ESTIMATION OF DIRECT RUNOFF AND SEDIMENT YIELD IN UPPER RIVER NJORO CATCHMENT IN KENYA

HESBON OTIENO

A Thesis submitted to the Graduate School in partial fulfillment for the requirements of the Masters of Science degree in Agricultural Engineering of Egerton University

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DECLARATION

I declare that this thesis is my original work and has not been submitted to any other university for award of any degree.

HESBON OTIENO

BM11/1080/03

SIGNED ....**Date**....04/09/06..............................

APPROVAL

This Thesis has been submitted to Egerton University Board of Postgraduate Studies for the fulfillment of Masters of Science degree in Agricultural Engineering with the approval of:

1. **Prof. Japheth O. Onyando**

   Department of Agricultural Engineering

   Egerton University

   P. O. Box 536

   Egerton, Kenya

SIGNED ....**Date**....4/09/06..............................

2. **Dr. Wycliffe W. Saenyi**

   Department of Civil and Environmental Engineering

   Egerton University

   P. O. Box 536

   Egerton, Kenya

SIGNED..**Date**....11/9/2006..............................

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DEDICATION

First to GOD who makes all things possible, secondly to my dear parents and siblings for their affection, love, support and guidance they offered to me and finally to my uncles Moses and Peter for their material support.

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ABSTRACT

Natural resources and environment are the bases for human social and economic development. Human interference in the upper River Njoro catchment has led to the increased exposure of the land to accelerated erosion. Tonnes of soil have been swept away from the upland to the waterways. This has led to the reduction in discharges in stream channels, useful life of hydraulic structures and enormous loss of fertile soil from agriculturally productive land. An application that combined the capabilities of Remote sensing, GIS and AgNPS model was used to estimate peak runoff rate and sediment yield from the upper River Njoro catchment. Remotely sensed Landsat Thematic Mapper (TM) images were used to obtain land cover and associated AgNPS model input parameters. Other input parameters for the model were extracted from GIS layers using the AgNPS-ILWIS interface. Surface water quantity and quality data including peak runoff and sediment yield of selected storm events were obtained from two gauging stations within the catchment. Base flow separation was done so that measured direct peak runoff rate and sediment yield generated by direct runoff could be determined and compared directly with the model simulated results. The runoff was then routed using Muskingum routing method to estimate the runoff hydrographs at the outflow downstream monitoring station while the inflow hydrographs were taken from the upstream monitoring station. The routed peak runoff rates were used together with sediment rating equation to predict the sediment yield for the downstream station. The predicted output was compared to observed data and evaluated using the Nash and Sutcliffe efficiency (EFF) criterion. Simulated peak runoff rates in upstream station were satisfactory with an EFF of 0.78 and a percent error of 4.1%. The sediment yield was also reasonably estimated with an EFF of 0.88 and a 2% error. The downstream station results were also satisfactorily predicted with peak runoff rate having an EFF of 0.69 and a 5.5% error of estimates. The estimated sediment yield had an EFF of 0.86 and a 2.5% error. The routed hydrograph through Muskingum method gave reasonable results in the outlet monitoring station downstream. The statistical analyses of the routed hydrographs were EFF of 0.97 and a 1.9% error which is satisfactory. In addition, the sediment yield for the downstream station was well predicted using the regression equation (relating the sediment yield to discharge) and routed peak runoff rates with an EFF of 0.57. These results are useful in estimating discharge and sediment downstream.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

AgNPS	Agricultural Non Point Source
ANSWERS	Areal Nonpoint Source Watershed Environment Response Simulation
ASCE	American Society of Civil Engineers
AWLR	Automatic Water Level Recorder
CN	Curve Number
COD	Chemical Oxygen Demand
CREAMS	Chemicals, Runoff and Erosion from Agricultural Management Systems
DEM	Digital Elevation Model
EPIC	Erosion Productivity Impact Calculator
GIS	Geographical Information System
GRIPs	Geo-Referenced Interface Package
IAHS	International Association of Hydrological Sciences
ILWIS	Integrated Land & Water Information System
RS	Remote Sensing
RUSLE	Revised Universal Soil Loss Equation
SCS	Soil Conservation Service
STAND	Sediment Transport Associated Nutrient Dynamics
UNEP	United Nation Environment Programme
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation
WEPP	Water Erosion & prediction Project

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

CHAPTER ONE
INTRODUCTION

1.1 Background

Soil erosion and sedimentation are major environmental problems which cause degradation of natural resources in river basins. Such degradation may be in the form of reduction of land productivity due to loss of fertile soil from agriculturally productive land and undesirable deposition of eroded material in the lower reaches of the river channels increasing frequency of floods and depletion of ground water resources. Sediment deposits also cause accumulation of silts in lakes or reservoirs reducing their useful life. Fertilizer chemicals are transported into water bodies together with sediments causing excessive growth of water plants, which result in clogging of water courses, loss of aquatic life and other related problems. Scouring of river channels has also been noted to destroy hydraulic structures along the river courses.

The destruction of soil through erosion is becoming of particular concern because soil formation is an extremely slow process. Serious soil erosion is occurring in Kenya's major agricultural regions and the problem is growing as more land is brought under agricultural production. Surface runoff is a critical variable in determining the rate of soil erosion and sediment transport. Its turbulence is known to be an influential factor in detachment of soil by overland flow. The rapid growth in the world population, which leads to the need for more crops, will only intensify the water problem, particularly if soil erosion is not contained.

The River Njoro catchment is part of the larger Lake Nakuru catchment, and one of the rivers originating from the Eastern Mau forest of the Mau Complex and draining into the saline Lake Nakuru. The River Njoro catchment is a high potential area and is under intensive cultivation. The forested hillslopes of the catchment have undergone extensive deforestation, which has led to increased soil erosion, low recharge and remarkable fluctuation in stream flows. Through erosion, the fertile topsoil and the sediment generated are transported by the stream and get deposited in the lower reaches in the river and the Lake. Lake Nakuru is a protected area for biodiversity conservation. As a habitat for various flora and fauna, its degeneration in quantity and quality has adverse effects on biodiversity which it supports.

Recent developments in computer technology have provided new techniques to study and tackle environmental problems for effective and efficient environmental systems management. It is now easier to analyze and process enormous amount of data within a very short time. The computer has become a versatile tool for studying and modeling our environment. In addition, since the early 1970's, satellites have scanned the earth and furnished digital images of several wavelengths ranging from the visible part of the spectrum to the middle infra red (De Jong & Riezebos, 1992). Developments in the field of erosion studies have led to the deveopment of new models that can handle large number of parameters and perform large number of calculations. These models are often linked to Geographical Information System (GIS) thus simplifying the modeling task.

In the present study, the Integrated Land and Water Information System (ILWIS) developed by International Institute for Geoinformation and Earth Observation-ITC (Meijerink et al., 1988) was used in a GIS-Model link to determine and handle the distributed input and output of the Agricultural Non-Point Source (AgNPS) Pollution model. The distributed model was used to predict sediment yield and runoff for single storm events. Further to this, routing of direct runoff was accomplished using Muskingum method in order to determine the magnitude of streamflow hydrograph downstream. A regression analysis was also carried out between observed discharges and sediment yield.

1.2 Problem Statement

The clearing of the forests followed by intensive agricultural activities (Crops & Livestock production), which is the major economic activity in the River Njoro watershed, exposes the land to serious erosion. Furthermore the poor farming practices especially by the small-scale farmers worsen the problem of erosion and silt deposition in the flat lands as well as in the waterways. This reduces the capability of the land to meet the agricultural demands of the people. Increased suspended sediment concentrations in the river channel also contribute greatly to the reduction in the life of hydraulic structures in addition to increasing the cost of producing potable water.

1.3 Justification

Based on the problems stated, there is need to accurately estimate the catchments sediment yield and runoff volumes for efficient management of the catchment resources currently and in future given that consistent observed data is lacking. This information is important in the development of strategies for efficient and sustainable management of land and water resources in the catchment.

1.4 Objectives

The overall objective of the study was to estimate and route direct runoff rate, and sediment yield in upper River Njoro catchment. The following specific objectives were suggested:

i) To estimate direct runoff and sediment yield using AgNPS model.

ii) To determine runoff rate and sediment yield downstream through hydrological routing.

1.5 Research Questions

Based on the above study objectives, the following research questions were proposed in this study.

i) Can the sediment yield and direct runoff of rainfall-runoff events in the upper river Njoro catchment be estimated using RS, GIS, and AgNPS model?

ii) Can hydrological routing techniques be used to route direct runoff and determine the hydrographs and sediment downstream?

CHAPTER TWO
LITERATURE REVIEW

2.1 Runoff Generation Processes

During a storm event, water is deposited on many different surfaces from which it travels by a large number of routes into the streams. Stream flows are a response to direct precipitation, base flow as influenced by catchment characteristic. How fast the stream reacts to rainfall depends on the catchment factors. Proper estimation and determination of these factors requires experience and good judgment on the part of the hydrologist. The generation of overland flow in upland catchments can occur through two distinct mechanisms (Wahlstrom et. al., 1999). These may be, the Horton mechanism which occurs when the rainfall intensity exceeds infiltration capacity rate or the saturated hydraulic conductivity of the near surface soil for a period sufficient to allow ponding to occur and the Dunne mechanism, occurs when sufficient rainfall infiltrates into the soil to temporarily raise the water table to the ground surface. Field studies by Dunne and Black (1970) and numerical simulations by Freeze (1972) have identified the occurrence and relative importance of the Horton and Dunne overland flow mechanisms. Freeze (1972) showed that Horton overland flow can become an important runoff generation mechanism in areas of low saturated hydraulic conductivity and in areas where the water table is sufficiently deep.

The water table in the upper River Njoro catchment (where the study focuses on) is relatively deep (Chemelil, 1995). The deep water table, reduces the possibility of saturated runoff thus Horton overland flow is the major surface runoff generation mechanism. Runoff process has got two phases, the land phase and channel phase. Singh (1995) noted that, large catchments have well developed channel networks and thus, channel storage is dominant. These catchments are less sensitive to short duration, high intensity storms, while small catchments that have dominant land phase and overland flow, have relatively less conspicuous channel phase, and are highly sensitive to high intensity, short duration storms. The upper River Njoro catchment is a small catchment of 127 km^2 and most of its drainage networks only have flows during and after storm events except for the main channel, thus it has a dominant land phase and a less conspicuous channel phase.

2.1.1 Runoff Estimation

Numerous approaches are employed for the estimation of runoff, namely: use of hydrographs, unit hydrographs, empirical equations, models amongst others. However the choice and validity of the approach depend on the type of the problem, available data as well as runoff processes that are likely to be dominant. Biamah et al., (2002) showed that when models are used to estimate runoff, the accuracy of prediction of the hydrologic response of a catchment in terms of adequacy and reliability greatly depends on the model used and the determination of input parameters such as the causative and conditioning factors, accuracy of prediction and application of predicted data.

Runoff rates are important in the evaluation of erosional processes from individual storms and significant trends in peak runoff rates could be associated with the use or misuse of the drainage area. Peak runoff rate which is the maximum instantaneous rate of flow of a stream occurring in response to physiographic and hydro-meteorological effects of a catchment represents the crest of a hydrograph (Biamah et al., 2002). The time to peak runoff rate is largely determined by catchment characteristics such as the travel distance, drainage density, channel slope, channel roughness, soil infiltration characteristics and causative factors such as rainfall duration. However to get the direct runoff hydrograph, there is need for the base flow to be separated from the total hydrograph. Various techniques exist for separating the two components of the total hydrograph such as normal depletion curve, recession curve analysis method, straight line method, logarithmic method and variable slope method (Wanielista, 1990). The variable slope method was adopted for use in the current study because of the high accuracy of its results.

The United States Department of Agriculture Soil Conservation Service (USDA-SCS) method is widely used for runoff estimation on small to medium sized ungauged catchments and has replaced the rational method to a significant degree due to its wider apparent data base and the manner in which physical characteristics are considered in its application (Ramirez, 2000). The method was developed empirically with data collected from numerous Agricultural Research Service (ARS) research catchments in the U.S.A. This method is based on a Runoff Curve Number (CN) that quantifies the effect of the soil and land cover type on the runoff. The method is based on the assumption that the ratio of runoff to rainfall for a given event is equal to the ratio of water retained during runoff for that event to the potential amount that could be retained during an extremely long storm.

Unit hydrographs are used in ungauged basin to calculate, the time to peak t_p, peak flow Q_{pk} and time base T_b (Bras, 1990) amongst others. The time to peak is defined as the time from the start of rise of surface runoff hydrograph to the attainment of peak flow at the outlet of the catchment. The time of concentration is defined as the time for a drop o rain from the remotest part of the catchment to travel to the outlet. At this time the whole of the catchment is assumed to contribute to the runoff at the outlet. It can be measured as the time from the onset of rainfall to the positive inflection point on the receding limb of the hydrograph, whereas the lag time is defined as the difference in time between the centre of mass of effective rainfall and the centre of runoff at the outlet, or alternatively as the mean flood wave travel time (Perrone et. al., 1998). Both the lag time and the time of concentration are theoretically regarded as constants for a given watershed.

Hydrographs can be grouped into three types (Chow et al., 1988) as

1. Those that relate the hydrograph characteristics to the characteristics of the watershed.
2. Those that are based on a dimensionless unit hydrograph.
3. Those based on models of watershed storage

Previous studies have shown that a synthetic unit hydrograph can be defined by two parameters, the unit peak flow rate and the time to peak. When the two parameters are adequately defined, then a triangular approximation of the unit hydrograph is satisfactory (Sheridan et al., 2002). Therefore, the main reason for developing improved methods of defining synthetic unit (triangular) hydrographs is development of a predictive relationship between watershed characteristics and unit hydrograph peak rate factors. (Rodriguez-Iturbe &Valdes, 1979)

SCS Triangular Hydrograph is a synthetic hydrograph developed by Mockus (1957), often referred to as the soil conservation service (SCS) standard unit hydrograph. It assumes a hydrograph shape which is triangular, and is suitable for basins with areas less than 260km^2. In this unit hydrograph the discharge is expressed by the ratio of discharge q to peak discharges q_p and the time by the ratio of time t to the time of rise of the unit hydrograph, T_p. The area under the unit hydrograph should be equal to a direct runoff of 1unit and therefore it can be shown that, (Chow et al., 1988)

$$q_p = 0.21\frac{QA}{T_p} \tag{2.4}$$

where A= Drainage area (km^2)

Q= Direct runoff volume (mmday^{-1})

T_p= Time to peak (h)

q_p= Peak runoff rate (m^3s^{-1})

Onyando (1997) adopted a t_r/T_p ratio of 1.67 based on analyses of flood hydrographs from Sambret and Lagan catchments in Lake Victorian basin in Kenya just like Mockus (1957) in the Midwestern United States. A study of unit hydrographs of many large and small rural watersheds indicate that the basin lag (time to peak) T_p is approximately equal to $0.6t_c$, where t_c is the time of concentration of the watershed (Thompson, 1999)

$$T_p = 0.5t_r + T_L \qquad (2.5)$$

Also

$$T_p = 0.5t_r + 0.6t_c \qquad (2.6)$$

where

T_p =Time of rise

T_L = Basin lag

t_r =Duration of effective rainfall

Most models used in the prediction of runoff utilize both the USDA-SCS and SCS triangular hydrograph equations (Singh, 1996). In the AgNPS model, peak flow rate is calculated in the hydrology part of the model based on the SCS Curve Number method. This method was chosen because of its simplicity and widespread use among the principle user agencies for which the model was developed.

The peak runoff rate can be calculated by two options. One, using an empirical relationship proposed by Smith and Williams (1980) which assumes a triangular shaped channel and uses the equation

$$Q_p = 8.48A^{0.7}CS^{0.16}\left(RO^{0.82A^{0.017}}\right)LW^{-0.19} \qquad (2.7)$$

where Q_p= peak flow rate (ft^3/s)

A= drainage area in acres

CS= length of weighted channel slope (ft/ft)

RO= Runoff volume in inches

LW= catchment Length-Width ratio, calculated by

$$\frac{L^2}{(43560A)} \tag{2.8}$$

Where L= channel length (ft)

The second option is based on TR55 (USDA, 1986), which is used for estimating runoff and peak discharge in small catchments. This method assumes, a rectangular-shaped channel and the peak flow is based on the time of concentration (T_c), which is computed by assuming all the travel times for consecutive cells in a specific flow path in a catchment. The peak flow is calculated from T_c by

$$Q_p = 10^{\log[C_{0_0} + C_1(\log T_c) + C_2(\log T_c)]^2} \left[\frac{A}{640}\right] Q \tag{2.9}$$

where Q_p= peak flow rate (ft^3/s)

A= drainage area ($miles^2$)

Q= runoff volume (inches)

C_0, C_1 and C_2 are coefficients based on 24 hour precipitation and initial abstraction as determined from the curve number

With either method of calculating peak flow, the user has the option of entering known channel characteristics such as length, width and depth or using hydro-geomorphic relationships to determine channel geometry. The hydraulic geometry predicted by the geomorphic calculations is a data-smoothing approach that predicts the downstream trend of increasing channel widths, depths, and lengths within well defined geomorphic regions. This has the advantage of allowing the user to estimate the channel dimensions as a function of total catchment area. The adopted approach was that of using an empirical relationship proposed by Smith and Williams (1980).

2.1.2 Runoff Routing

Flow routing is a procedure of estimating the time and magnitude of flow hydrograph at a point in a stream from known or assumed hydrographs at one or more points upstream. Routing methods are broadly classified into lumped and distributed flow routing. Lumped flow routing is also known as hydrologic routing whereas the distributed flow routing is hydraulic routing.

Hydrologic routing methods calculate the flow as a function of time alone at a particular location. These routing methods are adequate for a considerable majority of problems encountered in hydrology, however these methods may not perform well in predicting the flow conditions when backwater effects are significant and the river slope is mild, since hydrologic routing methods have no hydraulic mechanism to describe upstream propagation of changes in flow momentum (Chow et. al., 1988). Notable methods of hydrologic routing are Muskingum and Runge-Kutta method. Hydraulic routing methods calculate the flow as a function of space and time throughout the system, it deals directly with the hydraulic characteristics of the channel and may take dynamic effects into account. The advantage of these methods is that they compute the flow rate and water level simultaneously instead of separately. These methods are also used in areas where there is reversal of flow, variable backwater and where the channel is complex as in a delta. However, the solution of the St. Venant equations which are the backbone of hydraulic routing is a relatively complex task. The most commonly used method of hydraulic routing is the Muskingum-Cunge (Chow et. al, 1988).

The Muskingum routing model selected to be used in this study is designed to estimate the runoff hydrograph at a downstream point given runoff hydrographs at one or more upstream locations. The Muskingum routing model which shows components of channel storage i.e wedge and prism storage is shown in the Figure 2.1 below

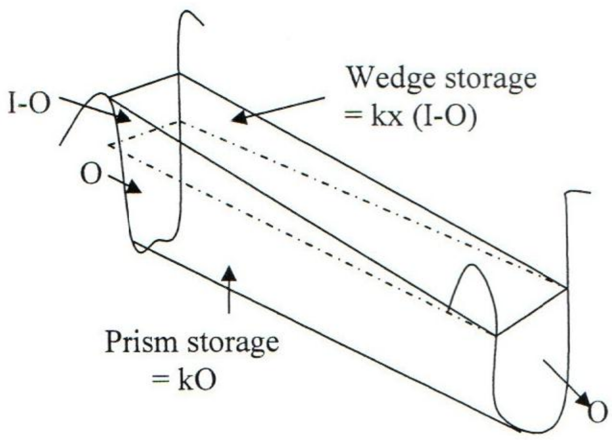

Figure: 2.1 Muskingum routing model (Source: Chow et. al., 1988)

The wedge storage represents the difference between the inflow and outflow within the reach, whereas the prism storage represents a scenario in which there is no storage in a river reach. This method of flow routing uses storage and continuity equations (Chow et. al, 1988) which are stated respectively as:

$$S = K[IX + (1 - X)O] \tag{2.10}$$

and

$$\frac{\partial S}{\partial t} = I - O \tag{2.11}$$

Where

I = The reach's inflow

O = The reach's outflow

S = Storage volume within the reach.

T =Time

k and x are Muskingum parameters i.e. k (travel time) and x (discharge weighting factor)

Equations (2.27) and (2.28) when expressed in finite difference form and solved for the outflow at a time step t+1 yield.

$$\overline{O} = C_0 I_{t+1} + C_1 I_t + C_2 \overline{O_t} \tag{2.12}$$

Where C_0, C_1 and C_2 are expressed in terms of k, x and Δt as

$$C_0 = \frac{\Delta t - 2kx}{2k(1-x) + \Delta t} \tag{2.13}$$

$$C_1 = \frac{\Delta t + 2kx}{2k(1-x) + \Delta t} \tag{2.14}$$

$$C_2 = \frac{2k(1-x) - \Delta x}{2k(1-x) + \Delta t} \tag{2.15}$$

The Muskingum parameters, k and x are usually estimated using a graphical or least square procedure. This routing method has been applied in Godovari River in India which flows through the states of Maharashtra and Andhra-Pradesh with a 500 km reach from the source, flow observation was made at Dhelagon and Gangakhed with a reach of 93 km between them (Kshiragar et. al., 1995). The ungauged catchment between the two gauging sites is 3035 km^2 and the flood case studied was during the period of 31st August and 5th September 1997 and they got values of K_1= 2 hours, x_2 = 0.01, k_2 = 8.42 hours, x_2 = 0.01 for two sub-reaches. Birkhead and James (1998) also compiled direct relationship between local stages and the remote discharges of Sabie River in the Kruger National Park of South Africa where they considered a 4.6 km reach.

2.2 Erosion Process

Soil erosion in Kenya has occurred at an alarming rate at a time when awareness of the problem all over the world is increasing. Erosion harms soil productivity, the environment, agriculture, the national economy and the well being of the people. Thousands of hectares undergo land use changes in Kenya annually. Forests and rangelands are converted to agricultural and pastoral uses while rural areas are rapidly urbanizing. These man induced changes that alter the ground cover or degrade the land are potential catalyst of increased erosion.

Soil erosion is a three phase process consisting of the detachment of individual particles from the soil mass and their transport by erosive agents such as running water and wind (Morgan, 1986). When sufficient energy is no longer available to transport the particles, the third phase, deposition occurs. Auzet et. al. (1990) classified the various forms of erosion with respect to soil particles detachment conditions on slope and in the valley into (i) Interril erosion where soil particle detachment is mainly by raindrops and running water without initiating incision, (ii) Rill erosion where there are incised flow lines due to splash and/or sheet runoff. Here detachment is mainly by shear stress exerted by runoff on the bed and the wall sides of the rill, (iii) Concentrated flow erosion in the valley floor, where detachment is mainly due to shear stress exerted by runoff concentrated in the valley floor or hollows without a permanent channel and various mechanism acting on the side walls, and (iv) Gulley erosion. Although many agents cause erosion, in River Njoro watershed it is caused mainly by water. Water erosion on land is related to the effective erosivity of raindrop impact and surface runoff, the susceptibility of the soil to erosion and the land topography. These basic parameters are clearly modified by the absence or presence of vegetation. Because of the tropical climate, rainfall has a relatively high ability to erode the soil (erosivity) since high volumes of precipitation fall in a short period of time (Lal, 1990; Mati & Morgan., 2000; Okoth, 2003). Getis et al. (1999) also concluded that there is no more important erosional agent than water. The key factors that are found to influence soil erosion are the erosivity of the causal agent and the erodability of the soil.

2.2.1 Upland Erosion

The tropical highlands are a unique environment. Their topography is mostly steep and rugged, and the soils are often poorly structured (Hudson, 1981). Hill slope agriculture in Kenya is associated with resource poor farmers, land degradation, and soil and water losses. The process of soil movement from a field is theoretically separated into that from interrill and rill areas. The dominant process that characterizes interrill areas are detachment by rain drop and transport by raindrop impacted shallow flow. In rills, the dominant processes are detachment and transport by concentrated flow.

Soil detachment by water is the process of separating soil particles from the bulk soil by the shear forces of water (Lei et al., 2002). The detachment occurs when the shear stress of the flowing water is greater than the critical shear stress. Energy is needed in the runoff for it to cause erosion. The runoff energy is divided into that for detaching the soil particles and that for transporting the detached soil particles. The sediment transport capacity of water flow and the unit flow rate are factors which have an influence on the detachment rate.

The net detachment rate has its maximum value when water is clear, on the other hand detachment rate is zero when the sediment load of the flowing water reaches a limit and all the energy of the flowing water is used for sediment transport. When the unit flow rate is greater than the sediment transport capacity of the flow, sediment load of the flowing water is greater than what the flow can carry and deposition occurs, while, when the unit flow rate is less than the sediment transport capacity of the flow but greater than zero, part of the energy of the flowing water is used for detachment of soil particles and part for transport of sediment (Biamah et al., 2002).

Catchment characteristics such as land use/land cover slope and soil attributes affect water quality by regulating sediment and chemical concentration. Among these characteristics, land use/land cover can be manipulated to gain improvement in water quality. These land use/ land cover can serve as nutrient detention media or as nutrient transformers as dissolved or suspended nutrients move towards the stream.

2.2.2 Channel Erosion

Rivers and other water bodies can not be treated as isolated systems. Fresh water systems are intimately linked to their catchments or drainage systems. Rivers are down hill from human influences and so much of what happens in the catchment eventually has an effect on the aquatic system. With increasing population and increased technological growth, the ecosystem we depend on is under great stress. The supply of fresh water is especially at risk.

Apart from runoff removing and transporting the soil particles from the land, it also erodes soil from the channels. Generally, discharge and flow velocity are greater for large rainfall and runoff events compared to small events, and this results in increased channel scouring. The movement of sediments in suspension is influenced by; the particle size distribution, the weight and form of the particles, the cohesion between the particles, the arrangement of particles within the channel, the channel geometry, the turbulence of flow, the discharge volume, and the root growth (Anderson, 1988). The impact of pollution on a river depends on the nature of the pollutant and the unique characteristics of the individual river. These characteristics may include; the river depth, nature of the channel bottom, the volume and speed of flow in the river, the surrounding vegetation, climate of the region, the mineral heritage of the catchment, land use patterns among others (Mackenzie & David, 1991).

Estimation of the changes in suspended sediment concentration with time in a river system still remains a challenge. The challenge reflects the complexity of the processes involved in the detachment and transport of fluvial suspended sediment. The only well known hydrological parameter in the upper River Njoro catchment is the river discharge. The river discharge is an integrating measure of all the hydrological processes operating within the catchment and therefore models based on stream flow are of interest.

2.3 Sediment Generation

2.3.1 Sediment Sources and Sinks

Sediment materials are generally divided into two categories based on their sources: allochthonous and autochthonous. Allochthonous refers to material that originated from outside the water body i.e. from its watershed or atmosphere e.g. clay, soil particles eroded into a water body while Autochthonous materials originate from the water body itself (Smol, 2002).

In recent years, there has been increasing recognition of the need to include sediment control strategies within catchment management plans. Information on the source and sinks of the sediment transported by a river is an important requirement for designing effective sediment control strategies. Classification of sources and sinks is instrumental in identifying and evaluating the extent of erosion and sedimentation as well as recommending their control. Sediment sources produce sediments whereas sinks trap sediments. The corresponding sediment sources and sinks are summarized in Table 2.1.

Table 2.1 Sediment Sources and Sinks

Sediment sources	Sediment sinks
Agricultural land	Concave slopes
Construction sites	Vegetative strips
Roadway embankments	Flood plains
Cuts and ditches	Reservoir areas etc.
Disturbed forest lands	
Surface mines etc.	

An accurate estimate of sediment yield must consider the entire catchment erosion-sedimentation system. It is important to identify the major sediment sources and sinks as well as the catchment's erosion-sedimentation history (Haan et al., 1994). Sediments can reduce the recreational value of water; is a carrier of plants nutrients, crop chemicals, and plant and animal bacteria; and increase water treatment costs. Effective erosion control is a positive solution to sediment problem. The rates of erosion relate to how the land is being used and the characteristics of the soil (Loerh, 1984).

2.3.2 Sediment Yield

Human activities are constantly altering catchments and posing new problems to environmental managers. Rapid population growth has put pressure on the environment and natural resources. Some of the activities that contribute significantly to increased turbidity in stream water include cultivation in areas not suitable for agriculture, for example, steep slopes, river banks and reserved areas. Deforestation caused by increased demand for forest products is high in the River Njoro catchment.

Accelerated erosion has serious consequences on the catchment. Farmland productivity decreases, natural habitats are destroyed, and infrastructure made less stable. Increased sediment loads have serious direct and indirect consequences on the catchment e.g. increased scouring effect of the water which increase channel erosion and shortens useful life of hydraulic machines such as pumps, increased export of contaminants and nutrients, and increasing water turbidity thus raising the cost of producing potable water among others.

The concentration of sediment is normally used as a measure of the sediment carried by the flow. It is normally expressed in parts per million (ppm) or kilograms per cubic meter (kg m^{-3}). High sediment concentrations were recorded for Missouri and Colorado rivers in the United States i.e. approximately 3.54 and 27.5 kg m^{-3}, respectively (Maidment, 1992). However the Yellow river in China is the greatest sediment carrying stream in the world with an average of 37.6 kg m^{-3} and maximum of 911 kg m^{-3} (Maidment, 1992).

Saenyi (2002) found out that Masinga reservoir is threatened with serious siltation resulting from accelerated erosion in Masinga catchment. The storage capacity of the reservoir is declining due to high rates of sedimentation. Between 1981 and 1988, the reservoir which was originally 120 km^2 reduced by 6.4% and 13.7% between 1981 and 2002. In addition, Mutua & Klik (2006) found out that only 9.3% of the total catchment area is experiencing soil loss within the allowable tolerable rates of between 2.2 to 10 t/ha/yr recommended for Masinga area.

Studies in the Lake Naivasha catchment in Kenya showed that Malewa River supplied long-term sediment concentration of 0.24 kg m^{-3} from 1957 to 1990 (Rupashinga, 2002). The author found the long term estimated annual average suspended sediment load of Malewa catchment to be about $55.9x10^3$ tonnes for the period 1957 to 1990, this translates to a total estimated suspended sediment load to Lake Naivasha of about $2.5x10^6$ tonnes for the same period. A comparison of the lake sedimentation with suspended sediment fluxes of Malewa and Gilgil rivers reveal that the Malewa wash load contributes 35% of the lake sedimentation. He further noted that sediment delivery into Lake Naivasha between 1957 and 2001 resulted in a 7% reduction of the lake volume capacity, and the current annual volume depreciation rate is about 0.0016%. Therefore assuming this constant depreciation rate the Lake is expected to shrink to half in 400 years.

Onyando et. al., (2005) found out a sediment delivery ratio of 0.83 for the River Perkerra catchment. This high figure indicates that the ecosystem is fragile and there is a high sediment concentration in stream flow which leads to higher proportions of sediment generated in the catchment finding its way to the outlet. The catchment which is 1207 km^2 has a sediment yield of 1.43 million tonnes per year whereas the larger Lake Baringo catchment with an area of 6820 km^2 had a sediment yield of 13.5 million tonnes per year. This influx of sediment into the lake, which has no outlet, chokes the lake to the extent that its depth has reduced from 8m in 1972 to 2.5m in 2005.

Studies conducted by Maina-Gichaba et al (2006) at the mouth of rivers Njoro, Makalia, Nderit, and Baharini springbok which drain into Lake Nakuru showed that river Njoro delivers most loads of total suspended solids (48%), this is because it drains rural and urban areas with intensively cultivated erodible landscapes. In the study, in situ measurements of discharge were done on a monthly basis and 500ml water samples were taken and determination of total suspended solid done in the laboratory unlike in the present study which proposed to predict the suspended sediment load using the AgNPS model.

2.3.3 Sediment Yield Determination

Sediment yield estimates are required for studies of soil and water conservation and design of erosion control measures. Hydrologists have adopted different approaches in modeling erosion and sediment transport, amongst them regression techniques, physically based models, conceptual models etc. the regression techniques leads to regression models, which in most cases are based on multi-regression analysis and usually give the total suspended sediment transported during a particular hydrological event. These models do not take into account the time evolution of suspended sediment concentration during a storm event and usually need a spatially distributed approach. The empirical models describing relationships between sediment load and instantaneous discharge are also often used. The most common relationship is a rating curve that takes the form of a power function. Physically based erosion models describe the erosion, transport and deposition processes with equations derived from mechanic and hydraulic sciences. They allow theoretical description of time evolution of suspended sediment concentration. Sediment graphs may also be computed using conceptual models. Most of these models are based on a lumped parametric approach as is the case of models based on the Instantaneous Unit Sediment Graph (IUSG). IUSG models as well as 'supply based' models do not finally explain the way the suspended load is acquired. Other conceptual models use different reservoirs to describe the main natural processes involved in erosion.

Models are also gaining importance in sediment estimation studies. This is because they are able to automate the process of obtaining sediment data. In most sediment transport models, after runoff and upland erosion are calculated detached sediment is routed from cell to cell through the catchment to the outlet. In AgNPS model, the procedure involves sediment transport and depositional relations described by Foster et al., (1981) and Lane (1982) and derived from steady state continuity equation as follows

$$Q_s(x) = Q_s(o) + Q_{sl}\left(\frac{x}{L_f}\right) - \int D(x) w \partial x \quad (2.1)$$

Where $Q_s(x)$ = Sediment discharge at the downstream end of the channel reach

$Q_s(o)$ = Sediment discharge into the upstream end of the channel reach

Q_{sl} = lateral sediment inflow rate

x = reach length

w = channel width

D(x) = depositional rate, estimated as,

$$D(x) = \left[\frac{V_{ss}}{q(x)}\right]\left[q_s(x) - g'_s(x)\right] \tag{2.2}$$

Where V_{ss}= particle fall velocity

q(x)= discharge per unit width

$q_s(x)$= sediment load per unit width

$g_s'(x)$= effective transport capacity per unit width

the effective transport capacity is computed using a modification of the Bagnold stream power equation (Bagnlod 1966) as follows

$$g_s'(x) = \eta g_s = \frac{\eta k \tau v^2}{V_{ss}} \tag{2.3}$$

Where g_s= transport capacity

η= effective transport factor

k= transport capacity factor

τ= shear stress

v= average channel flow velocity determined by Manning's equation

The sediment transport calculations allow for deposition and/or scouring of all particle sizes during channel flow based on transport capacity and sediment availability. However, the user has the option of not allowing any scouring incase a non erodible channel is involved.

Sediment data are available for relatively few rivers prompting hydrologists to attempt to predict sediment yields from empirically based equations. Jensen and Painter (1974) suggested simple regression models between annual sediment yield and a number of catchment parameters. Regression models can be used to predict sediment yield in rivers with no sediment records, however, until both the quantity and quality measurements of sediment loads are improved, and the erosion process better understood, models of this nature will continue to be used to estimate sediment yields. Considerable care must be taken when such estimations are made for catchments lying outside the population on which the analysis was based (Walling and Peart, 1980). Onyando et al (2005) working on River Perkerra catchment used an empirical equation developed by Williams and Berndt (1972) which requires two catchment parameters, slope and length of the main river channel which were easily derived from the catchment. The equation was found to be of value as a predictive tool to assess the scale of the sediment problem in rivers where no sediment data exist.

In their regression equations for the Worlds major climatic zones, Jensen and Painter (1974) showed expected trends, i.e. sediment increases with increasing runoff, altitude, relief, precipitation, temperature and rock softness, and decreases with increasing area and protective vegetation. Williams (1975) also noted that Stream discharge is also an important parameter which can be regressed with the sediment yield and the resulting model used to estimate the sediment yield for remote sites along the stream.

2.4 Models for Runoff and Sediment Generation

The major challenge that is normally faced when developing a runoff and sediment generation model is finding a satisfactory way of linking upland phase with the channel phase. A hydrologic model is a collection of physical laws and empirical observations written in mathematical terms and combined in such a way as to produce hydrologic estimates (outputs) based on a set of known and/or assumed conditions (inputs) (Haan et al, 1994). It represents the behaviour of a catchment. Most models have a deterministic structure, and make use of mathematical relationships to describe the relevant hydrological and erosion process. Hence, they are mixtures of physical-based and empirical approaches. Physically based models are based on mathematical equations to describe the process involved in the model, taking in consideration the laws of conservation of mass and energy whereas empirical models are based on identifying statistically significant relationships between assumed important variables where a reasonable database exists.

River basin models may be lumped, semi-distributed or distributed. A distributed model is one in which all processes are described at a point and then integrated over a three-dimensional space and time to produce the total catchment response, whereas lumped models aggregate catchment parameters over the entire catchment (Chow et al., 1988). Semi distributed models fall in between lumped and distributed models, here aggregation is done based on hydrologically similar events. This makes them less complex than distributed models but more representative than lumped models (Shaw, 1996). Three types of model analysis are recognized: (i) Black box- where only main inputs and outputs are studied. (b) Grey box- where some details of how the system works is known (c) White or glass box- where all details on how the system operates are known. In this study the grey box model analysis was considered since some details of the catchment that affect its behaviour were analysed. A well-conducted modeling study requires detailed knowledge of the system being modeled as well as the strengths and weaknesses of the model under consideration. Some of the important factors to consider when modeling as reported by Singh (1996) are.

1. Model's complexity and input data requirements.
2. Potential of the model to predict specific effects of specific changes.
3. Transferability of the model to other sites and conditions.
4. Implicit uncertainties in the model predictions.

The model must contain parameters that are sensitive to the catchment changes taking place. Models accuracy is a function of the accuracy of the input data and the degree to which the model structure correctly represents the hydrologic processes appropriate to the problem. The more complex the model, the more complex is its data requirements. Physically based, distributed models are preferred due to the fact that their parameters are physically based and have physical interpretation, in addition most hydrological problems are distributed in nature. Some of the distributed models employed on a catchment scale for runoff and sediment generation are discussed below.

2.4.1 Areal Nonpoint Source Watershed Environment Response Simulation model (ANSWERS)

ANSWERS is an example of a distributed parameter model developed at Purdue University in West Lafayette, Indiana (Beasley et al., 1980) and used for modeling spatially varying processes of surface runoff (Hortonian only) and soil erosion of single storm events in agricultural catchments. The model allows variation in soil, cover and topographic conditions within the catchment to be represented explicitly, and effects of rainfall intensity and soil water content on runoff are simulated. It is primarily applied in planning and evaluation of various strategies for controlling surface runoff and sediment transport from intensively cropped areas.

The model is fully integrated within the GIS so that the spatial data can be entered easily and results can be displayed as maps and tables (De Roo et al., 1989). This model was not selected for use in the study because it is recommended for intensively crop areas unlike in the study area which had various land uses.

2.4.2 Water Erosion Prediction Project (WEPP)

The WEPP model is a distributed parameter continuous simulation model for predicting daily soil loss and deposition due to rainfall, snow melt and irrigation (Flanagan et al., 2001). This model was first developed to estimate soil erosion from single storm events, long-term soil loss from hill slopes, and sediment yield from small watersheds. WEPP watershed scale model extends the capability of the hillslope model to provide erosion prediction technology (both spatial and temporal distribution of soil loss) for small cropland and rangeland catchments. The model is based on erosion theory, channel flow hydraulics, rainfall and runoff relationships, and soil and plant science, and contains hill slopes, channels and impoundments as the primary components. Channel infiltration is calculated by Green Ampt Mein Larson infiltration equation. A continuous channel water balance is maintained including calculation of evapotranspiration, soil water percolation, canopy rainfall, interception and surface depression storage. The channel peak runoff rate is calculated using either modified rational equation or the equation used in the CREAMS model. Flow depth and hydraulic shear stress along the channel are calculated by regression equations. A steady state to the sediment continuity equation is used to calculate the detachment, transport and deposition within artificial channel or concentrated flow gullies. The runoff characteristics, sediment loss and deposition are first calculated on each hill slope then routed through several types of impoundment structures by the impoundment components of the model (Fernandez et al., 2003).

Since the model is process-based it is suited for a broad range of conditions that may not be practical or economical when field tests are used (Saenyi, 2002). It is often linked to a GIS thus simplifying the analysis, storage, processing and presentation of spatial data (Raper, 1989). The WEPP model however, requires a lot of input parameters, which in most cases, is costly and time consuming to determine especially in the developing countries and thus was not considered for use in the study.

2.4.3 Sediment Transport Associated Nutrient Dynamics (STAND)

The Sediment Transport Associated Nutrient Dynamics (STAND) is a hydrological model for simulating stream flow, sediment transport and the interactions of sediment with other attributes of water quality. The model employs a fully dynamic basis for quantifying sediment transport and has three level structure.

The first level accounts for hydraulics of open channel flow using the conventional St. Venant equations (continuity and momentum equations). The second level computes sediment transport potential and the actual transport rates based on the information provided by the first level, and in the third level, changes of nutrient concentrations along the studied river can be computed as a function of nutrient transport, absorption/desorption of nutrients to suspended sediment and release from bed sediment pore water (Zeng & Beck, 2003). However, the model does not take care of deposition of sediment and thus not used in the present study.

2.4.4 Erosion Productivity Impact Calculator (EPIC)

The Erosion Impact Calculator (EPIC) model is a model that is capable of modeling integrated systems because of its flexibility in handling a wide array of crop rotations, management systems, and environmental conditions (Williams, 1995). Originally EPIC was designed to simulate the impact of erosion on soil productivity. The current version of EPIC can also produce indications such as nutrient loss from fertilizer and animal manure applications, climate change impacts on crop yield and soil carbon sequestration as a function of cropping and management systems.

The EPIC model can be subdivided into nine separate components namely: weather, hydrology, erosion, nutrients, soil temperature, plant growth, plant environment control, tillage and water budgets. It is designed to simulate catchments of up to 100ha that are characterized by homogenous weather, soil landscape, crop rotation and management systems parameters. It operates on a continuous basis using a daily time step and can perform long term simulations of hundreds of years (Williams, 1995).

EPIC model is also capable of keeping various soil layer parameters for its use. These may include soil layer depth, bulk density, wilting point, field capacity, percentage sand, percentage silt, pH and percentage organic carbon amongst others. The models driving force are observed and/or predicted daily climatic inputs that include total precipitation, maximum and minimum air temperature, total solar radiation, average relative humidity, and the average wind speed (Chung et al., 2000). However it was not possible to apply this model due to the additional required data for the soil temperature, plant growth, plant environment control components etc which are not necessary in other models

2.4.5 Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS)

CREAMS was developed to monitor non point source pollutant loadings for alternate management systems at the edge of a field, on a long term daily simulation basis in order to asses the difference between storms from year to year. It has several simplifying assumptions such as, homogenous soil in the field unit, considers one crop at a time, a single management practice cover over the entire area as well as a uniform area.

The hydrology component of the model has a time step of one day between storms and the important processes to be formulated include precipitation, infiltration, snow melt, soil water redistribution, percolation, evaporation, transpiration and surface runoff. The erosion component of the model is a modification of the Universal Soil Loss Equation (USLE) as proposed by Foster et al. (1981). The equations used in CREAMS are steady state equations and peak discharges are used to estimate sediment concentration, which in turn is used with the runoff volume to estimate the total sediment yield (Haan et al., 1994). Morgan et al., (1989) found that CREAMS simulates yearly amount of runoff quite well, but the accuracy of daily values is quite poor. Even though this model has been used to estimate watershed erosion, it is not intended for that purpose, but it is meant to model erosion for a field-sized area.

2.4.6 Universal Soil Loss Equation (USLE)

The Universal Soil Loss Equation (USLE) first developed by Wischmeier and Smith (1958), and modified to be Revised Universal Soil Loss Equation (RUSLE) by Renard et al. (1991) has been widely used as a tool for predicting soil erosion in many parts of the world. This erosion model is designed to compute long term average soil loss from sheet and rill erosion under specified conditions. It groups the variables affecting sheet and rill erosion in six generic factors. The equation is expressed as

$$A = R\,K\,L\,S\,C\,P \tag{2.33}$$

Where

A- Average soil loss per unit area

R- Rainfall erosivity factor

K- Soil erodability factor

LS-Topographic factor

C- Cover and management factor

P- Support practice factor

R which is a measure of energy of falling raindrops represents the power of rainfall to erode the soil, while soil erodability factor K, is a measure of the susceptibility of a soil to erosion. It is important to note that the erodability of soil varies with different soil factors, but the USLE erodability factor only comprises the physical characteristics of the soil and management factors (Onyando et al., 2005). The land management component of USLE is taken care of by the topographic factor of slope length L and percent slope S and conservation practice factor P. The crop management factor C, compares soil loss under a given crop relative to that of bare soil whereas P factor compares soil loss from cultivated land without conservation practice to that with conservation practice.

The USLE model has some limitations. The equation can only predict interril and rill erosion, but not gully, channel and stream bank. It estimates the movement of soil particles, does not consider deposition and it was designed to model long term erosion rates, not storm based erosion. Therefore for these reasons applying this model to landscape is more difficult than applying it to simpler hill slopes thus it was not applied in the current study.

2.4.7 Agricultural Non Point Source Pollution Model (AgNPS)

Wischmeier and Smith (1978) argued that the Universal Soil Loss Equation (USLE) model is limited to sheet and rill erosion and is unable to predict sediment yield. To measure soil erosion and sediment yield in a watershed, led to the development of the Automatic Water Level Recorder (AWLR) model which was found to be more accurate than USLE (Kusumandari & Mitchell, 1997). However, the model was found to be expensive, time consuming and required substantial inputs. To solve these problems, AgNPS model was developed by the Agricultural Research Service (ARS) in cooperation with the Minnesota Pollution Control Agency and the Soil Conservation Service (Young et al., 1989). It was found to be less expensive and runs faster than AWLR.

The AgNPS is a distributed parameter, event based pollution model used extensively to simulate surface runoff, sediment yield and nutrient transport in mainly agricultural watersheds. The philosophy in developing this model was to balance model complexity and model parameterization, the main objective being to describe major transport processes related to non point source pollution within landscapes while using empirical and quasi-physically based algorithms. The model has got three basic components namely hydrology, sediment and nutrient transport. In the hydrology component, runoff volume and peak runoff flow are calculated. The erosion portion computes total upland erosion and total channel erosion. The upland erosion is routed through the watershed. The chemical transport portion is separated into one part handling soluble pollutants and another part handling sediment-attached pollutants. It considers Nitrogen and phosphorous in addition to Chemical Oxygen Demand (COD) which is a measure of the oxygen required to oxidize organic and oxidizable inorganic compounds in water. Various output options are available with the model. These can be examined for a single cell or for the entire catchment. The outputs include runoff volume, peak runoff rate, sediment concentration, and sediment yield. Detailed nutrient analysis including the unit area amount of Nitrogen, Phosphorous and COD in runoff, and Nitrogen and phosphorous for sediment adsorbed nutrients as well as the nitrogen and phosphorous concentration in runoff are the output. The model requires input data presented in Table 2.2

Table 2.2: AgNPS data requirements

AgNPS parameters	Other parameters
i). Watershed data	i) Soil characteristics
Area of the watershed	COD factor
Number of cells in the watershed	Soil texture group
Cell number	Manning coefficient of the soil
Receiving cell number	Surface condition constant (SCC)
Area of each cell	
ii). Land use information	ii) Rainfall characteristics
Runoff curve number (SCS)	Storm precipitation
Land slope (%)	Storm erosivity
Slope factor	Storm duration
Field slope length	Storm type
Channel slope	
Channel Manning's roughness coefficient	
Soil erodability factor (K)	
Cropping factor (C)	
Support practice factor (P)	

The model is linked to a GIS to assist in data handling and automation of the modeling process (Tim & Jolly, 1994)

The AgNPS model was favoured mainly because its capability of estimating spatial distribution of peak runoff and sediment yield, its ability to allow for deposition of sediment and/or scouring of all sediment during flow, as well as being a storm event based model applied at catchment scale. The size of the study area is 38381.7 acres is far much below the maximum limit of 50,000 acres required for the model.

2.5 GIS and RS Techniques of Data Acquisition

2.5.1 Remote Sensing (RS)

Remote sensing is the science of obtaining information about an object from data collected by a device not in physical contact with it. Specifically it refers to the study of imagery resulting from the reflectance and emittance properties of the earth surface or atmosphere. Remote sensing utilizes the Electromagnetic (EM) radiation, and to date is primarily concerned with the visible, infra-red and Microwave region of the electromagnetic spectrum (Lo, 1986). All bodies with a temperature above absolute zero emit EM radiation. Ideally, the amount of radiation emitted is given by the Stefan Boltzmann law which says that the amount of radiation emitted at a given wavelength is proportional to the fourth power of temperature (Barker, 1988), meaning that the emitted radiation rises rapidly with temperature of the body. The wavelength at which most of the radiation is emitted is given by Wiens displacement law (Williams, 1994), which states that, the wavelength at which maximum radiation is emitted is inversely proportional to its temperature. Both the sun and the earth are sources of EM radiation, however, the earth is a much weaker source of EM radiation than the sun. When EM radiation is incident upon a material, some of the radiation will be reflected away, absorbed by the material and finally transmitted through the material. It is the different absorption, reflection and transmission properties of materials that make the science of remote sensing possible.

Remote sensing devices may be passive or active. Passive remote sensing devices just point their sensors on to the object and receive radiation from them, whereas an active remote sensing device generates its own pulsed beam of radiation, directs it on successive strips of the terrain below, and registers the information reflected back. They are therefore all weather systems because it is not dependent on sunlight. The radar is a good example of an active remote sensor.

The remotely sensed information is recorded and transmitted in dot-like picture elements called "pixels". The pixel is the smallest item of information registered by the sensor on a satellite, it determines the resolution of the image, and, any feature on earth surface smaller than the area covered by a pixel will not be seen as an entity itself. As the satellite scans the earth, it senses the average intensity of radiation from each pixel and records it as a digital number i.e. a binary number consisting of a combination of 0's and 1's. The digital numbers (DN) are used to convert the information into a form which can be transmitted, handled, processed, stored and retrieved by computer (ERDAS, 1991). The pixels are allocated a number from 0 to 255, depending on the strength of signal received in each spectral band. Zero is taken as representing black and 255 represents white, while the range of 254 numbers representing different tones of grey (ILWIS, 2001).

Once the information reaches the ground stations, computer software's are used to decode the binary data and allocate the appropriate tone to each pixel. The raw and basic images can then be displayed on a monitor screen as a print-out. However before using the raw image it has to be corrected for earth curvature, earth rotation and satellite altitude errors and then georeferenced. Studies in recent years have shown that many inputs for runoff and sediment generation models can be derived from aerial photographs or satellite data. In the current study the land cover map of the study area was processed from a Landsat satellite imagery and subsequently used to come up with model parameters that are dependent on the land use.

2.5.2 Geographical Information System (GIS)

A GIS is a computerized data management system that facilitates the phases of data entry, data analysis and data presentation of spatially georeferenced data (ESRI, 1996). The process of using a GIS, essentially involves three important stages of data preparation and entry, data analysis and finally, data presentation (ILWIS, 2001).

1. Data preparation and entry

This is the early stage in which data about the study phenomenon is collected and prepared to be entered into the system. Before using GIS, it must be provided with data. Much of the success of a GIS work however depends on input data quality and thus this phase of a GIS project is critical and must be taken seriously (Chris, 2000).

Spatial data may be obtained from scratch, using direct spatial data acquisition techniques like direct observation of the relevant geographic phenomenon, through ground based field surveys or by using remote sensors or satellites (Lucas & Gerrit, 2001). Direct spatial data acquisition has the advantage, that the data can be interpreted immediately even though this technique is expensive and time consuming. Spatial data can also be obtained indirectly by making use of spatial data collected earlier possibly by others or by digitizing maps.

Spatial data preparation aims at making the acquired data ready for use. Images may require enhancement and corrections of the classified schemes of data. Vector data are edited and may be converted to raster format to match the other data sets. Acquired data sets should be checked for consistency and completeness. This applies to geometric and topological quality as well as the aesthetic quality of the data. This may be done manually or automatically.

2. Data analysis

This process entails transforming and combining data from diverse sources into useful information to satisfy the objectives of the user. Analytical capabilities of GIS can be classified into,

Measurement, retrieval and classification functions- which allows one to explore the data without making serious changes, often used at the beginning of data analysis. Measurement functions include computations, spatial queries retrieve features selectively using user defined logical conditions, while classification is a technique of purposefully removing details from an input data set, in the hope of revealing important patterns of spatial distribution (Jonathan, 2000).

Overlay functions- allow data layers to be combined and new information is derived, usually by creating a feature in a new layer.

Neighbourhood functions- evaluate the characteristics of an area surrounding a feature's location. This allows one to look at buffer zones around features and spreading effects if features are a source of something that spreads.

Connectivity functions- evaluate how features are connected. This is useful in applications dealing with networks of connected features.

3. Data presentation

The data presentation phase deals with putting all data together in a form that communicates the results of spatial data analysis in the best possible way (Kraak & Brown, 2000). After the data manipulation, it is prepared for production of maps. The most important characteristic of these on-screen maps are that they are interactive and have a link to the database. For optimal presentation of the results, the following must be taken into consideration: the message, audience, medium, techniques used as well as the rules of aesthetics.

Development and use of an automated GIS can expedite data integration problems and the time consuming process of synthesizing tremendous amounts of information for the spatial examination of non-point pollution. An automated information system, through which geographically referenced data can be input, manipulated, and analyzed, can improve the decision making process of an organization. The process of refining models using computer based information (GIS), results in fast and reasonable predictions of the various parameters. Many spatially distributed hydrology and water quality models rely on a cellular structure to capture the landscape. GIS allows spatial variations to be taken into account, and also automates the process of manually entering data that corresponds to each pixel, since in most cases the catchments are big resulting in very many pixels. GIS, therefore represents an adequate framework for pre- and post processing geo-referenced model input variable or output data. Two approaches exist for coupling models with GIS:

1. **Linking models with GIS (" linked model" approach)**

The process of linking the model with GIS entails passing relevant information back and forth between the GIS and the "stand alone" model. Models can be linked to GIS in two ways namely

Ad-hoc integration

In this case the GIS and the model are developed separately. The model required Input data is extracted from GIS by running different GIS utility command and the model is run independently from the GIS and model results are evaluated with measured data separately. This method of integration has high potential for errors. Figure 2.2 below shows the GIS and Model sharing the same data which can be accessed by the user through a user interface.

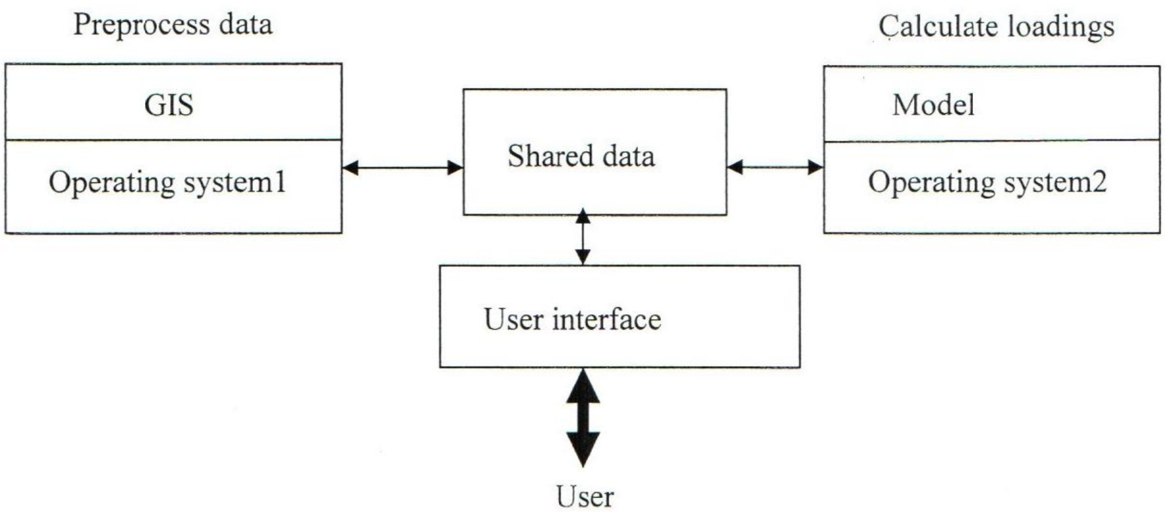

Figure 2.2: Ad-hoc integration of model and GIS (Source: Burrough, 1986)

Partial integration

In this level the GIS database that can assist in parameterizing the model are developed. An interface model is then developed on top of the existing GIS database, which produces inputs of the model. The interface further uses the model results for processing and presentation. A typical example of this level of integration is coupling of a grid based model with a GIS. Figure 2.3 below shows the GIS and Model sharing the same data which can be accessed by the user through a user interface. However the user interface has direct connections to the model, data and GIS.

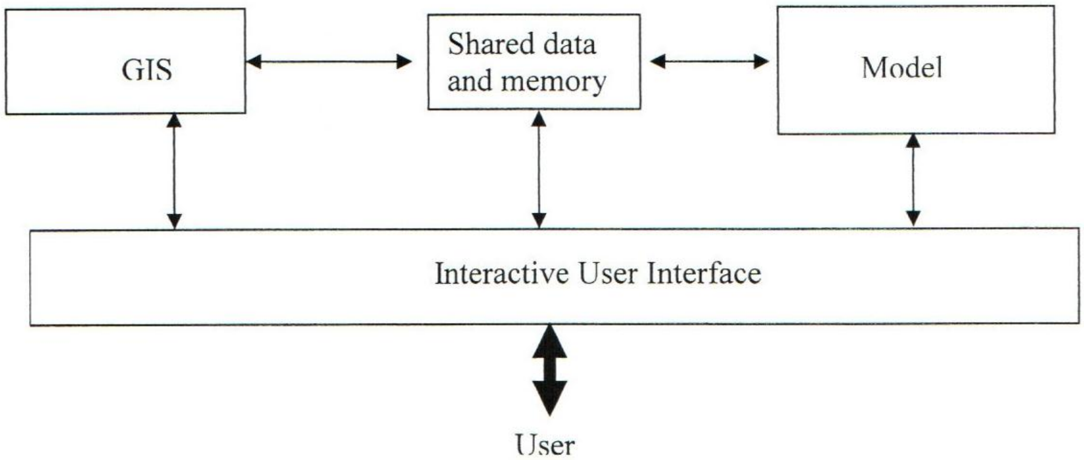

Figure 2.3: Partial integration of model and GIS (Source: Burrough, 1986)

In this study, the partial integration of the model and GIS is adopted. Linkage between the AgNPS model and ILWIS GIS software is established through special purpose computer programs and interfaces that provide the access points between the GIS database, AgNPS, and the user.

2. **Modeling within the GIS ("modeling within" approach)**

Modeling within GIS involves complete integration of the two technologies mentioned above. The GIS and model are developed in close interaction and in a single operating environment. The data stored in GIS is structured to meet the demands of the model and vice-versa. The complete integrated model and GIS can therefore be easily adapted to produce the model requirements data and thus mimic the model limitations and objectives. This level of integration is the most difficult in terms of developmental efforts, this is because of the lack of communication between the developers of the model and those of the GIS, moreover, property rights of commercial GIS software's also limit the complete integration of model and GIS thus the other two levels are the only practical solution. Figure 2.4 below shows the GIS and Model in a common operating system.

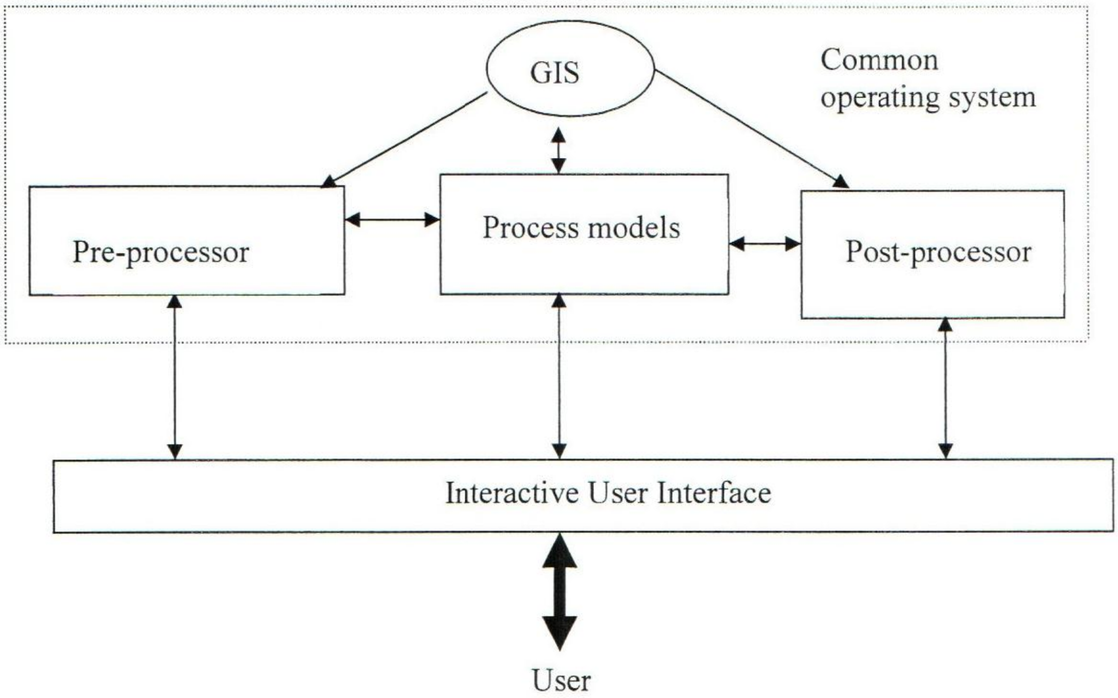

Figure 2.4: Complete integration of model and GIS (Source: Burrough, 1986)

2.6 Concluding Remarks

Estimation and assessment of runoff, soil loss, and nutrient transport from a catchment is important for catchment management. Over the recent past, hydrologic modeling has received considerable attention, and applied research on estimation of soil loss and nutrient transport needs to be used by managers.

A few researchers have used the AgNPS model for evaluating the impacts of agriculture in catchments. Perrone and Madramootoo (1999) calibrated and then validated the model for the St.Esprit watershed in Quebec, Canada. Mankin et.al, (1999) applied the model in the Melvern catchment in Kansas. Khoelliker and Humbert (1989) also applied the model in five Kansas catchments to evaluate the sediment and nutrient outputs with the present land cover conditions. Their findings were satisfactory with EFF values of greater than 0.85 and percentage errors of less than 5%. The present study envisages using the model to estimate the Peak runoff rates and sediment yield for the Upper River Njoro catchment.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

3.1.1 Location

The River Njoro catchment which is the study is located approximately 150 km North West of Nairobi, Kenya. The catchment is part of the larger Lake Nakuru catchment. The area of the catchment is approximately 250 km^2 and varies in altitude from 2700 m a.s.l on the eastern side of the Mau complex, one of Kenya's major water towers to 1700 m a.s.l at the outlet in Lake Nakuru. The mean annual precipitation is 1200 mm distributed bimodally with peaks in May and October. The present study focuses on the upper catchment which is approximately 127 Km^2. The map of Kenya is shown in Figure 3.1 below with Nakuru District in which the study catchment is found. The upper River Njoro catchment, the study area, is also shown in the Figure.

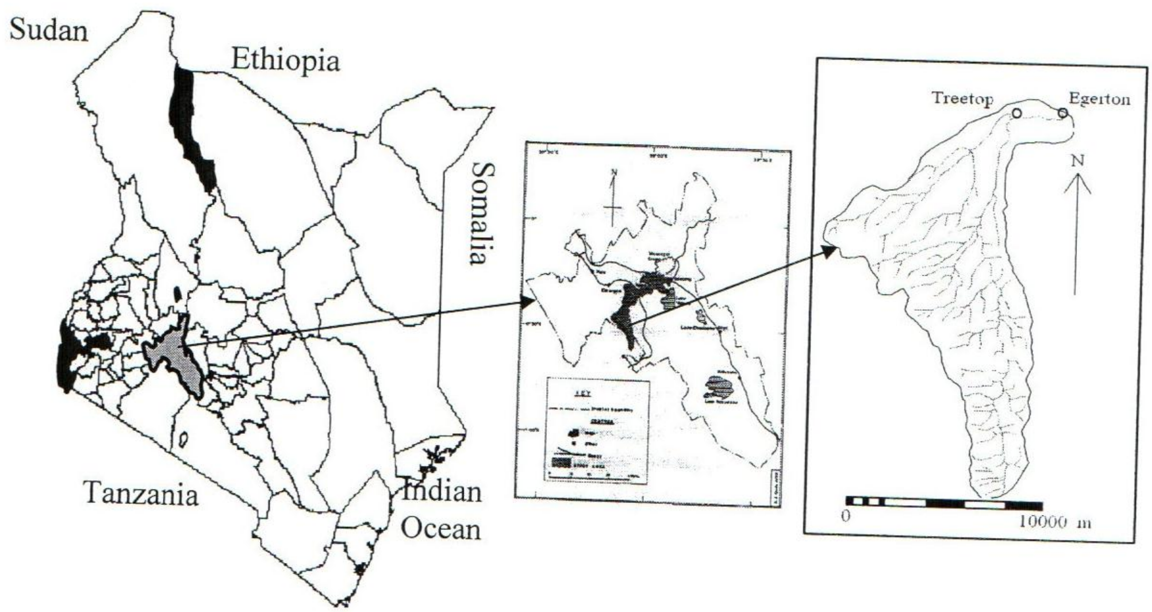

Figure 3.1: Maps showing Kenya, and the Upper River Njoro catchment with drainage network and the two gauging stations.

The upper River Njoro catchment has the Egerton university bridge gauging station (00.37347^0S, 35.94077^0E) at 2203m a.s.l as the outlet. This point has a monitoring station and therefore monitors the response of the sub-catchment. The other monitoring station is Treetops gauging station (00.37528^0S, 35.92029^0E) located at 2285m a.s.l. and 3.7 kilometers upstream of the outlet. This length of the river forms the river reach which was used in this study for flow routing.

3.1.2 Geology and Soils

The geology and soils of the area is influenced by the volcanic nature of the Rift valley. The upper part of the catchment is predominantly loamy soils that developed from ashes and other pyroclastic rocks of recent volcanoes (Ralph & Helmidt, 1984), whereas the lower catchment is covered by erosive lucustrine soils.

3.2 Data Acquisition

3.2.1 Rainfall and Stream flow

The rainfall data were taken from the readings of non-recording rain gauges of the Egerton University weather station ($00^0$23'S, $35^0$55'E) at 2238m a.s.l within the sub-catchment. Eleven storm events were considered in the study. The corresponding stream flow was also taken at the two monitoring sites selected for the study. Stream flow measurements were made by recording the height of the surface of water read from a staff gauge after the storms. The elevation readings were converted to discharge using a rating equation.

3.2.2 Water Quality

Runoff sampling was done at the two monitoring sites after storm events for sediment concentration analysis in the laboratory. A depth integrating hand sampler was lowered into the stream at a constant vertical speed, and also raised to the surface at a constant speed. Three traverses were made across the stream section to come up with the suspended sediment load for the section.

The samples were then filtered, oven dried and weighed. Using the direct runoff volume the weight of the sediment was converted into a sediment yield in tonnes for a particular storm.

3.3 GIS Data Processing

The AgNPS being a GIS based model requires the catchment to be subdivided into uniform squares grids or cells. The gridding and subsequent processing of topographic and terrain variables from basic GIS data layers entailed the creation of vector maps (point, segment and polygon), vector to raster conversion, map algebra (calculations), spatial filtering and use of neighbourhood operators, in addition to the use of extraction routines which are mostly model specific. In this study the Geo-referenced Interface Package (GRIPs) was used to extract the model input parameters in Table 2.2 from the GIS (ILWIS) to the AgNPS model for use in the simulation. ILWIS integrates image processing and spatial analysis capabilities, tabular databases and conventional GIS characteristics. The GIS database created in this study for the catchment, focused on the attributes and data required to run the model.

When gridding (dividing the catchment into cells) a cell size of 50 m was used then aggregated to 250 m. Border cells with less than 50% of their area within the catchment were excluded. The catchment grid cells are numbered proceeding from the northwest corners from west to east in a southward direction. This process resulted in the creation of 2006 grid cells. The cell numbering presented the essential key index for the input data files and was used to check the routing of peak flow rate, sediment concentration and phosphorous levels through the grid system.

3.3.1 Derivation of Contour Map.

A topographical map of 1:50000 of the catchment was scanned, imported into ILWIS and geo-referenced. Using the method of on-screen digitization, the contours were digitized extending slightly outside the boundary of the catchment. The contours were then labeled using the topographical map sheet as a reference. In ILWIS, a digital contour map is the necessary sole input in the process of deriving a Digital Elevation Model (DEM) and therefore the contour map must be checked for correctness with respect to code consistency, overlap and crossing. The digitized contour map whose layout was created at 100m vertical interval for clarity is shown in the Figure 3.2.

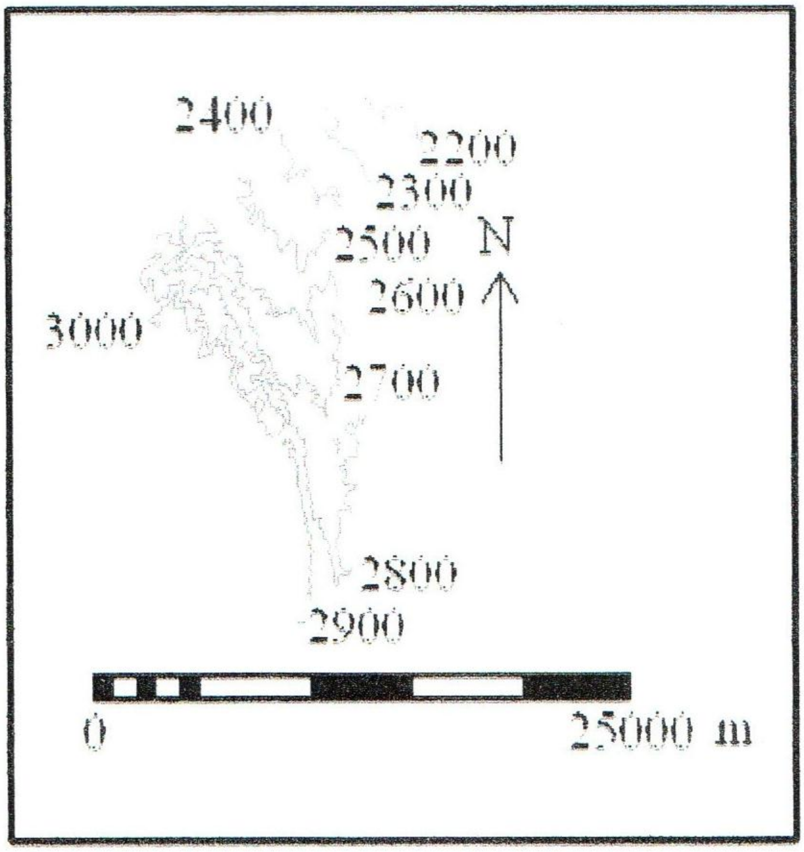

Figure 3.2: The digitized contours map of the study area

3.3.2 Derivation of a Digital Elevation Model (DEM)

The DEM is a raster map showing the elevation of each point in the catchment. The DEM was developed using the derived contour map described and shown in Section 3.3.1 above. The DEM was based on segment lines describing 20 m spaced contour lines on 1: 50000 topographic sheet of the River Njoro catchment. The contour lines were rasterized with a pixel resolution of 250 m, this pixel size was found to be optimum for the whole 127 km^2 drainage area to ensure a trade-off between the accuracy of the results and the technicalities involved in running the model which depends on the number of cells such as the manual elimination of sink holes as was the case in the study and the time to run the model. The accuracy of the result can be increased by reducing the cell size, but this increases the time and labor required to run the model. Conversely, enlarging the cell size reduces time and labour, but the savings must be balanced against the loss of accuracy resulting from treating larger areas as homogeneous units. The DEM was then calculated by interpolation between two nearest contour lines.

Numerous topographic variables and land surface characteristics required by the model as inputs depend on the DEM. These variables include the flow direction, land slope, slope shape indicator, slope length, channel indicator and channel length. These were extracted from the derived Digital Elevation Model.

The flow direction map was derived using neighbourhood operators and shows the direction of runoff flow which is largely dependent on the slope gradient for each pixel in the DEM. It is determined using the first derivative in the X and Y directions of the pixel movement. The square root of the sum of both squared derivatives divided by the pixel size was taken to be the slope gradient. The flow direction syntax used by the AgNPS model had to be respected as it may not coincide with the GIS neighbourhood denominations.

The slope length map indicates the distance on a homogeneous slope needed either for surface runoff to concentrate in rills and channels, or to enter a well defined channel. A slope shape map indicates the dominant slope shape of the cell, as uniform, convex or concave, while a channel indicator map distinguishes pixels that have stream channels in them from those that do not have.

3.3.3 Derivation of a Land Cover Map

A Landsat Thematic Mapper (TM) satellite imagery of 2001 was used to obtain the land cover map of the study area by multi spectoral image processing capabilities of the ILWIS software. It was assumed that there were no major changes in land use that had occurred between the year 2001 and 2005 when the data collection was done. Three spectoral bands, bands 3, 5 and 7 were used in the supervised classification using Gaussian maximum likelihood classifier method to extract thematic information from the satellite imagery. This decision making algorithm was preferred due to its ability to have an efficient decision boundaries. Supervised classification is divided into two phases namely a training phase where the user trains the computer by telling for a limited number of pixels to what class they belong in the image, followed by the decision phase, where the computer assigns a class label to all (other) image pixels, by looking for each pixel to which of the trained classes the pixels is most similar. The land use was clustered and grouped into four predominant groups: Forest, Agriculture, Shrubs and Settlement as shown in Figure 3.3.

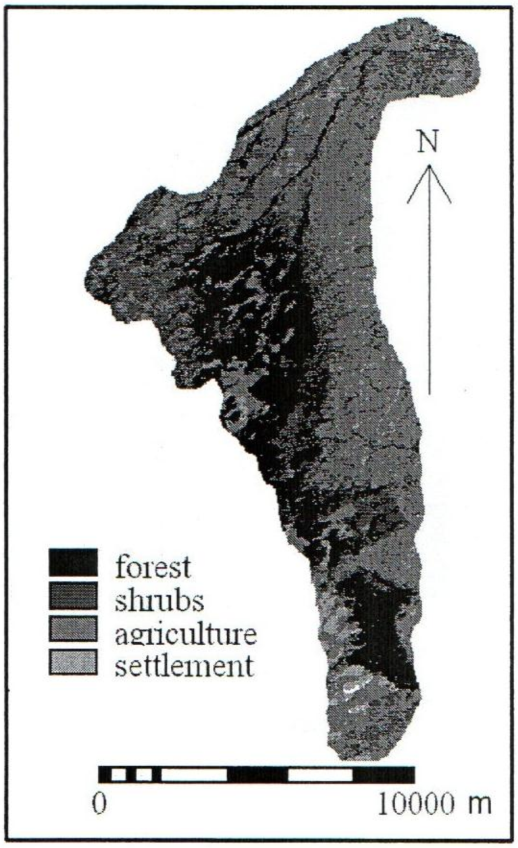

Figure 3.3: The derived land cover map of the study area

The computation capabilities of the ILWIS software was used to come with the proportions of the various land covers within the study area. Agricultural and shrub land was found to account for 38% each of the catchments land mass whereas, 21% of the land was under forest with the remaining 3% of the land under settlement. The higher proportion of crop and shrub lands shows the threat under which the catchment faces as far as accelerated erosion is concerned. This is occasioned by increased encroachment into the forest land.

The land cover data was then used to provide input coefficients for AgNPS, assigned for SCS-Curve number, Surface Condition Constant (SCC), COD-factors, K-factors (soil erodibility), C-factors (Cropping), and Manning's coefficient of the soil. The spatial distribution of the Surface Condition Constant (SCC) is shown in Figure 3.4 and others in section 3.4.

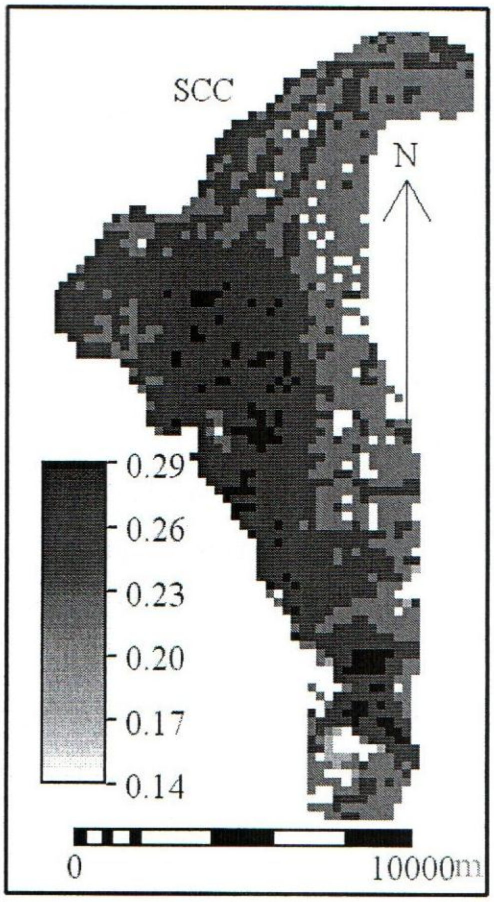

Figure 3.4: The derived Surface Condition Constant (SCC) map of the study area

3.3.4 Derivation of a Drainage Map

The drainage map of the study area was also obtained through digitization of a scanned topographical map using the same procedure used in the digitization of contours. Digitization was started from the headwaters to the outlet of the study area to ensure that the flows are properly routed throughout to the outlet. The digitized drainage map is shown in Figure 3.1 with the two monitoring stations

River Njoro is a second order stream, with its major tributary joining it at the confluence slightly above the Treetop station. The other high order tributaries are seasonal and only have flows during and shortly after storm events. The high drainage density indicates the study area is located at high altitudes on the slopes of Mau hills with high erosion potential and deposits along the drainage channels.

3.4 AgNPS model Simulations

The process of predicting the required outputs via the model-GIS link was divided into three phases.

(i) Spatial database preparation

The AgNPS model requires a large volume of data from various sources as shown in Appendix Table A1. The basic input data into the GIS were contours, drainage, boundary and land cover maps. The contour, drainage and boundary maps were created by vectorization as described in Section 3.3.1, whereas the land cover map was processed from a Landsat TM image of 2001 as discussed in Section 3.3.3. The other parameters required by the model were either derived from the basic input maps or input as constants.

(ii) Derivation of spatial layers

This phase was enhanced by utilizing the capabilities of GIS (calculation, classification, overlay, neighbourhood, and connectivity functions) to come up with other spatial layers related to the basic input layers. The contour, drainage and boundary maps were rasterized (converted to raster maps) and used to generate the DEM which was later used to generate dependent raster layers of cell number, slope length, slope shape, flow direction, channel indicator and channel gradient. The land cover map was used to derive USLEs' K (soil erodibility), C (Cropping), and P (Conservation Practice) factors, SCS-CN (Soil Conservation Service-Curve Number), SCC (Surface Condition Constants), COD (Chemical Oxygen Demand) and Manning's coefficient maps. The values of these parameters for the study area were determined and are presented in the Table 3.1.

Table 3.1: Land use and its related variables

	SCC	SCS	COD-factor	K-factor	C-factor	Manning. Coeff.
Forest	0.29	25	20	0.035	0.038	0.04
Agriculture	0.29	78	170	0.290	0.350	0.04
Shrubs	0.22	58	80	0.090	0.087	0.04
Settlement	0.14	90	37	0.150	0.320	0.15

The C (crop management) factor compares the ratio of soil loss under a given crop to that of bare soil. For the study area, C-factor values were found to range from 0.038 to 0.35 depending on the various land use when checked in literature (Crops C-factor manual) and its spatial distribution is presented in Figure 3.5.

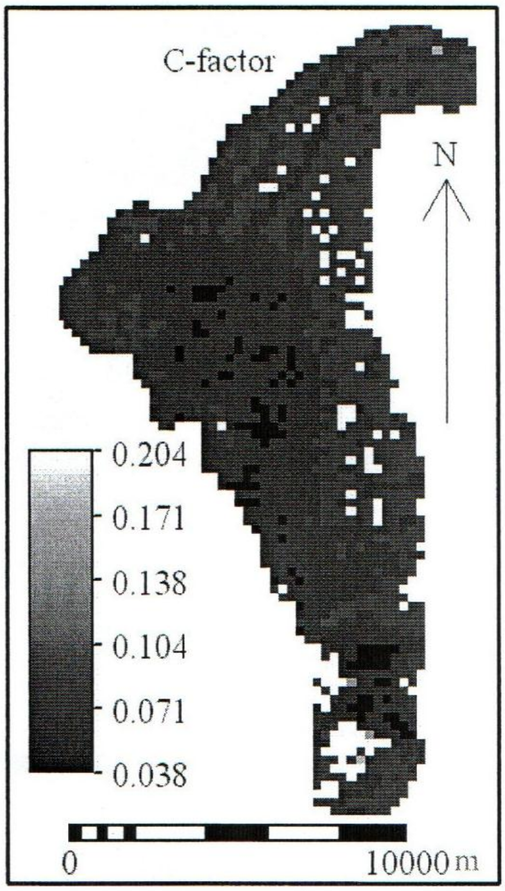

Figure 3.5: Spatial distribution of C factor

The forest cover had a lower value of C indicating good protection to the soil as compared to the shrub land, settlement and agriculture. A high C-factor has the effect of reducing infiltration during a storm, resulting to an increase in surface runoff and sediment concentration in the runoff.

Another parameter for the model is the Chemical Oxygen Demand (COD) which is a measure of oxygen required to oxidize organic and oxidizable inorganic compounds in water, is an indicator of the degree of pollution and varies with land cover. AgNPS assumes soluble COD. COD estimates in runoff is based on average concentration of COD in runoff, and allowed to decay with time once they enter a channel according to an exponential decay. Soil samples from the various land uses was collected for COD tests in the laboratory. The values of this parameter for the various land cover which ranged from 20 to 170 is presented in Figure 3.6.

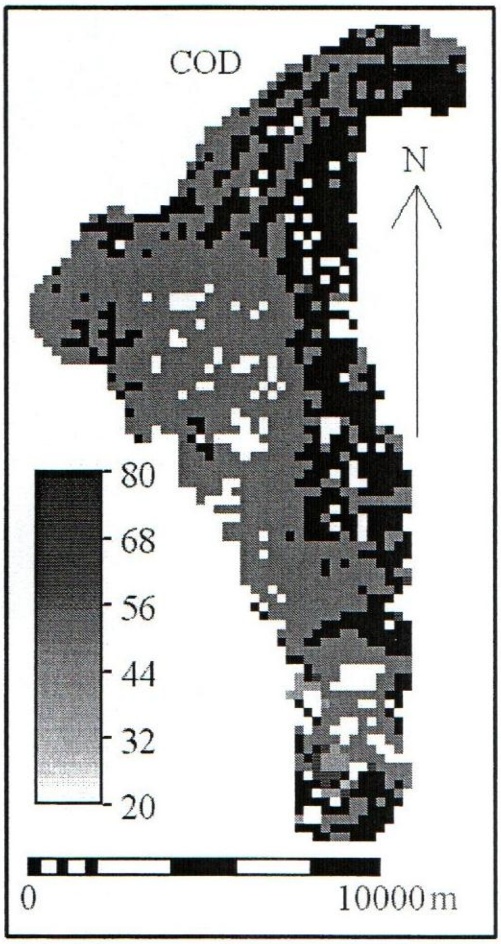

Figure 3.6: Spatial distribution of COD factor

The COD factor was found to increase in the order of forests, settlement, shrubs and agriculture, implying that agricultural land required more oxygen to oxidize organic and oxidizable inorganic compounds in runoff.

Soil erodibility factor (K) is a soil dependent parameter. It is a function of the percentage of silt and coarse sand, soil structure, permeability of soil and the percentage organic matter. These four parameters of the soil were established in the laboratory and used for getting K-factor based on soil Nomographs by Morgan (1986), the K-factors for the various land covers were found to be in the range 0.035 to 0.29 and their spatial distribution shown in Figure 3.7.

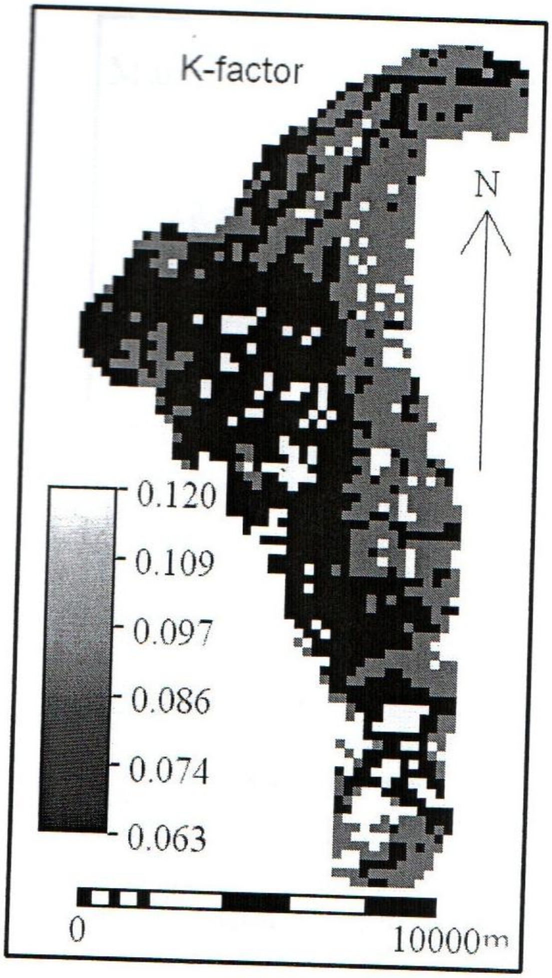

Figure 3.7: Spatial distribution of K factor

Another parameter, the soils manning coefficients refers to the soils roughness and thus implies the resistance of flow of water in and on the soils. Therefore it is one of the important parameters for describing water flow over the ground. Lower values of this coefficient denote less resistance to flow and vice versa. Foster et al., (1981) estimated the average Manning's coefficient values for different land uses, and based on their tabulated values, the spatial distribution of the coefficient for the various land covers in the study area are presented in Figure 3.8.

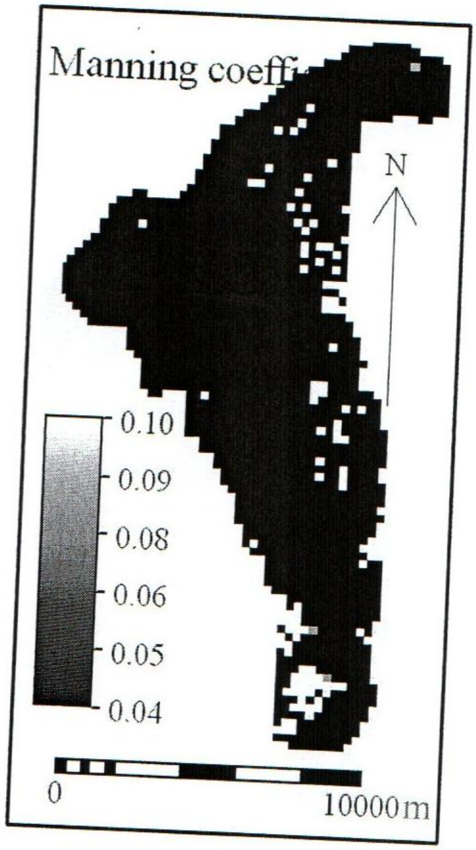

Figure 3.8: Spatial distribution Manning coefficient of the soil

The Curve Number (CN) is a dimensionless index that describes runoff as a range between 1 and 100, with 100 indicating maximum runoff. The Curve Number is dependent on the hydrological soil cover complex of the catchment. This cover complex comprises of a combination of the hydrologic soil group and a land use and treatment class. Curve Number values were assigned to each complex to indicate their specific runoff potential. The curve number values for the catchment ranged from 25 to 90 based on literature by Chow et al., (1988). The greater the curve number, the greater the surface runoff volume. The spatial distribution of this parameter over the study area is presented in Figure 3.9.

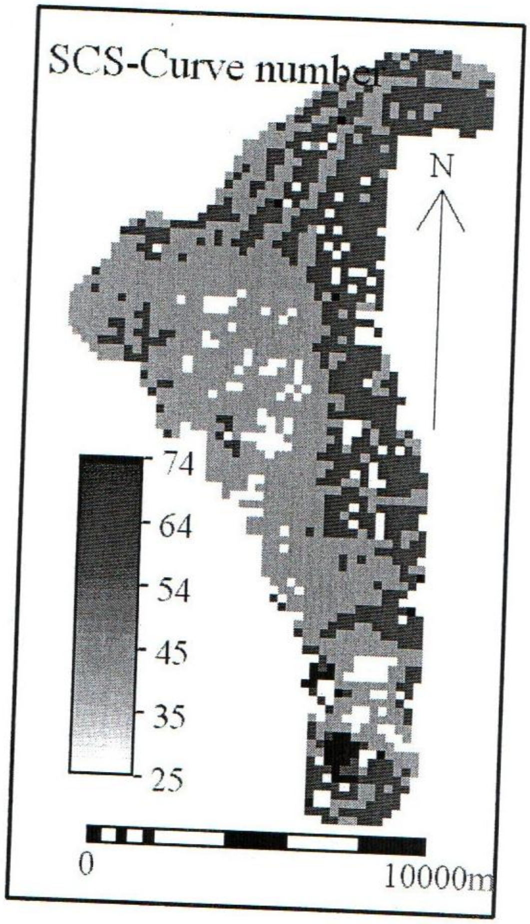

Figure 3.9: Spatial distribution of SCS-Curve Number

(iii) GIS and model interface

This phase involved the coupling of the interface GIS with the model. An extraction program was used to extract data from the GIS environment and transform and take it to the model. An interface program (GRIPs) developed by ITC-Water Resources and Environmental Studies (WRES) was used to convert ILWIS map files, containing the parameter data, to an input data file acceptable by the model. This program is available for a two-way conversion from ILWIS 2.x and 3.x to and from AgNPS v.5. It reads the map values for the respective cells and writes these values to a file in AgNPS data format.

The input data was then entered in the interface and checked for flow routing, by eliminating sink holes and ensuring that the catchment drains through the outlet. The GRIPs then run the model and created ILWIS files which contains the model outputs to be compared with the observed outputs.

A simplified schematic diagram of the integration process is presented in the Figure 3.10 below.

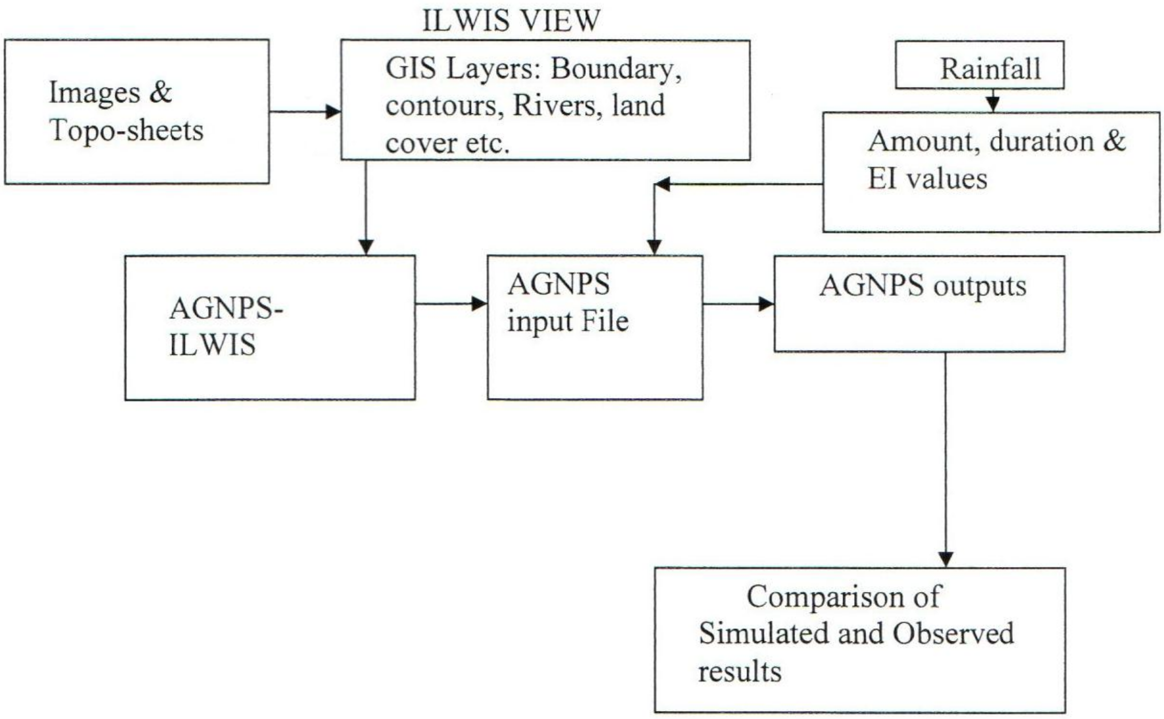

Figure 3.10: Schematic diagram of the entire integration approach

3.5 Estimation of observed peak direct runoff rate

The peak direct runoff rate is the highest discharge occurring after a storm event. It is the result of accumulating direct runoff volume within a stream channel. The peak flow rates were taken at the time of concentration of the catchment, the assumption being that at this time all the catchment is contributing discharge at the outlet. It was calculated by the Kirpich formula as

$$T_C = 0.01947 \ * L^{0.77} \ * S^{-0.385} \qquad (3.1)$$

where

T_c = Time of concentration (min)

L = Maximum length of flow (m)

S = Catchment gradient

The Kirpich formula was selected in this study because it is capable of giving an estimate of the time to concentration of a catchment by relying on only two parameters, the slope and maximum length of flow. The two parameters are the most important and effective in estimating time of concentration. The average time of concentration was found to be about two hours and forty five minutes for the 127 km^2 catchment.

Discharge in rivers is not measured directly but is estimated from curves relating stage to discharge. Existing rating equations for the two gauging stations were obtained from SUMAWA- a project that deals in Sustainable Management of Watersheds based in the River Njoro watershed. These rating equations had been developed using the Velocity-Area method using a current meter. This method entailed dividing the cross section of the river into sub-areas, and summing the product of these sub areas and average velocities. The rating equation is used to convert sequences of water levels measured on a staff gauge placed on a riverbank to sequences of discharge. A quality analysis was conducted for the two rating equations and updated to justify their use in the study. The resulting rating equations 3.2 and 3.3 are given as.

Egerton bridge (Downstream)

$$Q = 2.996H + 0.0032 \tag{3.2}$$

Treetops (Upstream)

$$Q = 2.04H + 1.635 \tag{3.3}$$

where

Q = Discharge (m^3s^{-1})
H = Stage Height (m)

The discharge estimated is a stream flow hydrograph which includes the base flow and the direct runoff hydrographs. To get the direct runoff, the base flow values were thereafter separated from the total discharge values using the variable slope method of storm hydrograph separation. This was necessary because with the direct runoff and sediment concentration data it is possible to obtain the observed sediment yield.

In the variable slope method of base flow separation, the base flow curve before the surface runoff begins is extrapolated forward to the time of peak discharge. The curve after the surface runoff ceases is extrapolated backwards to the time of the point of inflection on the recession limb. A straight line is then used to connect the endpoints of the extrapolated curves, so that the area of the hydrograph below the straight line represents the base flow whereas the area above is due to the direct runoff. The separated peak runoff rates were then used in assessing the model performance with respect to predicted peak runoff rates. The Variable slope method of hydrograph separation is presented in Figure 3.11, the approximate line of which was used in the separation process (Shaw, 1996).

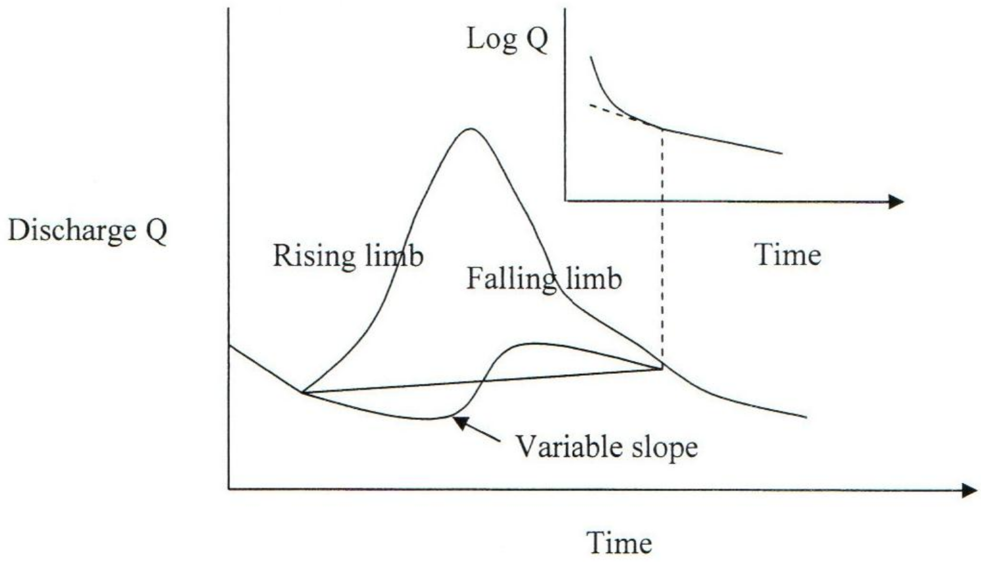

Figure 3.11: Variable slope method of hydrograph separation

3.6 Flow Routing

Flow routing is a technique used to determine flow hydrographs of remote location when flow hydrographs at an upstream station exist. Numerous flow routing techniques exist for this purpose as discussed in Section 2.3.2. The Muskingum routing model was applied in this study to estimate the flow hydrographs at the Egerton (downstream) station using flow hydrographs from the Treetop (Upstream) station. This routing model has three fundamental parameters which are presented in the Table 3.2.

Table 3.2: Muskingum routing model parameters

Parameters to be estimated	
k	Time propagation of a given flow along the reach
x	Weighting factor expressing the relative influence of inflow and outflow
t	Routing period

The length of flow between the two monitoring stations was considered as the river reach length, with the Treetops station having the inflow hydrograph and the Egerton station outflow hydrograph. The storage in the reach at various times was established by subtracting the outflow from the corresponding inflow, after which the Muskingum storage constant (k) which is the ratio of storage to discharge was determined through an iterative process by plotting S vs. [xI+(1-x)O].

The values of x considered were 0, 0.05, 0.1, 0.15, 0.2, 0.25 and 0.3. The best value of x is that which caused the data to plot nearly as a single-valued curve. The Muskingum method assumes that this line is a straight line with slope k. The coefficients C_o, C_1 and C_2 were then computed by taking a routing period (t). This period should never be greater than the time of travel through the reach. The travel time of the 4 km reach was found to be approximately 25 minutes by the wave celerity method. The Muskingum model showing the river reach and the equations used are also discussed in Section 2.3.2.

The routing models results were then evaluated against the observed results to see how closely they agree, and establish whether routing can replace direct observations in the study area.

3.7 Sediment Yield Determination

The data on discharge and sediment yield for the two monitoring stations was used to come up with a relationship between the discharge and the sediment yield. Regression techniques were used to establish the best model to fit the data for the two stations. The two models developed (Polynomial equations) were important in presenting the trend in sediment yield that exist at the two stations.

Using the Muskingum routed hydrograph for the downstream (Egerton) station, the sediment yield for the station was estimated using the derived Polynomial equation for the station and the measure of goodness of fit between the estimated sediment yield and the observed sediment yield established in terms of Nash and Sutcliffe efficiency (EFF).

3.8 Methods of Evaluating the Results

The measurement of goodness of fit was achieved by the use of objective functions. An objective function is an equation for computing a numerical measure of the difference between observed and simulated outputs. The objective functions used in the study to measure the goodness of fit based on the difference between the observed and simulated results is outlined by ASCE (1993). One of these is the Nash and Sutcliffe (Model) efficiency (EFF). The Nash and Sutcliffe efficiency used to compare observed and predicted values is presented in equation 3.4.

$$EFF = \frac{\sum_{i=1}^{n}(Q_i - \overline{Q})^2 - \sum_{i=1}^{n}(Q_i - P_i)^2}{\sum_{i=1}^{n}(Q_i - \overline{Q})^2} \qquad (3.4)$$

where:

Q_i = Observed values

P_i = Predicted values

The EFF value approaches one as the predicted values approach observed values. The lower limit of the EFF statistics is less than zero, it can take negative values. If the model predicted values exactly matches the observed values then EFF=1. Percent Error (PE) was also used in the study to show the resulting degree of accuracy from the use of the model. This is a dimensional quantity and takes the unit of the variable being examined. Values of PE close to zero indicate a perfect fit of estimated values.

$$PE = \left|\frac{Q - P}{Q}\right| * 100 \qquad (3.5)$$

The quantitative techniques described here were complemented with graphical displays that showed how the results were distributed in relation to a 1:1 line thus, providing a sound basis for analysis of the results.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Simulation Results

4.1.1 Peak Runoff Rates

The observed peak gauge heights, for eleven rainfall events in the study area, were converted into peak discharge using rating equations and their base flow separated. The observed and AgNPS simulated results for the two gauging stations are presented in Tables 4.1 and 4.2.

Table 4.1: Treetop's (upstream) station Peak runoff rate results

Event	Rainfall (mm)	Peak Runoff Rate (m^3/s) Observed	AgNPS Simulated	Error (%)
15/01/04	40.6	2.966	3.065	-3.3
11/04/04	42.5	2.981	3.088	-3.6
23/05/04	45.0	3.055	3.179	-4.1
22/07/04	37.0	2.267	2.406	-6.1
11/08/04	28.0	2.843	2.692	5.3
14/11/04	8.4	2.522	2.406	4.6
23/11/04	9.5	2.747	2.617	4.7
25/11/04	17.5	2.521	2.670	-5.9
16/12/04	25.6	2.910	2.882	1.0
26/01/05	16.5	2.468	2.521	-2.2
22/03/05	26.5	2.863	2.747	4.1

Table 4.1 presented above show the observed and predicted peak runoff rates as well as the percentage error for the predictions for the upstream gauging station, whereas Table 4.2 presented below show the observed and predicted peak runoff rates as well as the percentage errors for the predictions of the downstream gauging station.

Table 4.2: Egerton's (downstream) station Peak runoff rate results

Event	Rainfall (mm)	Peak Runoff Rate(m^3/s) Observed	AgNPS Simulated	Error (%)
15/01/04	40.6	2.547	2.622	-2.9
11/04/04	42.5	2.534	2.603	-2.7
23/05/04	45.0	2.714	2.876	-6.0
22/07/04	37.0	2.018	2.160	-7.0
11/08/04	28.0	2.543	2.321	8.7
14/11/04	8.4	2.192	2.019	7.9
23/11/04	9.5	2.349	2.191	6.7
25/11/04	17.5	2.253	2.369	-5.2
16/12/04	25.6	2.887	2.790	3.4
26/01/05	16.5	2.239	2.352	-5.1
22/03/05	26.5	2.469	2.358	4.5

The results presented in Table 4.1 and 4.2 showed the model to have slightly over and under predicted the peak runoff rates in both the stations. On an individual basis all the storm events were predicted with a percent error ranging between 1 and 8.7. Events 22/07/04 and 11/08/04 were the most poorly predicted in the two stations with percent error values of -7.04 and 8.7 (Treetop) and -6.1 and 5.3 (Egerton) respectively. However, the gross errors in peak flow rates estimation represented an overestimate of only 0.139 (Treetop) and 0.142 m^3/s (Egerton) for event 22/07/04 and an underestimate of only 0.15 (Treetop) and 0.222 m^3/s (Egerton) for event 11/08/04, this could be due to fact that these two were complex storms with rainfall following an irregular pattern. The event of 16/12/04 was the best predicted. An error of 3.4% (Treetop) and 1% (Egerton) was produced for this simulation. The results were subjected to statistical analysis by comparing the observed and predicted output data for individual storm events at the two monitoring stations. The scatter graph of the upstream station runoff data is shown in Figure 4.1.

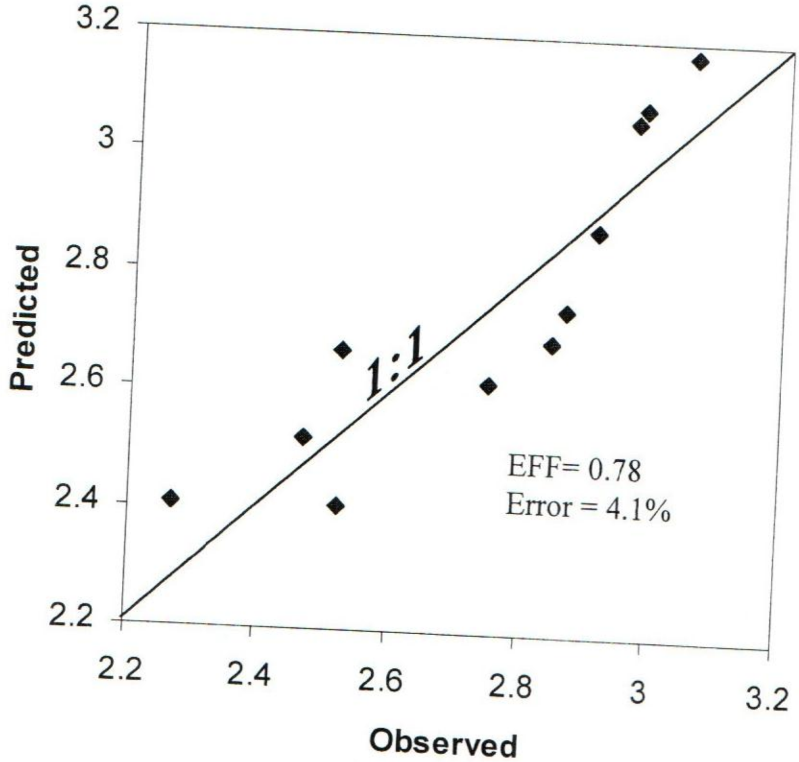

Figure 4.1: Observed vs. predicted Peak runoff rates (m^3/s) for Treetop (upstream) station

In a perfect modeling situation all the points in a scatter graph are supposed to fall along the 1:1 line. However this is rarely the case due to experimental errors and model assumptions. The scatter plot for the upstream station showed a rather equally spread around the line of 1:1. Furthermore the goodness of fit between the predicted and observed peak runoff rates was assessed for the stations. For the upstream station the average percentage error between observed and predicted values was 4.1%. This agreement is confirmed by satisfactory EFF values of 0.78 as shown in Table 4.3.

Table 4.3: Statistical parameters of observed and predicted Peak runoff rate

Catchment	Area (km^2)	No. of events	Peak runoff rate EFF	Peak runoff rate %Error
Egerton	127	11	0.69	5.5
Treetop	110	11	0.78	4.1

For Egerton station, there is generally a good correlation between the observed and predicted peak runoff rates. The average Percent error between observed and predicted values was 5.5%, and EFF value of 0.69 as shown in Table 4.3. The points are scattered closer to the line of equal values as shown in Figure 4.2.

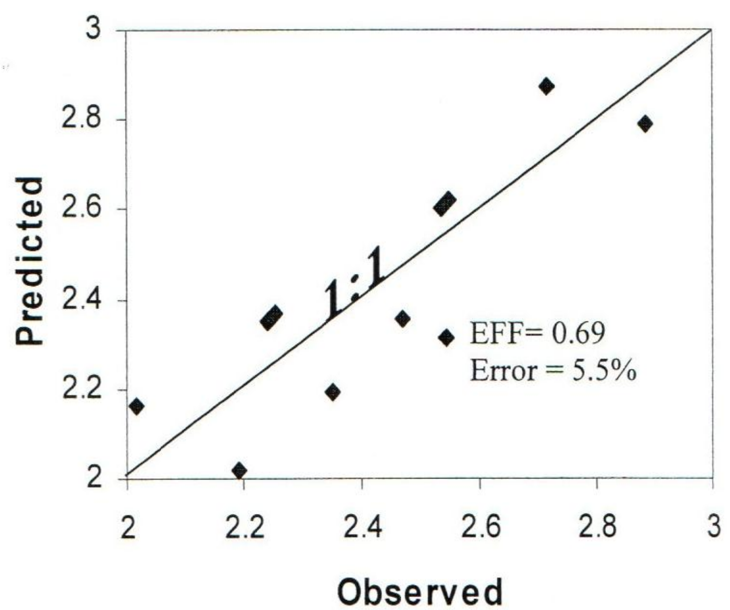

Figure 4.2: Observed vs. predicted Peak runoff rates (m^3/s) for Egerton (Downstream) station

The proximity of the EFF to 1 and scatter values nearing the line of equal values in addition to smaller percentage errors is an indication of good predictive ability of the model as far as peak runoff rate is concerned. The statistics presented above were found to be consistent with those for similar work involving AgNPS done in other parts of the world. Khoelliker and Humbert (1989) in their work in northeast Kansas found a percent error of 3%, Young et al (1987) in an agricultural catchment in Minnesota had a 1.6% error in their estimations and a correlation coefficient of 0.81. Lee & White (1992) also found a good agreement between observed and simulated data for runoff. Suttles et al. (1999) simulation of runoff rate in Georgia coastal plain had an EFF of 0.85, whereas Mostaghini et al. (1997) simulation of runoff was nearly 100% of the observed. In Hesse, central Germany 3.8% was the error found for runoff simulations.

4.1.2 Sediment Yield

Runoff and upland erosion are active contributors to sediment amount in the stream flow. Detached sediment is routed from cell to cell through to the outlets (Treetop and Egerton) after the calculation of runoff and upland erosion using the AgNPS model. The observed sediment concentrations were converted into sediment yields for the storms using by multiplying with the separated direct runoff volume. The sediment yield results for the observed and predicted scenarios for downstream and upstream stations are presented. Table 4.4 shows the observed and predicted sediment yields in tonnes as well as in tonnes per hectare for the upstream station.

Table 4.4: Treetop's (upstream) station Sediment yield results

Event	Rainfall (mm)	Sediment Yield (tonnes)		Sediment Yield (tonnes per ha)		Error (%)
		Observed	Simulated	Observed	Simulated	
15/01/04	40.6	326.12	331.51	0.0296	0.0301	-1.7
11/04/04	42.5	335.45	327.62	0.0305	0.0301	2.3
23/05/04	45.0	340.66	336.62	0.0310	0.0308	1.2
22/07/04	37.0	290.22	295.14	0.0264	0.0269	-1.7
11/08/04	28.0	331.98	325.44	0.0302	0.0299	2.0
14/11/04	8.4	288.14	295.55	0.0262	0.0269	-2.6
23/11/04	9.5	290.64	296.89	0.0264	0.0269	-2.2
25/11/04	17.5	295.84	306.26	0.0269	0.0278	-3.5
16/12/04	25.6	318.88	324.83	0.0290	0.0296	-1.9
26/01/05	16.5	307.23	303.34	0.0279	0.0276	1.3
22/03/05	26.5	312.00	306.73	0.0284	0.0296	1.7

Table 4.5 show the observed and predicted sediment yield for the downstream gauging station as well as the percentage errors for the individual rainfall-runoff events.

Table 4.5: Egerton's (downstream) station Sediment yield results

Event	Rainfall (mm)	Sediment Yield (tonnes)		Sediment Yield (tonnes per ha)		Error (%)
		Observed	Simulated	Observed	Simulated	
15/01/04	40.6	276.21	282.21	0.0217	0.0222	-2.2
11/04/04	42.5	288.43	283.33	0.0227	0.0223	1.8
23/05/04	45.0	279.57	286.77	0.0220	0.0227	-2.6
22/07/04	37.0	239.38	248.73	0.0188	0.0196	-3.9
11/08/04	28.0	264.14	270.06	0.0208	0.0213	-2.2
14/11/04	8.4	239.37	246.72	0.0188	0.0195	-3.1
23/11/04	9.5	241.36	247.14	0.0190	0.0195	-2.4
25/11/04	17.5	266.35	258.34	0.0210	0.0203	3.0
16/12/04	25.6	281.30	275.71	0.0221	0.0218	2.0
26/01/05	16.5	248.42	243.51	0.0196	0.0201	2.0
22/03/05	26.5	266.11	259.63	0.0210	0.0218	2.4

Only a fraction of the sediment eroded within a catchment finds its way to the outlet as sediment yield. Large storms were generally seen to result in high sediment yield as shown in Tables 4.4 and 4.5. As is the case of runoff, the sediment yield was under and over-estimated for the various storms considered. The individual percent error values for the various rainfall-runoff events ranged between 1.2 and 3.9. Sediment results presented in the two Tables (4.4 & 4.5) indicate that Event 25/11/04 was the worst predicted for the two stations, with an error of -3.5% for the Treetop station and 3.0% for Egerton station. The best predicted event was that of 26/01/05, which had an error of 1.3% and 2.0% for Treetop and Egerton stations respectively. The difference in errors between the best and worst sediment yield predictions was found to be small, in addition the errors for sediment yield were lower than those for the runoff results. This could be due to the fact that, all particles were allowed to participate in the channel scouring, and not the AgNPS default that allows only sand particles to erode. The study area also falls in the tropics where storms are intense. The choice of storm type influences the energy-intensity value, and hence the erosive potential of a storm. Four AgNPS storm types exist according to AgNPS model classification of storms, these are 1a, 1, 2 and 3 in increasing amount of the energy intensity-values. The lower percent errors in the sediment yield results were realized when storm type 2 is used in the simulations. This type of storm is normally common in tropical environments and has a high potential to erode due to its high intensity. The storm type and channel scouring assumptions were deemed valid in this work because of the resulting increase in the accuracy of predictions upon their use. This argument has also been confirmed by Perrone and Madramootoo (1998) when using AgNPS for watershed modeling in Quebec. They used storm type 1 which was appropriate for Quebec conditions. The sediment yield results were then subjected to further statistical analysis to establish the model efficiency and the average percentage error for the predictions. Graphical analysis of the results was also done. The scatter graph for the upstream station is presented in Figure 4.3.

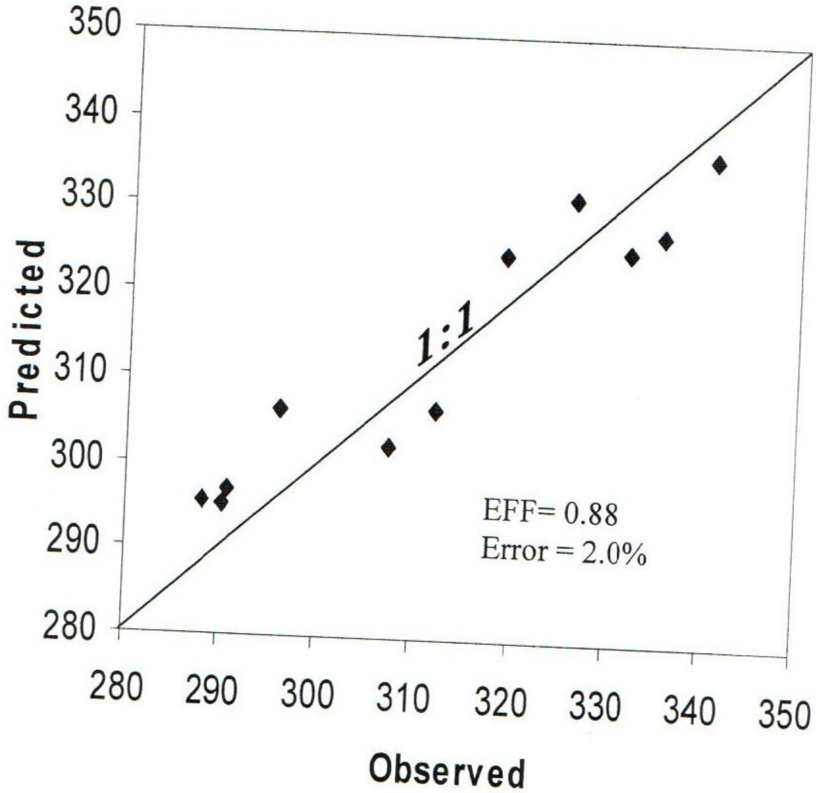

Figure 4.3: Observed vs. Predicted Sediment yield (tonnes) for Treetop (upstream) station

As in the case of peak runoff rates, the goodness of fit between the predicted and observed sediment yield was assessed for each of the two stations separately. For the upstream station the average percentage error between observed and predicted values was 2.0%. A satisfactory EFF value of 0.88 was obtained for this station and a graphical representation of the results shows a scatter graph (Figure 4.3) with a good spread around the line of equal values. The statistical parameters described above are summarized in Table 4.6.

Table 4.6: Statistical parameters of observed and predicted Sediment yield

Catchment	Area (km^2)	No. of events	Sediment yield EFF	%E
Egerton	127	11	0.86	2.5
Treetop	110	11	0.88	2.0

For Egerton station, there was also a good correlation between the observed and predicted sediment yields. The average percent error between observed and predicted values was 2.5%. For the model efficiency, an EFF value of 0.86 was obtained as shown in Table 4.6, and an equally good scatter around the line of equal values as shown in Figure 4.4.

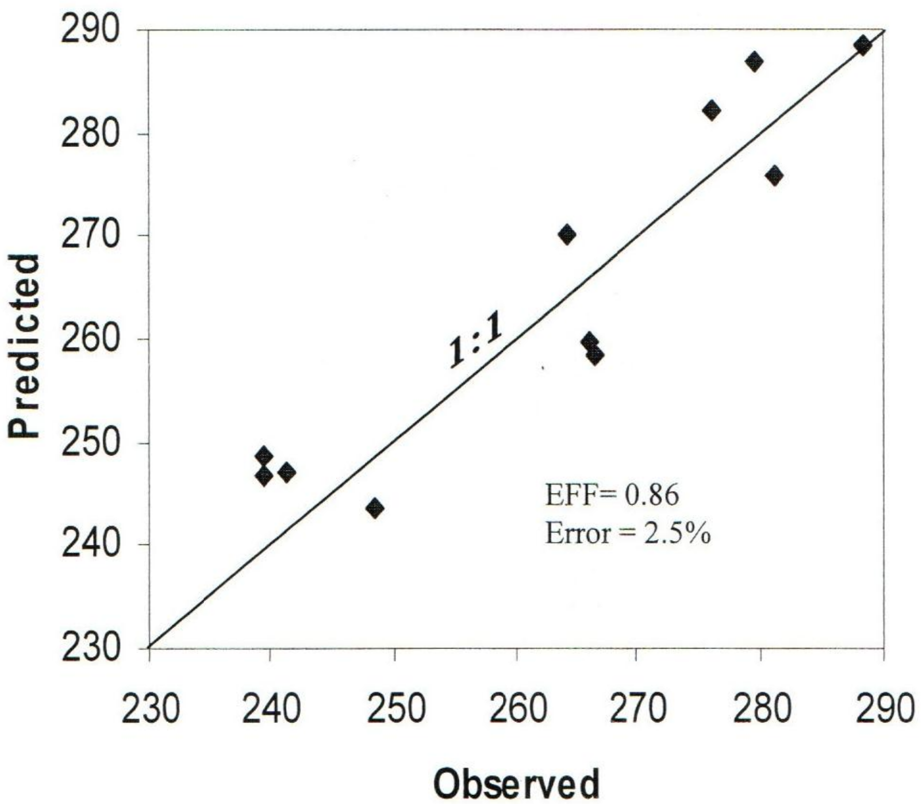

Figure 4.4: Observed vs. Predicted Sediment yield (tonnes) for Egerton (downstream) station

The results obtained in the study compared favourably to works using AgNPS by Young et al. (1987), which over predicted sediment yield by 2.5% and had an EFF of 0.95 in the Trevor watershed. In Hesse, central Germany, there was a 5% error in sediment estimation. Walling et al (2003) compared the performance of AgNPS and ANSWERS models coupled to GIS in estimating sediment concentration and found the two models to be reasonably consistent with the recorded values, although the AgNPS model appeared to provide closer agreement between observed and simulated values.

Erosion represents an important component of land degradation, bringing about reduction in vegetation growth, siltation of water courses, reservoirs etc. The soil loss map for the catchment is shown in Figure 4.5.

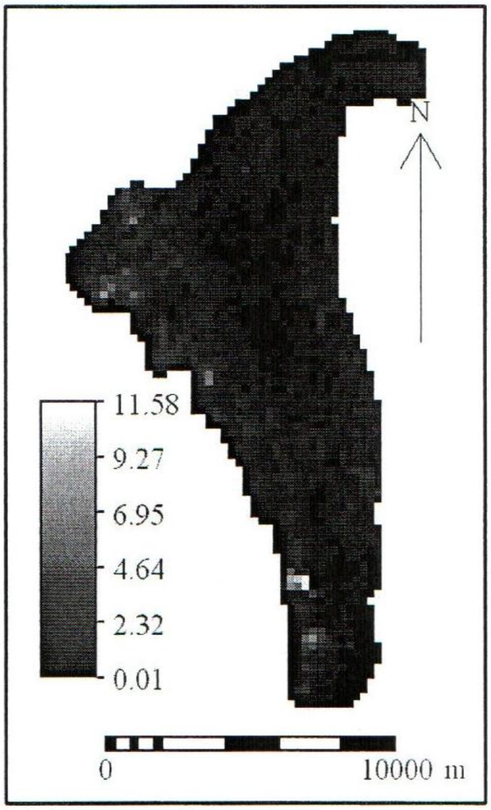

Figure 4.5: Spatial distribution of soil loss (tons/acre) for a one inch storm

The soil loss map shows that erosion rates from the catchment are generally low, i.e. in range of 0.01 to 2.23 tons per acre for the one inch storm. However, there are some spots in the catchment that have higher values of soil loss. Most of these erosion hot spots are in the headwaters of the catchment. Accelerated erosion has occurred in this region due to the intensive deforestation and cultivation on steep slopes. The agricultural patches of land within the forested area have made the areas geologically weak, unstable and hence prone to low water retention and high soil loss associated with runoff. The erosion rates decrease as one moves away from the headwaters to the outlet. This is mainly due to the lower elevations and gentle slopes.

4.2 Correlation between Sediment and Discharge

Several studies have been carried out trying to relate the sediment yield to many contributing variables in catchments. In this study an attempt was made to relate the sediment yield of the catchment to peak runoff rate. This process involved utilizing the existing observed data on sediment yield and runoff to generate sediment rating curves and equations for the two monitoring stations. The estimation of the amount of sediment transported out of the catchment was done through a rating curve made using the suspended load data and the discharge. Figures 4.7 and 4.8 show the relationship between the suspended load and discharge with considerable scatter, it was difficult to find a good relationship but a polynomial function proved to provide some significant relationship for the two stations. The sediment rating curve for the upstream station is presented in Figure 4.6.

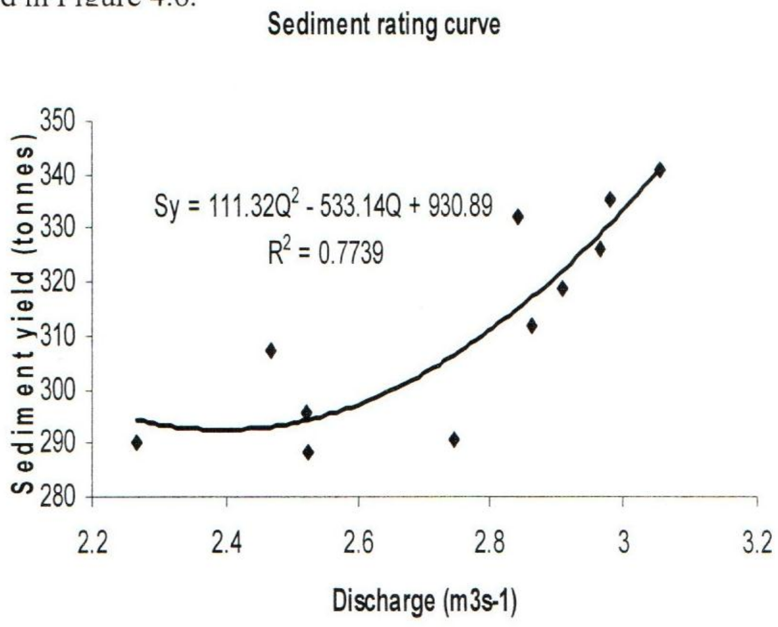

Figure 4.6: Treetop's (upstream) station sediment rating curve

From Figure 4.6 it can be seen that the sediment yield of the upstream station increases with increase in the discharge. However the increase is gradual with lower discharges and rapid with high discharges and has a strong relationship according to their high correlation coefficient value of 0.77. This could be due to the steeper slopes and channel gradient upstream of this station which has the effect of increasing the transport capacity of the flow. A similar sediment rating curve for the downstream station is presented in Figure 4.7.

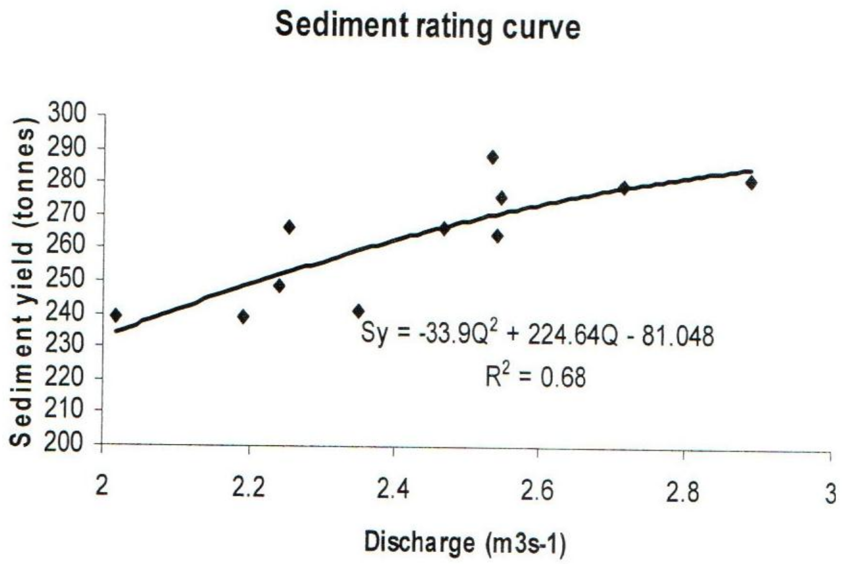

Figure 4.7: Egerton (downstream) station sediment rating curve

Sediment-Discharge relationship at the downstream station is slightly different from that of the upstream station. Figure 4.7 shows that there is a steady increase in sediment yield with discharge. The river reach between the two monitoring stations, has a gentle slope regime compared to the slopes upstream of the upper station, this change in the slope regimes from a steeper to a gentle one leads to deposition and temporary or permanent storage of sediment occurring in the channel reach between the two stations. This explains the difference in shape between the Egerton (downstream) station sediment rating curve and Treetop's (upstream) station sediment rating curve. A correlation coefficient (R^2) value of 0.68 for Egerton (downstream) station suggests a good correlation between the sediment yield and discharge. The sediment rating equation for the downstream station was later used with Muskingum routed peak runoff rate to test the applicability of the method in determining the sediment yield from downstream ungauged sites.

4.3 Runoff Routing

Routing of direct runoff was done using Muskingum method. Routing was necessitated by the need to predict the magnitude of flood. This is a hydrological routing method with two conceptual parameters. These are x, which is the time of propagation of a given flow along a reach and k, the weighting factor expressing the relative influence of inflow and outflow on a storage level (storage constant). In order to determine these parameters a flow hydrograph is required. A storm event of date 22/09/1997 which produced a suitable hydrograph was used. The hydrograph is shown in Table 4.7.

Table 4.7: Inflow and outflow hydrograph for event 22/09/1997

Time (hours)	Inflow (m^3/s) Treetops	Outflow (m^3/s) Egerton
1	3.784	2.321
2	3.874	2.294
3	4.037	2.258
4	4.377	2.173
5	4.202	2.217
6	3.991	2.269
7	3.861	2.301

The reach's storage which is the difference between the inflow and the outflow was obtained and used to determine the Muskingum parameters graphically by plotting a graph of S vs. [xI+ (1-x) O]. After using values of x ranging from 0 to 0.3 at an interval of 0.05, x equals 0.2 showed a loop which was closest to a single line and thus considered the best value of x, whereas K which is the time required for the incremental flood wave to traverse the reach, was found by getting the inverse of the gradient of the graph of S vs. [xI+ (1-x) O] with unit of time in seconds in this case. Figure 4.8 shows the best loop that results when x equal to 0.2.

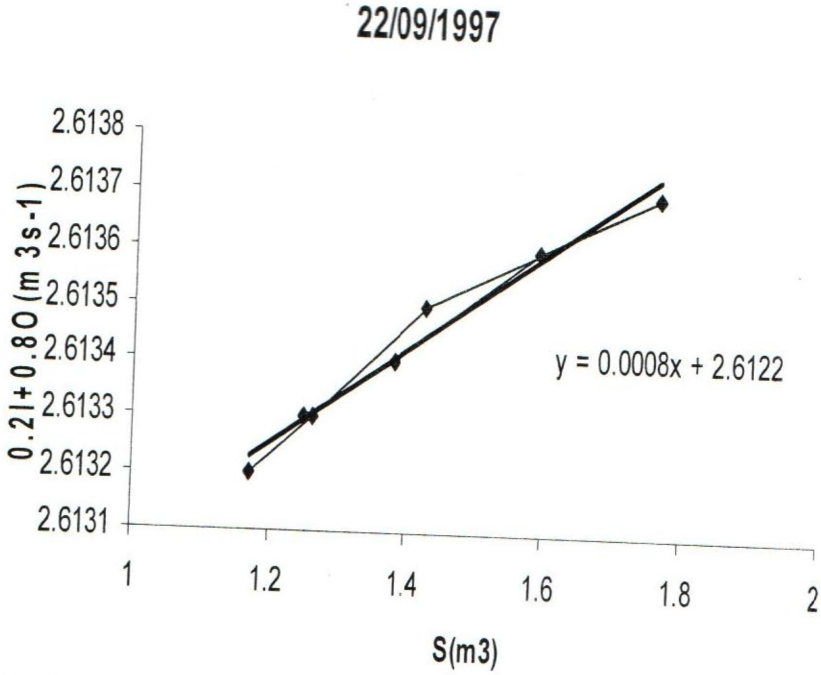

Figure 4.8: Graph of S vs 0.2I+0.8O for event 22/09/1997

The resulting value of the storage constant, k for the storm considered which has the dimension of time was found to be 0.34 hours. This estimate of k is consistent with the field estimate of travel time in the reach and also agrees with the value obtained from other methods used to get the observed time of travel of peak flow through the reach (Chow et al., 1988). x is dependent on the length of the reach as well as the relative importance of the wedge storage. The reach is usually such that x is significantly greater than zero. The routing period is normally considered to be less than the storage constant value. Taking, the derived parameters with a routing period of 0.25 hours which is less than k, the Muskingum coefficients C_o, C_1 and C_2 were determined. All the three coefficients C_o, C_1 and C_2 were positive and found to be 0.144, 0.486, and 0.37 respectively, this conforms to Linsley et al., (1982) demand that all the coefficients must be positive for valid results to be obtained, i.e.

$$C_0 + C_1 + C_2 = 0.144 + 0.486 + 0.37 = 1 \tag{4.1}$$

The obtained coefficients were then used to route the eleven rainfall-runoff events. The values of the Muskingum parameters estimated are shown in Table 4.8

Table 4.8: Estimated Muskingum routing model parameters

Parameter	Value
k	0.34 hours
x	0.2
t	0.25 hours

Routing of the runoff was done using the Muskingum routing equation (2.12). Table A3 (in the Appendix) presents the observed and routed outflow hydrographs for the various storm events considered. To test the accuracy of the hydrological routing process, statistical inspection was done according to ASCE (1993) in order to verify the routed results. Table 4.9 presents the observed and routed peak runoff rates for various rainfall-runoff events together with their individual EFF values and percentage errors.

Table 4.9: Percent error and EFF values for various storm events

Event	%Error	EFF	$Q_{observed}$ (m^3/s)	Q_{routed} (m^3/s)
15/01/04	3.03	0.931	2.547	2.700
11/04/04	1.59	0.981	2.534	2.640
22/07/04	1.77	0.974	1.947	2.018
11/08/04	1.69	0.977	2.456	2.543
23/11/04	1.72	0.977	2.349	2.447
25/11/04	1.83	0.975	2.253	2.325
26/01/05	1.54	0.980	2.239	2.316
22/03/05	1.87	0.979	2.469	2.557
Average	**1.88**	**0.972**		

The EFF values obtained for the storms were greater than 0.9, in addition the average Percent error was less than 2%. This statistics indicate that the Muskingum parameters were reasonably estimated and the Muskingum model did well in predicting the peak runoff rates for the downstream station using the upstream hydrographs.

Birkhead and James (1998) have worked in many rivers in South Africa including the Sabie River in the Kruger National park in which a reach with a site located 4.6 km downstream of a gauging weir from which a continuous record of discharge is available gave almost similar values of k and x. They concluded that the Muskingum routing approach is adequate under reasonably steady flow conditions but would be inaccurate for highly variable flows, and where the distance between the locations of the measured discharge and the required stage is large. However, Kshisagar et al, (1995) on Godovari river in India working on a 93 km reach, found values of the parameters to be K = 2.00 hours, x = 0.01 and K = 8.45 hours, x = 0.01 for two sub-reaches and still got satisfactory results. Chow et al, (1988) observed that great accuracy in determining x may not be necessary because the results of this method of routing are relatively insensitive to the value of this parameter.

4.4 Sediment Prediction

The process of predicting suspended sediment concentration in a river system is challenging. This is due to the complexity of the processes involved in the detachment and transport of the fluvial suspended sediment. However different approaches have been employed by hydrologist for modeling erosion and sediment transport. Regression models which result in empirical models are one the approaches employed (Jensen & Painter 1974). A sediment prediction approach based on regression techniques that result in an empirical model was utilized in this study. The empirical model in Figure 4.7 describes the relationship between sediment yield and the peak runoff rate for a given hydrological event in this case a storm for the downstream station. The sediment rating equation for the downstream station is presented below

$$S_Y = -33.9Q^2 + 224.64Q - 81.04 \qquad (4.2)$$

Figure 4.7 (Section 4.2) shows a steady increase in sediment yield with discharge. This sediment rating equation 4.2 of the downstream station was then used to predict the sediment yield for various storms using the routed peak runoff rates (Muskingum routed) and then compared with the observed sediment yield. This method of sediment prediction was necessitated by the need to make use of the only available data i.e. discharge and sediment. Table 4.10 shows the results of the sediment yield predicted using the developed regression equation 4.2.

Table 4.10: Observed and Routed peak runoff rates and sediment yield for various storm events

Event	Peak runoff rate (m^3/s)		Sediment yield (tonnes)	
	Observed	Routed	Observed	Routed
15/01/04	2.547	2.700	276.21	277.92
11/04/04	2.534	2.640	288.43	275.30
22/07/04	1.947	2.018	239.38	233.79
11/08/04	2.456	2.543	264.14	270.55
23/11/04	2.349	2.447	241.36	265.23
25/11/04	2.253	2.325	266.35	257.56
26/01/05	2.239	2.316	248.42	256.95
22/03/05	2.469	2.557	266.11	271.28

Table 4.10 shows that the empirical equation to have captured the sediment yield fairly well when using the routed peak runoff rates. The difference between the mean predicted and observed sediment yield is minor, with the predicted value exceeding the observed by 2.27 tonnes. There was a fair correlation between the observed and predicted sediment yield. The goodness of fit by the Nash and Sutcliffe criterion, EFF was found to be 0.57 with an average percent error of 3.36. The scatter graph of Observed versus Routed sediment yield is shown in Figure 4.9.

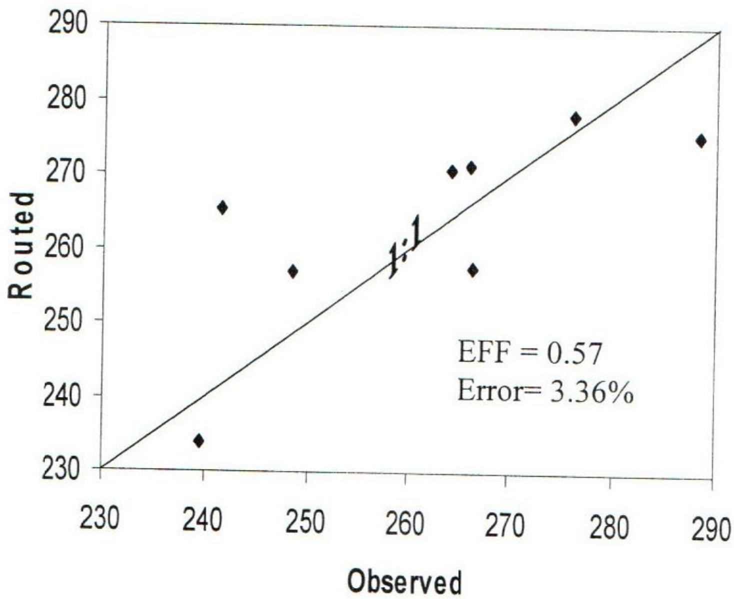

Figure 4.9: Observed versus predicted sediment yield using regression equation (tonnes) for the downstream station

From the scatter, the routed sediment yield exceeds the observed sediment yield in most of the storms considered except for three storms. The statistical parameters presented above indicate that prediction was satisfactory.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Deterioration of surface water quality and quantity is a problem in the River Njoro catchment. In the present study the peak runoff rate and sediment yield from the upper River Njoro catchment was predicted using a combination of Remote sensing and AgNPS model in a GIS environment. The GIS platform provided a faster and better method for spatial modeling and availed output maps that are easy to understand. The Muskingum routing approach was also used to relate flow at the catchment outlet to discharge recorded at a location some 3.7 km upstream.

The observed data for the eleven selected storm events were used for validation of the model predicted output. From the results obtained the predicted peak runoff rate and sediment yield were acceptable with an EFF of 0.78 and 0.88 respectively for the Treetop monitoring station and 0.69 and 0.86 respectively for the Egerton Bridge monitoring station. The percent errors were 4.1% and 5.5% for peak runoff rate, 2%and 2.5% for sediment yield for Treetop and Egerton Bridge respectively.

A classical operational hydrological problem is the estimation of runoff from a catchment consequent to a storm and the routing of the runoff downstream through a channel. The derived values of the Muskingum parameters for the reach were k = 0.34 hours and X = 0.2, while the Muskingum coefficients C_0, C_1 and C_2 were 0.144, 0.486 and 0.370 respectively when a routing period of 0.25 hours is used. High EFF and very low percent error values were obtained from the validation results, with average values of 0.97 and 1.88 for the EFF and percentage error respectively. The routing results together with a sediment rating equation for the downstream station obtained through regression techniques was used to predict the sediment yield for the study area.

The stream flow is an integrating measure of all the hydrological processes operating within the catchment. Most catchments in the developing countries are not gauged with the appropriate instruments for runoff measurement. However, AgNPS, a storm event based model can be used to predict the runoff and sediment yields based on the rainfall information and land use and its related parameters which can be derived in a GIS environment using Remote sensing information. The combination of AgNPS, GIS and Remote Sensing has showed to be useful substitute to the *in situ* measurement of runoff and sediment yield based on the results realized in the study. The runoff results for the upstream station predicted by the model can be used together with the Muskingum routing method to come up with the hydrograph of a downstream station and using the derived relationship between sediment yield and discharge, the sediment yield for the downstream station can be predicted.

5.2 Recommendation

The use of models in hydrological studies is becoming increasingly necessary in the hydrological studies in order to automate the acquisition of hydrological and erosion data. However care should be taken on the selection and use of the models with respect to the power, utility, accuracy and ease of use as this influences the results. Remote sensing and GIS seen as one of the promising aspect in modeling is highly recommended. The land cover and its related parameters that are always dynamic can be derived through remote sensing and together with the other AgNPS model parameters. The routing of flow at remote stations using predicted results of upstream stations is also recommended as this is important in enabling data generation in ungauged catchments. This has been shown to be possible from the results of this study. Further work should be done to test the accuracy of routing simulated direct runoff to reflect ungauged stations.

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APPENDICES

Appendix A (Tables)

Table A1: AgNPS model input parameters and their sources

Parameters	Data source
Cell number	Topography
Receiving cell number	Topography
Flow direction	Topography
SCS curve number	Land use
Land slope	Topography
Slope shape indicator	Topography
Slope length	Topography
Manning coefficient	Land use
K-factor	Soil
C-factor	Land use
P-factor	Land use
Surface Condition Constants	Land use
Chemical Oxygen Demand	Land use
Soil texture number	soil
Channel indicator	Hydrography
Channel length	Hydrography

Table A2: Obtaining peak runoff rate from peak flow rate

Event	Rainfall (mm)	Peak flow rate (m^3/s)	Egerton Base flow (m^3/s)	Peak runoff rate (m^3/s)	Peak flow rate (m^3/s)	Treetop Base flow (m^3/s)	Peak runoff rate (m^3/s)
15/01/04	40.6	2.707	0.162	2.547	3.116	0.150	2.966
11/04/04	42.5	2.696	0.162	2.534	3.129	0.148	2.981
23/05/04	45.0	2.896	0.182	2.714	3.222	0.167	3.055
22/07/04	37.0	2.156	0.138	2.018	2.385	0.118	2.267
11/08/04	28.0	2.674	0.131	2.543	2.954	0.111	2.843
14/11/04	8.4	2.291	0.099	2.192	2.617	0.095	2.522
23/11/04	9.5	2.450	0.101	2.349	2.847	0.100	2.747
25/11/04	17.5	2.374	0.121	2.253	2.632	0.111	2.521
16/12/04	25.6	3.035	0.148	2.887	3.033	0.123	2.910
26/01/05	16.5	2.389	0.150	2.239	2.607	0.139	2.468
22/03/05	26.5	2.615	0.146	2.469	3.003	0.140	2.863

Table A3: The observed and routed outflow hydrographs for various storm events

15/01/04			11/04/04			22/07/04		
I	O_{obs}	O_{rout}	I	O_{obs}	O_{rout}	I	O_{obs}	O_{rout}
1.324	1.103	1.1034	1.321	1.1061	1.1061	1.191	1.0082	1.0082
1.896	1.371	1.3246	1.807	1.3613	1.3115	1.386	1.2072	1.1514
2.498	1.701	1.7713	2.417	1.6495	1.7115	1.843	1.3404	1.3650
2.966	2.165	2.4566	2.981	2.1054	2.2372	2.267	1.6435	1.7272
2.428	2.547	2.7001	2.523	2.5341	2.6398	1.924	1.9474	2.0179
1.906	2.440	2.4535	2.213	2.5074	2.5216	1.448	1.8954	1.8902
1.448	2.118	2.0426	1.764	2.3109	2.2625	1.262	1.6415	1.5848

11/08/04			23/11/04			25/11/04		
I	O_{obs}	O_{rout}	I	O_{obs}	O_{rout}	I	O_{obs}	O_{rout}
1.412	1.0027	1.0027	1.233	1.0169	1.0169	1.462	1.2311	1.2311
1.902	1.4527	1.3311	1.652	1.2678	1.2134	1.717	1.4832	1.4133
2.313	1.7263	1.7500	2.274	1.5242	1.5793	2.222	1.6497	1.6774
2.843	2.0830	2.1810	2.747	1.9631	2.0851	2.521	1.9796	2.0636
2.460	2.4563	2.5429	2.361	2.3489	2.4465	2.333	2.2525	2.3247
1.926	2.4139	2.4138	1.848	2.3128	2.3188	1.816	2.2525	2.2555
1.482	2.1170	2.0426	1.329	2.0220	1.9475	1.499	1.9935	1.9258

26/01/04			22/03/05		
I	O_{obs}	O_{rout}	I	O_{obs}	O_{rout}
1.269	1.0056	1.0056	1.427	1.2146	1.2146
1.722	1.3066	1.2368	1.871	1.4639	1.4123
2.206	1.5682	1.6122	2.328	1.7188	1.7671
2.551	1.9368	2.0360	2.863	2.0879	2.1975
2.242	2.2385	2.3160	2.447	2.4690	2.5569
1.912	2.2130	2.2219	2.021	2.4354	2.4263
1.336	2.0048	1.9437	1.642	2.1831	2.1164

Table A4: Derivation of Muskingum storage parameter

I	S	O	0.2I+0.8O	0.1I+0.9O	0.3I+0.7O
3.784	1.1708	2.321	2.6132	2.4673	2.7599
3.874	1.2607	2.294	2.6133	2.4520	2.7680
4.037	1.4235	2.258	2.6135	2.4359	2.7917
4.377	1.7633	2.173	2.6137	2.3934	2.8342
4.202	1.5884	2.217	2.6136	2.4155	2.8125
3.991	1.3776	2.269	2.6134	2.4412	2.7856
3.861	1.2477	2.301	2.6133	2.4570	2.7690

Appendix B (Figures)

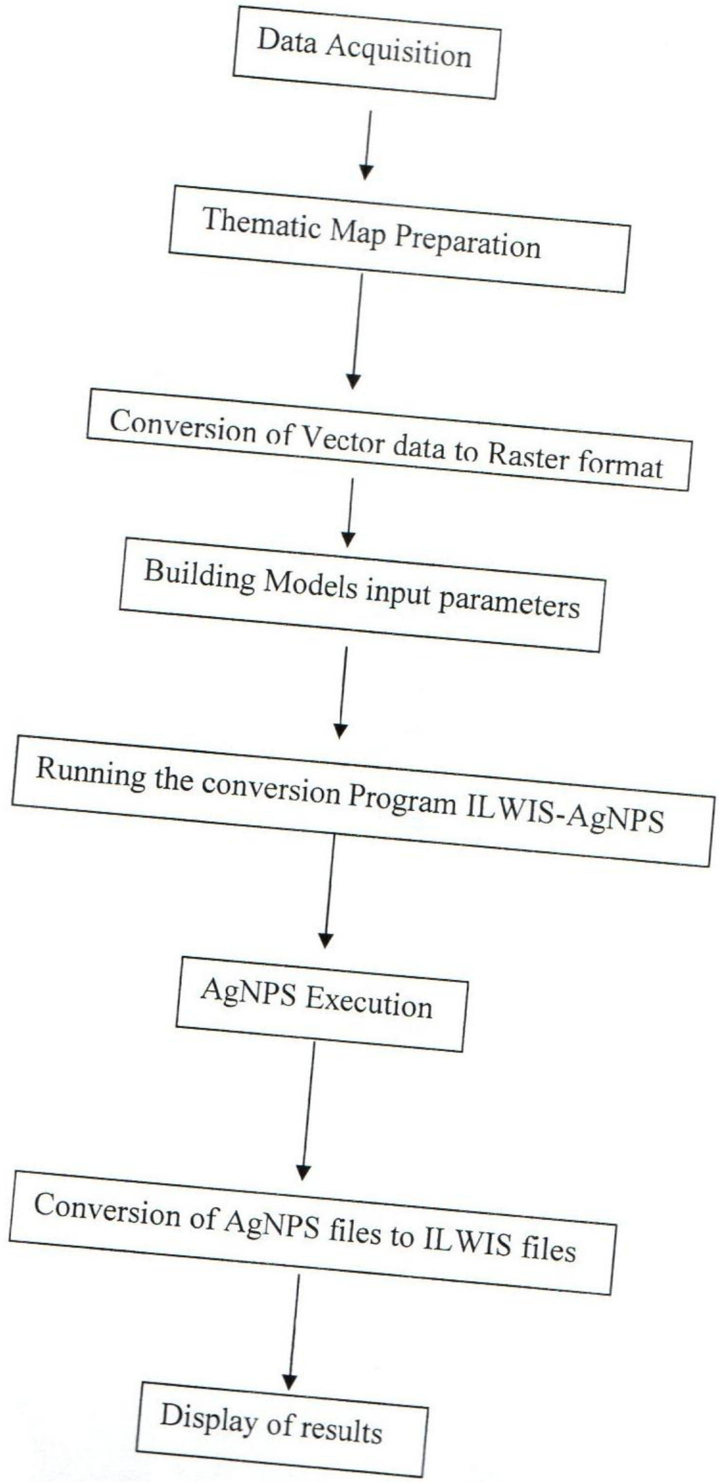

Figure B1: Procedure used to come up with the GIS Database

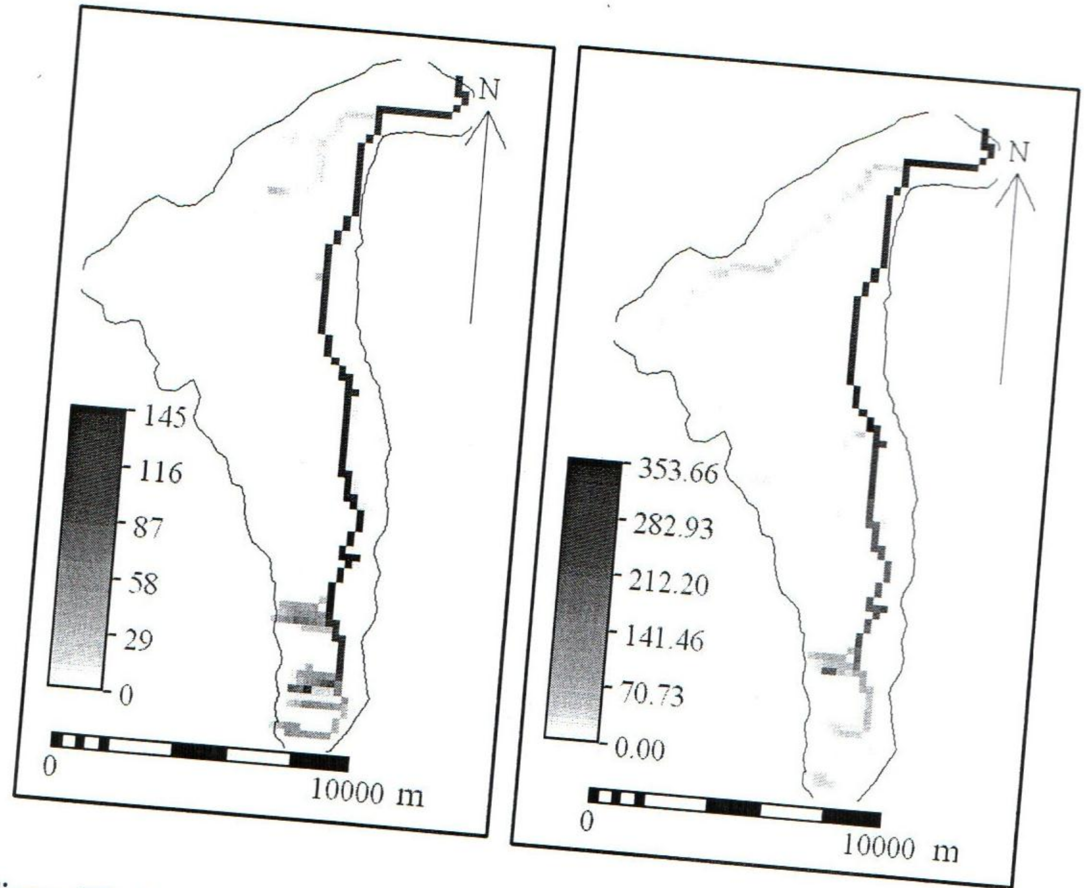

Figure B2: Predicted values of Q_p and S_y for a 45 mm storm