ANALYSIS OF CATCHMENT HYDROLOGIC RESPONSE UNDER CHANGING LAND USE: THE CASE OF UPPER MOLO RIVER CATCHMENT, KENYA

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God bless you all.

DECLARATION AND RECOMMENDATION

DECLARATION

I solemnly declare that this is my original work and that it has not been presented before in any other institution known to me for the award of any Degree or Diploma.

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BM11/1333/04

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RECOMMENDATION

This thesis is the candidate's original work and has been prepared with our guidance and assistance. It is submitted for examination with our approval as official University Supervisors.

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DEDICATION

To my late Grand father Mr. Chemasi, for encouraging me to pursue education to the highest levels, my caring parents, Mr. Joseph Soi and Mrs. Ruth Soi. To my Wife Mrs. Jennifer C. Kirui and daughter, Joy Chebet who was born on 9th October 2008, the defense date of this thesis.

ABSTRACT

Change in land use has a direct effect in catchment hydrologic response. It is caused by human intervention to enhance and diversify their livelihood needs, and at the same time get economic benefits from the land resources. These interventions result in changes in surface runoff, soil erosion and sediment yield among others. If the change in land use is not well managed then it will affect the quantity and quality of water resources as well as production potential of the land. Based on this ground this study was formulated to investigate the effects of land use changes on catchment response, in particular surface runoff and sediment yield. Such a study required continuous hydrologic data such as stream flow and sediment yield for a number of gauging stations within the study catchment. However, most catchments in Kenya do not have adequate data to accomplish such study. In this study upper Molo River catchment in eastern Mau was used because of its consistent stream flow data. In this catchment there has been significant reduction in stream flow during dry season and flooding in the rainy season. This study investigated a modelling approach for predicting the changes in catchment response as a result of land use change. Soil and Water Assessment Tool (SWAT) was identified as suitable model and used to simulate the catchment response under different land use types. The input data used were digital elevation model (DEM), land cover, soils and rainfall. The DEM was processed in Arc View GIS and land cover maps derived from satellite image using ERDAS 8.5 imagine software. The land cover analysis results show that forest cover reduced by 48% as a result of increase in agricultural and settlement areas between the years 1986 to 2001. Simulation analysis carried out for 1986 and 1995 land cover maps, show an increase in surface runoff of 13.3%. In the simulation the data set was divided into two; 1980 to 1989 for calibration and 1991 to 2000 for validation. Conceptual parameters derived during calibration were used in the model to simulate streamflow for the two data sets and gave a Nash Sutcliffe coefficients of 0.87 and 0.72 respectively. The sediment yield values were 1.5t/ha for the calibration and 2.7t/ha for validation periods respectively. These results show insignificant change in the catchment response but demonstrated the effects of land use changes on catchment response. It is therefore concluded that land cover change of less 48% have insignificant change on catchment hydrologic response.

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LIST OF ABBREVIATIONS AND ACRONYMS

AGWA	Automated Geospatial Watershed Assessment Tool
CN	Curve Number
DFID	Department for International Development
ERDAS	Earth Resources Data Analysis System
FAO	Food and Agricultural Organisation
GIS	Geographic Information System
GPS	Global Positioning System
HSG	Hydrologic Soil Groups
ILWIS	Integrated Land and Water Information System
KINEROS	Kinematic Runoff and Erosion Model
MUSLE	Modified Universal Soil Loss Equation
NS	Nash and Sutcliffe Efficiency
RS	Remote Sensing
RSR	RMSE-Observation Deviation Standard Ratio
SCS	Soil Conservation Service
SHE	Systeme Hydrologique Europeen
STATSGO	State Soil Geographic Data Base
SUSRGO	Soil Survey Geographic
SWAT	Soil and Water Assessment Tool
USLE	Universal Soil Loss Equation
WRMA	Water Resources Management Authority

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CHAPTER ONE

INTRODUCTION

1.1 Background

Increase in population over the past few years has put great pressure on the natural resources. The population increase has led to increase in demand for more water and land resources, consequently causing the reduction of forested areas (Séguis *et al*., 2004; Sintondji, 2005; Notter *et al*., 2007). People are in need of timber, fuel wood and space for agricultural development, and settlement (Chemelil, 1995). The natural vegetated areas have been cleared and cultivated (Séguis *et al*., 2004). This has been observed not only in the high potential areas but also in marginal areas which were earlier on predominantly under livestock production because of low rainfall (Onyando, 2000). In tropical countries such as Kenya, the rural communities encroach into the humid areas to open up new lands for agricultural production (Onyando, 2000; Olang, 2004; Hartemink *et al*., 2006). This has been as a result of the fact that the communities have no other option but to cultivate in the rich soils of the once forested areas (Maingi and Marsh, 2001; Agatsiva and Oroda, 2003; Pearce *et al*., 2003). In Kenya for instance, the humid area covers about one third of the total area of the country. This area supports a greater part of the rural population who earn their living mainly through agriculture.

The urban and agricultural developments have both led to change in land cover and land use patterns. These changes have led to environmental degradation, which has negatively altered hydrologic regimes of many catchments in Kenya. For instance, deforestation and urbanisation which affect the environmental stability have significantly altered the seasonality and magnitude of discharge, and annual distribution of stream flow (Karanja *et al*., 1986; Donner, 2004; Mustafa *et al*., 2005). Degradation resulting from intensive agriculture and other activities include: loss of top fertile soil due to erosion, siltation of rivers, high incidence of floods, eutrophication of surface water bodies and hypoxia condition resulting in loss of aquatic biodiversity, effluent of agrochemicals and low stream flows during dry periods (Donner, 2004; Onyando *et al.,* 2005; Lim *et al*., 2005; Araujo and Knight, 2005). These effects need to be studied to enable proper measures to be put in place. The understanding of such effects through catchment modelling allow for monitoring and correlating environmental changes with factors such as socio-economic and health among others (Troyer, 2002). In addition, it enables planners to formulate policies to minimize the undesirable effects of future land use changes on catchment response (Mustafa *et al*., 2005).

Studies on effects of land use change on hydrologic regimes have been carried out at macro-scale levels. However, there is need to establish the trends and magnitude of the changes and to quantify the cause effects relative to land use change at catchment level. The catchment is a complex system and hence any disturbance therein is bound to have certain resultant adverse effects. The hydrologic cycle is influenced by climate, physical characteristic and human activities (Ma *et al*., 2008). The inhabitants of the catchment do not instantly recognize the negative effects of these influences instead, it takes several years to be observed and felt.

Land development activities need to be planned such that their effects on the environment are minimal. Before planning for such activities, there is need to understand the hydrologic processes taking place in a given catchment. The hydrologic processes are part of the hydrologic cycle. The hydrologic cycle is made up of several sub elements, which include: precipitation, evapotranspiration, infiltration, stream flow and runoff. These elements are interconnected and therefore cannot be clearly separated from each other. Hence any event that has a negative effect on one element will affect the entire cycle (Kimani *et al*., 1991).

The upper Molo River catchment is one of the catchments that have undergone rapid land cover and land use changes over the last 40 years (Kenya Forest Working group, 2001). The catchment is located in a high potential zone where intensive agriculture is being practiced (Johnsson and Svensson, 2002; Koyo, 2002). The catchment has a high population that depends on the scarce natural resources such as forest and water. As a result of high population growth over the years, the forest cover has rapidly been replaced by crop cover and built up areas, which has led to changes causing the soils to be impervious (Mustafa *et al*., 2005). This effect has reduced the infiltration rates and therefore caused increased runoff generation from the catchment.

Land use in the catchment varies greatly and depends on the rainfall reliability. In the upper part of the catchment, where forest was cleared, crop production and livestock keeping is carried out. The lower part of the catchment receives low rainfall and is not very reliable as compared to the upper part. In this area, livestock keeping and crop farming is practiced together with irrigation along the river banks. The practice of farming in sloppy areas and near the streams contributes to the sediment transported out of the catchment. This contributes to the degradation of the catchment. The degradation of the catchment leads to poor soil fertility which reduces crop yields. This reduction in crop yields result in low income. Therefore the catchment degradation has some bearing on the increase in poverty levels.

In order to understand the effects of land use and land cover on hydrological processes of a catchment, the hydrologic data such as stream flow, runoff and sediment data are required. There is lack of reliable hydrologic data in most catchments especially in developing countries (Demlie *et al*., 2007). The monitoring of these data is limited due to lack of gauging instruments in most of these catchments. For instance, the upper Molo River catchment there is no automated stream flow gauging and sediment gauging station. However a weir was installed at the catchment outlet but it has since been destroyed by heavy floods and no replacement was done. The lack of automated gauging instruments may be attributed to the high cost associated with their procurement and maintenance (Onyando, 2000; Onyando and Chemelil, 2004; Olang, 2004). The most appropriate task therefore is the provision of a hydrologic data using other techniques such as hydrologic models. In this regard therefore, catchment modelling and correlating the environmental changes to catchment response is an alternative to meet this challenge (Onyando and Sharma, 1995; Koka, 2004).

The availability of remotely sensed imagery and Geographical Information Systems (GIS) allow for efficient and quantitative resource mapping and land cover change detection (Baldyga *et al*., 2004; Mekonnen, 2005). The use of GIS and remote sensing tool has made it possible to efficiently process spatial data for deriving physical parameters needed by hydrologic models (Koka, 2004). The application of GIS as a major modelling tool in many catchment studies has become very common. For instance, it has been used to overlay layers of information to produce specific hydrologic parameters such as curve numbers (Onyando, 2000; Mustafa *et al*., 2005). Remote sensing on the other hand is used to acquire general information such as hydrologic components in spatial and temporal domain. This information is important in successful model analysis, prediction, calibration and validation. The central importance of remote sensing is its ability to detect the changes in land cover and land use patterns for planning and resources management (Fashtali, 2003).

1.2 Problem Statement

The rapid land use/cover changes caused by clearing of the forest for agricultural production and settlement are presumed to adversely affect the hydrologic response of the upper Molo River catchment. This is shown by reduced stream flow during dry periods and increased flash floods in wet seasons. In addition spatial variability in soil erosion and siltation has also occurred in the catchment. To study and develop means of reducing these problems there is need for continuous hydrologic data. The catchment lacks consistent hydrologic data, making the effective management of catchment resources difficult. There is need to develop an alternative approach for generating the hydrologic data such as stream flows and sediment yield, which will be used in land use and water resource planning.

1.3 Main Objective

The main objective is to analyse catchment hydrologic response under changing land use in upper Molo River catchment.

1.4 Specific Objectives

The specific objectives for the present study are:

i. To assess the temporal and spatial distribution of land use and land cover changes using remote sensing and GIS.
ii. To assess the impact of land use and land cover change on water and sediment yield.

1.5 Research Questions

i. Can the SWAT model fairly simulate the catchment hydrologic response?
ii. Is the change in land use having significant effect on catchment hydrologic response?
iii. Can the established data enhance efficient catchment and water resource management?

1.6 Justification

Increasing population pressure has created stress on natural resources especially in the high potential areas. The rural communities have migrated to forested areas and cleared them for agricultural production and settlement. This has led to changes in land cover/use and consequently accelerated environmental degradation. The reduced stream flows and increased flash floods have been observed in upper Molo River catchment in the last few years together with increased erosion and siltation of streams. Based on these problems, there was need to assess the hydrologic catchment response under changing land use/cover. The assessment needed consistent hydrologic data such as stream flow and sediment yield data. However, the upper Molo River catchment lacks continuous hydrologic data records. Therefore, there was need to develop an alternative approach for predicting stream flow and sediment yield data. The simulation of runoff, stream flow and sediment yield was carried out using Soil and Water Assessment Tool (SWAT), for different land use practices over a period of time. This enabled acquisition of data which was used in the analysis of the hydrologic catchment response. The study provided a technique for improving hydrologic data and filling the existing gaps for effective water resource planning and management.

CHAPTER TWO
LITERATURE REVIEW

2.1 Impact of Land Use and Land Cover change on Catchment Hydrologic Response

Human activities such as agriculture and urban development affect land cover and land use. Land cover is the biophysical state of the earth's surface and immediate subsurface, which include: Biota, Soil, topography, surface and underground water, and human structures (Hartemink *et al*., 2006). The land use involves the manner in which the biophysical attributes of the land are manipulated and the intent underlying that manipulation for which the land is used (Lambin *et al*., 2003; Hartemink *et al*., 2006).

Land use and land cover change are significant in catchment studies especially in assessing environmental change. The environmental impacts at local, regional and global levels significantly affect hydrological response of a catchment. Alterations in the earth's surface have major implications for the radiation balance, complexity and, water quality and quantity, surface runoff dynamics, lowering of groundwater tables (Lawal, 2004; Mungai *et al*., 2004). Furthermore, vegetation modification, whether resulting from harvesting or planting, alters the water balance of the site. This may eventually alter the hydrologic regime of the catchment. If vegetation is significantly reduced the flow path of precipitation can be altered and significant surface flow can take place causing erosion, and sedimentation of water bodies.

Some work by Golosov and Panin (2006) showed that hydrological regime and sediment flux change drastically following the farming activities within a basin. Cultivation of land exerts a major influence on the relationship between surface and subsurface flow. Annual surface runoff from a loam soil increases by four times in a cultivated catchment, according to data from long-term observations done in paired catchments in the forest zone of Central Russia (Golosov and Panin, 2006). Surface runoff is extremely limited under grass or forest vegetation compared with agricultural land.

Hydrological effects of land use/cover change are manifested in many ways and at different spatial and temporal scales. Most obvious is the immediate and direct effects on the quantity and quality of catchment's runoff. For instance, land cover change is the most significant factor driving hydrologic changes such as runoff volume, timing and variability (Fohrer *et al.*, 2001; Maingi and Marsh, 2001; Miller *et al*., 2002; Donner, 2004). The simplest method to assess these effects on hydrological response of a catchment is by comparing stream flow and runoff generated from the catchment areas with the contrasting land use types (Barkhordari, 2003). The main concern is with the direct and local effects of land use change on hydrology within a catchment level (Maidment, 1993). Catchment land use change is always due to natural and man-made causes, where the man-made causes are mainly attributed to the search for resources to meet human needs. For instance, deforestation is a resultant of the need for timber for construction, fuel wood, and clearing for agricultural development and for settling the ever increasing population (Chemelil, 1995; Krishnaswamy *et al*., 2001). The need for fertile land to meet the ever increasing demand for food has left the rural population with no option but to clear the natural and artificial forested areas for agricultural development (Maingi and Marsh, 2001).

As the landscape in a catchment is altered in both space and time, the factors that influence hydrologic response of the catchment also change (Singh and Fiorentino, 1996). The evaluation of the relationship between the land use and land cover is important for the efficient catchment management. This evaluation has normally been done using several types of models that vary from strictly empirical to physically based distributed models (Barkhordari, 2003). Physically distributed models in particular need specific data on land use and soil types and their locations within a catchment (Chakraborty *et al*., 2005).

Remote sensing and Geographical Information System (GIS) have been used as powerful tools for managing and analysing geographic data to levels of coverage and accuracy not possible before, especially land use and land cover data. For instance, it has been shown that there is a direct linkage in catchment factors that can easily be expressed using GIS in combination with remote sensing and modelling (Baldyga, 2004). This combination provides the framework within which spatially distributed data are collected and used to prepare model files and evaluate model results. One application of remote sensing technique is in the acquisition and analysis of satellite imageries. For instance, the multi-spectral data can be utilized for land use and land cover classification using supervised and unsupervised classification algorithms. Supervised classification algorithms use training data to locate similar pixels in an image with similar spectral characteristics. This is the most commonly used classification method, which employs maximum likelihood classifier technique (Mekonnen, 2005).

2.1.1 Precipitation

The transfer of water from the atmosphere to the land is called precipitation and is the most important part of hydrological cycle (Sintondji, 2005). Precipitation can be in form of rain, snow, hail and sleet. Precipitation in the form of rain is the driving force of the land phase of hydrologic cycle. It is characterized by both high spatial and temporal variability. Rainfall is random or probabilistic in nature. Part of the precipitation is intercepted by natural vegetation cover. The intercepted precipitation is either redistributed through runoff or evaporates back to the atmosphere. Precipitation also moves into the soil through the process of infiltration. Some of this infiltrated water percolates deep down into the ground to recharge the ground water reservoir.

Several methods have been developed to estimate precipitation. some of these methods include recording and non-recording gauges. The recording gauges produce a continuous plot of rainfall against time and provide valuable data of intensity and duration of rainfall for hydrological analysis. These gauges automatically record the depth of rainfall in intervals ranging from as little as one minute in duration while non-recording gauges are read manually at longer time interval at 9 am and 3 pm. There are three types of recording gauges in general use. These are, the weighing-bucket type, float type and the tipping bucket type. These gauges have been described in several hydrologic books (Subramanya, 1984; Maidment, 1993). The two types of non-recording gauges are the standard and the storage type. They are the most widely used rainfall data measuring devices in hydrology.

Rainfall data need to be checked for continuity and consistency before being used. The continuity of the records may be broken with missing data due to reasons such as damage or fault in a rain gauge during a period. The missing data is usually estimated using the data of the neighbouring stations. In this calculation, the normal rainfall is used as a standard of comparison. The normal rainfall is the average value of rainfall at a particular date, month or year over a specified 30 year period. The methods applied are the simple arithmetic method and normal ratio method. The latter is used if the normal precipitation varies considerably.

The spatial rainfall is usually used in hydrology for various applications. Several procedures have been developed to convert point rainfall data into spatial format. The methods are: Simple arithmetic method, Isoyetal and Thiessen polygon. The arithmetic method is usually applied when the rainfall measured for various stations show little variation. The average precipitation over the catchment is taken as the arithmetic mean. In Isohyetal method the catchment area is drawn to scale and the rain gauge stations are marked. The isohyets are drawn; these are lines joining points of equal rainfall magnitude. The area between two adjacent isohyets is determined and the average rainfall indicated by the two isohyets is assumed to be acting over the inter-isohyetal area.

Isohyetal method is superior to the other two methods, when stations are large in number. For Thiessen Polygon method, the rainfall recorded at each station is given weightage on the basis of an area closest to the station. The catchment area is drawn to scale and the stations marked on it. Stations are joined to form a network of triangles and perpendicular bisectors for each of the sides of the triangles are drawn. These bisectors form a polygon around each station. The area of each polygon is determined and used to calculate the average weighted rainfall. The formula is given as:

$$\overline{P} = \frac{\sum_{i=1}^{n} P_i A_i}{A_i} \tag{2.2.1}$$

Where $\overline{P}$ is the average rain fall over the catchment, $P_1 \ldots P_n$ are the rainfall magnitude recorded by each station, $A_1 \ldots A_n$ are the polygon areas.

Thiessen polygon method is more superior to the arithmetic method because it applies some weightage. This weightage is given to the rainfall station on a rational basis. Due to this reason and the use of fixed area polygons it is preferred average rainfall and especially because it lends itself to computer analysis.

2.1.2 Infiltration

Infiltration is the passage of water through macro pores from the surface to the subsurface and determines the amount of runoff that causes erosion (Mao *et al.*, 2008). It is the downward movement of water from the land surface into soil or porous rock (Maidment, 1993; Sintondji, 2005). This process is directly or indirectly influenced by vegetation cover and land use practices. The other factors that affect infiltration rate include the intensity and duration of precipitation, soil characteristics, soil saturation and the slope of the land. As infiltration continues, the soil becomes increasingly wet, causing the rate of infiltration to decrease with time until it reaches a steady value referred to as the infiltration capacity.

Initial rate of infiltration depends on the moisture content of the soil prior to the introduction of water on the soil surface. The final rate of infiltration is equivalent to the saturated hydraulic conductivity of the soil. In order to calculate or determine the infiltration rate, a number of methods have been proposed. These include Green and Ampt infiltration method. It was developed to predict infiltration assuming excess water at the surface at all times (Chow *et al.*, 1988). The equation assumes that the soil profile is homogenous and antecedent moisture is uniformly distributed in the profile. As water infiltrates into the soil, the model assumes the soil above the wetting front is completely saturated and there is a sharp break in moisture content at the wetting front. Green and Ampt infiltration method is given as:

$$f = K\left[1+\frac{(\Phi-\theta_i)S_f}{F}\right] \tag{2.2.2}$$

Where f is the infiltration rate, K is the effective hydraulic conductivity, S_f is the effective suction in the wetting front, Φ is the soil porosity, θ_i is the water content and F is the accumulated infiltration.

Amount of water entering the soil profile is calculated as the difference between the amount of rainfall and the amount of surface runoff. The Green and Ampt infiltration method directly models infiltration, however it requires precipitation data in smaller time steps.

2. 1.3 Stream Flow and Runoff Generation

Runoff is that portion of precipitation that does not evaporate or infiltrate. It makes its way towards stream channels, lakes and oceans as surface or subsurface flow. It is the essential factor in determining the hydrologic response change in a catchment that is affected by land use changes (Barkhordari, 2003). Land use change is an important factor in the runoff process that affects infiltration, erosion and evapotranspiration (Croke *et al.*, 2004). Due to rapid land development, land cover is subjected to changes causing soils to become impervious surfaces. This leads to decrease in the soil permeability, and consequently increase the amount and rate of runoff. It is possible to describe the catchment characteristics when determining runoff response to rainfall input (Mustafa *et al*., 2005). Several methods have been developed for estimating runoff from a given catchment. One of these methods is the Soil Conservation Service (SCS) curve number method. The curve number model is stated as:

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \tag{2.2.3}$$

Where Q is the runoff in mm, P is the rainfall in mm, I_a is the initial abstraction in mm and S is the potential maximum retention after the runoff begins in mm.

The retention parameter varies spatially due to changes in soils, land use, management and slope, and temporarily due to changes in soil water content. The retention parameter is defined as:

$$S = \frac{25400}{CN} - 254 \tag{2.2.4}$$

Where CN is the curve number.

The initial abstraction I_a is all losses before runoff begins. It includes water retained on the surface depression, water intercepted by vegetation, evaporation and infiltration. I_a is highly variable, however it is commonly approximated as 0.2S. By substituting this approximate variable into equation 2.2.3, the equation reduces to:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}, \quad \text{for } P>0.2S \tag{2.2.5}$$

Runoff will only occur when the $P > I_{a,}$.

Major factors that determine CN are hydrologic soil group, cover type, treatment, and antecedent soil condition. The hydrologic soil group is a group of soils having similar runoff potential under similar storm and cover conditions.

The SCS has classified all soils into four major hydrologic soil groups denoted as A, B, C and D according to their infiltration rate which is obtained for bare soil after prolonged wetting. The four groups are summarised in Table 2.1.

Table 2.1: Soil Conservation Service Hydrologic Soil Groups (HSG)

H S G	Soil Textural class	Runoff Potential and Infiltration Rate
A	Sand, Loamy sand and Sandy loam	Low runoff potential and high infiltration rate
B	Silt loam and loam	Moderate infiltration rates
C	Sandy clay loam	Low infiltration potential
D	Clay loam, sandy clay, silty clay loam, silty clay and clay	High runoff potential and very low infiltration rates

The SCS defines three antecedent moisture conditions. These are moisture conditions I, II and III for dry, average and wet conditions respectively.

Runoff becomes stream flow when it is concentrated in a channel. It is possible to measure the amount of water in this phase of the cycle as it leaves the catchment (Linsley and Franzini, 1989). The streamflow data is an important indicator of biophysical changes in the catchment (Onyando and Chemelil, 2004). For instance, the stream flow rate at a particular point in time and location on a drainage system, integrates all the hydrologic processes and storages upstream of that location. The rate of streamflow depends on several factors such as: rainfall events, the seasonal distribution, type and transpiration of the vegetation (Maidment, 1993). These factors when altered through land development significantly affect the seasonal and annual distribution of stream flow. Among these factors, vegetation cover has been recognised as a key factor in runoff production and protection against erosion (Gimeno-García *et al.*, 2007). Vegetation increases infiltration and surface roughness, and reduces the kinetic impact of raindrops.

Gimeno-García *et al.* (2007), concluded in their study that after the clearing of vegetation by fire there was a significant change in hydrologic response in the catchment. In another study carried out by Li *et al.* (2007), it was concluded that total deforestation increases the simulated runoff ratio from 0.15 to 0.44 and the annual stream flow by 35-36%, depending on the location of the catchment. Some studies in Mississippi indicated that there is a reduction in discharge due to increase in vegetation density (Donner, 2004). The understanding of how these activities influence stream flow will aid planners in formulating policies towards minimizing undesirable effects on stream flow patterns. Therefore there is need to establish the relationship between land use change and the stream flow regime in upper Molo River catchment.

2.1.4 Transmission Loss

Transmission losses are losses of surface flow via leaching through the streambed. This type of loss occurs in ephemeral or intermittent streams where groundwater contribution occurs only at certain times of the year, or not at all. A number of methods have been proposed to estimate transmission losses. One method that can be applied to estimate these losses is the Lane's method (Neitsch *et al.,* 2002), which has been used in Soil and Water Assessment Tool SWAT model to determine the transmission losses.

On a global scale, there is no loss of water, since water changes from one phase of hydrological cycle to another. However, at catchment level water loss may be observed. When water falls as rain at one point of the catchment, it collects and flows forming a stream and flow further down to the catchment outlet. Not all water that falls on the catchment and collects as a stream arrives at the catchment outlet. When carrying out catchment response analysis due to land use change it is important that water transmission losses in rivers are taken into account. The losses in rivers include; evaporation and transpiration by riverine vegetation, bed and bank storage seepage. These losses cause variation on river flows throughout the year. To make optimum use of this limited and varying resource, river flows need to be regulated. This can be done via reservoirs as is the case in some parts of Southern African countries (DFID, 2003).

2.1.5 Water Yield

Water yield is the total water outflow from a catchment during a given time. One way of determining effects of land cover change on water yield from the catchment is by use of paired catchment. The paired catchment studies have been widely used as a means of determining the magnitude of water yield change resulting from changes in vegetation cover (Stednick, 1995; Brown *et al*., 2003). These paired catchments studies involve the use of two catchments. The catchments must be similar hydrologically and adjacent to each other. This characteristic might not be achieved as there are few catchments which are totally the same. In Malaysia a paired catchment study which involved three catchments was carried out by Nik (1988), the conclusion was that forest conversion normally leads to increase in water yield from the catchment. Li *et al*. (2007) concluded that there is no significant impact on the water yield and river discharge when the deforestation percentage is below 50% or grazing percentage below 70% for savanna and 80% for grassland areas. However, it was observed that the water yield increases drastically when land cover change exceeds these thresholds. Bren and Hopmans (2007) in their study found that conversion of a radiata pine led to an increased water yield of up to 300mm per annum immediately after clearing. In general water yield and discharge is influenced greatly by change in land use and land cover. The increase in vegetation density has been shown to affect the water yield by alterations of infiltration and evapotranspiration rates (Donner, 2004).

2.2 Sediment Yield

Sediment yield is the total sediment outflow from a catchment during a given time (Lawal, 2004; Lim *et al*., 2005). Sources of sediment include soil erosion usually carried as suspended loads and material eroded from the stream channel. Many factors influence the sediment production in natural catchments. The major controlling factors for sediment yield are: climate, vegetation, catchment size, elevation and relief, rock and soil type, and human activities, all which in turn determine soil erosion rate and stream capacity (DFID, 2004; Sintondji, 2005; Szilassi *et al*., 2006; Wei *et al*., 2007). Houban *et al*. (2006) concluded in their study that sediment processes are highly influenced by human activities. There has been increase in soil erosion and land degradation since man started cultivating the land.

Soil erosion is defined as the detachment and displacement of soil particles from one part of the earth's surface to another location (Wei *et al*., 2007). Some materials are deposited at various locations in the catchment while a portion is delivered to the streams. The sediment delivered to the streams carry with it several materials. These materials may have detrimental effects on the survival of the stream and biodiversity.

Soil erosion problems have been on the increase in the recent past. The accelerated soil loss is a serious concern worldwide because of its negative environmental and economic impacts. For instance, the extensive soil erosion has contributed very significantly to the impoverishment of the land and its resources (Kaur *et al.*, 2003). Colter and Larrocea (2006) indicated that soil erosion is one of the most widespread forms of land degradation resulting from changes in land use in Mexico.

Many human induced activities such as mining, construction and agricultural, disturb land surfaces, resulting in accelerated erosion (Lim *et al.*, 2005). This has occurred especially in developing countries such as Kenya (Onyando *et al.*, 2005). In these countries agriculture is the main economic activity for the rural community. Lack of proper soil and water conservation practices in developing countries has continued to increase catchment degradation. Protection of soil as an important non-renewable natural resource should be given first priority (Koroluk and Boer, 2007). In order to develop efficient strategies for sustainable management of soil resources, it is important to understand and model processes that can lead to soil quality degradation due to land use practices (Szilassi *et al.*, 2006).

There have been several methods that were developed to estimate sediment produced from catchments. One among such methods which is inbuilt in Soil and Water Assessment Tool (SWAT) is the Modified Soil Loss Equation (MUSLE). The MUSLE equation was modified from Universal soil loss Equation (USLE) developed by Wischmeier and Smith (1978). USLE predicts average annual gross erosion as a function of rainfall energy. In MUSLE, the rainfall energy factor is replaced with a runoff factor. This improves the sediment yield prediction and eliminates the need for delivery ratios. The Modified Universal Soil Loss Equation is shown in equation 2.2.6

$$S = 11.8 \times (Q \times q \times A)^{0.56} \times K \times C \times P \times LS \tag{2.2.6}$$

Where S is the sediment yield, Q is the surface runoff volume, q is the runoff rate, A is the area of the hydrological response, K is the USLE soil erodability factor, C is the USLE cover and management factor, P is the USLE support practice factor and LS is the USLE topographic factor. The above equation shows that sediment yield varies directly with variation in discharge implying that discharge estimates could give an indication of sediment yield.

Rapid erosion by water has been a problem since land was first cultivated. The break down of soil structure and redistribution of soil particles make it easy for soil to be removed. Results of this are: decline in soil fertility and reduction in cultivable depth (Lawal, 2004;

Koroluk and Boer, 2007). Erosion also reduces available soil moisture, resulting in a more drought prone condition.

Erosion, sediment transport and deposition are major environmental issues that affect the environment through reduction of reservoir, siltation of rivers and streams, intensification of both water pollution and flood (Araujo and Knight, 2005; Szilassi *et al*., 2006). Water resource management requires sediment yield information in order to make and implement sustainable catchment management policies. The increase in sediment yield from many catchments has resulted from changes in land use. The related increase in urban areas and road construction has increased the impervious surfaces hence reducing the infiltration capacity. This has resulted in high runoff which transports sediment from the catchment to the receiving water bodies. Therefore, this study seeks to assess the magnitude of the effect of land use change on sediment yield in upper Molo River catchment.

2.3 Hydrologic Models

Hydrologic modelling has proved to be a powerful tool that can be applied to understand and explain the effects of land use and land cover change on hydrologic response of a catchment (Baldyga, 2005; Mustafa *et al*., 2005). It allows generation of runoff data in order to make forecasts and calculate the probable maximum flood (PMF) (Fleischbein *et al*., 2006). Hydrologic models provide a framework to investigate the relationship between human activities, climate and water resources. They have been applied in studies to assess the effects of land use and climate change on runoff (Notter *et al*., 2007).

Hydrologic models are relatively complex mathematical description of the hydrologic cycle (Linsley *et al*., 1982; Singh and Woolhiser, 2002). They describe the actual physical processes of the hydrologic cycle and represent the behaviour of the catchment in transforming a hydrologic input (rainfall) into output (streamflow or runoff). Stream flow models are therefore mathematical expressions that simulate stream flow or runoff in a manner similar to the way a catchment would operate on the same rainfall event (Mudgal, 2005). However, in developing a hydrological model, assumptions are made in applying the physical laws and equations that govern the processes to simplify the larger and more complex hydrologic systems.

Hydrological models are classified depending on how a model treats the randomness of the hydrological phenomena and spatial variation of the hydrological process. These classifications have been documented in several hydrological texts (Linsley *et al*., 1982; Chow *et al*., 1988; Shaw, 1996). One such classification of the hydrological models adopted from Chow *et al*. (1988) is shown in Figure 2.1.

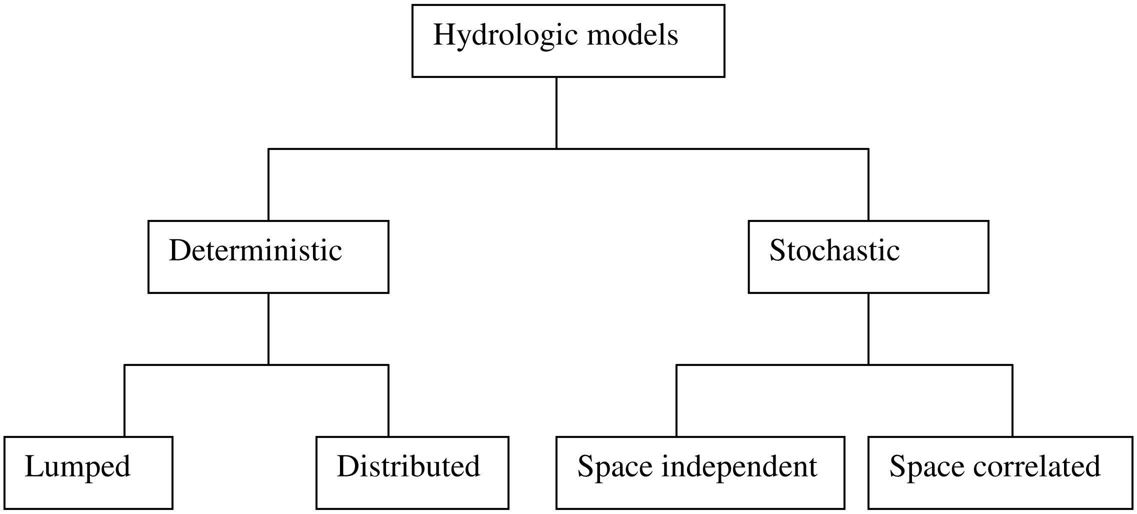

Figure 2.1: Classification of hydrological models.

Hydrologic models are broadly categorised into stochastic and deterministic models (Figure 2.1). The stochastic models are mathematical models of sequence of hydrologic variables governed by probability laws (Singh and Fiorentino, 1996). They are generally used for time rainfall-runoff analysis and have outputs that are at least random (Chow *et al*., 1988). On the other hand, the deterministic models seek to simulate part of the hydrologic cycle at a point (Freeze, 1978). Further more, deterministic models have physical and conceptual parameters and can be classified as lumped, semi distributed and distributed. Lumped models treat the whole catchment or a portion of it as if it was homogeneous in character and that it is subject to uniform rainfall (Latron and Gallart, 2007). These models do not consider the spatial variation of parameters and other hydrologic processes (Koka, 2004). However, lumped models are relatively simple and less complex in application (Singh and Fiorentino, 1996).

Distributed models account for spatial variation of hydrologic processes and parameters (Koka, 2004). They are important to compensate for the lack of extreme runoff data and provide a potentially powerful means for predicting the impacts of possible future changes in land use on river catchment response (Bathursta *et al*., 2004; Fleischbein *et al*., 2006). These models need in particular specific data on land use, soil types and their locations within the catchment (Mustafa *et al*., 2005). A truly distributed model is found only if the process can be described by an equation having an analytical solution (Singh and Fiorentino, 1996). Such models divide the catchment into a number of small homogeneous sub-catchments. Runoff for each subcatchment is simulated separately and then combined to obtain catchment response (Linsley *et al*., 1982). In principle they deal with the variations over a catchment more logically than the lumped models. However, unless the input rainfall is known with comparable details, the solution is no better than for the lumped models. Distributed models require a vast amount of data compared to lumped models and they are computationally very demanding and intensive. This problem of computation is no longer an issue due to the advent of computer technology. The semi-distributed model is in between the distributed and lumped models. They are less complex than distributed models.

2.4 Stream Flow Models

The stream flow model accounts in time continuously for all precipitation that falls on the catchment and the movement of water through the catchment to the outlet. In periods of no rainfall, stream flow models account for depletion of water stored in the catchment in various storage reservoirs. These models are physically based distributed parameter models that describe the major hydrologic processes governing water movement through the catchment (Maidment, 1993). The following section reviews some commonly used stream flow models.

2.4.1 Systeme Hydrologique Europeen (SHE)

SHE model (Abbot *et al.*, 1986) is a physically based distributed catchment parameter model. It considers the major processes that influence the flow of water through the catchment. The model simulates major hydrologic processes and can be applied to solve a variety of hydrologic problems such as rates of sediment transport and deposition (Singh, 1995). Application of this model is limited due to the large number of computation needed (Linsley *et al.*, 1982). Hence it was not considered in the present study.

2.4.2 River Catchment Flood Model (RBM-DOGGS)

The model is used to derive flood hydrographs from storm rainfall. The unit hydrographs are computed from recorded rainfall and runoff data from gauged catchments. For ungauged catchment, the unit hydrograph is computed from catchment characteristics (Shaw, 1996). To compute a flood hydrograph, particulars of storm rainfall must be selected and assessment of losses carried out. The model is a physically distributed model that simulates discharge by routing the flow down the sub reaches to the outlet. The model is event based, hence cannot be used for continuous stream flow simulation.

2.4.3 Precipitation-Runoff Modelling System (PRMS)

Precipitation-Runoff modelling system (PRMS) was developed to simulate catchment response over long periods of time. PRMS is a modular designed, physically based distributed model system simulating water fluxes and storages at the catchment scale. It evaluates the effects of various combination of precipitation, climate and land use on catchment response (Maidment, 1993). The model provides simulations on both daily and storm time scale by using variable time step.

2.4.4 Standford Watershed Model

Standford Watershed Model is one among the earliest models (Linsley *et al*., 1982). The model is used for continuous stream flow simulation. It needs a great deal of data to produce hourly river flows (stream flow) and requires more than twenty-five parameters. Some of these parameters may need quite a substantial period of time to be determined. For remote catchments where there are data shortages, regional values of the required inputs may be used. Due to the enormous amount of data required and that the model only simulates stream flow, thus this model was not selected for this research.

2.4.5 Topmodel

Topmodel (Beven *et al*., 1995) is a distributed model designed to simulate runoff from hill slopes and source areas of ungauged catchment of up to 500 km^2. It routes the runoff from different subcatchments down to the outlet producing a final catchment discharge. The model requires the computation of the frequency or spatial distribution of topographic index from topographic data, such as a Digital Elevation Model (Wolock and Price, 1994). It is flexible and incorporates the contributing area concept (Wolock and Price, 1994; Shaw, 1996). In addition, it is suitable for continuous simulation, but not single event isolated storms as was evident in the work done by Onyando (2000). Topmodel is not suitable for hortonian runoff and hence not suitable for upper Molo River catchment which experiences both hortonian and saturation excess flow.

2.4.6 Automated Geospatial Watershed Assessment Tool (AGWA)

Automated Geospatial Watershed Assessment Tool (AGWA) is a multipurpose hydrologic analysis system that can be used in catchment scale studies (Semmens *et al*., 2002). AGWA model has three components namely, the catchment delineation component, parameterisation component, component that writes the parameter files and that allows visualisation of simulation results. It provides the functionality to conduct all phases of catchment assessment for the two widely used models (Hernandez *et al*., 2005; Nedkov and Nikolova, 2006; Miller *et al*., 2006). These models are Soil and Water Assessment Tool (SWAT), and Kinematic Runoff and Erosion Model (KINEROS2). Both models provide insight into the response of the catchment to land cover and management change. They operate at different temporal and spatial scales, and can be applied in a range of environmental conditions to evaluate the impacts of land cover change on hydrologic and erosion response (Miller *et al*., 2006).

AGWA data requirements are: Digital elevation model, soils information, land cover and precipitation. These are used by the model in preparing input files for any of the models it supports. SWAT model in addition requires rainfall station coverage data for rainfall weighting, in case data from several gauging station is used.

AGWA model is an extension of Arc View, a geographical information system (GIS) software package. The GIS frame work is ideally suited for catchment based analysis, which relies heavily on landscape information for both deriving model input parameters and presenting the results. Previously, the model supported only the State Soil Geographic Database (STATSGO) and Soil Survey Geographic (SUSRGO) soil data. However, the new version can accommodate the Food and Agricultural Organisation (FAO) soil data. Therefore, for any given case study, there is no need to convert the FAO soil data into the US soil Taxonomy as was the case previously.

For instance, Baldyga (2005) used the model in Njoro catchment to simulate hydrologic response due to change in land use. In this case, techniques of converting the FAO soil data to the US taxonomy for it to be compatible with the model had to be developed. The results were quite satisfactory as the model performance was reasonably good. The Nash and Sutcliffe Efficiency was 0.7 and 0.9, therefore indicating that the simulated was approximating the observed stream flow. In other studies carried out elsewhere using the AGWA model, it was concluded that the results were particularly useful for assessing the effects of land cover change in the catchment and highlighting subcatchments that require careful management (Hernandez *et al*., 2003).

In a catchment where there is a large degree of spatial variability in topographic, soil and land cover characteristics, AGWA uses an area weighting scheme to determine an average value for each parameter within an up land model element (Miller *et al*., 2006). It also reduces the time needed for the estimation of the parameter models especially for SWAT which requires a lot of parameter values. SWAT and KINEROS2 component models supported by AGWA are reviewed in the subsequent sub-section.

2.4.7 **Kinematic Runoff and Erosion Model (KINEROS)**

Kinematic Runoff and Erosion Model (KINEROS) (Smith *et al*., 1995) is a physically-based model designed to simulate runoff and erosion for single storm events in small catchment of less than 100 km^2 (Semmens *et al*., 2002; Nedkov and Nikolova, 2006). It utilizes a network of planes to represent a catchment and kinematic wave method to route water off the catchment. The model is restricted to cover about 100 km^2 and is used for single event storms. Therefore it was not considered for application in the current study. However it is usually applied for critical areas that require immediate attention.

2.4.8 **Soil Water Assessment Tool (SWAT)**

Soil Water Assessment Tool (SWAT) (Arnold *et al*., 1994) was developed to predict the effect of alternative decisions on water, sediment and chemical yields with reasonable accuracy for ungauged catchments. It is a physical and empirical based distributed model operating on a daily time step (Sintondji, 2005; Miller *et al*., 2006; Bekele and Nicklow, 2007; Wu and Johnston, 2007; Schuol *et al*., 2008). The model is integrated and incorporates several interdependent catchment processes that are linked together and affect each other (Baldyga, 2005). It is capable of simulating spatial heterogeneity within a watershed and can provide spatially distributed outputs (Bekele and Nicklow, 2007; Schuol *et al*., 2008). Suitable for assessing land cover change impacts on catchment hydrologic response (Baldyga *et al*., 2004). It also allows the catchment to be divided into subcatchments based on unique land cover and vegetation changes (Wu and Johnston, 2007; Guo *et al*., 2008). This makes it possible to describe spatial heterogeneity in land cover and soil types within the catchment.

The model uses modified curve number approach, which is the core mechanism for determining excess rainfall (USDA-NRCS, 1986; Miller *et al*., 2006; Bekele and Nicklow, 2007; Ma *et al*., 2008). It can be used in ungauged catchments and hence allows evaluation of hydrologic changes resulting from land cover change in areas without gauges (Baldyga, *et al*., 2004). SWAT model is capable of simulating various hydrologic processes of a catchment such as runoff, stream flow and sediment yield, and transmission loss (Miller *et al*., 2006; Wu and Johnston, 2007). Therefore, SWAT model has been selected to assess the impact of land cover change in hydrologic catchment response in the present research.

2.5 Geographical Information System (GIS)

Geographical Information System (GIS) can be defined as a computer software designed specifically to manage large values of geocoded data derived from various sources (ESRI, 1995; Singh and Fiorentino, 1996). As opposed to other computer softwares, it is capable of performing sophisticated manipulation and provides a framework within which spatially distributed data are captured. The spatially distributed data are used to prepare model files and evaluate model results. Its capabilities are to accept, overlay, store and generate buffer around points (Maidment, 1993; Singh and Fiorentino, 1996; Scultz and Engman, 2000; Lim *et al*., 2005; Mustafa *et al*., 2005). GIS is used in hydrologic modelling to facilitate the processing, managing and interpretation of hydrological data. There are several GIS softwares in the market and each permit spatial data analysis. Some of these are: ILWIS, Arc View GIS, ERDAS and IDRISI. All these softwares are able to handle large quantities of raster and vector data, and they permit inter transfer of processed data. In addition GIS softwares can be used to merge remote sensed data with digital elevation data. However each component has a unique extension enabling it to manage and analyse certain types of raw and higher forms of spatial data. For instance, image processing in ILWIS, ERDAS and hydro extension in Arc View. These three GIS softwares were used in the current study since they were accessible and have the necessary extension to accomplish the study. In addition, AGWA is an extension of Arc View GIS. GIS also accounts for the spatial heterogeneity of the catchment in a statistical manner. This allows the models to account for the spatial heterogeneity of hydrologic variables within the catchment.

One of the most useful capabilities of GIS is the ability to describe the topography of a region (Singh and Fiorentino, 1996). This capability is used to develop Digital Elevation Model (DEM). A DEM is a digital representation of the elevation of a land surface. It is used to process ground elevation values measured at intersection of horizontal grid lines (Maidment, 1993). Gridded elevation data is a kind of raster data, which is an array of values measured at evenly spaced locations throughout an area. The DEM is required to generate streamlines, flow direction, flow accumulation, flow length, slope steepness and catchment boundary among other catchment attributes (Lim *et al*., 2005). The DEMs are important tools in hydrologic research and water resources. They have intrinsic geomorphologic features for simulation of important water flow processes such as runoff and infiltration (Våzquez and Feyen, 2007). The GIS based systems have greatly enhanced the capacity for researchers to develop and apply models due to the improved data management.

2.6 Remote Sensing Application in Land Use and Land Cover

Remote Sensing (RS) is the science and art of obtaining information about an object, area or phenomena through the analysis of data acquired by a sensor that is not in direct contact with the target of investigation (Townshed, 1981; Lo, 1986; Ritchie and Rango, 1996; Fashtali, 2003). RS deals with the acquisition, recording, processing and classification of data obtained through the electromagnetic radiation sensors. Sensing is taken to mean observation of the average value of a variable over some areal extent by examining the electromagnetic energy (Singh, 1995). The measurement techniques used are either passive or active. Passive measurement techniques determine the amount of reflected sunlight or the amount of natural emissions from the target at various wave lengths. Active measurement techniques direct artificially generated signal at a target and measure the reflected signal.

Prime objective of RS is to extract environmental and natural resource data related to the earth surface. It provides measurement of many hydrological variables used in hydrologic and environmental model applications comparable to traditional form of land use change detection. It also plays the role of surveying, inventorying and mapping of the environmental features. RS from various satellites in various spectral bands can provide information on catchment characteristics in a spatial and temporal domain (Scultz and Engman, 1996; Mustafa *et al*., 2005). In the current, study satellite imagery was used to define land cover in upper Molo River catchment, which was required to determine the catchment hydrologic response, in particular surface runoff and sediment yield. Land use is an important characteristic of the runoff process that affects infiltration, erosion and evapotranspiration (Mustafa *et al*., 2005). Thus almost any physically based hydrologic model uses some form of land use data or parameters based on these data. Distributed models in particular require specific data on land use and its location in the catchment (Maidment, 1993; Mustafa *et al*., 2005).

Remote sensing and GIS are increasingly becoming important tools in hydrology and water resources management. This is because data required in hydrological analysis can easily be obtained by using these tools. With the development of these techniques, the hydrological catchment models have become more physically based and distributed to enumerate various interactive hydrologic processes considering spatial heterogeneity.

CHAPTER THREE

MATERIAL AND METHODS

3.1 Study Area

3.1.1 Location

The upper Molo River catchment where the present study was carried out is part of the larger Lake Baringo catchment area. The study area covers approximately 528 km^2, lying to the west of Nakuru town (Figure 3.1). It is located within Latitude 0° 5´ S and 0° 25´ S, and longitude 35° 40´E and 35° 55´E. The area forms part of the Mau complex, which is an important water catchment in Kenya (Jenkins *et al.*, 2005). The elevation ranges from 1600 to 2400 m above mean sea level (a.m.s.l) and is drained by Molo River that has its outlet in Lake Baringo. It is in the humid zone, receiving rainfall of about 1100 mm to 2700 mm annually.

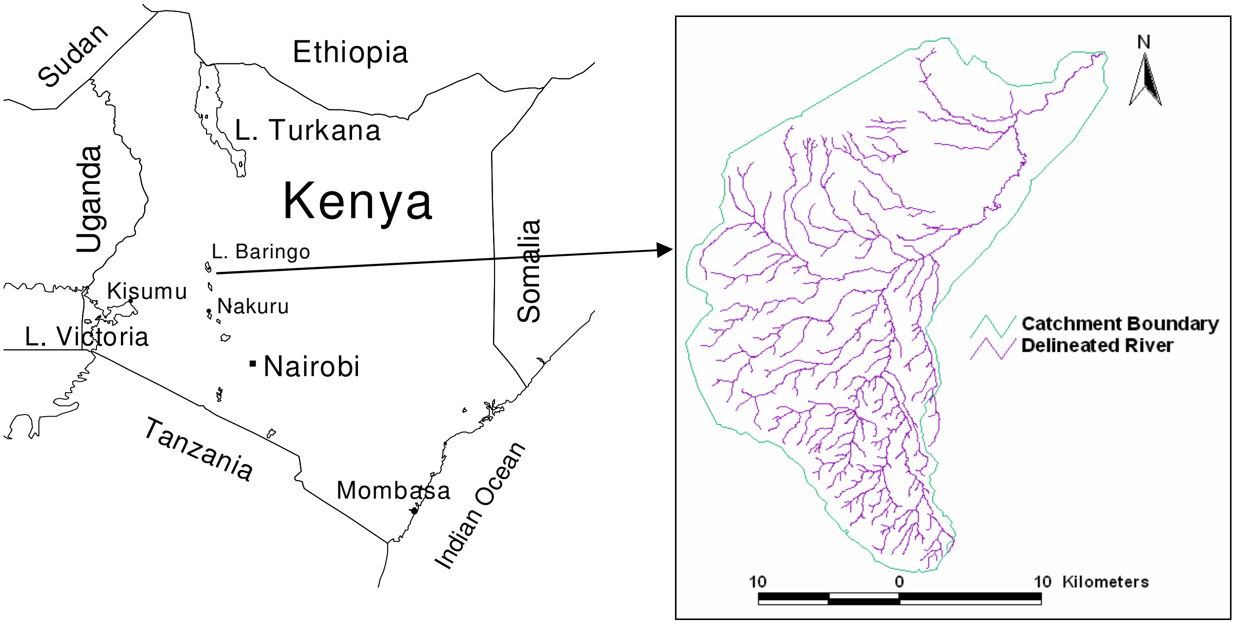

Figure 3.1: Map of Kenya showing the location of upper Molo River catchment

3.2 Data Acquisition and Processing

The data required for the study included: Geophysical and hydrologic data. Geophysical data were: topographic and soil survey maps, and satellite imagery. They were used to derive raster layers. The hydrologic data were precipitation and stream flow. Stream flow was acquired for calibration and validation of the model. Rainfall data was used as an input to simulate catchment hydrologic response.

3.2.1 Rainfall Data

Recorded daily rainfall data from weather stations within the catchment was obtained from Kenya Meteorological Department, Nairobi. The data used was from 1959 to 2003. Table 3.1 shows a summary of the data that was available for each station within the study area.

Table 3.1: Rainfall gauging stations

Station Name	Station ID	Data Duration
Elburgon Divisional Forest	9035237	1961 - 2003
Mau Summit	9035038	1959 - 1991
Molo Water Bailiff	9035266	1967 - 2001
Molo Pyrethrum	9035093	1959 - 1990
Gatheri Turi	9035099	1959 - 1975
Marioshoni Forest	9035117	1959 - 2003
Molo Forest	9035273	1969 - 2003

3.2.2 Estimating Missing Data

Transect survey was conducted to obtained the location of all the weather stations within the study area. Location of each station was georeferenced using the Global Positioning System (GPS) and a point map of the rainfall stations was prepared (Figure 3.2). The point map together with the unweighted rainfall data were used to estimate the missing rainfall data in an inbuilt algorithm scheme in Automated Geospatial Watershed Assessment tool (AGWA) discussed in section 2.4.6. This scheme estimates the missing data basing on those gauges that have data for the day of interest.

Rainfall data was prepared in the format accepted by the model. Unweighted rainfall data was used with the point map to obtain a spatial distributed rainfall data using Thiessen polygon method (Figure 3.2). Spatial distributed rainfall was utilized in writing the precipitation files as input for SWAT simulation.

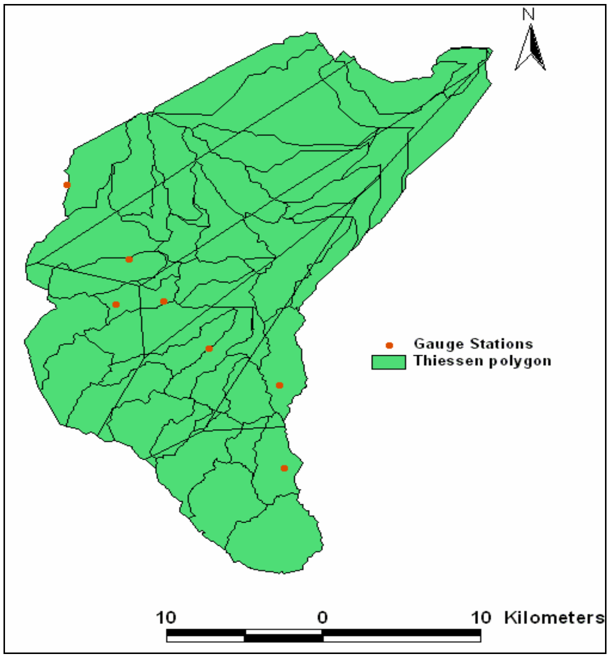

Figure 3.2: Rainfall Gauging stations and Thiessen polygon map

Figure 3.2 show the locations of the rainfall stations in upper Molo River catchment. They are mainly concentrated at the upper part of the catchment. In the lower part there was no rain gauge station therefore in developing the spatial rainfall distribution, it was assumed that the rainfall data from these gauges was representative.

3.2.3 Quality Data Analysis

Quality data analysis was carried out to ensure that the data used in the study were of good quality. Measured data is not error free, as it was noted by ASCE, (1993). During collection of data errors may be introduced in several ways such as: erroneous reading, recording, copying and by instrument defects (Shaw, 1996). Also errors may be introduced if the gauging station is moved to another location. Therefore any collected data need to be analysed and the necessary corrections done. The double mass curve was used in the present study to carry out homogeneity and consistency tests. Marioshoni station had complete rainfall data and therefore it was used as the base station in homogeneity and consistency tests. Table B1 in appendix B, shows the rainfall data that were used in double mass curve analysis.

3.2.4 Stream Flow Data

Stream flow data from the stream flow gauging station named (2EG02) at the outlet of the upper Molo River catchment was acquired from the Water Resources Management Authority (WRMA) regional office in Nakuru Town. The length of the data was from 1932 to 2000. This data was used in this study and it formed the basis for selection of the study area. To ascertain its reliability quality control was undertaken. This involved consistency test using single mass curve method.

3.2.5 Maps

The maps that were required for the study included the topographic and soil maps. They were obtained from Survey Department and Soil Survey Department of Kenya respectively. They were in 1:50000 and 1:1000000 scales respectively. Topographic maps were used in developing contour maps. The soil map was used in soil classification and obtaining soil characteristics for the study area.

3.2.6 Satellite Imagery

Satellite imagery was obtained from Regional Centre for Mapping and Resource Development (RCMRD). Satellite data were provided in CD-ROMS in a format supported by the Integrated Land and Water Information System (ILWIS) software and Arc view GIS. Each data contain several bands depending on the sensor used. All these were imported into the ILWIS software via geogateway method which is one of the methods used in ILWIS to import external data. Geogateway allows the program to access data in many geomatic file formats and convert them into ILWIS format. This made it possible for data to be viewed and be used in geoprocesing. Through geoprocessing the satellite imagery were used to determine and obtain the land cover thematic maps.

3.3 Geophysical Data Acquisition and Processing

3.3.1 Land Use and Land Cover Classification

Satellite data is affected by geometric distortions due to the sensor geometry, scanner and platform instability, earth rotation and earth curvature. Therefore pre-processing of the imagery is usually done by the producers to correct these distortions. The acquired format is therefore free from these distortions and can thus be processed to obtain land cover maps. Processing of satellite imagery involves; Image Enhancement, Georeferencing and Geocoding.

Image Enhancement is the process of making a raw image better interpretable for a particular application. This is the process of increasing the apparent distinction between the features in the scene (Feshtali, 2003). In this study, satellite image was loaded into ILWIS software and enhancement carried out. A contrast enhancement was carried out using linear stretching technique. Linear stretching is the act of extending the imagery to allow for easy identification of spatial features. For enhancing the specific data ranges for land cover types, the piece-wise linear contrast stretch technique was used in the present study (ITC ILWIS, 2001).

To allow for easy integration of different data layers in a GIS environment, georeferencing was done. Georeferencing is the process of establishing the relationship between row and column numbers, and real world coordinates. When an image is created either by a satellite, airborne scanner or office scanner, it is stored in row and column geometry in raster format which have no relation in anyway with the real world coordinates. Tie point technique which is a technique where the row/column numbers are specified so as to obtain a correct X, Y coordinate was applied. The process involved identifying same locations on the map and on the image. After specifying the tie points, projection transformation was carried out.

A distortion free image, after georeferencing was created by executing the transformation defined during georeferencing. This was possible through geocoding processing. Geocoding is a process of producing a new image in which the pixels are arranged in the geometry of the master image or map. Radiometric values of the image were found by resampling the image using the nearest neighbour interpolation method. This is an interpolation method in which the value for a pixel in the output image is determined by the value of the nearest pixel in the input image.

Image Classification

Image classification is the process of finding the relationship between land cover and measured reflection values on satellite imagery. Classification methods are divided into two categories; density slicing and multi-spectral classification. Density slicing is a technique, whereby the digital numbers distributed a long the horizontal axis of an image histogram are divided into a series of user defined intervals. It gives only reasonable results where digital number values of the land cover classes are not overlapping.

Multi-spectral classification extracts thematic information from satellite images in a semi-automatic way. This type of classification uses two techniques. These techniques are Unsupervised and Supervised classification. In Unsupervised classification, all pixels of an image are plotted in a feature space. The feature space is analyzed and grouped into clusters. Usually the user specifies the number of clusters and there is no knowledge about the thematic land cover class names. In supervised classification, the processed image is classified by defining land cover classes, sampling and land use/land cover classification. This technique was used in the current study, for there was need to get knowledge on the land cover class names.

In this study, the procedure used in the imagery classification was based on Earth Resources Data Analysis System (ERDAS Imagine 8.5) Field guide. The first stage in image classification was defining land use types of the study area. This was accomplished through conducting field survey and use of topographic maps. The land use types represented by the various classes were identified.

The second stage was sampling or training phase, where limited number of pixels were sampled and assigned the corresponding land use type. During the training, the sample statistics and the feature space were simultaneously displayed. The former contains the standard deviation of the samples. This value was checked when a sample was selected to ensure that it was kept to a minimum. Feature space showed the graphical distribution of the selected samples of any two bands. Pixels belonging to the same class and therefore representing the same land cover end up close to each other in the same feature space. It enabled judgement to be made where different classes can spectorally be distinguished and whether class corresponds to only one spectoral cluster.

The third stage involved land use classification, where the processed imagery was used to classify different land use/cover types within the catchment. The satellite imagery for 1986, 1995 and 2001 were used. Thematic land cover and land use maps for these images were prepared. Classification of different land use and their areal extent was accomplished through Gaussian Maximum likelihood Classifier. This technique is one of the decision algorithms used in supervised classification. It is known to produce the best results compared to other classifiers (Onyando, 2000; Mekonnen, 2005). The classifier assumes that the feature vectors of every land cover class are statistically distributed according to multivariate normal distribution density function (ITC ILWIS, 2001; Onyando *et al.*, 2005). Training samples were used to estimate the parameters of distribution.

3.3.2 Soil Information

Soil data is a significant component of the AGWA model. Soil classification data for this study was based on Food Agricultural Organization of the United Nation Version 3.6 (FAO/UNESCO, 1995) data. Soil types were already in the standard that is supported by the model. Soil texture for various soil types were derived from the soil map obtained from the Soil Survey Department of Kenya. The soil map for the study area was clipped using geoprocessing wizard in Arc view GIS. The map was clipped to entirely cover the generated catchment (Figure 3.3).

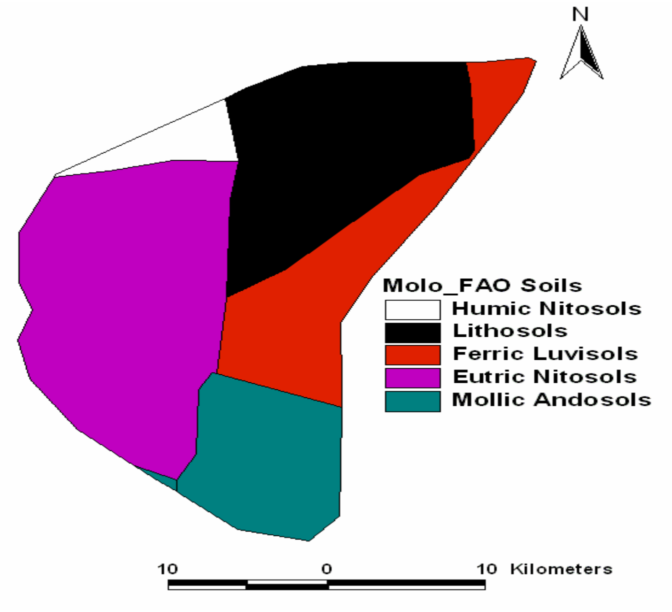

Figure 3.3: FAO soil units for upper Molo River catchment

3.3.2 Terrain Data Processing

Derivation of Contour Map

Digitised contours were used in developing Digital Elevation model which is one of the main inputs in AGWA model. In deriving the contour map, a number of steps were followed. The first step involved scanning the topographic maps. In this study, four topographic maps:

sheet numbers 118/1, 118/2, 118/3 and 118/4 of scale 1:50,000 were scanned and imported to ILWIS. They were georeferenced and glued to form one map. Glueing is a process of merging two or more maps into a single map. Merging required that the maps be compatible. An on-screen digitization was carried out to trace the contours. Map sheets 118/1 and 118/2 were in feet, therefore they were digitised separately from sheets 118/3 and 118/4 which were in metres. Digitisation was done over approximately bigger area to ensure complete coverage of the study area. Digitised contours were labelled using the topographic map sheets as reference. The two contour maps are shown in Figures (3.4 and 3.5) respectively.

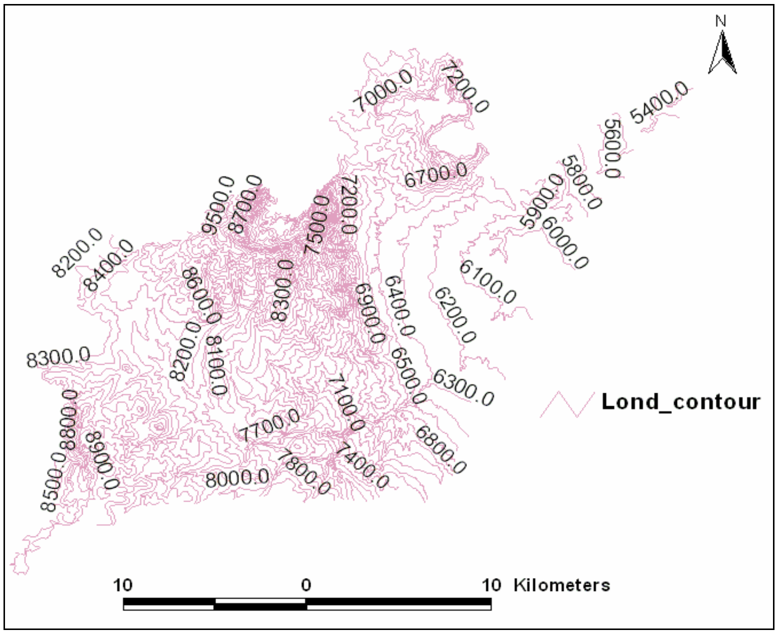

Figure 3.4: Londiani contour map

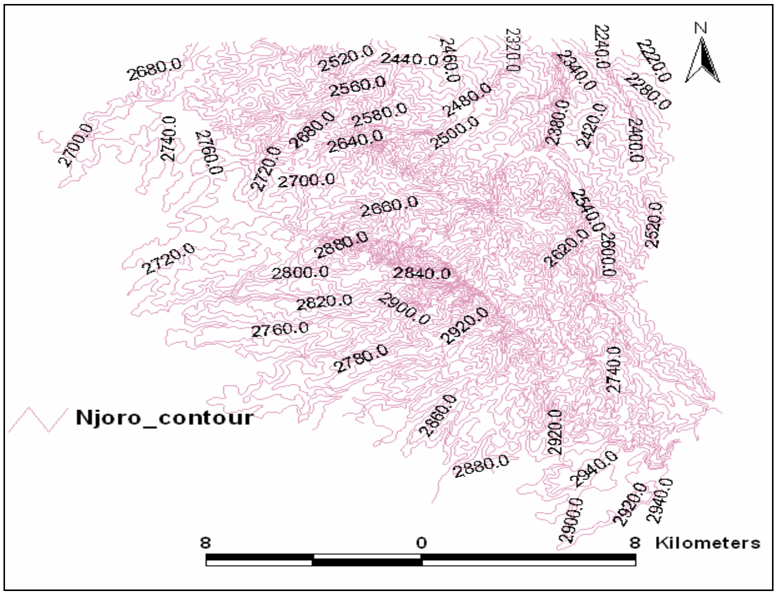

Figure 3.5: Njoro contour map

Generation of Digital Elevation Model (DEM)

DEM is a raster map showing the elevation of each point in the catchment. The main input in DEM generation was the digital contour map. Digitised Londiani and Njoro contour maps were exported as shape files into Arc view GIS platform. The maps were checked for correctness with respect to code consistency and ensured that they maintained their georeference.

In this study, the two digitised contour maps were used to generate the DEM. Generation of the DEM was done by first creating a Triangulated Irregular Network (TIN) for each contour map. It was achieved by following the guidelines in Arc View manual. TIN is an object used to represent the surface and is a specific storage structure of the surface data (ITC ILWIS, 2001). It partitions the surface into a set of contiguous, non overlapping triangles. A height value is recorded for each triangle node. TINs can accommodate irregularly distributed as well as selective data sets.

The Triangulated Irregular Network was converted into Grid (Raster) format. A Grid is partitioned into square cells and each cell stores a numeric data value. The Londiani DEM was converted from feet to metres and merged together with the Njoro DEM to form one complete DEM for upper Molo River catchment. The DEM was filled using the hydrologic filling routines inbuilt in Arc View to correct for any depression. Flow direction and Flow accumulation grids were generated from the DEM. Figures 3.6 and 3.7 below shows the Londiani and Njoro DEMs.

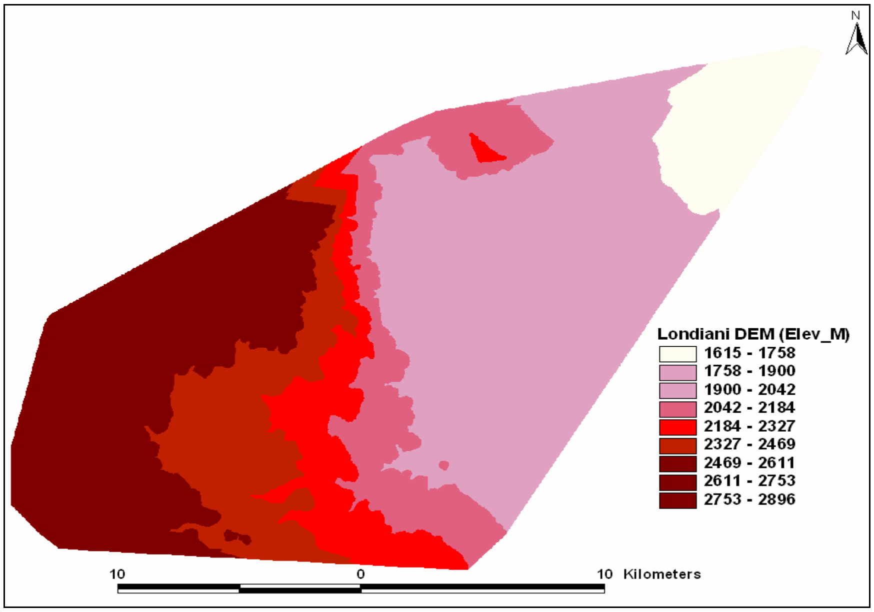

Figure 3.6: Londiani DEM

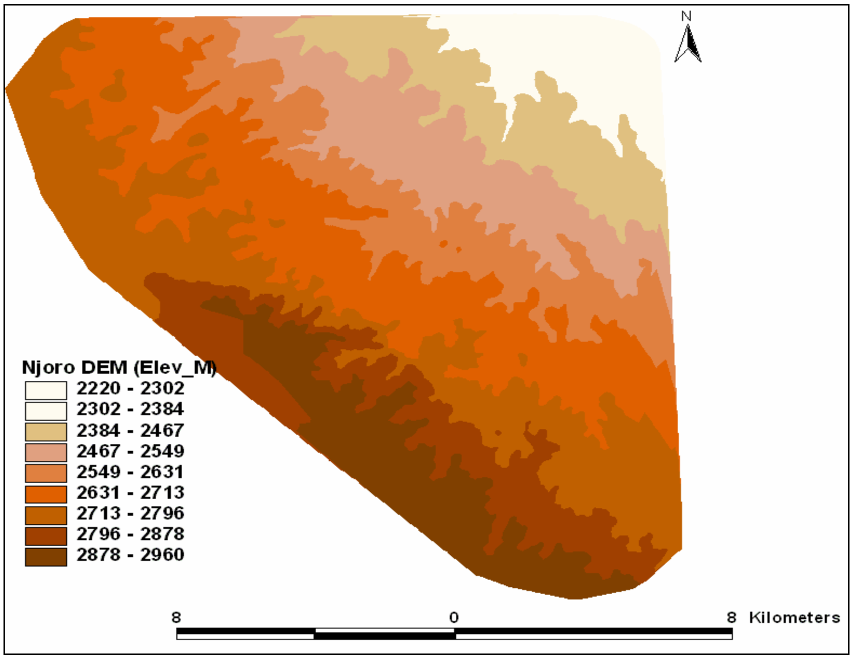

Figure 3.7: Njoro DEM

The merged DEM for upper Molo River catchment is shown in Figure 3.8

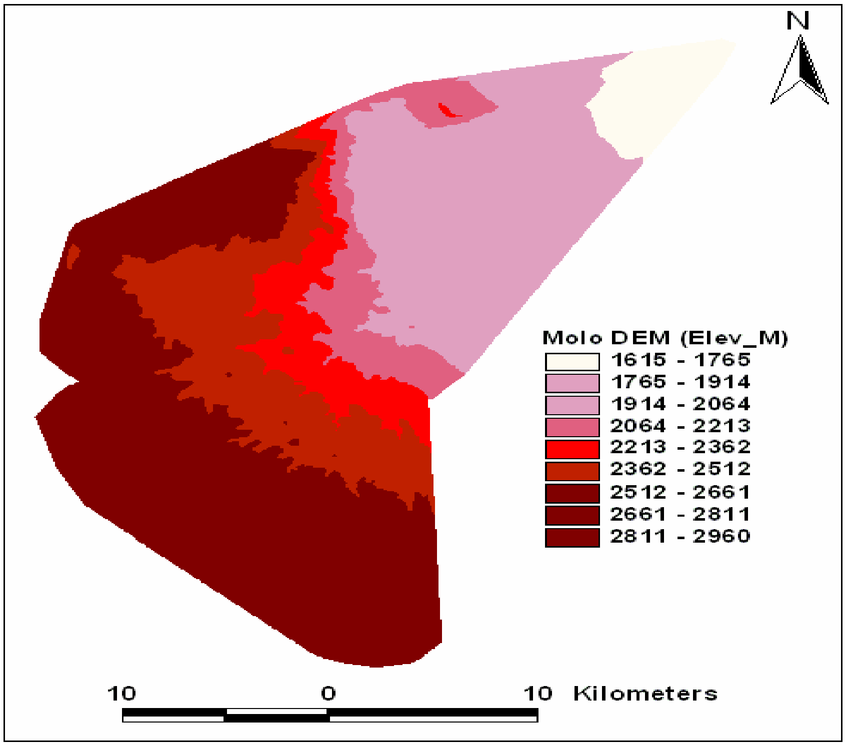

Figure 3.8: Merged Digital Elevation Model

Flow Direction

Flow direction is a raster map that shows the direction of runoff at every point through out the landscape. It allows determination of drainage areas, flow lengths and delineation of the catchment. Flow direction was derived using the D8 method. In D8 method, a pixel is potentially surrounded by eight pixels. The slope of each of these eight directions is calculated by taking the difference in elevation indicated by the DEM value at each of these neighbouring locations and the value at the pixel being examined. The difference in elevation is then divided by the centre to centre distance between two pixels. The direction that yields the steepest downhill slope is taken as the direction of runoff. Derived flow direction grid for upper Molo River catchment is shown in Figure 3.9.

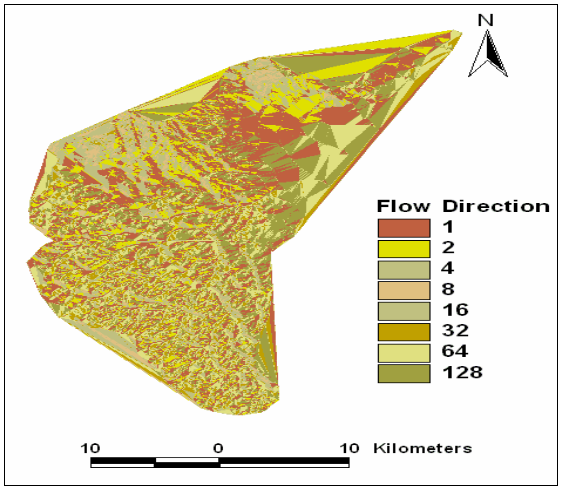

Figure 3.9: Flow Direction for upper Molo River catchment

Flow Accumulation

Flow accumulation is the raster map that represents accumulation of runoff throughout the study area. Using the flow direction, the flow accumulation at a given location was determined by following two rules. If the pixel had no neighbouring pixels, it was assigned the value of one and if the pixel was draining from neighbouring pixels, it was assigned the value of one plus the sum of flow accumulation draining from each of the neighbouring pixels. The flow accumulation map for upper Molo River catchment is shown in Figure 3.10.

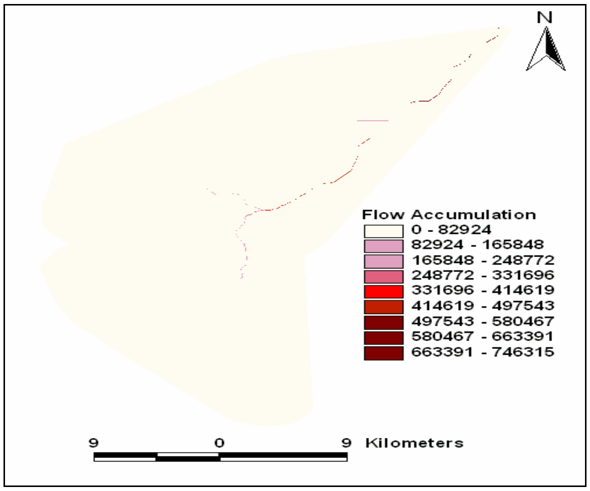

Figure 3.10: Flow Accumulation for upper Molo River Catchment

Stream Map

Another raster layer that was needed for catchment delineation was the stream network map. Stream map is a theme containing all the streams for a given DEM (Scott *et al.*, 2006). It represents all the cells in the DEM that receive runoff from a certain number of cells. The map was generated using algorithms in AGWA model. Threshold number of cells was set at 2500. This threshold is recommended for DEMs with a resolution of 30m (Scott *et al.*, 2006). These are the minimum number of cells contributing runoff to a given cell before it can be considered a stream. The stream map is a visual aid when locating an outlet for individual catchment. Generated stream map is shown in Figure 3.11.

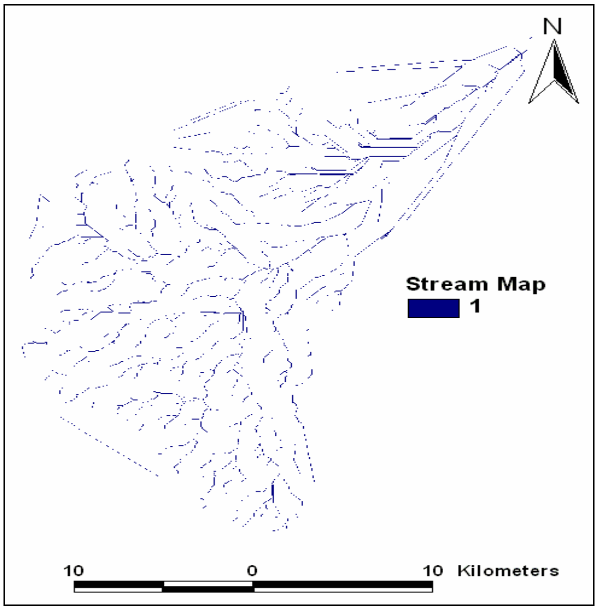

Figure 3.11: Generated stream map

Sub-Catchments

SWAT model required that the catchment be sub-divided into sub-units. AGWA model therefore was used to generate the sub-catchments by utilizing the watershed delineation and discretization component. Generated sub-catchments for upper Molo River catchment were 46 in number. The maximum flow length, area, slope, curve number and percent cover were calculated for each sub-basin (Table B2, appendix B). The generated sub-catchment map and stream network for upper Molo River catchment are shown in Figures (3.12 and 3.13). The stream network is a polyline shapefile representing the stream elements at the specified contributing source area for the catchment outline.

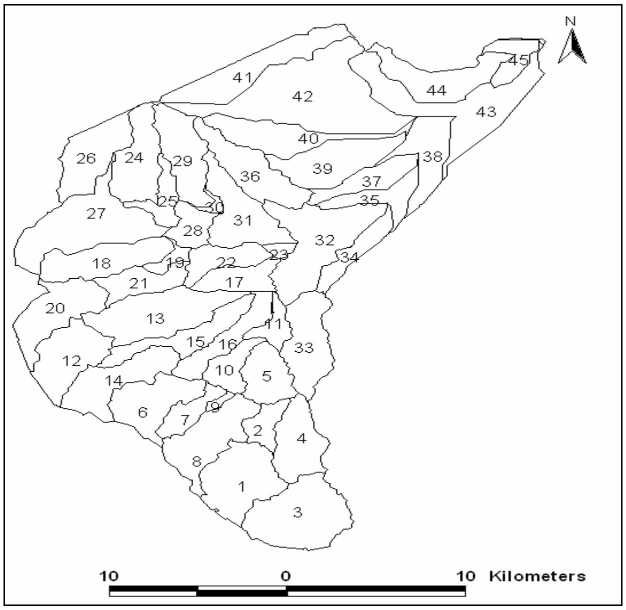

Figure 3.12: Generated sub-catchments

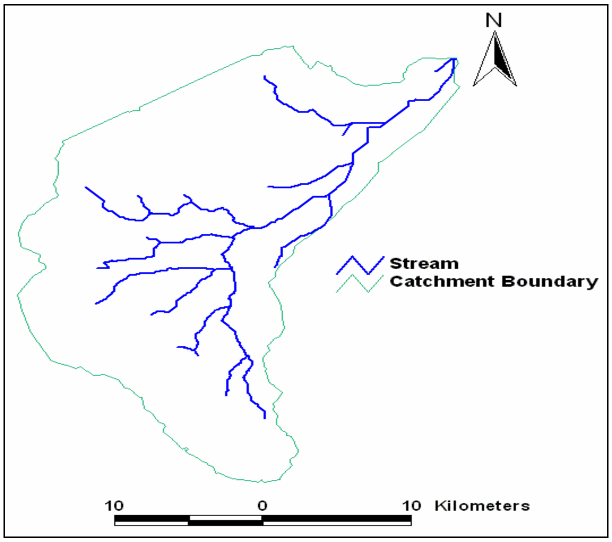

Figure 3.13: Generated stream network

3.4 Model Components and Parameters

Simulation of the surface runoff and sediment yield was done using (SWAT) model. The model is a component of Automated Watershed Assessment Tool (AGWA), which is a multipurpose hydrologic analysis system for use in catchment scale analysis (Semmens *et al.*, 2002). AGWA has a catchment delineating component, parameterisation component and result visualisation component for two models which it supports as discussed in section (2.4.6). The data required by this model are Digital Elevation Model (DEM), Land Cover data, Soils Data and Precipitation. The AGWA model was used to prepare input files for SWAT model.

3.4.1 Model Parameters

SWAT model as discussed under section 2.4.6 required several physical parameters, in addition to daily rainfall data. The files were prepared in AGWA and input into SWAT model for catchment hydrologic response simulation. Table 3.2 show the physical parameters of the SWAT model and their method of determination.

Table 3.2: Physical Parameters of the SWAT model

Parameters	Description	Determination
CN	Curve Number	Land use, Hydrologic group and soil type with the help of GIS
KS	Saturation Soil Conductivity	Soil type
HSG	Hydrologic Soil Group	Land use and soil type with the help of GIS
S	Soil water retention	Optimised from curve number
SL	Slope length	Derived from DEM
FD	Flow direction	Derived from DEM
FA	Flow Accumulation	Derived from DEM
Soil ID	Value of the soil ID field or dominant soil type	Derived from soil map
CV	Coefficient of variation of KS	Derived from soil
G	Net capillary drive	Derived from soil
Smax	Maximum relative soil saturation	Derived from soil
Kff	Soil erodibility factor	Derived from soil
Clay	Fractional clay content	Derived from soil
Silt	Fractional silt content	Derived from soil
Sand	Fractional sand content	Derived from soil

3.4.2 Geophysical Parameters

Curve Numbers

The curve number (CN) is a dimensionless index that describes runoff as a range between 1 and 100, with 100 indicating maximum runoff potential. CN is dependent on the hydrologic soil group cover complex of the catchment. This cover complex comprises the hydrologic soil group, land use and treatment condition. The curve numbers were assigned to each complex to indicate their specific runoff potential. CN values for the catchment ranged from 57 to 86 shown in Figure 3.14.

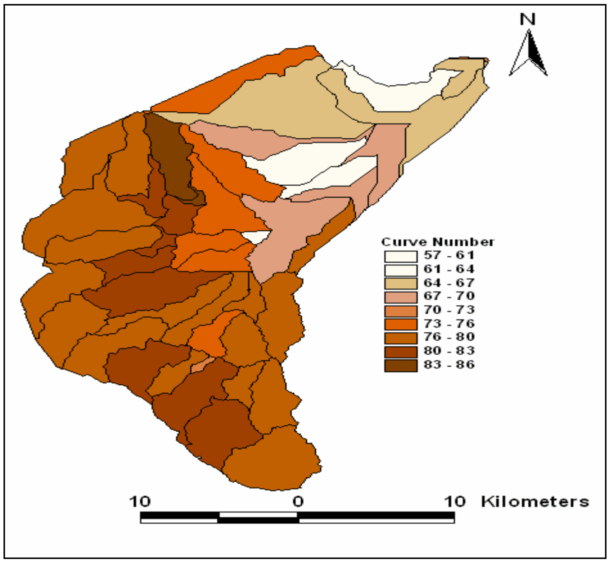

Figure 3.14: Spatial distribution of SCS-Curve Numbers

Hydraulic Conductivity

Hydraulic conductivity is the measure of the ability of the soil to transmit water and depends upon both the properties of the soil and the fluid. Figure 3.15 shows the spatial distribution of hydraulic conductivity over the study area. Each soil type under FAO classification has been assigned a hydraulic conductivity value. This was used in developing the hydraulic conductivity map.

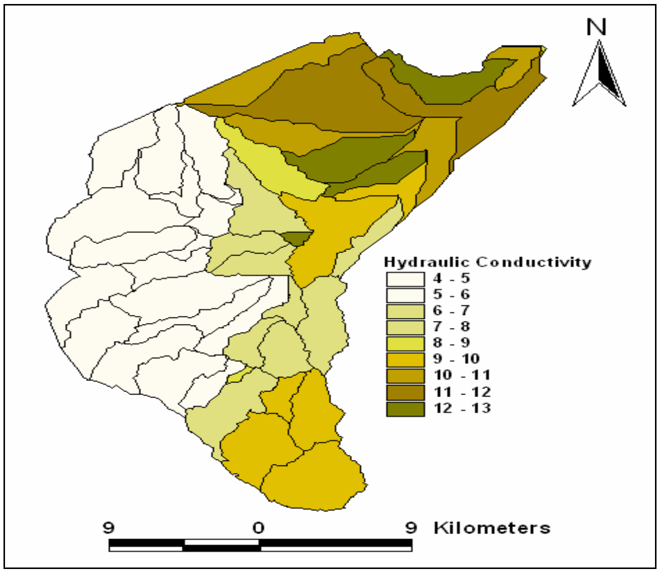

Figure 3.15: Spatial distribution of hydraulic conductivity

3.4.3 Conceptual model Parameters

The conceptual parameters of the SWAT model which needed to be determined to effect the simulations are baseflow factor, evaporation from groundwater coefficient and minimum depth in shallow aquifer. These parameters and their boundary conditions are shown in Table 3.3.

Table 3.3: Conceptual parameters for SWAT model

Parameter	Description	Minimum	Maximum
Alpha_BF	Baseflow alpha factor in days, which refers to groundwater flow response to recharge. When set to zero, there is no connection to groundwater (no return flow). Consequently when rainfall stops, the hydrographs falling limb immediately drops.	0	1
GWQmn	Depth of water in mm required in the shallow aquifer before return flow can occur.	0	4000
GW_Revap	'Revap' coefficient indicates how restricted water flow is from the shallow aquifer into the unsaturated zone to be taken up by plants.	0.02	0.2
Revapmn	This is the minimum depth in mm that must be present before water from shallow aquifer can percolate into the unsaturated zone or deep aquifer	0	3000

The boundary conditions express the minimum and maximum possible values of the parameters. The maximum values for GWQmn and Revapmn were determined based on trial tests. These two parameters are left to the discretion of the user to determine their values (Neitsch *et al.*, 2002). Trial tests indicated that beyond the maximum values indicated (Table 3.4) there were no significant changes in the simulations. They are intended to restrict the optimal parameters during model calibration.

3.4.4 Model Calibration and Validation

Models are used to represent hydrologic responses of the catchments and they enable studies of very complex problems. The reliability of the model results depend on the parameter estimation. SWAT model was developed for different catchment where the conditions and catchment parameters do not resemble the one for upper Molo River catchment. Thus there was need to determine conceptual parameters using data from the study catchment before undertaking the simulation.

Calibration and validation was carried out using the split sample method. Split sample is a method commonly used in determining model parameters and testing their validity. It involves dividing the data into two sets one for calibration and the other for validation. In the present study the data was divided into two decades basing on the available land cover maps and the data set. The first decade of data of 1980 to 1989 was used for calibration with land cover map of 1986 while the second decade for validation, 1991 to 2000, land cover of 1995 was used. In both cases of calibration and validation, it was assumed that there were no significant changes in land cover in a decade hence the use of one land cover map per decade.

Calibration was performed by comparing the simulated annual stream flows with the observed at the main catchment outlet 2EG01. SWAT model was run first using the default parameters set by AGWA and the adjustment within recommended ranges of maximum and minimum values. A number of simulations were run while iteratively adjusting the conceptual parameters to match the simulated flows with the observed flows. The process was carried out by changing one parameter while holding the others constant as simulation is done. During the calibration process the Nash and Sutcliffe efficiency (see section 3.4.5) whose value varies from less than zero for poor fit to one for perfect fit was used as an objective function. The parameter combination which gave the highest value of efficiency was taken as being representative of the catchment. These parameters were used for simulation in validation decade to verify their validity for use with other data sets within the same catchment.

Determination of key conceptual parameters was carried out through a process called sensitivity analysis. Sensitivity analysis is the process of determining the rate of change in model output with respect to changes in model parameters. It is a recommended step before calibration to identify key parameters and parameter precision (Moriasi *et al.*, 2007). The process was carried out by changing one parameter while holding the others constant. The parameters which were sensitive were chosen for calibration and for the less sensitive a mean was taken. The derived parameters are presented in section 4 (Table 4.3).

3.4.5 Model Performance Criteria

General model performance assessment involves comparing the simulated results and the observed ones using both statistical methods and visual observation through graphical display. There are several statistical techniques which have been recommended for use in assessing the model performance (Nash and Sutcliffe, 1970; ASCE, 1993; Moriasi *et al.*, 2007).

Statistical techniques that were used are Nash and Sutcliffe Efficiency (NS), and RMSE-observation Standard Deviation Ratio (RSR). The NS Efficiency is given as:

$$E = \frac{\sum_{i=1}^{n}(Q_o - Q_{av})^2 - \sum_{i=1}^{n}(Q_o - Q_s)^2}{\sum_{i=1}^{n}(Q_o - Q_{av})^2} \qquad (3.1)$$

Where, E is the Nash and Sutcliffe Efficiency, Q_o is the observed discharge, Q_{av} is the average observed discharge, Q_s is the simulated discharge.

Nash and Sutcliffe coefficient is a statistical method recommended by ASCE (1993) and is the most commonly used objective function for hydrologic studies (Shuol *et al.*, 2008). In addition, this method is preferred in the current study to index of agreement (d), because d is overly sensitive to extreme values due to the squared differences (Legates and McCabe, 1999). It expresses the proportion of the variance of the observed flows that can be accounted for by the model and provides a direct measure of the ability of the model to reproduce the observed flows. When $E = 1.0$, it indicates that the predicted flows are the same as the observed flows (Chemelil, 1995; Moriasi *et al.*, 2007). When $E = 0.5$ or less, it indicates that the model simulation does not correspond to the observed and there is no strong correlation between the observed and simulated flows. In other words it defines the relative percentage difference between the average simulation and measured data time series over any given n time steps (Tolson and Shoemaker, 2007).

RSR standardises the Root Mean Square Error (RMSE) using the standard deviation. RMSE is one of the commonly used error index statistics. RSR is calculated as a ratio of RMSE and standard deviation of the measured data as shown in equation 3.2.

$$RSR = \frac{RMSE}{STDEV_{obs.}} = \frac{\left[\sqrt{\sum_{i=1}^{n}(Q_o - Q_s)^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}(Q_o - Q_{av})^2}\right]} \tag{3.2}$$

RSR incorporates the benefits of error index statistics and includes a normalization factor. The RSR varies from the optimal value of 0, which indicates zero RMSE or residual variation and therefore perfect model simulation. It was used in current study to test and ascertain that the model simulated the catchment response with low residual errors.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Land Use and Land Cover Change

The land cover types for upper Molo River catchment were clustered and grouped into five predominant groups: Settlement, Riparian vegetation, Agricultural land, Scrubs and Forest. Land cover maps obtained were for 1986, 1995 and 2001 Figures (4.1, 4.2 and 4.3).

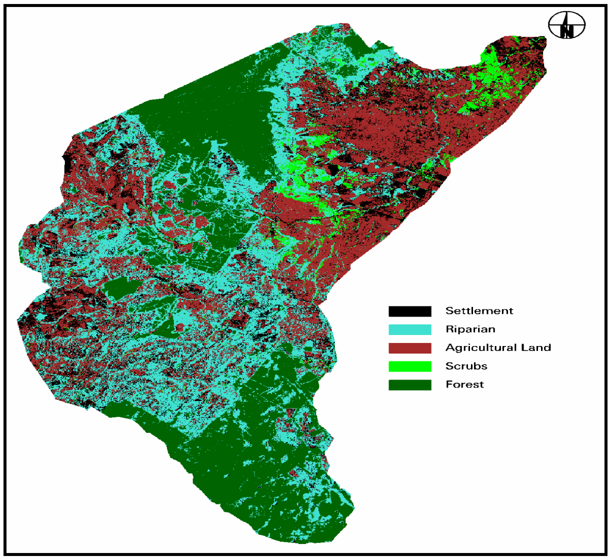

Figure 4.1: Land cover map for 28th January 1986

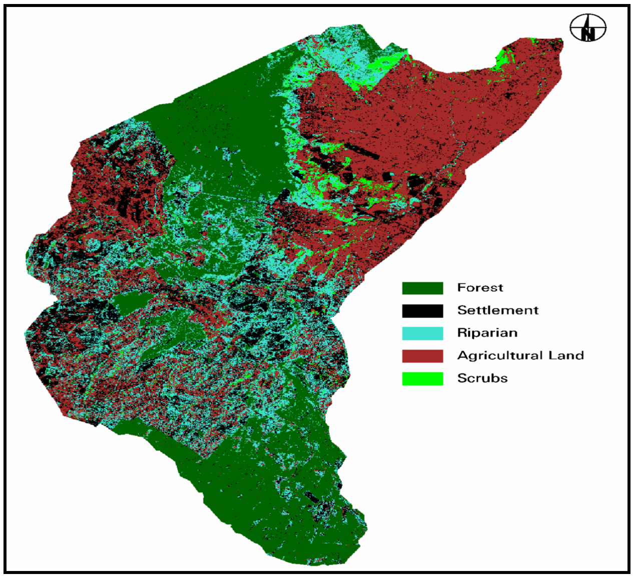

Figure 4.2: Land cover map for 21st January 1995

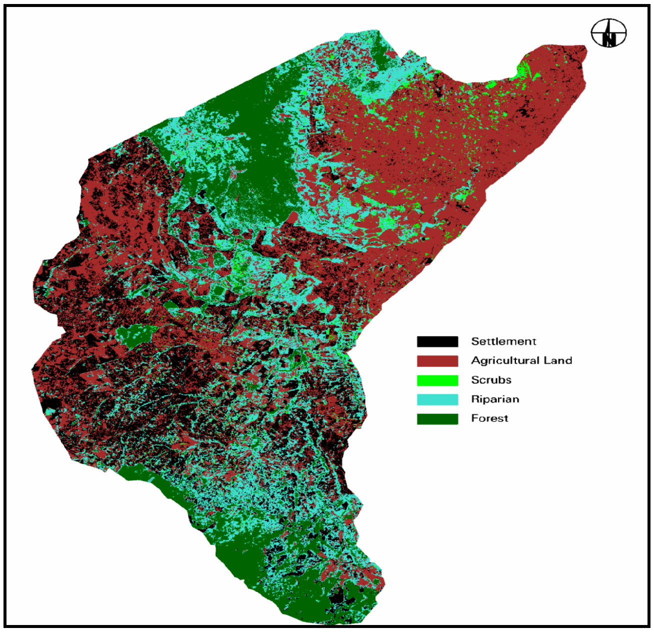

Figure 4.3: Land cover map for 3rd April 2001

Land cover map for 1986 indicates that the settlement, riparian, agricultural land, scrubs and forest cover; 31.06, 14.06 23.97, 27.4 and 3.4 percent respectively. Results show that forest cover decreased by 48.0% in the period 1986 to 2001. Agricultural land increased from 27.4% to 41.0% between 1986 and 2001. Settlement increase from 14.6% to 21.5% and riparian reduced from 23.4% to 18.6% within the same period. There was no significant change in percentage cover for scrub land. Table 4.1 shows the percentage land cover for each class.

Table 4.1: Percentage cover

Year	1986	1995	2001
Forest	31.06	27.5	16
Settlement	14.06	20.1	21.5
Riparian	23.4	18.7	18.6
Agricultural Land	27.4	30.8	41
Scrubs	3.4	3	2.9

4.2 Quality Data Analysis

Double Mass Curve (DMC)

Cumulative daily rainfall data for seven stations within the catchment were used (Table B1, appendix B1) in developing double mass curve. Double mass curve technique investigated whether the collected rainfall data were homogenous and consistent through the selected period of study and reveal if correction was needed.

Figure 4.1 show that rainfall data were homogenous and consistent since a straight-line plot through multiple regression analysis was obtained.

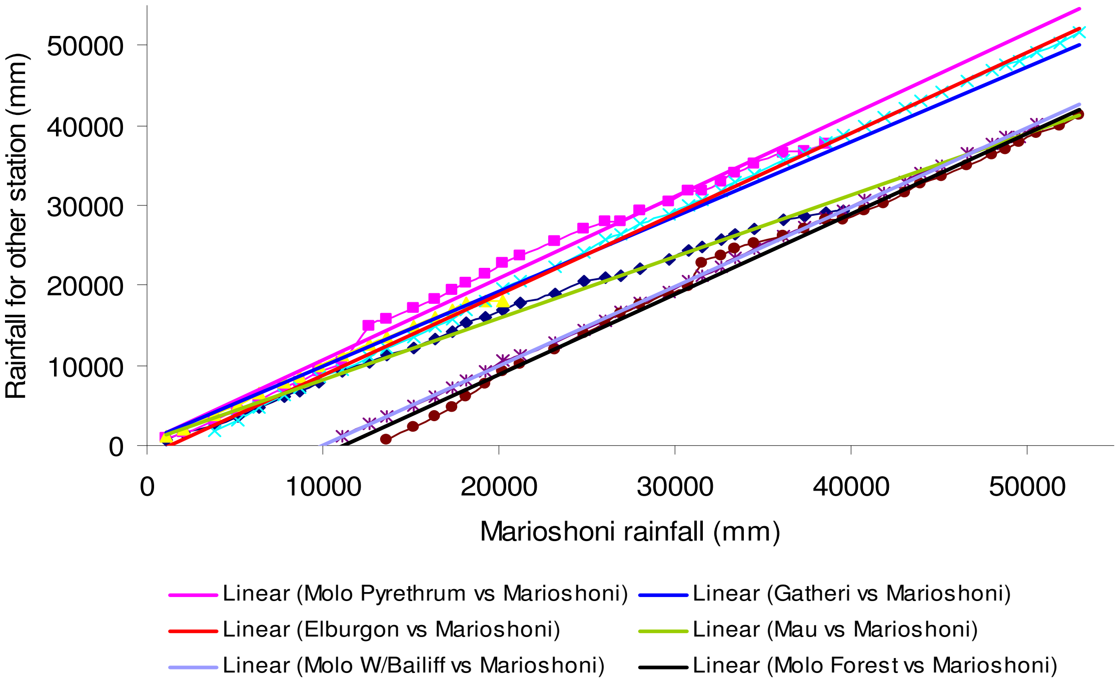

Figure 4.4: Daily annual rainfall double mass curve

Coefficient of determination (R^2) of 0.99 shown in Table 4.1, which is close to unity and the positive gradient confirms the good quality data (Chemelil and Smout, 2000; Mwetu, 2004; Albert, 2004). The results also show that the stations received almost equal rainfall for the curves are fairly closer to each other. Rainfall data for other six stations which were plotted against Marioshoni in Table 3.2 had very strong relationship since R^2 approached unity.

Table 4.2: Gradient and coefficient of determination of double mass curve

Rainfall Gauging Station	DMC Gradient	R^2
Molo Pyrethrum vs Marioshoni	+1.021	0.9889
Gatheri vs Marioshoni	+0.938	0.9942
Elburgon vs Marioshoni	+1.010	0.9993
Mau vs Marioshoni	+0.771	0.9957
Molo W/Bailiff vs Marioshoni	+0.989	0.9997
Molo Forest vs Marioshoni	+1.006	0.9925

The positive gradient in all the stations revealed that the data were of the same kind and frequency (Albert, 2004). Therefore it can be concluded that the data were homogenous and of good quality for use.

Single Mass curve

The cumulative stream flow was used to plot single mass curve against time.

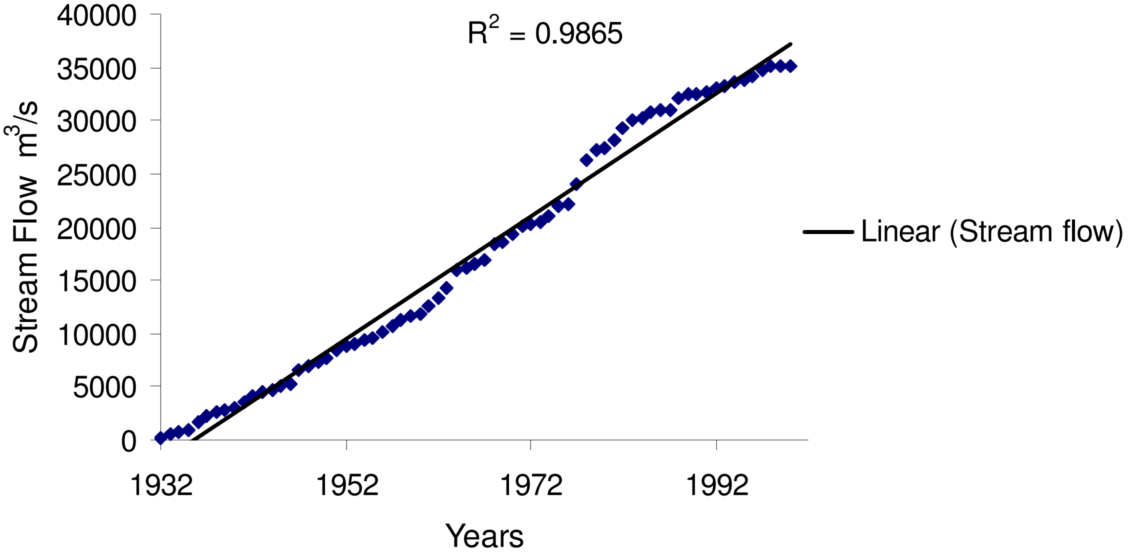

Figure 4.5: Daily annual streamflow single mass curve

Figure 4.5 shows that the stream flow data were consistent, as the plot forms a straight line. Therefore the stream flow data was of good quality and was used in calibration and validation of the SWAT model.

4.3: Surface Runoff

Surface runoff for calibration and validation periods were simulated. The average depths per year were 1274 mm and 1444 mm for calibration and validation respectively. Figures 4.6 and 4.7 show the simulated surface runoff for calibration and validation.

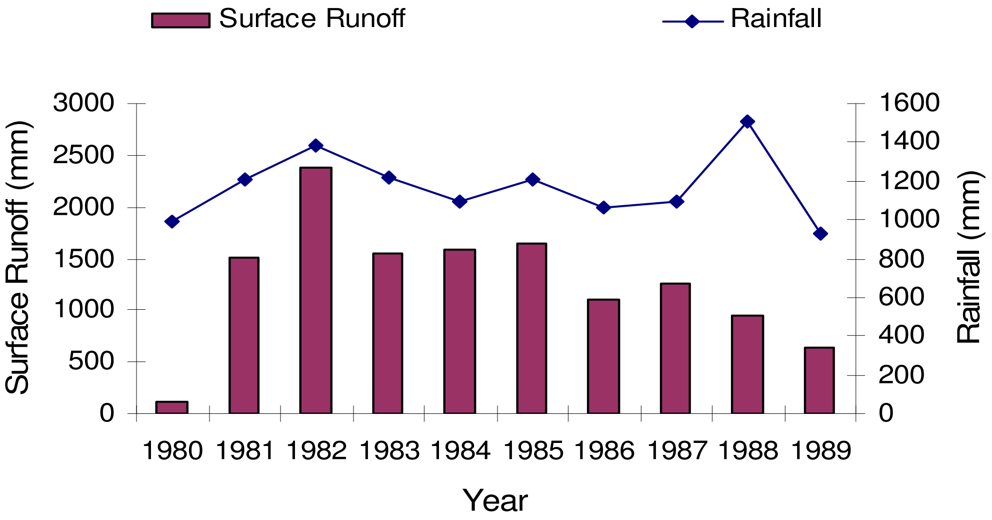

Figure 4.6: Simulated surface runoff for the period 1980 to 1989

Figure 4.6 shows that there was high surface runoff for 1982 which agrees well with the average increase in rainfall received in the catchment for that year. In 1980 there was low surface runoff due to low rainfall as shown in the rainfall curve. In Figure 4.6 the surface runoff and rainfall followed the same trend. In 1988 there was high rainfall, but low surface runoff was simulated, this could be attributed to error in simulation. In Figure 4.7 the chart shows that the surface runoff and rainfall follow the same trend.

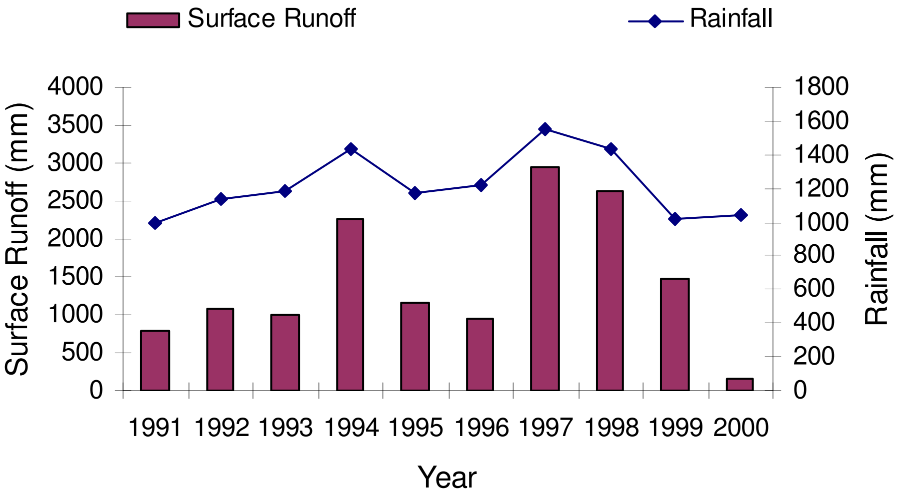

Figure 4.7: Simulated surface runoff for period 1991 to 2000

In the two periods of simulation there was an increase in surface runoff of 13.3%. The result agrees closely with the work done by Li *et al*. (2007). It was concluded that total deforestation to agriculture increases runoff by ratio from 0.15 to 0.44. There was no total deforestation to agriculture in the current study. Another reason is that in some of the areas converted from forest, the land was used for agriculture with some conservation principles being applied. This retards flow of water and consequently increase infiltration while at the same time reducing surface runoff. These results indicate that the model suitably simulated the surface runoff trends for both decades satisfactorily.

4.4: Sediment Yield

SWAT model was used to predict the amount of sediment for calibration and validation periods. The average sediment yield at the outlet for the period 1980 to 1989 was 1.5 t/ha. Figure 4.8 shows the simulated sediment yield for the calibration period 1980 to 1989. For validation period the average simulated sediment yield was 2.7 t/ha shown in Figure 4.9.

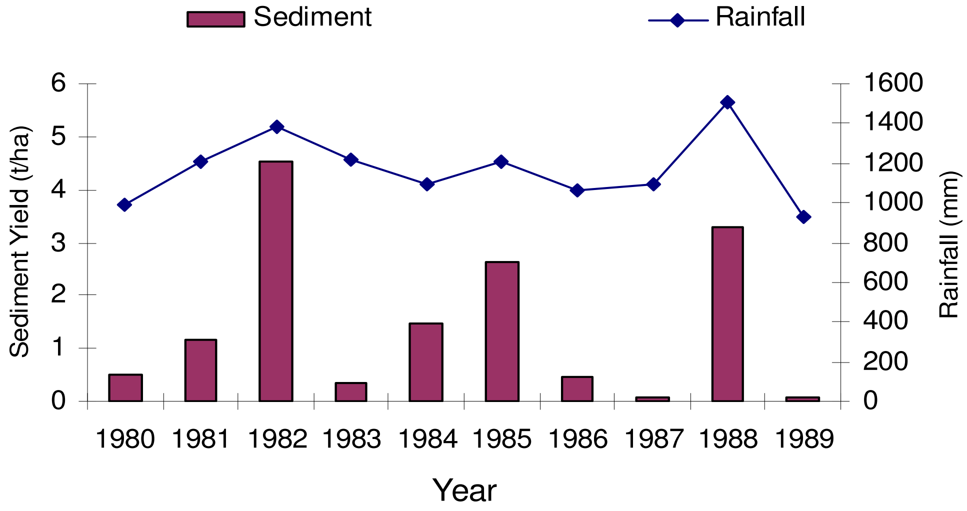

Figure 4.8: Simulated sediment yield for the period 1980 to 1989

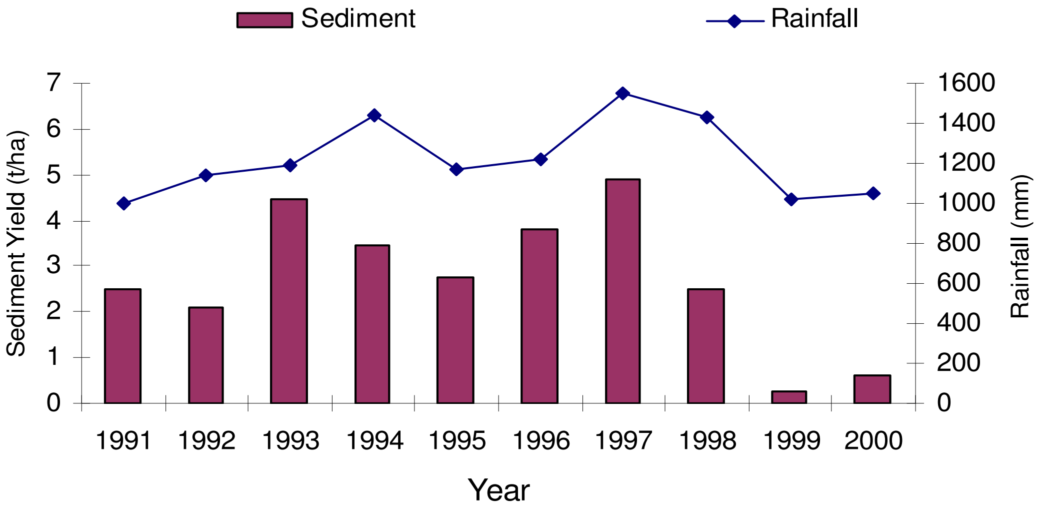

Figure 4.9: Simulated sediment yield for the period 1991 to 2000

The increase in sediment yield from an average of 1.5 t/ha in calibration period to 2.7 t/ha in validation indicates the effect of land use change. Brown *et al.* (2005) concluded that due to deforestation there is bound to be a resultant change in catchment response. This agrees with the work done by Festhali (2003) in Sar-chi catchment, the report was that there was an increase of 94% sediment yield due to land use change to agriculture. Cultivation was carried out up and down the slope instead of following the contours. In this case therefore it increased the soil erosion from the hill slope where the protection cover was disturbed. In the current study the increase in sediment was 1.2t/ha.

Okelo *et al*. (2005) carried out a study on effects of various land use treatment on soil loss and reported 86g/m^2 soil erosion in agricultural land and 31g/m^2 for deforested land, the other land uses had low soil losses. This indicates that agricultural land contributes high soil loss almost twice to deforested land. They used a mini simulator which could not perfectly represent the natural rainfall conditions, therefore the results can not fully be compared to the current study. However it gives knowledge on the effects of various land uses on soil losses.

Deforestation to agriculture without proper soil conservation measures put in place result in accelerated soil loss and high sediment yield (Maidment, 1993). Soil conservation and proper land cultivation leads to minimal soil erosion. Therefore the low sediment yield in the current study is acceptable, since the upper site where it experienced deforestation, cultivation was done along the contours as oppose to up and down hill.

4.5: Streamflow Simulation

Calibration Decade

Calibration was carried out for a decade from 1980 to 1989 and the land cover map for 1986 was used for catchment parameterisation. Conceptual parameters were varied several times while simulating until flows which gave high NS and low RSR were achieved. This was done to ensure that simulated results closely matched the observed values. The results show a good correlation between the predicted and observed flows (Figure 4.10). The calculated Nash Sutcliffe coefficient (NS) and RMSE-observation Standard Deviation Ratio (RSR) were 0.87 and 0.35 respectively. The NS coefficient approached unity indicating that the predicted and the observed discharge have a good correlation and the model can fairly simulate the catchment response. The RSR approached zero showing that the root mean square errors are minimal and therefore the model can satisfactorily simulate the catchment response with reasonable accuracy. A value of 0.35 is within a very good range of model performance according to Moriasi *et al*. (2007). Thus RSR value indicates that the model can be applied to simulate catchment response in the study catchment. The three performance criteria indicate that the conceptual parameters modified during calibration represented the catchment hydrologic response. The optimised conceptual parameters are presented in Table 4.3.

Table 4.3: Conceptual parameters obtained through calibration

Parameter	Description	Final
Alpha_BF	Baseflow alpha factor in days, which refers to groundwater flow response to recharge. When set to zero, there is no connection to groundwater (no return flow). Consequently when rainfall stops, the hydrographs falling limb immediately drops.	0.6
GWQmn	Depth of water in mm required in the shallow aquifer before return flow can occur.	3000
GW_Revap	'Revap' coefficient indicates how restricted water flow is from the shallow aquifer into the unsaturated zone to be taken up by plants.	0.14
Revapmn	This the minimum depth in mm that must be present before water from shallow aquifer can percolate into the unsaturated zone or deep aquifer	2500

The predicted discharges using the optimised parameters are shown in Figure 4.10. Also shown in the same Figure are the observed discharges. Apart from the magnitudes, the trend of the streamflow is also reasonably predicted by the model.

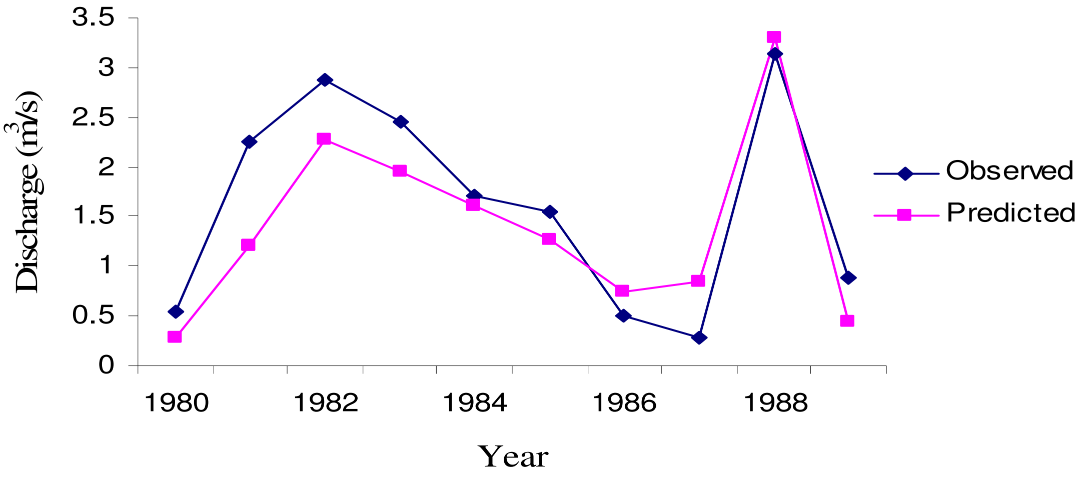

Figure 4.10: Simulated and observed discharges for the calibration

Validation Decade

Model validation was carried out for the period 1991 to 2000 and 1995 land cover grid was used for catchment land cover parameterisation. Validation results indicate that the model is capable of fairly predicting the catchment response. Figure 4.11 indicates that the model under predicted the flows except for 1999 and 2000. The calculated Nash and Sutcliffe efficiency and RSR error index were 0.723 and 0.53 respectively. The NS coefficient shows that the model can predict the catchment response with acceptable accuracy. However, the performance is slightly lower than that for calibration. This agrees well with the case study reported by Moriasi *et al.* (2007). In their work the calibration results showed a better match than validation. Regardless of the low performance during validation, the results indicate that the model could with fair accuracy simulate the catchment hydrologic response. The graphs for validation results for the study area are shown in Figure 4.11.

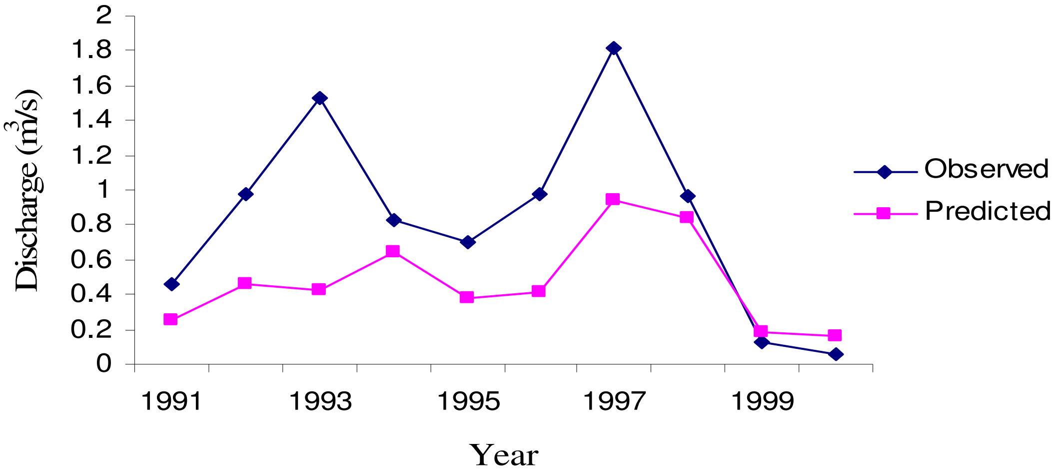

Figure 4.11: Simulated and observed discharges for the validation

The results indicate that the estimation of discharge were reasonable in terms of trends but under predicted with regard to magnitude. Although the magnitude of under-prediction was consistently low, the value of Nash and Sutcliffe efficiency of 0.72 shows that the results are within acceptable range, since it approached unity.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Upper Molo River catchment has experienced rapid land use and land cover changes. The study shows that forest was reduced by about 48% to agricultural land which increased from 27.4% to 41% and settlement from 14.6% to 21.5% in the period between 1986 and 2001 with significant change noted to have occurred in the period between 1995 and 2001.

SWAT model inbuilt in AGWA was capable of simulating the catchment response to a reasonable degree. Nash and Sutcliffe calculated coefficients for calibration and validation were 0.87 and 0.72 respectively and RSR index error values were 0.35 and 0.53 respectively. The results show that the predicted discharge closely matches the observed discharge and that there is a strong positive correlation between the predicted and the observed discharge. RSR index error indicates that the model performance during calibration was better than during validation which was expected because the calibration decade had a different data set. The low values of RSR obtained show that the Root mean square errors were kept at minimal. Therefore it can be concluded that SWAT model using the identified parameters could fairly simulate the catchment hydrologic response for the study area.

There was an average increase in sediment yield of 1.2 t/ha for the periods 1980 to 1989 and 1991 to 2000, respectively. The increase would suggest that there was change in hydrologic response caused by the clearing of the forest to agriculture and settlement in the catchment. Surface runoff increased by 13.3% due to the change in land use. In the catchment, soil conservation measures were undertaken which helped to reduce surface runoff and consequently sediment yield. Also as found in literature review, the change of forest to agriculture of less than 48% if well managed as was found in the present study does not alter much both sediment yield and surface runoff at catchment scale.

In conclusion, it can be stated that the present study demonstrated that analysis of impact of land use and land cover change on hydrologic response of a catchment requires such times spans with more than 48 % land cover change if such changes are to be detected at catchment scale. Also through modelling, it is possible to simulate the magnitude as well as the trend in both surface runoff and sediment yield in conformity with the rainfall trends. The use of

GIS and remote sensing is noted as being key in providing the spatial distribution of catchment responses and subsequently ensuring effectiveness in management interventions.

5.2 Recommendations

Based on the results of the study and the conclusions thereof, the following recommendations are made.

- Investigations on impact of land use change on catchment response be carried out for a period of more than three decades. During this period, chances of land use and land cover changes being manifested at macro-scale are high as the change would be significant depending on the activities.
- The use of models in simulating catchment response should encompass extensive application of GIS and remote sensing. These tools will ensure that geophysical parameters of the catchment are effectively incorporated in the simulation. Consequently the simulation results and the parameters both physical and conceptual will be unique for the catchment under study.

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APPENDICES

Appendix A (Figures)

Figure A1: Cleared forest near Marioshoni centre in the study area

Figure A2: Level of water during the rainy season at 2EG01 gauging station

Figure A3: Level of water during dry period at the gauging station 2EG01

Figure A4: Stream flow with high sediment at 2EG01 gauging station

Figure A5: Section of the weir swept away by the floods at 2EG01 gauging station

Figure A6: Remaining section of the weir at the catchment outlet 2EG01

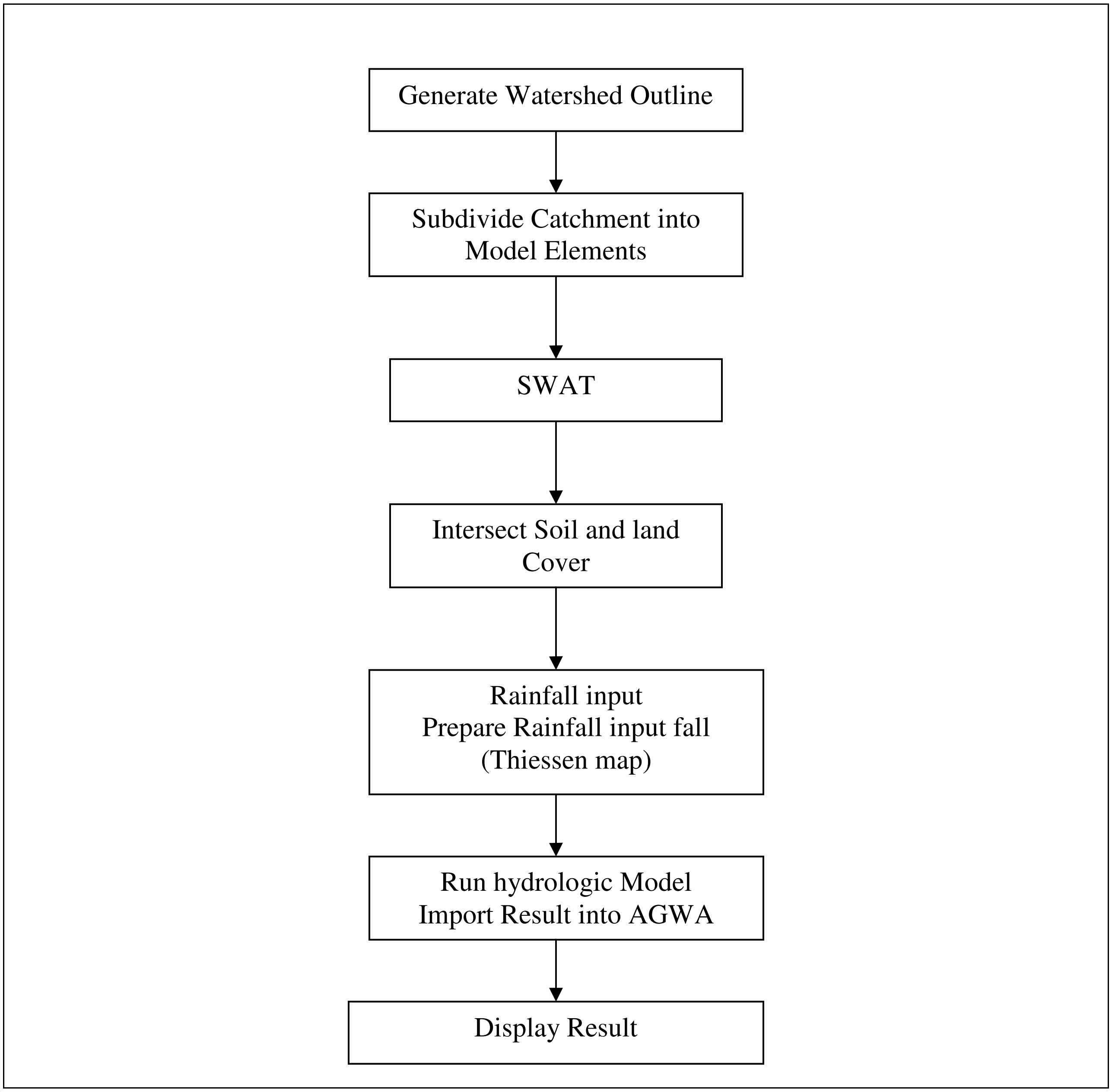

Figure A7: Schematic diagram of hydrologic AGWA simulation

Appendix B (Tables)

Table B1: Annual Rainfall Data (mm)

Year	Marioshoni	Mau	Molo Pyrethrum	Gatheri	Elburgon	Molo W/Bailif	Molo Forest
1959	1150	684.6	817.3	1049.2	_	_	_
1960	2047.3	1524.3	1636.6	2061.9	_	_	_
1961	3828.2	2545.9	3110.1	3819.5	1796.1	_	_
1962	5171.2	3604.2	4209.3	5028.9	3213.9	_	_
1963	6409.5	4833.4	5662.1	6573.4	4786.9	_	_
1964	7804.3	6139.6	7230.8	7878	6250.1	_	_
1965	8644	6852.6	7991.4	8661.4	7132.5	_	_
1966	9806.4	7914.8	9175.3	9945.5	8500.8	_	_
1967	11082.6	9192.7	10349.7	11235.8	9535.9	1187.7	_
1968	12666.6	10362.7	14854.3	12565.7	11123.4	2694	_
1969	13617.5	11167.8	15742.6	13431.3	12111.2	3666.3	686.3
1970	15134.9	12254.7	17174.1	14866.2	13599.1	5039.5	2364.8
1971	16368.8	13324.6	18308.1	16061.9	14823.1	6137.4	3574.9
1972	17419.7	14276.3	19402.2	16973.4	15831.6	7147.4	4771.9
1973	18171.3	15274.3	20382.9	17854.7	16829.1	8090.2	6037.9
1974	19291.6	16018.7	21523.9	18095.1	18144.6	9336.2	7569.8
1975	20273.6	16872.8	22815.1	18128.2	19500.8	10485.8	9353
1976	21256.4	17732.3	23653.6	_	20559.3	11369.3	10232
1977	23212.9	19015.8	25410.3	_	22426.1	12917.9	12004.3
1978	24851.9	20400.1	26995.7	_	24219.7	14485.7	13973.7
1979	26064.1	20869.7	27959.4	_	25585.6	15604.7	15381.9
1980	26919.3	21122.1	27959.4	_	26450.2	16614.9	16345.9
1981	28021.4	22100.3	29199.7	_	27752.8	17820.6	17626.4
1982	29679	23278.2	30439.7	_	28923.4	19264.9	18975.9
1983	30843.4	24269.6	31750.1	_	30005.2	20429.6	19802.1
1984	31595.8	24753.6	31771.9	_	30707.6	21169.7	22758.9
1985	32666.8	25766.8	33009	_	31832.7	22398.5	23563
1986	33437.9	26393.4	34099.8	_	32832.9	23465.2	24481.3
1987	34584.4	27080.5	35078.7	_	33901.3	24537.5	25225.9
1988	36170	28195.1	36602.1	_	35594.6	26212.3	26222.1
1989	37381.4	28587.3	36723.8	_	36618.4	27236	26967.5
1990	38612.6	29148.8	37619.8	_	37850.4	28451.5	28081.9
1991	39604.4	29363.1	_	_	38878.4	29301	28081.9
1992	40849.1	_	_	_	39864.1	30619	29365.6
1993	41890.5	_	_	_	40994.3	31541	30214.8
1994	43116.2	_	_	_	42212.1	32926.8	31576
1995	44044.3	_	_	_	43122.8	33934.7	32608.1
1996	45178.5	_	_	_	44164.2	34914.5	33550.1
1997	46659.4	_	_	_	45533.7	36434.9	34924.3
1998	48036.7	_	_	_	46781.5	37702	36190.1
1999	48843.1	_	_	_	47477	38527.9	36965.4
2000	49595.5	_	_	_	48048.5	38527.9	37828.3
2001	50630.6	_	_	_	49139.7	40087.8	39063
2002	51919.9	_	_	_	50359.9	_	39977.4
2003	53001.1	_	_	_	51644.4	_	41311.6

Table B2: Calculated properties of the generated sub-basins.

ID	SLOPE (%)	CENTROID_X (M)	CENTROID_Y (M)	SOIL_ID	CN	COVER (%)	HYDVALUE	KS (mm/hr)
46	3.05	825269.67	9991108.91	737	72.36	45.37	2.68	9.15
45	3.18	823462.53	9989461.98	76	66.56	35.71	3.13	11.25
44	5.32	819600.03	9988788.90	76	62.30	32.20	3.50	13.00
41	13.71	809132.10	9989380.00	76	74.71	24.42	3.07	10.91
42	10.08	811102.53	9987858.87	76	65.87	33.21	3.39	12.48
40	15.55	812257.68	9984026.66	76	69.33	29.47	3.08	10.74
43	3.26	819922.25	9985993.39	76	66.79	30.92	3.27	11.92
39	5.77	813675.03	9982265.89	76	57.44	42.20	3.50	13.00
24	9.1	802535.14	9982753.95	823	78.79	44.70	2.10	5.04
37	2.37	815167.53	9980848.39	76	57.55	41.10	3.50	13.00
29	12.49	805218.67	9982636.32	823	85.86	19.54	2.11	5.08
36	13.34	809149.99	9982048.95	76	75.13	27.19	2.89	9.39
30	7.21	807073.66	9979364.80	823	84.08	29.05	2.00	4.30
25	5.69	804321.11	9979997.19	823	81.06	42.75	2.00	4.30
31	9.94	808929.01	9979361.26	823	74.79	35.39	2.55	7.52
28	6.62	805672.53	9977435.89	823	83.06	33.05	2.00	4.30
23	17.14	810652.53	9975455.89	76	60.91	44.60	3.50	13.00
27	6.56	800276.41	9978245.89	823	79.91	50.65	2.00	4.30
19	7.38	804285.03	9975112.12	823	82.26	35.90	2.00	4.30
18	7.91	800927.95	9974810.52	823	79.21	46.45	2.00	4.30
22	13.06	806489.90	9974419.53	823	75.44	42.37	2.41	6.65
34	4.85	814732.38	9975628.39	737	80.37	41.50	2.30	7.34
32	7.84	813103.02	9975342.83	737	70.00	44.07	2.82	9.77
21	9.35	802807.53	9972988.10	823	81.23	41.15	2.00	4.30
17	12.57	808095.03	9973018.39	823	74.68	56.47	2.38	6.89
13	10.72	804232.53	9970640.89	823	80.77	43.00	2.00	4.33
11	10.03	810524.48	9970213.39	737	78.90	53.65	2.30	7.34
20	6.67	798361.17	9970032.83	823	77.69	58.90	2.00	4.30
16	9.94	807377.86	9969142.13	823	78.07	57.65	2.13	5.58
10	10.41	808072.53	9966982.83	823	76.25	51.03	2.25	6.74
33	7.87	812138.36	9968390.89	737	78.68	53.08	2.31	7.38
5	10.34	809987.27	9966368.26	737	78.86	40.08	2.42	8.21
12	8.52	798988.12	9967188.40	823	78.27	50.05	2.00	4.30
9	12.33	807285.03	9964345.12	941	71.58	48.32	2.50	8.63
14	8.75	801690.03	9965607.41	823	80.46	47.65	2.00	4.30
7	15.45	805630.64	9963665.89	823	79.58	48.21	2.07	4.87
6	11.3	803692.19	9963681.95	823	80.87	42.90	2.00	4.30
2	12.1	809825.37	9962398.39	941	78.20	27.05	2.60	9.52
4	11.12	811800.71	9961535.89	941	79.86	24.50	2.60	9.52
8	13.2	806790.03	9961032.63	941	81.12	28.19	2.31	6.96
1	10.75	808588.09	9958212.56	941	80.75	18.90	2.60	9.52
3	9.67	811602.15	9956096.77	941	79.07	24.20	2.60	9.52
26	6.7	800407.29	9982685.89	823	76.69	48.97	2.14	5.30
38	1.04	818992.14	9981718.39	76	69.05	35.56	3.07	10.96
35	1.91	815361.97	9979678.39	737	67.66	46.04	2.89	10.11
15	10.34	806181.16	9969570.17	823	79.58	49.77	2.03	4.57