meandering of the channel. whole channels inside the catchment show high vegetated slopes and presence of boulders and rock outcrop in channel bed . see table 6.4 for the estimated values and Appendix A for the detailed calculations of the discharge of many streams inside the catchment.

Table 6.4 Estimated Roughness coefficient

Stream	Roughness coefficient
Malewa	0.068
Turasha	0.07
Kitiri	0.09
Wanjohi	0.057

6.5 From DEM into ASAs

Contour map was digitised from two topographic maps, sheets of scale 1:50000 for 90% of the catchment and sheets of scale 1:250000 for the rest 10 % which located in the upper part of it. A digital elevation model DEM was created using interpolating technique. DEM have been transferred from ILWIS into TOPAZ as ASCII file after resampling it with pixel size 500 m regarding to the capacity of TOPAZ. Figure 6.3 (a) and (b) shows DEM map and ASAs which created by TOPAZ respectively.

6.6 Calibration of SLURP parameters

SLURP uses ten parameters related to soil and land cover unites, these parameters are:

- Initial contents of snow store (mm).
- Initial content of slow store (%).
- Maximum infiltration rate (mm/day).
- Manning roughness n.
- Retention constant for fast store.
- Maximum capacity for fast store (mm).
- Retention constant for slow store.
- Maximum capacity for slow store (mm).
- Precipitation factor.
- Rain/snow division temperature (degree c°).

For this study, four parameters have been calibrated for each land cover, retention constant for fast store, maximum capacity for fast store, retention constant for slow store, and maximum capacity for slow store, rest of the parameters have been measured, estimated or neglected. The model was calibrated twice because of changing of land cover between years of the seventies and years of the nineties. Trial and error method has been adopted to calibrate these parameters. by changing individual parameter, making series of simulations and comparing the criteria values with the generated hydrograph, the parameters can be optimised.

Because of calibrating process demands very long time, long series of meteorological data, reliable data, and non presence of missing values particularly in the rainfall and discharge data, it was stopped after series of attempts regarding to limitation of time. therefore, might be the result of the model was not accurate enough, and computed discharges were compared with the observed ones only on the basis of percentage of total. For further work, calibration of the model should be repeated with more reliable data (logger data) and long series of meteorological data.

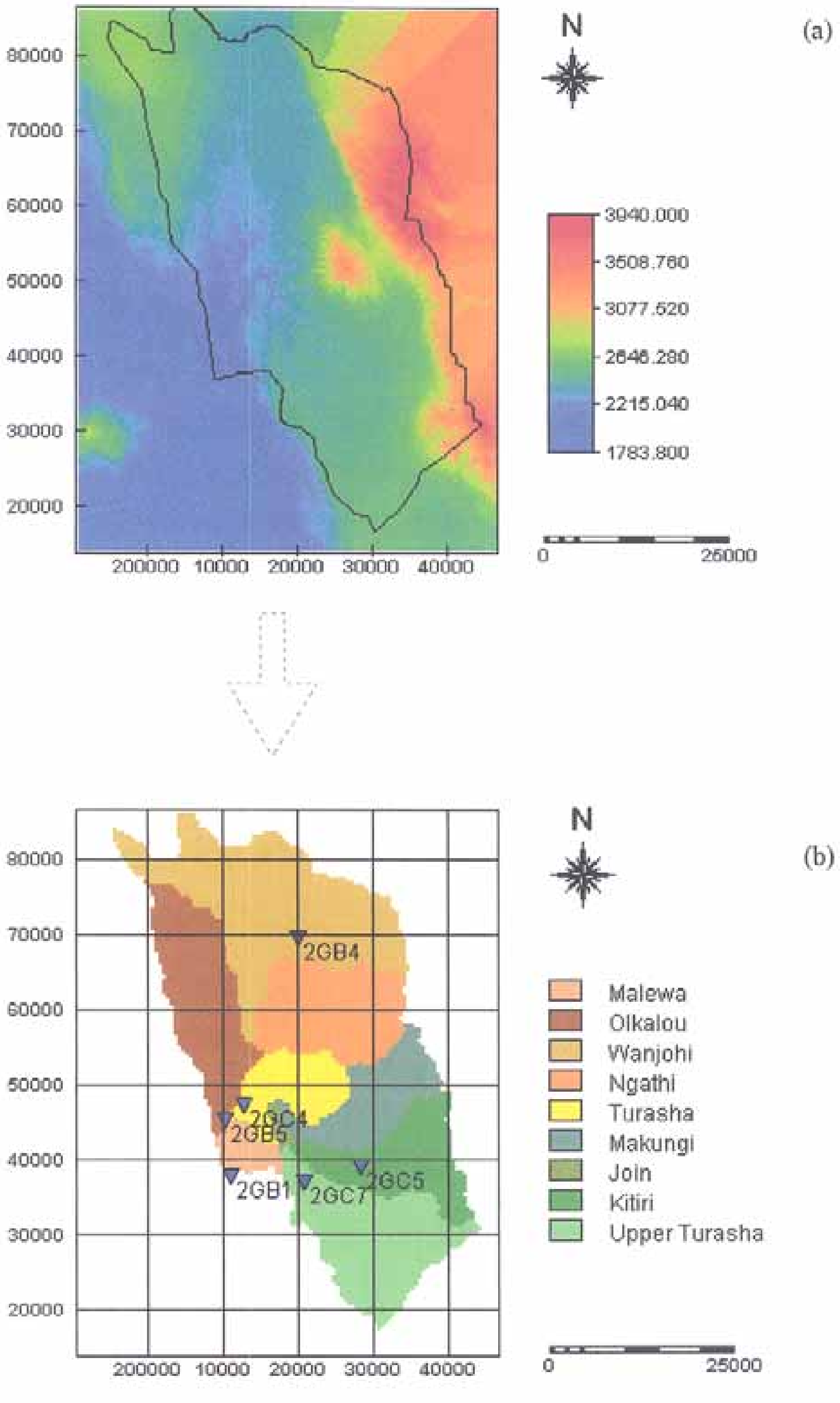


Figure 6.3 (a) and(b), DEM map and ASAs generated by TOPAZ respectively

6.7 Results and discussion

The model has been run four times, firstly, for 1975 and 1977 simulation, and then it recalibrated again to simulate years of 1992 and 1993. discussion of the results was built depending on three criteria, Whole basin, ASAs , and land covers.

6.7.1 Analysis based on whole basin

Many conclusions can be derived from the results shown in table 6.7.1.1, figures 6.7.1.1 a, b, and 6.7.1.2.a, b, below.

- Computed discharge exceeds observed one (2-5) times, this clear difference could be attributed into non well calibrating of the model, low estimation of evapotranspiration which will be discussed later on, or non reliability of observed discharge.

- Observed discharge for dry year is more than observed discharge for wet year and that proves interest of availability of missing values in the discharge measurements or non reliability of the discharge measurements in general.

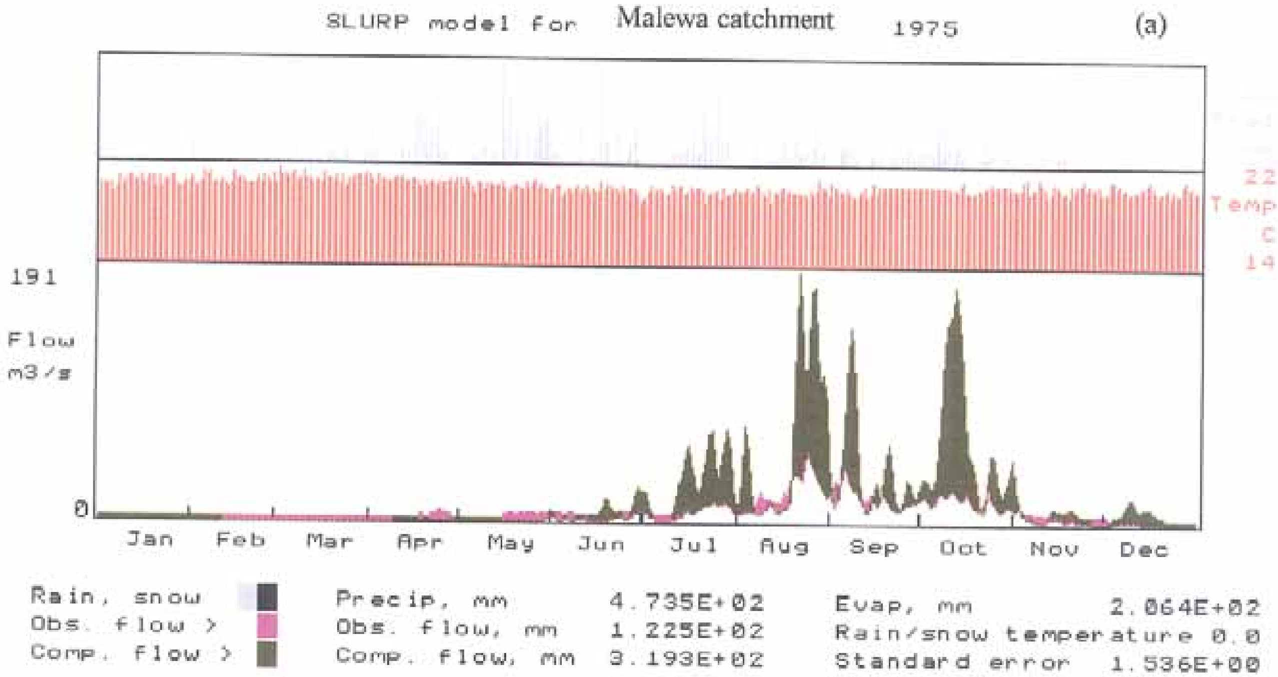
- The annual evapotranspiration is too low comparing to the literatures which estimated evapotranspiration in Naivasha basin, for Malewa catchment it varies between (1000-1300)mm/year depending on the elevation, (Phd. thesis, estimation of regional evaporation under different weather conditions from satellite and meteorological data, 2001, H. O. Farah, 161pp), for calculation of evapotranspiration, SLURP calculates it for slow storage and fast storage depending on monthly values of leaf area index, LAI values which were derived from the satellite image were entered as stable values for whole months as mentioned before and LAI values for the mixed area in general were low (0.3-0.6), may be that affected the amount of evapotranspiration, even though an attempt was done to increase LAI values, but evapotranspiration remained between (400- 600) mm/year and that is still almost half of the estimated values mentioned before.

- Non response of the catchment into rainfall storms, that is more clear in 1975 than the others, could be attributed to either just hydrologic behaviour of Malewa catchment, or calibration of the model is still unfinished yet.

- Computed peakflows are so high comparing with observed ones, as whole computed discharge, but there is temporal compatibility more or less between the observed peakflows and computed ones. As runoff coefficients are also too high.

Table 6.7.1 results of SLURP based on whole basin

	Year	Precipitation	Observed discharge		Computed discharge		Computed Evapo-transpiration	Runoff coefficient		peakflow	
								observed	computed	observed	computed
		mm	mm	m^3/sec	mm	m^3/sec	mm			m^3/sec	m^3/sec
Dry years	1975	864	122	6.6	319.3	17.3	194.9	0.14	0.37	55	190.90
	1993	786.5	---	---	280.0	15.18	303.9	---	0.36	---	165.8
Wet years	1977	1219	112.5	6.10	582	31.6	237.6	0.09	0.47	57	263
	1992	1033	---	---	557.8	30.1	263.2	---	0.54	---	176.10



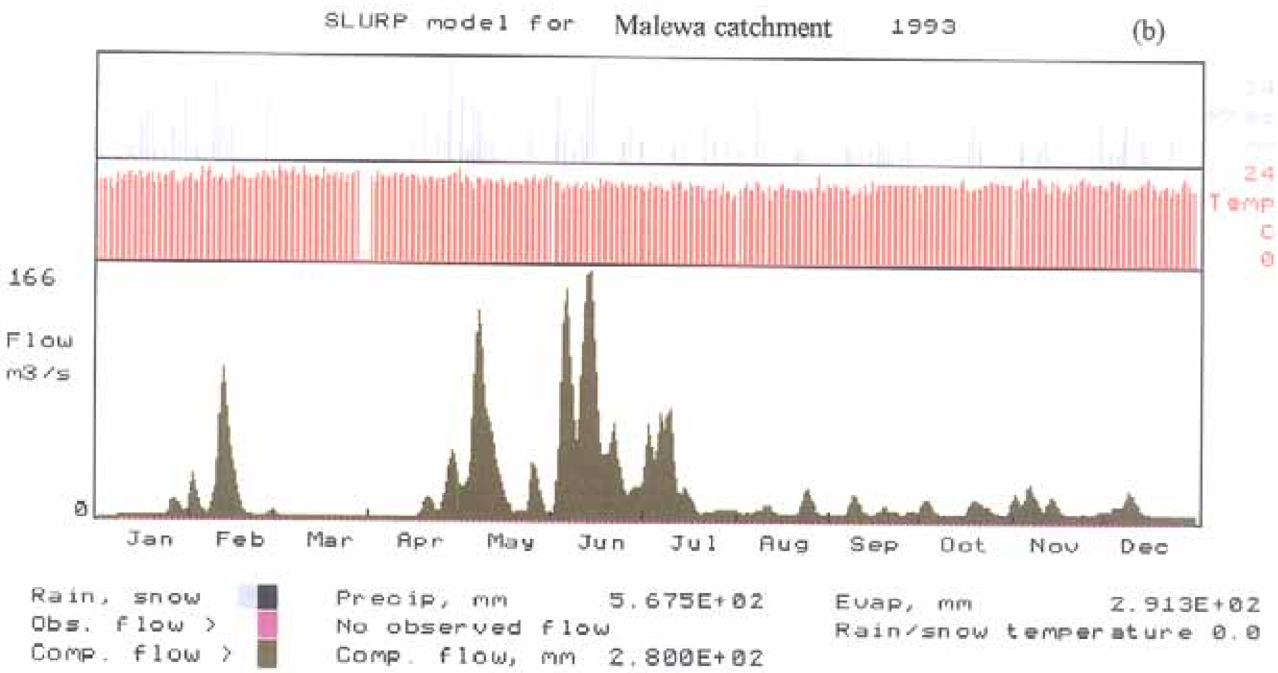
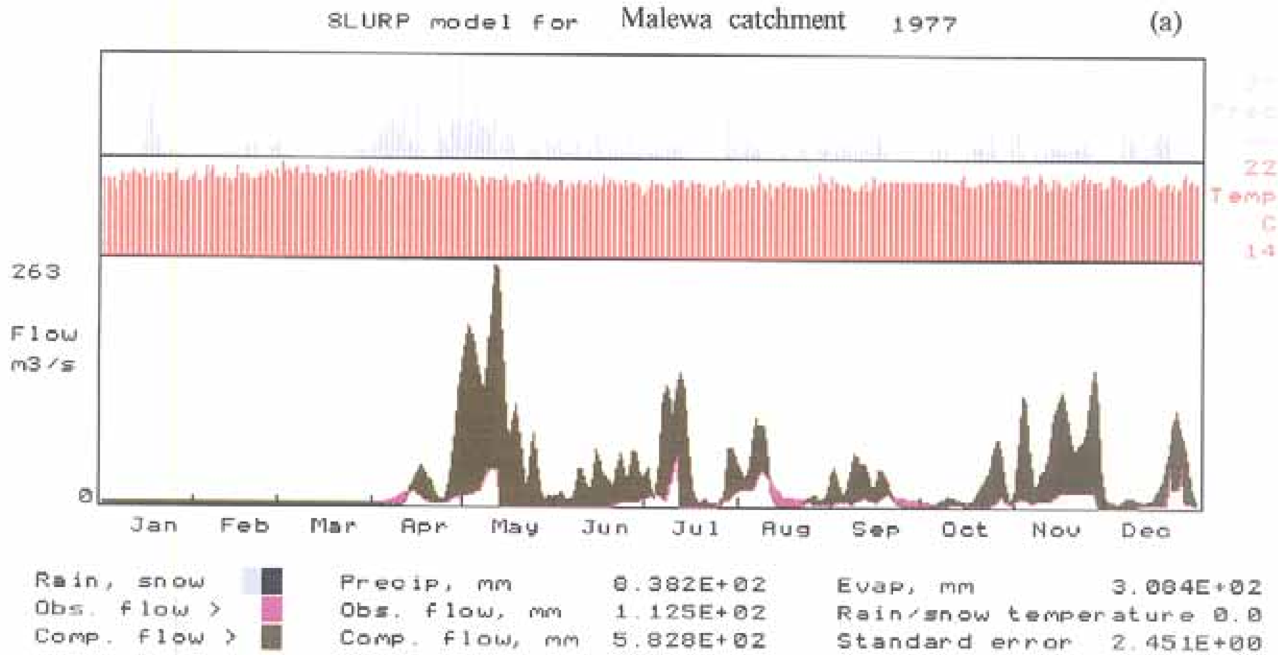


Figure 6.7.1.1. a, and b, hydrographs of the main outlet taken from SLURP for dry years 1975 and 1993 respectively.



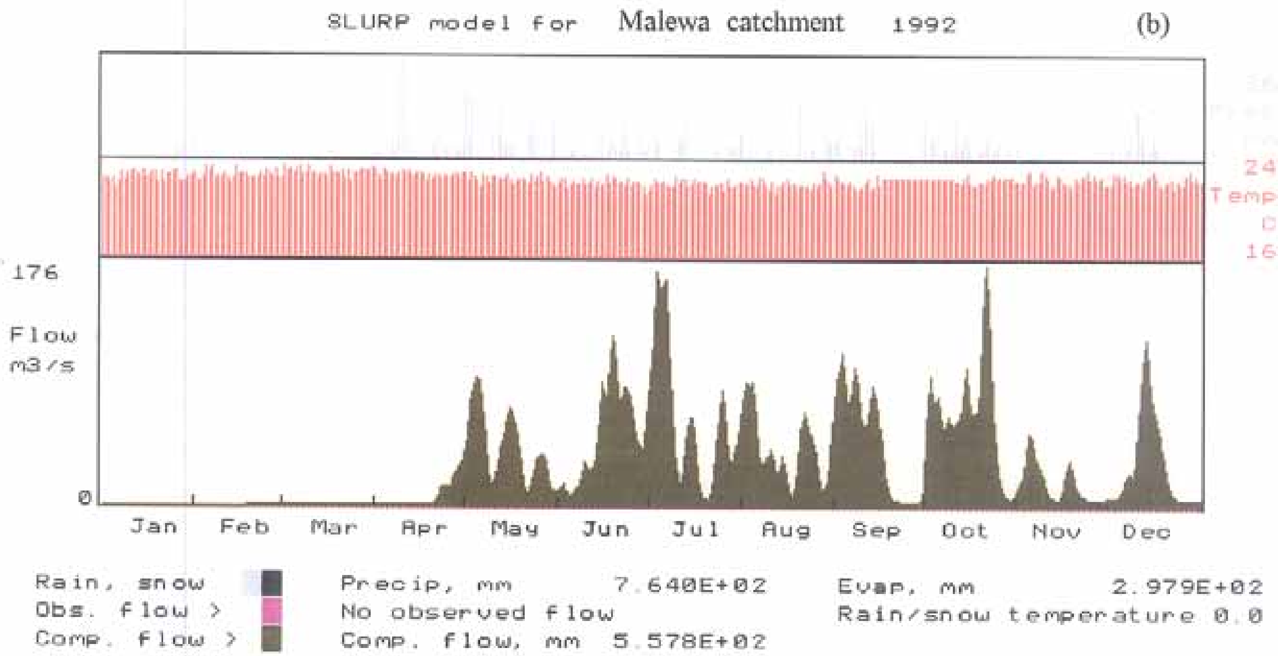


Figure 6.7.1.2. a, and b, hydrographs of the main outlet taken from SLURP for rainy years 1977 and 1992 respectively.

6.7.2 Analysis based on the ASAs

As it was mentioned before, comparing of computed discharges which related to each ASA with the observed ones have been done just on the basis of percentages of total discharge, the following conclusions can be derived:

- Wanjohi which is located in the northern east part of Malewa catchment and it covers 26% of Malewa area, it contains one main river Wanjohi flowing mainly from Nayandarua mountain, result of SLURP says that it contributes with 5.5 m^3/sec which represent almost 30% of Malewa discharge in the dry years and 17% in the rainy years. The observed discharge of this ASA gives almost 3.5 m^3/sec, this value represents 48% of observed Malewa discharge. So, the computed discharge of this ASA is higher than the observed one but its percentage of Malewa discharge is lower.

- Ngathi contains one main river Ngathi and many small tributaries of Malewa which flowing from Kipipiri mountain, it contributes with discharge varies between(2.5-4.55)m^3/sec for dry year and rainy year respectively, which represents 15% of computed Malewa discharge. Unfortunately, there is not gauge station inside this ASA for comparison.

- Olkalou shows fluctuation between the seventies and the nineties, while it contributes with (2-5) % for dry year and rainy year respectively of Malewa discharge in the seventies, this percentage increases in the nineties till (10-12) %, however. comparison of computed discharge with the observed ones shows a gap between both, because gauge station GB5 measures almost 50% of Malewa discharge according to the observed measurement in 1975 (the only available measurement if the measurement of 1977 was neglected because of missing data for GB1), this clear difference can be removed if it was known that GB5 which located almost at the outlet of Olkalou covers three ASAs Olkalou, Wanjohi, and Ngathi. So, if the comparision was done with the accumulated computed discharge the result will be satisfied, because also these three ASAs contribute with almost (35-60)% of Malewa discharge. In all cases Olkalou still shares with low portion of Malewa discharge and that seems to be logical in term of what has been seen during the field work period that low discharge is coming from the streams related to this ASA.

- Kitiri and Upper Turasha have very dense drainage system flowing from the southern part of Nyandarua mountain. they contribute almost equally with almost 12% in the dry year and 20% in the rainy year for each one. the observed discharge in the dry year shows low contribution for both ASAs (6% for Kitiri and almost zero for Upper Turasha), while in the rainy year it shows (17% for Kitiri and 8% for Upper Turasha). In general, Kitiri and Upper Turasha are considered important sources for Malewa catchment .

- In respect to the small areas of ASAs Join and Malewa which were generated by TOPAZ, they will not be included in the analysis, their roles just to rout the discharge received from the upper ASAs more than to generate additional flow.

- There is not gauge station inside Makungi for the comparison, however, the computed discharges show well contribution for this ASA, 10% in the dry year and 15% in the rainy year. this ASA contains one main river Makungi and many tributaries which flowing from Aberdares and Kipipiri mountains.

- Turasha contributes with (4 -6)% of Malewa discharge in the dry years and rainy years respectively. GC4 which available near the outlet of this ASA measures the discharge for whole Turasha basin containing (Upper Turasha, Kitiri, Makungi and Turasha ASAs), so, for the comparison, the observed discharge should be compared with the accumulated one at this ASA (as had been done for Olkalou), the computed accumulated discharges represent (40 – 60)% of Malewa discharge in the dry year and rainy year respectively, and also the observed ones represent almost 50% of observed Malewa discharge(of course, the discharge of GB1 or Malewa ASA in 1977 is not reliable because of presence of too much missing data) , so, there is compatibility in degree of contribution of whole Turasha basin between the observation and the computation. see tables 6.7.2.1, 6.7.2.2, 6.7.2.3, and 6.7.2.4 for more detail.

- As average generated discharges by the ASAs(overall years) as proportions of total are Wanjohi (24%), Kitiri and Upper Turasha (17%) for each, Ngathi (16%), Mankungi (14%), Olkalou and Turasha (5%) for each, Malewa and Join (2%) .

Table 6.7.2.1 discharges of ASAs for year 1975

Year of simulation 1975									
ASA	Local area	Cum. Area	Rainfall	Local discharge		Cum. Discharge		Obser. Discharge	
	Km^2	Km^2	Mm	mm	m^3/sec	mm	M^3/sec	mm	m^3/sec
Wanjohi	448.5	448.5	941	408	5.81	408	5.81	227	3.22
Ngathi	227.3	227.3	1010	477	3.44	477	3.44	---	---
Olkalou	243.8	919.6	688	136	1.05	353	10.3	122	3.57
Kitiri	180	180	950	405	2.31	479	2.31	74	0.42
UpperTurasha	280.5	280.5	843	233	2.07	238	2.07	5	0.05
Join	10.75	471.3	629	8.5	0.028	83	4.41	---	---
Makungi	153.5	153.5	947	436	2.12	436	2.12	---	---
Turasha	121.5	746.3	648	127	0.49	254	7.02	127	3.01
malewa	44.25	1710	474	6.5	0.009	319	17.3	122	6.64

Table 6.7.2.2 discharges of ASAs for year 1993

Year of simulation 1993									
ASA	Local area	Cum. Area	Rainfall	Local discharge		Cum. Discharge		Obser. Discharge	
	Km^2	Km^2	Mm	mm	m^3/sec	mm	m^3/sec	mm	m^3/sec
Wanjohi	448.5	448.5	896	371	5.27	371	5.27	175	2.5
Ngathi	227.3	227.3	781	349	2.51	349	2.51	---	---
Olkalou	243.8	919.6	819	245	1.89	332	9.67	---	---
Kitiri	180	180	774	301	1.72	301	1.72	167	0.95
UpperTurasha	280.5	280.5	731	174	1.55	174	1.55	---	---
Join	10.75	471.3	627	135	0.05	222	3.31	---	---
Makungi	153.5	153.5	706	264	1.28	264	1.28	---	---
Turasha	121.5	746.3	671	207	0.8	228	5.39	129	3.05
malewa	44.25	1710	568	99	0.14	280	15.2	---	---

Table 6.7.2.3 discharges of ASAs for year 1977

Year of simulation 1977									
ASA	Local area	Cum. Area	Rainfall	Local discharge		Cum. Discharge		Obser. Discharge	
	Km^2	Km^2	Mm	mm	m^3/sec	mm	m^3/sec	mm	m^3/sec
Wanjohi	448.5	448.5	1030	398	5.66	398	5.66	---	---
Ngathi	227.3	227.3	1230	631	4.55	631	4.55	---	---
Olkalou	243.8	919.6	797	113	0.87	338	11.1	225	6.57
Kitiri	180	180	1630	1040	5.91	1040	5.91	187	1.07
UpperTurasha	280.5	280.5	1450	777	6.92	777	6.92	54	0.48
Join	10.75	471.3	1360	660	0.23	873	13.1	---	---
Makungi	153.5	153.5	1630	1060	5.18	1060	5.18	---	---
Turasha	121.5	746.3	1180	549	2.11	860	20.3	263	6.22
malewa	44.25	1710	838	136	0.19	583	31.6	113	6.1

Table 6.7.2.4 discharges of ASAs for year 1992

Year of simulation 1992									
ASA	Local area	Cum. area	Rainfall	Local discharge		Cum. discharge		Obser. discharge	
	Km^2	Km^2	Mm	mm	m^3/sec	mm	m^3/sec	mm	m^3/sec
Wanjohi	448.5	448.5	1000	533	7.58	533	7.58	291	4.13
Ngathi	227.3	227.3	1070	612	4.41	612	4.41	---	---
Olkalou	243.8	919.6	909	406	3.13	519	15.10	---	---
Kitiri	180	180	1200	762	4.35	762	4.35	255	1.45
UpperTurasha	280.5	280.5	1050	549	4.88	549	4.88	15	0.13
Join	10.75	471.3	844	341	0.12	625	9.34	---	---
Makungi	153.5	153.5	1250	791	3.85	791	3.85	---	---
Turasha	121.5	746.3	874	403	1.55	623	14.7	200	4.72
malewa	44.25	1710	764	271	0.38	558	30.2	---	---

6.7.3 Analysis based on land cover

Results of simulation of Years 1975 and 1993 were used to analyze how much each land cover contributes to Malewa discharge. in 1975, The numbers indicate that Mixed area (3), Moor land, and Mixed forest contribute with (25-30) % of Malewa discharge for each one separately, Bamboo forest contributes with 11%, Mixed area (2) and Mixed area (1) contribute with 3% separately. In 1993, there is slightly decreasing of Moor land and Mixed area (3) contribution, while contribution of Mixed forest decreased into 14% may be because of shrinking of its area, but Bamboo forest maintained its portion, Rainfed agriculture contributes with 5%, and there is slightly increasing in contribution of Mixed area (1) and mixed area (2).

As average generated discharge by different land covers (average of two years) as proportions of total was found as the following: Mixed area (3) (28%), Moor land (24%), Mixed forest (18%), Bamboo forest (11%), Mixed area(1) (9%), Mixed area(2) and Rainfed agriculture (5%) for each. See tables 6.7.3.1 and 6.7.3.2 below for more detail

Table 6.7.3.1 computed discharges on the basis of land cover, year 1975

ASA	Moor land	Mixed forest	Bamboo forest	Mixed area (1)	Mixed area (3)	Mixed area (2)	Total flow
	m3/s	m3/s	m3/s	m3/s	m3/s	m3/s	m3/sec
Wanjohi	3.48	0.08	0.00	0.00	2.16	0.09	5.81
Ngathi	1.04	1.43	0.01	0.00	0.94	0.01	3.44
Olkalou	0.00	0.00	0.00	0.46	0.09	0.50	1.05
Kitiri	0.06	0.79	0.94	0.00	0.52	0.00	2.31
UpperTurasha	0.06	0.45	0.20	0.00	1.37	0.00	2.07
Join	0.00	0.00	0.00	0.00	0.03	0.00	0.03
Makungi	0.01	1.09	0.72	0.00	0.29	0.00	2.12
Turasha	0.00	0.36	0.00	0.00	0.12	0.00	0.49
malewa	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	4.67	4.19	1.87	0.46	5.52	0.61	17.3

Table 6.7.3.2 computed discharges on the basis of land cover, year 1993

ASA	Moor land	Mixed forest	Bamboo forest	Rain. ag-riculture	Mixed area (1)	Mixed area (2)	Mixed area (3)	Total flow
	m3/s	m3/s	m3/s	m3/s	m3/s	m3/s	m3/s	m3/sec
Wanjohi	2.47	0.08	0.00	0.00	1.57	0.08	1.07	5.27
Ngathi	0.78	0.66	0.01	0.34	0.00	0.02	0.72	2.51
Olkalou	0.00	0.00	0.00	0.00	0.74	0.98	0.18	1.89
Kitiri	0.05	0.43	0.80	0.11	0.00	0.00	0.33	1.72
UpperTurasha	0.06	0.37	0.22	0.02	0.00	0.00	0.89	1.55
Join	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05
Makungi	0.01	0.26	0.53	0.29	0.00	0.00	0.18	1.28
Turasha	0.00	0.37	0.00	0.07	0.00	0.02	0.33	0.80
malewa	0.00	0.00	0.00	0.00	0.00	0.11	0.02	0.14
	3.37	2.17	1.55	0.83	2.31	1.20	3.77	15.21

6.8 Conclusion

- Computed discharge of Malewa catchment was over estimated.
- The average actual evapotranspiration calculated by SLURP was very low comparing with another literature.
- Wanjohi, Upper Turasha, Kitiri, and Makungi play important role in generating discharge for Malewa catchment.
- Mixed area (3), Moor land, and Mixed forest are the most land covers in generating discharge for Malewa catchment.
- It was difficult to extract from SLURP the surface runoff and base flow separately.

6.9 Limitations

Accuracy of results of the model have been affected by many factors:

- Non completing of Calibration of the model because of limitation of time.
- Lacking of complete reliable meteorological data, especially for rainfall and discharge.
- Presence of missing values in the meteorological data vary from days to months for each year of simulation.
- Converting of discharge measurements from gauge discharge into ASAs discharge.
- Non availability of well distributed rainfall stations over the catchment.
- Non availability of meteorological data(except rainfall and discharge data) for years of simulation, the data of year 2000 were used for years of the seventies and the nineties and only from one station (Oserian)which its elevation is lower than average of elevation of Malewa with 900.00 m
- Contour map was digitised from many topographical sheets of different scales and dates (20 years lag time).

6.10 Further work

In spite of importance of the distributed or semi distributed hydrological model, however, it is not preferable to be used unless complete reliable input data are available. For modelling of Malewa catchment, the following steps could be taken into account before repeating the work:

- Using of logger data for all meteorological time series.
- Repeating of digitising of contour map from topographical sheets have the same scales and dates.
- Repeating of the infiltration tests inside the catchment to verify of the high values.
- Enforcing of TOPAZ to differentiate between ASAs locating in the mountainous area and ASAs locating in the valley, because SLURP uses Theissen average method to convert the point meteorological data into areal data, and this method is not realistic where a high difference in elevations is present.
- Recalibration of the model.

CHAPTER 7

SUMMARY AND CONCLUSIONS

The relationship rainfall-runoff in a catchment is a function to the hydrologic and physiographic characteristics of it. The natural features (land-cover) and human-made features (land-use)play important role in the runoff process as well. Studying of this relationship through computer-based hydrologic model is useful tool to simulate runoff from precipitation and understand response of a catchment into the precipitation events, further more, it will enable the user from knowing the impact of changing of a certain factor on the runoff.

For this study, semi distributed hydrologic model SLURP was used, but unfortunately it was risky adventure because of the excessive data needed and time consuming in preparing the huge amount of these data, in addition to calibrating of the model which needs more than MSc thesis period. Therefore, after series of trials and errors steps, calibrating process was stopped.

Malewa catchment in Kenya was used as a case study. The area of the catchment is 1700 km^2, the elevation varies from 1940 m to 3700 m above mean sea level. The elevation differences induce a variation in the areal patterns of precipitation. The catchment has a divers landscape ranging from forests in the mountains to dry range land in the valley. Malewa river is the main river in the catchment, it consider the main source of water for Lake Naivasha. Lake Naivasha is the only source of fresh water in Naivasha basin, there has been an increasingly large demand for water in the basin during the last 30 years due to high population increase of up to 70%, spreading of irrigated flower farms around the lake, generation of electricity, tourism, wildlife, fish cultivation, etc.

In chapter 4, analysis of the rainfall data was achieved to select the reliable years for simulation. Too many rainfall stations are available inside the catchment but very few which have data, therefore, only seven stations were selected, the distribution of the stations was reasonable. Data series are not complete, Almost all stations have missing data vary from days to months per year. By using mass curve and double mass curve methods the outliers were detected and corrected, and reliable periods were selected. For areal rainfall, a relationship was found with the elevation, the correlation factor was (0.65), also Thiessen polygon method was used to calculate the average annual rainfall for years of simulation. It should be mentioned here that SLURP model uses Thiessen polygon method to convert the point rainfall data into areal data.

In chapter 5, gauging stations were selected inside the catchment with respect to availability of the stations and reliability of data, consistency of data were checked using mass curve method. Missing values are present in all stations, TIME PLOT was used for base flow separation. Runoff coefficient was calculated for Malewa and Turasha , it was around 6% . SLURP can not be enforced to create outlets of ASAs at the locations of the gauges exactly , so, flow data was multiplied with a factor to fit the outlet of ASAs.

In chapter 6, whole input data and parameters needed for running of the model were prepared, in addition to discussing of the results of the model. Daily meteorological data were prepared in a certain format to be understandable by SLURP. Whole meteorological data (mean air temperature, global radiation, wind speed, relative humidity, dew point temperature) except rainfall and discharge were taken only from one station (Oserian) which located in the valley near Lake Naivasha. Physiographic data of the catchment have been derived by TOPAZ starting from DEM, most of contour map has been digitized from topographic sheets of scale 1:5000 by WRAP project in Kenya and corrected in ITC because of many errors were found, while the upper part of the catchment has been digitized in ITC from topographic sheets of scale 1:250000.

Infiltration rate is one of the required parameters for slurp, it has been measured for different land covers and soil types, in general, the values were high and varied between (432-2880) mm/day, the highest value was found in the mixed forest, although the soil was classified in most places of the catchment as clay to clay loam, it is advised to check the test again and associated with laboratory soil tests.

Land cover classification, leaf area index, and surface albedo have been derived from the satellite image. Resultant map of supervised classification was not satisfied because of the wide mixing of vegetation inside the catchment, therefore, and according to the ground truth, a classified map was created by segmentation of the catchment into many segments. Another land cover map was created after converting whole rainfed agriculture areas on slopes of the mountains into mixed forest to fit the period of the seventies.

Values of LAI varied between 0.25 for Mixed area (2) and 6.5 for Bamboo forest, comparing of these values with typical ones as which available in (AHVRR hydrological analysis system, algorithm and theory, version 1.0 ,page 9, by Ir. Gabriel N. Parodi) gives reasonable impression. Values of surface albedo varied between 0.05 for moor land and 0.15 for mixed area(2), Comparing of these values with literatures relevant to the area indicated at reasonable results (estimation of regional evaporation under different weather conditions from satellite and meteorological data, phd. thesis, H.O. Farah, 48.pp)

In general, Calibration of any hydrological model requires long time. For SLURP, four parameters have to be calibrated for each land cover, but because of limitation of time from one hand and the complicated structure of SLURP itself for another hand, calibration process was stopped after many trials. Consequently, may be the results were not well reasonable . For further work, calibration of the model should be repeated.

The computed discharge of whole basin was found over estimated (2-5) times comparing with the observed one , this could be due to non completing of calibration of the model, or just because of under estimated value of computed evapotranspiration, or non reliability of observed discharges. Because no way to compare the computed discharges of the ASAs with the observed ones on the basis of value to value, this comparison was done on the basis of proportional representation of total, and this comparison led to reasonable result. The following conclusions can be derived from the results, Wanjohi, Upper Turasha, Kitiri, and Makungi play important role in generating discharge for Malewa catchment. Mixed area (3), Moor land, and Mixed forest are the most generators of the discharge for Malewa catchment.

RECOMMENDATIONS

- To develop a link between ILWIS and SLURP to enable the user from transferring the maps from and into each other easily.
- As future plan, it is advised to install loggers in appropriate locations inside Malewa catchment in order to measure accurately whole meteorological parameters.
- Reconstruction of the rating curves for whole gauging stations of the catchment to obtain more reliable measurement.
- Measuring staff at 2GC10 which located on Makungi river was made of plastic material before its breaking, it should be replaced with metal one.
- The observer of 2GC5 locating on Kitiri river takes one measurement per day , it is preferable to be two measurements per day.
- Many of the observers are staying far away from locations of the gauges which should be measured twice per day, these long distances may create slacking for their performance and subsequently false measurements.

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APPENDICES

Appendix A

Base Data

Table A-1 daily rainfall files of the following rainfall stations:

Station code	records	Annul rainfall (mm)	Station code	records	Annual rainfall (mm)
9036002 *	1935-1998	655.068	9036253	1960-1989	811.08
9036011	1926-1972	835.411	9036257	1962-1998	828.56
9036025 *	1957-1998	1128.87	9036259	1963-1998	2495.96
9036034	1959-1998	577.97	9036261	1964-1998	891.67
9036059	1957-1974	564.37	9036262	1964-1998	674.49
9036061	1957-1998	1322.68	9036264 *	1964-1998	955.88
9036062	1967-1991	631.85	9036272	1965-1998	1296.67
9036065	1957-1981	715.33	9036277	1966-1977	78.85
9036072	1957-1998	902.19	9036278	1967-1980	66.45
9036073	1957-1992	583.61	9036279	1968-1991	32.5
9036076	1957-1998	854.53	9036280	1969-1982	67.72
9036081	1957-1998	689.34	9036281	1965-1998	618.12
9036085	1957-1998	687.64	9036285	1967-1975	467.60
9036109	1957-1998	641.04	9036289	1969-1994	871.30
9036129	1957-1977	717.54	9036290 *	1969-1994	641.30
9036147	1957-1998	721.31	9036294 *	1969-1986	394.72
9036150	1957-1990	606.98	9036296	1970-1982	38.34
9036151	1957-1998	1027.61	9036307	1971-1992	811.66
9036152	1957-1998	1153.02	9036308	1971-1998	1286.37
9036162	1957-1996	660.11	9036309	1972-1985	672.12
9036164	1957-1998	1382.88	9036310	1972-1998	988.08
9036174	1967-1978	940.84	9036312	1973-1998	968.77
9036179	1957-1985	631.15	9036313	1973-1989	7.06
9036183	1957-1975	782.31	9036317	1973-1992	703.13
9036188	1957-1996	1444.61	9036319	1974-1994	540.76
9036198	1957-1975	1229.25	9036320	1979-1997	603.23
9036214	1957-1984	614.48	9036322	1973-1998	537.23
9036227	1957-1997	740.42	9036323	1975-1998	2337.28
9036236	1957-1994	794.12	9036331	1980-1997	766.72
9036241 *	1958-1998	1221.63	9036336 *	1981-1998	941.14
9036243	1958-1998	1250.05	9036337	1984-1998	834.53
9036244	1958-1997	1288.04	9036342	1984-1993	582.7
9036252	1960-1998	1026.02	9036343	1984-1998	627.3

* Indicates used stations for the study.

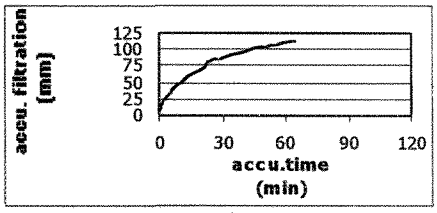
Table A-2 Daily discharge files of the following gauging stations

Gauge Code	River	Record	Gauge Code	River	Record
2GA3	Gilgil	1958-1998	2GB7	Malewa	1960-1994
2GA5	Gilgil	1958-1988	2GC4 *	Turasha	1950-1997
2GA6	Gilgil	1967-1994	2GC5 *	Turasha	1958-1994
2GB1 *	Malewa	1931-1985	2GC7 *	Turasha	1950-1994
2GB3	Malewa	1950-1992	2GD2	Karati	1958-1982
2GB4 *	Malewa	1961-1994	2GD7	Karati	1961-1990
2GB5 *	Malewa	1958-1988			

* indicates used Gauging stations for the study.

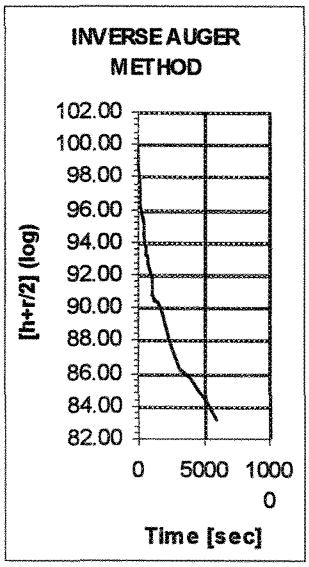
- Water levels data for years (1997-2000) for two gauging stations (2GA3, 2GA6)
- Daily other meteorological data(mean air temperature, relative humidity, wind speed, and radiation) from Ouserian meteorological station
- Topographic maps:
  scale 1:50000, sheets(Naivasha 133/2, Kinangop 134/1, Gilgil 119/4, Kipipiri 120/3)
  scale 1:250000, sheet Neyri
- Satellite images:
  LANDSAT7, TM(1-8) dated on february 2000 (dry season) for the right part of Malewa catchment
  LANDSAT7, TM(1-8) dated on may 2000, (rainy season) for the left part of Malewa catchment
- Field measurements:
  Infiltration test and Hydraulic conductivity for different land cover in the catchment(forest, grass land, maize land), cross sections for many streams(Malewa, Turasha, Kitiri and Wanjohi).

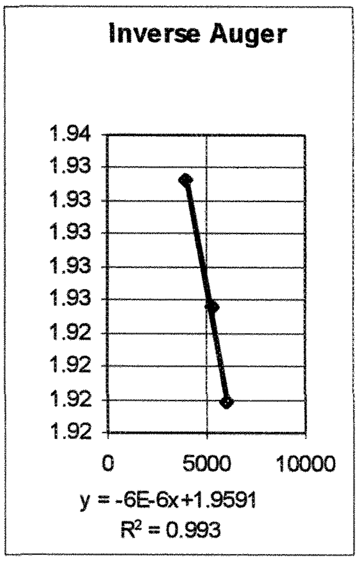
Infiltration test in the pastured area(range land)
Point (1), Coordinates: 0221728, 9930362
Lethological condition: volcanic tuffs
Land cover : natural vegetation soil : clay loam
Basic infiltration rate is ;0.4 mm/min = 24 mm/hr = 576 m/day



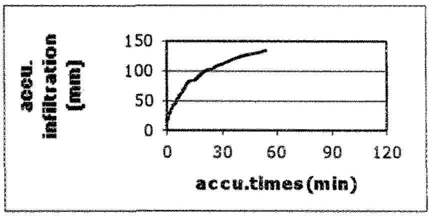
time interval (min)	Accu. time (min)	Level (cm)	infiltration (mm)	accu.infil (mm)	Infil. rate (mm/min)
0	0	24.9	0	0	0
0.5	0.5	24.97	7	7	14
0.5	1	25	3	10	6
0.5	1.5	25.03	3	13	6
0.5	2	25.07	4	17	8
0.5	2.5	25.1	3	20	6
0.5	3	25.13	3	23	6
0.5	3.5	25.15	2	25	4
0.5	4	25.17	2	27	4
0.5	4.5	25.19	2	29	4
0.5	5	25.21	2	31	4
0.5	5.5	25.23	2	33	4
0.5	6	25.24	1	34	2
0.5	6.5	25.27	3	37	6
1	7.5	25.3	3	40	3
1	8.5	25.33	3	43	3
1	9.5	25.35	2	45	2
1	10.5	25.38	3	48	3
1	11.5	25.4	2	50	2
1	12.5	25.42	2	52	2
1	13.5	25.45	3	55	3
2	15.5	25.48	3	58	1.5
2	17.5	25.52	4	62	2
2	19.5	25.55	3	65	1.5
2	21.5	25.58	3	68	1.5
3	24.5	25.63	5	73	1.7
5	29.5	25.71	8	81	1.6
5	34.5	25.75	4	85	0.8
5	39.5	25.81	6	91	1.2
5	44.5	25.86	5	96	1
5	49.5	25.9	4	100	0.8
5	54.5	25.94	4	104	0.8
10	64.5	25.98	4	108	0.4
10	74.5	26.02	4	112	0.4

		******** INVERSE AUGER METHOD ********								
Site:			TMU:			UTM X:	221734			
Point n: 1			Lithology Unit:volcanic tuff			UTM Y:	1E+07			
Photo Nr:			Toposheet name:							
UTM Zone:	37			**Time**	**Level**	**(h+r/2)**	**log(h+r/2)**			
				[sec]	**[cm]**	**[cm]**	**log[cm]**			
Hole diam. [cm]:		7		0	0	99.75	2.00			
Hole depth [cm]:		98		30	0.5	99.25	2.00	X Coefficient(s)	-6.00E-06	
Height reference				60	1	98.75	1.99			
point-surface [cm]:		0		90	2	97.75	1.99			
K[cm/day]:		2.1		120	2.5	97.25	1.99			
				150	2.8	96.95	1.99			
				180	3	96.75	1.99			
				210	3.5	96.25	1.98			
				330	4	95.75	1.98			
				390	4.5	95.25	1.98			
				450	5	94.75	1.98			
				510	5.3	94.45	1.98			
				570	6	93.75	1.97			
				630	6.2	93.55	1.97			
				690	6.5	93.25	1.97			
				750	6.6	93.15	1.97			
				810	7	92.75	1.97			
				1020	8	91.75	1.96			
				1110	9	90.75	1.96			
				1170	9.2	90.55	1.96			
				1230	9.3	90.45	1.96			
				1290	9.4	90.35	1.96			
				1500	9.5	90.25	1.96			
				1800	10	89.75	1.95			
				2520	12	87.75	1.94			
				3300	13.5	86.25	1.94			
				3960	14	85.75	1.93			
				5280	15.5	84.25	1.93			
				6000	16.6	83.15	1.92			



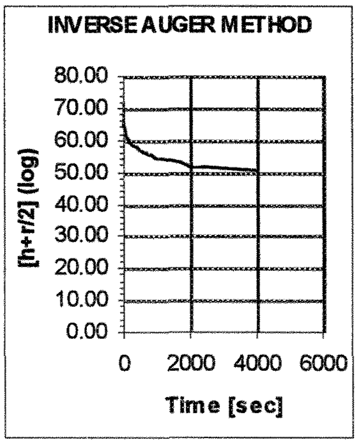


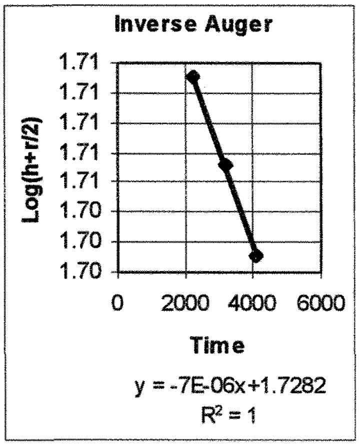
Infiltration test in grass land (60 % grass-30 %maiz-10 %trees)
Point (2), coordinates: 0207473 , 9964142
Date: 21,sep, 2000
Lethologic condition:volcanic tuffs
Soil : the upper 20 cm is very porous soil and the rest is clay loam
Basic infiltration rate : 0.6 mm/min = 36 mm/hr = 864 mm/day



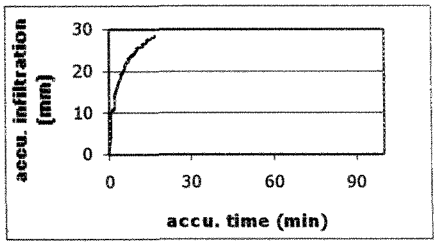
time (min)	accu. Time (min)	Level (cm)	Level (cm)	Level (cm)	infiltration (mm)	Accu. infil. (mm)	Infil. rate (mm/min)
0	0	248			0	0	0.00
0.5	0.5	249			10	10	20.00
0.5	1	250			10	20	20.00
0.5	1.5	250.5			5	25	10.00
0.5	2	251			5	30	10.00
0.5	2.5	251.5			5	35	10.00
0.5	3	251.8			3	38	6.00
0.5	3.5	252			2	40	4.00
0.5	4	252.3			3	43	6.00
0.5	4.5	252.5			2	45	4.00
0.5	5	252.7			2	47	4.00
0.5	5.5	253	248		3	50	6.00
0.5	6		248.3		3	53	6.00
0.5	6.5		248.6		3	56	6.00
0.5	7		248.8		2	58	4.00
0.5	7.5		249.1		3	61	6.00
0.5	8		249.4		3	64	6.00
0.5	8.5		249.5		1	65	2.00
1.5	10		250.1		6	71	4.00
2	12		250.9		8	79	4.00
3	15		251.5		6	85	2.00
2	17		252		5	90	2.50
2	19		252.5		5	95	2.50
3	22		252.9	247.5	4	99	1.33
3	25			248	5	104	1.67
5	30			248.6	6	110	1.20
5	35			249.3	7	117	1.40
5	40			249.9	6	123	1.20
5	45			250.4	5	128	1.00
5	50			250.7	3	131	0.60
5	55			251	3	134	0.60

		******** INVERSE AUGER METHOD ********								
Site:			TMU:			UTM X:	207473			
Point n: 2			Lithol-	volcanic tuff		UTM Y:	1E+07			
Photo Nr:			Toposheet name:							
UTM	37			**Time**	**Level**	**(h+r/2)**	**log(h+r/2)**			
				[sec]	**[cm]**	**[cm]**	**log[cm]**			
Hole diam. [cm]:		7		0	46.5	71.75	1.86			
Hole depth		70		30	53.5	64.75	1.81	X Coefficient(s)		-7.00E-06
Height refer-				60	55.2	63.05	1.80			
point-surface		46.5		90	56.4	61.85	1.79			
K[cm/day]:		2.4		120	57.5	60.75	1.78			
				150	58	60.25	1.78			
				180	58.5	59.75	1.78			
				210	59	59.25	1.77			
				240	59.4	58.85	1.77			
				270	59.7	58.55	1.77			
				300	60	58.25	1.77			
				330	60.3	57.95	1.76			
				360	60.5	57.75	1.76			
				420	61	57.25	1.76			
				480	61.4	56.85	1.75			
				540	61.6	56.65	1.75			
				600	62.2	56.05	1.75			
				660	62.5	55.75	1.75			
				720	62.9	55.35	1.74			
				780	63	55.25	1.74			
				900	63.6	54.65	1.74			
				960	64	54.25	1.73			
				1020	64.2	54.05	1.73			
				1080	64.2	54.05	1.73			
				1380	65	53.25	1.73			
				1680	65.6	52.65	1.72			
				1980	66.6	51.65	1.71			
				2280	66.6	51.65	1.71			
				3180	67.3	50.95	1.71			
				4080	68	50.25	1.70			



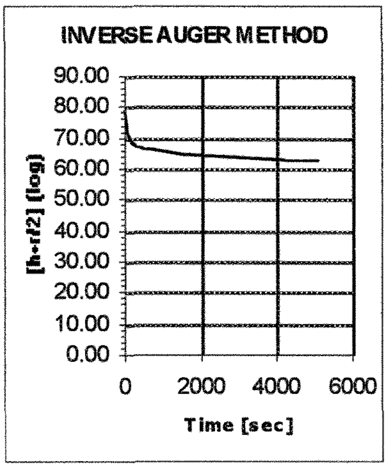


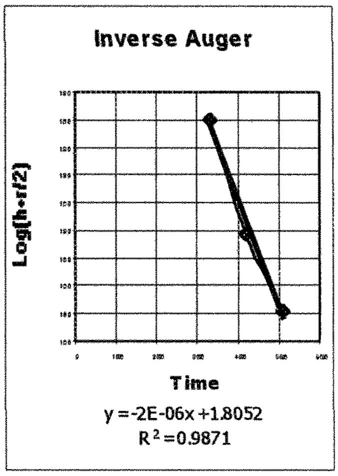
Infiltration test in grass land (60 % grass-30 %maiz-10 % trees)
Point (3), coordinates: 213162 , 9964552
Date: 22,sep, 2000
Lethological condition: :volcanic tuffs
Soil : loam or clay with small gravel
Infiltration rate : 0.4 mm/min =24 mm/hr = 576 mm/day



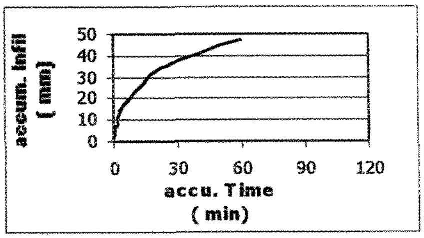
time (min)	accu. time (min)	level (cm)	Level (cm)	Level (cm)	Level (cm)	Level (cm)	infiltration (mm)	accu. infil (mm)	Infil. rate (mm/min)
0	0	251					0	0	0.00
0.5	0.5	255	248				4	4	8.00
0.5	1		252				4	8	8.00
0.5	1.5		254.5				2.5	10.5	5.00
0.5	2		255.5	247.5			1	11.5	2.00
0.5	2.5			250			2.5	14	5.00
0.5	3			251.8			1.8	15.8	3.60
0.5	3.5			253.3			1.5	17.3	3.00
0.5	4			254.3			1	18.3	2.00
0.5	4.5			255.1			0.8	19.1	1.60
0.5	5			255.5	249		0.4	19.5	0.80
0.5	5.5				249.8		0.8	20.3	1.60
0.5	6				250.6		0.8	21.1	1.60
0.5	6.5				251.2		0.6	21.7	1.20
0.5	7				251.9		0.7	22.4	1.40
0.5	7.5				252.3		0.4	22.8	0.80
0.5	8				252.8		0.5	23.3	1.00
0.5	8.5				253.2		0.4	23.7	0.80
0.5	9				253.5		0.3	24	0.60
0.5	9.5				254		0.5	24.5	1.00
0.5	10				254.3		0.3	24.8	0.60
0.5	10.5				254.9		0.6	25.4	1.20
0.5	11				255.1		0.2	25.6	0.40
0.5	11.5				255.2	249	0.1	25.7	0.20
0.5	12					249.2	0.2	25.9	0.40
0.5	12.5					249.7	0.5	26.4	1.00
0.5	13					250	0.3	26.7	0.60
0.5	13.5					250.2	0.2	26.9	0.40
0.5	14					250.4	0.2	27.1	0.40
0.5	14.5					250.7	0.3	27.4	0.60
0.5	15					250.9	0.2	27.6	0.40
0.5	15.5					251.1	0.2	27.8	0.40
0.5	16					251.3	0.2	28	0.40
0.5	16.5					251.5	0.2	28.2	0.40
0.5	17					251.7	0.2	28.4	0.40

		******** INVERSE AUGER METHOD ********								
Site:			TMU:			UTM X:	213162			
Point n: 3			Lithol-ogy Unit:	volcanic tuffs		UTM Y:	1E+07			
Photo Nr:			Toposheet name:							
UTM Zone:	37			Time	Level	(h+r/2)	log(h+r/2)			
				[sec]	[cm]	[cm]	log[cm]			
Hole diam. [cm]:		7		0	42	78.75	1.90			
Hole depth [cm]:		77		30	47.2	73.55	1.87	X Coefficient(s)		-2.00E-06
Height refer-ence				60	48.8	71.95	1.86			
point-surface [cm]:		42		90	50.5	70.25	1.85			
K[cm/day]:		0.7		120	51.2	69.55	1.84			
				150	51.9	68.85	1.84			
				180	52.4	68.35	1.83			
				210	52.9	67.85	1.83			
				240	52.9	67.85	1.83			
				270	53.3	67.45	1.83			
				300	53.3	67.45	1.83			
				360	53.6	67.15	1.83			
				420	53.8	66.95	1.83			
				480	54	66.75	1.82			
				600	54.3	66.45	1.82			
				1500	56.4	64.35	1.81			
				2400	57.1	63.65	1.80			
				3300	57.8	62.95	1.80			
				4200	58.1	62.65	1.80			
				5100	58.3	62.45	1.80			



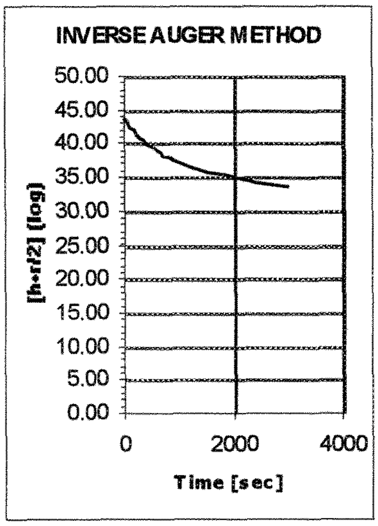


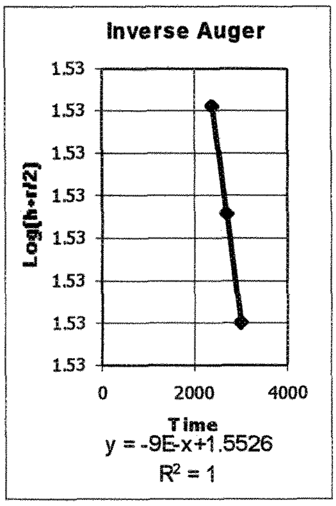
Infiltration test in grass land (60 % grass-30 %maiz-10 % trees)
Point (4), Coordinates:211754 , 9964696
Date: 22,sep, 2000
Lethological condition: volcanic tuffes
Soil : loam, soil depth :45 cm
Infiltration rate : 0.3mm/min =18mm/hr = 432 mm/day



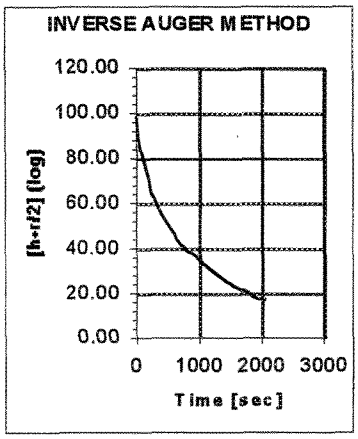
time (min)	accu. Time (min)	level (cm)	infiltration (mm)	accu. infiltration mm	infiltration rate (mm/min)
0	0	246.3	0	0	0.00
0.5	0.5	246.6	3	3	6.00
0.5	1	246.8	2	5	4.00
0.5	1.5	247	2	7	4.00
0.5	2	247.1	1	8	2.00
1	3	247.6	5	13	5.00
1	4	247.8	2	15	2.00
1	5	248	2	17	2.00
5	10	248.6	6	23	1.20
5	15	249.1	5	28	1.00
5	20	249.5	4	32	0.80
5	25	249.8	3	35	0.60
5	30	250	2	37	0.40
10	40	250.4	4	41	0.40
10	50	250.7	3	44	0.30
10	60	251	3	47	0.30

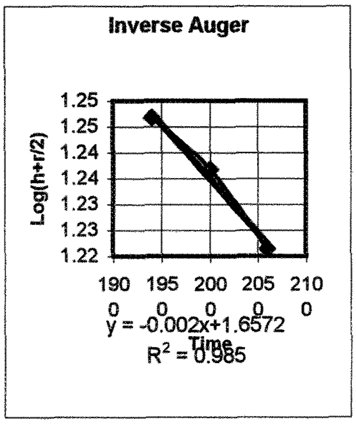
		******** INVERSE AUGER METHOD ********								
Site:			TMU:			UTM X:	211754			
point n: 4			Lithol-ogy Unit:	volcanic tuffs		UTM Y:	1E+07			
Photo Nr:			Toposheet name:							
UTM Zone:	37			Time	Level	(h+r/2)	log(h+r/2)			
				[sec]	[cm]	[cm]	log[cm]			
Hole diam. [cm]:		7		0	44	43.75	1.64			
Hole depth [cm]:		42		30	44.4	43.35	1.64	X Coefficient(s)		-9.00E-06
Height reference				60	44.5	43.25	1.64			
point-surface [cm]:		44		90	45	42.75	1.63			
K[cm/day]:		3.1		120	45.4	42.35	1.63			
				180	45.9	41.85	1.62			
				240	46.4	41.35	1.62			
				300	46.9	40.85	1.61			
				360	47.3	40.45	1.61			
				420	47.8	39.95	1.60			
				480	48.1	39.65	1.60			
				540	48.5	39.25	1.59			
				600	48.9	38.85	1.59			
				660	49.1	38.65	1.59			
				720	49.6	38.15	1.58			
				780	49.8	37.95	1.58			
				840	50.1	37.65	1.58			
				900	50.4	37.35	1.57			
				1200	51.2	36.55	1.56			
				1500	52	35.75	1.55			
				1800	52.5	35.25	1.55			
				2100	53.1	34.65	1.54			
				2400	53.7	34.05	1.53			
				2700	53.9	33.85	1.53			
				3000	54.1	33.65	1.53			



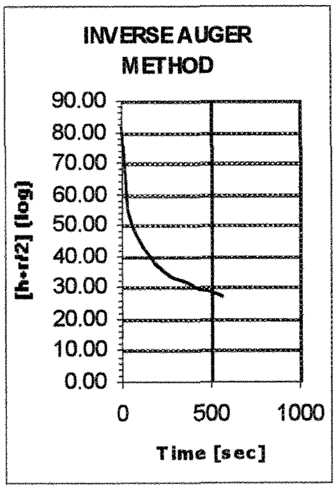


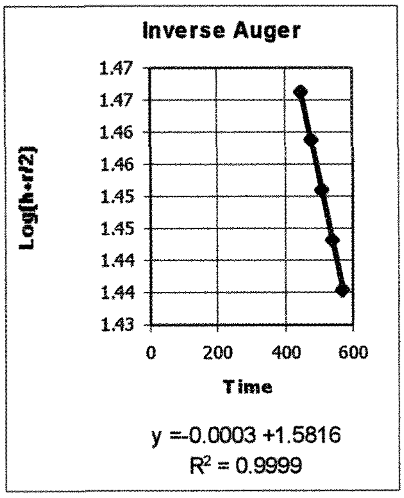
		******** INVERSE AUGER METHOD ********								
Site:	bamboo forest		TMU:			UTM X:	236666			
Point n: 5			Lithology Unit:		tuffs	UTM Y:	1E+07			
Photo Nr:			Toposheet name:							
UTM Zone:				Time	Level	(h+r/2)	log(h+r/2)			
				[sec]	[cm]	[cm]	log[cm]			
Hole diam. [cm]:		7		0	39.5	98.75	1.99			
Hole depth [cm]:		97		30	49.4	88.85	1.95	X Coefficient(s)		-2E-04
Height reference				60	54.5	83.75	1.92			
point-surface [cm]:		39.5		90	57.4	80.85	1.91			
K[cm/day]:		69.6		120	61	77.25	1.89			
				180	67.5	70.75	1.85			
				240	73.4	64.85	1.81			
				300	77	61.25	1.79			
				360	80.9	57.35	1.76			
				420	84	54.25	1.73			
				540	89.5	48.75	1.69			
				600	92	46.25	1.67			
				660	94.5	43.75	1.64			
				720	96.5	41.75	1.62			
				840	99.5	38.75	1.59			
				900	101	37.25	1.57			
				960	102.5	35.75	1.55			
				1020	104	34.25	1.53			
				1080	105.2	33.05	1.52			
				1140	106.5	31.75	1.50			
				1200	108	30.25	1.48			
				1440	113.1	25.15	1.40			
				1500	114.1	24.15	1.38			
				1560	115.2	23.05	1.36			
				1620	116.2	22.05	1.34			
				1680	117	21.25	1.33			
				1740	117.8	20.45	1.31			
				1820	118.6	19.65	1.29			
				1880	119.6	18.65	1.27			
				1940	120.6	17.65	1.25			
				2000	121	17.25	1.24			
				2060	121.6	16.65	1.22			



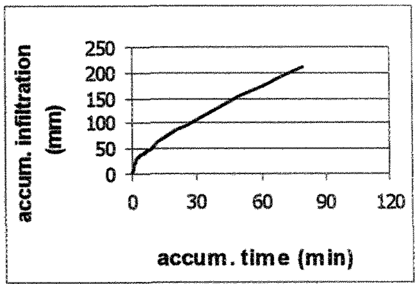


		******** INVERSE AUGER METHOD ********								
Site:	cabbage field in the agriculture area		TMU:			UTM X:				
Point n:	6		Lithology Unit:	tuffs		UTM Y:				
Photo Nr:			Toposheet name:							
UTM Zone:				**Time**	**Level**	**(h+r/2)**	**log(h+r/2)**			
soil :	sandy loam			**[sec]**	**[cm]**	**[cm]**	**log[cm]**			
Hole diam. [cm]:		7		0	43	81.75	1.91			
Hole depth [cm]:		80		30	70	54.75	1.74	X Coefficient(s)		-3E-04
Height reference				60	75	49.75	1.70			
point-surface [cm]:		43		90	79	45.75	1.66			
K[cm/day]:		104.3		120	82	42.75	1.63			
				150	84.5	40.25	1.60			
				180	86.5	38.25	1.58			
				210	88	36.75	1.57			
				240	90	34.75	1.54			
				270	91	33.75	1.53			
				300	92	32.75	1.52			
				330	92.7	32.05	1.51			
				360	93.4	31.35	1.50			
				390	94	30.75	1.49			
				420	95	29.75	1.47			
				450	95.5	29.25	1.47			
				480	96	28.75	1.46			
				510	96.5	28.25	1.45			
				540	97	27.75	1.44			
				570	97.5	27.25	1.44			



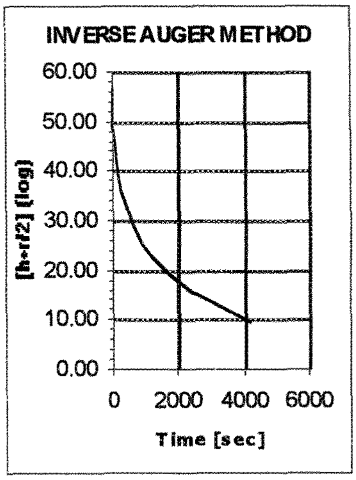


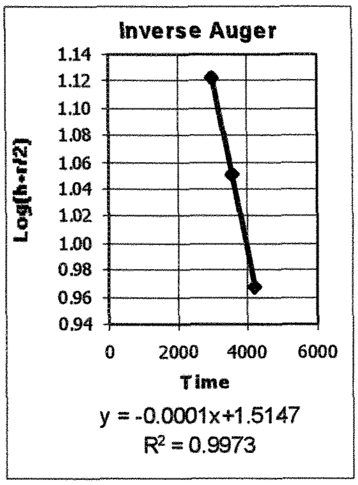
Infiltration test in the forest land (cypres)
Point (7), Coordinates 0222277 , 9949536
Date:30,sep, 2000
Lethological condition: Volcanic tuffes
Soil : silt loam
The infiltration rate is ;2.00 mm/min =120 mm/hr = 2880 m/day



time (min)	Accu.time (min)	level (cm)	Level (cm)	Level (cm)	infiltraion (mm)	accu infil (mm)	Infil. rate (mm/min)
0	0	248			0	0	0.00
0.5	0.5	249.2			12	12	24.00
0.5	1	249.7			5	17	10.00
0.5	1.5	250.2			5	22	10.00
0.5	2	250.4			2	24	4.00
1	3	251			6	30	6.00
1	4	251.5			5	35	5.00
1	5	251.8			3	38	3.00
1	6	252.1			3	41	3.00
1	7	252.5			4	45	4.00
1	8	252.8			3	48	3.00
1	9	253.1			3	51	3.00
1	10	253.4	247.5		3	54	3.00
5	15		249.2		17	71	3.40
5	20		250.5		13	84	2.60
10	30		252.8		23	107	2.30
10	40		255.1	248.3	23	130	2.30
10	50			250.5	22	152	2.20
10	60			252.5	20	172	2.00
10	70			254.5	20	192	2.00
10	80			256.5	20	212	2.00

		******** INVERSE AUGER METHOD ********								
Site:	cypres forest		TMU:			UTM X:	222277			
Point n: 7			Lithology Unit:			UTM Y:	1E+07			
Photo Nr:			Toposheet name:							
UTM Zone:				Time	Level	(h+r/2)	log(h+r/2)			
soil type	silty loam			[sec]	[cm]	[cm]	log[cm]			
Hole diam. [cm]:		7		0	44	56.75	1.75			
Hole depth [cm]:		55		30	51.8	48.95	1.69	X Coefficient(s)		-0.0001
Height reference				60	55.8	44.95	1.65			
point-surface [cm]:		44		120	60	40.75	1.61			
K[cm/day]:		34.8		180	62.7	38.05	1.58			
				240	64.5	36.25	1.56			
				300	66	34.75	1.54			
				600	72	28.75	1.46			
				900	76.2	24.55	1.39			
				1200	78	22.75	1.36			
				1800	82.2	18.55	1.27			
				2400	85.5	15.25	1.18			
				3000	87.5	13.25	1.12			
				3600	89.5	11.25	1.05			
				4200	91.5	9.25	0.97			



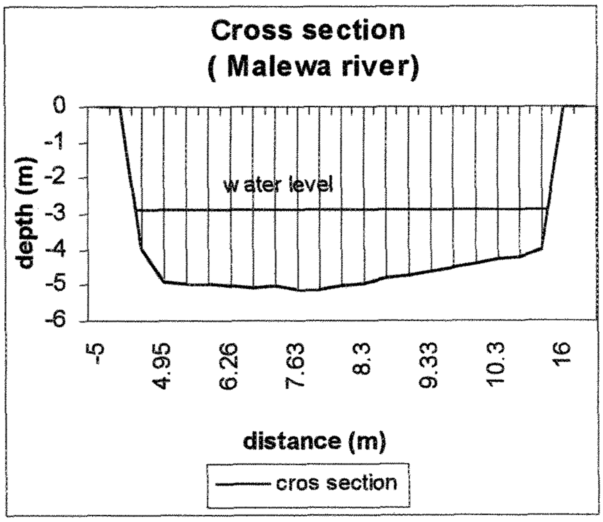


Cross section on Malewa river at GB5.

Date: 14 Sep 2000

point	x	y	Water height (m)	Area (m^2)	distance (m)	Height (m)		Bottom (m)
1	-5	0						
2	0	0						
3	4.35	-4	0	0				
4	4.95	-4.92	-0.92	0.28	0.6	0.92	1.21	1.10
5	5.45	-4.97	-0.97	0.47	0.5	0.05	0.25	0.50
6	5.85	-5	-1	0.39	0.4	0.03	0.16	0.40
7	6.26	-5.03	-1.03	0.42	0.41	0.03	0.17	0.41
8	6.75	-5.07	-1.07	0.51	0.49	0.04	0.24	0.49
9	7.25	-5.02	-1.02	0.52	0.5	-0.05	0.25	0.50
10	7.63	-5.14	-1.14	0.41	0.38	0.12	0.16	0.40
11	7.9	-5.13	-1.13	0.31	0.27	-0.01	0.07	0.27
12	8.05	-5.06	-1.06	0.16	0.15	-0.07	0.03	0.17
13	8.3	-5	-1	0.26	0.25	-0.06	0.07	0.26
14	8.55	-4.83	-0.83	0.23	0.25	-0.17	0.09	0.30
15	8.75	-4.78	-0.78	0.16	0.2	-0.05	0.04	0.21
16	9.33	-4.62	-0.62	0.41	0.58	-0.16	0.36	0.60
17	9.8	-4.51	-0.51	0.27	0.47	-0.11	0.23	0.48
18	10.05	-4.41	-0.41	0.12	0.25	-0.1	0.07	0.27
19	10.25	-4.32	-0.32	0.07	0.2	-0.09	0.05	0.22
20	10.65	-4.23	-0.23	0.11	0.4	-0.09	0.17	0.41
21	11.65	-4	0	0.12	1	-0.23	1.05	1.03
22	16	0						
23	21	0		5.21				8.02

$Q = A * 1/n * R^{0.667} * I^{0.5}$		
slope I	0.00887	
area A	5.21	m^2
P	8.02	m
Radius R=S/P	0.650	m
n	0.068	
v	1.039	m/sec
Q	5.41	m^3/sec



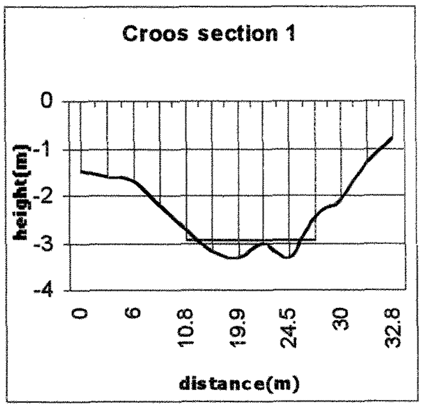
Cross section on Turasha river after join Kitiri
Cross section 1 coordinates : 217803 , 9943072
distance between the two cross sections is 22 m

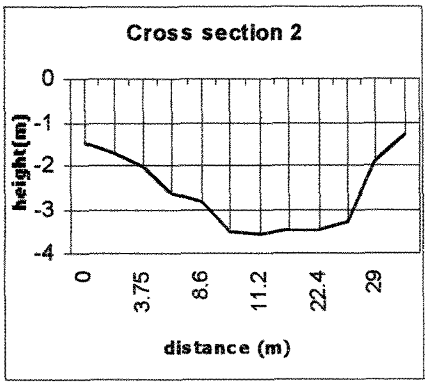
point	X (m)	Y (m)	water height (m)	water level (m)	distance (m)	distance (m)	area (m^2)	perimeter (m)
1	0	-1.5						
2	3.7	-1.6			3.7			
3	6	-1.72			2.3			
4	8.7	-2.22			2.7			
5	10.8	-2.74		-2.92	2.1			
6	15.7	-3.2	-0.28	-2.92	4.9	3.2	0.448	3.212
7	19.9	-3.34	-0.42	-2.92	4.2	4.2	1.47	4.202
8	22.1	-3.04	-0.12	-2.92	2.2	2.2	0.594	2.265
9	24.5	-3.32	-0.4	-2.92	2.4	2.4	0.624	2.456
10	28.4	-2.46		-2.92	3.9	1.81	0.362	1.854
11	30	-2.1			1.6			
12	31.55	-1.3			1.55			
13	32.8	-0.8			1.25			
							3.498	13.989

Cross section 2

point	X (m)	Y (m)	water level (m)	water level (m)
1	0	-1.5		
2	2.5	-1.7		
3	3.75	-2.05		
4	7	-2.64		
5	8.6	-2.82		
6	10.75	-3.52		
7	11.2	-3.6	-0.34	-3.26
8	17.5	-3.5	-0.24	-3.26
9	22.4	-3.5	-0.24	-3.26
10	26.45	-3.3		
11	29	-1.9		
12	31.3	-1.3		

area A(m^2)	3.50
perimeter(m)	13.99
slope I	0.01
n	0.07
v(m/sec)	0.50
Q(m^3/sec)	1.74

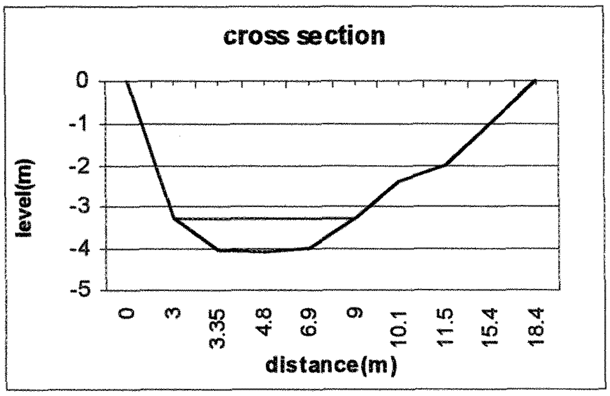




Cross section on Malewa river after joining Dundori
Date 28.sep. 2000
Coordinates : 0212159 , 9971744
Dundori is almost dry, River bed is silt and rock, not so vegetated

distance (m)	Level (m)	water depth (m)	water level (m)	Distance (m)	Area (m^2)	perimeter (m)
0	0					
3	-3.25	0	-3.25	3		
3.35	-4.03	-0.78	-3.25	0.35	0.14	0.855
4.8	-4.1	-0.85	-3.25	1.45	1.18	1.452
6.9	-3.99	-0.74	-3.25	2.1	1.67	2.103
9	-3.25	0	-3.25	2.1	0.78	2.227
10.1	-2.4			1.1		
11.45	-2			1.35		
15.4	-1			3.95		
18.4	0			3		
					3.76	6.64

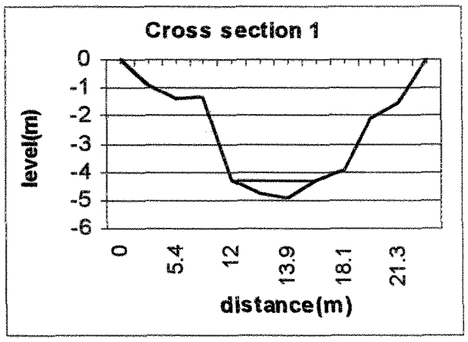
measured slope **I**	0.01
measured velocity ~	0.5 m/sec
R = a/p(m)	0.57
n	0.103
v (m/sec)	0.67
Q (m^3/sec)	2.5



Cross sections on Kitiri river, date 26 Sep 2000

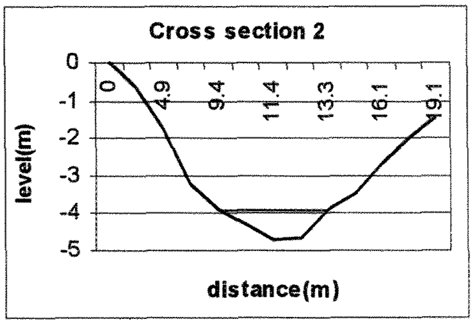
Cross section 1

Disance (m)	Level (m)	Waterdepth (m)	water level (m)
0	0		
3.1	-0.9		
5.4	-1.4		
8.1	-1.34		
12	-4.34	0	-4.34
12.85	-4.82	0.48	-4.34
13.9	-4.96	0.62	-4.34
15.6	-4.34	0	-4.34
18.1	-3.93		
19.7	-2.13		
21.3	-1.55		
21.75	0		



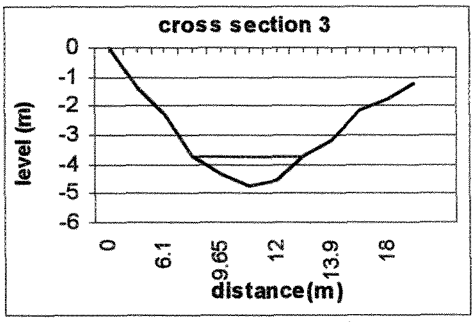
Cross section 2

distance (m)	Level (m)	waterdepth (m)	water level (m)
0	0		
2.9	-0.64		
4.9	-1.78		
7.75	-3.24		
9.4	-3.9	0	-3.9
9.6	-4.3	0.4	-3.9
11.4	-4.74	0.84	-3.9
12.35	-4.68	0.78	-3.9
13.25	-3.9	0	-3.9
14.55	-3.5		
16.1	-2.7		
17.2	-2		
19.1	-1.43		



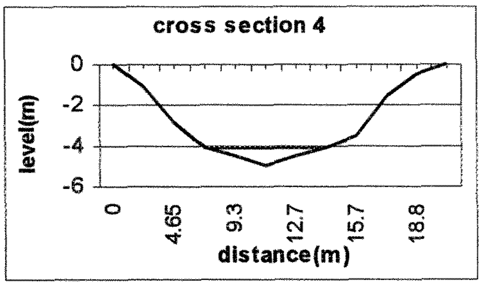
Cross section 3

distance (m)	Level (m)	water depth (m)	water level (m)
0	0		
4.2	-1.37		
6.1	-2.23		
9	-3.74	0	-3.74
9.65	-4.38	0.64	-3.74
11.1	-4.77	1.03	-3.74
12	-4.56	0.82	-3.74
12.75	-3.74	0	-3.74
13.85	-3.2		
15.35	-2.18		
18	-1.79		
19.4	-1.25		



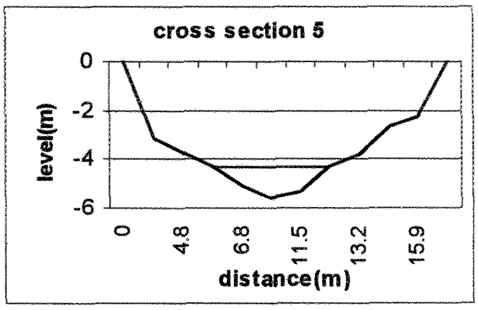
Cross section 4

distance (m)	Level (m)	water depth (m)	water level (m)
0	0		
3	-1.04		
4.65	-2.88		
8.65	-4.12	0	-4.12
9.3	-4.52	0.4	-4.12
11.4	-5.02	0.9	-4.12
12.65	-4.5	0.38	-4.12
13.75	-4.12	0	-4.12
15.7	-3.55		
17.65	-1.59		
18.8	-0.5		
19.3	0		



Cross section 5

distance (m)	Level (m)	water depth (m)	water level (m)
0	0		
3	-3.2		
4.8	-3.72		
6	-4.32	0	-4.32
6.8	-5.14	0.82	-4.32
9.25	-5.6	1.28	-4.32
11.5	-5.32	1	-4.32
12.3	-4.32	0	-4.32
13.2	-3.78		
13.8	-2.65		
15.9	-2.25		
17	0		



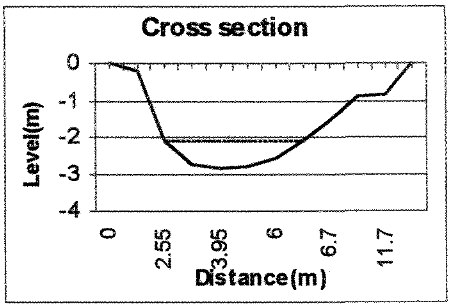
Slope of the channel by clinometer is 3%

Velocity is 0.48m/sec

Span	Distance (m)
Sec 1 – Sec 2	13.80
Sec 2 – Sec 3	17
Sec 3 – Sec 4	20
Sec 4 – Sec 5	7

Cross section on Wanjohi river
Date 28.sep.2000
Coordinates; 0219735 , 9970998

distance (m)	Level (m)	water depth (m)	water level (m)
0	0		
1.4	-0.2		
2.55	-2.11	0	-2.11
3.1	-2.75	-0.64	-2.11
3.95	-2.89	-0.78	-2.11
5.98	-2.79	-0.68	-2.11
6	-2.61	-0.5	-2.11
6.1	-2.11	0	-2.11
6.7	-1.55		
7.4	-0.9		
11.7	-0.85		
15.7	0		



measured slope I = 0.01
measured velocity ~ 0.85 m/sec

Appendix B

Table 3.4.2.1 calibration factors for LANDSAT 7 to convert the digital number into radiance

	Low gain $mW/cm^2/str/\mu m$		High gain $mW/cm^2/str/\mu m$	
TM- Channel	Lmin,i	Lmax,i	Lmin,i	Lmax,i
1	-0.62	29.37	-0.62	19.16
2	-0.64	30.09	-0.64	19.65
3	-0.5	23.44	-0.5	15.29
4	-0.51	24.11	-0.51	15.74
5	-0.1	4.757	-0.1	3.106
6	0.0	1.704	0.32	1.265
7	-0.035	1.654	-0.035	1.08
8	-0.47	24.31	-0.47	15.83

Table 13.4.2.2 solar exo-atmospheric spectral irradiances and thermal calibration constants, in $mW/cm^2/\mu m$

TM- Channel	1	2	3	4	5	6	7
$S_{sun,i}$	195.8	182.8	155.9	104.5	21.910		7.457
K_1						60.776	
K_2						1260.560	

Table 3.4.2.3 cofficients used in equation (3-9) and RMSE for different θ_z

Solar zenith angle(deg)	a	b	RMSE
0	0.031	0.776	0.017
20	0.033	0.773	0.018
40	0.041	0.761	0.018
50	0.048	0.748	0.018
60	0.060	0.729	0.018
65	0.069	0.713	0.019
70	0.081	0.692	0.019
75	0.099	0.661	0.020
80	0.126	0.610	0.020
85	0.174	0.509	0.021

Appendix C

Table 4.1 Average Monthly rainfall of the selected rainfall stations

station	9036002	9036025	9036241	9036264	9036290	9036294	9036336
jan	34.36	53.65	55.17	45.35	40.19	53.74	30.47
feb	37.43	57.25	43.31	36.85	23.56	9.90	26.79
mar	68.18	82.63	72.10	48.91	95.63	66.87	47.72
apr	116.84	165.56	166.33	163.56	110.29	172.12	164.25
may	77.43	167.61	157.41	154.07	96.65	100.78	134.70
jun	44.70	99.20	114.72	101.07	85.89	56.32	122.03
jul	46.69	72.57	107.04	75.89	66.02	68.70	139.31
aug	68.17	90.31	266.27	92.72	79.45	98.60	141.65
sep	43.88	104.43	126.72	77.94	61.41	45.10	116.47
oct	53.57	103.76	109.74	200.27	58.56	30.40	100.03
nov	64.14	111.30	96.24	81.94	53.47	64.90	86.48
dec	40.57	64.47	50.97	46.18	27.88	42.36	36.55
total	695.95	1172.74	1366.01	1124.76	798.97	809.79	1146.45

Table 5.1.2 Average monthly discharge of the selected gauging stations

station	GB1	GB4	GB5	GC4	GC5	GC7
jan	1.90	0.54	0.97	1.86	0.48	0.13
feb	1.70	0.45	0.85	1.56	0.37	0.12
mar	1.74	0.47	0.87	1.85	0.46	0.17
apr	5.05	1.09	2.36	4.84	1.02	0.52
may	8.30	1.13	3.53	8.80	1.34	0.51
jun	5.31	0.93	2.06	4.66	0.86	0.21
jul	6.14	1.21	3.45	4.28	0.85	0.16
aug	9.55	1.74	6.83	4.68	0.78	0.13
sep	8.48	1.73	4.52	3.75	0.97	0.14
oct	5.92	1.55	2.66	4.36	1.22	0.30
nov	5.92	1.56	3.05	5.48	1.25	0.41
dec	3.72	0.84	1.84	2.86	0.91	0.20