HYDROLOGICAL INVESTIGATION FOR WATER HARVESTING POTENTIAL USING GIS, RS AND RUNOFF MODELS

A case study of Lake Naivasha Area, Kenya

by

Umuro G. Sharamo

March, 2002
Enschede, The Netherlands

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This thesis is submitted in partial fulfilment for the degree of Master of Science in Water Resources and Environmental Management with emphasis on Watershed Management at the International Institute for Geo-information Science and Earth observation (ITC), Enschede, The Netherlands.

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Abstract

The study was concentrated in three main areas: Kinangop plateau, Ndabibi plain and Longonot in west of Kenya where rainfall is the only source of accessible water. In each of these areas, there is not enough water or food because of dry periods and drought, while soil erosion remains a problem on sloping lands. On the basis of these prevailing conditions, the study intended to assess whether rainwater harvesting from micro-catchments is feasible from hydrological point of view to bridge the dry periods and enhance crop production.

A basic problem in water harvesting is to estimate the local runoff because success of rainwater harvesting depends to a great extent on the quantity of excess rain that is available from the runoff area for subsequent use to complement rain.

Runoff models and Soil-water balance model were used together to predict surface runoff that is available from the given storms. The prediction was made from 98 wet days with daily rainfall >1mm for the year 1998, recorded at 2GB1 gauging station on Malewa river. The models used other climateorological data, soil and crop data of the study area. The total rainfall during this simulation was 789mm and was used for all the prediction by models.

The topography, soil profile, soil hydraulic properties, geology and other catchment characteristics were measured or estimated in the field, or determine in the laboratory from the samples.

The first approach used US Soil Conservation Service (SCS) Curve Number method where daily surface runoff was estimated by characterising the surface characteristics of the catchment. The Curve Number method relates hydrological soil group to the curve number as a function of soil cover, land use type, antecedent moisture conditions to estimate runoff depth from small catchments. Within this period reviewed, 320mm occurred as runoff depth.

The second method computes runoff by adopting Thornthwaite and Mather model (T & M). On a monthly time step, the model did not yield any surplus. However, on a daily time steps, the model generated 319mm of moisture surplus.
The effective root zone depth was taken as 50cm in order to determine the water holding capacity of the root zone.

The CN method and T & M model predicted annual runoff as 320mm and 319mm respectively. This runoff could be collected and conserved as soil water to improve growth conditions further during that season. Moreover, if this runoff yield is conserved, erosion risk will also be reduced and runoff potential for efficient use is highly enhanced. Though the aggregated annual runoff values were very close for the two models, the monthly values show variation within the seasons.

Flow components at 2GB1 station were separated by TimesPlot program to quantify base flow and quick flow. The runoff depth (1055mm) was found to be inconsistent with rainfall data. The runoff depth was actually larger than the total rainfall values and was not considered as initially planned for computing effective rain and comparing simulated runoff with observed runoff.

Soil hydraulic conductivity was investigated at many locations to quantify infiltration process using auger hole test. The hole was rewetted prior to measurements and subsequently, the quantity of water infiltrated under saturated conditions was measured based on Darcy's law. The average hydraulic conductivity estimates were 2.4 cm/hr, 21.2cm/hr, and 40cm/hr for Kinangop, Ndabibi and Longonot respectively. The hydraulic conductivity was high, which enhances percolation through the profile. The result shows large variability of saturated hydraulic conductivity in the area, which is often a wide recognised problem. The hydraulic conductivity depends on soil texture, structure, soil depth and organic matter, which vary everywhere. Due to the limited time for data collection it was not possible to conduct as many measurements within soils with similar characteristics and cover to establish reasonable estimates.

ILWIS was used for spatial data analysis and generating digital elevation model. From the DEM, it was possible to compute and slice the slopes into suitable elevation. The 2-dimensional tables were used to reclassify the TMU's, slope and land use maps into suitability maps by assigning values or ratings. The ratings were based on knowledge of the area and available data's. Based on the terrain catchment, land cover and slopes a suitability map was generated to identify sites water harvesting is feasible.

The Parched thirst model was also used to predict the grain yield and runoff that could be realised by adopting rainwater harvesting. Based on dry and wet years the prediction was made and repeated for varying sizes of runoff area and cropped area. The results are discussed in section 5.2 of the thesis. The model generated 41mm of annual runoff for the year 1998. For a given design the model predicts the runoff, grain yield, total evaporation, harvest index etc. that is dependent on the input data. This will enable the farmer to decide whether or not the conservation practices adopted are economically viable and to determine the best size of a runoff area until good growth target is reached.
Patched-thirst model incorporates the effect of surface crusting in the simulation that is lacking in other hydrological models. However, the large input data required by the Patched-thirst model makes applicability limited because in remote areas runoff and meteorological data are not readily available.

There was not much difference in the applicability of Runoff-models and Soil-water balance model since both gave similar results. However, it was not possible to compare patched thirst model with CN and T&M because it does not simulate runoff on daily basis. Because of its uniqueness in accounting for surface crust patched thirst model is also worth adopting for future studies.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1. Importance of study

In this study, Remote Sensing, GIS, "Parched-Thirst", the Curve Number method and Soil Water Balance model were used to assess hydrological conditions and terrains for water harvesting potential in Naivasha.

The assessment of whether or not the terrains are suitable for water harvesting is important prior to design of water harvesting structures.
The actual evapotranspiration, soil moisture deficit, soil moisture surplus, and surface run-off, are other components determined using the Water Balance model developed by Thornthwaite and Mather (1955).

Naivasha area receives average 650 mm annual rainfall varying between 911mm and 385mm, most of which are concentrated during the long and short rain season
The study will focus on limitation of water supply for crop production and investigate the feasibility of adopting within field (micro-catchments) runoff water harvesting.

The fate of small-scale farmers especially in semi arid areas is closely tied to the prospect of an alternative way of continued agricultural production. What is needed is the development of a sustainable technique that farmers can adopt to increase yields.

Use of water conservation structures is one such alternative for harnessing excess rain. If surface runoff were induced to infiltrate, the moisture in the rooting zone would increase so that the effects of irregular rainfall are mitigated.

Moreover, not all the terrains are suitable for water harvesting and thus selection will be made to identify priority areas.

Therefore there is an urgent need for a comprehensive study of water harvesting for planning and adoption by farmers. This research aims at evaluating the local runoff component for water harvesting.

1.2. Research objectives

The research intends to analyse the rainfall-runoff process and evaluate terrain units to work out feasibility for water harvesting potential.

Specific objectives are:

- To estimate hydrological parameters of the selected sites within terrain units.

- To evaluate surface runoff and peak flows from micro catchments for optimum designs of conservation structures.
- To select terrain units based on the geology and geomorphology potentially suitable for water harvesting.
- To evaluate results from different methods and estimate runoff and recommend a suitable method.
- To apply the results to evaluate suitability of terrains for water harvesting.
- Apply the Parched-thirst model to investigate the grain yield from adoption of rainwater as soil water to bridge dry periods.

1.3. Methodology

- Aerial photograph Interpretation to derive terrain-mapping units with sufficient runoff.
- To collect soil and other field data for runoff simulation.
- Simulate the Soil Water Balance Model by Thornthwaite & Mather and compute daily water balance components.
- Apply SCS Curve Number method to estimate surface runoff.
- Make water harvesting suitability assessment.

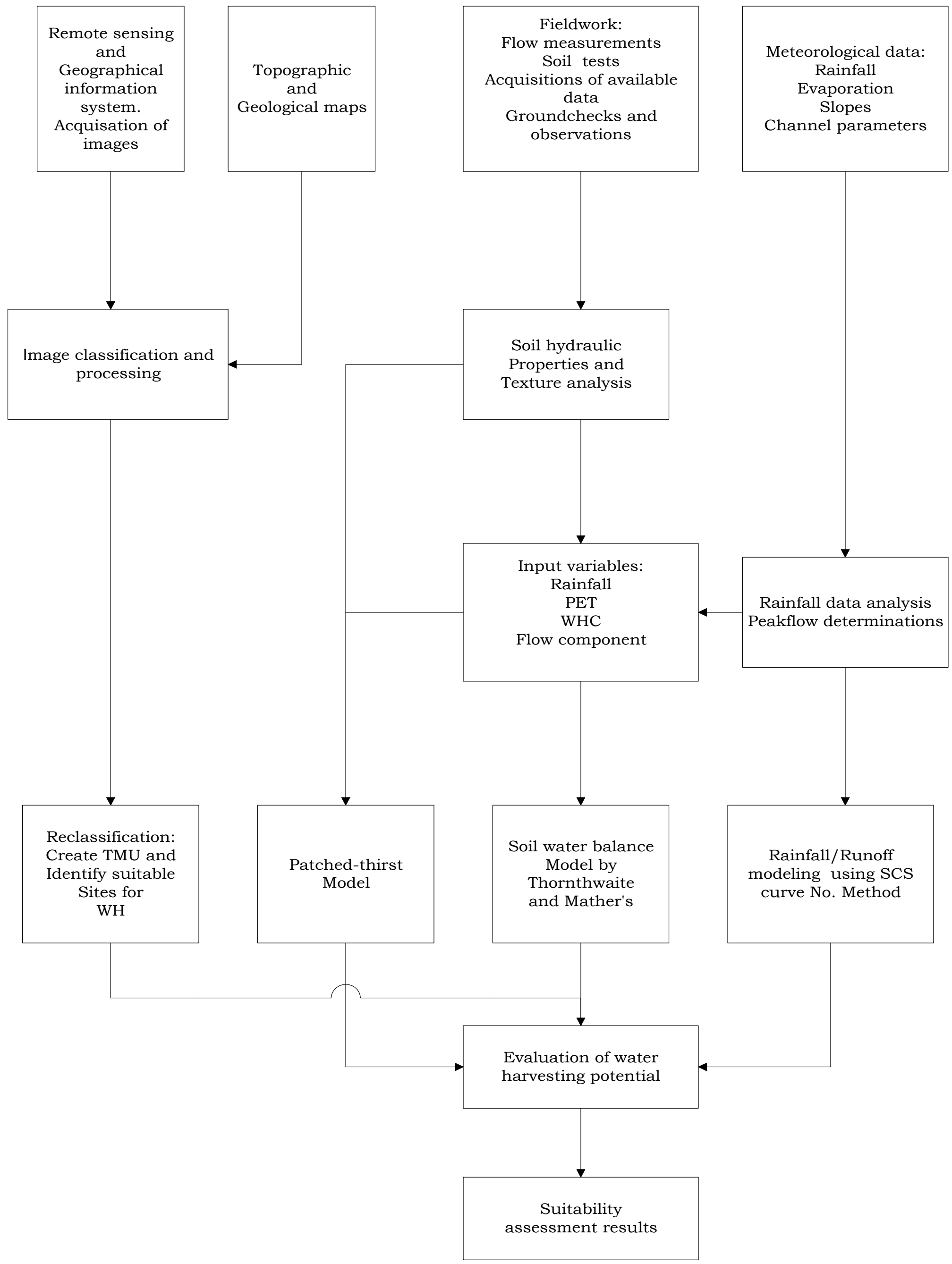


Figure 1.1 Flow chart for research methodology

2. GENERAL ASPECT OF STUDY AREA

2.1. Study area Locaion

Naivasha basin lies in the Eastern African Rift valley, about 80km north west of Nairobi. It is located at latitude 00 46' to 00 52'S, longitude 36 15' to 36 25' and UTM zone 37 with an altitude varying between 1900m to 3200m above mean sea level. The research focused on three areas: Kinangop, Longonot, and Ndabibi. In this chapter general description of the entire basin is given followed by detailed description of the specific sites. The area is bounded by Kinangop plateau to the East, Longonot Volcano to the Southeast, Kipipiri Mountain on the North side, Eburu mountains to the Northwest and karati escarpment to Northeastern.
Because of its exceptional water quality, lake Naivasha plays a vital role to this area; extensive horticultural irrigation farms are located around the lake, producing nearly 75% of Kenya's horticultural exports. The lake also contributes indirectly to geothermal power generation.
Administratively the area falls under Naivasha division of Nakuru district in the Rift Valley province of Kenya.

Location	ID	Latitude	Longitude	Elevation (m)	Land Use
Kijabe	J1	184591	9920450	2192	Wheat
Kijabe	J2	184919	9921106	2240	Wheat
Kinangop	K1	217529	9942014	2410	Grass
Kinangop	K2	217518	9942168	2394	Maize
Longonot	L1	224791	9900076	2104	Maize
Ndabibi	N1	192912	9920020	1980	Maize
Ndabibi	N2	192851	9919828	1972	Maize

Table 2.1 Location of study sites

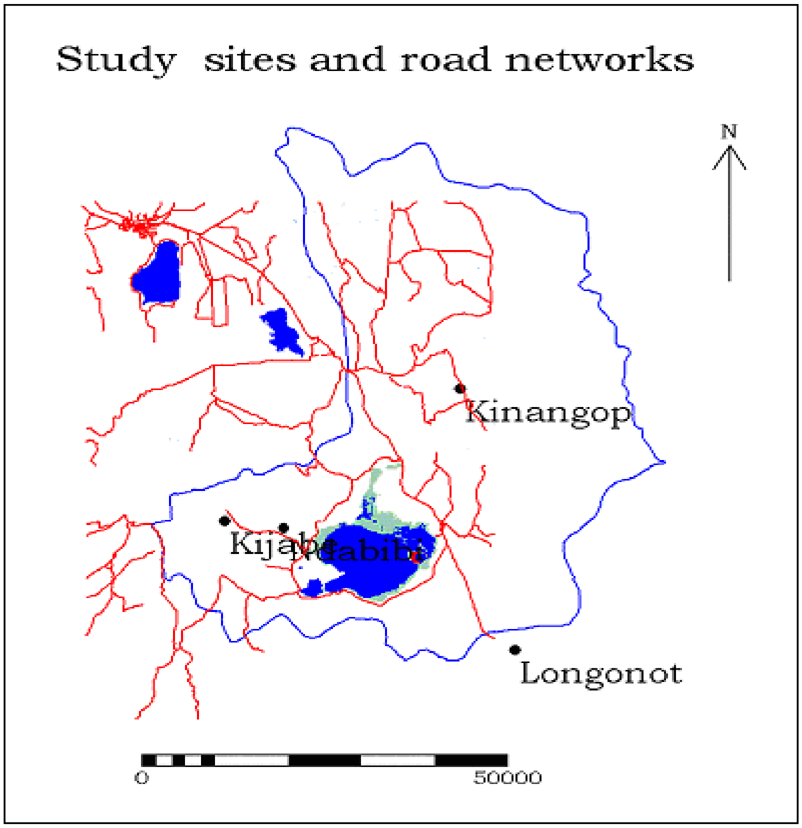


Figure 2.1 Location of study area in the Naivasha basin

2.2. Geology

The TMU's were established through interpretation of aerial photos at the scale of 1:50,000, satellite images and topographic map.
Initial step in identifying TMU's involves delineation of areas of similar relief, dissections and slope forms. The main units easily mapped were volcanic complex, plateau, foot slope, scarps, lacustrine and alluvial units as tabulated below.
The geological evolution has influenced the geomorphology of the study area. Volcanic and tectonic activities have resulted in the formation of extensive areas of plateau and scarps, mountains and hills.
The volcanic rocks in the area include tuffs, pumice, tephrites, agglomerates, tephrites, trachytes phonolites and acid lavas rhyolite, comendite and obsidian (Thompson et al. 1958 and Clark et al. 1990).

Landform Units	Area	Lithology	Soil	Land cover	Drainage density	Slope
Lacustrine	Plain around lake Naivasha, Ndabibi & Kongoni.	Lacustrine sediments, Volcanic deposits.	Mainly sandy clay loam to silt loam. Very deep with high infiltration rate.	Agriculture, rangeland, sparse vegetation	Has none. Flat basin. Terminal drainage of the surrounding highlands, narrow incised. The lower plains are often flooded.	<2%
Volcanic complex	Olkaria hills and areas SW of the lake Naivasha.	Dome-like hills, Lava flow or ashes of volcanoes	Generally sandy loam. Shallow, Thin stony soils.	Shrubs and natural vegetation. Very little or no agriculture importance	Dendritic and ephemeral streams.	10-30%
Footslopes	Longonot Volcano and Rift valley. Falls just below scarps.	Colluviums, volcanic ash, pumice and eroded deposits from the scarps.	Deep permeable soils, sandy to gravely alluvial deposits.	Sparse vegetation, small agriculture and bare soils.	Longitudinal channels. High infiltration	Low internal relief. 4-10%
Volcanic plateau	Kinangop plateau	Fine tuff, fluvial deposits, pumice	Loam-clay loam to silt clays Very fertile. Low infiltration	Rain fed agriculture and agro forestry	Low drainage density.	Elevated Gentle uniform slope. 10-20% slope
Scarps	Eburu and Maumau scarpment	Volcanic ash, tryachyte pumice and Basalts tuffs occur.	Clay loam. Stony and shallow soils.	Agriculture, Mountain forest and shrub land.	A highly dissected topography. Dendritic.	Steeply Hilly escarpments. 20-50% slope
Sediments/ Upper lacustrine Plain	Dried bed of lake Naivasha and western part.	Lacustrine sediments, volcanic and weathered/deposited river sediments.	Silt loam to clay. Very fertile.	Rain fed agriculture, Horticulture, yellow fever trees	Natural depression Flat basin topography. Very low internal deposits.	Highland drains here. <2% slope

Table 2.2 Terrain mapping units with their attributes

2.3. Land use, cover and Vegetation

Land cover information is basic requirement for input for any hydrological models because interception and its effect on rooting depth.

The plains and foot slopes were used for rain fed agriculture and grazing. Around the lake and its environment there is rapid development of horticulture in green houses that rely on lake Naivasha.

Until the arrival of the first white settlers Ndabibi plains was mainly used for grazing. Changes in the land use were induced by clearing of forests and shrub land to give way to large commercial wheat farms.

During the last few years' population growth has exerted a lot of pressure on land around the lake. Beside the floriculture farms spreading, new horticultural techniques are being introduced (i.e. pivot systems) which depends on the lake water. Near the lake "yellow fever tree" is common.

Overgrazing is not a problem but it is worth mentioning that cattle, sheep and goatherds are present on most farms.

2.4. Rainfall

Naivasha area has semi-arid type of climate with a bimodal pattern of rainfall (Kamoni, 1988, Bemigisha, 1998 and Sombroek et al. 1980) with long rains occurring from February to May and the short rains occurring mid-October to November. The mean annual rainfall in Naivasha basin is 650 mm and at the Aberdare ranges 1525mm.

The long-term rainfall shows high spatial variability, which is partly influenced by topography. The gauging station placed at high altitude records more rainfall than those at low altitudes.

The results of total rainfall recorded by tipping bucket at Kijabe farm showed no relation with one placed 2km away. The differences are attributed to the closeness of the storm to the recording bucket.

Rainfall records in one studied area catchments cannot be used for analysis in the other catchment

2.5. Temperature

The mean maximum and minimum temperature are 8.5 and 30 C, occurring in July and February, respectively (Sulmac, 2001). However these temperatures are not representative for every part of Naivasha.

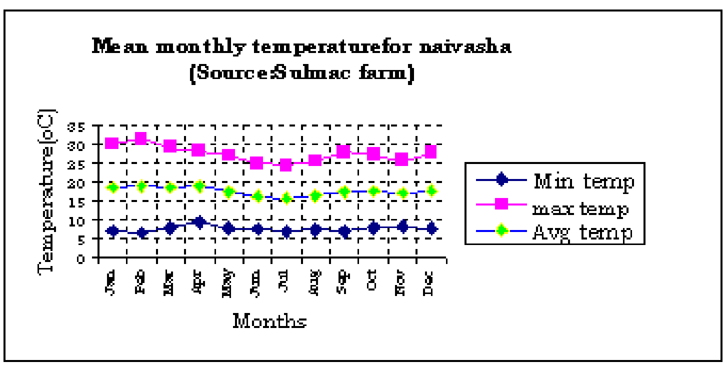


Figure 2.2 Mean monthly temperature

2.6. Evapotranspiration

The process of evaporation from the land surface and transpiration from vegetation are collectively termed evapotranspiration (Thornthwaite and Mather's). The average annual potential evapotranspiration is over 800mm for entire Naivasha basin, which is more than the average annual rainfall of 600 mm. If this condition prevails then there would be water deficiency and the water capacity of the root zone is never reached. In addition to knowing the amount of rainfall in the study area it is also important to know that much of it is lost through evapotranspiration. Evapotranspiration helps in determining water balance of the area.

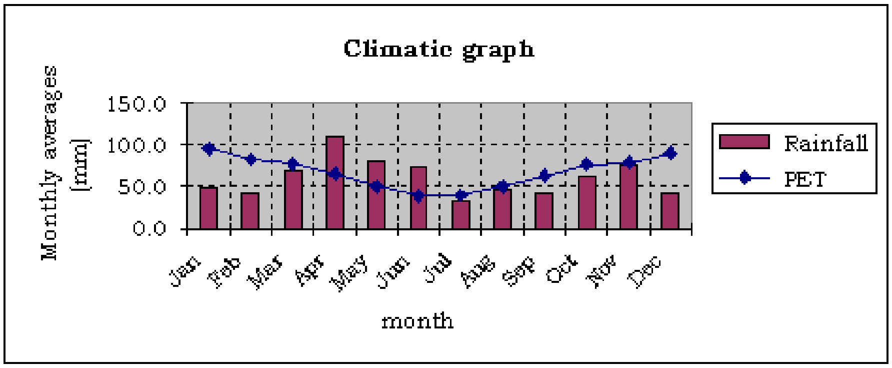


Figure 2.3 Long term mean monthly rainfall and Evapotranspiration (Source: Kenya Meteorological department)

2.7. Soil and water conservation

There are few indications that some forms of water harvesting systems are already used in Naivasha. In Kinangop plateau a form of road runoff is used for domestic and animal use. Some other small holders make ditches approximately along the contour to conduct runoff away from the field and in the process reduce the slope length though often not use the excess water. Vast majority of the farms are not terraced in Longonot.

In Kijabe farm contour ridge has been constructed to protect wheat fields from erosion, conserve moisture and preserve fertile soils. This has enhanced effective use of excess water by harvesting and made to pond on the cultivated areas.

Figure 2.4: A contour ridge terrace for Water conservation in Kijabe farm

3. LITERATURE REVIEW

3.1. Definition of Water harvesting

According to Boers and Ben-Asher (1982) water harvesting is defined as a method of collecting surface runoff from a contributing area and storing it for consumptive use in the root zone of an adjacent infiltration basin.

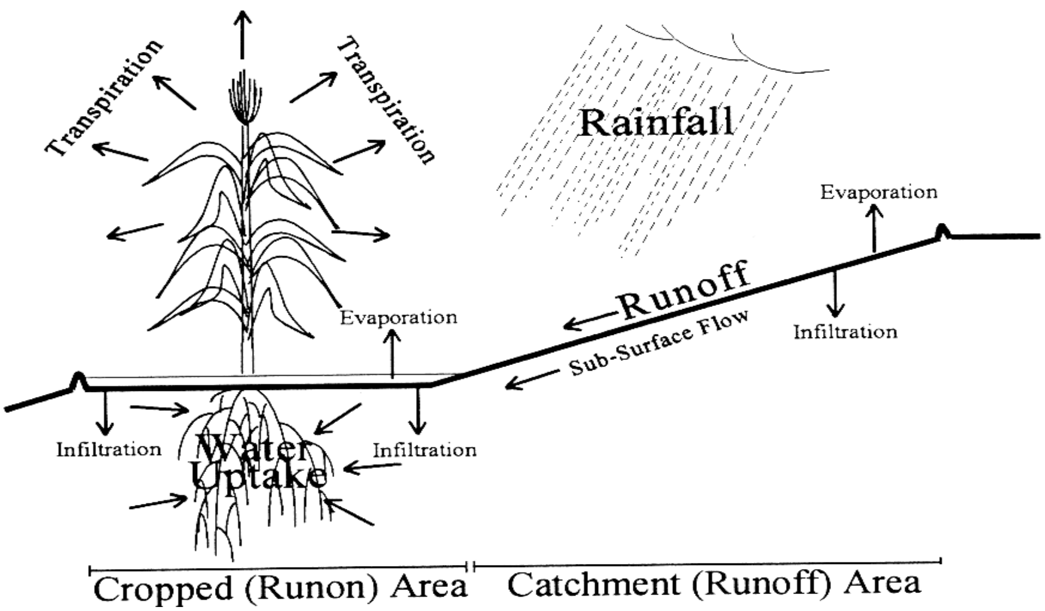


Figure 3.1 A typical micro-catchment rainwater harvesting system

Figure 3.1 represents a micro catchment consisting of runoff area and basin area. Rainfall induces runoff, which collects in the basin area, where the water infiltrates, is stored, and is available for root uptake and transpiration. In the basin area, losses occur by interception, soil evaporation, and deep percolation below the root zone. The components of water balance shown can be equated for a defined period of time consisting of a rainy season and a dry season.

3.2. Requirements for water harvesting

The efficient use of the small runoff basins requires proper design. Design elements include runoff efficiency under different rainfall and land characteristics and the size of the runoff area needed to ensure sufficient water for development.

Runoff of a given rainstorm is a function of soil infiltration rate, surface storage capacity, and rainfall intensity, distribution and sequence, during a particular storm event.

The aim of a water harvesting design is therefore to estimate the catchments area required for a given crop area so that a crop gets sufficient moisture to produce the needed grain or fruit.

3.2.1. Catchment and Cropped area

For the purpose of this research catchment and cropped area will be differentiated depending upon the slope terrains. The catchment area represents the surface that yields runoff. The catchment area could either be located on a slope with crop fields at its foot or lies within-field in between conservation structures. Where the catchment lies within field it is considered as micro-catchment. The limitation of micro-catchment is the low crop yield per unit area, even when each crop is producing a high yield per m^3 of water caused by low number of crops per unit area.

The cropped area is the target area for runoff collection. When the catchment area is located on a slope with terraced fields at the foot slope then no potential arable land is lost since the slopes are already unfavourable for agriculture.

Runoff decreases with slope length and hence within-field water harvesting is more efficient. The optimum ratio should be found for each set of local condition (Boers et al. 1986B). In semi-arid areas a larger runoff area is required to increase total infiltration because the percentage of runoff increases with a decrease in catchment size (American and McGuinness 1968).

3.2.2. Crop water requirements

This is the amount of water required by a crop to grow from planting to maturity based on Crop potential evapotranspiration. Different crops require different amounts of water depending on the crop type, the length of the growing season and the particular season (refer to appendix). Overall water requirement of annual crops is generally less than that of perennial crops like fruit trees. The crop water requirement is estimated by the reference crop evapotranspiration.

3.2.3. Runoff efficiency factor

Efficiency factor represents the proportion of rainwater harvested that is not lost through seepage, evaporation or overflow (i.e. runoff per unit area).

This factor is used because a portion of water entering the soil is inevitably lost through deep percolation. The runoff efficiency hence decreases exponentially with increasing size of the catchment as is illustrated by figure 3.2 because of infiltration losses, surface storage and depressions.

For designing a water harvesting structures it is desirable to have small runoff area to reduce storages losses.

For surface irrigation systems, an efficiency factor of 0.4-0.85 is commonly used. A figure of 0.4-0.6 was suggested for drier areas (Oweis et al. 1996).

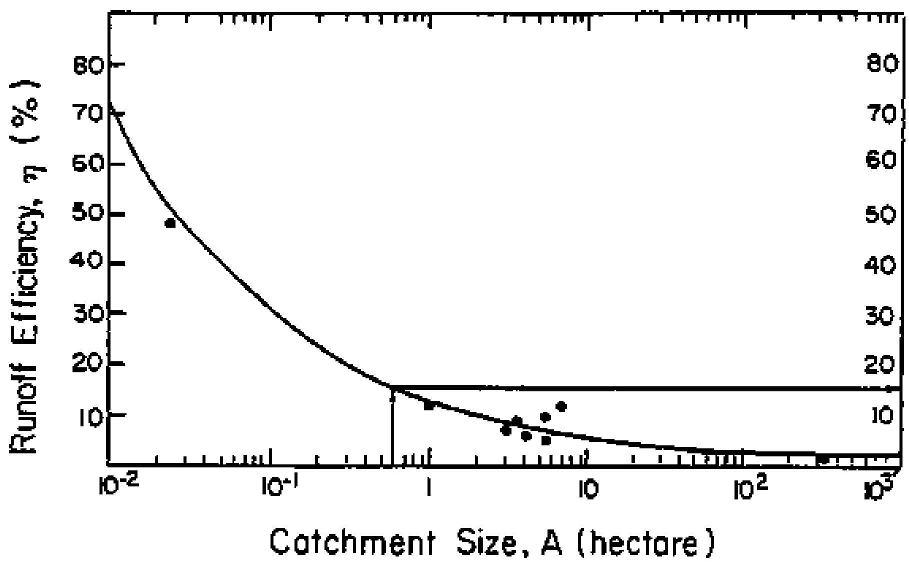


Figure 3.2 Runoff efficiency as a function of catchment size (Source: Ben Asher 1988)

3.2.4. Computing probability rainfall

For the purpose of designing water harvesting system it is necessary to estimate, from the local rainfall data, how much rain can be expected on average (say in two years out of three) during the cropping season.

Since rainfall for each period will vary from year to year, 10 years rainfall data for Kinangop was selected for computing the probabilities for the growing seasons.

The steps involved are:

1. Rainfall data are tabulated for given period.
2. The data was arranged in descending magnitude and given rank number
3. Plotting position was tabulated using the equation,

$$F_a = \frac{100 * M}{(N+1)}$$

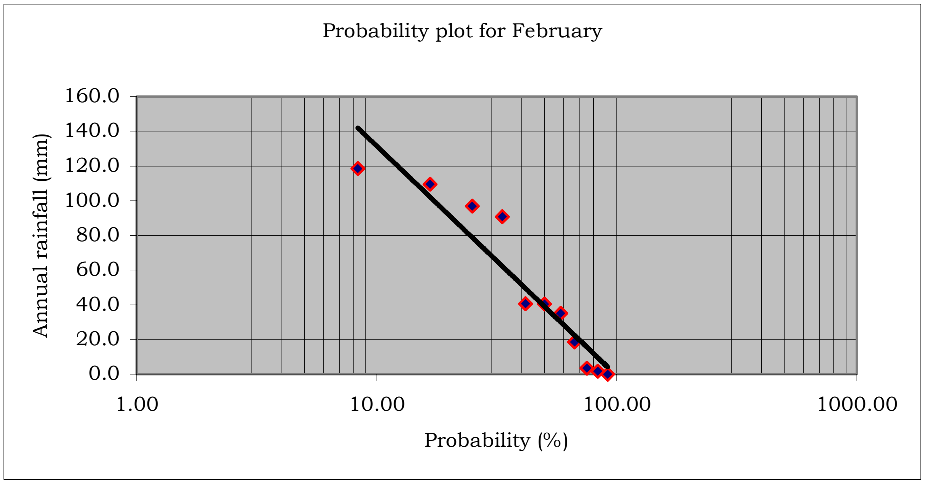
Where

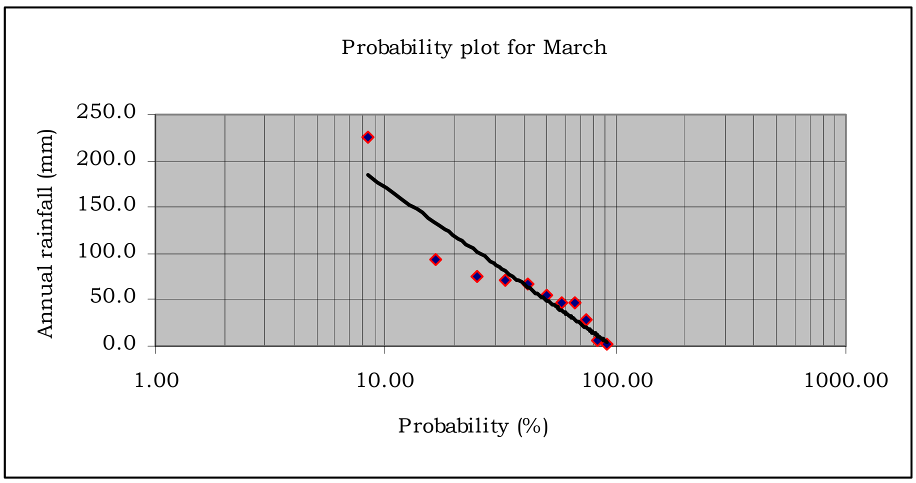
F_a = Plotting position

M=Rank number of rainfall value (with m=1 for the highest)

N=Total number of data (months, seasonal or years)

4 Plotting the rainfall according to F_a position on Log-normal probability





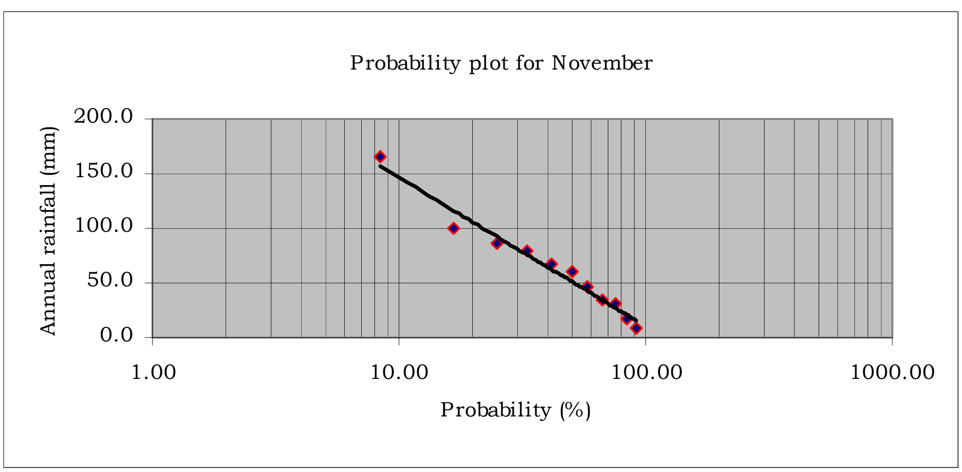


Figure 3.3 Probability plots for growing seasons in Naivasha: Short and Long rains seasons

The probability plot shows the percentage of time that rainfall is equal to or greater than the amount indicated. The best design value is the probability rainfall because it is related to the frequency of occurrence of such rainfall. This will help the planner to get a reasonable catchment size to supplement rainfall, rather than one that is inadequate or too large and not appropriate for the type of scheme.

3.2.5. Estimating the Runoff coefficient

Runoff coefficient depends on catchment and rainfall characteristics such as catchment size, shape, degree of slope, land use, and rainfall intensity, duration and distribution. The most that can be done to cater for different catchment conditions is to estimate the proportions of the catchment that have different coefficients and obtain a weighted average (Hudson, 1981).
Runoff could be up to 70% for bare crusting soils under intense storms (Critchley, 1986). See the appendix G for values of runoff coefficient, C.
The runoff coefficient for small catchment increases with increasing rainfall, because the rainfall excess increases with large rainfall depths, which generally lasts longer than shorter storms (Meijerink, 2001). However, as data reported by Roder (1995), including those for the Sahelian, the type of rainfall do not suggest an importance change except in the desert zone (<100mm annual rainfall) where the runoff coefficients were somewhat higher than in the zone with >300mm rainfall.

3.2.6. Soil requirements

The soils of the cropped area should be sufficiently permeable to allow adequate moisture to the crop root zone without causing waterlogging problems. The infiltration rate of a soil depends primarily on its texture.

Soil Texture	**Infiltration Rate (mm/hr)**
Sand	50
Sand loam	25
Loam	12.5
Clay loam	7.5

Table 3.1 Comparative figures of infiltration rates

A very low infiltration rate can be detrimental to water harvesting systems because of the possibility of water logging in the cultivated area. On the other hand, a low infiltration rate leads to high runoff, which is desirable for the catchment area. Therefore, the requirements of the cultivated area should always take precedence.
Crust formation poses a challenge in semi-arid areas. On the impact of raindrops, a surface crust is formed which rapidly reduces infiltrate increasing runoff.
Thornthwaite & Mather's and Curve Number models adopted for the study do not account for soil crusting. However the parched-thirst model was a good alternative to simulate the performance of rainwater harvesting under crusting soils.

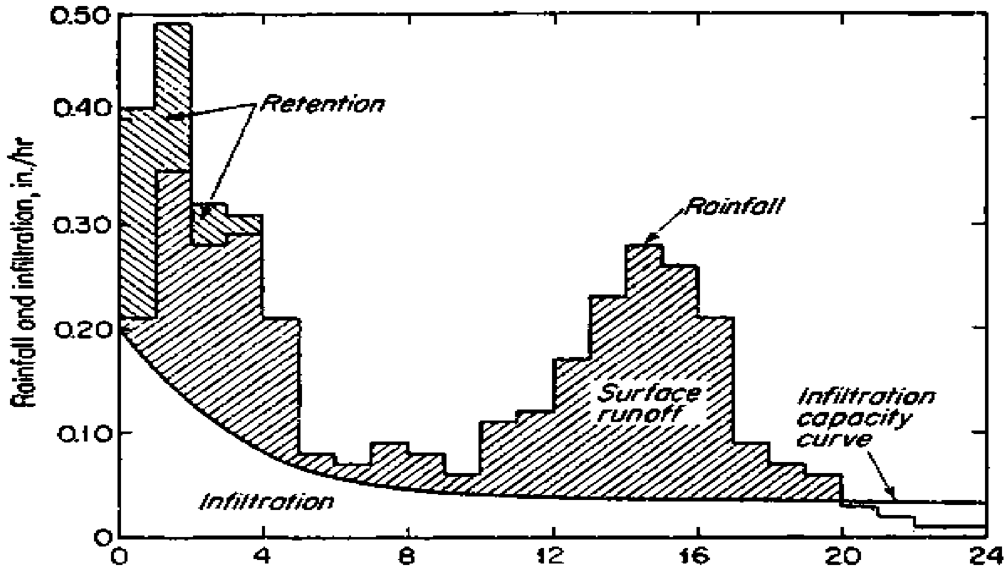


Figure 3.4 Schematic diagram illustrating relationship between rainfall, infiltration and runoff (Source: Linsley et al. 1958)

Considering the shape of infiltration curve, high rainfall intensities occurring at the start of the storm may not cause runoff but, the soil pore becomes filled with water and soil sorptivity decreases. Runoff is more likely to occur when the minimum infiltration rate is reached. As the rain continues, water reaching the ground surface infiltrates into the soil until it reaches a stage where the rate of rainfall (intensity) exceeds the infiltration capacity of the soil. Thereafter, surface puddles, ditches, and other depressions are filled (depression storage), after which runoff is generated.

The process of runoff generation continues as long as the rainfall intensity exceeds the actual infiltration capacity of the soil but it stops as soon as the rate of rainfall drops below the actual rate of infiltration.

3.2.7. Slope

The aspect of slope is important because many gently sloping terrains in the study area have very high infiltration rate generating little or no runoff at all. Because of limited farming areas much cultivation takes place on slopes greater than 5% and water conservation is needed. Where slopes are greater than 5% water harvesting is usually not recommended because large quantities of earthwork is required.

3.3. Design selection criteria

The main technique listed below are those already been adopted by farmers. A water-harvesting system suitable for micro-catchment application should preferably have the following characteristics:

- Should be cost effective.
- Construction should be possible by manual labour with minimum equipment, suitable for self-help groups.
- Easy to carry out operation and maintenance

On the basis of these criteria, flow chart on selection criteria was prepared for micro-catchment rainwater harvesting where runoff is induced on natural surface (i.e. slope or between conservation bunds).

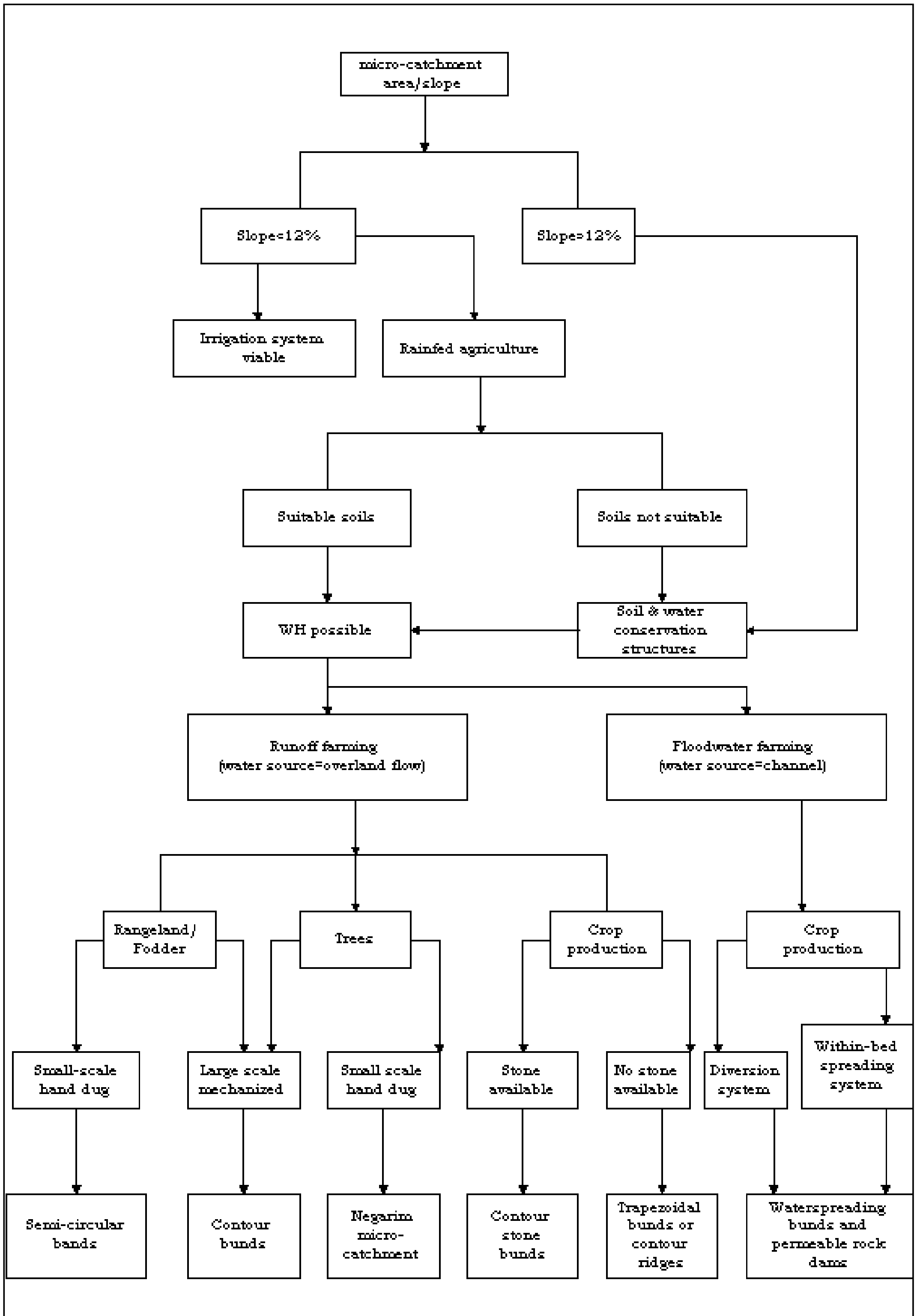


Figure 3.5 Water harvesting techniques selection criteria

4. HYDROLOGICAL DATA ANALYSIS

4.1. Rainfall data analysis

To quantify the rainfall intensity and duration that may cause runoff the rainfall data obtained from Kenya meteorological department will be analysed. Because of large variation in rainfall distribution the analysis will be carried out separately for each of the study area (Kinangop, Longonot and Ndabibi). Longonot flower farm station is the nearest representative weather station for the Longonot study area. Below is a map showing the locations of rainfall stations within the study field.

A recording (tipping bucket type) rain gauge was installed for two weeks at the site of Kijabe site 02, to understand the rainfall intensity patterns and to compare the variability of rainfall with other nearby rain station records. Apart from that rain gauge, daily rainfall data for Kijabe and Ndabibi for the year 2001 up to the end of September and past rain records from Mr. Data were used for the study.

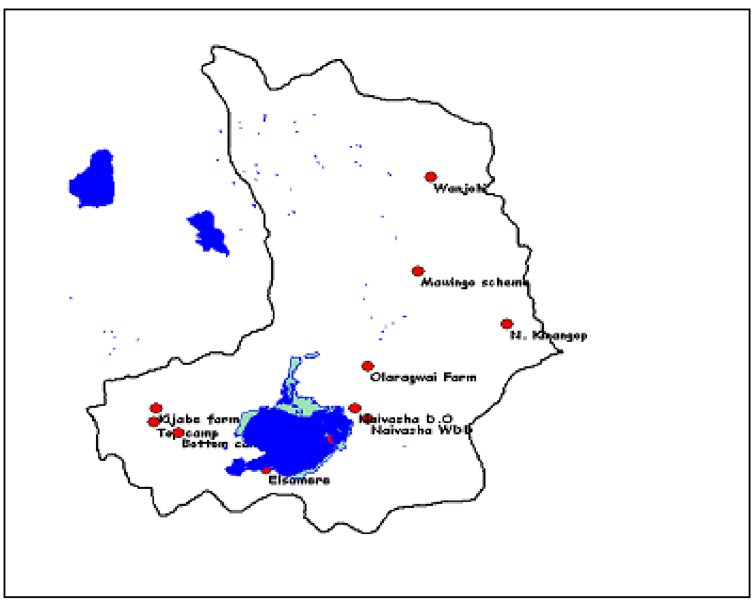


Figure 4.1 Location of rainfall stations

4.1.1. Checking the consistency of the rainfall data

More often meteorological data collected from the stations lack consistency due to observations error or failure of rainfall gauges. The double mass curve analysis, graphical regression method and single mass curve analysis are common techniques for correcting anomalies. Double mass curve method will be used to check the consistency of the data.

- Naivasha DO –9036002 (1900m a.s.l)
- N.Kinangop Forest station –9036025 (2629m a.s.l)
- Naivasha WDD –9036281(2066m a.s.l)

The analysis involves plotting of successive cumulative annual rainfall collected at one-gauge against successive cumulative average annual rainfall for the same period of years collected at several gauges in the same area. Once a double a mass curve reveals a change in slope that is significantly noticeable then the annual values of the earlier portion is adjusted to make it consistent with the later portion.

K (factor)=slope for period after change/slope for period before change

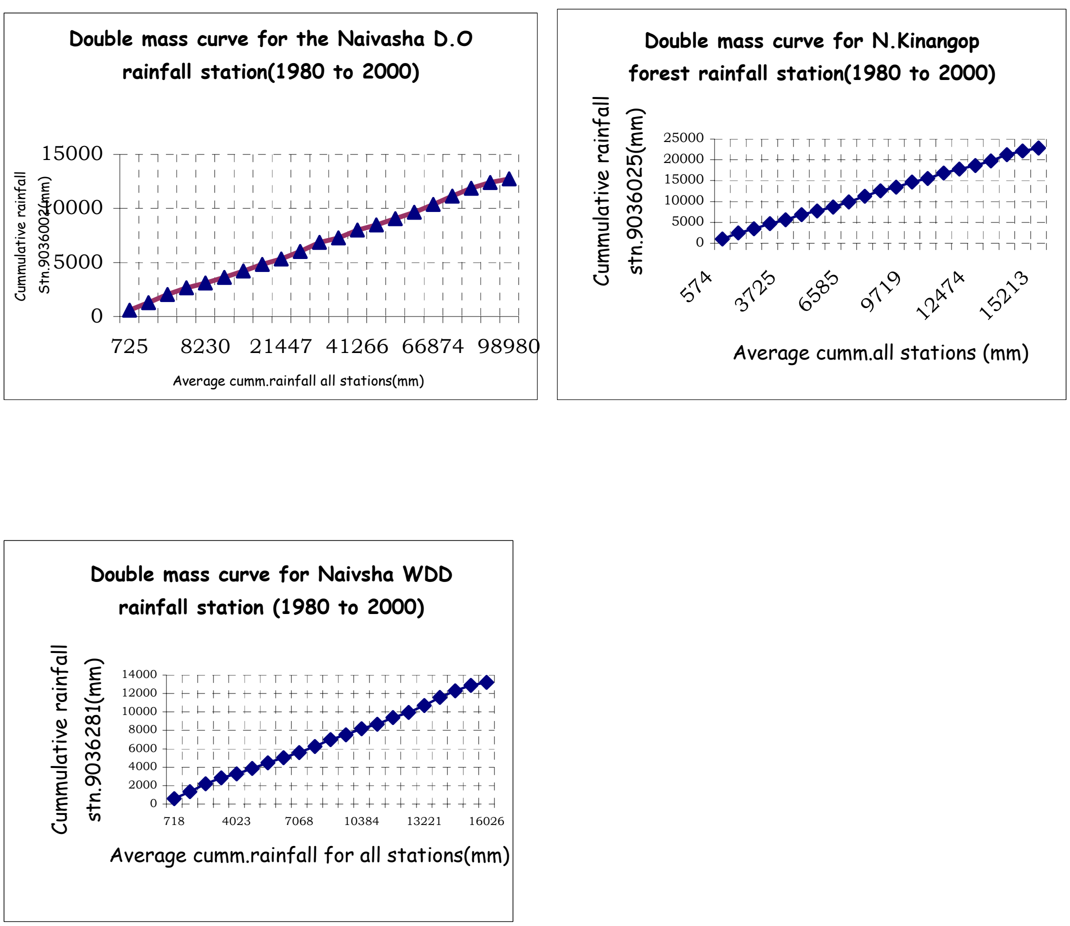


Figure 4.2 Double mass curves

The three rainfall gauging stations shows good consistency since the data is continuous and shows no significant change in trends.

4.1.2. Graphical regression method for missing observations

Once the data were checked for consistency and corrected missing records was filled using observations from the nearby station. Linear regression was used to fill in the missing records of the 3 rainfall stations covering the eastern, western and northern parts of the study area. These stations are located at different elevations.

Relationship between two pairs of station was established by fitting a linear regression model for each month, which was then used to fill the missing data. Despite the variations linear regression was used to generate missing monthly rainfall data.

Months	9036002 Vs 9036025	9036002 Vs 9036281	9036025 Vs 9036281
Jan	0.98	0.83	0.82
Feb	0.78	0.27	0.44
Mar	0.93	0.79	0.78
Apr	0.76	0.35	0.61
May	0.7	0.49	0.46
Jun	0.85	0.35	0.35
Jul	0.86	0.25	0.36
Aug	0.58	0.56	0.23
Sep	0.80	0.12	0.06
Oct	0.65	0.25	0.41
Nov	0.38	0.01	0.29
Dec	0.94	0.01	0.69

Table 4.1 Linear regression results

4.1.3. Annual rainfall data

In order to observe the long-term trend in the rainfall regime within Naivasha area, an annual plot for the average rainfall of three stations was compared from 1980 to 2000 and plotted as shown.

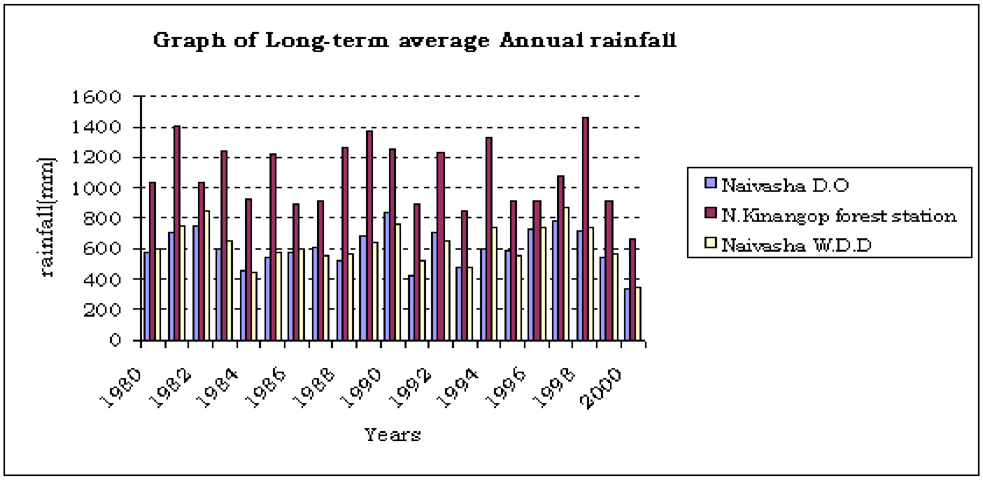


Figure 4.3 Long-term average annual rainfall

The graph shows that the rainfall pattern across the study area, with high rainfall occurring at the stations located at higher altitudes (N.Kinangop forest station) than those situated at lower elevation (Naivasha D.O and Naivasha W.D.D). The average over these twenty years was 600mm varying between 911mm and 385mm.

4.1.4. Monthly rainfall

For clear understanding of rainfall pattern in Naivasha namely Naivasha D.O, Naivasha WDD and North Kinangop stations are selected for the analysis. The stations are located in areas different in elevation and their average monthly values will be used for subsequent analysis.

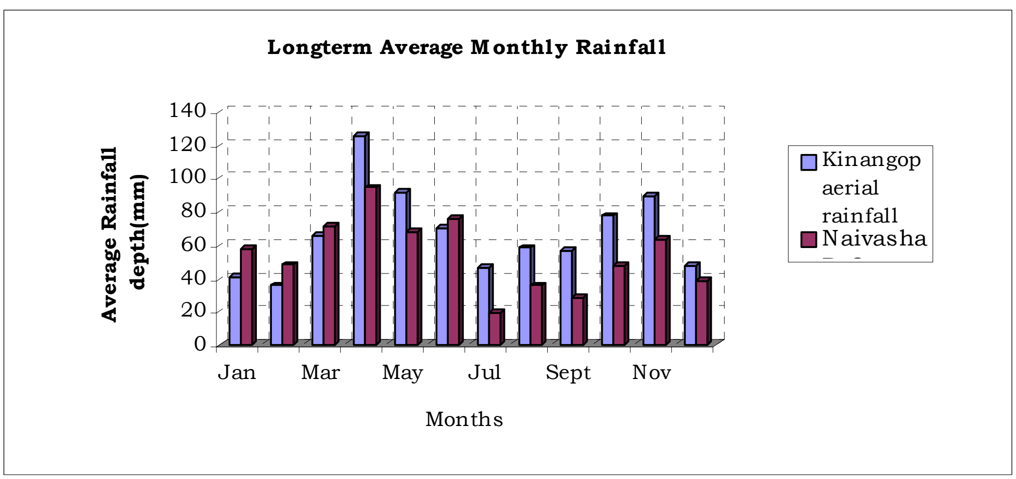


Figure 4.4 Longterm average monthly rainfall at Kinangop and Naivasha D.O stations.

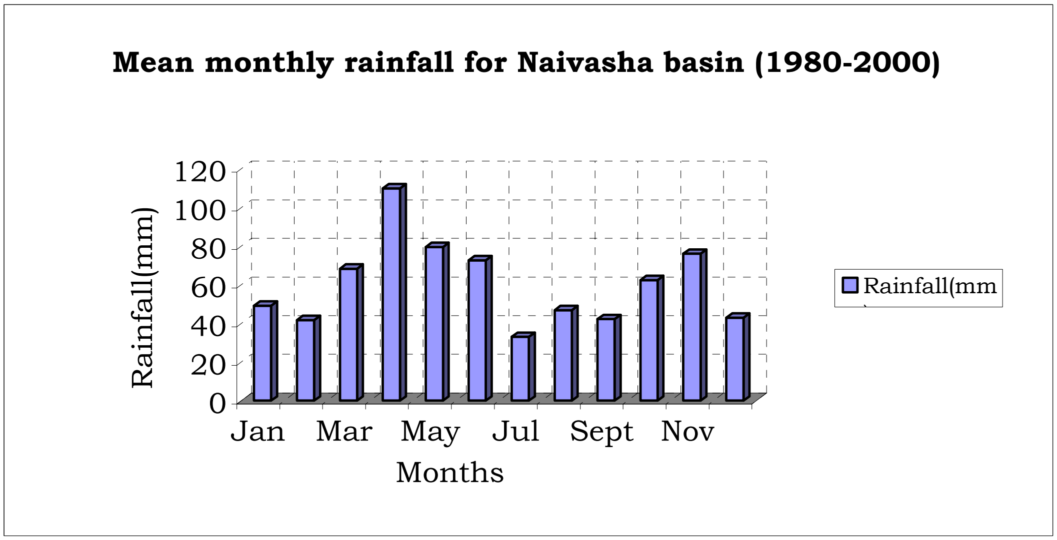


Figure 4.5 Mean monthly rainfall for Naivasha

The long rain is experienced from March to May and short rainy season from November to January.

4.2. Frequency rainfall

The frequency with which rainfalls of high intensity occur has important bearing on the sustainability of any conservation structures. From the graphs the rainfall events that could generate runoff occur less frequent and vary widely. Runoff will depend on crusting and other factors governing the infiltration rate but considerable runoff may occur when daily rainfall is greater than 20mm. In Naivasha most of the rainstorms do not have sufficient depth to exceed infiltration and have low intensities ranging between 0.5-4.5 mm/hr and thus producing little or no runoff.

For crusting soils a threshold level of 7.8mm rainfall has been observed before runoff begins (Critchley, 1991).

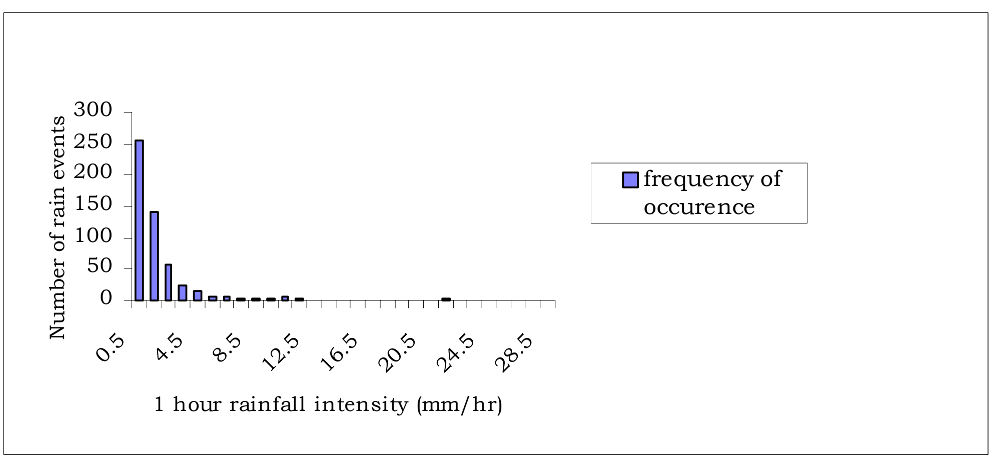


Figure 4.6 Frequency of occurrence for hourly intensity (Naivasha D.O, 1997).

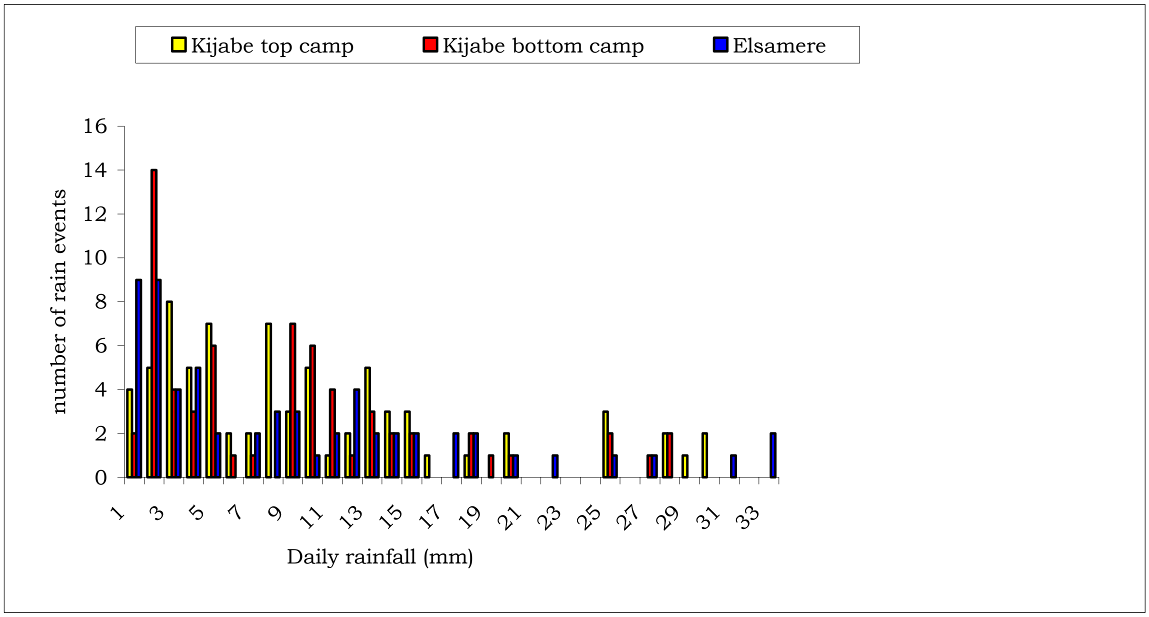


Figure 4.7 Frequency of occurrence for daily rainfall compiled for year 2001 at Elsamere research station.

4.2.1. Hyetographs

Figure 4.8 shows a dimensionless plot of hourly rainfall events recorded at Naivasha D.O. As illustrated by the curves, intensity distribution of rainfall differs with duration. They are skewed toward right with less intense prolonged showers at the beginning of the storm and reaching the peak as the storm progresses. The first rainstorm normally cause sealing of the soil surface, so that runoff increases as rainfall continues.

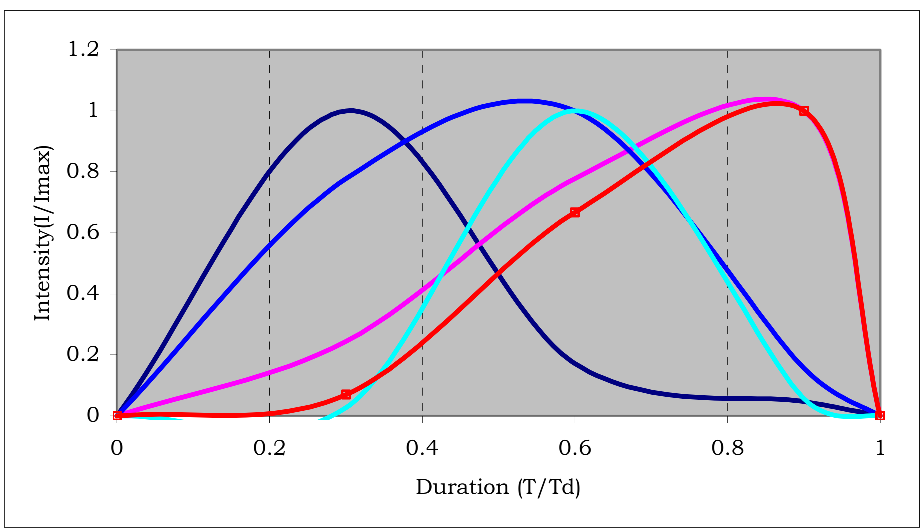


Figure 4.8 Dimensionless hyetograph

4.2.2. Selecting design rainfall and IDF curves

In water harvesting design, the aim is to prevent overflow of the structures. Therefore the peak discharge of the catchment area has to be estimated with some level of certainty. The most common approach is to use a design storm or event that involves a relationship between rainfall intensity (depth), duration, and the frequency or return period. Technically, a selection of such a rainfall level enables a design, which should work for approximately 10years or less return periods. The hourly rainfall data recorded in Naivasha D.O station was used to approximately develop from one year observation Intensity-Duration-Frequency curves for a return period of 2, 5 and 10 years.

Rainfall duration (min)	5	10	15	30	60	120
Ratio	0.29	0.45	0.57	0.79	1	1.25

Table 4.2 Short rainfall intensity conversion ratio for USA

Time	Return period		
(Min)	2years	5years	10years
5	90	122	139
10	45	61	70
15	30	41	46
30	15	20	23
60	8	10	12
120	4	5	6

Table 4.3 Design rainfall depth for various duration and return periods at Naivasha D.O

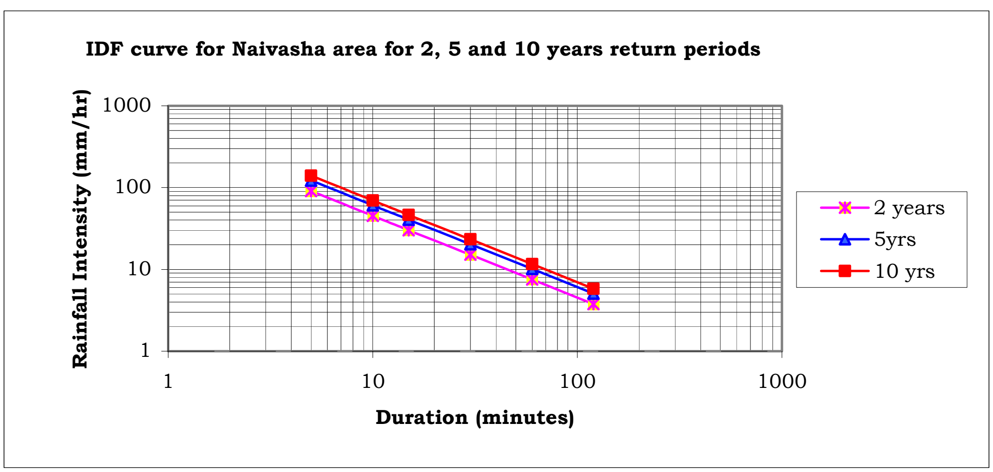


Figure 4.9 The intensity-Duration-Frequency curves for Naivasha D.O

The curves show the expected rainfall intensities occurring in anyone of the selected period and therefore runoff volume can easily be read depending on the duration. From IDF curve it is possible to obtain the probability of occurrence or exceedence of a rainfall value of a specific magnitude. Inversely, it is also possible to obtain the magnitude of the rain corresponding to a given probability.

4.3. Peak flow measurements

The peak flow of a micro-catchment is taken as a measure of its response to rainstorm. Large peak flows indicate rapid response due to low storage and vice versa.

4.3.1. Slope Area Method

In some areas there was good high water marks available to define the water surface profile at the time of the peak. A fairly uniform reach was selected in which water surface profile was expected to have been parallel to the streambed for all the measurements. The slope-area method is necessary to determine the peak discharge of ungauged ephemeral streams.
Local information and aerial photographs enabled us to make measurements of high watermarks, channel dimensions, average cross-sectional areas of uniform reach, roughness coefficient and channel slopes in the field.
By establishing the slope of the water surface in a uniform reach of the channel measurements of average cross-sectional area would be made to determine the rate of discharge. These measurements were made for six sites in Naivasha and the results tabulated in table 4.4. The manning equation was used for computing the peak discharges of the catchments.

$$Q = \frac{1}{n} AR^{2/3} S^{1/2}$$

Where

Q= Discharge (m^3/s)
n= Manning's roughness coefficient depending on the character of the channel lining
A= Cross-sectional (m^2)
R= Hydraulic radius
S= the head loss per unit length of channel

Site	Channel Area A (m^2)	Hydraulic Radius (m)	Mean Velocity (m/s)	Manning Coeff. (n)	Slope (%)	Peak Discharge (m^3/s)	Peak Flow (l/sec/m^2)
Longonot (Flat)	3.1	0.16	0.069	0.05	0.013	0.21	68
Ndabibi (maize)	1.52	0.41	2.48	0.05	0.05	3.77	2480
Kijabe farm (1)	0.1	0.012	0.0059	0.045	0.055	0.00006	0.6
Ndabibi (wheat)	0.028	0.023	5.8	0.03	0.03	0.17	6071
Kijabe farm (2)	0.01	0.013	0.008	0.04	0.077	0.000092	9.2
Kipipiri	0.008	0.0018	0.002	0.03	0.041	0.000016	2

Table 4.4 Summarised computation of Peak flow estimates using Slope area method

Ndabibi area has very high discharge rate because of its rugged terrain aggravated by nature of the soil. Gullies have been formed as a result of tunnel erosion, which later collapses leading to formation of new gullies. Longonot have loam to clay loam soils, which has tendency of forming surface crust. Because of varying terrain units, soil and lithology in the catchments sufficient measurements are needed to make reasonable comparisons and estimates.

5. RAINFALL-RUNOFF MODELLING

5.1. Parched thirst Model

The parched thirst model simulates key processes that influence the performance of rain-water harvesting systems. It comprises a number of sub-models linked together as shown below.
Rainwater harvesting is simulated by having two profiles running simultaneously with run-off from the upper part becoming an input for the lower of the two. Except for climate and soil texture, the catchment area and cropped can have different characteristics.
The model is driven by daily rainfall and the daily weather data's for every year simulated.

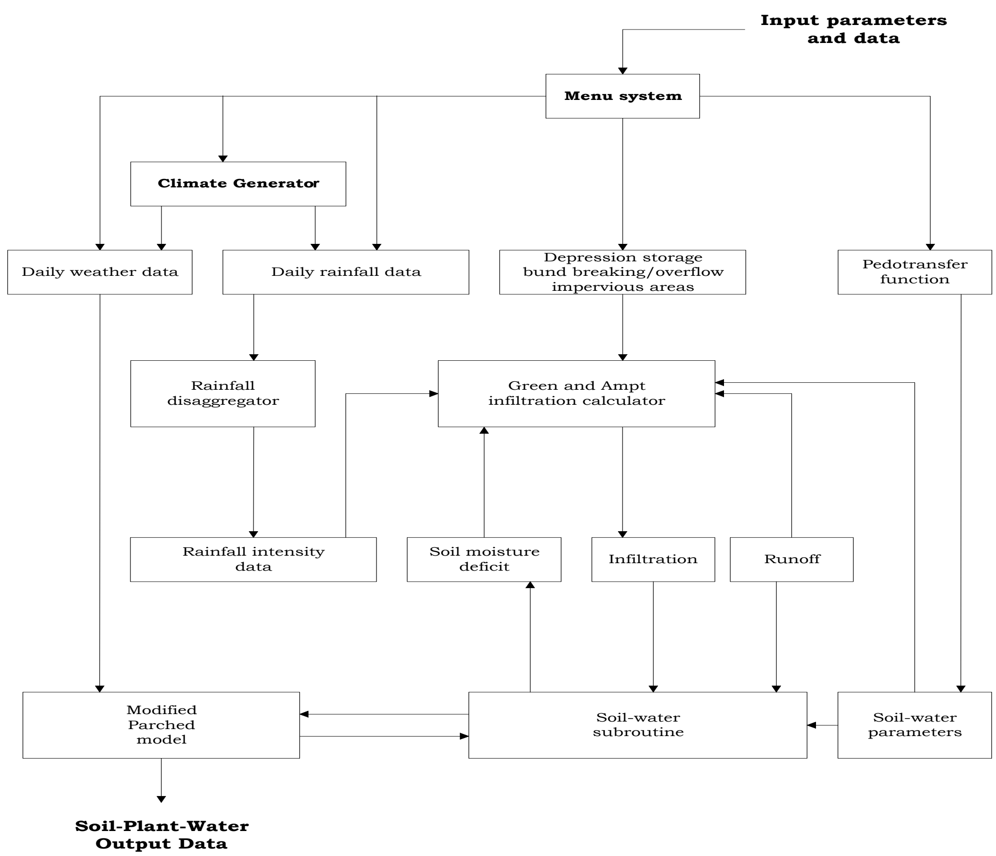


Figure 5.1 Interactions between the parched thirst sub models (Source: Parched thirst user guide manual)

5.2. Model input data

5.2.1. Daily rainfall

Daily rainfall data from 2GB1 gauging station was used to simulate the model. The daily rainfall values are converted by the rainfall disaggregator into intensity data that are required by the infiltration model.

5.2.2. Infiltration

The rainfall-runoff process is simulated as infiltration excess with infiltration being determine by the Green-Ampt infiltration calculator. A pedotransfer function option is included in the model to allow for the prediction of infiltration from the available soils data.

5.2.3. Layer width

5 layers represented the soil profile, which was considered as homogenous unit to allow the calculations of soil water movement. The width of each soil layer was entered in millimetres. The total profile depth was 1100mm. The initial soil moisture content was set to 200% (vol/vol), which specifies the moisture status of the soil at the beginning of the simulation.

5.2.4. Soil Properties

The soil sub model gives access to the items soil water, texture, tillage and soil fertility, which were entered based on the assessment made during the fieldwork. According to the nomenclature United States Department of Agriculture (USDA) and the texture triangle, texture classes were determined in the Laboratory for each of the site where hydraulic conductivity test was made. The texture classes determined in the laboratory are given in Table 5.1. The texture determined by feel method was only an estimate and was not used for P_T model because it was subjective though remains the only method available in the field. The texture for each soil, fractions of each of sand, silt, clay, organic matter and bulk density were entered into the Parched-Thirst model as summarised in table 5.1.
Cation Exchange Capacity, Permanent Wilting Point, Residual Soil Moisture, Field Capacity and Saturated Soil Moisture were automatically calculated by pedotransfer function because field data were not available.
Surface crusting and macro pores were allowed for the topsoil soil, which will consequently affects the runoff.

Soil type ID	Soil type	%Sand	%Silt	%Clay	%OM	Bulk density
JI	Loam	35	30	27	8	0.86
J2	Clay loam	27	36	28	9	0.87
K1	Sandy loam	55	27	14	4	0.93
K2	Loam	50	27	19	4	0.83
L1	Loam	48	32	15	5	0.83
N1	Clay loam	29.8	28.3	36.5	5.4	0.58

Table 5.1 Soil hydraulic parameters

Location	ID	Land preparation date	Date collected	Soil Texture determined by Feel method
Kijabe	J1	04 / 08 / 2001	17 / 09 / 2001	Silt Clay
Kijabe	J2	25 / 08 / 2001	20 / 09 / 2001	Silt Clay
Kinangop	K1	February 2001	14 / 09 / 2001	Silt Clay
Kinangop	K2	4 years old	14 / 09 / 2001	Silt Clay
Longonot	L1	February 2001	26 / 09 / 2001	Sandy Clay Loam
Ndabibi	N1	February 2001	21 / 09 / 2001	Sandy Clay
Ndabibi	N2	February 2001	21 / 09 / 2001	Sandy Clay

Table 5.2 Soil texture determined by feel method

5.2.5. Crop data

Maize was used during the simulation period because it is a common crop with small-scale farmers in Naivasha. Two seasons were simulated for plant density of 40000/ha.

No. of Season	Start simulation	Sowing date
1	1-Jan-01	1-Feb-01
2	1-Jul-01	1-Aug-01

Table 5.3 Timing data

5.2.6. Slope

The slope of runoff area was set to 7%. Changing the slope had no change on both yield and runoff.

5.3. Model output

Below is an output result of 1-year simulation with two seasons on a Catchment: Cropped area ratio of 1:1. The data shown are those for the first season of 2001 only.

The Alter window in the model facilitates the effects of increasing or decreasing the runoff area and rainfall on the grain yield.

Increasing the runoff area and rainfall increases the grain yield slightly to a certain level beyond which the grain yield start declining but the runoff shows a enormous increase with an increase in runoff area as shown in table 5.4.

Increasing the daily rainfall by 10%, 20% and 30% on a C:CAR of 2:1 has the effect of increasing the yield and runoff gradually as illustrated in table 5.4 and figure 5.2.

When the model was simulated with clay loam and loam each separately by allowing surface crusting, soil with loam texture had a grain yield of 0.83 ton/ha while clay loam had no yield (table 5.5). Both soil generated 20mm runoff. Soil with surface crust yields same result as ones without crust (Table 5.6). The model was not sensitive to change in crop type.

C:CAR	Yield (ton/ha)	Runoff (mm)	Above ground (ton/ha)
1:1	2.26	20	7.73
2:1	2.34	40	8.15
3:1	2.36	61	8.1
4:1	2.35	81	8.07

Table 5.4 Sensitivity analysis of grain yield to CCAR (Season1:Jan-July)

C:CAR	Increase rain by	Yield (ton/ha)	Runoff (mm)	% Increase in runoff
2:1	2gb1 rain (1997)	2.34	40	0
	10%	2.39	46	15
	20%	2.42	52	30
	30%	2.44	56	40
	40%	2.44	57	42

Table 5.5 Sensitivity analysis by altering the rainfall (Season 1: Jan-July)

CCAR	Texture	Rain (mm)	Ground dry wt.	Yield (ton/ha)	Runoff (mm)
1:01	Clay loam	420	0.55	0	20
	Loam	404	3.05	0.83	20

Table 5.6 Soil without surface crust

CCAR	Texture	Rain (mm)	Ground dry wt.	Yield (ton/ha)	Runoff (mm)
1:01	Clay loam	406	0.53	0	20
	Loam	423	3.02	0.82	20

Table 5.7 Soil with surface crust

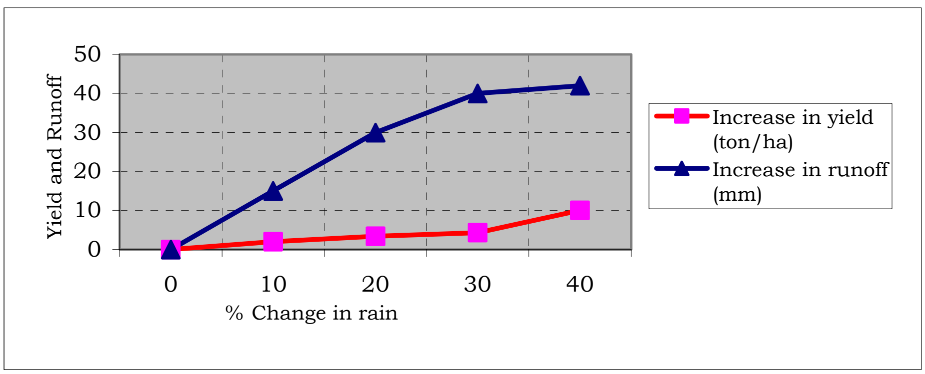


Figure 5.2 The effects of altering rain on yield and runoff

Simulation Year: 2001-1 (2001-1, 2001-2)

RUNON AREA	
Total Rainfall(mm):	404
Growing Season Rain(mm):	379
Average Sat Deficit(KPa):	2.89
Crop Type:	MAIZE
Sowing Date:	1/2/01
Length of Growing Season:	151
Grain Yield (t/ha):	2.26
Above Ground Dry Weight (t/ha):	7.73
Harvest Index:	0.29
Crop Transpiration(mm):	344
Weed Transpiration(mm):	
Total Runon(mm):	20
Total Evaporation(mm):	191
Starting Water(mm):	252
Final Water(mm):	141
Drainage(mm):	0
Overflow/Release(mm)	0

RUNOFF AREA	
Total Rainfall(mm):	404
Growing Season Rain(mm):	0
Average Sat Deficit(KPa):	2.89
Crop Type:	No Crop
Sowing Date:	1/2/01
Length of Growing Season:	0
Grain Yield (t/ha):	0.00
Above Ground Dry Weight (t/ha):	0.00
Harvest Index:	0.00
Crop Transpiration(mm):	0
Weed Transpiration(mm):	
Runoff per Unit Area(mm):	20
Total Evaporation(mm):	255
Starting Water(mm):	252
Final Water(mm):	380
Drainage(mm):	0

EXIT

Table 5.8 Simulation summary

5.4. Saturated hydraulic conductivity

A study of soil hydraulic conditions is essential for the selection of suitable sites for water harvesting. Auger hole tests for soil permeability were used in the study area for infiltration assessment.

Saturated hydraulic conductivity measurement was carried out under closely similar preparation and test procedures in 29 sites spread over 4 locations. In all areas of study the soils were saturated prior to measurements.

The procedure

1. A hole of radius r was augered in the soil to a depth of d cm.

2. The hole was then filled with water, which was left to drain freely. The hole was refilled with water several times until the soil around it was saturated over a considerable distance and the infiltration rate has attained a more or less constant value.
3. The rate of drop of the water level in the hole was then measured.
4. Plot of the data log (h+0.5r) against time yields a straight line and shows that a linear relationship exists between the two sets of values.
5. The slope of the graph is then used to calculate saturated hydraulic conductivity of the area.

The quantity of water infiltrated under saturated conditions is measured based on Darcy's law, (Kessler & Oosterbaan, 1974) as follows:

$$K_s = r/2\{[LN(h_{t1} + r/2) - LN(h_{t2} + r/2)]/(t_2 - t_1)\}$$

Where

K_s =Saturated hydraulic conductivity of the soil

r = is the radius of the auger hole

h= Water level in the hole

t = is the elapse time between two successive head measurements under saturated conditions,

The relation between log (h (t)+r/2) and elapse time is linear, so the saturated hydraulic conductivity was estimated by linear regression through the measurement points. The results of the analysis are tabulated below.

The infiltration capacity depends on the moisture content prevailing in the soil at the onset of measurements, texture and structure (Viessman et al; 1996, Hillel 1998).

For all the sites soil texture was determined to see if a relation could be established between the saturated conductivity and texture. The land use also influences the physical condition of the soil, which in turns affects infiltration. With repeated cultivation soil becomes more porous and exhibits high hydraulic conductivity, which could be true for measurements made in Ndabibi within areas under maize cultivation.

Site	**No. Of measurements**	**Estimated Avg.Ks (cm/hr)**	**Theoretical Estimates (cm/hr) (Source: Byron, 1994)**
Kinangop (Olmogogo) sandy loam and Loam	7	2.4	3.78 or 0.24
Longonot (Loam)	5	40	3.78
Ndabibi (Clay loam)	7	21.2	0.29
Kijabe (Loam or Clay loam)	10	3.4	3.78 or 0.29

Table 5.9 Saturated hydraulic conductivity estimates study sites

Previous research on similar soil texture (Byron, 1994) has indicated wide variability of hydraulic conductivity, which can also be recognized from these measurements. In practice infiltration rate varies from time to time and it was difficult to achieve accurate representative that covered the whole study area.

5.5. US SCS Curve Number method

In this part runoff will be estimated according to the surface characteristics of the catchments using an empirical rainfall/runoff model based on daily rainfall records of Naivasha D.O station (Source: Kenya meteorological departments).

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

The US Soil Conservation Service (SCS) runoff Curve Number method relates hydrological soil group type to the curve number as a function of soil cover, land use type and antecedent moisture conditions and estimate runoff depth from small catchments. The reason for application of this method is that useful hydrologic data concerning rainfall-runoff relations and erosion are limited for the region.

The SCS Curve Number method relates depth of excess rainfall, total rainfall depth, initial abstractions, additional abstraction in the watershed and maximum surface retention as follows:

$$\frac{F_a}{S} = \frac{P_e}{(P - I_a)}$$ ……………………………………………………………….(Equation 1)

Where

P = Total rainfall depth (inch)

F_a = Continuing abstraction in the watershed (inch)

P_e= = Excess rainfall (inch)

I_a = Initial abstraction before ponding (inch)

S = Maximum potential surface retention (inch)

From continuity principle

$$P = P_e + I_a + F_a$$ ……………………………………………………………………….(Equation 2)

Combining equation1 and equation2 to solve for Pe gives

$$P_e = \frac{(P - I_a)^2}{P - I_a + S}$$ ……………………………………………………………………….(Equation 3)

Eq3 is the basic equation for computing depth of excess rainfall (direct runoff) from a storm (Soil Conservation Service, 1986).

By study of results from many small experimental watersheds, an empirical relation was developed.

$$I_a = 0.2 * S$$ ………………………………………………………………………….(Equation 4)

$$S = \frac{1000}{CN} - 10$$ ……………………………………………………………………….(Equation 5)

Therefore,

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S}$$ For P>0.2S. …………………………………………………………(Equation 6)

In order to characterize the hydrological soil group within the study area the percentage contribution of different soil groups and land use types was considered. The descriptions of the categories of the soil groups and the land use are included in the appendix. Since only limited soil data was available measurements of soil depth, soil texture and infiltration was done in the field.

Kinangop area

From the auger hole test and field checks the dominant soil type of Kinangop plateau is silty clay loam, moderately deep (approximately 60cm) and high in clay content. Has very high runoff potential and slow infiltration when wet.
The main land use types are crop cultivation, pasture, road and settlements. The cultivated land (80%) has good conservation treatment with little erosion. The pasture or rangeland (8%) is in good condition with grass cover 85%. 10% built up areas and dirt roads (2%).

Longonot area

Soils are made up of colluvial deposits, very light gravels, very deep (80cm deep) and highly permeable and excessively drained. Soil depth >1m and 50% porous. With medium texture and very high infiltration. Shows low runoff potential.
Land use types: Pasture (60%) grass cover on 60-80% of the area, cultivated land (24%) with no conservation treatment (presence of gullies), built up areas (10%), Road (5%), Open bare land (1%).

Ndabibi and Kijabe area

Soil types: Silty clay to Sandy clay, Very deep (depth>80cm) and volcanic ash material. Has very high infiltration when dry.
Land use: small-scale agricultural practices to large Wheat fields (60%) with 50-60% conservation treatment, Pasture and rangeland (30%), Built up areas (4%) and dirt road (4%), Shrubs with thin stand (2%)
Curve Numbers for entire catchments of Kinangop, Kijabe/Ndabibi and Longonot was calculated by area weighing of the CN of the particular land use and cover (refer to appendix SCS table used for the calculation of the weighted CN).
Under SCS curve number method the precipitation that will shift the soil moisture from one AMC to another vary over the season.
By considering 5 days total rainfall preceding the particular day under review the antecedent moisture level of the soil as to whether it was wet or dry was determined. The range of antecedent rainfall for each class is shown in the appendix 6, table 2. The average of the seasonal category was adopted for the research.
Thus,

Weighted CN (Kinangop)= (3031+5029)/100=80.60
Weighted CN (Longonot)= 8198/100=81.98
Weighted CN (Kijabe & Ndabibi)= (3551+4124)/100=76.75

Area of study	Weighted average CN
Kinangop	81
Longonot	82
Ndabibi	77

Table 5.10 Estimated weighted averages Curve Numbers

For dry conditions, $CN(I) = \frac{4.2 * CN(II)}{10 - 0.058 * CN(II)}$ ……………………………………………(Eq6)

For wet conditions, $CN(III) = \frac{23 * CN(II)}{10 + 0.13 * CN(II)}$ ....(Eq7)

The differences in runoff response of individual rainfall days as a result of variations in antecedent soil moisture conditions were adjusted for dry (CN (I)) or wet conditions (CN (III)) (Eqns (6) and (7); Haan et al., 1994).
Runoff calculation was done using excel for each rainy day using the weighted average Curve Number in table5.9 above.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rain (mm)	14	0	56	174	81	22	38	17	48	80	152	107	789
Runoff (mm)	8	0	11	33	6	19	36	7	32	37	54	78	320

Table 5.11 Aggregated runoff estimates for Kinangop based on SCS Curve Number method

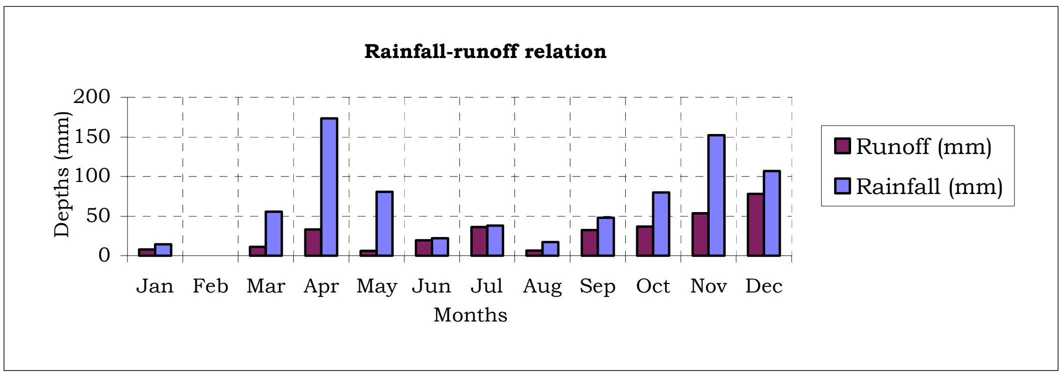


Figure 5.3 Rainfall and Runoff by CN method for Kinangop area

Only 98days with rain>1mm was considered for this computation. The runoff plotted against rainfall shows no significant correlation illustrating the non-linear behaviour of the rainfall-runoff process as determined by the CN method.
Some linearity exists for very wet days (April/November) because infiltration rates are low in relation to rainfall.
From the calculation out of the 789 mm of rainfall recorded that year 320mm occurred as rainfall excess for kinangop area. The CN method indicates that same amount of the rainfall can be conserved in the field (in-situ conservation of the rainfall in an on-farm reservoirs to meet a larger portion of crop water requirements).

5.6. Runoff coefficient

Runoff coefficient defines the percentage of rainfall that becomes runoff. Seasonal runoff coefficients were derived for Kinangop as shown below.
Depending on the periods of interest different types of runoff coefficients can be determined such as for annual, seasonal, wet and dry period.
Studies in West Africa, India and Kenya have indicated seasonal runoff rates of crusting soils of 26.2% to 45.4% (Lal, 1976; Sharma et al., 1993; Okwach, 1994). Refer to estimated runoff coefficients for mini-catchments, 300-550mm annual rainfall zone in table 5.13 (Meijerink, 2001).
Water harvesting potential is indicated by this ratio of runoff to rain. Low runoff coefficient corresponds to low runoff available for harvest and vice versa.

Month	Rain	Runoff	RC by CN method
Jan	14	8	0.55
Mar	56	11	0.20
Apr	174	33	0.19
May	81	6	0.07
Jun	22	19	0.86
Aug	17	7	0.39
Nov	152	54	0.35
Dec	107	78	0.72

Table 5.12 Seasonal runoff coefficients for Kinangop

For a site in Jordan, Oweis and Taimeh (1996) found variation of runoff coefficient values from 6 to 77%. Data from a small rural catchment in northern Tunisia with mean annual rainfall about 450mm illustrated increase of the runoff coefficient during short periods with consecutive rainfall.
Apart from the rainfall characteristics mentioned above, which strongly influence the rainfall-runoff process, it should also be considered that the physical conditions of the catchment area are not homogenous. Even at the micro level there are a variety of different slopes, soil types, vegetation covers etc. Each catchment has therefore its own runoff response and will respond differently to different rainstorm events.
However, more measurements are required to estimate the runoff coefficient accurately because runoff coefficient influences site and design selection of water harvesting potential areas.

Small catchments <Few hectares	Range of RC for average precipitation		
Category	Dry	Average	Wet
I, impermeable	15	28	53
III, permeable	3.5	7	15

Table 5.13 Runoff coefficients for mini-catchments, 700mm annual rainfall zone based on data from Sahel (Meijerink, 2001)

6. SOIL WATER BALANCE MODEL

6.1. Water balance model

In this chapter Water Balance Model will be simulated on a monthly and weekly time step to estimate soil moisture deficit, soil moisture surplus, actual evapotranspiration, and surface runoff of the study area. In spite of the simple structure of the model by Thornthwaite, they have estimated monthly run-off values reasonably well (Alley 1984, Calvo 1988).

Water balance for catchments can be represented by the following conservation equation (Dunne and Leopold, 1978);

$$P = I + AET + OF + \Delta SM + \Delta GWS + GWR$$

Where:
P= Precipitation (mm)
I= Interception (mm)
AET= Actual evapotranspiration (mm)
OF= Overland flow (Quick flow)(mm)
$\Delta SM =$ Change in soil moisture (mm)
$\Delta GWs =$ Change in groundwater storage (mm)
GWR=Groundwater runoff (Base flow)(mm)

Assumptions made;

1. Inflow to the catchment is only by precipitation
2. The study area has one vegetation type defined by the single value of the rooting depth.
3. The water holding capacity of the root zone is uniform throughout the modelled area.

6.2. Definitions of model parameters

The various water balance parameters considered in the model are defined below.

Rainfall (P)

Precipitation entered as rain only. No interception losses have been considered.

Overland flow (OF)

Overland flow is subtracted from the rainfall to obtain the effective rain. Then it bypasses the water balance calculations and is eventually added to the river discharge. For this study it was taken as zero and direct rainfall taken as effective rain.

Potential evapotranspiration

Potential evapotranspiration could not with the Penman method (FAO, 19) because of insufficient data on solar radiation, relative humidity, wind speed and other required data for penman, and therefore the method of Hargreaves was used. The equation for monthly evapotranspiration is as follows:

$$ET_o = 0.023\,(T_{mean} + 17.8)(T_{\max} + T_{\min})^{0.5} R_a$$

Where

R_a =Extraterrestrial radiation for different latitudes for the 15th day of the month

$T_{\max}$ = Maximum daily temperature (oC)

$T_{\min}$ = Minimum daily temperature (oC)

T_{mean} = Mean for maximum and minimum temperature

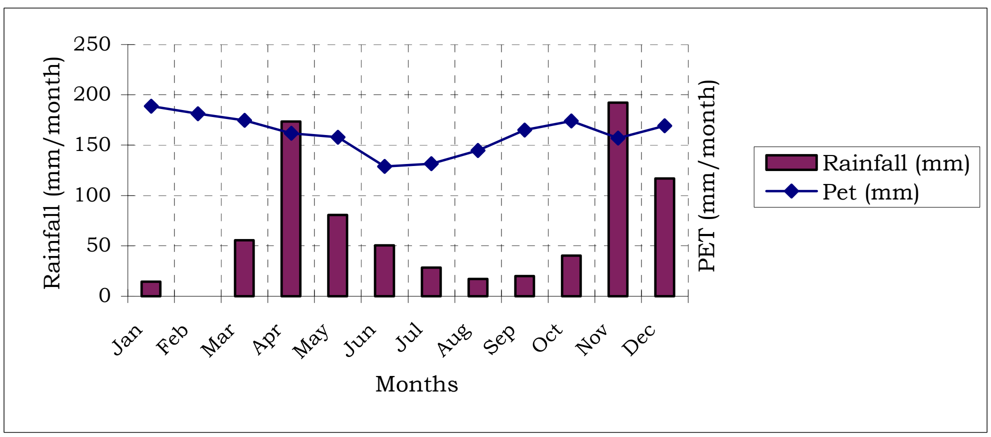


Figure 6.1 Monthly average Rainfall, Potential evapotranspiration (Hargreaves method) for Kinangop

Accumulated potential water loss (APWL)

The APWL is obtained by accumulation of the negative values of the differences between monthly rainfall and potential evapotranspiration. The summation begins with the first month of the dry season.

Soil moisture

The accumulated potential water loss is used to obtain the soil moisture during the dry months using the following formula:

$$S_m = W * EXP\left(-\frac{La_m}{W}\right)$$

Where

S_m = Soil moisture during month M (mm)

La_m = Accumulated potential water loss at month M (mm)

W = Available water capacity of the root zone (mm)

Soil moisture values for each wet month are obtained by adding the excess of rainfall of the current month to the soil moisture of the month before. Since this sum may not exceed the water holding capacity of the root zone, any excess is booked as surplus.

Soil moisture difference

$$dS_m = S_m - S_{(m-1)}$$

Where

dS_m = Difference in soil moisture between month M and month M-1 (mm).

S_m = Soil moisture during month M (mm)

Actual evapotranspiration (AET)

For the wet months the AET equals the potential evapotranspiration. For the dry months the AET is the sum of the monthly rainfall and monthly amount of water extracted from the soil.

$$AET_m = R_m + dS_m$$

Where

AET_m = Actual evapotranspiration during month M (mm)

R_m = Average rainfall of the month

dS_m =Difference in soil moisture between month M and month M-1 (mm)

Soil moisture deficit

The monthly soil moisture deficit is the difference between the monthly potential evapotranspiration and monthly actual evapotranspiration.

$$Smdef_m = PotEvp_m - AET_m$$

Where

$Smdef_m$ = Soil moisture deficit at month M (mm)

$PotEvp_m =$ Potential evapotranspiration at month M (mm).

$AET_m =$ Actual evapotranspiration at month M (mm)

Soil moisture surplus

The amount of water that cannot be stored

Runoff

Within the time step considered, the moisture surplus drains as fast runoff and deep subsurface runoff. According to Thornthwaite and Mather's for large catchments 50% of the
Surplus will be available for runoff and the other 50% is detained in the subsoil, groundwater and channels of the catchment and is available for runoff in the next month.

Water holding capacity

Soil and vegetation characteristics are combined by means of the water holding capacity of the root zone. The average effective root zone depth of the study area is 50cm. Maize, wheat, and beans are the major crops grown in the area in rainy season covering large percent of total cultivated area. The vegetation types are short pasture grass and few agro-forestry trees. Based on the soil description during the fieldwork, estimates were made regarding the water holding capacity of the main units taking into account texture and thickness of the rooting depth. See appendix: Showing a table of suggested available water capacities for combination of soil texture and vegetation.

Land cover	Rooting depth	Soil texture	Ava. WHC
	(m)		W (mm)
Maize, beans	0.5	Clay loam	125

Table 6.1 Water balance Model input

6.3. Flow components

A program TimesPlot program (Donker, 1995) was used for base flow separation. Year 1998 long rainy season (March to June) and short rainy season (October to December) for which the daily data's available (gauging station 2GB1) was used to estimate daily base flow and quick flow. A filter parameter of 0.96 was used, which is an average value described in previous research (Nathan and McMahon, 1990) for removal of base flow from high frequencies of quick flow. It is the surplus that forms the water available for base flow, which consequently emerges as stream flow. The direct flow was used to calculate effective rain.

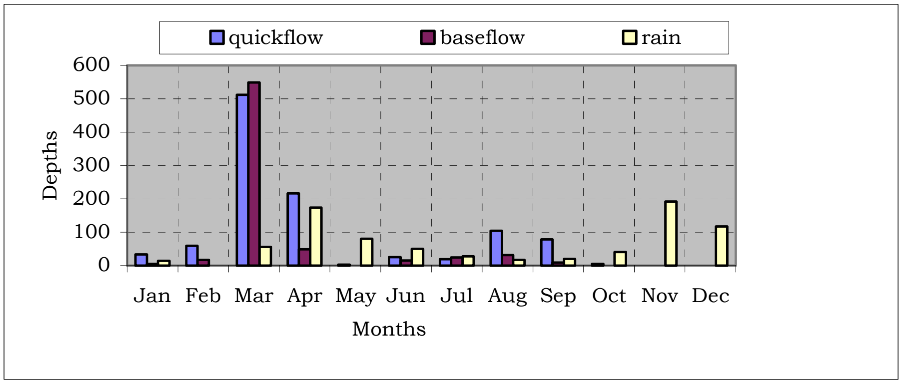


Figure 6.2 Monthly rainfall, quick flow and baseflow at 2GB1 gauging station

As can be seen from figure 6.3, the rainfall and runoff data are incompatible; e.g. runoff in March greatly surpasses the rainfall in same month and preceding periods. Because of this inconsistency run-off was not used to calibrate the water balance model.

6.4. Model Output

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Tot
Rain	19	0	57	177	84	23	39	17	48	80	153	109	789
OF	0	0	0	0	0	0	0	0	0	0	0	0	
Eff.rain	19	0	57	177	84	23	39	17	48	80	153	109	
Ref. Pet	189	181	175	162	158	129	131	145	165	174	157	169	1934
Rain-PET	-170	-181	-117	15	-74	-106	-92	-128	-117	-94	-3	-60	-1127
APWL	-221	-402	-519	-252	-326	-432	-524	-652	-769	-863	-866	-926	
SM	21	5	2	17	9	5	2	1	0	0	36	83	
DSM	-62	-16	-3	15	-7	-4	-3	-1	-1	0	36	47	
AET	81	16	60	162	91	57	31	18	21	42	157	166	902
D	108	165	114	0	67	71	100	126	144	132	0	3	
S	0	0	0	0	0	0	0	0	0	0	0	0	

Table 6.2 Longterm average monthly water balance (T&M) at Naivasha

The table above represents long-term average monthly water balance (T & M) at Naivasha, for AWHC of 125mm.The soil is clay-loam under maize cultivation with a rooting depth of 0.5m. All the values in the table are in millimetres.

On a monthly time step the Thornthwaite and Mather's model did not produce any surplus as shown in table 6.2. There was no moisture surplus generated because of the accumulated moisture deficit occa-sioned by many dry days in the months. Daily time step was considered and yielded surplus as shown in Appendix.2.

The result obtained from the simulation on daily basis was aggregated for months as shown in table 6.3. The total rainfall used for the simulation was 789mm. Based on 50% detention value adopted by previous studies for moderate to large watershed (Thornthwaite and Mather's, 1955), detention was also set to 50%. The moisture surplus all appeared as runoff.

Considering the rainfall data adopted to execute Thornthwaite and Mather's model on a daily time step, 40% of the rainfall occurred as surface runoff and remaining 60% may have been detained or evaporated. This indicates that 319mm(40%) of the rainfall can be conserved in the field after all the losses have been considered.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rain	14	0	56	174	81	23	39	17	48	80	152	109	789
PET	188.6	181.1	174.7	161.8	157.8	128.8	131.4	144.8	165.1	173.9	157.1	169.3	
Rain-Pet	2.13	0	33.06	92.60	55.14	24.65	-1.38	7.56	-13.12	-10.20	85.87	2.18	278.50
APWL							-6.06		-1.30	-15.17	-9.60	-7.79	
SM	121.66	118.27	125.00	125.00	125.00	125.00	119.08	125.00	123.70	125.00	125.00	125.00	
Deficit	2.30	0.14	0.14	0.29	0.00	0.01	-8.43	-9.26	-8.02	1.01	-4.62	-2.45	
Surplus	0.00	0.00	29.90	92.90	55.16	24.71	4.72	1.64	0.00	3.80	88.25	17.47	318.53
Runoff	0.20	0.10	19.15	102.32	40.67	35.43	9.65	0.96	0.85	3.78	86.77	18.84	318.73

Table 6.3 Aggregated values of water balance based on daily time step by T & M model

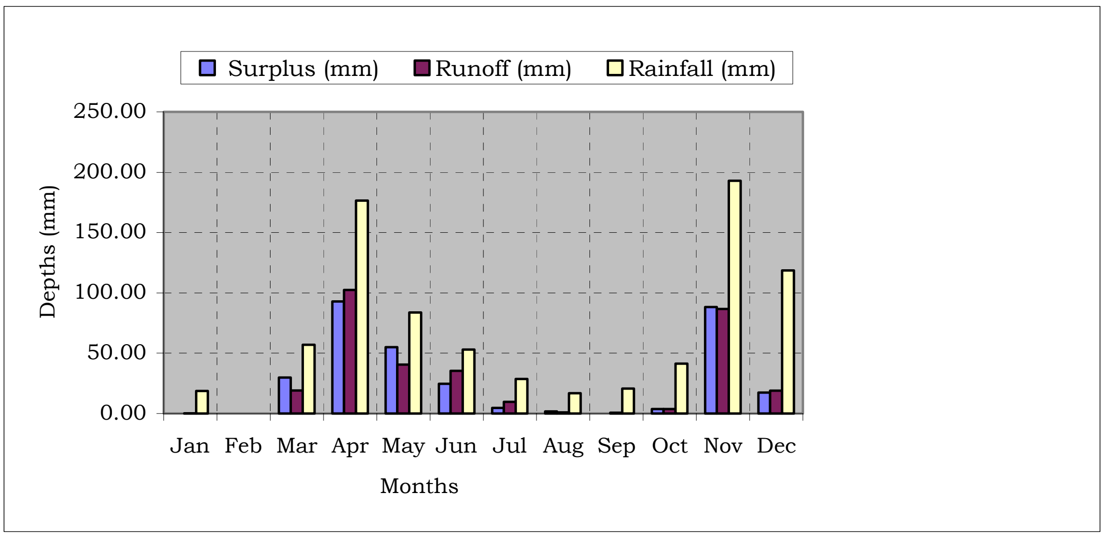


Figure 6.3 Simulation results based on daily time step by T & M

7. Application of GIS and RS for determining suitable sites for water harvesting

7.1. General

The conservation measures that are most likely to be adapted are those leading to increase production and income. Whereas tea can be grown on slopes up to about 60% without risk of erosion (once it is established), most other crops require some special conservation measures on slopes over 5%. As the slope increases, the velocity of runoff water increases, which in turn increases its erosive power. Steep slopes with unstable soils are also unsuitable for water retention structures because of the risk of mass movement.

In determining potential areas for water harvesting by means of remote sensing and GIS, satellite images and aerial photos enabled us effectively, derive data's and identify land features. ILWIS was used to transform spatial and attributes data to desired formats.

7.2. Digital Elevation Model

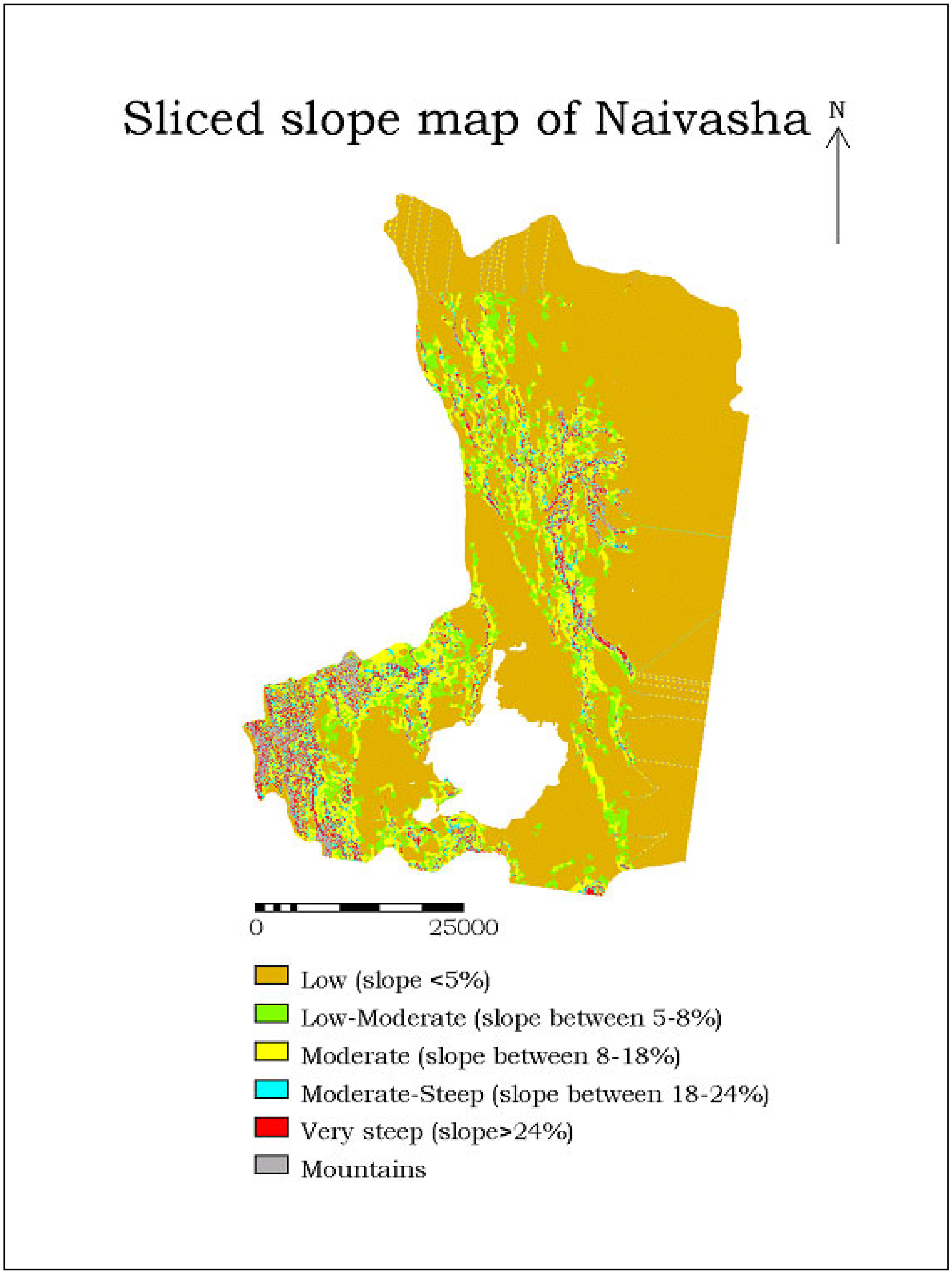
Runoff water harvesting relies very much on the terrain slope besides other significant parameters that are basis for determining suitable areas. The catchment area requires terrain slope that can generate runoff to be collected.

For this study digital terrain model (DTM) was created from the contour map through contour interpolation.

DTM was filtered in X and Y direction using a linear filter to obtain slope steepness map of the study area.

The slope map was sliced into 5 classes to be used as an input for identifying suitable areas for water harvesting. The classification was done using ILWIS.

1. Low Slopes < 5%. Flat land, sloping less than 2% (around lake Naivasha), do not require any special soil conservation measures.
2. Low to moderate (slope between 5-8%): Gently sloping land, physical soil conservation measures are recommended particularly on slopes of erodible soils. These slopes are suitable for water conservation without much earth works.
3. Moderate (Slopes between 8-18%). For slopes exceeding 8%, but not exceeding 18%, water conservation structures are obligatory.
4. Moderate to steep (slope between 18-24%): Terraces and cut-off drains must be constructed
5. Very Steep (Slopes >24%). This is considered too steep and cultivation not recommended at all except for crops, which provide good ground cover.


Sliced slope map of Naivasha
N
0
25000
Low (slope <5%)
Low-Moderate (slope between 5-8%)
Moderate (slope between 8-18%)
Moderate-Steep (slope between 18-24%)
Very steep (slope>24%)
Mountains

Fig

7.3. Geology and landforms

The study area has terrain encompassing different lithologies. The lithology was derived from the geological map. The geology and geomorphology of landforms were found very useful for evaluating terrain characteristics under GIS environment, which was used to identify potential areas for water harvesting.

In the area around the lake sediments and pumice are in abundance. The deposits in addition to clays and silts have large amount of volcanic material in the form of ash.

The Kinangop area is on the eastern rift valley plateau forming a platform or plain, which lies at the foot of Aberdare Mountain.

Scarps that are steep and highly dissected define the Eburu volcanic complex. Lacustrine deposits composed by reworked volcanic material cover the Ndabibi plain. Young volcanic sediments cover Longonot floor, which is highly permeable.

	Sediments	**Foot slopes**	**Alluvial deposits**	**Volcanic complex**	**Low plateau**			**Volcanic lava-flow plateau**
					Mesa	Vale	Escarp-ments	
Soils	Sand clay and gravel	Silt clay loam	Silty clay	Sandy loam/leptosol	Sandy Loam/Coarse sand	Clay loam to fine sandy loam	Silty clay loam	Silt loam
Infiltration	Low	Medium	High	Medium	High	Medium	Low	Medium
WHC	High	Low	Medium	Low	Very deep	Medium	High	High
Surface run-off	Low	Low to me-dium	Low	High	Low	Medium	Medium	Very low
Slope steep-ness	Flat	Gentle	Flood plain	Gentle to steep	Gentle	Gentle	Gentle	Flat topogra-phy
Suitability for WH	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Un-suitable	Suitable

Table 7.1 Hydrological characteristics of terrain

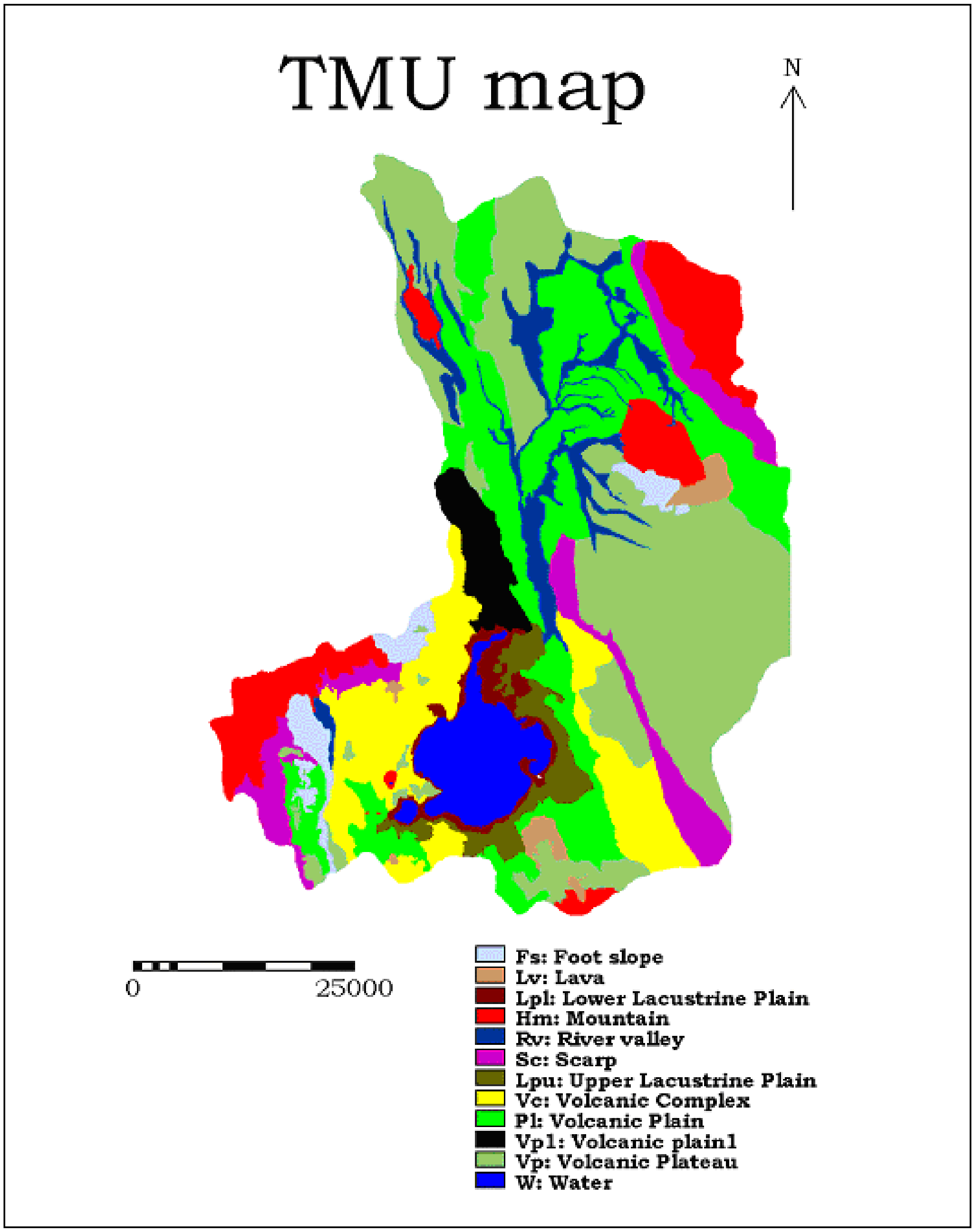


Figure 7.2 Terrain Mapping Units of Naivasha basin

7.4. Principal components analysis

The principal components analysis is used to compress redundant data into few layers reducing the amount of data required among many variables. The first two or three layers components will carry most of the real information of the original data set. The new layers are not correlated with one another. This analysis is particularly useful for mapping land cover and land use classes from multi-spectral images.

The operation creates a matrix that contains the eigenvectors of the calculated covariance matrix between the selected bands. The total variance per band is also calculated as shown below.

	TMb1	TMb2	TMb3	TMb4	TMb5	TMb7
PC1	0.302	0.297	0.409	0.207	0.567	0.537
PC2	0.556	0.437	0.306	0.209	-0.487	-0.354
PC3	0.173	0.054	0.184	-0.867	-0.257	0.339
PC4	0.546	0.052	-0.511	-0.278	0.486	-0.353
PC5	0.346	-0.13	-0.553	0.281	-0.372	0.583
PC6	0.389	-0.836	0.372	0.066	0.019	-0.084

PC	PC1	PC2	PC3	PC4	PC5	PC6
Variance (%)	77.98	14.64	3.96	1.75	1.25	0.42

Table 7.2 Eigenvalues and Variance for thematic mapper

	TMb1	TMb2	TMb3	TMb4	TMb5	TMb7
TMb1	1					
TMb2	0.93	1				
TMb3	0.83	0.92	1			
TMb4	0.62	0.69	0.66	1		
TMb5	0.5	0.59	0.73	0.56	1	
TMb7	0.56	0.64	0.79	0.5	0.93	1

Mean (%)	67.61	56.52	64.24	55.35	108.55	84.12
Stdev. (%)	24.26	21.72	26.96	18.43	37.22	34.62

Table 7.3 Correlation matrix for TM bands

The principal component coefficients and the variances for bands are shown in table 7.2 and were subsequently used to derive the land cover classes for Naivasha area. The principal component analysis carries a lot of information that would have been difficult to extract from individual bands. The PC1, PC2 and PC3 have variance of 77.98%, 14.64% and 3.96% respectively. A colour composite of the images PCI, PC2 and PC3 was created and used for supervised classification along with field experience and aerial photo interpretation. The correlation matrix had revealed good correlation for bands 1, 2 and 3.

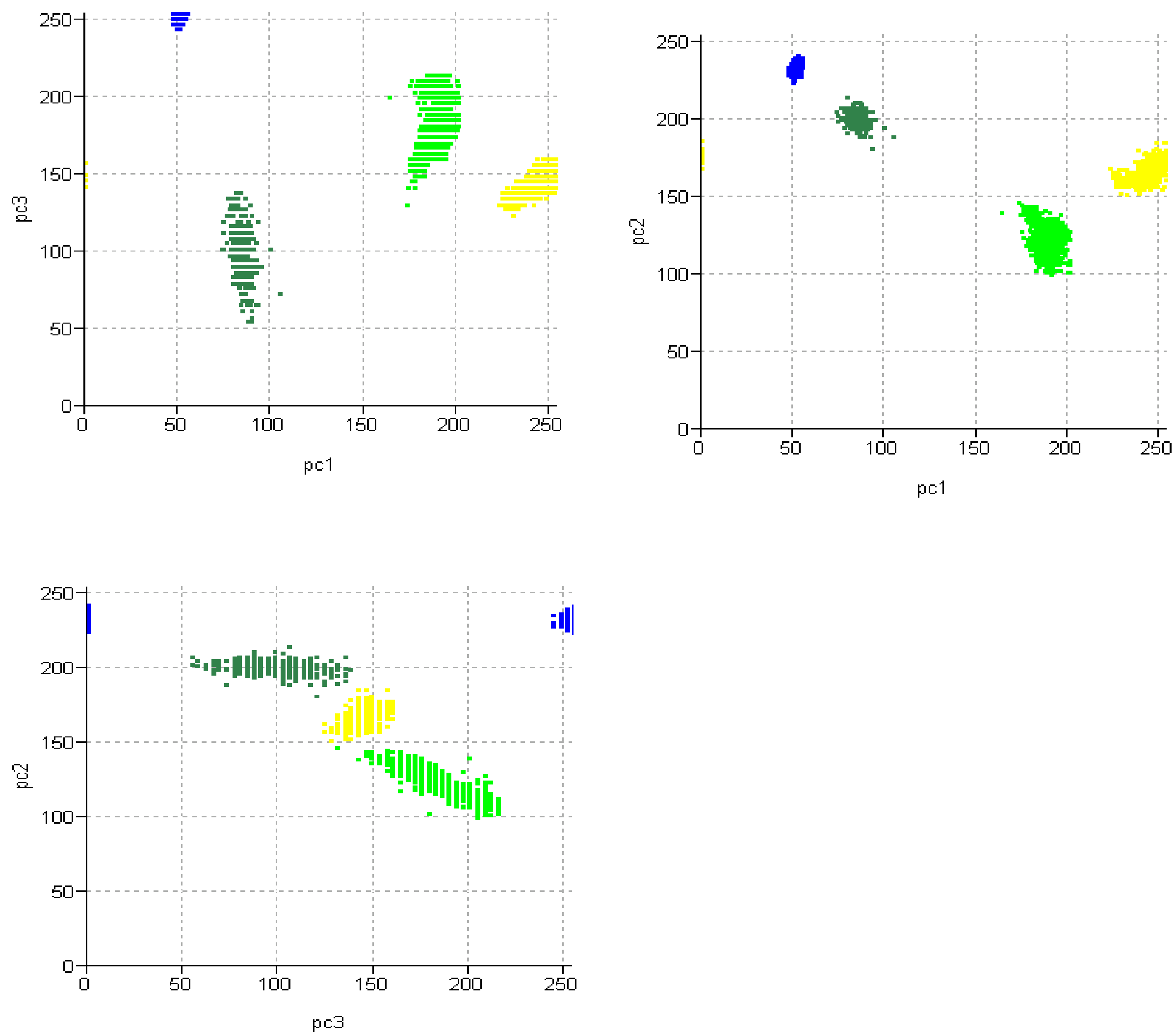


Figure 7.3 Feature space of PC1, PC2 and PC3

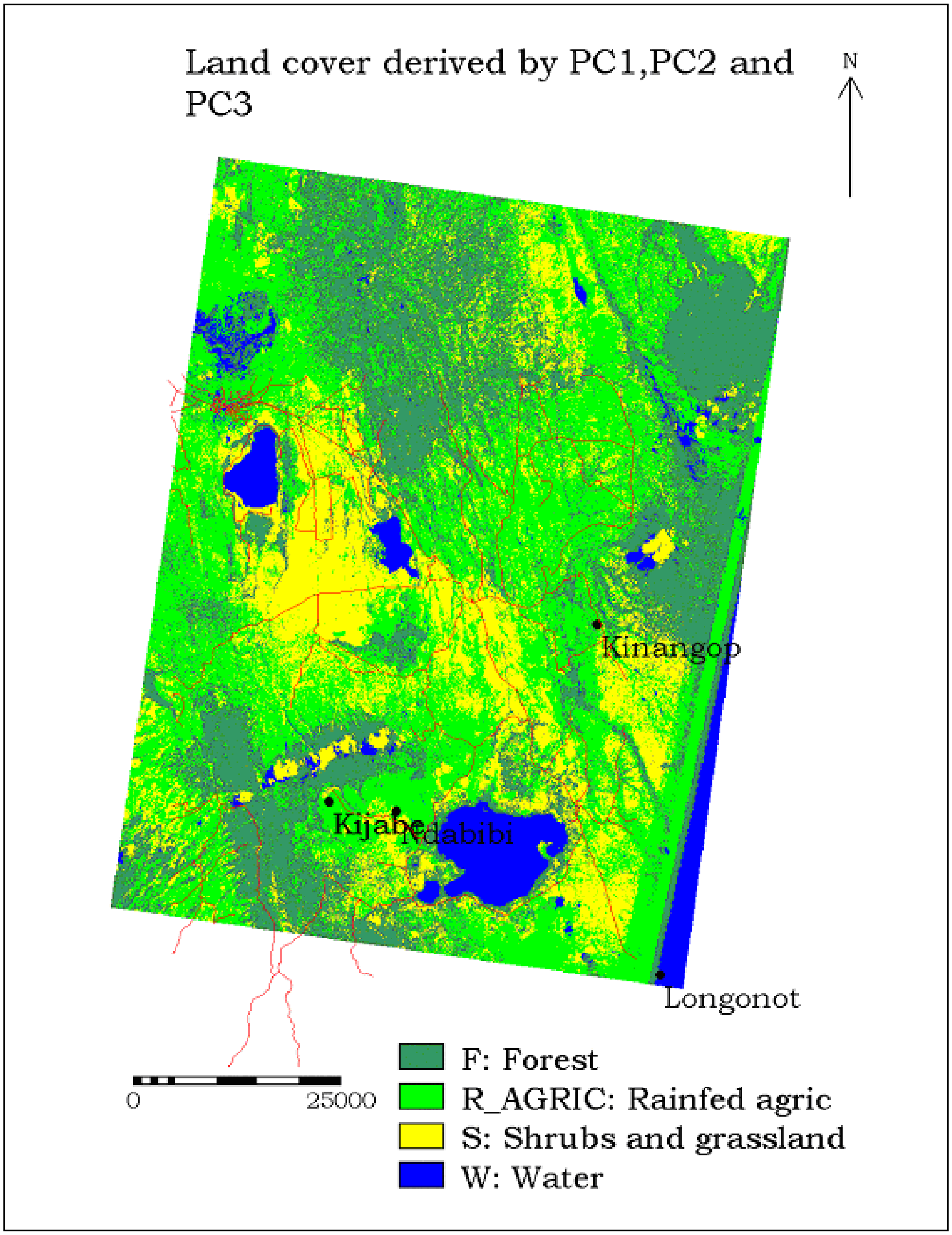


Figure 7.4 Landcover derived by Principal components (all 6 bands)

7.5. Normalised Difference Vegetative Index

The vegetative index gives the reflectance properties of vegetated areas compared to none vegetative areas. The differences between the land cover types are greatly enhanced by the creation of a vegetation index. Vegetative area yields high values because of their relatively high near-infrared reflectance and low visible reflectance. Water, clouds, and snow have larger reflectance than near-infrared reflectance. Thus, these features yield negative index values. Rock and bare soil areas have similar reflectance in the bands 3 and 4 resulting in vegetation indices near zero.

To create NDVI map, Landsat TM imagery of 2000 was used.

$$NDVI = \left(\frac{tmb4 - tmb3}{tmb4 + tmb3} \right)$$

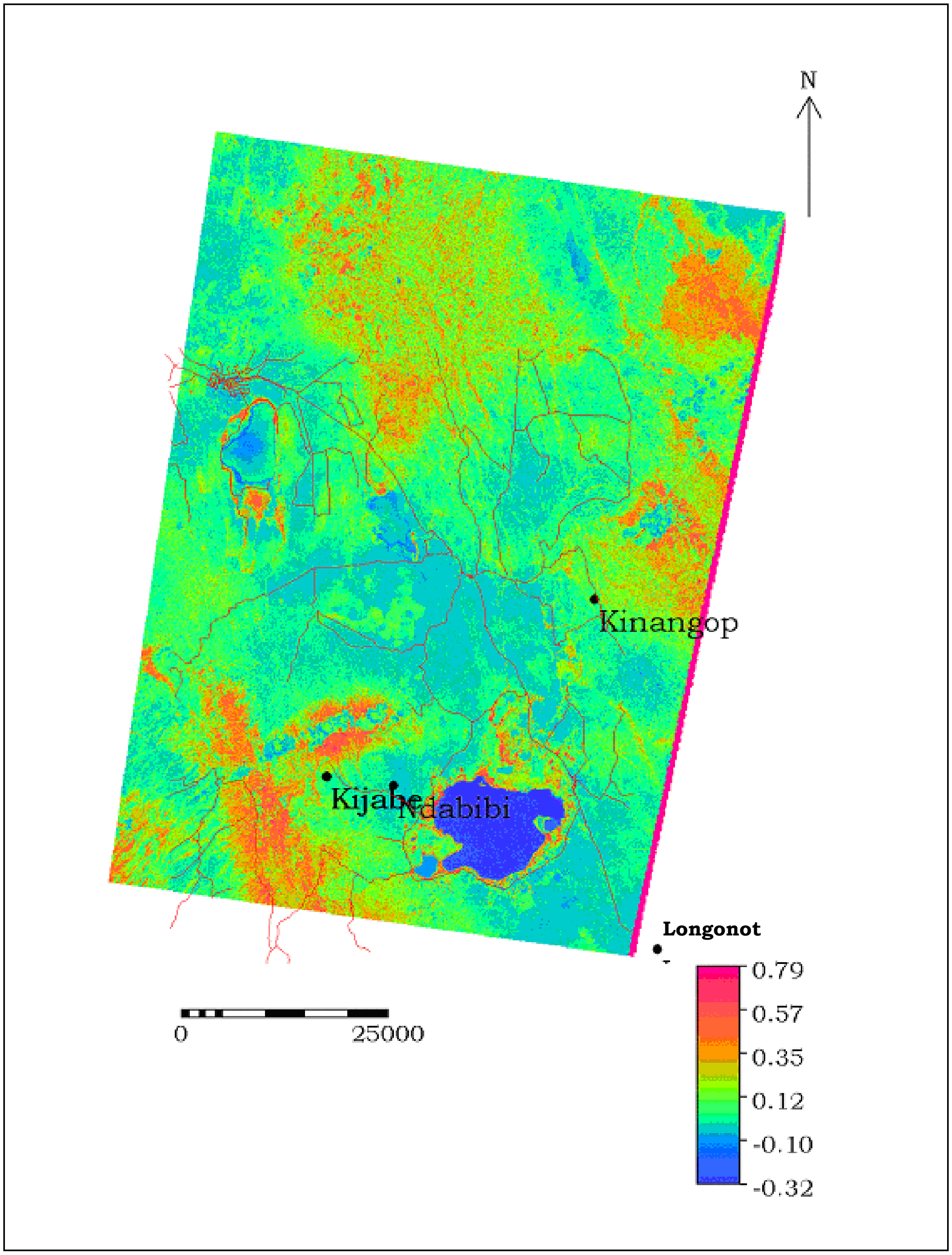


Figure 7.5 NDVI map derived by bands 3 and 4

7.6. Multispectral Classification

Multi spectral image classification was used to extract the land cover classes from the Landsat image of 2000. In the sample set for the supervised image classification only a few land cover classes were created; Rainfed agriculture, Irrigated agriculture, Bare soils, Forest, Shrubs and Water. The training was done with the aid of aerial photos and field experience. Large part of the study area is under agriculture mixed with vegetation, which made the training samples difficult.

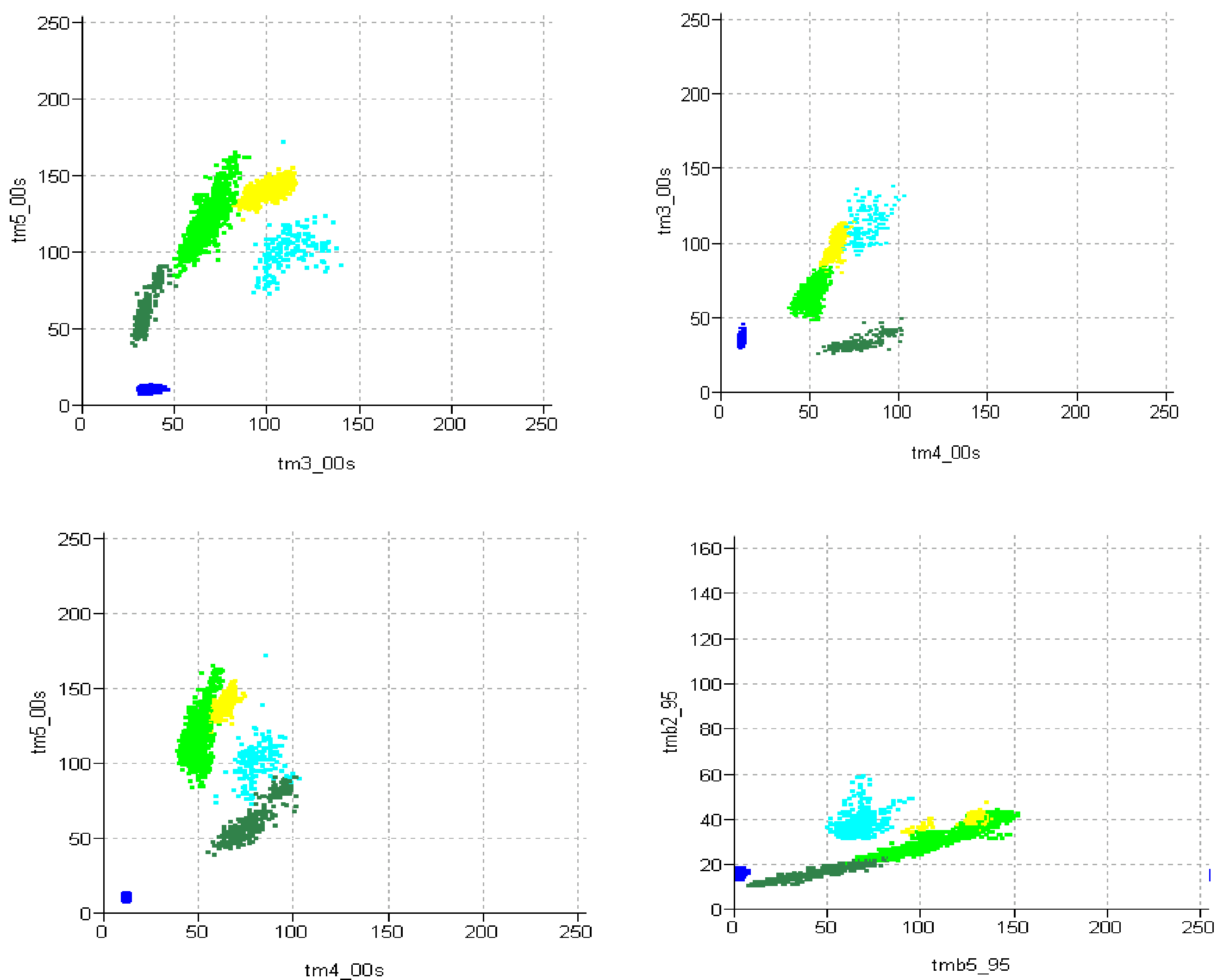


Figure 7.6 Feature space for bands 2, 3, 4 and 5

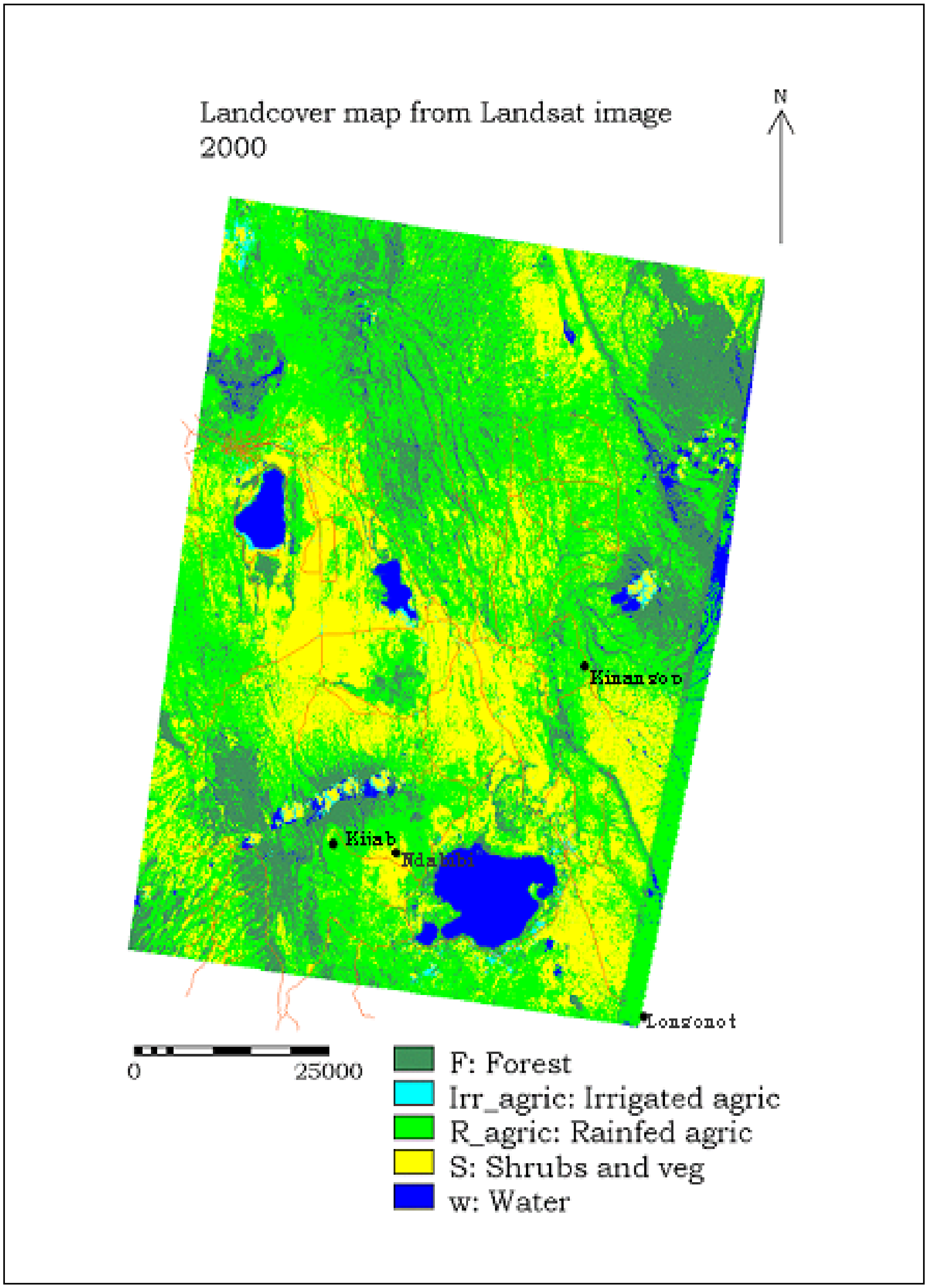


Figure 7.7 Landcover derived by FCC 453

7.7. Transformation of the TMU, Slope and Land cover map into Suitability map

2-Dimensional table was used to classify the terrain units and land cover maps into either suitable or unsuitable. These transformations were based on the available data and fieldwork experience. The suitability classes for each combination of the geology and the land use units are shown in table 7.6. The letter S stands for areas suitable for water harvesting while U indicate unsuitable areas. The resulting maps as shown represent areas that are suitable or unsuitable.

Rules pertaining to classification within the 2-D tables are as follows:

1. In the rain fed agriculture, on alluvial soils (e.g. Longonot, Ndabibi), which are partly denuded, there is serious problem of gullying. The problem cannot be solved without increasing the infiltration of rainwater through retention structures, and minimising the inflow to the gully.
2. Under forest on any of the terrain, there is little or no overland flow. This is mainly due to litters that reduce the risk of detachment by splash and sheet erosion.
3. On the lacustrine plains only little overland flow occurs due to fine textured sediments soil but runoff is further reduced due to low slopes. However, sheet wash may occur at times and need grass cover whose roots can hold soil in place.
4. Footslopes and scarps, there are overland flow due to poor soil cover or cultivation a long the slope, a tunnel develop as result. Terracing can be adopted on the embankment and in this way land is not wasted
5. Mountains with steep slopes with unstable soils are also unsuitable for water conservation structures because of the risk of mass movement and reduced benefits.
6. Shrub land where there are animals, a portion of land can be kept under grass or fodders to promote conservation that is beneficial to the land.
7. The already irrigated areas around the lake are not considered suitable for rainwater harvesting because these farms are under green houses and requires continuous supply to produce horticultural crops.
8. The bare soil, have no cover and the strong winds easily sweeps the soil particles away. Conservation measures must be adopted and in this way land is not wasted. Long closures are need if all the land cover has been depleted.

	Forest	Irr.agric	Rainfed agric	Shrubs & grass	Water	Bare soil
Foot slope	U	U	S	S	U	S
Lava	U	U	U	S	U	U
Lower Lac.	U	U	S	S	U	S
Mountain	U	U	U	S	U	S
R.Valley	U	U	S	S	U	S
Scarp	U	U	U	S	U	U
Upper.Lac.	U	U	S	S	U	S
Volcanic complex	U	U	S	S	U	S
Volcanic plain	U	U	S	S	U	S
Volcanic plain 1	U	U	S	S	U	S
Volcanic plateau	U	U	S	S	U	S
Water	Lake	Lake	Lake	Lake	Lake	Lake

Table 7.4 2-Dimensional tables for TMU and Land cover

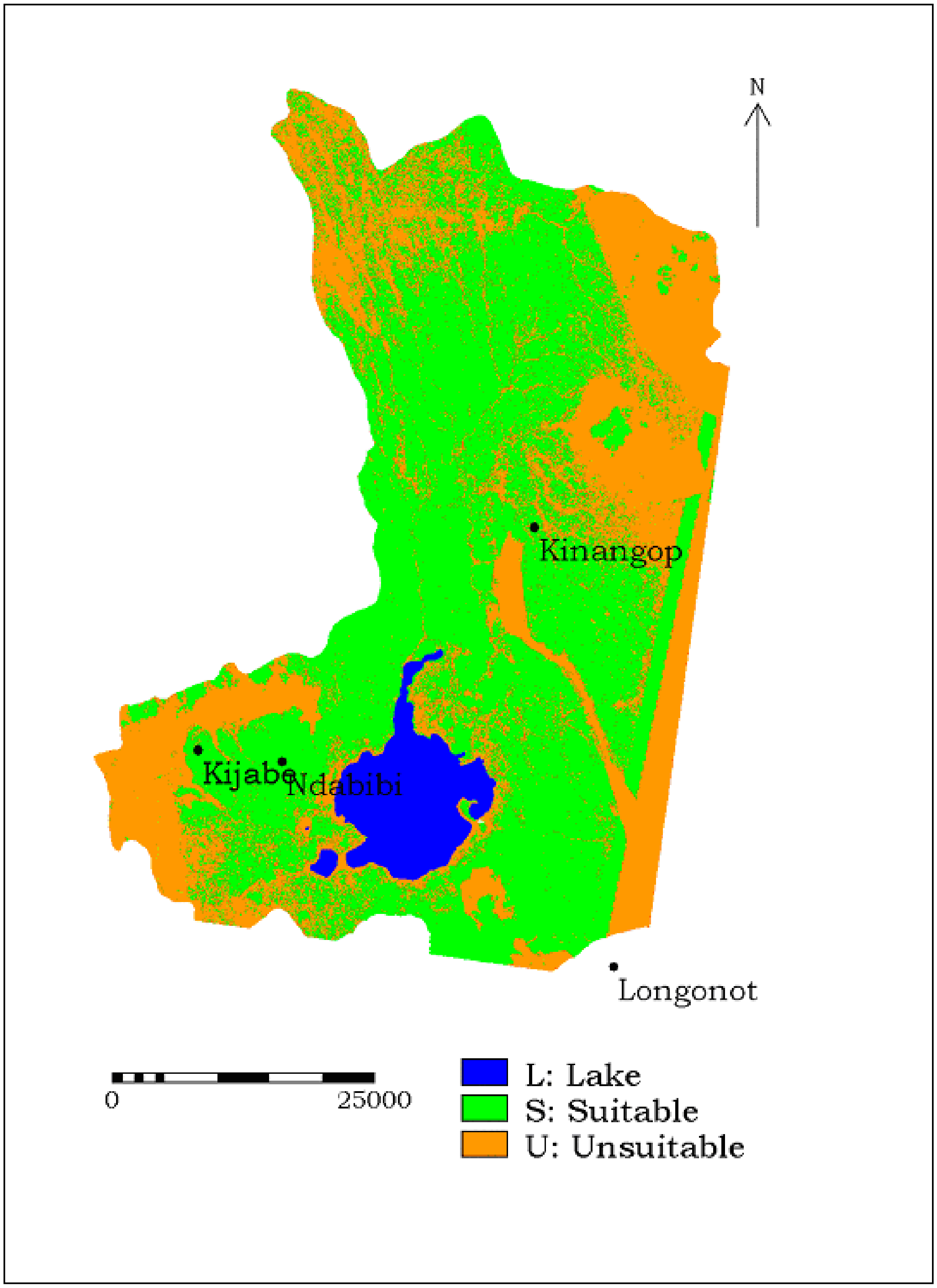


Figure 7.8 Suitability map based on TMU and Land cover

The slope map was crossed with TMU and Land cover map to obtain a cross map with the possible combinations of slopes, terrain units and land cover. The resultant cross map and 2-D table were formulated to carry out further reclassification to obtain suitability assessment map.

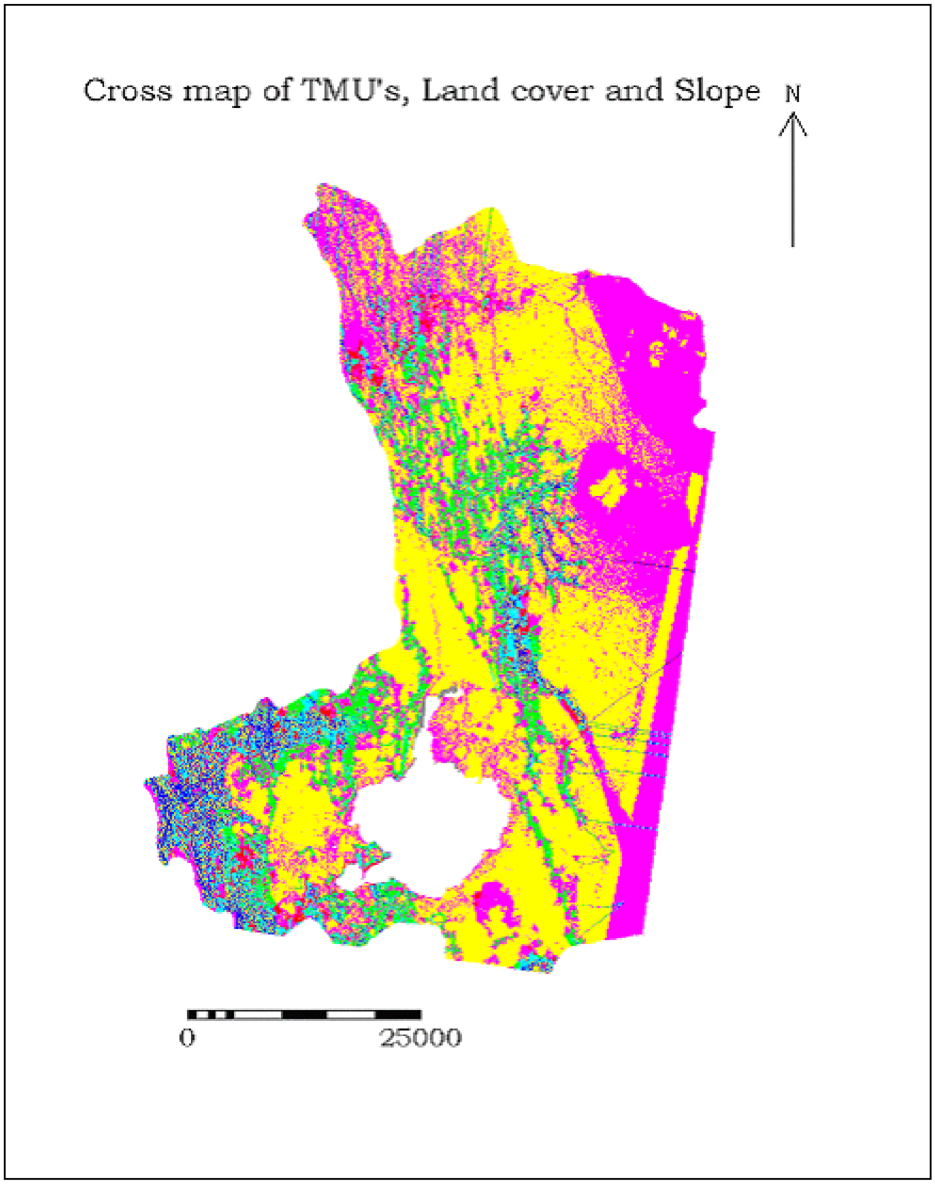


Figure 7.9 Cross map of Slope, TMU and Land cover

S= Suitable based on TMU and Land cover alone
U= Unsuitable based on TMU and Land cover alone
L= Lake

	TMU, slope and Landcover
Low (slope <5%) * S	Highly suitable area
Low (slope <5%) * U	Unsuitable area
Low (slope <5%) * L	Lake Naivasha
Low-Moderate (slope between 5-8%) * S	Highly suitable area
Low-Moderate (slope between 5-8%) * U	Unsuitable area
Low-Moderate (slope between 5-8%) * L	Lake Naivasha
Moderate (slope between 8-18%) * S	Highly suitable area
Moderate (slope between 8-18%) * U	Unsuitable area
Moderate (slope between 8-18%) * L	Lake Naivasha
Very steep (slope>24%) * S	Unsuitable area
Very steep (slope>24%) * U	Unsuitable area
Very steep (slope>24%) * L	Lake Naivasha
Moderate-Steep (slope between 18-24%) * S	Suitable area
Moderate-Steep (slope between 18-24%) * U	Unsuitable area
Moderate-Steep (slope between 18-24%) * L	Lake Naivasha
Mountains * S	Unsuitable area
Mountains * U	Unsuitable area
Mountains * L	Unsuitable area

Table 7.5 2-D table for TMU/Land cover and Slope

The above table was used to classify the cross map (Fig 7.9) to obtain suitability assessment map (Figure 7.10).

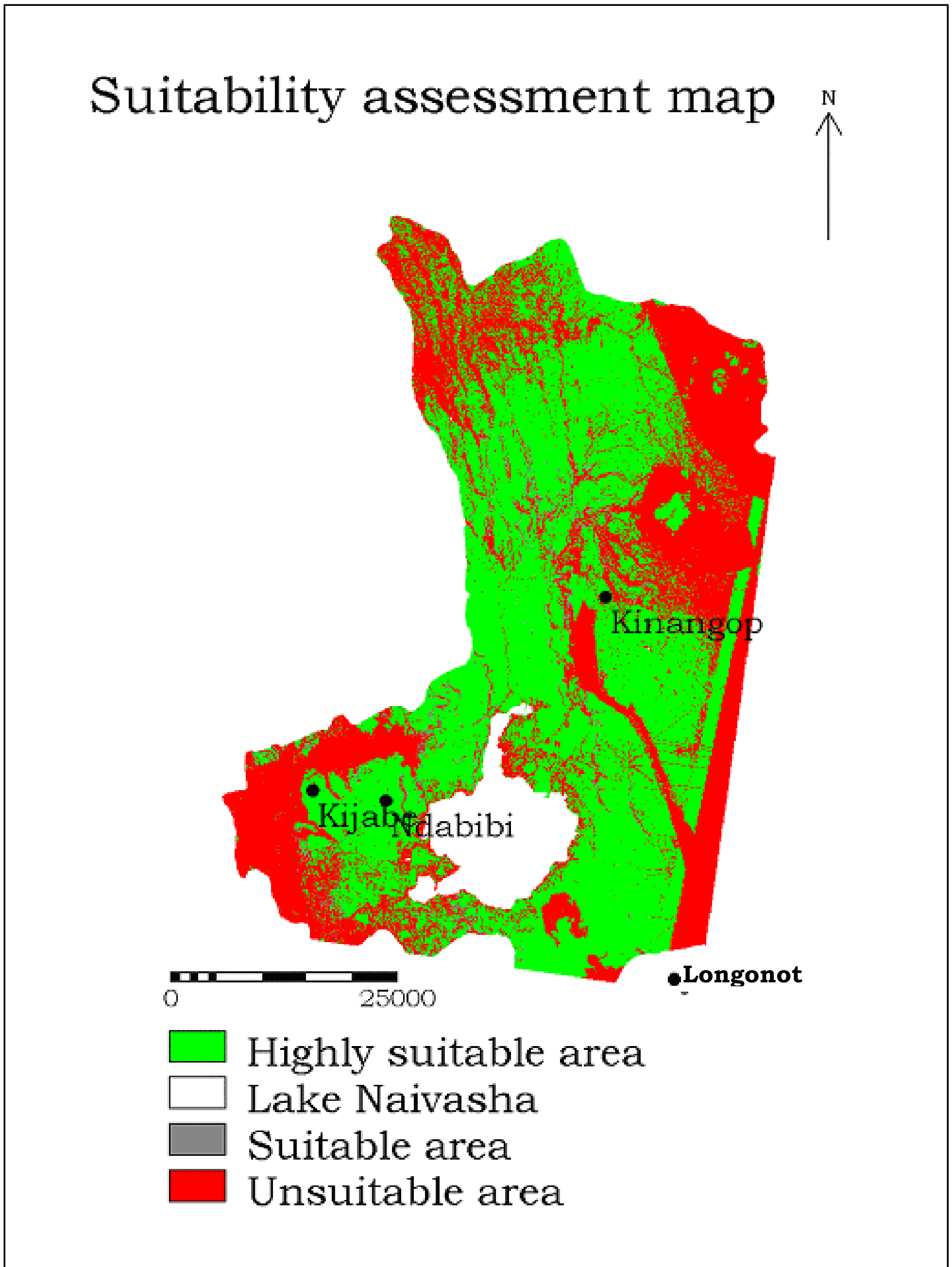


Figure 7.10 Suitability assessment map for water harvesting potential

8. Discussion, conclusion and recommendations

8.1. General discussion

This chapter summarizes the finding of the study.

8.1.1. Cropping seasons

The figure 8.1, shows that 80% of the rainfall is concentrated at the beginning of the season and during the late half dry spell occurs. The duration of crop establishment, crop development, mid season and late season stages for most dry land crops from the day of planting till harvest is much longer than the rainfall seasons, where the dry spell coincides with the critical growth stage of the crop.
Moisture supply during the reproductive stage is considered crucial in obtaining proper yield that lies from 70 to 80 days after sowing (say maize) to the harvest after 120days. It is essential for farmers to store excess rainfall to partly or fully meet this moisture sensitive period.

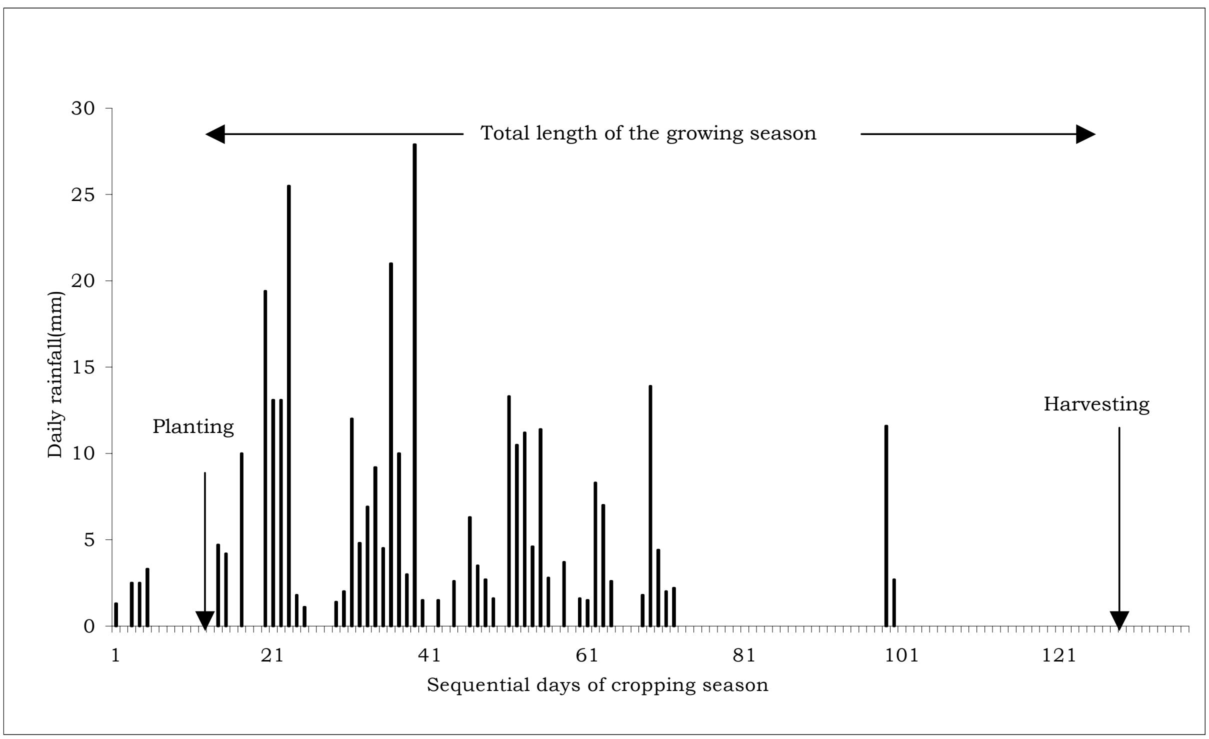


Figure 8.1 Rainfall and growing seasons in Naivasha, Kenya (For the year1998 beginning in Mid-Oct-Jan- Short rainy season)

8.1.2. Soils

A study of soil hydraulic conditions is essential for the selection of suitable sites for water harvesting. Auger hole tests for soil permeability were used in the study area for infiltration assessment. Hydraulic conductivity measurement was carried out under closely similar preparation and test procedures in 29 sites spread over 4 locations. In all the cases soils were saturated before conductivity was estimated. The average saturated hydraulic conductivity estimates for Kinangop, Longonot, Ndabibi and Kijabe were 2.4cm/hr, 40cm/hr, 21.2cm/hr and 3.4cm/hr respectively. Values of saturated hydraulic conductivity (Ks) for soil textures as reported in the literature are given in table 5.10. The results show that Ks values in the field were much higher. Since the auger hole method removes the topsoil and sealing, this method does not account for the presence of surface crusting that commonly occurs on soils. Sealing and crusting of the soil surface is common in semi arid areas, due to nature of the soil and the high intensity of rainstorm. This causes high rates of runoff, even when the rainfall is short and the amount is low. The high hydraulic conductivity enhances rapid drainage of the soil profile.

At each measurement site soil texture was determined to see if a relation could be established between the saturated conductivity and texture. The soils in higher plains and plateaus i.e. Kinangop area consist of clay loam to clay. They are deep (60 cm to 100 cm) and have good water holding capacity. In the lower plains Ndabibi and Longonot, the dominant soils group is clay loam, and are deep and well drained. On the hills and scarps, the soils are shallow (<50 cm) to moderately deep and consist of loam, clay loam and clay in texture. The infiltration capacity of soils depends mainly on soil texture, depth to impervious layers and susceptibility to crusting. The soils formed from volcanic ash, which are abundant in Naivasha, are susceptible to rapid runoff because of the high silt content which has a tendency of forming surface sealing. However, our measurements were limited to few sites only and may not be representatives of the whole area.

8.1.3. Runoff simulation

Three methods has been used for calculating surface runoff which relates catchment characteristics, slope steepness, geology and land cover.

The annual rainfall of 789mm was used to predict the runoff based on Curve Number (CN) method. The simulation showed that of the 789mm received during that year 320mm occurred as excess rainfall. The general pattern of rainfall during the rainy season indicates that distribution tends to be bimodal. Rainfall excess increases with the larger rainfall depth. As illustrated by Figure 8.3 most of the rain, which produces runoff falls during the long rainy season (March-April) and Short rainy season (Oct-Nov). The high values of surface runoff occurring during these peak periods of the two seasons (short and long rain season) if encouraged to infiltrate can improve moisture supply significantly to enhance complete growth

The simulation was carried out for 98 wet days with precipitation >1mm. Since rainfall years vary from time to time a very wet year would likely result in very higher runoff.

The adoption of Thornthwaite and Mather (T & M) Model on a daily time step revealed that of the 789 mm of rainfall used for simulation at an effective rooting depth of 30mm, 50mm and 60mm, the moisture surplus were found out to be 320mm, 319mm, 318mm respectively. In the study the soil moisture also varied linearly with the water holding capacity as illustrated by figure 8.2 under unsaturated condition.

Hamududu (Msc.1998) considered long-term water balance approach and obtained a runoff of 289mm at a water holding capacity of 200mm.
The models T&M model and CN gave about the same total runoff i.e. 319mm (averaged) and 320mm respectively which is very high. Although T & M and CN models gave close annual value the runoff depth shows variation within the season. CN method estimated low runoff in April and November, which could either be attributed to the limitation of the method or soil moisture status at the onset of the rain that allowed more infiltration and abstractions. SCS Curve Number method was developed for conditions in USA and may not be very accurate under this circumstance. The method has some limitations as discussed in the paper by (Kumar et al., 1982). In the findings it was mentioned that CN method was used to estimate effective rainfall for 11 storms in IOWA catchment and the results obtained were not in agreement with results by Hydrograph separation.

No calibration was done on any of the models because the flow components and the rainfall data were not compatible. Based on studies on moderate to large catchments (Thornthwaite and Mather, 1955) detention values was set to 50% to enable the available surplus water to run off in a given month and the rest being retained for later runoff (see table 8.1). The simulation by T & M as illustrated in figure 8.2 and figure 8.3 is not realistic because most of the studied area, especially the soils of Ndabibi and Longonot exhibits high hydraulic conductivity, which facilitates deep percolation of moisture to the groundwater. The varied lithology of the studied area also has much influence on the runoff. In Kinangop area the impervious basalt layers encourages throughflow to occur in the soil, which is expected to emerge far away from agricultural fields. Therefore, the runoff simulated by the CN method though close to T&M method is more acceptable.

Figure 8.2 illustrates variation of soil moisture with different rooting depth as simulated by T & M, which is not realistic. The monthly simulation by T & M showed deficits for the soil moisture while the daily simulation aggregated to monthly values shows no deficits. In the analysis overland was not considered i.e. all the rain was assumed to infiltrate, which is not the case because surface runoff occurs. Moreover, the hydraulic conductivity Ks estimates of the study area were very high. The soil moisture calculation formula by T&M don't account for other inherent catchment characteristics. Therefore under these conditions the soil moisture available for crops is less than the simulated ones. Of the 320mm available moisture surplus simulated by CN method all turn up to become surface runoff (see table 8.1). This runoff can be harnessed within the field by proper soil conservation methods. In table 8.1, aggregated daily runoff to monthly values as obtained by the three models is given.

Months	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
Rainfall	**14.30**	**0.00**	**55.60**	**173.50**	**80.60**	**22.40**	**38.30**	**16.90**	**39.90**	**80.30**	**152.30**	**108.90**	**789**
CN method	7.92	0.00	10.91	32.89	5.99	19.27	36.14	6.53	32.43	36.75	53.51	78.13	320
T&M model	0.20	0.10	19.15	102.32	47.67	19.43	13.65	2.96	3.85	3.78	86.77	18.84	319
Patched	20						21						41

Table 8.1 Runoff estimates by CN method, Parched thirst and Thornthwaite & Mather (aggregated values) models

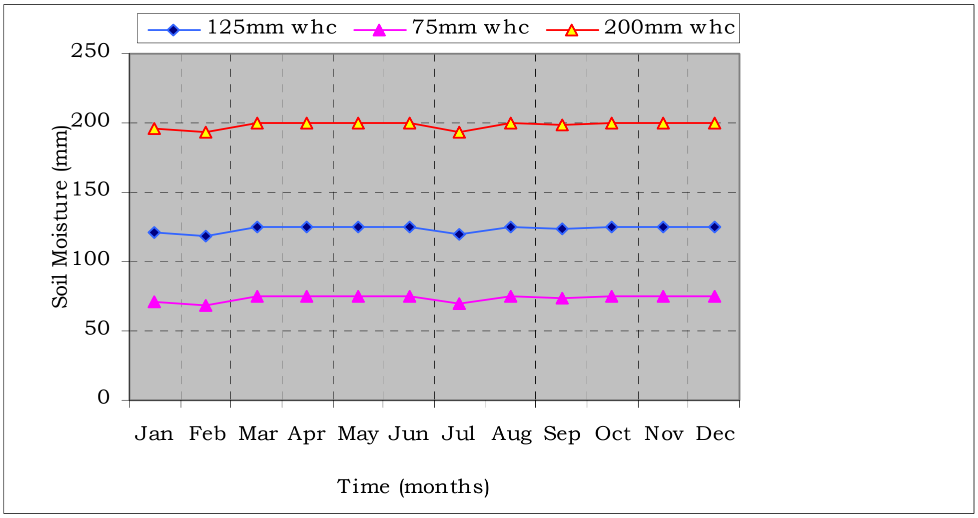


Figure 8.2 Soil moisture at different rooting depths

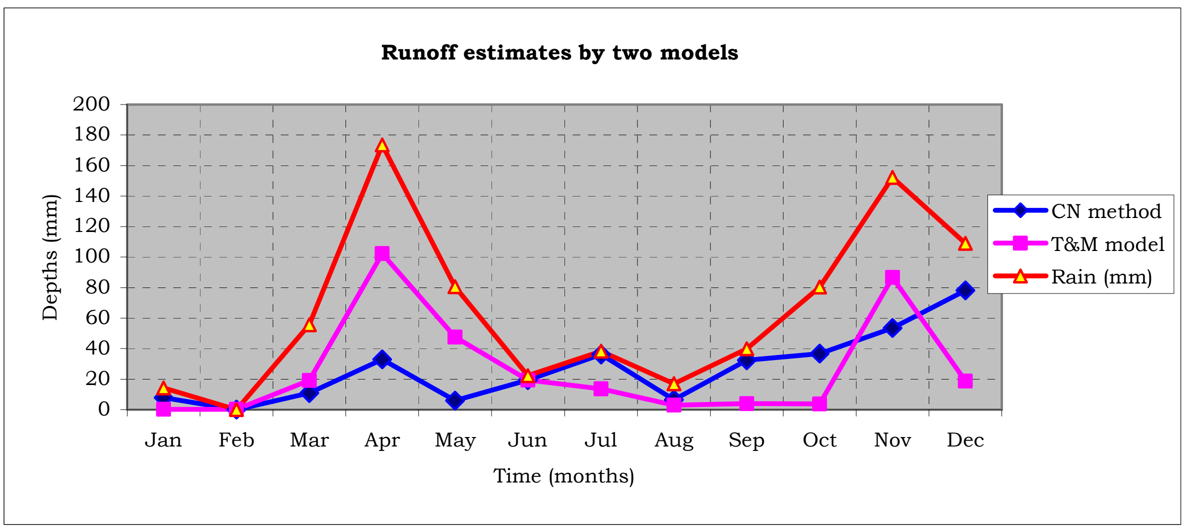


Figure 8.3 Aggregated monthly runoff estimates by CN method and Thonthwaite & Mather models

The Parched-thirst model was applied to simulate the performance of the rainwater harvesting for different scenarios in Naivasha. The model has been developed to predict runoff and grain yield for both within field and slope catchment. This prediction was made for average, dry and wet years and was then repeated for varying sizes of runoff area and cropped area. The results are summarised in table 5.3 and table5.4.

An increase in runoff area had little effect on overall grain yield because no crops are present in the parts, which serve as catchment areas in the field. The model estimated maize yield as 2.26, 2.34, 2.36 ton/ha for ratios of 1:1, 2:1 and 3:1 respectively compared to an average harvest by small-scale farmers in Kinangop region of 1.17ton/ha. 1.17ton/ha is an estimate made during the fieldwork. The difference may be partly explained by the assumption of use of fertilizers in the Parched-thirst model.

The resulting relationship between runoff and yield with varying rainfall is also illustrated in figure 5.2. The relations are essentially linear though yield response is not pronounced. However, this analysis alone was not adequate to predict the yield and runoff.
Although it is possible to increase the runoff area until the good growth target is reached, a large area may create problem during the wet year.
A number of illustrations of the effects of altering the input data's on the model output are presented in chapter 5. When the effect of crusting (or non-crusting) soil was included in the simulation the change in runoff and grain yield was negligible. Due to insufficient data only season1 (March-April: long rain) was simulated. The last column of table 8.1 indicates 41mm annual total runoff as estimated by Parched-thirst model. This value is very low compared to estimates made by other two models. With the current hydrological data alone it was difficult to state why the runoff estimates were low. However, the Parched-thirst model simulates seasonal runoff, which is much less than the rates simulated by the CN method or T&M.
The analysis indicates that storing more water in the soil to supplement moisture during the dry months is achievable with proper land management.

8.1.4. GIS and RS

The first principal component analysis PC1, PC2 and PC3 (all 6 bands) and NDVI (Landsat TM image obtained in the year 2000) was used to generate a more recent land cover thematic map of the area. The knowledge of the area acquired during the fieldwork and aerial photo interpretation helped in ascertaining land covers which otherwise would have been difficult.

Computer assisted (Supervised) classification was carried out where the spectral features of the individual classes were predetermined by the use of the training fields for different land cover classes. The maximum likelihood classification was used to calculate the probability of the picture elements belonging to respective classes on the basis of statistical spectral features of preset classes

GIS was used to generate suitability assessment map for water harvesting potential areas using the 2-dimensional tables. The interactions of TMU's, land use and slope were the main factors considered for the classification. The rules for rating the maps were based on fieldwork experience and aerial photo interpretation. The maps were combined to account for soil permeability, texture, slope steepness and other lithological properties that resulted in a final suitability assessment map.

The mountains and scarps were area considered not suitable because of steep slope, shallow or no soil, poor vegetation, high runoff and therefore low permeable condition.

Around Longonot volcano and Ndabibi, large gullies have developed due to few heavy rainstorms characterised by high intensity and erosion was evident. Here people are forced to grow food crops on steep slopes (>8%) because of lack of alternatives land. In this situation soil and water conservation measures become even more important to sustained land use. Terraces and check dams should be constructed on the agricultural plots to reduce the slope length, steepness and velocity of water, and store water in the soil.

8.2. Conclusion

The objective of this study was defined in the introduction.

- Of the three methods for runoff modelling only the CN method may be applicable.
- Use of RS and GIS should be considered as an important tool when identifying suitable areas.
- Computations of moisture for different months and seasons using water balance model requires small simulation time step (daily).
- In Naivasha, rainfall is inadequate and should be supplemented using water harvesting methods. Rainwater harvesting should be seen as complementing irrigated agriculture where high capital investment are not required and source of water unavailable.
- There is no single suitable approach to water harvesting that can be adopted in all situations. Differences like soil type, topography, large temporal variability of rainfall and financial constraints must be considered and therefore farmers need to adapt that which fits the local situation

8.3. Recommendations

- Before selecting a specific technique, due consideration must be given to the social and cultural aspects prevailing in the area of study as they are paramount and will affect the success or failure of the project.
- Runoff water harvesting can make a big contribution to increasing yields and food security. However where farmers own little land they may not have resources to set aside land solely for harvesting runoff.
- The study of water harvesting potential should begin with a single farm coupled with economic analysis to indicate the level of success and the result be used as basis for implementing water-harvesting for entire region.
- Within-field systems using with larger C: CAR ratio, a suitable conservation structure should be designed with spillways to allow excess water to be discharged safely during heavy storms.
- There is a need for improvement of the Soil-water balance model to account for the other processes influencing the catchment water balance.

8.4. Limitation in the study

- Insufficient daily rainfall and discharge data limited thorough estimate of the runoff.
- The influence of the accuracy of measurement of rainfall. The flow components of Malewa River were not consistent with rainfall, which made the data questionable
- The daily rainfall data used for analysis may not be representative for all part of Naivasha area and therefore the suitability assessment may vary in time and space. More often rainfall gauging stations are situated in areas suitable for observers. In Longonot and Ndabibi study area there was no single rainfall gauging station.
- The aerial photos were rather old, dated 1972, which means that land cover is no longer valid satellite images, however it was useful for other interpretations.
- The large size of the study area with varying terrains limited detailed investigation

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APPENDIX

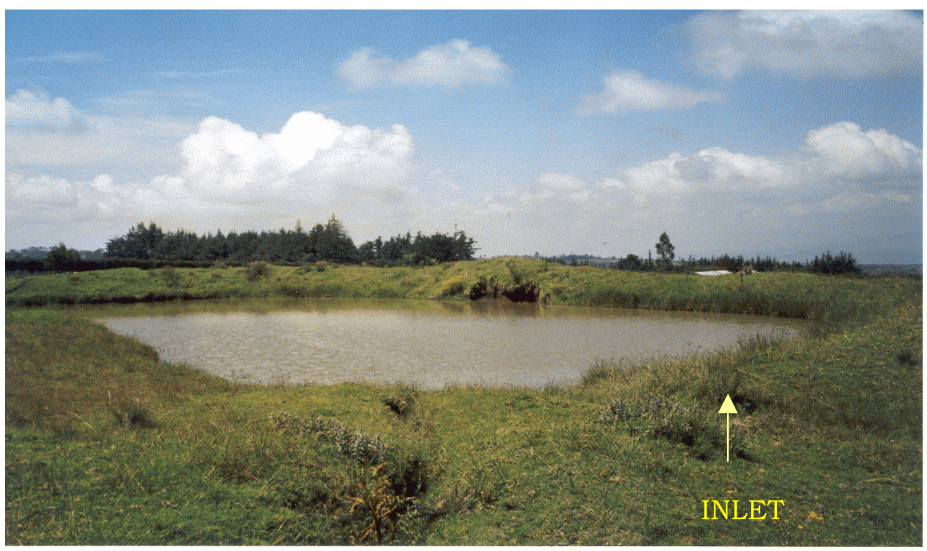
Appendix 1: Field photos

Gully in Kinangop

Footpath turned gully in Longonot foot slope

Appendix 1

Destroyed footpath in Kinangop



Road runoff harvesting in Kinangop

Appendix 2: Daily water balance results

No. of days	1	2	3	4	5	6	7	8	9	10
Rain	11.6	2.7	2.1	23.5	2.8	27.2	25.6	2.7	24	4.20
OF	0	0	0	0	0	0	0	0	0	0.00
Eff.Rain	11.6	2.7	2.1	23.5	2.8	27.2	25.6	2.7	24	4.20
PET	6.08	6.08	5.64	5.64	5.64	5.64	5.39	5.39	5.39	5.39
Rain-PET	5.52	-3.38	-3.54	17.86	-2.84	21.56	20.21	-2.69	18.61	-1.19
APWL	-2.27	-3.38	-6.92		-2.84			-2.69		-1.19
SM	122.75	121.66	118.27	136.13	122.20	125.00	125.00	122.34	125.00	123.81
DSM	5.30	-1.09	-3.39	17.86	-13.94	2.80	0.00	-2.66	2.66	-1.19
AET	6.08	3.79	5.49	5.64	5.64	5.64	5.39	5.36	5.39	5.39
D	0.00	2.30	0.14	0.00	0.00	0.00	0.00	0.03	0.00	0.01
S	0.00	0.00	0.00	11.13	0.00	18.76	20.21	0.00	15.94	0.00
Tot.ava.	0.13	0.07	0.03	11.15	5.57	21.55	30.98	15.49	23.69	11.84
RO	0.07	0.03	0.02	5.57	2.79	10.77	15.49	7.75	11.84	5.92
Detention	0.07	0.03	0.02	5.57	2.79	10.77	15.49	7.75	11.84	5.92
No. of days	11	12	13	14	15	16	17	18	19	20
Rain	28.10	23.10	1.70	1.80	7.80	7.40	22.40	1.80	6.00	11.20
OF	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Eff.Rain	28.10	23.10	1.70	1.80	7.80	7.40	22.40	1.80	6.00	11.20
PET	5.39	5.39	5.39	5.39	5.39	5.39	5.39	5.39	5.39	5.39
Rain-PET	22.71	17.71	-3.69	-3.59	2.41	2.01	17.01	-3.59	0.61	5.81
APWL			-3.69	-7.29				-3.59		
SM	125.00	125.00	121.36	117.92	120.33	122.34	125.00	121.46	122.06	125.00
DSM	1.19	0.00	-3.64	-3.44	2.41	2.01	2.66	-3.54	0.61	2.94
AET	5.39	5.39	5.34	5.24	5.39	5.39	5.39	5.34	5.39	5.39
D	0.00	0.00	0.05	0.15	0.00	0.00	0.00	0.05	0.00	0.00
S	21.52	17.71	0.00	0.00	0.00	0.00	14.34	0.00	0.00	2.87
Tot. Ava.	27.44	31.43	15.71	7.86	3.93	1.96	15.32	7.66	3.83	4.79
RO	13.72	15.71	7.86	3.93	1.96	0.98	7.66	3.83	1.92	2.39
Detention	13.72	15.71	7.86	3.93	1.96	0.98	7.66	3.83	1.92	2.39
No. of days	21	22	23	24	25	26	27	28	29	30
Rain	5.70	16.90	3.10	20.80	9.50	30.30	1.10	21.80	6.00	2.60
OF	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Eff.Rain	5.70	16.90	3.10	20.80	9.50	30.30	1.10	21.80	6.00	2.60
PET	5.39	5.09	5.09	5.09	5.09	5.09	4.29	4.29	4.29	4.29
Rain-PET	0.31	11.81	-1.99	15.71	4.41	25.21	-3.19	17.51	1.71	-1.69
APWL			-1.99				-3.19			-1.69
SM	125.00	136.81	123.02	125.00	125.00	150.21	121.85	125.00	125.00	123.32
DSM	0.00	11.81	-13.78	1.98	0.00	25.21	-28.36	3.15	0.00	-1.68
AET	5.39	5.09	5.09	5.09	5.09	5.09	4.29	4.29	4.29	4.28
D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
S	0.31	11.81	0.00	13.73	4.41	25.21	0.00	14.36	1.71	0.00
Tot. Ava.	2.70	13.16	6.58	17.02	12.92	31.67	15.83	22.28	12.85	6.42
RO	1.35	6.58	3.29	8.51	6.46	15.83	7.92	11.14	6.42	3.21
Detention	1.35	6.58	3.29	8.51	6.46	15.83	7.92	11.14	6.42	3.21

Appendix 2 (Continued)

No. of days	31	32	33	34	35	36	37	38	39	40
Rain	6.00	12.90	2.60	2.80	12.00	3.30	3.20	1.70	2.70	9.30
OF	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Eff.Rain	6.00	12.90	2.60	2.80	12.00	3.30	3.20	1.70	2.70	9.30
PET	4.29	4.29	4.24	4.24	4.24	4.24	4.24	4.24	4.24	4.67
Rain-PET	1.71	8.61	-1.64	-1.44	7.76	-0.94	-1.04	-2.54	-1.54	4.63
APWL			-1.64	-3.08		-0.94	-1.98	-4.52	-6.06	
SM	125.00	133.61	123.37	121.96	125.00	124.06	123.04	120.56	119.08	123.71
DSM	1.68	8.61	-10.24	-1.41	3.04	-0.94	-1.03	-2.47	-1.48	4.63
AET	4.29	4.29	12.84	4.21	4.24	4.24	4.23	4.17	4.18	13.93
D	0.00	0.00	-8.60	0.03	0.00	0.00	0.01	0.07	0.06	-9.26
S	0.03	8.61	0.00	0.00	4.72	0.00	0.00	0.00	0.00	0.00
Tot.ava.	3.24	10.23	5.11	2.56	6.00	3.00	1.50	0.75	0.37	0.19
RO	1.62	5.11	2.56	1.28	3.00	1.50	0.75	0.37	0.19	0.09
Detention	1.62	5.11	2.56	1.28	3.00	1.50	0.75	0.37	0.19	0.09
No. of days	41	42	43	44	45	46	47	48	49	50
Rain	7.60	1.90	2.90	3.40	1.40	6.10	4.20	1.10	11.00	9.70
OF	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Eff.Rain	7.60	1.90	2.90	3.40	1.40	6.10	4.20	1.10	11.00	9.70
PET	4.67	5.50	5.50	5.50	5.50	5.50	5.50	5.61	5.61	5.61
Rain-PET	2.93	-3.60	-2.60	-2.10	-4.10	0.60	-1.30	-4.51	5.39	4.09
APWL		-3.60	-6.21	-8.31	-12.41		-1.30	-5.81		
SM	125.00	121.45	118.95	116.96	113.19	113.78	123.70	119.32	124.71	125.00
DSM	1.29	-3.55	-2.50	-1.98	-3.78	0.60	9.92	-4.38	5.39	0.29
AET	4.67	5.45	5.40	5.38	5.18	5.50	14.12	5.48	5.61	5.61
D	0.00	0.05	0.10	0.12	0.33	0.00	-8.62	0.13	0.00	0.00
S	1.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.80
Tot.ava.	1.73	0.87	0.43	0.22	0.11	0.05	0.03	0.01	0.01	3.80
RO	0.87	0.43	0.22	0.11	0.05	0.03	0.01	0.01	0.00	1.90
Detention	0.87	0.43	0.22	0.11	0.05	0.03	0.01	0.01	0.00	1.90
No. of days	51	52	53	54	55	56	57	58	59	60
Rain	1.30	2.50	2.50	3.30	4.70	4.20	10.00	19.40	13.10	13.10
OF	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Eff.Rain	1.30	2.50	2.50	3.30	4.70	4.20	10.00	19.40	13.10	13.10
PET	5.61	5.61	5.61	5.61	5.61	5.61	5.07	5.07	5.07	5.07
Rain-PET	-4.31	-3.11	-3.11	-2.31	-0.91	-1.41	4.93	14.33	8.03	8.03
APWL	-4.31	-7.42	-10.53	-12.84	-13.76	-15.17				
SM	120.76	117.79	114.90	112.79	111.97	110.72	115.65	125.00	125.00	125.00
DSM	-4.24	-2.97	-2.90	-2.10	-0.82	-1.26	4.93	9.35	0.00	0.00
AET	5.54	5.47	5.40	5.40	5.52	5.46	5.07	5.07	5.07	5.07
D	0.07	0.14	0.22	0.21	0.09	0.15	0.00	0.00	0.00	0.00
S	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.98	8.03	8.03
Tot.ava.	1.90	0.95	0.48	0.24	0.12	0.06	0.03	4.99	10.53	13.30
RO	0.95	0.48	0.24	0.12	0.06	0.03	0.01	2.50	5.26	6.65
Detention	0.95	0.48	0.24	0.12	0.06	0.03	0.01	2.50	5.26	6.65

Appendix 2 (continued)

No. of days	61	62	63	64	65	66	67	68	69	70
Rain	25.50	1.80	1.10	1.40	2.00	12.00	4.80	6.90	9.20	4.50
OF	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Eff.Rain	25.50	1.80	1.10	1.40	2.00	12.00	4.80	6.90	9.20	4.50
PET	5.07	5.07	5.07	5.07	5.07	5.07	5.07	5.07	5.07	5.07
Rain-PET	20.43	-3.27	-3.97	-3.67	-3.07	6.93	-0.27	1.83	4.13	-0.57
APWL		-3.27	-7.24	-10.90	-13.97		-0.27			-0.57
SM	125.00	121.77	117.97	114.56	111.78	118.71	124.73	125.00	125.00	124.43
DSM	0.00	-3.23	-3.80	-3.41	-2.78	6.93	6.02	0.27	0.00	-0.57
AET	5.07	5.03	4.90	4.81	4.78	5.07	10.82	5.07	5.07	5.07
D	0.00	0.04	0.16	0.26	0.29	0.00	-5.75	0.00	0.00	0.00
S	20.43	0.00	0.00	0.00	0.00	0.00	0.00	1.56	4.13	0.00
Tot.ava.	27.08	13.54	6.77	3.39	1.69	0.85	0.42	1.77	5.02	2.51
RO	13.54	6.77	3.39	1.69	0.85	0.42	0.21	0.89	2.51	1.25
Detention	13.54	6.77	3.39	1.69	0.85	0.42	0.21	0.89	2.51	1.25
No.of days	71	72	73	74	75	76	77	78	79	80
Rain	21.00	10.00	3.00	27.90	1.50	1.50	2.60	6.30	3.50	2.70
OF	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Eff.Rain	21.00	10.00	3.00	27.90	1.50	1.50	2.60	6.30	3.50	2.70
PET	5.07	5.07	5.07	5.07	5.07	5.07	5.07	5.46	5.46	5.46
Rain-PET	15.93	4.93	-2.07	22.83	-3.57	-3.57	-2.47	0.84	-1.96	-2.76
APWL			-2.07		-3.57	-7.14	-9.60		-1.96	-4.73
SM	125.00	125.00	122.95	125.00	121.48	118.06	115.76	116.59	123.05	120.36
DSM	0.57	0.00	-2.05	2.05	-3.52	-3.42	-2.31	0.84	6.46	-2.69
AET	5.07	5.07	5.05	5.07	5.02	4.92	4.91	5.46	5.46	5.39
D	0.00	0.00	0.02	0.00	0.05	0.15	0.16	0.00	0.00	0.07
S	15.37	4.93	0.00	20.78	0.00	0.00	0.00	0.00	0.00	0.00
Tot.ava.	16.62	13.24	6.62	24.09	12.05	6.02	3.01	1.51	0.75	0.38
RO	8.31	6.62	3.31	12.05	6.02	3.01	1.51	0.75	0.38	0.19
Detention	8.31	6.62	3.31	12.05	6.02	3.01	1.51	0.75	0.38	0.19
No.of days	81	82	83	84	85	86	87	88	89	90
Rain	1.60	13.30	10.50	11.20	4.60	11.40	2.80	3.70	1.60	1.50
OF	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Eff.Rain	1.60	13.30	10.50	11.20	4.60	11.40	2.80	3.70	1.60	1.50
PET	5.46	5.46	5.46	5.46	5.46	5.46	5.46	5.46	5.46	5.46
Rain-PET	-3.86	7.84	5.04	5.74	-0.86	5.94	-2.66	-1.76	-3.86	-3.96
APWL	-8.59				-0.86		-2.66	-4.43	-8.29	-12.25
SM	116.70	124.54	125.00	125.00	124.14	125.00	122.37	120.65	116.98	113.33
DSM	-3.66	7.84	0.46	0.00	-0.86	0.86	-2.63	-1.71	-3.67	-3.65
AET	5.26	5.46	5.46	5.46	5.46	5.46	5.43	5.41	5.27	5.15
D	0.20	0.00	0.00	0.00	0.00	0.00	0.03	0.05	0.19	0.31
S	0.00	0.00	4.57	5.74	0.00	5.08	0.00	0.00	0.00	0.00
Tot.ava.	0.19	0.09	4.62	8.05	4.02	7.09	3.55	1.77	0.89	0.44
RO	0.09	0.05	2.31	4.02	2.01	3.55	1.77	0.89	0.44	0.22
Detention	0.09	0.05	2.31	4.02	2.01	3.55	1.77	0.89	0.44	0.22

Appendix 2 (continued)

No. of days	91	92	93	94	95	96	97	98
Rain	8.30	7.00	2.60	1.80	13.90	4.40	2.00	2.20
OF	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Eff.Rain	8.30	7.00	2.60	1.80	13.90	4.40	2.00	2.20
PET	5.46	5.46	5.46	5.46	5.46	5.46	5.46	5.46
Rain-PET	2.84	1.54	-2.86	-3.66	8.44	-1.06	-3.46	-3.26
APWL			-2.86	-6.53		-1.06	-4.53	-7.79
SM	116.17	117.70	122.17	118.64	127.08	123.94	120.56	117.45
DSM	2.84	1.54	4.47	-3.53	8.44	-3.14	-3.39	-3.11
AET	5.46	5.46	7.07	5.33	5.46	7.54	5.39	5.31
D	0.00	0.00	-1.60	0.13	0.00	-2.07	0.08	0.16
S	0.00	0.00	0.00	0.00	2.08	0.00	0.00	0.00
Tot.ava.	0.22	0.11	0.06	0.03	2.09	1.05	0.52	0.26
RO	0.11	0.06	0.03	0.01	1.05	0.52	0.26	0.13
Detention	0.11	0.06	0.03	0.01	1.05	0.52	0.26	0.13

Appendix 3: Daily runoff depths results analysed by SCS CN method

Months	Dates	Rain (mm)	5-days antecedent rainfall (mm)	AMC Classes	Estimated CN	Surface retention S=(25400/CN)-254 (mm)	Runoff depth (mm)
Jan	25	11.6	1.5	I	64	142	2.25
	26	2.7	12.4	I	64	142	5.67
March	24	2.1	0.5	I	64	142	5.97
	28	23.5	3.7	I	64	142	0.17
	29	2.8	26.7	II	81	60	1.65
	30	27.2	27.4	II	81	60	3.12
April	5	25.6	0.7	I	64	142	0.06
	7	2.7	27.3	II	81	60	1.69
	8	24	30	II	82	56	2.41
	9	4.2	53.7	III	91	26	0.04
	11	28.1	32.1	II	81	60	3.46
	12	23.1	59.2	III	91	26	7.33
	13	1.7	79.6	III	91	26	0.54
	18	1.8	2.4	I	64	142	6.12
	22	7.8	1.8	I	64	142	3.49
	23	7.4	9.6	I	64	142	3.64
	25	22.4	15.3	I	64	142	0.26
	26	1.8	37.7	II	81	60	2.07
	27	6	39.5	II	81	60	0.65
	29	11.2	41.8	III	91	26	1.13
	30	5.7	41.7	III	91	26	0.01
May	1	16.9	23.2	II	81	60	0.38
	3	3.1	34.6	II	81	60	1.53
	5	20.8	26.5	II	81	60	1.15
	11	9.5	0.8	I	64	142	2.90
	14	30.3	10.1	I	64	142	0.03
June	13	21.8	0.8	I	64	142	0.32
	14	1.1	21.8	I	64	142	6.49
	18	6	24.1	II	81	60	0.65
	19	2.6	8.3	I	64	142	5.72
	27	6	0	I	64	142	4.19
	29	12.9	18.9	I	64	142	1.89
July	2	2.6	19.6	I	64	142	5.72
	6	2.8	2.9	I	64	142	5.62
	7	12	5.7	I	64	142	2.14
	23	3.3	0	I	64	142	5.38
	24	3.2	0	I	64	142	5.43
	25	1.7	6.5	I	64	142	6.18
	27	2.7	8.2	I	64	142	5.67
Aug	2	9.3	2.7	I	64	142	2.96
	3	7.6	9.3	I	64	142	3.56
Sept	4	1.9	0	I	64	142	6.07
	5	2.9	1.9	I	64	142	5.57
	7	3.4	4.8	I	64	142	5.33

	27	1.4	0	I	64	142	6.33
	29	6.1	1.4	I	64	142	4.15
	30	4.2	7.5	I	64	142	4.96
Oct	13	1.1	0.8	I	64	142	6.49
	14	11	1.9	I	64	142	2.42
	15	9.7	12.9	I	64	142	2.83
	16	1.3	22.6	I	64	142	6.38
	18	2.5	23.1	II	81	60	1.77
	19	2.5	24.5	II	81	60	1.77
	20	3.3	16	I	64	142	5.38
	29	4.7	0.4	I	64	142	4.74
	30	4.2	5.1	I	64	142	4.96
Nov	2	10	8.9	I	64	142	2.73
	5	19.4	10.4	I	64	142	0.61
	6	13.1	29.8	II	81	60	0.02
	7	13.1	42.9	II	81	60	0.02
	8	25.5	46	III	91	26	8.93
	9	1.8	71.8	III	91	26	0.51
	10	1.1	73.2	III	91	26	0.76
	14	1.4	2.9	I	64	142	6.33
	15	2	2.5	I	64	142	6.02
	16	12	3.4	I	64	142	2.14
	17	4.8	15.4	I	64	142	4.70
	18	6.9	20.2	I	64	142	3.83
	19	9.2	27.1	II	81	60	0.13
	20	4.5	34.9	II	81	60	1.05
	21	21	37.4	II	81	60	1.20
	22	10	46.4	III	91	26	0.76
	23	3	51.6	III	91	26	0.20
	24	27.9	47.7	III	91	26	10.62
	25	1.5	66.4	III	91	26	0.61
	27	1.5	42.4	III	91	26	0.61
	29	2.6	30.9	II	81	60	1.73
Dec	1	6.3	4.1	I	64	142	4.07
	2	3.5	10.4	I	64	142	5.29
	3	2.7	12.4	I	64	142	5.67
	4	1.6	15.1	I	64	142	6.23
	6	13.3	14.1	I	64	142	1.79
	7	10.5	21.1	I	64	142	2.58
	8	11.2	28.1	II	81	60	0.01
	9	4.6	36.6	II	81	60	1.02
	10	11.4	39.6	II	81	60	0.00
	11	2.8	51	III	91	26	0.24
	13	3.7	30	II	81	60	1.31
	15	1.6	18.6	I	64	142	6.23
	16	1.5	8.8	I	64	142	6.28
	17	8.3	7.5	I	64	142	3.31
	18	7	15.8	I	64	142	3.79

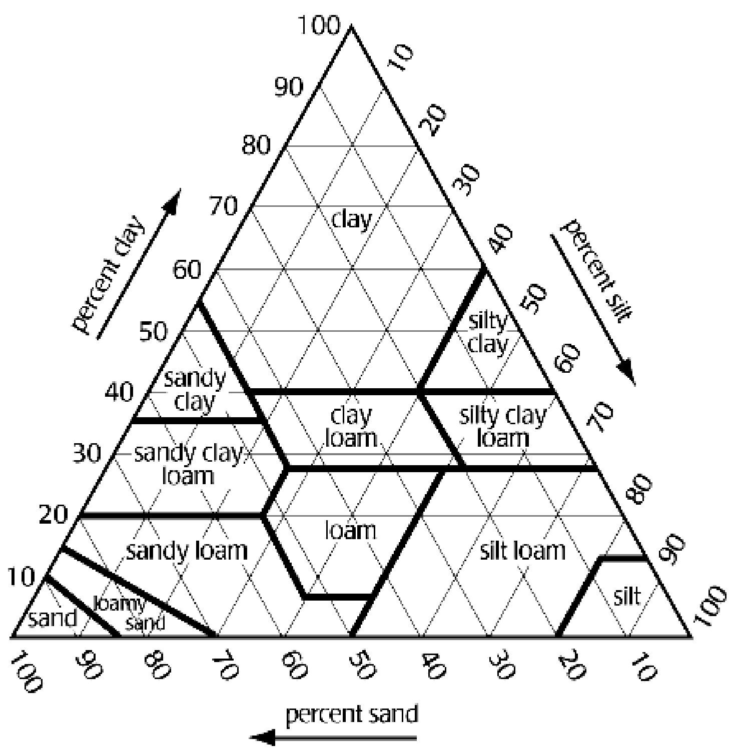
	19	2.6	19.1	I	64	142	5.72
	23	1.8	10.7	I	64	142	6.12
	24	13.9	5.5	I	64	142	1.64
	25	4.4	16.8	I	64	142	4.87
	26	2	20.2	I	64	142	6.02
	27	2.2	22.2	I	64	142	5.92
		789					320.46

Appendix 4: The Parched-thirst model output files

	Season 1	Season 2
Length of Simulation (days)	181	184
Total Rainfall (mm)	403.5661	422.6569
Total Runoff (mm)	40.35661	42.26569
Total Overflow (mm)	0	0
Total Infiltration1 (mm)	363.2095	380.3912
Total Infiltration2 (mm)	484.2794	507.1883
Total Runon(mm)	80.71323	84.53138
Average Saturation Deficit (KPa)	2.893443709	2.883831
Sowing Date	30	30
Growing Season Length1 (days)	0	0
Population1 (plants / ha)	4.4	4.4
Total Grain Yield1 (t/ha)	0	0
Growing Season Rain1 (mm)	0	0
Total Weed Transpiration1 (mm)		
Total Rainfall1 (mm)	399.6	418.3
Total Above Ground Dry Weight1 (t/ha)	0.0001	0.0001
Total Crop Transpiration1 (mm)	0	0
Total Soil Evaporation1 (mm)	251.8044107	237.3699
Final Soil Water1 (mm)	363.5192143	391.1354
Final Depression Storage1 (mm)	0	0
Total Drainage1 (mm)	0	0
Initial Soil Water1 (mm)	252	248
Growing Season Length2 (days)	151	0
Population2 (plants / ha)	4	4
Total Grain Yield2 (t/ha)	2.35	0.39
Growing Season Rain2 (mm)	379	389.7
Total Weed Transpiration2 (mm)		
Total Rainfall2 (mm)	399.6	418.3
Total Above Ground Dry Weight2 (t/ha)	0.807323897	0.219934
Total Crop Transpiration2 (mm)	358.074031	137.0001
Total Soil Evaporation2 (mm)	198.4364354	243.1164
Final Soil Water2 (mm)	179.8828866	375.1923
Final Depression Storage2 (mm)	0	0
Total Drainage2 (mm)	0	0
Initial Soil Water2 (mm)	252	248

APPENDIX 5: Soil samples

	< 2micron	2-50microns	50 125 microns	125-2000microns	O matter
Sample ID	Clay	Silt	Very fine sand	Sand	
A.2_R	27.7	36.2	12.7	14.1	9.1
E.3_R	19.0	26.7	29.0	21.1	4.1
Labx_38	27.5	39.3	19.9	8.4	5.0
A.2	27.5	35.8	12.9	14.7	9.1
A.1.1	36.5	28.2	13.8	16.0	5.4
E.3	18.0	31.2	25.0	21.6	4.1
E.1	15.0	31.8	20.9	27.6	4.8
C.1	26.7	30.2	20.3	14.5	8.2
G.1	14.5	26.5	21.7	33.2	4.0
J.1	13.5	30.8	21.6	30.2	4.0



Appendix 6:

Table H1.Hydrological soil groups as defined by US SCS (1972)

Soil Group	Description	Infiltration rate (mm/hr)
A	Lowest runoff potential. Includes deep sands and gravel with very little silt and clays (soils with high infiltration capacities even when thoroughly wetted)	8-12
B	Moderately low runoff potential. Mostly sandy soils less deep than A.	4-8
C	Moderately high runoff potential. Comprises shallow soils and soils containing considerably clay and colloids, though less than those of group D. The group has below-average infiltration after saturation	1-4
D	Highest runoff potential. Includes mostly clays of high swelling percent, but the group also includes some shallow soils with nearly impermeable sub-horizons near the surface.	0-1

Table 2: Seasonal rainfall limits for AMC classes

AMC classes	5-days antecedent rainfall (mm)		
	Dormant season	Growing season	Average
I	<13	<36	<23
II	13-28	36-53	23<40
III	>23	>53	>40

Table 3: Runoff coefficient Values (Source: Hudson, 1981)

Topography and vegetation	Soil texture		
	Sandy loam	Clay and silt loam	Clay
WOODLAND			
Flat (0-5%)	0.10	0.3	0.4
Rolling (5-10%)	0.25	0.35	0.5
Hilly (10-30%)	0.3	0.5	0.6
PASTURE			
Flat	0.1	0.3	0.4
Rolling	0.16	0.36	0.55
Hilly	0.22	0.42	0.6
CULTIVATED			
Flat	0.3	0.5	0.6
Rolling	0.4	0.6	0.7
Hilly	0.52	0.72	0.82
URBAN	30% impervious	50% impervious	70% impervious
Flat	0.4	0.55	0.65
Rolling	0.5	0.65	0.8

TABLE 4: Runoff curve numbers for selected agricultural, suburban, and urban land uses (antecedent moisture condition II, *Ia* = 0.28) (Source: Applied hydrology by Chow/Maidment/Mays)

	A	B	C	D
Cultivated land[1]: without conservation treatment	72	81	88	91
with conservation treatment	62	71	78	81
Pasture or range land: poor condition	68	79	86	89
good condition	39	61	74	80
Meadow: good condition	30	58	71	78
Wood or forest land: thin stand, poor cover, no mulch	45	66	77	83
good cover[2]	25	55	70	77
Open Spaces, lawns, parks, golf courses, cemeteries, etc.				
good condition: grass cover on 75% or more of the area	39	61	74	80
fair condition: grass cover on 50% to 75% of the area	49	69	79	84
Commercial and business areas (85% impervious)	89	92	94	95
Industrial districts (72% impervious)	81	88	91	93
Residential[3]:				
Average lot size / Average % impervious[4]				
1/8 acre or less / 65	77	85	90	92
1/4 acre / 38	61	75	83	87
1/3 acre / 30	57	72	81	86
1/2 acre / 25	54	70	80	85
1 acre / 20	51	68	79	84
Paved parking lots, roofs, driveways, etc.[5]	98	98	98	98
Streets and roads:				
paved with curbs and storm sewers[5]	98	98	98	98
gravel	76	85	89	91
dirt	72	82	87	89

1 For a more detailed description of agricultural land use curve numbers, refer to Soil Conservation Service, 1972 Chap. 9

2 Good covers are protected from grazing and litter and brush cover soil.

3 Curve numbers are computed assuming the runoff from the house and driveway is directed towards the street with a minimum of roof water directed to lawns where additional infiltration could occur.

4 The remaining pervious areas (lawn) are considered to be in good pasture condition for these curve numbers.

5 In some warmer climates of the country a curve number of 95 may be used.

Table 5: Crop water requirements

Table 6: Guideline CCAR values for cultivated clay and silt loam soils at different land slopes.[1]

AEZ	E=60% Rain	Crop	Mean CWR	Slope of land (%) 2	4	6	8	10
LM4,	210	Maize (Kat)	355	2.3	2.3	1.9	1.9	1.6
		F. Millet	365	2.5	2.5	2.1	2.1	1.7
		B. Millet	350	2.2	2.2	1.9	1.9	1.5
		Wheat	375	2.6	2.6	2.2	2.2	1.8
		Sorghum	475	4.2	4.2	3.5	3.5	2.9
		C. Peas	295	1.3	1.3	1.1	1.1	0.9
		G. Grams	295	1.3	1.3	1.1	1.1	0.9
		Soya	638	6.8	6.8	5.7	5.7	4.7
		Sunflower	365	2.5	2.5	2.1	2.1	1.7
	560[2]	Cotton	750	1.1	1.1	0.9	0.9	0.8
		Citrus	800	1.4	1.4	1.2	1.2	1.0
		Mango	900	2.0	2.0	1.7	1.7	1.4
		Pawpaw	1250	4.1	4.1	3.4	3.4	2.9
LM5,	(E=50%)							
	148	Maize (Kat)	355	5.6	4.7	3.9	3.9	3.2
		F. Millet	365	5.9	5.9	4.1	4.1	3.4
		B. Millet	350	5.5	5.5	3.8	3.8	3.2
		Wheat	375	6.1	6.1	4.3	4.3	3.6
		Sorghum	475	8.8	8.8	6.1	6.1	5.1
		C. Peas	295	4.0	4.0	2.8	2.8	2.3
		G. Grams	295	4.0	4.0	2.8	2.8	2.3
		Soya	638	13.2	13.2	9.2	9.2	7.7
		Sunflower	365	5.9	5.9	4.1	4.1	3.4
	350	Cotton	750	4.6	4.6	3.2	3.2	2.6
		Citrus	800	5.1	5.1	3.6	3.6	3.0
		Mango	900	6.3	6.3	4.4	4.4	3.6
		Pawpaw	1250	10.3	10.3	7.1	7.1	6.0
L5,	(E=40%)							
	123	Maize (Kat)	355	9.4	9.4	7.9	7.9	6.5
		F. Millet	365	9.8	9.8	8.2	8.2	6.8
		B. Millet	350	9.2	9.2	7.7	7.7	6.4
		Wheat	375	10.2	10.2	8.5	8.5	7.1
		Sorghum	475	14.3	14.3	11.9	11.9	9.9
		C. Peas	295	7.0	7.0	5.8	5.8	4.9
		G. Grams	295	7.0	7.0	5.8	5.8	4.9
		Soya	638	20.9	20.9	17.4	17.4	14.5
		Sunflower	365	9.8	9.8	8.2	8.2	6.8
	328	Cotton	750	6.4	6.4	5.4	5.4	4.5
		Citrus	800	7.2	7.2	6.0	6.0	5.0
		Mango	900	8.7	8.7	7.3	7.3	6.1
		Pawpaw	1250	14.1	14.1	11.7	11.7	9.8

[1]Based on 60% probability rainfall in LM4, LM5 and L5 as given by Jaetzold and Schmidt (1983), p202. The lower of the two seasonal rainfall is used for design.
[2]For cotton and other perennial crops, rainfall values for both seasons are added.

Table 6: Available water holding capacity for different soil textures

Suggested available water capacities for combinations of soil texture and vegetation. (From Thornthwaite and Mather 1957.)

VEGETATION	SOIL TEXTURE	AVAILABLE WATER CAPACITY (% VOLUME)	ROOTING DEPTH (M)*	AVAIL. WATER CAP. OF ROOT ZONE (MM)
Shallow rooted crops (spinach, peas, beans beets, carrots, etc.)	Fine sand	10	0.50	50
	Fine sandy loam	15	0.50	75
	Silt loam	20	0.62	125
	Clay loam	25	0.40	100
	Clay	30	0.25	75
Moderately deep rooted crops (corn, cereals, cotton, tobacco)	Fine sand	10	0.75	75
	Fine sandy loam	15	1.00	150
	Silt loam	20	1.00	200
	Clay loam	25	0.80	200
	Clay	30	0.50	150
Deep rooted crops (alfalfa, pasture grass, shrubs)	Fine sand	10	1.00	100
	Fine sandy loam	15	1.00	150
	Silt loam	20	1.25	250
	Clay loam	25	1.00	250
	Clay	30	0.67	200
Orchards	Fine sand	10	1.50	150
	Fine sandy loam	15	1.67	250
	Silt loam	20	1.50	300
	Clay loam	25	1.00	250
	Clay	30	0.67	200
Mature forest	Fine sand	10	2.50	250
	Fine sandy loam	15	2.00	300
	Silt loam	20	2.00	400
	Clay loam	25	1.60	400
	Clay	30	1.17	350

Table 7: Manning roughness coefficients

TABLE 2.5.1
Manning roughness coefficients for various open channel surfaces

Material	**Typical Manning roughness coefficient**
Concrete	0.012
Gravel bottom with sides — concrete	0.020
— mortared stone	0.023
— riprap	0.033
Natural stream channels	
Clean, straight stream	0.030
Clean, winding stream	0.040
Winding with weeds and pools	0.050
With heavy brush and timber	0.100
Flood Plains	
Pasture	0.035
Field crops	0.040
Light brush and weeds	0.050
Dense brush	0.070
Dense trees	0.100

Source: Chow, 1959.