APPLICATION OF REMOTE SENSING AND GIS IN ASSESSING LAND USE AND LAND COVER CHANGES AND THEIR IMPACT ON HYDROLOGICAL REGIME IN RIVER GUCHA CATCHMENT, KENYA

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other university.

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TABLE OF CONTENTS

Declaration ii

Table of contents...iii

List of figures..v

List of tables..vi

List of appendices vii

List of abbreviations and acronyms...viii

Operational definitions...x

Acknowledgements xii

Dedication xiii

Abstract xiv

Chapter one: Introduction 1

1.1 Background of the study 1

1.2 Statement of the problem..5

1.3 Justification for the study...6

1.4 Research objectives 8

1.5 Research hypotheses..9

Chapter two: Literature Review 10

2.1 Land use and land cover change..10

2.2 Rainfall, temperature and stream flow trends...14

2.3 Effects of temperature and rainfall on hydrological processes..........................17

2.4 Effects of land use/cover changes on hydrological processes...........................20

  2.4.1 Effect of soil conservation and afforestation on hydrological processes.........24

2.4.2 Effect of selective logging on hydrological processes............................25

2.4.3 Effect of land clearing on hydrological processes...............................28

2.4.4 Effects of land use/cover change on flooding......................................34

2.5 Watershed modeling...37

2.5.1 Precipitation loss modeling...39

2.5.2 GIS-based watershed modeling..41

2.5.3. GIS-based hydrological model – HEC-HMS approach...........................43

Chapter three: Materials and Methods 49

3.1 The study area..49

3.2 Data collection...51

3.3 Land use/cover classification..53

3.4 Assessing trends in rainfall, temperature and stream flow regimes............54

3.5 Relating between temperature, rainfall and land use/cover with stream flow.............56

3.6 Basin delineation..56

3.7 Hydrologic soil groups...57

3.8 HEC-HMS model...58

3.8.1 Model evaluation...60

3.8.2 Simulating the effect of land use/cover change on stream flow................61

Chapter four: Results and Discussions 63

4.1 Trends in land use/cover change..63

4.2 Trends in rainfall, temperature and stream flow over a period of 34 years................66

4.3 Relationship between rainfall, temperature and land use/cover with stream flow.........71

4.4 Evaluation of the performance of HEC-HMS model in River Gucha Catchment..........74

4.5 Effect of land use/cover change on stream flow regime of River Gucha....................86

Chapter five: Conclusions and Recommendations 89

References 92

Appendices 114

LIST OF FIGURES

Figure 3.1: Location of the River Gucha Catchment 50

Figure 3.2: Hydrologic soil group's map of the River Gucha Catchment.........................58

Figure 4.1a: Land use/cover (1976)...64

Figure 4.1b: Land use/cover (1993)...64

Figure 4.1c: Land use/cover (2010)...64

Figure 4.2a: Trend of total annual rainfall (mm) in River Gucha Catchment 67

Figure 4.2b: Trend of average annual temperature (°C) in River Gucha Catchment 67

Figure 4.2c: Trend of total annual discharge (m^3/s) in River Gucha............................67

Figure 4.3a: Relationship of rainfall with stream flow regime.....................................72

Figure 4.3b: Relationship of temperature with stream flow...72

Figure 4.3c: Relationship of the forest cover with stream flow.....................................72

Figure 4.3d: Relationship of the residential with stream flow.......................................73

Figure 4.3e: Relationship of the agricultural area with stream flow...............................73

Figure 4.3f: Relationship of rainfall with temperature..74

Figure 4.4a: Calibration results of 16-29 January 1976 event......................................75

Figure 4.4b: Calibration results of 16-29 June 1993 event..75

Figure 4.4c: Calibration results of 16-29 January 2010 event......................................76

Figure 4.4d: Validation results of 16-29 August 1976 event..77

Figure 4.4e: Validation results of 16-29 August 1993 event..78

Figure 4.4f: Validation results of 16-29 April 2010 event...78

Figure 4.4g: Simulation results of 16-29 May 1976 event..79

Figure 4.4h: Simulation results of 16-29 January 1993 event.....................................80

Figure 4.4i: Simulation results of 16-29 September 2010 event.................................80

Figure 4.5a: Simulated versus observed flow for the 16-29 January 1976 event...............81

Figure 4.5b: Simulated versus observed flow for the 16-29 June1993 event.......................81

Figure 4.5c: Simulated versus observed flow for the 16-29 January 2010 event...............82

Figure 4.5d: Simulated versus observed flow for the 16-29 August 1976 event................82

Figure 4.5e: Simulated versus observed flow for the 16-29 August 1993 event................82

Figure 4.5f: Simulated versus observed flow for the 16-29 April 2010 event....................83

Figure 4.5g: Simulated versus observed flow for the 16-29 May 1976 event.....................83

Figure 4.5h: Simulated versus observed flow for the 16-29 January 1993 event...............83

Figure 4.5i: Simulated versus observed flow for the 16-29 September 2010 event............84

Figure 4.6: Effect of land use/cover change on stream flow regime of River Gucha...........86

LIST OF TABLES

Table 3.1: Location of rainfall and stream flow gauging stations in the study area............52

Table 3.2a: Total monthly rainfall in River Gucha Catchment 54

Table 3.2b: Average monthly temperature in River Gucha Catchment 55

Table 3.2c: Total monthly stream flow at Kanga Regular Gauging Station......................55

Table 3.3: Stream flow, rainfall, land use/cover and average annual temperatures............56

Table 3.4: Sub-catchments and their curve numbers for 1976, 1993 and 2010..................57

Table 3.5: Methods used in HEC-HMS modeling..59

Table 3.6: Curve number look-up table.....59

Table 3.7: Parameters used in HEC-HMS model evaluation processes.....61

Table 3.8: Parameters used to simulate stream flow due to land use/cover change.....62

Table 4.1: Land use/cover change of the River Gucha Catchment (1976, 1993, 2010).....63

Table 4.2: Analysis of annual total rainfall, stream flow and average temperatures.....68

Table 4.3: Simulated and observed peak flows from the HEC-HMS model evaluation.....76

Table 4.4: Effect of land use/cover change on stream flow regime of River Gucha.....87

LIST OF APPENDICES

A: Baseline dataset of the study area.....114

Figure A1: GDEM of the River Gucha Catchment at 15 m resolution.....114

Figure A2: Soil characteristics map of the study area.....114

Table A1: Definition of hydrologic soil groups.....115

B: Standard look up table and curve number grid maps for the study area.....116

Table B1: Land use categories and associated curve numbers (look up table).....116

Figure B1: Curve number grid map (1976).....117

Figure B2: Curve number grid map (1993).....117

Figure B3: Curve number grid map (2010).....117

C: Daily rainfall and stream flow data used in HEC-HMS model evaluation.....118

Table C1: Rainfall events at Coffee Research Foundation (CRF) station.....118

Table C2: Stream flow events at Kanga regular gauging station.....119

LIST OF ABBREVIATIONS AND ACRONYMS

AGNPS- Agricultural Non-Point Source Model

CN- Curve Number

DEM- Digital Elevation Models

EPA- Environmental Protection Agency

ETM- Enhanced Thematic Mapper

ETM+- Enhanced Thematic Mapper Plus

GIS- Geographic Information System

GPS- Global Positioning System

HEC- Hydrologic Engineering Center

HMS- Hydrologic Modeling System

HSPF- Hydrological Simulation Program - FORTRAN Model

IAHS- International Association of Hydrological Sciences
IARI- Indian Agricultural Research Institute

ICRAF - International Centre for Research in Agroforestry

IGBP- International Geosphere-Biosphere Programme

IPCC – Intergovernmental Panel on Climate Change

IHDP- International Human Dimensions Programme

IMSD- Integrated Mission for Sustainable Development

ISRO- Indian Space Research Organization

JICA- Japanese International Corporation Agency.

KARI- Kenya Agricultural Research Institute

KNBS- Kenya National Bureau of Statistics

MODIS- Moderate Resolution Imaging Spectroradiometer

MSS- Multispectral scanner

NDVI- Normalized Difference Vegetation Index

NELUP- NERC/ESRC Land Use Programme

NRCS- Natural Resources Conservation Service

PRMS- Precipitation-Runoff Modeling System Model

RAS- River Analysis System

RCMRD- Regional Centre for Mapping of Resources for Development

RELMA- Regional Land Management Unit
RGS- Regular Gauging Station

SCS- Soil Conservation Service

SWAT- Soil and Water Assessment Tool

TOPMODEL- Topography Model

UM- Upper Midland

UNEP- United Nations Environmental Program

UNESCO- United Nations Educational, Scientific and Cultural Organization

USA- United States of America

USACE- American Society of Civil Engineers

USDA- United States Department of Agriculture

USGS- United States Geological Survey

WEHY- Watershed Environmental Hydrology Model

WHO- World Health Organization

WMS- Watershed Modeling System

OPERATIONAL DEFINITIONS

- **Climate change**- refers to the change in climate attributed directly/indirectly to human activities which in addition to natural climate variability is observed over comparable period.
- **Curve Number**- is an empirical parameter used in hydrology for predicting direct runoff or infiltration from rainfall excess.
- **Digital elevation model (DEM)** - is a digital representation of ground surface topography or terrain. It is also widely known as a Digital Terrain Model (**DTM**). A DEM is represented as a raster (a grid of squares).
- **Geographic Information System (GIS)** - is a computer system capable of capturing, storing, analyzing, and displaying geographically referenced information; that is, data identified according to location. Practitioners also define a GIS as including the procedures, operating personnel, and spatial data that go into the system.
- **Global Positioning System**- is the only fully functional Global Navigation Satellite System (GNSS). The GPS uses a constellation of at least 24 (32 by March 2008) Medium Earth Orbit satellites that transmit precise microwave signals, that enable GPS receivers to determine their location, speed, direction, and time.
- **Hydrograph**- Is a graph showing flow rate as a function of time in a given location on a stream.
- **Lag time**- 0.6 times the time of concentration (tc)
- **Land cover**- Implies the physical or natural state of the Earth's surface.
- **Land use**- This is the manner in which human beings employ land and its resources.

- **Non-Point Source-** Diffuse pollution sources (without a single point of origin or not introduced into a receiving stream from a specific outlet).
- **Physically-based models-** is a model which has a physical interpretation, and makes physical predictions which are identical to every observation, since no one can prove that either actually exists.
- **Semi-distributed-** is a model which is not full raster model.
- **Time of concentration (tc) -** Is the time of flow from the most hydraulically remote point in a watershed to the watershed outlet.

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DEDICATION

This thesis is dedicated to my wife Catherine, my daughters Faith and Valentine for their patience, love and time endured without my presence during this study.

ABSTRACT

A study to assess the impact of climate and land use/cover on hydrological regime in River Gucha Catchment was conducted with the principal objectives of (a) assessing trends in land use/cover change for the past 34 years (b) assessing trends in rainfall, temperature and stream flow regimes over the past 34 years (c) determining the relationship between land use/cover change, rainfall amounts and temperature patterns with stream flow regime (d) assessing the performance of the HEC-HMS hydrologic model in predicting stream flow and (e) simulating effect of land use/cover change on stream flow of River Gucha using HEC-HMS model. Satellite images of 1976, 1993 and 2010 of the study area were classified and percentage area changes of land use/cover types determined for the period between 1976-1993 and 1993-2010. Rainfall, temperature and stream flow monthly data trends of the study area for the year 1976, 1993 and 2010 were analyzed and their percentage changes calculated over the period. Regression scatter diagrams were computed and coefficient of determination (R^2) determined using data on total annual rainfall, average annual temperatures, and area percentages of land use/cover types against total annual stream flow for the period 1976-2010. HEC-HMS model was evaluated using nine selected rainfall and observed stream flow events for the year 1976, 1993 and 2010. Based on the HEC-HMS model evaluation parameters, curve number grid maps (1976, 1993 and 2010) and one selected rainfall event, stream flow hydrographs were simulated to quantify the change in outflow due to land use/cover change over the period. Forest cover decreased by 62.94 and 68.49%, agricultural land increased by 30.36 and 7.53% and residential area increased by 7.35 and 32.89% of the original area for the period between 1976-1993 and 1993-2010 respectively. The reduction of forest cover and increase of residential area could be attributed to clearing of forests to give room to cultivation and settlement. Total annual rainfall increased by 17.9 and 212.5 mm, average annual temperature increased by 0.23 and 1.08 °C and total annual stream flow increased by 3468.51 and 670.06 m^3/s for the period between 1976-1993 and 1993-2010 respectively. The observed increase in average annual temperature could be in some part due to greenhouse warming. Stream flow showed a higher relationship with the land use/cover change (R^2 of 0.8440) than with the temperature (R^2 of 0.5564) and rainfall (R^2 of 0.4595). The higher correlation of land use/cover with stream flow could be due to expansion of agriculture and reduction of forest cover hence reducing evapotranspiration which cause soils to be wetter and therefore more responsive to rainfall. If rainfall and temperature were held constant, a significant increase in stream flow was expected as a consequence of expansion of agriculture and reduction of forest. The shape of simulated hydrographs generally followed the observed hydrographs during the HEC-HMS evaluation process. Modeled flows against observed stream flows attained R^2 values ranging from 0.7604 to 0.9987. The performance of HEC-HMS was considered satisfactory. Lag time decreased by 16.67 and 16.67%, base flow decreased by 4.0 and 4.17% and peak flow increased by 30.4 and 7.36% for the period between 1976-1993 and 1993-2010 respectively. The reduction of base flow over the period could be due to replacing natural vegetation with exotic vegetation. Understanding how these land use activities and climatic factors influence stream flow will enable planners to formulate policies towards minimizing undesirable effects of future land-use changes on streamflow patterns.

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Land cover change is an important factor in the process of runoff formation that affects infiltration, erosion, and evapotranspiration. Due to rapid development, land cover changes are causing many soils to become impervious. This leads to decrease in the infiltration rate and consequently increase the amount and rate of runoff hence increasing stream flow. Deforestation, urbanization, and other land use activities can significantly alter the seasonal and annual distribution of stream flow (Meybeck *et al.,* 1989). Fu *et al.* (2007) showed that rainfall reduction alone was unable to account for the observed inflow reduction. However, the study also showed non-linear dependence of stream flow on temperature. The study pointed to a 35% decrease in stream flow with a 20% precipitation decrease. Fu *et al.* (2007) also indicated that, if temperatures were to rise 0.4°C this would lead to a 45% decrease in stream flows.

Also Chiew *et al.* (1995) simulated both substantial increases and decreases in runoff and stream flow for several small, ungauged catchments in the upper Murray region with increase in temperature. Rising temperature is expected to increase the evaporative loss and water demand from plants, contributing to a reduction in soil moisture and groundwater recharge. However, historical soil moisture data are inadequate to provide such evidence. Land clearing, agricultural activities, construction, mining, urban and industrial development, and similar activities can have a major impact on the quantity and rate of surface runoff, and on the rates of erosion and sediment transport that take place.

Work done on the interaction between Sahelian vegetation and rainfall suggests that the persistent rainfall anomaly observed in the 1980s could be related to land surface changes (IPCC, 2001). Fortunately, such changes can now be monitored from space using different earth observation sensors. In Kenya, the relative magnitude of the identified long-season rainfall declines is generally more than three times the associated standard errors (Williams and Funk, 2010). These declines in rainfall were accompanied by significant increases in average air temperatures (Williams and Funk, 2010). Actual observed temperature trends indicated significant warming, which was consistent with the IPCC temperature projections (Christensen *et al.*, 2007) for Eastern Africa. This warming may exacerbate evaporation and crop water deficits while the rainfall is declining. In Western Kenya, trend analysis of rainfall showed on average, an increase of about 2.3 mm per year between 1962 and 2001. Out of a total of 14 stations, four have shown significant trends at 1% significance level. Out of ten rainfall stations that showed an increasing trend, eight were found in the highlands. It was not however clear whether the observed trends were attributed to human activities or whether they have been caused by natural climatic factors. Temperature showed increasing trends with higher increases in the lowlands than in the highlands of Western Kenya (Githui, 2008).

Understanding how these land use activities and climatic factors influence stream flow will enable planners to formulate policies towards minimizing undesirable effects of future land-use changes on stream flow pattern. This is especially critical in River Gucha Catchment which is within the large Lake Victoria basin because it is threatened by higher population growth rate (KNBS, 2009). Most of the streams originating from this region, which used to flow at large volumes through out the year have now decreased in base flow, increased peak flows during rainy seasons and some have dried up (Githui, 2008; ICRAF, 2000; Sang, 2005; Patts *et al.*, 2010).

The problem of dry season stream flow reduction and high peak flows during rainy season can only be approached from a whole-catchment perspective. Hydrological modeling is a powerful technique of hydrological system investigation for both the research hydrologist and practicing water resources engineers involved in the planning and development of integrated approach for the management of water resources (Seth *et al.,* 1999). With advances in computational power and the growing availability of spatial data, it is possible to accurately describe watershed characteristics when determining runoff response to rainfall input (Arwa, 2001). With the advent of Geographic Information System (GIS) and Remote Sensing (RS) techniques, the hydrological catchment models have been more physically based and distributed to enumerate various interactive hydrological processes considering spatial heterogeneity (Mohan and Shrestha, 2000). Geographic Information System (GIS) is an organized collection of computer hardware, software, geographic data, and personnel designed to efficiently capture, store, update, manipulate, analyze, and display all forms of geographically referenced information (Shamsi, 2002). Remote Sensing (RS) is the small or large-scale acquisition of information of an object or phenomenon, by the use of either recording or real-time sensing device(s) that is not in physical or intimate contact with the object (Barbara, 1997; Hartkamp *et al.,* 1999). Modeling capabilities for evaluating and predicting hydrological consequences of land use/cover change at multiple scales have advanced at a rapid rate in recent years, owing largely to technological improvements in data collection and computing capabilities. Satellite remote sensing now has the potential to provide extensive coverage of key variables such as precipitation (Smith *et al.*, 1996; Sturdevant-Rees *et al.*, 2001), soil moisture (Sano *et al.*, 1998) and flooding (Townsend and Foster, 2002), as well as many of the parameters such as vegetation cover (Nemani *et al.*, 1993), vegetation change (Nemani *et al.*, 1996) and land imperviousness (Slonecker *et al.*, 2001) that are important inputs to modern hydrological models. These inputs would have been virtually impossible to obtain through traditional data collection techniques (Entekhabi *et al.*, 1999). At the same time, computational improvements now allow faster data processing and more rigorous testing of hydrological paradigms (Entekhabi *et al.*, 1999).

Modeling of land use/cover changes has thus rapidly evolved from simple empirical approaches (for example, unit hydrographs; Jakeman *et al.*, 1993) to lumped-parameter models (Eeles and Blackie, 1993) and to spatially distributed methods (Adams *et al.*, 1995; Dunn and Mackay, 1995) that can make use of high-resolution information on land use/cover patterns and processes. In this study Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS- model) developed by U. S. Army Corps of Engineers has been used to estimate the effects of land use/cover changes on stream flow regime. HEC-HMS which is an advancement of HEC-1 model can be justified based on the work of Kristina and Terri (2008); Bengtson and Padmanabhan (1999), where; the HEC-HMS, PRMS, HSPF, and AGNPS hydrologic models were evaluated for predicting stream flow. It was decided that HEC-HMS was the best choice due to its ability to model flood and stream flow events (Bengtson and Padmanabhan, 1999; Kristina and Terri, 2008).

1.2 Statement of the problem

Following population increase over the last decade, River Gucha Catchment which is within the Lake Victoria Basin has been settled on and different land use activities have been practiced including cultivation and infrastructure (Ongwenyi *et al.*, 1993). Most of the streams originating from this region, which used to flow at large volumes through out the year have now decreased in base flow, increased peak flows during rainy seasons and some have dried up (Githui, 2008; ICRAF, 2000; Sang, 2005; Patts *et al.*, 2010; Nyangaga, 2008). This problem of drying up of streams and volume reduction and high peaks during wet seasons in relation to land use/cover and climate change in the catchment need to be urgently addressed. Although scientists have long recognized that changes in land use/cover and climate are important factors affecting hydrological cycle and the spatial-temporal variations in the distribution of water resources, little is known about the quantitative relationship between land use/cover characteristics and runoff generation or processes in Kenya (Kokkonen and Jakeman, 2002; Hundecha and Bardossy, 2004). Although some quantitative research methods and numerical models have been developed to address this dearth of data, no widely accepted theory and model have been established to reveal the mechanism underlying the impact of land use/cover changes on hydrological processes (Vorosmarty *et al.*, 2000; DeFries and Eshleman, 2004). Land use/cover and natural climatic factors can influence hydrological processes in different ways. It is not clear whether hydrological changes are attributed to human activities or caused by natural climatic factors. Understanding how these land use activities and climatic factors influence stream flow will enable planners to formulate policies towards minimizing undesirable effects of future land-use changes on stream flow patterns. Hence, there is a need to conduct a case study in a representative region in order to explore and establish a theoretical system elucidating the effects of land use/cover and climate changes on the hydrological processes of a catchment. It is foreseen that interactions between land-use change and hydrologic processes will be a major issue in the decades to come.

1.3 **Justification for the study**

Collaboration among scientists from different disciplines, though still challenging, is gaining acceptance as a necessary approach to addressing global environmental issues such as climate change (Steffen *et al.*, 2003). Perspectives from fields such as remote sensing to observe land cover, from economics and other social sciences to develop future land-use scenarios, from ecology to assess the biological implications of changes in water flow and quality, as well as from hydrology to understand hydrological effects of land-cover changes in a catchment, are all required to comprehend fully the hydrological consequences of land use/cover and climate change. In summary, dramatic changes in land use/cover have taken place on a global scale in river basins due to population growth. This has become one of the widespread issues of scientific concern, the focus of which are the impacts of land use/cover and climate changes on the Earth's resources, the environment, and the prospects for sustainable development (Potter, 1991; Vorosmarty *et al.*, 2000; Sang, 2005). On a catchment scale, such impacts on hydrological processes are reflected in fluctuations in the supply-and-demand relation of water resources and flooding effects, which in turn will significantly affect the ecosystem, environment, and economy. Therefore, a better understanding of how land use/cover and climate changes impact catchment hydrological processes is a crucial issue for the planning, management, and sustainable development of water resources. Kenya is vulnerable to drought, due to its dependence on rainfall for its economic and social development. Most water for domestic use and other uses is derived from rivers whose recharge depends on rainfall. Kenya's per capita water availability is very low and the situation could get worse due to the climate change among other factors such as population growth and environmental degradation. It is predicted that aggregate water demand will rise by 2020 (Mogaka *et al.*, 2006). Study of linkages between vegetative cover, hydrologic processes and water quality has a relatively long history based on modeling, experimental watersheds, and measurements. The consequences of anthropogenic land-use change on hydrology have received little attention in the study of land-use change. As such, understanding the consequences of land-use and climate change on hydrologic processes, and integrating this understanding into the emerging focus on land-change science, is a major need for the future.

Research aimed towards explicit understanding of these interactions will provide necessary input to decisions that could balance trade-offs between the positive benefits of land use/cover change and potentially negative unintended consequences. Such a research focus calls for a multidisciplinary approach with a comprehensive view towards the hydrologic processes that maintain ecological health and human requirements for food, water, and shelter. Continued high rates of population expansion within the River Gucha Catchment and climate change pose a great danger to the water resources. The assessment of the impacts of this increased population pressure, change of land use/cover and climate on water resources is of great importance and will play an important role in devising future water resources planning and management strategies in the catchment. A number of initiatives (for example, soil and water conservation) within the Lake Victoria Basin both international and local have come up in the recent past. River Gucha Catchment is within the large Lake Victoria Basin. They have sought to understand the interaction of various processes within the basin in an effort to assess the state of the natural resources and impacts of external forces, such as climate, on these resources for the benefit of the communities living in this area. This study is important because it adds on to these initiatives by enhancing the understanding of the impact of climatic and land use/cover changes on stream flow.

1.4 **Research Objectives**

The broad objective was to assess the impact of changes in land use/cover and climate on hydrological regime of River Gucha Catchment using HEC-HMS hydrologic model.

The specific objectives were:

1 To assess trends in land use/cover change within the River Gucha Catchment for the past 34 years.

2 To assess trends in rainfall, temperature and stream flow regimes within the River Gucha Catchment over the past 34 years.

3 To determine the relationship between land use/cover change, rainfall amounts and temperature patterns with stream flow regime in the study area.

4 To assess the performance of the HEC-HMS hydrologic model for River Gucha Catchment in predicting stream flow.

5 To simulate the effect of land use/cover change on stream flow of River Gucha using HEC-HMS model.

1.5 Research Hypotheses

1. Land use/cover has been changing in the River Gucha Catchment for the last 34 years.
2. There has been change in rainfall, temperature and stream flow regimes in the River Gucha Catchment over the last 34 years.
3. There is relationship between land use/cover change, rainfall amounts and temperature patterns on stream flow regime in the study area.
4. Performance of the HEC-HMS hydrologic model in predicting stream flow in River Gucha Catchment is satisfactory.
5. Expansion of agricultural land and reduction in forest cover increase peak flow and decrease lag time and base flow of River Gucha.

CHAPTER TWO

LITERATURE REVIEW

2.1 Land use and Land cover change

The term 'land use' is used to describe human uses of the land, including actions that modify or convert land cover from one type to another (Lambin *et al.*, 2003). Examples include categories such as; human settlements (urban and rural settlements), agriculture (irrigated and rain-fed fields), national parks, forest reserves, and transportation and other infrastructure. The term 'land cover' refers to the vegetative cover types and other surface cover such as rock outcrops that characterize a particular area (Lambin *et al.*, 2003). Examples include forest, savannah or desert. Under such categories there can be more refined categories of specific plant communities for example; shrub-lands, mangroves or seasonally flooded grassland. Land use types can be approximately classified into two types of natural vegetation and exotic vegetation. The natural vegetation includes indigenous forest, grassland, shrub-land, etc. Crops are the main type of the exotic vegetation. Natural vegetation variations are more sensitive to climate change than exotic vegetation, which mainly reflects the human activities (Deng *et al.*, 2006).

The need to provide food, water and shelter to people worldwide has led to changes in land use/cover such as forests and agricultural lands. Researchers have in the past decades recognized the need to understand how land use/cover change processes link to broader changes in the global environment and how environmental sustainability can be achieved. Enormous efforts have been made to understand the driving forces of land use/cover change and to develop regionally and globally integrated models of land use/cover change (Lambin *et al.*, 1999). The great interest in land use/cover results from their direct relationship to many of the earth's fundamental characteristics and processes, such as land productivity, diversity of plant and animal species, and the biochemical and hydrological cycles (De Sherbinin, 2002). Land cover is transformed by land-use changes, for example, forest can be converted to agricultural land or pasture. Overgrazing and other agricultural practices lead to land degradation and desertification. It have recognised that, a systematic analysis of local scale land use/cover change studies, conducted over a range of timescales, helps to uncover general principles to provide an explanation and prediction of new land-use changes (Lambin *et al.*, 2003).

Different types of vegetation respond to the changes of temperature and precipitation differently. Grass and shrub are usually more sensitive to climate changes than forest (Li and Shi, 2000). The results from the Yellow River Basin study indicated that vegetation cover had an increasing trend during the past 20 years (Liu and Xiao, 2006). The inter-annual variability of Normalized Difference Vegetation Index (NDVI) in the Yellow River Basin had a close relationship with precipitation and this relationship is enhanced in the grassland, but weakened in the forest and irrigated agricultural areas (Liu and Xiao, 2006). As an outcome of climate changes and human activities, vegetation variations have profoundly memorized the human activities especially with the increasing human activities. However, most studies have focused on the analysis of inter-annual NDVI variations due to climate changes without giving a proper consideration of roles of human activities, such as land use, soil and water conservation and vegetation construction. This has affected the objectivity of the analysis of the driving mechanism of vegetation variations. In another study in North-western China, Deng *et al.* (2006) found that, annual maximum NDVI increased significantly in grassland and farmland, and decreased in forest over the past 22 years. A lot of soil and water conservation measures have been executed on the Loess Plateau since the 1950s, which include terrace and check dam construction and afforestation. Small watershed management has been extensively carried out during the 1980s and the project of returning farmland to forests or grassland has been put into action since 1999. All of these have directly affected the vegetation cover of the Loess Plateau. Yan'an and Yulin, located in Northern Shaanxi, is the main region suffering from serious soil and water loss and producing a high and coarse sediment yield, and also the mostly key region where vegetation recovery project of returning farmland to forests or grassland was carried out recently (Xin ZhongBao *et al.,* 2008). Accompanying with the implementation of the vegetation rehabilitation projection on a large scale since 1999, a significant ascending tendency of vegetation cover has been presented. This fact of vegetation change has also been reported by other studies (Li *et al.*, 2007). Study of land use/cover change in Yom Watershed of Central–Northern Thailand showed an expansion of urban areas by 132% from 210 km^2 in 1990 to 488 km^2 in 2006 (Petchprayoon, *et al.,* 2010).

Mutie *et al.* (2006) analyzed land cover change of the trans-boundary Mara River Basin from dry season LANDSAT MSS, TM and ETM images of 1973, 1986 and 2000 respectively. Digital image analysis using IDRISI showed that between 1973 and 2000, forests and shrub-land had reduced by 32% and 34% respectively. Grass-land, savannah and water bodies reduced by 45, 26, and 47% respectively. However agricultural land, tea and open forests, and wetlands all increased by over 100% as a result of land use pressure in the basin. Research work by JICA (1992) in Lake Victoria Basin found that, replacement of indigenous vegetation by exotic plantations had reduced interception of storm water, increased peak flows and loss through evapo-transpiration by about 18%. Results from the work done in Itare sub-catchment within the Lake Victoria Drainage Basin, of Kenya indicated that, there has been a tremendous change in land use in the catchment, with more conspicuous being the reduction in forest cover by 33% and increased land under the various uses such as urbanization, development of road network, provision of social facilities, agriculture and settlement (Nyangaga, 2008). In the case-study of Nzoia River Catchment by Patts *et al.* (2010), area under forest cover decreased between 1970's and 1986 by 6.4% in the northwest and south of the catchment. But between the 1980's and the 2000's there was an increase in area under forest cover by 41.3% as a result of afforestation. Agricultural land use showed an increase in areal coverage between 1970's and 1986 by 6.7%, but in the year 2000's the agricultural activities declined by 4.6%. The area under bush-land, shrub-land or riverine agriculture increased between the 1970's, 1986 and the 2000's by about 123.4% and 11.10% respectively. This could be as a result of an expansion in riverine agriculture due to high population growth in the area. No work has been recently done specifically in River Gucha Catchment to study how land use/cover has been changing over time. Therefore, it is worth while to study how land use/cover has been changing over time in this catchment.

2.2 Rainfall, temperature and stream flow trends

Analyses of rainfall trends by Petchprayoon *et al.* (2010) found that, there were no significant long-term trends in precipitation characteristics in the Yom Basin of Central–Northern Thailand except for one station. Yom River's daily discharge long-term trend significantly increased at most of the measurement stations (*p* value <0.05), and the rate of increase in discharge at areas downstream was significantly greater than that at areas upstream due to rapid urbanisation downstream. Funk *et al.* (2010) work in Kenya clearly indicated cohesive patterns of observed climate change during the 1960–2009 in rainfall and temperature data. Modeling the observed 1960 – 2009 changes out until 2025, they found that large parts of Kenya will have experienced more than a 100 millimeters decline in long-season rainfall. Evaluations of independent rainfall data sets by Williams and Funk (2010) produced similar results.

The relative magnitude of the identified long-season rainfall declines in Kenya was generally more than three times the associated standard errors. These decreases in rainfall were accompanied by significant increases in average air temperatures. Although these warming and drying trends will continue to be punctuated by good and poor rainy seasons, the frequency of dry years was increasing. This recession has already impacted negatively the densely populated areas to the South, East, North, and North-East of Nairobi. In addition to substantial rainfall declines in Kenya, the country also will have warmed substantially during these 50 years from 1975 to 2025. It was estimated that from 1975 to 2025, warming generally will represent more than a 1° Celsius increase in temperature for Kenya (Funk *et al.*, 2010).

However, the observed rainfall decrease tendencies are substantially different from the results presented during the 4th Intergovernmental Panel on Climate Change (IPCC) assessment. It was indicated that, Eastern Africa will likely experience a modest (5–10 percent) increase in June-July-August precipitation (Christensen *et al.*, 2007). The IPCC report acknowledged that the models it uses often have difficulties in representing the key processes affecting rainfall in Eastern Africa; the spread between the rainfall projection results they produce is substantial. The models represent seasonal rainfall poorly, with typical correlations of less than 0.3 over land surfaces (Funk and Brown, 2009). Many of the models indicate a future tilt towards a more El Nino-like climate (indicating there will be more rains) which in this region would be expected to produce enhanced long rains in Kenya. By 2010, however, there appeared to be little observational data supporting such a shift (Funk *et al.*, 2010).

Generally, it was found that, both in the IPCC simulations and in the historical records, there was a strong warming tendency in the Western Indian Ocean (Funk *et al.*, 2010; Williams and Funk 2010), which is likely driven in part by increases in greenhouse gases. This large scale circulation shift appears to be modulating the impact of natural climate variations. Recent La Nina years are tending to be drier, whereas El Nino long rain seasons are tending more towards average, rather than above-average rainfall totals. It was found that air temperatures and precipitation increase in the Indian and Western Pacific Oceans. In the Indian Ocean, this produces an East to West wind pattern that disrupts onshore moisture transports into Kenya, and brings dry subsiding air (that tends to depress rainfall) down across the Eastern Horn. The observed link between greenhouse gas emissions, Indian Ocean warming, and drought-inducing subsidence across Kenya may indicate that continued declines are likely over at least the next several decades (Williams and Funk, 2010). Actual observed temperature trends indicated significant warming, which was consistent with the IPCC temperature projections (Christensen *et al.*, 2007) for Eastern Africa. This warming may exacerbate evaporation and crop water deficits while the rainfall is declining.

In Western Kenya, trend analysis of rainfall showed that, on average, the annual rainfall increased by about 2.3 mm/year between 1962 and 2001. Out of a total of 14 stations, four had shown significant trends at 1% significance level. Of particular interest with respect to the above-mentioned problem is that, out of ten rainfall stations that showed an increasing trend, eight were found in the highland areas. It was not however clear whether the observed trends were attributed to human activities or whether they have been caused by natural climatic factors. Temperature showed increasing trends with higher increases in the lowlands than in the highlands (Githui, 2008). In addition, Githui *et al.* (2009) work in Western Kenya using General Circulation Models (GCMs) results showed increased amounts of annual rainfall for all the scenarios but with variations on a monthly basis. All but one GCM showed consistency in the monthly rainfall amounts. Rainfall was higher in the 2050s than in the 2020s projections. According to climate change scenarios by Githui *et al.* (2009), temperature will continue increasing in this region, with the 2050s experiencing much higher increases than the 2020s with a monthly temperature change range of 0–1.7 °C. Also Laderach *et al.* (2010) predicted that, in Kenya the yearly and monthly rainfall will increase and the yearly and monthly minimum and maximum temperatures will increase by 2020 and progressively increase by 2050. The overall climate will become less seasonal in terms of variation through the year in temperature with temperature in specific districts increasing by about 1 °C by 2020 and 2.3 °C by 2050 and more seasonal in precipitation with the maximum number of cumulative dry month staying constant at 4 months. Like wise, in the case-study of Nzoia River Catchment, by Patts *et al.* (2010), results indicated an increasing trend in rainfall amounts between 1970 and 1998. A study of three rainfall stations had shown a significant increase in rainfall while one station, in the lower part of the catchment, has shown a significant decrease. No work has been recently done specifically in River Gucha Catchment to study trends in temperature, rainfall and stream flow. Therefore, it is worth-while to assess if climate change in this catchment has been conforming to the work of other researchers.

2.3 **Effects of temperature and rainfall on hydrological processes**

Climate model projections show an increase of more than 1°C in the global mean near-surface air temperature by 2025 (Christensen *et al.*, 2007). This is likely to lead to a more vigorous hydrological cycle, with changes in precipitation and evapotranspiration rates that are regionally variable. These changes will in turn affect water availability and runoff and thus may affect the discharge regime of rivers. In Kenya, impacts of climate/weather were well manifested in the 1998–2000/2001 La-Nina related severe and prolonged drought. Hydrologic models have been used to investigate the relationship between climate and water resources. Application of hydrologic models in the assessment of the potential impacts of climate change on water resource issues has been carried out in various studies. Middelkoop *et al.*'s (2001) study to assess the impact of climate change on the river flow conditions in the Rhine Basin, generated climate change scenarios from General Circulation Models (GCMs) using the Model for the Assessment of Greenhouse gas Induced Climate Change (MAGICC). Their results showed higher winter discharge as a result of intensified snowmelt and increased winter precipitation, and lower summer discharge due to the reduced winter snow storage and an increase of evapo-transpiration. Chaplot (2007) used Soil and Water Assessment Tool model (SWAT) to predict the effect of variations in precipitation and rainfall intensity and surface air temperature associated with increased CO_2 concentration in two agricultural watersheds in Iowa and Texas. The study showed that, precipitation changes affected flow while temperature and changes in atmospheric CO_2 concentration had a smaller effect, and that increasing precipitation in the humid watershed significantly increased runoff while changes in surface air temperature had only a slight impact. Fontaine *et al.* (2001) also applied SWAT to assess impacts of potential climate change in Black Hills of South Dakota, USA using arbitrary changes in climatic inputs (increase in average annual temperature of 4.0 °C and ±10% change in precipitation). The results of their study showed that generally increased temperature caused a decrease in water yield while increased precipitation caused an increase in water yield.

In recent years, rainfall across the Murray-Darling Basin (MDB) in Australia has been below the long-term average, but not unprecedented. In contrast, stream flows to Australia's longest river system, the Murray-Darling, reached a historical low. Cowan and Cai (2009) examined the possible causes for this disparity. Although annual total inflow was more sensitive to rainfall fluctuations over South Eastern Australia, where rainfall over recent years had been the lowest over the entire record, this alone was unable to explain the observed decreasing trend in inflow. A relationship existed between inflow variations and fluctuations of temperature not associated with rainfall in winter and spring whereby a rise of 1°C led to an approximate 15% reduction in the annual inflow. Their results provided a strong link between rising temperatures, due to the enhanced greenhouse effect, and the impact this has on Australia's water resources, in addition to any reduction in rainfall (Cowan and Cai, 2009).

Yosop *et al.* (2007) examined rainfall-runoff processes in a small oil palm catchment in Johor, Malaysia where storm hydrographs showed rapid responses to rainfall with a short time to peak. The estimated initial hydrologic loss for the oil palm catchment was 5mm. Despite the low initial loss, the catchment exhibited a high proportion of base flow, approximately 54% of the total runoff. On an event basis, the storm flow response factor and runoff coefficient ranged from 0.003 to 0.21, and 0.02 to 0.44, respectively. Peak flow and storm flow volume were moderately correlated with rainfall. Based on these findings, it was suggested that the oil palm plantation served reasonably well in regulating basic hydrological functions.

Githui *et al.* (2009) simulated stream flow in Western Kenya using SWAT model where the range of change in mean annual rainfall of 2.4 – 23.2% corresponded to a change in stream flow of about 6 – 115%. The analysis revealed important rainfall–runoff linear relationships for certain months that could be extrapolated to estimate amounts of stream flow under various scenarios of change in rainfall. Stream flow response was not sensitive to changes in temperature. It was suggested that, if all other variables like land cover and population growth, were held constant, a significant increase in stream flow would be expected in the coming decades as a consequence of increased rainfall amounts (Githui *et al.*, 2009). Sang (2005) also used SWAT model in Nyando Basin, where he observed that, an increase of rainfall by 15 % would increase peak flow from 111 to 159 m^3/s. Change in temperature was associated with reduced peak flow and lower dry season flow; however the effect of the expected changes was less than the change associated with rainfall. Others who have studied impacts of climate change on water yields studies include Pao-Shan *et al.* (2002); Varanou *et al.* (2002) and Miller *et al.* (2003), among many others.

From all these studies, varied results were obtained depending on the physiographic features, climate and seasons of the region studied, as well as the different climate change scenarios and hydrologic models used. One of the major challenges in East Africa is that very little has been done on hydrologic modeling, making a comparison of results quite difficult. Scientists have long recognized that changes in land use/cover and climate are important factors affecting hydrological cycle and the spatial-temporal variations in the distribution of water resources. However, little is known about the quantitative relationship between land use/cover characteristics and runoff generation processes.

2.4 **Effects of land use/cover changes on hydrological processes**

Conversion of land from forests and other natural vegetation types to cultivated areas and settlement has been one of the primary modes for human modification of the global environment. Over the coming decades, expansion and intensification of agriculture, growth of urban areas, and extraction of timber and other natural resources will likely accelerate to satisfy demands of increasing numbers of people to attain higher standards of living. Human transformation of the earth's land surface has multiple consequences to biophysical systems at all scales (Kalnay and Cai, 2003) and alterations in stream flow patterns (Rose and Peters, 2001). Land-use change is a major challenge for this century. Some researchers suggest that the consequences may outweigh those from climate change (Sala *et al.*, 2000; Vorosmarty *et al.*, 2000).

Much of the research investigating the consequences of land-use change has focused on two issues: (i) the effects of land use change on climate, either indirectly through emissions of carbon dioxide and other greenhouse gases from burning and decaying biomass (Houghton, 1995), or directly through altered exchanges of energy, water, and momentum between the land surface and atmosphere (Bonan, 1997) and (ii) the effects of habitat loss on biodiversity (Sala *et al.*, 2000). The development of models for reliably predicting the hydrological effects of future land-use changes was literally in its infancy by 2000 (Beven, 2000). Much of the present understanding of land-use effects on hydrology is derived from controlled, experimental manipulations of the land surface, coupled with pre- and post-manipulation observations of hydrological processes, commonly precipitation inputs and stream discharge outputs. Most notable are studies of the effects of forest management practices (including cutting, removal activities, and regrowth of forest vegetation) on annual and seasonal water yields, evapotranspirative losses, interception rates, and flood peaks. Forest cutting and removal activities usually cause increases in water yield (Bosch and Hewlett, 1982) and flood peaks (Harr, 1986) for several years following disturbance, but some studies have suggested that these effects can be at least partially attributed to soil compaction during road and skid trail construction (Jones and Grant, 1996; Whitehead and Robinson, 1993).

Comparable experimental studies of urbanization and agricultural management practices are much less common in the literature, but both of these types of disturbance have generated an extensive literature of their own, mostly from analysis of observational data from 'comparative' or 'case' studies (Potter, 1991; Rose and Peters, 2001). Two of the more widely used models for assessing the effects of land-use practices on hydrological response (the rational method and the USDA-SCS curve number approach) are based on field data. Literature contains very few examples of controlled studies of the effects of land 'conversions' (for example, forest to agriculture, agriculture to urban). However, a major limitation of paired watershed studies is the obvious lack of experimental replication across a full range of natural conditions.

Fortunately, paired studies usually provide very high quality experimental data with which to advance the mechanistic understanding of the hydrologic response of watersheds to land-use change and allow testing of mathematical models. In this case, it is expected that experimental approaches combining hydrometric measurements from paired watersheds with process modeling will serve to unravel rapidly the response to land-use change of watersheds of varying size, topography, and spatial configuration. Several studies now focus on the hydrological impacts of land-use change, which is feasible. The feasibility of observing land-cover changes with satellite data is unprecedented. LANDSAT data are collected systematically around the world (Williams and Funk, 2010) and data from moderate-resolution sensors, such as MODIS, are freely available (Justice *et al.*, 2002). Laboratories can now manage the data volumes and image processing that was not possible a decade ago. Satellite data, appropriately calibrated and validated with ground data, provide spatial information on the distribution of land cover types and changes over time (Hansen and DeFries, 2004). Whereas such information could previously only be obtained over small areas from ground surveys or aerial photographs, satellite data extend the coverage over larger areas at more frequent time intervals. Information on land-use over larger areas allows new kinds of investigation, such as the effects of spatial patterns of land-use within a watershed on hydrological processes and modeling of large drainage basins (Donner *et al.*, 2002). Land-use change was considered as the main reason for increased runoff and sediment in tropical region from the study of Bernam Watershed in Selangor state of Malaysia (Alansi *et al.*, 2009). Effect of rainfall amount was negligible. In Central–Northern Thailand, the rate of change in discharge after changes in land use/cover showed a systematic increase over a range from 0.0039 to 0.0180 m^3/s per day over a 15-year period, with the increase in urbanised area spanning a range from 81 to 149% in two flood-prone provinces (Petchprayoon, *et al.*, 2010). A rainfall-runoff model simulated a small increase of 10% in peak flows. Mutie *et al.* (2006) investigated the effects of the derived land cover changes on river flow in Mara River Basin using the semi distributed United States Geological Survey (USGS) geo-spatial stream flow model. Simulation results showed that land cover data for 2000 produced higher flood peaks and faster travel times compared to the 1973 land cover data. The changes indicated the effects of land use pressure in the basin. Like wise, long-term hydrological study in Upper Ewaso Ng'iro Basin by Mungai *et al* (2004) showed that, the conversion of land use from natural forest to small-scale agriculture often practiced without adequate conservation lowered infiltrability of the soils causing an increased runoff and flash floods. In addition, river water abstractions impacted on the dry season water supply functions of the watershed.

Pereira and Wangati (1981) conducted a study in Kericho to determine the effects of land-use changes from indigenous forest to tea estates. The long-term mean value of water use by the forest was found to be 92% of the Penman open water evaporation (E_0) while the value was 84% for the partially converted catchment. The annual variability in water use was greater for the forested area than for the experimental (converted) catchment. Mean water use and its variability for the bamboo sub-catchment was similar to that for the experimental catchment. Interception capacity (for rainfall) of the tea canopy was about 2.5 mm and water stored in the canopy evaporated at a much higher rate than the transmission rate through the canopy. Interception in bamboo resulted in loss rates comparable with those from tea, but losses from both tea and bamboo were lower than those from the indigenous forest. The study concluded that replacement of forest by a tea estate did not result in any long-term reduction in water yield from the catchment. Moreover, surface runoff from the mature tea did not exceed that from the forest although some increase occurred during the clearing and planting phases (Pereira and Wangati, 1981).

2.4.1 **Effect of soil conservation and afforestation on hydrological processes**

It is believed generally that the hydrological impact of soil conservation practices is to reduce and delay surface runoff, and hence decrease soil erosion (Quinton *et al.*, 1997; Liu and Huang, 2001). At the catchment scale these practices were reported to result in reduction in flood peak discharges and volumes and increase in base flow. However, it is not clear whether these hydrological responses are noticeable in the medium to large catchments. Since 1970s, China's Yellow River ceased to flow during dry spring seasons and this may have significant implications for regions in the lower reaches of the Yellow River in terms of irrigation and water supply (Liu and Cheng, 2000). It is possible that the soil conservation practices may have contributed to the reduced runoff in the Yellow River during spring. Further there are conflicting results reported in the literature on the impact of afforestation on base flow in other countries. Most of the catchment studies indicate that the dry season flow is lower from forested catchments than from natural grassland because for forests transpire more than grasses (Smith and Scott, 1992; Kramer *et al.*, 1999, Best *et al.*, 2003). Other studies, however, have suggested an increase in base flow following afforestation in some semi-arid and humid regions (Bonell and Balek, 1993; Sandstrom, 1995). Work done in Itare sub-catchment within the Lake Victoria Basin, of Kenya showed that, changes in land use from forest to agricultural have reduced dry spell flows; sometimes leading to water shortages, but with a marked increase in total flow (Nyangaga, 2008). It is, therefore, important to understand the impact of land management practices including afforestation on the regional hydrological regime of River Gucha Catchment.

2.4.2 **Effect of selective logging on hydrological processes**

Selective logging generally leaves the forest as an irregular mosaic of vegetation with different degrees of disturbance. A considerable part of the surface may consist of bare, compacted soil. Although both evaporative demand of the atmosphere and soil temperature in large gaps are much higher than under mature phase forest (Uhl and Jordan, 1984), this does not necessarily imply that the soil profile will be drier in clearings. In fact, there are strong arguments for the reverse to occur. The regrowth will, at least initially, possess a smaller total leaf area, a less extensively developed root system, and possibly a higher albedo (Pinker *et al.*, 1980; Parker, 1985). Soil moisture contents during the dry season in lowland Costa Rica were highest in a large clearing and lowest under mature forest. This could be due to reduction in evapotranspiration from the forest which cause soils to be wetter. Whilst differences between sites were small by the end of the rainy season (suggesting that any rainfall interception effect will be small) (Nortcliff *et al.,* 1990), trends diverged as the dry season progressed, particularly so during the first year. Interestingly, during the second year, a 10 m x 50 m strip of cleared forest exhibited a pattern that was quite similar to that of 6-year-old regrowth, possibly because of "colonization" of the strip by roots of surrounding trees (Parker, 1985).

Alternatively, soils may become drier because of a combination of direct insolation and deteriorated infiltration characteristics due to compaction by machinery (Lai, 1987; Jetten, 1992). In such cases, the potential gain in soil water content associated with reduced evapotranspiration (ET) from a cleared surface (as compared with mature forest) is more than offset by the loss in water intake by the damaged soil surface (Bruijnzeel, 1989). Therefore, depending on the spatial extent and degree of damage to vegetation and soil, dry season soil water content (and thus base-flow) after forest exploitation may be above or below original values. Given the extent of logging operations in tropical rainforests, the small number of reliable studies addressing the associated impacts on hydrological regime is rather astonishing. Results for only two paired catchment studies (Babinda, Queensland: Gilmour *et al.*, 1982; Bukit Berembun, Peninsular Malaysia: Abdul Rahim *et al.*, 1990) have been published. Their results can be summarized as follows; at Babinda, "light" logging (<20 m^3 ha^{-1}, did not produce a significant effect on total water yield or base-flow recession (Gilmour *et al.*, 1982). At Bukit Berembun, the extraction of 40% of the commercial stocking by crawler tractors and winch Lorries resulted in an increase in stream-flow of about 70%. Upon harvesting 33% of the stocking according to closely specified prescriptions (concerning lay-out, gradient and drainage of tractor tracks; leaving a 40 m wide riparian buffer strip), the increase in water yield was only 40%. Interestingly, there was no trend of a decline in the net gain of stream-flow (base-flow) with time over a period of four years, suggesting that water use by regrowth in the gaps created by logging still remained below that of the original stock (Abdul Rahim *et al,* 1990). There is no published information on the time span required for regrowth to return to pre-logging levels of ET (and thus water yield). It is expected that different logging intensities will result in different recovery periods.

Results obtained by Maimer (1993) for rainforest in Sabah, East Malaysia, that had been selectively logged five years before the start of stream-flow observations, did not reveal any trend in annual ET over the next five years, except for higher values during wetter years. The average value found for the ET of the regenerating forest over this period was 1540 mm year^{-1}, which was close to the overall mean of 1465 mm year^{-1} derived for Southeast Asian rainforests. As such, it could be argued that the Sabahan forests, which were claimed to have been "lightly" logged despite a reduction in biomass of at least 33%, had re-attained pre-logging levels of ET after 5-10 years (Bruijnzeel, 1990). Since basin leakage through the sandy valley fill cannot be excluded entirely (Maimer, 1993), the actual recovery period may be longer. In Kenya, accelerated loss of vegetation cover in most catchments is associated with land degradation, which consequently poses a threat to the river flows and the ecosystem (Mutie *et al* 2005; Mati *et al*, 2005; Machiwa, 2002; Aboud *et al*, 2002; Pereira, 1989). Further work in River Gucha Catchment is thus desirable to determine the effects of land use/cover change on stream flow.

2.4.3 **Effect of land clearing on hydrological processes**

A common notion about the role of forests is that the complex of forest soil, roots and litter acts as a sponge soaking up water during rainy spells and releasing it evenly during dry periods. Indeed, accounts of springs and streams drying up after forest removal are numerous enough (Hamilton, 1983; Bartarya, 1989; Pereira, 1989). On the other hand, the number of reports of the reverse (streams drying up after afforestation of degraded land) is increasing as well. When trying to reconcile these apparent contradictions, it is helpful to distinguish between effects of clearing on water yield (total stream-flow) and flow regime (the seasonal distribution of flow). Before addressing the issue, a few methodological comments are in order. Firstly, simply comparing stream-flow totals for basins with contrasting land-use types may produce erroneous results because of the possibility of geologically determined differences in basin leakage (Bruijnzeel, 1989). Also, the strong spatial and year-to-year variability in tropical rainfall may compound direct comparisons between basins or years (Blackie, 1979; Maimer, 1993).

Rigorous experimental designs (the "paired catchment" or "single basin" techniques are needed to overcome such problems (Hewlett and Fortson, 1983; Ibrahim and Chang, 1989). Such controlled experiments are time consuming and expensive and consequently relatively few of them have been conducted in the tropics. Perhaps surprising to some, removal of tropical rainforests resulted in substantial increases in total stream-flow during the first three years, ranging from 125 to 820 mm year^{-1}, depending on the amount of rain received after the event (Bruijnzeel, 1991). In addition, the gain in water yield is roughly proportional to the fraction of biomass removed. This could be due to reduction in evapotranspiration which cause soils to be wetter and therefore more responsive to rainfall. No effect has been found for disturbances affecting less than 20% of a forested catchment. There can be no doubt that such changes reflect the different evaporative characteristics of mature and young exotic vegetation. Under mature forest much of the water infiltrating into the soil is consumed again by the trees (1000 mm year^{-1}) in lowland rainforests that are never severely short of water and the remainder is used to sustain stream-flow (Bruijnzeel, 1990).

There is an irregular decline in stream-flow gain with time that is associated with the establishment of the new vegetation and year-to-year variability in rainfall. Water yields after maturation of the new crop may remain above original values in the case of a conversion to annual cropping, grassland, tea, rubber or cocoa plantations (typically by about 300 mm year^{-1}), or return to original levels after full canopy closure in the case of conversion to fast-growing plantation forest (usually after 5-10 years) or certain extractive tree crops (oil palm) and presumably also in the case of natural regrowth. Such differences typically reflect contrasts in ET between tall and deep-rooted (forests, mature plantations) and short and shallow-rooted vegetation (pioneer plants, most crops), both during rainy spells (differences in amounts of intercepted rainfall) and during the dry season (different ability to take up water) (Bruijnzeel, 1990; Pereira, 1952). One of the most important consequences of this finding is that the afforestation of degraded crop land or grasslands with fast-growing (exotic) tree species will result in a decrease in stream-flow totals, usually shortly after canopy closure. Values reported for seasonally tropical uplands (1500 - 2000 m) are in the order of 100-200 mm year^{-1} (Bruijnzeel, 1990), but stronger reductions can be expected in lowland situations (Waterloo *et al,* 1993). The replacement of natural grass or scrub vegetation by some of these exotics, particularly eucalyptus, has been under severe criticism for a variety of reasons, one of them being that eucalyptus are allegedly voracious consumers of water (Gush and Dye, 2003). The observations by Smith and Scott (1992), who reported stream-flow from re-afforested areas in upland South Africa to decline faster and earlier in the case of *Eucalyptus grandis* as compared to *Pinus patula,* would seem to confirm such fears. Since rainfall interception by tropical conifers is usually higher than that for eucalyptus (Pereira, 1952; Calder, 1986; Bruijnzeel, 1988), such differences in overall ET must reflect different rates of water consumption.

Work on young eucalyptus in sub-humid South India (annual rainfall 800 mm) suggested that transpiration can be severely reduced under such conditions as a result of soil moisture stress but also that daily uptake rates can be as high as 5-7 mm under conditions of ample soil water. Although it would take a long time before the tree roots would have ready access to the groundwater table (found at 30 - 100 m depth in this particular case) and thus be able to transpire continuously at a potential rate, there was growing evidence that the trees were "mining" soil water reserves as the root network developed (Calder, 1986; Calder, 1992; Calder *et al.*, 1992). Soil water contents under indigenous forest were similar to those recorded under *Eucalyptus;* however, subsequent recharge to the groundwater table was presumed to be equally small under *Eucalyptus* (Harding *et al.*, 1991). Also, decreases in catchment water yield following afforestation of natural grassland with blue-gum *(Eucalyptus globulus)* at high elevations elsewhere in South India were negligible during the first three years and stabilized afterwards at a modest 120 mm year-1 (Samraj *et al,* 1988). However, more severe reductions were observed after coppicing mature trees whose root systems remain intact (up to 285 mm $year^{-1}$; Vishwanatham *et al.,* 1980, 1982).

The results presented thus far all pertain to relatively small catchment areas involving a unidirectional change in cover. Although these provide a clear and consistent picture of increased water yield following replacement of tall vegetation by a shorter one and *vice versa,* effects may be more difficult to discern in larger basins with a variety of land-use types and vegetation in various stages of regeneration. In addition, the strong spatial and temporal variation in tropical rainfall tends to "drown" any effects associated with modifications of the surface (Qian, 1983; Dyhr-Nielsen, 1986). On the other hand, Madduma and Kuruppuarachchi (1988) reported a highly significant increase in annual runoff ratios (flow/rainfall) for the 1108 km^2 Mahaweli basin in Sri Lanka over the period 1944-1981. This increased hydrological response was caused by the widespread conversion of tea plantations to annual cropping and home gardens without appropriate soil conservation measures (Madduma and Kuruppuarachchi, 1988). In the first two cases, there was apparently a fair degree of vegetation regrowth, whereas in the Sri Lankan example, the soils remained more exposed to the weather elements. Evapotranspiration by these crops is known to be low to very low (Bruijnzeel, 1990), which, together with the extra inputs of moisture discussed earlier, causes stream-flow from such areas to be high. Interestingly, these low rates of water use are not so much a direct consequence of low radiation inputs and high humidity as is commonly thought

(Ash, 1987) or the frequent wetting of the canopy by passing clouds (suppressing transpiration; Calder, 1992). Observations in a Malaysian "cloud forest" have demonstrated that water uptake also remained suppressed during periods of bright sunshine under conditions of ample soil water and low to moderate vapour pressure deficits. The cause of the retarded growth of these stunted forests is still unknown although a wealth of hypotheses has been advanced over the years (Bruijnzeel *et al.* 1993).

Despite the demonstrated importance of mountain "cloud" forests for the continuing supply of water to adjacent lowlands, they have been converted to grazing land in many places in Kenya (Pereira, 1989). In the case-study of Nzoia River Catchment, (Patts *et al.*, 2010) results from SWAT model showed that, with the expansion of the area under agriculture, the stream flow increased during the rainy seasons and reduced during the dry seasons, whereas when the area under forest cover is increased the peak stream flow reduced, but when the forest cover is reduced to almost zero there is an increased peak and mean stream flow in the catchment. This could be due to reduction of evapotranspiration which cause soils to be wetter and therefore more responsive to rainfall.

Reports of greatly diminished stream-flow during the dry season abound in the literature and are usually ascribed to "deforestation". At first sight, this seems to contradict the evidence presented above, also in view of the fact that generally following forest clearance in experimental watersheds the bulk of the increase in water yield was observed during base-flow or dry season conditions (Bruijnzeel, 1990). The conflict can be resolved, however, by taking into account the net effect of changes in ET and rainfall infiltration that are brought about by the land-use change (Bruijnzeel, 1989). In short, if infiltration opportunities after forest removal have deteriorated to the extent that increases in storm-flow during rainfall exceed the gains in base-flow associated with the lower ET of a cleared surface then this results in diminished dry season. (Rijsdijk and Bruijnzeel, 1991). The converse applies as well as it was noted by Edwards, (1979).

Reduced infiltration after conversion of forest into cultivated land may result from the use of heavy machinery during clearing or from prolonged exposure of topsoil to raindrop impact; open cast mining; overgrazing; and improper agricultural practices (Lai, 1987). This situation is, of course, widespread and must be held responsible for the deterioration in stream-flow regimes that is so often observed (Rijsdijk and Bruijnzeel, 1991). If, on the other hand, surface infiltration characteristics are maintained over most of the cleared catchment, either because of a well-planned and maintained road system (Abdul Rahim, 1989), careful extraction of timber (Maimer, 1993), or subsequent soil conservation practices and controlled grazing (Edwards, 1979), then the effect of reduced ET after clearing will indeed show up as increased base-flow during dry spells (Edwards, 1979). The fact that total water yield from degraded crop or grassland is usually reduced considerably following reforestation, already indicates that the evapotranspirational factor may easily override the infiltration factor, particularly in the case of shallow soils (Bruijnzeel, 1989; Smith and Scott, 1992). Again, it could be argued that the controlled conditions of catchment experiments bear little relevance to the real world situation. The lesson that can be learned from such experiments is a most important one, however; the commonly observed deterioration in tropical river regimes following forest removal is not so much the result of the clearing itself but could be due to lack of good land husbandry during and after the operation (Smith and Scott, 1992). Ongwenyi *et al.* (1993) examined the hydrological and land use processes that were affecting the quality of water in the Gucha Catchment, Kenya. They suggested that although the waters of the catchment were of relatively good quality, it was expected that, with the high population growth rates, serious adverse changes will occur to water resources in the catchment which needed to be investigated.

2.4.4 **Effects of land use change on flooding**

The hydrological response of small catchment areas to rainfall depends on the interplay between climatic, geological and land-use variables. Stream-flow peaks that are produced by some form of overland flow are generally more pronounced than those generated by slower subsurface types of storm-flow. As such, it is especially the shift from subsurface flow to overland flow dominated storm-flows, which often accompanies land clearing due to effects of soil compaction and burning (Lai, 1987), that produces strongly increased peak flows (Bruijnzeel, 1990; Maimer, 1993; Van der Plas and Bruijnzeel, 1993; Fritsch, 1993). In general, carefully planned and conducted conversion operations will be able to keep soil compaction and disturbance, and hence occurrences of infiltration-excess overland flow is to a minimum (Maimer, 1993).

However, even with minimum soil disturbance, there will be increases in peak-flows after forest removal, since the associated reduction in ET will cause soils to be wetter and therefore more responsive to rainfall (Pearce *et al.*, 1980). Relative increases in response tend to be largest for small events (roughly 100%), declining to 10% or less for large events (Pearce *et al.,* 1980; Hewlett & Doss, 1984). Although such increases can be expected to diminish somewhat as a new cover establishes itself (Pearce *et al.,* 1980), they may become "structural" because of contributions from roads and residential areas where there were none before (Rijsdijk and Bruijnzeel, 1991; Douglas *et al,* 1993) or because soils remain wetter (Fritsch, 1992). Also, reduced infiltration after conversion of forest into cultivated land may result from increase in the area occupied by impervious surfaces such as roads, trails and settlement (Lai, 1987).

Whilst it is beyond doubt that adverse land-use practices after forest clearance generally cause serious local increases in storm-flow volumes and peak-flows, one has to be careful to extrapolate such effects over large river basins. High storm-flows generated by heavy rain on a misused part of a river basin may be affected by more modest flows from other parts receiving less or no rainfall at the time or with better land-use practices (Hewlett, 1982; Dyhr-Nielsen, 1986), whereas within-channel storage can be an important dampening factor on very large river systems (Zhang, 1990). Truly devastating and large-scale flooding is the result of an equally large field of extreme rainfall (Mooley and Parthasarathy, 1983), particularly when this occurs at the end of a rainy season when soils have become wetted up thoroughly by antecedent rains. Under such extreme conditions, basin response will be governed mainly by soil water storage opportunities rather than topsoil infiltration capacity. Nevertheless, it cannot be excluded that widespread forest removal, followed by poor cultivation practices, may have a cumulative effect and there are signs (for example, the widening of river beds) that such a thing were happening in parts of the Himalaya. However, other factors, which often tend to be overlooked, include torrential rains on the flood plains themselves during times of high water; backwater effects; raised river beds due to high sedimentation; and the breaking up of temporary barriers to river flow (Bruijnzeel and Bremmer, 1989; Zhang, 1990).

Effects of land-use changes on the magnitude of flood peaks in large rivers are very difficult to evaluate because such changes are rarely very fast and consistent and normally compounded by climatic variation. Moreover, such an analysis requires long-term and high quality data on land use, stream-flow and rainfall, which are rarely, if ever, available for humid tropical regions. Although attempts at routing flood peaks from headwater areas through river systems in warm humid regions are becoming increasingly successful (Zhang, 1990; Sambou and Thirriot, 1993), the evaluation of land-use effects on such peaks still constitutes one of the greatest challenges in the field of environmental hydrology. Agricultural practices and urbanization increase the percentage of impervious area in a watershed, thus the surface runoff in a post-development area becomes greater than in that in pre-development area. Consequently, the base flow in post-development area is significantly reduced (Meybeck *et al.,* 1989). Furthermore, the discharge flow time pattern changes, peak discharge increased and peak time became shorter. This has been supported by Patts *et al.* (2010) who found that the rapid expansion of urban centres in the lower parts of Nzoia River Catchment was the major contributing factor to the annual devastating floods in lower parts.

Various studies have shown that when agricultural land is tilled, compaction of lower soil horizons occurs and this lowers infiltration rates and increases bulk density (Ankeny *et al.*, 1990; Logsdon *et al.*, 1990; Nidal, 2003; Githui 2008). This compaction decreases water retention as rainfall saturates the soil profile quicker in agricultural lands than in the forested areas thus producing more runoff. In the study by Githui (2008) the bulk density of the top soil layer with which runoff interacts was on average greater for agricultural lands (1.22 Mg/m^3) than in forested (1.19 Mg/m^3) areas. From SWAT scenario simulation in Nyando Basin, Sang (2005) observed that 100% forest cover reduced the simulated peak flow from 111 to 69 m^3/s. On the other hand 0 % forest cover increased the simulated peak flow from 111 to 121 m^3/s. With rates of forest conversion being faster than ever and the availability of remotely sensed information on land use, such questions may be coming closer to an answer as it is in the case of this study. With the advent of Geographic Information System (GIS) and Remote Sensing techniques, the hydrological catchment models have been more physically based and distributed to enumerate various interactive hydrological processes considering spatial heterogeneity.

2.5 Watershed Modeling

Generally, models can be divided into two broad categories: physically based model (distributed model) and conceptually based models (lumped model). A review on rainfall-runoff modeling has been given by O'Loughlin *et al.* (1996). Singh (1988) provided a general survey of most of the techniques available for modeling hydrological systems. Physically-based models are models that are based on physical laws and known initial and boundary conditions. Few physically based models have been developed and applied including; kinematic wave model, Watershed Environmental Hydrology Model (WEHY) and Topography Model (TOPMODEL). Physically-based models are normally run with point values of precipitation, evaporation, soil moisture and watershed characters as primary input data and produce the runoff hydrographs. They are generally accurate, but difficult to use because users must determine a huge number of parameters, which are often difficult to obtain. Many of the assumptions in these models cannot be satisfied in practice (Singh, 1988).

In regions where precipitation data series are available but runoff data are scarce, a deterministic rainfall-runoff model is a good tool. Kavvas *et al.* (2004) developed a new model 'Watershed Environmental Hydrology Model (WEHY)' to the modeling of hydrologic processes in order to account for the effect of heterogeneity within natural watersheds. The parameters of the WEHY are related to the physical properties of a watershed, and they can be estimated from readily available information on topography, soils and vegetation/land cover conditions (Chen *et al.*, 2004). The parameters can be obtained from GIS database of a watershed without resorting to a fitting exercise. The WEHY model has been applied to the Shinbara-Dam Watershed and has produced promising runoff prediction results (Chen *et al.*, 2004). To investigate the influence of urban pavement and traffic on runoff water quantity, Cristina *et al.* (2003) developed a kinematic wave model, which accurately captured the significant aspects of typical urban runoff. The impacts of the paved urban surface and traffic were examined with respect to the temporal distribution of storm water runoff quantity. The kinematic wave theory gave predictions of the time of concentration that were more accurate than other more common methods currently in use. Campling *et al.* (2002) developed TOPMODEL, a semi-distributed, topographically based hydrological model, and applied it to continuously simulate the runoff hydrograph of a medium-sized (379 km^2), humid tropical catchment. They found that water tables were not parallel to the surface topography as it is always assumed.

Conceptual-based lumped models are well known for their simplicity. Many researchers apply them widely. Fontaine (1995) evaluated the accuracy of rainfall-runoff model simulations by using the 100-year flood of 1st July, 1978 on the Kickapoo River, in Southwest Wisconsin as a case study. It was concluded that the error in the precipitation data used for calibrating the model appeared to be the primary source of uncertainty. Liden (2000) did an analysis of conceptual rainfall-runoff modeling performance in different climates. It was found that the magnitude of the water balance components had a significant influence on model performance. Beighley (2002) presented a method for quantifying spatially and temporally distributed land use data to determine the degree of urbanization that occurs during a gauge's period of record. Madsen *et al.* (2002) presented and compared three different automated methods for calibration of rainfall-runoff models. Other widely used packaged software include Watershed Modeling System (WMS, developed by Environmental Modeling Research Laboratory, Brigham Young University), Storm Water Management Model (SWMM, developed by U. S. Environmental Protection Agency (EPA)), Soil and Water Assessment Tool Model (SWAT), Hydrologic Engineering Center Hydrological Modeling System (HEC-HMS) and HEC-GeoHMS 1.1 for Arcview GIS 3.2 or latest version developed by U. S. Army Corps of Engineering which was used in this study.

2.5.1 **Precipitation Loss Modeling**

Rainfall-runoff models compute runoff volume by calculating the volume of water that is intercepted, infiltrated, stored, evaporated and transpired and subtracted from the precipitation. The loss can be broadly categorized into infiltration and evaporation (upward loss). Infiltration from a watershed can be computed by the Soil Conservation

Service (SCS) curve number (CN) method. In the current study, SCS-CN abstraction method was employed to obtain excess rainfall, which was used to generate hydrographs. The Soil Conservation Service (SCS) curve numbers (CN) describe the surface's potential for generating runoff as a function of the soil type and land use on surface. Curve numbers are empirical parameters used in hydrology for predicting direct runoff or infiltration from rainfall excess. Curve numbers range from between $0 < CN \leq 100$, with 0 as the theoretic lower limit describing a surface that absorbs all precipitation, and 100 the upper limit describing an impervious surface such as asphalt, or water, where all precipitation becomes runoff (NRCS, 2004). Precipitation loss has been calculated based on CN and initial surface moisture storage capacity as shown in Equations 1 below. The standard SCS-CN method is based on the relationship between rainfall depth, P in millimetres, and runoff depth, Q in millimetres.

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \qquad \text{...(1)}$$

The potential maximum retention, S in millimetres, represents an upper limit of the amount of water that can be abstracted by a watershed through surface storage, infiltration, and other hydrologic abstractions. For convenience, S is expressed in terms of a curve number (Equation 2).

$$S = \frac{1000}{CN} - 10 \qquad \text{...(2)}$$

Where CN = Curve Number

Equation 1 applies only for $P \geq 0.2S$, otherwise all the precipitation is assumed to be lost to infiltration. As a result, the SCS method provides the depth of excess precipitation resulting from a given depth of precipitation falling over an area during a specific time interval.

2.5.2 GIS-Based Watershed Modeling

With the development of computer science, hydrological models have been combined with Geographic Information System (GIS) technology. GIS is a special type of information system in which the data source is a database of spatially distributed features and procedures to collect, store, retrieve, analyze, and display geographic data (Shamsi, 2002). In other words, a key element of the information used by utilities is its location relative to other geographic features and objects (Shamsi, 2002). It combines spatial locations with their corresponding various information. GIS is a class of concepts instead of one product. There are many kinds of GIS data, which are supported by different software packages. They may not be compatible with each other depending on their format.

GIS-based hydrological models utilize readily available digital geospatial information more expediently and more accurately than manual-input methods. Also, the development of basic watershed information will help the user to estimate hydrologic parameters. After obtaining adequate experience in GIS-generated parameters, users can make parameter estimation more efficiently. GIS-based hydrological models may use different GIS data as different layers. To make different GIS data display and work in the correct location, coincident spatial referencing is needed for different layers. There are different GIS-based hydrological models including; HEC-1, HEC-HMS and HEC-GeoHMS. HEC-GeoHMS was developed by U.S. Army Corps of Engineers, Hydrological Engineering Center (U. S. Army Corps of Engineers, 2003). HEC-GeoHMS links GIS tool (ArcView3.x) and hydrologic model (Hydrologic Modeling System - HMS). HEC-GeoHMS combines the functionality of Arc Info into a package that is easy to use with a specialized interface.

With the Arcview capability and the graphical user interface, the user can access customized menus, tools and buttons instead of the command line interface in Arc Info. The hydrologic algorithms in the model are the same as HEC-HMS. First, HEC-GeoHMS imports DEM data and fills sinks in the data. Second, it generates flow direction and streams based on DEM data. Then the next step is to delineate watershed and sub-watershed boundaries. The newly generated files are stored in separate layers. The pertinent watershed characteristics can be extracted from the source DEM data and the generated stream and boundary data. After these processes, a HEC-HMS schematic map and project can be exported. Other parameters, such as meteorological and time series need to be set before the project runs. In fact, HEC-GeoHMS prepares the input file and schematic map for HEC-HMS. By using GIS data, detailed watershed characteristics are obtained automatically for the HEC-HMS model. Another GIS environmental modeling package is Better Assessment Science Integrating Point and Non-point Sources (BASINS). (BASINS) was developed by the U. S. Environmental Protection Agency (EPA). It takes advantage of developments in software and data management technologies and uses the ArcView3.x as the integrating framework to provide the user with a comprehensive watershed management tool. In this manner, it is like HEC-GeoHMS. However, BASINS focus on point and non-point pollutant modeling instead of hydrological modeling.

2.5.3. **GIS-Based Hydrological Model – HEC-HMS Approach**

Although scientists have long recognized that changes in land use and land cover are important factors affecting water circulation and the spatial-temporal variations in the distribution of water resources, little is known about the quantitative relationship between land use/coverage characteristics and runoff generation or processes (Kokkonen and Jakeman, 2002; Hundecha and Bardossy, 2004). Although some quantitative research methods and numerical models have been developed to address this dearth of data, no widely accepted theory and model have been established to reveal the mechanism underlying the impact of land use and land cover changes on hydrological processes (Vorosmarty *et al.*, 2000; DeFries and Eshleman, 2004).

HEC-HMS, PRMS, HSPF, and AGNPS hydrologic models were evaluated to test their ability to model flood and stream flow (Kristina and Terri, 2008; Bengtson and Padmanabhan, 1999). HEC-HMS which is an advancement of HEC-1 model was successfully applied. It was decided that HEC-HMS was the best choice due to its ability to model flood and stream flow events, incorporate wetland storage (either as reservoirs or diversions), reflect spatial variation in wetland location by subdividing the watershed into sub-watersheds, and the variety of overland and stream flow routing methods available in the model. It was determined using continuous models such as PRMS and HSPF which would be too difficult to calibrate with the existing data, and these models lack overland and stream flow routing methods that would be most suitable for the undulating and hilly slopes like River Gucha catchment. The Hydrologic Modeling System (HEC-HMS) is designed to simulate the precipitation-runoff processes of watershed systems. It is designed to be applicable in a wide range of geographic areas to solve the widest possible range of problems. This includes large river basin, water supply and flood hydrology and small urban or natural watershed runoff. In this model, interception, evaporation and infiltration processes in a catchment are determined from loss components while runoff processes are computed as the pure surface routing using transform component (USACE-HEC, 2006). Hydrographs produced by the program are used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation and systems operation. Knebl *et al.* (2005) integrated different models to forecast flood on a regional scale. The model consisted of a rainfall-runoff model (HEC-HMS) that converts precipitation excess to overland flow and channel runoff, as well as a hydraulic model (HEC-RAS) that models unsteady state flow through a river channel network based on the HEC-HMS-derived hydrographs.

The HEC-HMS program is a generalized modeling system capable of representing many different watersheds. A model of the watershed is constructed by separating the hydrologic cycle into manageable pieces and constructing boundaries around the watershed. Any mass or energy flux in the cycle can then be presented with a mathematical model. In most cases, several model choices are available for representing each flux. Zorkeflee *et al.* (2009) analyzed the impact of land use change to hydrologic behaviour of Sungai Kurau Basin using the Geographical Information System (GIS) and HEC-HMS model for catchments' management. Each mathematical model included in the program is suitable in different environments and under different conditions. Making the correct choice requires knowledge of the watershed, the goals of the hydrologic study and engineering judgment (USACE-HEC, 2006). For example, Yener *et al.* (2006) used

HEC-HMS in event based hourly simulations and runoff scenarios using intensity duration frequency curves for modeling studies in Yuvacik Basin, Turkiye. Yuvacik Basin was selected as the study area and basin parameters (infiltration and base flow) were calibrated using the rainfall-runoff data of the basin collected in 8 rainfall and 3 runoff stations for 2001-2005 period. In some of the application case, the capabilities of the HEC-HMS for rainfall simulation have been exploited to describe single events on which the rating curves to be estimated were tested. Thus continuous simulations are not performed and modeling is limited to single events (Pistocchi and Mazzoli, 2002).

In HEC-HMS model, some parameters are required as inputs to simulate the runoff hydrographs. Some of the parameters can be estimated through observation and measurements of stream and basin characteristics (Yener *et al.*, 2006). The method generally uses either an empirically-derived unit hydrograph of some standard shape defined by one or two parameters, such as the time to peak (Pamela, 1992). After HEC-HMS is applied, the results must be checked to confirm that they are reasonable and consistent with what is to be expected. The model parameters are calibrated until the results are favorable with close proximity of the observed and the simulated hydrographs (USACE-HEC, 2006). Calibration is a process to determine the properties or parameters of a system. Some parameters such as initial abstraction, curve number, impervious, lag time, initial discharge, recession constant and ratio are determined through the calibration process where the parameters are adjusted until the observed and simulated hydrographs are close fit. Some parameters such as slope and length of river are obtained from topographic map (Zorkeflee *et al.*, 2009). The model parameters obtained are validated using different sets of events. In a small oil palm catchment of River Johor, Malaysia, Yosop *et al.* (2007) satisfactorily modelled hydrographs using HEC-HMS. The efficiency indexes of the calibration and validation exercises were 0.81 and 0.82, respectively. Based on these findings it was suggested that the oil palm plantation served reasonably well in regulating basic hydrological functions.

Kristina and Terri, (2009) studied burned City Creek Watershed in San Bernardino County, California using HEC-HMS model whereby five pre-fire storms were calibrated for the selected model resolution, defining a set of parameters that reasonably simulate pre-fire conditions. Six post-fire storms, two from each rainy (winter) seasons were then selected to simulate post-fire response and evaluate relative changes in parameter values and model behaviour. There were clear trends in the post-fire parameters (initial abstractions (Ia), curve number (CN), and lag time) that revealed significant changes in watershed behaviour (Kristina and Terri, 2009). CN returned to pre-fire (baseline) values by the end of Year 2, while Ia approached baseline by the end of the third rainy season. However, lag time remained significantly lower than pre-fire values throughout the three-year study period. Their results indicated that recovery of soil conditions and related runoff response was not entirely evidenced by the end of the study period (three rainy seasons post-fire). Also in Kota Tinggi Watershed, Malaysia, Razi *et al.* (2010) estimated flood using HEC-HMS. Calibration and validation processes were carried out using different sets of data. Evaluation on the performance of the developed flood model derived using HEC-HMS yielded a correlation coefficient (R^2) of 0.905. The simulated peak flow was 150.9 m^3 sec^{-1}, while the observed peak flow for 10 years record (1997-2006) was 145.12 m^3 sec^{-1}. It was suggested that the developed model using HEC-HMS could be used as a tool for estimating peak flow in Kota Tinggi Watershed.

In Kenya, Mutie *et al.*, (2006) evaluated land use change effects on river flow using USGS geospatial stream flow model in Mara River Basin. Correlation coefficient (R^2) for Amala, Nyang'ores and Mara Mines gauging stations were 0.72, 0.69 and 0.87 respectively. The model performed better for bigger areas of the basin. The model accurately captured the hydrograph rising limbs and peaks but was unable to capture the recession limbs and low flows. Validation was done for 3 years from 1989 to 1991. Similar behaviour of the generated hydrograph and area of calibrations was observed. The hydrograph generated from 2000 land cover dataset produced the highest peak of 877.9 m^3/s whereas the highest peak of 1973 dataset was 827.0 m^3/s. The 2000 dataset peak was higher by 6% compared to the 1973 dataset. This was due to increased run off curve number as a result of expansion of agricultural land at the expense of forest land. The hydrograph generated from the 2000 land cover dataset was shifted to the left and the peak occurred earlier by 4 days when compared to that of the 1973 land cover dataset. Changing vegetation gave different runoff curve number which resulted in changes in rainfall runoff response. The hydrographs showed that the 2000 land cover data produced stream flow even at small magnitudes of rainfall for which the 1973 data did not. The 2000 data set produced stream flow quicker, rising to the peak faster and receding equally faster than the 1973 data set. The erratic nature of the simulated hydrograph was more pronounced in the 2000 than in the 1973 data set and could be associated to the less conversion of overland flow to base flow.

Patts *et al.* (2010) used SWAT model to simulate flow in Nzoia River Catchment. The model was calibrated against stream flow data and parameters were adjusted based on a sensitivity analysis. There was good agreement between the measured and simulated daily stream flow for the calibration period and gave Nash Sutcliffe Efficiency (NSE) of 0.94). The simulation of base flow was slightly underestimated but overall, the relationship between the observed and simulated stream flow was acceptable. The statistical and graphical evaluations of the model performance showed that it could be reliably used for assessing impacts of land use/cover change on stream flow. These results showed that for this study region and for the considered period, land cover changes have contributed to greater runoff changes affecting the stream flow amounts and base flow, hence resulting in more frequent devastating floods. Sang (2005) also used SWAT model to simulate stream flow in the flood prone Nyando Basin in Western Kenya. Calibration of the model against stream flow attained a coefficient of determination (R^2) values ranging from 0.45 to 0.72. HEC-HMS model has been used in other countries but it has not been tested in Kenya and therefore, this study tested its performance in River Gucha Catchment.

CHAPTER THREE

MATERIALS AND METHODS

3.1 The study area

The River Gucha Catchment is located between longitudes 34°36'58''E and 34° 59'56''E and latitudes 00°34'40''S and 00°57'37''S. The catchment is located on the Southwestern part of the Lake Victoria Basin in Western Kenya (Figure 3.1). The total area of the River Gucha Catchment is 1036 km^2. River Gucha is one of the tributaries of the greater Gucha-Migori River whose total drainage area is 5180 km^2 (Ojany and Ogendo, 1986). The Gucha catchment constitutes approximately 20% of the total drainage area of the Gucha-Migori basin. The catchment covers large parts of Kisii and Nyamira districts with only a small portion in the South Nyanza District. The region has hilly terrain with an average altitude of between 1540 - 2000 m above mean sea level (Ongwenyi *et al.*, 1993). It experiences a bimodal pattern of rainfall with mean annual rainfall of 1800 mm and lies in Agro-Ecological Zone UM1 (Jaetzold *et al.*, 2005). Due to high elevation (1500 to 3000 m), temperature and rates of evapotranspiration in the catchment are generally low. The average minimum and maximum night temperatures are 13.5 and 30°C respectively (Ongwenyi *et al.*, 1993).

Volcanic rocks with few metamorphic rocks underlie soils within the catchment. The soils are generally moderately deep to very deep, reddish brown to red mostly Ferralsols and Nitisols. Along the valley bottoms, clay soils are common. In general soils are of fairly high infiltration rates of between 8-12 mm/hr except those, occurring in bottom lands and along river valleys. They have in general high moisture retention capacities of between $_p$F 2.0 to 3.7 or 316 – 5012 cm moisture content (Wielemaker and Boxen, 1982).

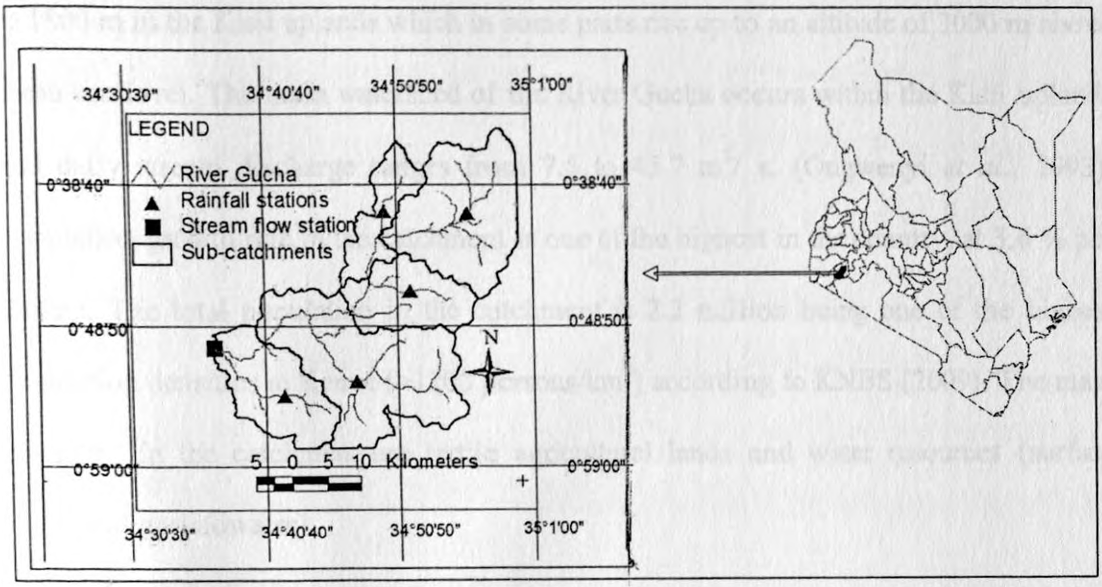


Figure 3.1: Location of the River Gucha Catchment.

No natural vegetation exists in most parts of the catchment with exception of the valley floors. This is due to the fact that the inhabitants have cleared natural vegetation to give room for cultivation and settlement. The agricultural land use covers most of the catchment. In 1985 it was estimated that 90% of the catchment was under cultivation. Farming units are generally small being in the range of 1.4 to 2.2 ha in size.Most of the current vegetation found in the basin is exotic and is mostly comprised of eucalyptus (*Eucalyptus grandis)*. In the recent years, even the natural vegetation that occurred within the valley bottoms has been cleared as a result of swamp reclamation and gave room for cultivation. The vegetation cover of the catchment presently being exotic in character consists of agricultural crops such as tea, coffee, maize, bananas, finger millet, beans, and pyrethrum. There are also tree species such as eucalyptus (*Eucalyptus grandis)* and pines (*Pinus paculata* and *Pinus radiata*). Grasses mostly consist of *Pennisetum clandistenum*. The River Gucha rises from an elevation of 1500 m at its confluence with Gucha-Migori to 1800 m in the Kisii uplands which in some parts rise up to an altitude of 3000 m above mean sea level. The main watershed of the River Gucha occurs within the Kisii uplands and daily stream discharge ranges from 7.5 to 45.7 m^3/ s. (Ongwenyi *et al.*, 1993). Population growth rate in the catchment is one of the highest in the country, at 3.6 % per annum. The total population in the catchment is 2.2 million being one of the highest population densities in Kenya (>1200 persons/km^2) according to KNBS (2009). The main resources in the catchment are fertile agricultural lands and water resources (surface water and groundwater).

3.2 **Data collection**

The Kenya Tea Development Authority (KTDA) and Coffee Research Foundation (CRF) provided rainfall data taken from 5 manual rain gauges, located in the tea factories within the River Gucha Catchment (Figure 3.1 and Table 3.1). Daily stream flow data (1976, 1993 and 2010) from outlet point (Kanga regular gauging station (RGS), 1KB03) of the River Gucha was accessed from the Water Resource Management Authority (WARMA), Kisumu, Kenya. The observed runoff data at 1KB03 and rainfall data were used to assess their trends over time and evaluate the HEC-HMS model. Temperature data was also collected from the same tea factories and later used to assess its trend over time and carry out relationship comparison with the observed stream flow regimes. Reconnaissance soil map at scale 1:100,000 (Wielemaker and Boxen, 1982) was obtained from Kenya Soil Survey, National Agricultural Research Laboratories (NARL), KARI. Field infiltration rates were determined in few major soil mapping units within the study area to confirm the infiltration rates data in the reconnaissance soil map report which were used to create hydrologic soil groups (HSG) using criteria provided in the NRCS (2007).

One Multi-Spectral Sensor (MSS) for 1976, one Enhanced Thematic Mapper (ETM) for 1993 and one Enhanced Thematic Mapper plus (ETM+) for 2010 were obtained from Regional Centre for Mapping of Resources for Development (RCMRD), Kenya. These LANDSAT imageries were used to assess land use/cover change in the study area. The selected years of the images were purposively chosen with an interval of 17 years considering the effect of cloud cover especially in the study area, temporal sensitivity and availability of stream flow data for comparison purposes. The Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) of the study area with spatial resolution of 15 metres (Appendix A, Figure A1) was downloaded from the Earth Remote Sensing Data Analysis Centre (ERSDAC) website. This GDEM was used to create background maps file for the study area.

Table 3.1: Location of rainfall and stream flow stations in River Gucha Catchment

Latitude	Longitude	Station name	Recording type
00°50'33''S	34°37'10''E	Kanga RGS	Stream flow, manual
00°41'32''S	34°48'32''E	CRF	Rainfall, manual
00°52'26''S	34°42'17''E	Tendere	Rainfall, manual
00°50'07''S	34°52'43''E	Nyamache	Rainfall, manual
00°46'06''S	34°53'00''E	Nyankoba	Rainfall, manual
00°37'06''S	34°57'55''E	Tombe	Rainfall, manual

3.3 Land use/cover classification

ENVI 4.7 software was used to process the LANDSAT imagery for the year 1976, 1993 and 2010. The image for the year 1976 with a spatial resolution of 60 m was resampled to that of year 1993 and 2010 (30 m resolution) using image fusion process. The selected years of the images were determined by absence of cloud cover. To avoid uncertainties, the selected images were acquired within the same season of the years (January). The images were classified into different land use/cover types using supervised classification where ground-truthing of the major land uses within the study area was done according to Chakraborty (2001) guidelines. False color composite (Bands 4, 3, 2) was used for the visual examination and interpretation of the images and maximum Likelihood method of classification was used as recommended by Dutta and Sharma, (1998). The method assumes that the statistics for each class in each band is evenly distributed and calculates the probability that a given pixel belongs to a certain class. Only three main land cover types were classified according to Anderson (1998) and selected to carry out statistic analysis. These classes included; agricultural, forests and residential which all covered about 99 percent of the catchment. Residential class included both built up areas and tarmac roads. The three land use/cover classified maps for the year 1976, 1993, and 2010 were converted to shapefiles and then exported to Arcview GIS 3.2 which later were used with hydrologic soil group's map to produce curve number polygon maps for the year 1976, 1993, and 2010 respectively. Thematic change detection was established using ENVI EX Software. This was done by comparing two images of different times (1976-1993 and 1993-2010 image changes). The software identified differences between the images with a resultant classification image and statistics. Statistics on image changes were saved in a Microsoft excel spreadsheet. The results were then examined and analyzed for land use/cover changes and their percentage changes calculated.

3.4 Assessing trends in rainfall, temperature and stream flow regimes

Climatic (rainfall and temperature) and stream flow data collected from the six stations was analyzed for monthly total rainfall, average temperature and total stream flow for the year 1976, 1993 and 2010 as shown in Tables 3.2a, 3.2b and 3.2c respectively and percentage changes calculated. Microsoft Excel was used to produce trend bar graphs for the year 1976, 1993 and 2010.

Table 3.2a: Total monthly rainfall in River Gucha Catchment

Month	Rainfall 1976 (mm)	Rainfall 1993 (mm)	Rainfall 2010 (mm)
Jan	56.2	156.6	33.8
Feb	134.5	121.3	56.3
Mar	154.4	159.2	300.7
Apr	163.3	156.1	296.9
May	312	234.4	118.5
Jun	163.9	227.3	135.1
Jul	110.7	165.4	210.2
Aug	196.2	134.3	164.3
Sep	149.4	113.6	202.4
Oct	100.4	100.9	245.3
Nov	153.4	117.4	154.3
Dec	75.1	100.9	82.1
Total	1769.5	1787.4	1999.9

Table 3.2b: Average monthly temperature in River Gucha Catchment

Month	Temp 1976 (°C)	Temp 1993 (°C)	Temp 2010 (°C)
Jan	18.50	21.71	21.85
Feb	17.00	19.50	21.88
Mar	20.50	20.90	21.54
Apr	20.75	20.50	20.25
May	19.00	19.97	20.69
Jun	19.75	19.92	19.75
Jul	19.45	19.00	19.59
Aug	20.00	18.00	19.99
Sep	19.70	18.00	20.84
Oct	21.25	19.00	20.42
Nov	18.75	19.00	20.65
Dec	18.85	20.79	21.81
Average	19.46	19.69	20.77

Table 3.2c: Total monthly stream flow at Kanga Regular Gauging Station

Month	Stream flow-1976 (m^3/s)	Stream flow-1993 (m^3/s)	Stream flow -2010 (m^3/s)
Jan	123.89	830.96	95.14
Feb	219.89	115.36	30.80
Mar	50.94	768.84	942.04
Apr	106.04	764.31	1754.24
May	591.89	766.64	879.18
Jun	912.90	764.31	329.39
Jul	743.58	782.83	488.40
Aug	827.45	793.32	1179.39
Sep	875.90	964.31	1259.29
Oct	269.22	389.50	887.97
Nov	134.15	764.31	1132.59
Dec	169.81	789.50	185.81
Total	5025.68	8494.19	9164.25

3.5 Determination of the relationship between temperature, rainfall and land use/cover with stream flow regimes.

The climatic data (rainfall and temperature) collected from the five rainfall stations and the statistics data on thematic image change were used for relationship statistical analysis. Data on total annual rainfall, average annual temperatures, total annual stream flow, forest cover, agricultural and residential area percentages for the year, 1976, 1993 and 2010 was computed as shown in Table 3.3 and used to determine the relationship between temperature, rainfall and land use/cover on stream flow regimes with River Gucha. The relationships were determined using simple regression and coefficient of determination (R^2).

Table 3.3: Total annual stream flow, rainfall, land use/cover and average annual temperatures (1976, 1993, 2010).

Year	Stream flow (m^3/s)	Rainfall (mm)	Temperature (°C)	Agricultural (%)	Forest (%)	Residential (%)
1976	5025.68	1769.50	19.46	65.41	31.87	2.72
1993	8494.19	1787.40	19.69	85.27	11.81	2.92
2010	9164.25	1999.90	20.77	91.69	4.43	3.88

3.6 Basin delineation

HEC-GeoHMS 1.1 extension of Arcview GIS 3.2 was run to create flow directions and flow accumulation files which were used later to delineate sub catchment's boundaries and stream networks using the background map file created from the GDEM. Using HEC-GeoHMS 1.1, River Gucha Catchment was divided into 5 sub-catchments (Table 3.4) based on the distribution of the rainfall stations within the catchment and saved as shapefile. The background map file was also used to compute geometric values of the basin such as sub-catchments areas, river slope, basin slope, stream lengths, longest flow path, time of concentration and sub-catchments lag time for the year 1976, 1993 and 2010 using the HEC-GeoHMS 1.1 (U. S. Army Corps of Engineers, 2003).

Table 3.4: Delineated sub- catchments and their curve numbers for the year 1976, 1993 and 2010.

Sub-catchments	CN-1976	CN-1993	CN-2010	Impervious (%)-1976	Impervious (%)-1993	Impervious (%)-2010
R670W420	65	72	77	2.72	2.98	3.88
R700W460	61	70	77	2.71	2.90	3.88
R780W760	59	76	77	2.68	2.92	3.90
R870W820	58	77	77	2.72	2.88	3.86
R950W930	60	76	77	2.75	2.90	3.88
Average	61	74	77	2.72	2.92	3.88

3.7 Hydrologic soil groups

The CSIRO disc permeameter (Perroux and White, 1988) was used to measure field infiltration rates of the major soil mapping units within the catchment which were found to be conforming to the previous infiltration rates data (Wielemaker and Boxen, 1982). Using Arc view-GIS 3.2, soil series in the digital reconnaissance soil survey map of the study area were classified into hydrological soil groups (A and D) (Figure 3.2) based on the physical soil characteristics (see Appendix A, Figure A2) described in the soil map following the NRSC (2007) method (Appendix A, Table A1). The classified hydrologic soil group's map (Figure 3.2) and the three land use/cover classified maps were later used to produce curve number (CN) polygon maps for the year 1976, 1993 and 2010.

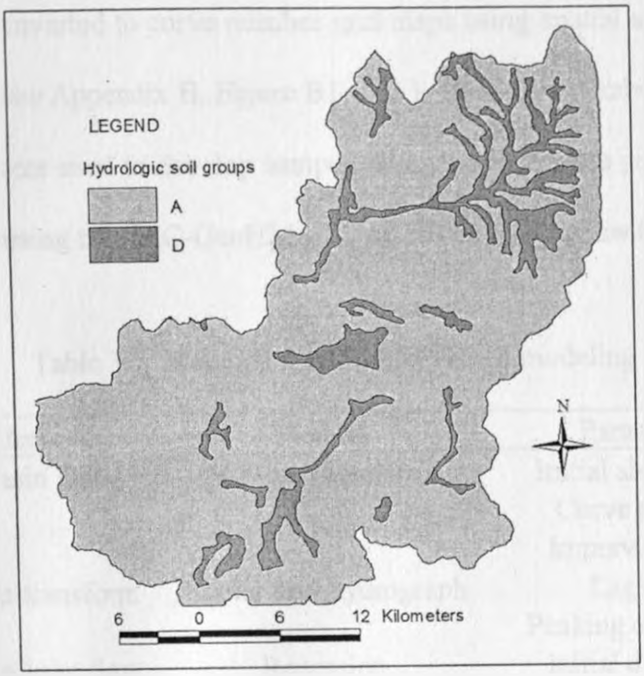


Figure 3.2: Hydrologic soil group's map for the River Gucha Catchment

3.8 HEC-HMS model

Soil Conservation Service (SCS) curve number (CN) and recession base flow methods (NRCS, 2004) were employed to simulate stream flow and generate Snyder unit hydrographs using criteria shown in Table 3.5. SCS-CN method describes the surface's potential for generating runoff as a function of hydrologic soil groups and land use/cover on surface (see Appendix B, Table B1). Curve number polygon maps were produced by overlying the delineated sub-catchments, hydrologic soil group map and the classified land use/cover map for the year 1976, 1993, and 2010 using Arcview GIS 3.2. This was based on the average soil moisture condition curve number look-up table in dbf format (Table 3.6) derived from the standard categories typically used for hydrologic analysis (SCS TR55, 1986). The three developed curve number polygon maps (1976, 1993, and

2010) were then converted to curve number grid maps using spatial analyst extension of Arcview GIS 3.2 (see Appendix B, Figure B1 - B3). The curve number grid maps (1976, 1993, and 2010) were used to develop lumped basin model for the year 1976, 1993, and 2010 respectively using the HEC-GeoHMS 1.1 extension of Arcview GIS 3.2.

Table 3.5: Methods used in HEC-HMS modeling

Criteria	Method	Parameter
Sub-basin loss	SCS curve number	Initial abstraction Curve number Impervious (%)
Sub-basin transform	Snyder unit hydrograph	Lag time Peaking coefficient
Sub-basin base flow	Recession	Initial discharge Recession constant

Table 3.6: Curve number look-up table (SCS TR55, 1986).

Value	Land use	A	B	C	D
1	Forest	43	65	76	82
2	Agricultural	67	77	83	87
3	Residential	77	85	90	92
4	Major roadways	98	98	98	98
5	Water	100	100	100	100

Lumped basin models, background map, and meteorological model developed from HEC-GeoHMS 1.1 extension were selected to run the HEC-HMS model in HEC-HMS program. To simulate stream flow using HEC-HMS model, time series data and control specifications were required. Meteorological model requires total rainfall event while, time series data require daily rainfall events and stream flow data which in this case were collected from the six stations in the study area. Daily rainfall data for the year 1976, 1993 and 2010 were used to compute average rainfall depths (mm) for each sub-catchment using the Thiessen polygon method (Mustafa *et al.*, 2004). Daily rainfall (Appendix C, Table C1) and stream flow (Appendix C, Table C2) events from 8th to 29th of nine selected events were chosen for the three years. Control specifications were required to guide the simulation process. Since HEC-HMS model can only accept simulation duration of up to a maximum of 14 days, rainfall events were set from 16th to 29th for all the selected events. Simulated runoff values were obtained from the cell (model outlet) that was located at Kanga (RGS). The outputs of the model simulations of the selected rainfall events at this cell point were tabulated in Microsoft Excel spreadsheet to estimate the statistical parameters for HEC-HMS model evaluation process.

3.8.1 **Model evaluation**

The model evaluation process included calibration, validation and simulation processes. Coefficient of determination (R^2) from regression was used to test the HEC-HMS model performance in simulating stream flow. Curve numbers and impervious area percentages in all the five sub-catchments (Table 3.4) were averaged for each year for the evaluation of HEC-HMS model (Table 3.7). Residential area percentages were used as the impervious area percentages. During model calibration, validation and simulation, three rainfall events and observed stream flow data were selected for each process making a total of nine events. The scatter plots of observed versus calibrated, validated and simulated stream flows were used for model evaluation at the model outlet station (Outlet-83) located exactly at Kanga RGS. The HEC-HMS model was run using one day recordings and total rainfall events as shown in Table 3.7. Simulated and the observed peak flows hydrographs from the evaluation process were also used to test the model performance in simulating stream flow.

Table 3.7: Parameters used in HEC-HMS model evaluation processes

Event	Total rain event (mm)	Initial abstraction (mm)	Initial discharge (m^3/s)	Impervious (%)	Lag time (hr)	CN
16-29 Jan 1976	48	6.4	0.20	2.72	0.72	61
16-29 May 1976	189	6.4	6.40	2.72	0.72	61
16-29 Aug 1976	49	6.4	0.68	2.72	0.72	61
16-29 Jan1993	150	3.5	7.48	2.92	0.60	74
16-29 Jun 1993	160	3.5	1.60	2.92	0.60	74
16-29 Aug 1993	55	3.5	5.00	2.92	0.60	74
16-29 Jan 2010	24	3.0	0.20	3.88	0.50	77
16-29 Apr 2010	230	3.0	5.00	3.88	0.50	77
16-29 Sep 2010	81	3.0	7.00	3.88	0.50	77

3.8.2 Simulating the effect of land use/cover change on stream flow using HEC-HMS

To quantify the change in stream flow due to land use/cover change, the rainfall event, which occurred after the land cover modification (rainfall event of 23 Jan 2010 (31 mm)), was assumed to have occurred before land use/cover change (1976 and 1993). Different values of curve number, initial abstraction and impervious area percentage derived from the model evaluation process were used for the year 1976, 1993 and 2010 runoff simulation accordingly as shown in Table 3.8. Control specification period was set from

0830 to 2300 h with a time interval of 30 minutes. The changes in peak flow, lag time and base flow, determined from the simulated hydrographs, were used as indicators to estimate the change in stream flow due to land use/cover change. Percentage changes in peak flow, lag time and base flow for the period between 1976-1993 and 1993-2010 were calculated.

Table 3.8: Parameters used to simulate stream flow due to land use/cover change.

Event	CN	Initial abstraction (mm)	Impervious (%)	Lag time (hr)	Base flow (m^3/s)	Peak flow (m^3/s)
23 Jan 1976	61	6.4	2.72	0.72	5	12.5
23 Jan 1993	74	3.5	2.92	0.60	4.8	16.3
23 Jan 2010	77	3.0	3.88	0.50	4.6	17.5

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Trends in land use/cover change

The area covered by each of the land use/cover type for 1976, 1993 and 2010 and their percentage changes for the period between 1976-1993 and 1993-2010 are shown in Table 4.1. Based on the analyses of LANDSAT images of River Gucha Catchment for the year 1976, 1993 and 2010, classified land use/cover maps (Figures 4.1a, 4.1b and 4.1c) were obtained. Agriculture, which is the main land use in the catchment, covered about 92% of the catchment's area. Forest covered about 4%, while settlement covered the remaining 4%. It is apparent that the forest cover has decreased markedly from 31.87% in 1976 to 11.81% in 1993 and to 4.43% in 2010. In contrast, the agricultural area is seen to have increased over the years from 65.41% in 1976 to 85.27% in 1993 and to 91.69% in 2010, while residential area increased from 2.72% in 1976 to 2.92% in 1993 and to 3.88% in 2010.

Table 4.1: Land use/cover change of River Gucha Catchment (1976, 1993, 2010)

	1976		1993		2010		Change (1976-1993)		Change (1993-2010)	
Land use/cover	Area (km^2)	% Area	Area (km^2)	% Area	Area (km^2)	% Area	Area (km^2)	%	Area (km^2)	%
Forest	330.17	31.87	122.35	11.81	45.89	4.43	-207.82	-62.94	-76.46	-68.49
Agriculture	677.65	65.41	883.40	85.27	949.91	91.69	+205.75	+30.36	+66.51	+7.53
Residential	28.18	2.72	30.25	2.92	40.20	3.88	+2.07	+7.35	+9.95	+32.89

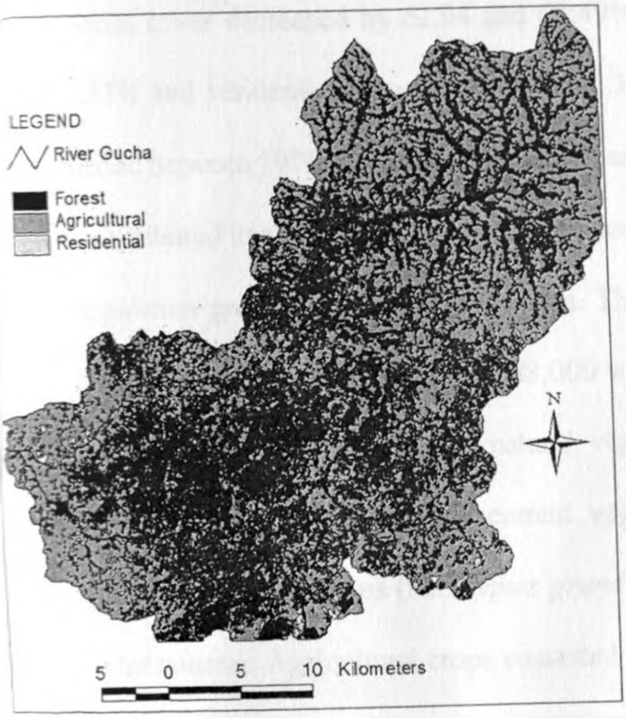


Figure 4.1a: Land use/cover (1976)

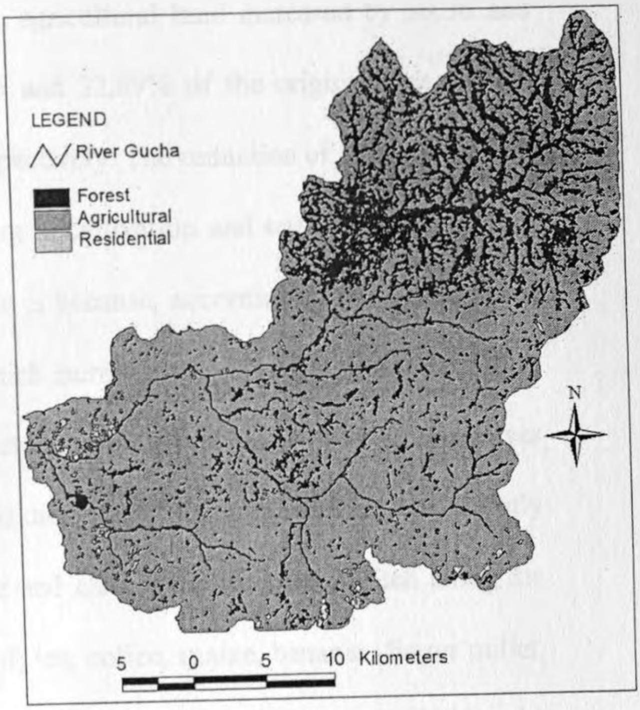


Figure 4.1b: Land use/cover (1993)

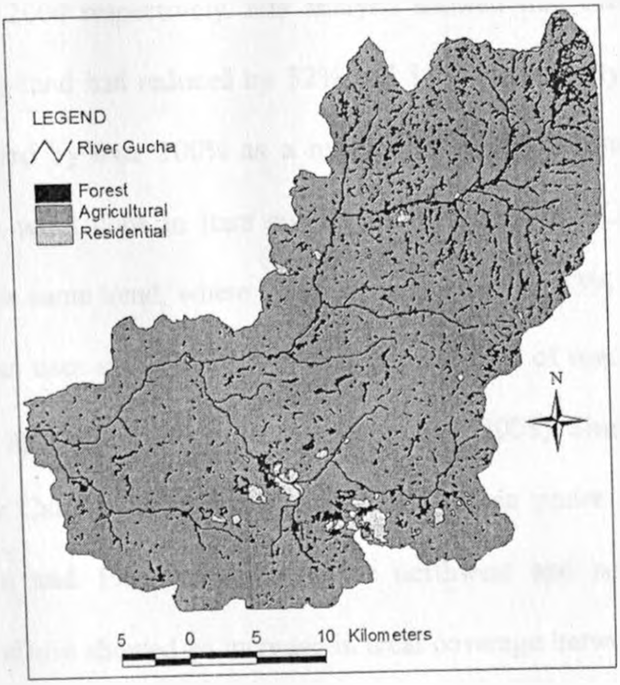


Figure 4.1c: Land use/cover (2010)

Forest cover decreased by 62.94 and 68.49%, agricultural land increased by 30.36 and 7.53% and residential area increased by 7.35 and 32.89% of the original area for the period between 1976-1993 and 1993-2010 respectively. The reduction of forest cover can be attributed to clearing of forests to give room to cultivation and settlement due to high population growth rate in the study area. This is because, according to the 1979 census the catchment had a population of 588,000 which increased to 1.02 million in 1989 and to 2.2 million (KNBS, 2009). No natural vegetation existed in most parts of the River Gucha Catchment. Most of the current vegetation found in the catchment was mostly comprised of eucalyptus (*Eucalyptus grandis* and *Eucalyptus saligna)* planted along the water courses. Agricultural crops consisted of; tea, coffee, maize, bananas, finger millet, beans, and pyrethrum. This was in consistent to the work of Mutie *et al.* (2006) who analyzed land cover change of the trans-boundary Mara River Basin from images of 1973, 1986 and 2000 respectively. His analysis showed that between 1973 and 2000, forests and shrub-land had reduced by 32% and 34% respectively where as agricultural land had increased by over 100% as a result of land use pressure in the basin. Also, results from the work done in Itare sub-catchment within the Lake Victoria Drainage Basin showed the same trend, where forest cover reduced by 33% due to increase of land under the various uses such as urbanization, development of road network, provision of social facilities, agriculture and settlement (Nyangaga, 2008). Similarly, in the case-study of Nzoia River Catchment by Patts *et al.* (2010), area under forest cover decreased between 1970's and 1986 by 6.4% in the northwest and south of the catchment. Agricultural land use showed an increase in areal coverage between 1970's and 1986 by 6.7%. This was as a result of an expansion in riverine agriculture due to high population growth in the area. Similar observations in reduction of forest cover with increasing agricultural and residential lands have been reported by Ongwenyi *et al.* (1993) and JICA, (1992); in Kenyan Basins and by Petchprayoon, *et al.* (2010) in Yom Watershed of Central–Northern Thailand.

4.2 **Trends in rainfall, temperature and stream flow over a period of 34 years**

Results from the analyses of rainfall, temperature and stream flow monthly data of river Gucha Catchment for the year 1976, 1993 and 2010 are shown in Figures 4.2a, 4.2b and 4.2c respectively. The rainfall, stream flow discharges and temperature levels and their percentage changes for the year 1976, 1993 and 2010 are shown in Table 4.2. Total annual rainfall amounts were 1769.50, 1787.4 and 1999.9 mm, average annual temperature levels were 19.46, 19.69 and 20.77 °C and total annual stream flows were 5025.68, 8494.19 and 9164.25 m^3/s for the year 1976, 1993 and 2010 respectively. Total annual rainfall increased by 17.9 mm (1.01%) and 212.5 mm (11.89%), average annual temperature increased by 0.23 °C (1.18%) and 1.08 °C (5.49%) and total annual stream flow increased by 3468.51 m^3/s (69.02%) and 670.06 m^3/s (7.89%) for the period between 1976-1993 and 1993-2010 respectively. It was observed that, stream flow was decreasing during dry seasons and increasing in wet seasons with time from 1976 to 2010. The observed increase in average annual temperature could be in some part due to greenhouse warming (Christensen *et al.,* 2007; Williams and Funk, 2010). It was not however clear whether the observed increasing stream flow and rainfall trends were attributed to human activities or whether they have been caused by natural climatic factors. This increasing trends in temperature was also observed and predicted by Christensen *et al.* (2007); Funk and Brown (2009); Githui, (2008); Githui *et al.* (2009);

Laderach *et al.* (2010); Patts *et al.* (2010); Funk *et al.* (2010) and Williams and Funk (2010) in Kenya.

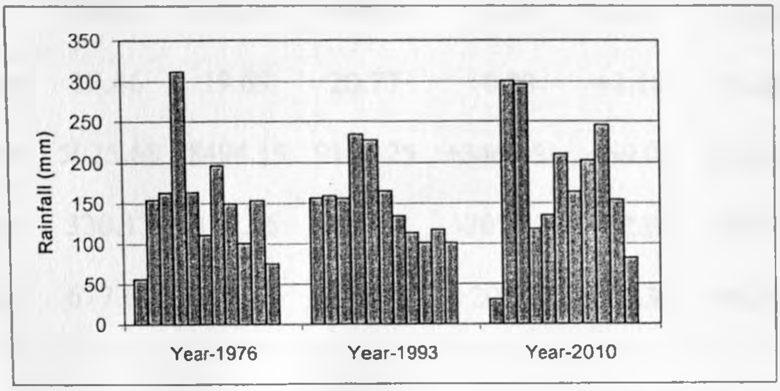


Figure 4.2a: Trend of rainfall (mm) in River Gucha Catchment

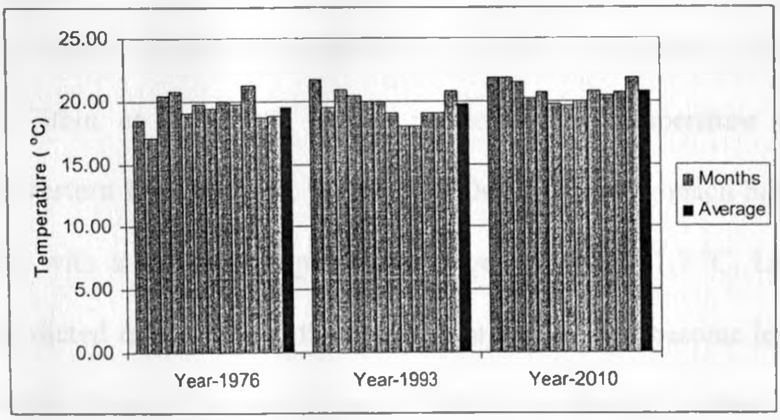


Figure 4.2b: Trend of temperature (°C) in River Gucha Catchment

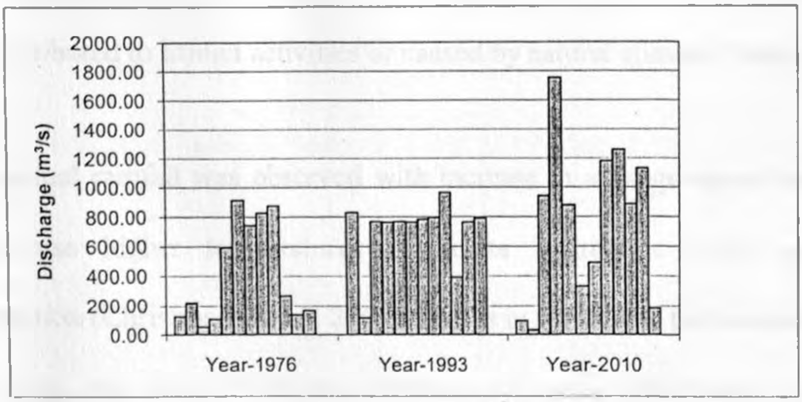


Figure 4.2c: Trend of discharge (m^3/s) in River Gucha

Table 4.2: Analysis of annual total rainfall, stream flow and average temperatures

				Change (1976-1993)		Change (1993-2010)	
Parameter	1976	1993	2010	Change	%	Change	%
Rainfall (mm)	1769.5	1787.4	1999.9	+17.9	+1.01	+212.5	+11.89
Temperature (°C)	19.46	19.69	20.77	+0.23	+1.18	+1.08	+5.49
Stream flow (m^3/s)	5025.68	8494.19	9164.25	+3468.51	+69.02	+670.06	+7.89
Forest cover (km^2)	330.17	122.35	45.89	-207.82	-62.94	-76.46	-68.49
Agricultural (km^2)	677.65	883.40	949.91	+205.75	+30.36	+66.51	+7.53

Funk *et al.* (2010) estimated that from 1975 to 2025, warming generally will represent more than a 1° Celsius increase in temperature for Kenya. According to climate change scenarios by Githui *et al.* (2009), it was predicted that, temperature will continue increasing in Western Kenya region, with the 2050s experiencing much higher increases than the 2020s with a monthly temperature change range of 0–1.7 °C. Laderach *et al.* (2010) also predicted that, in Kenya the overall temperature will become less seasonal in terms of variation through the year in specific districts increasing by about 1 °C by 2020 and 2.3 °C by 2050. They were all not however clear whether the observed and predicted trends were attributed to human activities or caused by natural climatic factors.

More total annual rainfall was observed with increase in average annual temperatures. This is because higher temperatures accelerate hydrologic cycle and increase evapotranspiration (Christensen *et al.*, 2007). This is in contrast to the work of Funk *et al.* (2010); Williams and Funk (2010) and Petchprayoon, *et al.* (2010) who observed and predicted reduction of rainfall in most parts of the world. Modeling the observed 1960–

2009 changes out until 2025, Funk *et al.* (2010) found that large parts of Kenya will have experienced more than a 100 millimeters decline in long-season rainfall. However, the current study's findings were consistent with the work of Christensen *et al.* (2007); Funk and Brown (2009); Githui, (2008); Githui *et al.* (2009); Laderach *et al.* (2010) and Patts *et al.* (2010), who observed and predicted increase of rainfall in some parts of Kenya because higher temperatures accelerate hydrologic cycle and increase evapotranspiration.

Christensen *et al.* (2007) indicated that, Eastern Africa will likely experience a modest (5–10 percent) increase in June-July-August precipitation. Many of the models by Funk and Brown (2009) indicated a future tilt towards a more El Nino-like climate (indicating there will be more rains), which in this region would be expected to produce enhanced long rains in Kenya. In Western Kenya, trend analysis of rainfall showed that, on average, the annual rainfall increased by about 2.3 mm/year between 1962 and 2001. Out of a total of 14 stations, four had shown significant trends at 1% significance level. Of particular interest with respect to the above-mentioned problem is that, out of ten rainfall stations that showed an increasing trend, eight were found in the highland areas (Githui, 2008). In addition, Githui *et al.* (2009) work in Western Kenya using General Circulation Models (GCMs) results showed increased amounts of annual rainfall for all the scenarios but with variations on a monthly basis. All but one GCM showed consistency in the monthly rainfall amounts. Rainfall was higher in the 2050s than in the 2020s projections. Laderach *et al.* (2010) predicted that, in Kenya the yearly and monthly rainfall will increase by 2020 and progressively increase by 2050. Like wise, in the case-study of Nzoia River Catchment, by Patts *et al.* (2010), results indicated an increasing trend in rainfall amounts between 1970 and 1998. A study of three rainfall stations had shown a significant increase in rainfall while one station, in the lower part of the catchment, had shown a significant decrease.

The observed increase in annual stream flow could be either as a result of expansion of agriculture and reduction of forest cover (Table 4.2) hence reducing evapotranspiration which cause soils to be wetter and therefore more responsive to rainfall or lack of good land husbandry which reduce infiltrability of the soil surface or prolonged exposure of topsoil to raindrop impact. This was similar to the work of Alansi, *et al.* (2009); Patts *et al.* (2010); Sang (2005); Pearce *et al.* (1980); Yozop *et al.* (2007); Bruijnzeel *et al.* (1993); Smith and Scott (1992); Abdulhadi *et al.* (1981); Maimer and Grip (1990); Kramer *et al.* (1999); Best *et al.* (2003); Bruijnzeel (1989); Mungai *et al* (2004) and Mutie *et al.* (2006) who observed and simulated increased stream flow with reduction of forest cover and expansion of agriculture in different basins.

From SWAT scenario simulation in Nyando Basin, Sang (2005) observed that 100% forest cover reduced the simulated peak flow from 111 to 69 m^3/s. On the other hand 0 % forest cover increased the simulated peak flow from 111 to 121 m^3/s because reduction of forest cover reduces evapotranspiration which cause soils to be wetter and therefore more responsive to rainfall. Mutie *et al.* (2006) also investigated the effects of the derived land cover changes on river flow in Mara River Basin. Simulation results showed that land cover data for 2000 produced higher flood peaks and faster travel times compared to the 1973 land cover data. The changes indicated the effects of land use pressure in the basin. Like wise, long-term hydrological study in Upper Ewaso Ng'iro Basin by Mungai *et al.* (2004) showed that, the conversion of land use from natural forest to small-scale agriculture often practiced without adequate conservation lowered infiltration of the soils causing an increased runoff and flash floods.

4.3 Relationship between rainfall, temperature and land use/cover with stream flow

Simple regression scatter diagrams shown in Figures; 4.3a, 4.3b, 4.3c, 4.3d and 4.3e were computed and coefficient of determination (R^2) determined using data on total annual rainfall, average annual temperatures, forest cover, agricultural and residential area percentages against total annual stream flow for the period 1976-2010. Stream flow versus forest cover and percentage agricultural area showed strong relationship with a coefficient of determination (R^2) of 0.9876 and 0.9928 respectively (Figure; 4.3c and 4.3e). The correlation between rainfall, temperature and percentage residential area with stream flow showed moderate coefficient of determination (R^2) of 0.4595, 0.5564 and 0.5515 respectively (Figure; 4.3a, 4.3b and 4.3d). Generally, stream flow showed a higher relationship with the land use/cover change (R^2 of 0.8440) than with the temperature and rainfall in this catchment. This higher correlation of land use/cover with stream flow could either be due to expansion of agriculture and reduction of forest cover hence reducing evapotranspiration which cause soils to be wetter and therefore more responsive to rainfall or lack of good land husbandry which reduce infiltrability of the soil surface or prolonged exposure of topsoil to raindrop impact. Therefore, if all other variables like rainfall and temperature were held constant, a significant increase in stream flow was expected as a consequence of expansion of agriculture and reduction of forest cover. This was consistent with the work of Sang (2005); Yosop *et al.* (2007); Nyangaga, (2008); Petchprayoon, *et al.* (2010); Alansi, *et al.* (2009); Mutie *et al.* (2006); Madduma and Kuruppuarachchi (1988) and Patts *et al.* (2010) who found and simulated a higher relationship of stream flow with expansion of agriculture and reduction of forest cover.

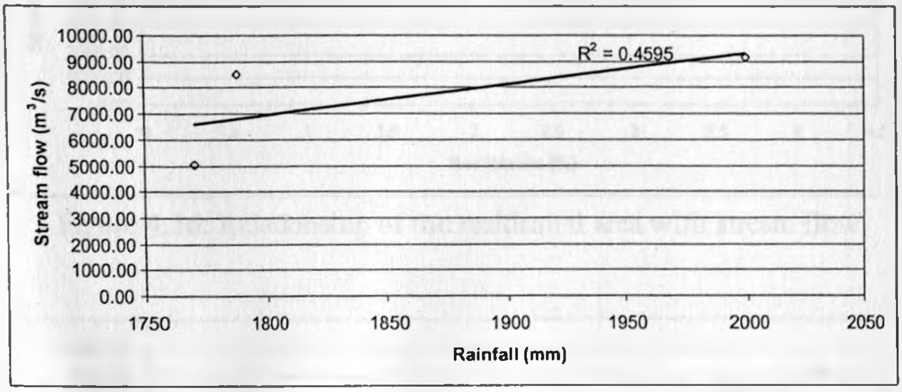


Figure 4.3a: Relationship of rainfall with stream flow regime

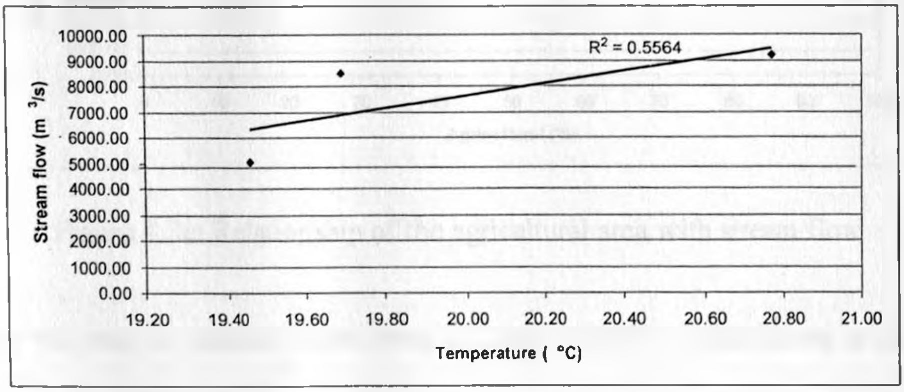


Figure 4.3b: Relationship of temperature with stream flow regime

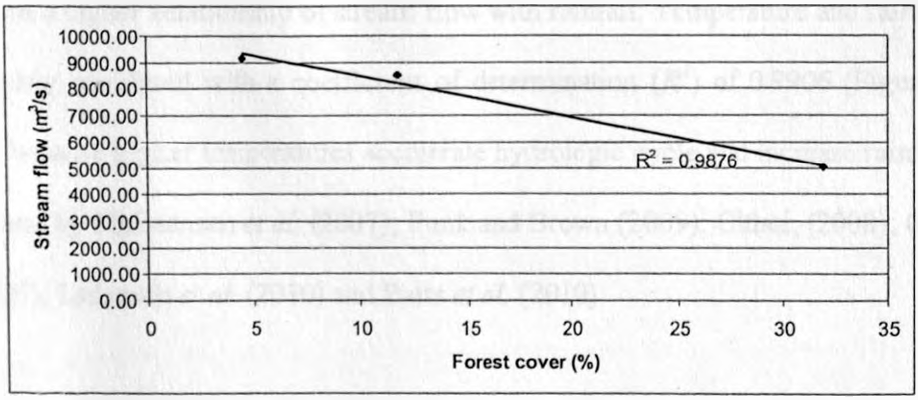


Figure 4.3c: Relationship of the forest cover with stream flow regime

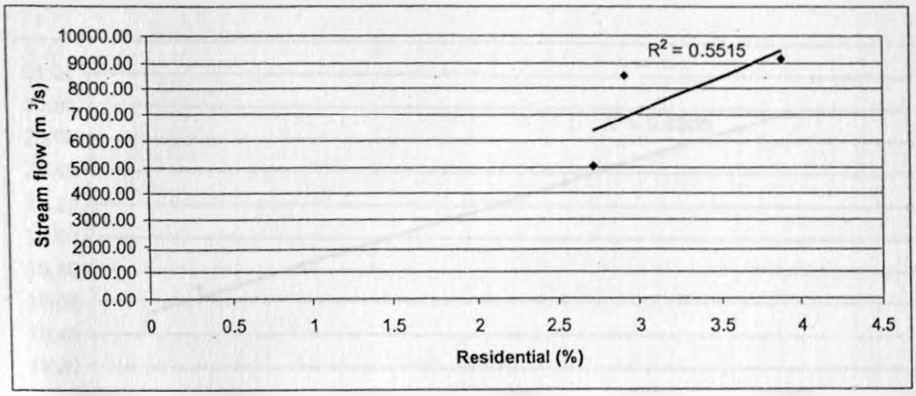


Figure 4.3d: Relationship of the residential area with stream flow

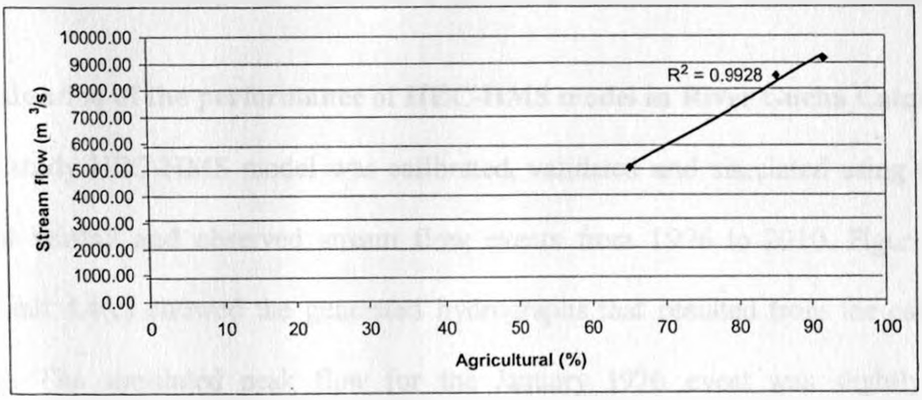


Figure 4.3e: Relationship of the agricultural area with stream flow

However this was in contrast to the work of Chaplot (2007); Middelkoop *et al.* (2001); Fontaine *et al.* (2001); Cowan and Cai (2009) and Githui *et al.* (2009) who found and simulated a higher relationship of stream flow with rainfall. Temperature and rainfall was also highly correlated with a coefficient of determination (R^2) of 0.9906 (Figure 4.3f). This is because higher temperatures accelerate hydrologic cycle and increase rainfall as it was found by Christensen *et al.* (2007); Funk and Brown (2009); Githui, (2008); Githui *et al.* (2009); Laderach *et al.* (2010) and Patts *et al.* (2010).

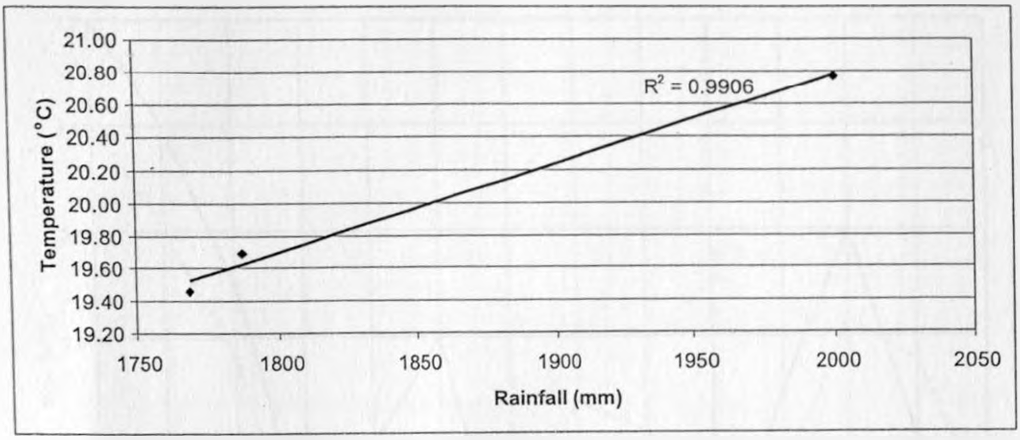
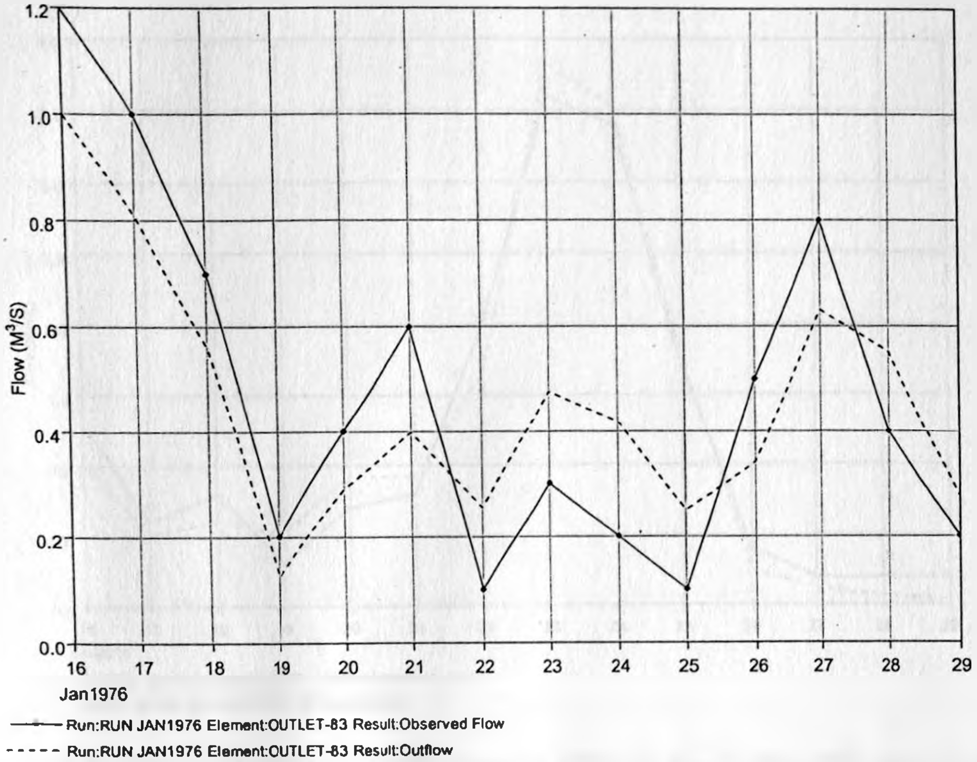


Figure 4.3f: Relationship of rainfall with temperature in River Gucha Catchment

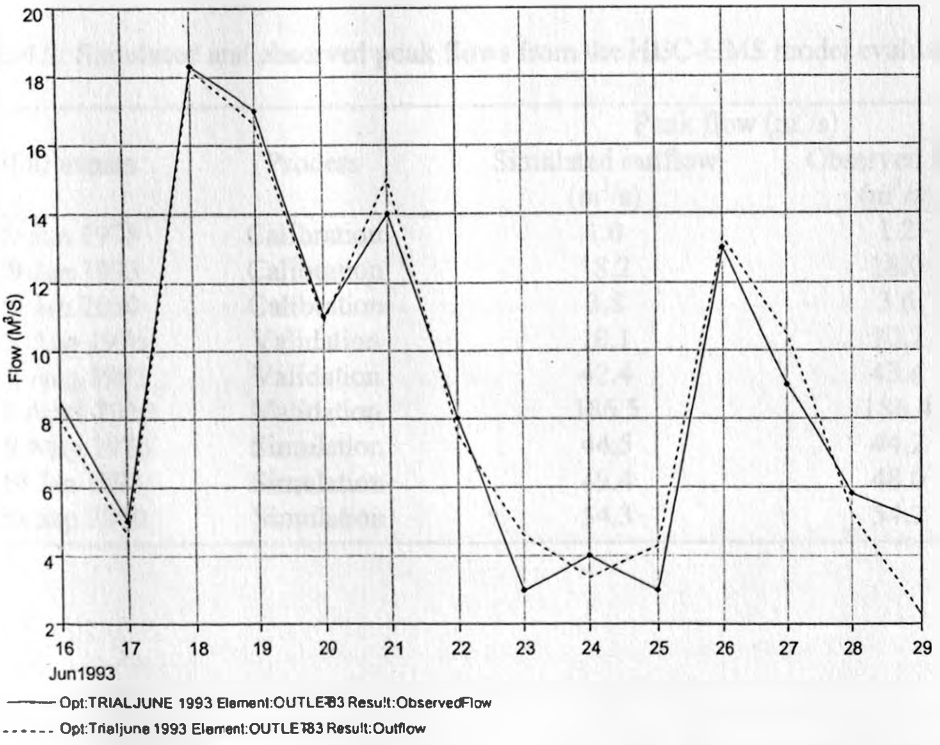
4.4 Evaluation of the performance of HEC-HMS model in River Gucha Catchment

In this study HEC-HMS model was calibrated, validated and simulated using the nine selected rainfall and observed stream flow events from 1976 to 2010. Figure 4.4(a), 4.4(b) and 4.4(c) showed the generated hydrographs that resulted from the calibration process. The simulated peak flow for the January 1976 event was slightly under-estimated, but generally, the relationship between the observed and simulated stream flows was acceptable. From the result of the calibration, 16-29 January 1976 yielded a maximum observed and simulated flow rates of 1.2 and 1.0 m^3/s, 16-29 June 1993 yielded a maximum observed and simulated flow rates of 18.0 and 18.2 m^3/s while the maximum observed and simulated flow rates for event from 16-29 January 2010 were 3.6 and 3.8 m^3/s respectively (Table 4.3).

(a)


Flow (M³/S)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
16
17
18
19
20
21
22
23
24
25
26
27
28
29
Jan1976
Run:RUN JAN1976 Element:OUTLET-83 Result:Observed Flow
Run:RUN JAN1976 Element:OUTLET-83 Result:Outflow

(b)


Flow (M³/S)
20
18
16
14
12
10
8
6
4
2
16
17
18
19
20
21
22
23
24
25
26
27
28
29
Jun1993
Opt:TRIALJUNE 1993 Element:OUTLET-83 Result:ObservedFlow
Opt:Trialjune 1993 Element:OUTLET-83 Result:Outflow

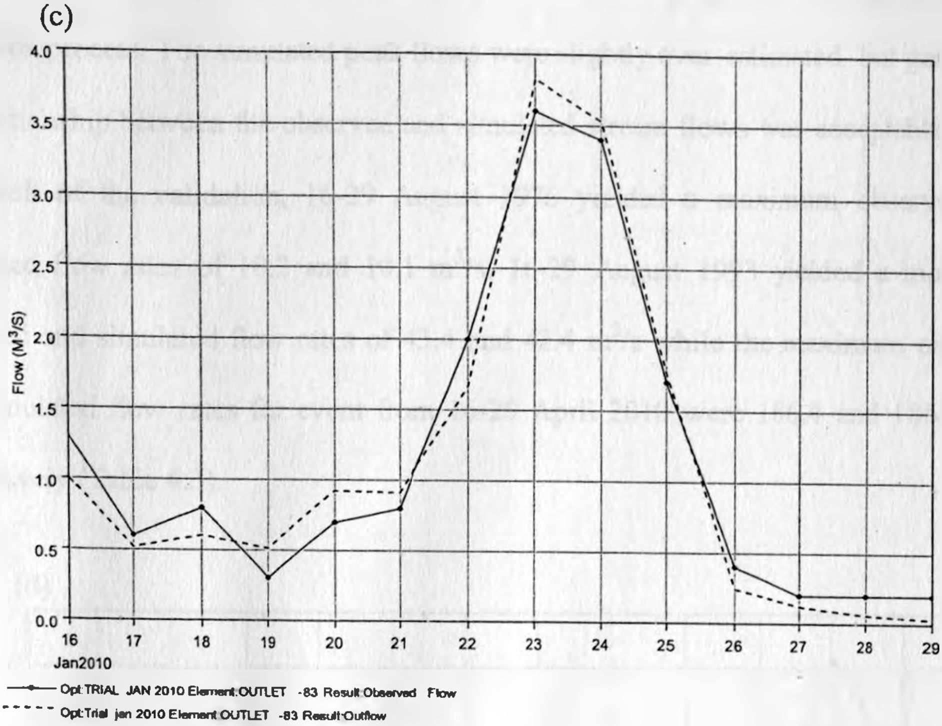
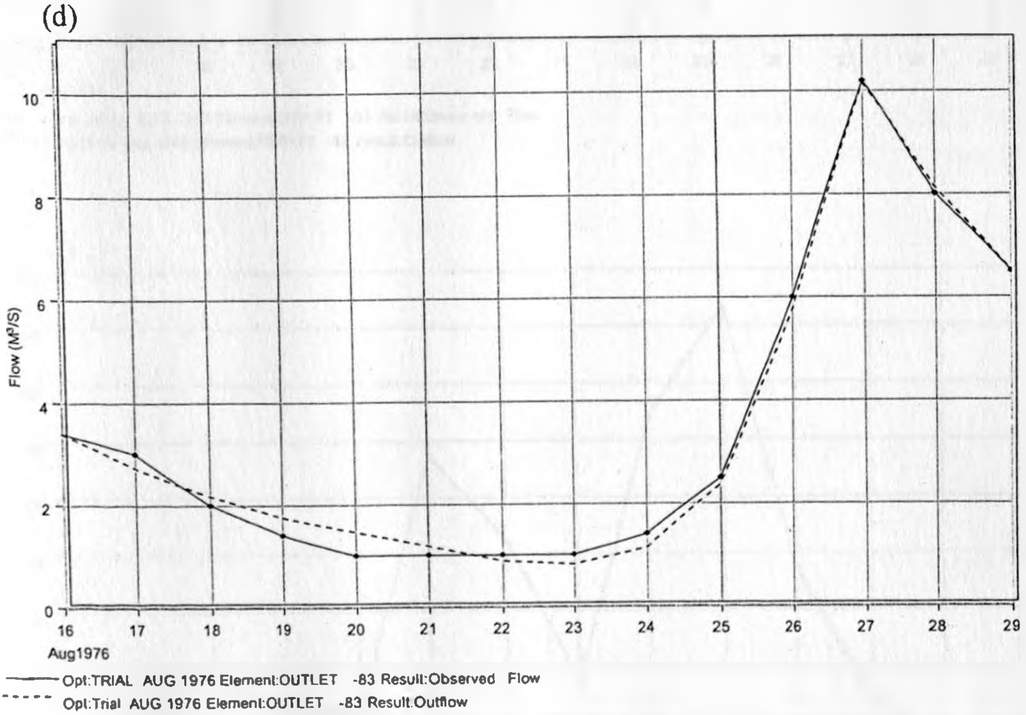


Figure 4.4: Calibration results (a) 16-29 January, 1976 (b) 16-29 June 1993 and (c) 16-29 January 2010

Table 4.3: Simulated and observed peak flows from the HEC-HMS model evaluation

Rainfall events	Process	Peak flow (m^3/s) Simulated outflow (m^3/s)	Observed flow (m^3/s)
16-29 Jan 1976	Calibration	1.0	1.2
16-29 Jun 1993	Calibration	18.2	18.0
16-29 Jan 2010	Calibration	3.8	3.6
16-29 Aug 1976	Validation	10.1	10.2
16-29 Aug 1993	Validation	42.4	43.4
16-29 April 2010	Validation	186.5	186.4
16-29 May 1976	Simulation	44.5	44.2
16-29 Jan 1993	Simulation	49.4	48.0
16-29 Sep 2010	Simulation	54.3	54.2

Figure 4.4(d), 4.4(e) and 4.4(f) showed the generated hydrographs that resulted from the validation process. The simulated peak flows were slightly over-estimated, but generally, the relationship between the observed and simulated stream flows was acceptable. From the result of the validation, 16-29 August 1976 yielded a maximum observed and simulated flow rates of 10.2 and 10.1 m^3/s, 16-29 August 1993 yielded a maximum observed and simulated flow rates of 43.4 and 42.4 m^3/s while the maximum observed and simulated flow rates for event from 16-29 April 2010 were 186.4 and 186.5 m^3/s respectively (Table 4.3).



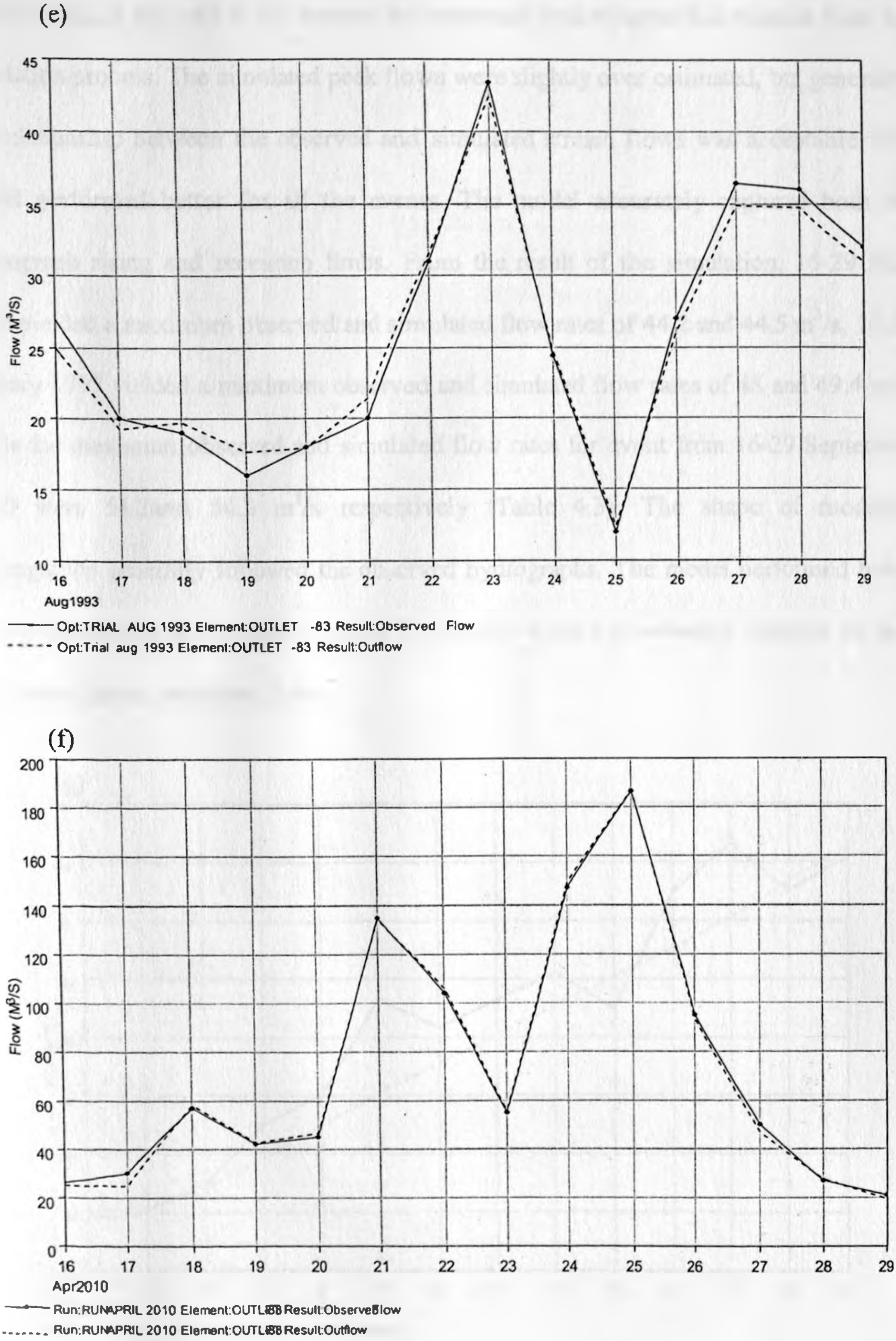
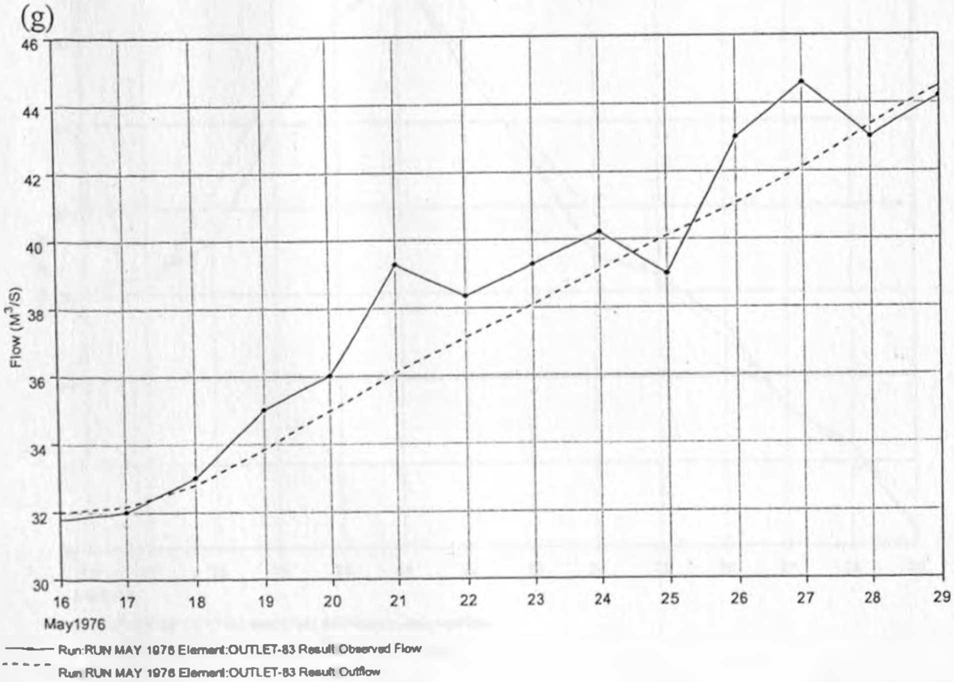


Figure 4.4: Validation results (d) 16-29 August 1976 (e) 16-29 August 1993 and (f) 16-29 April 2010.

Figure 4.4(g), 4.4(h) and 4.4(i) showed the generated hydrographs that resulted from the simulation process. The simulated peak flows were slightly over estimated, but generally, the relationship between the observed and simulated stream flows was acceptable. The model performed better for all the events. The model accurately captured both the hydrograph rising and recession limbs. From the result of the simulation, 16-29 May 1976 yielded a maximum observed and simulated flow rates of 44.2 and 44.5 m^3/s, 16-29 January 1993 yielded a maximum observed and simulated flow rates of 48 and 49.4 m^3/s while the maximum observed and simulated flow rates for event from 16-29 September 2010 were 54.2and 54.3 m^3/s respectively (Table 4.3). The shape of modelled hydrographs generally followed the observed hydrographs. The model performed better for all the events and therefore could be reliably used for assessing impacts of land use/cover change on stream flow.



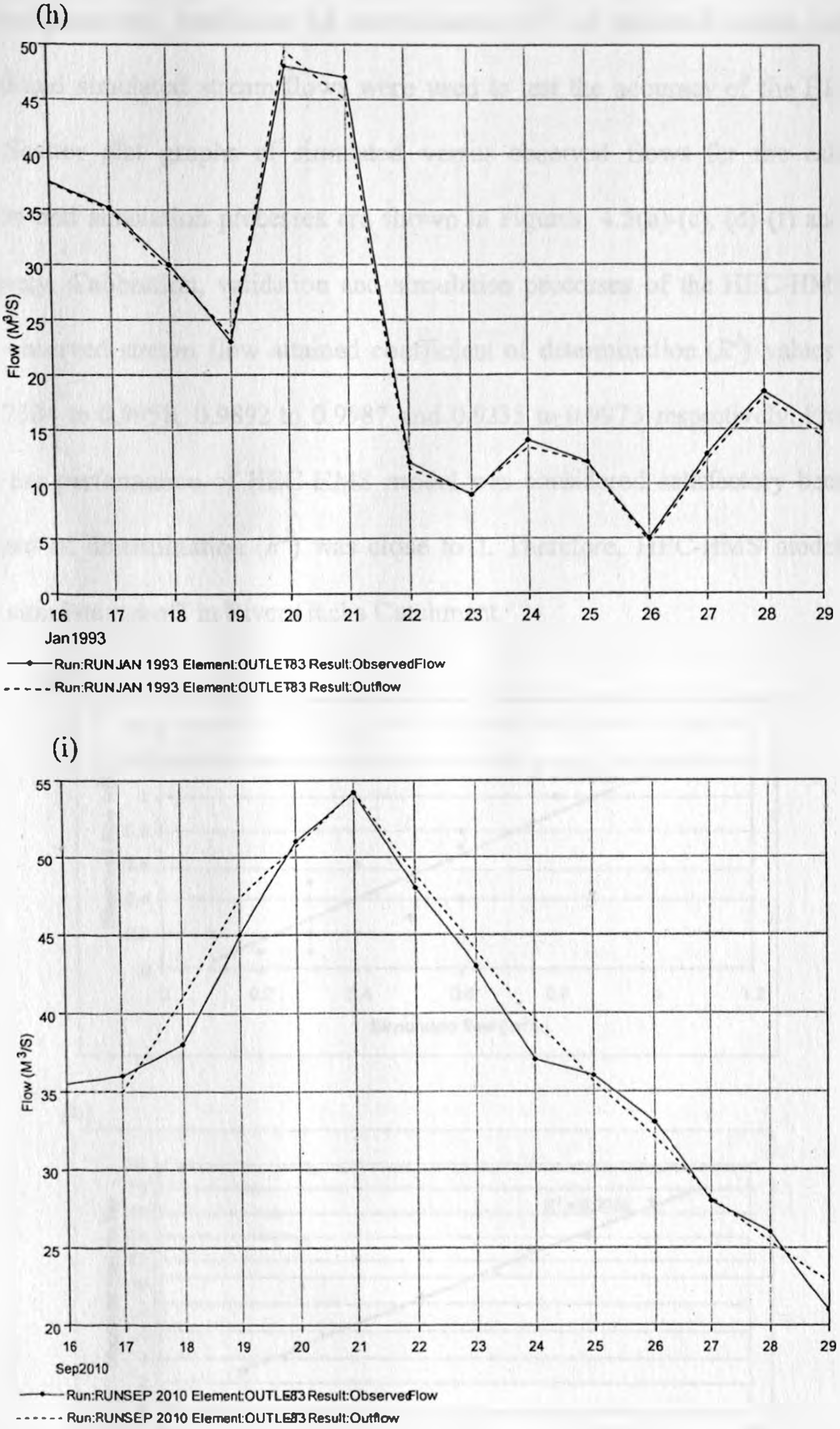
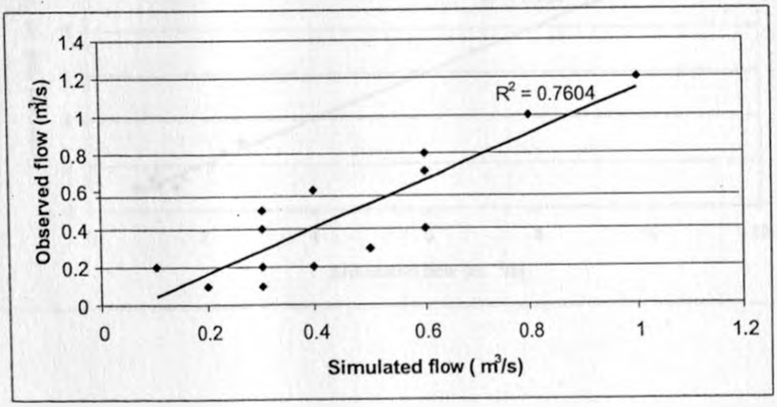


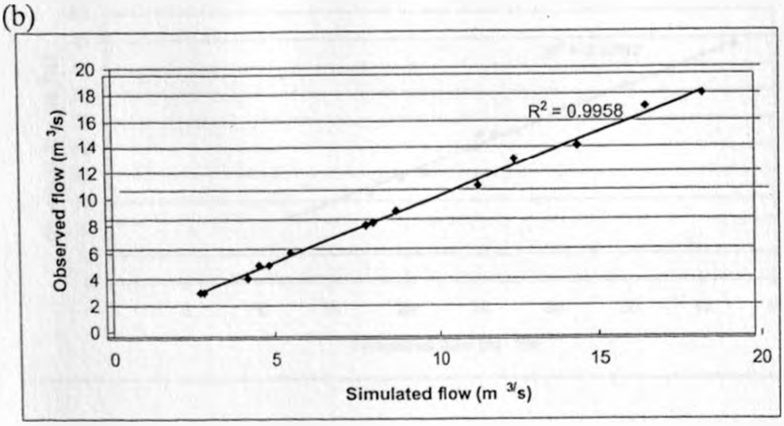
Figure 4.4: Simulation results (g) 16-29 May 1976 (h) 16-29 January 1993 and (i) 16-29 September 2010.

The scatter plots and coefficient of determination (R^2) of observed versus calibrated, validated and simulated stream flows were used to test the accuracy of the HEC-HMS model. Scatter plot graphs of simulated versus observed flows for the calibration, validation and simulation processes are shown in Figures; 4.5(a)-(c), (d)-(f) and (g)-(i), respectively. Calibration, validation and simulation processes of the HEC-HMS model against observed stream flow attained coefficient of determination (R^2) values ranging from 0.7604 to 0.9958, 0.9892 to 0.9987 and 0.9235 to 0.9973 respectively. From these results, the performance of HEC-HMS model was considered satisfactory because the coefficient of determination (R^2) was close to 1. Therefore, HEC-HMS model can be used to simulate run off in River Gucha Catchment.

(a)



(b)



(c)

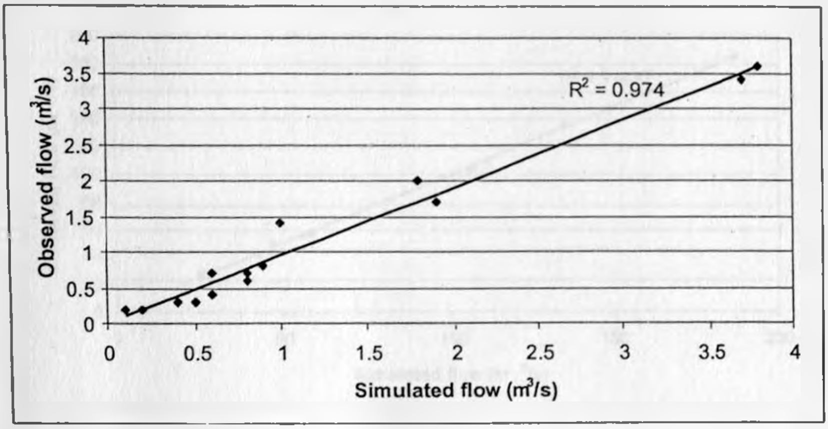
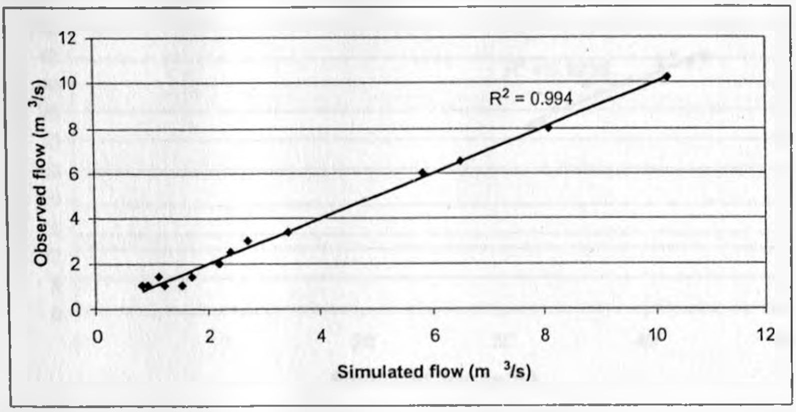
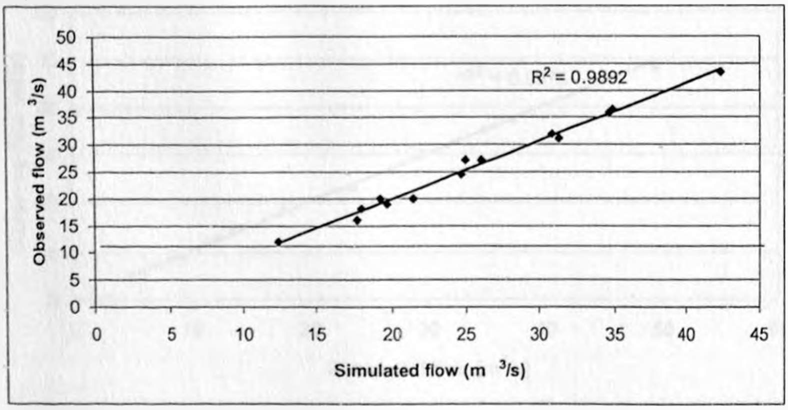


Figure 4.5: Simulated versus observed flows for (a) 16-29 January 1976 (b) 16-29 June 1993 and (c) 16-29 January 2010 (Calibration stage)

(d)



(e)



(f)

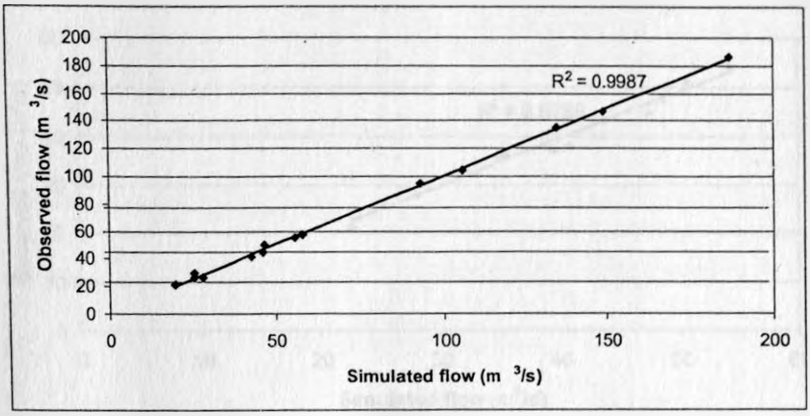
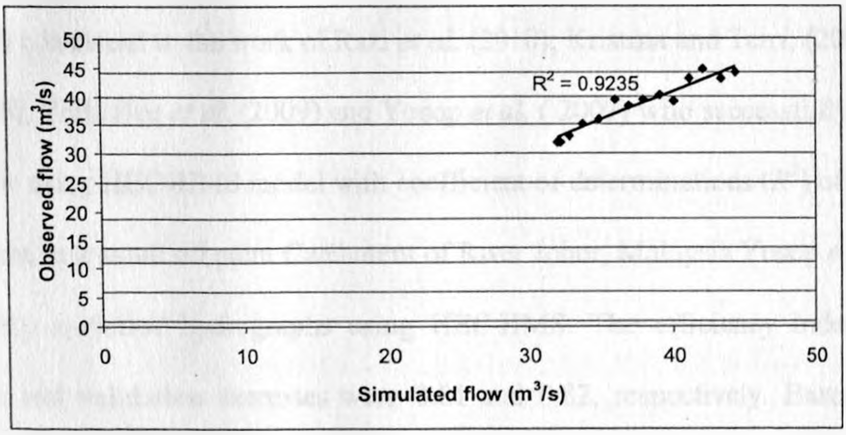
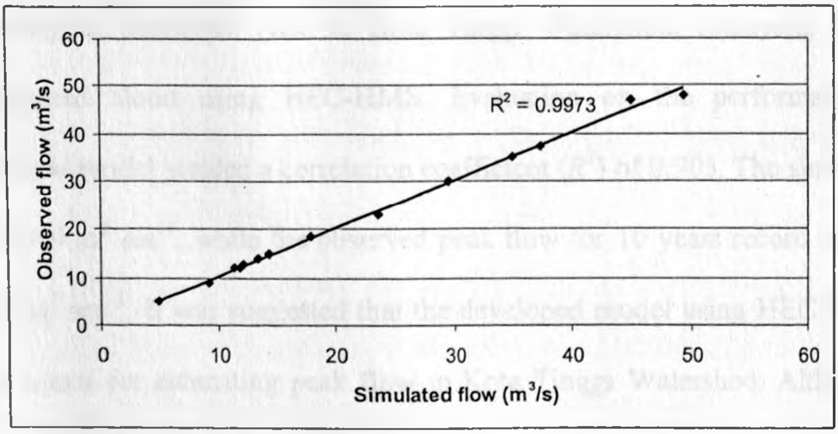


Figure 4.5: Simulated versus observed flows for (d) 16-29 August 1976 (e) 16-29 August 1993 and (f) 16-29 April 2010 (Validation stage)

(g)



(h)



(i)

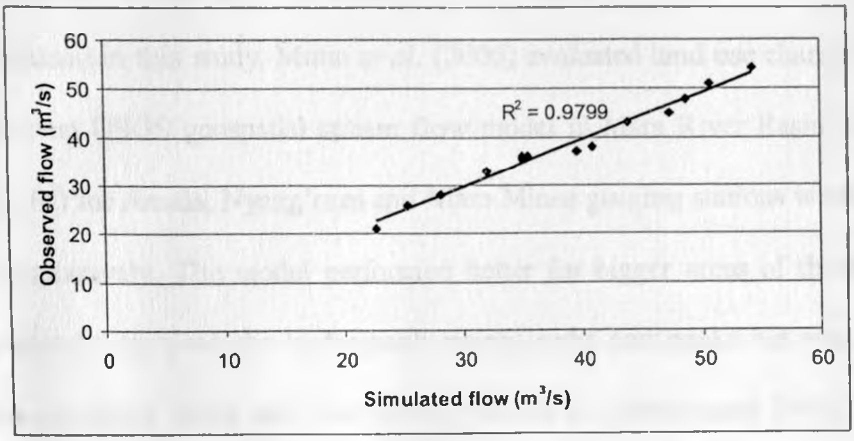


Figure 4.5: Simulated versus observed flows for (g) 16-29 May 1976 (h) 16-29 January 1993 and (i) 16-29 September 2010 (Simulation stage)

This was in consistent to the work of Razi *et al.* (2010); Kristina and Terri, (2009); Yener *et al.* (2006); Zorkeflee *et al.* (2009) and Yosop *et al.* (2007) who successfully simulated stream flow using HEC-HMS model with coefficient of determinations (R^2) of close to 1. For example, in a small oil palm Catchment of River Johor, Malaysia Yosop *et al.* (2007) satisfactorily modelled hydrographs using HEC-HMS. The efficiency indexes of the calibration and validation exercises were 0.81 and 0.82, respectively. Based on these findings it was suggested that the oil palm plantation served reasonably well in regulating basic hydrological functions. Also in Kota Tinggi Watershed, Malaysia, Razi *et al.* (2010) estimated flood using HEC-HMS. Evaluation on the performance of the developed flood model yielded a correlation coefficient (R^2) of 0.905. The simulated peak flow was 150.9 m^3 sec^{-1}, while the observed peak flow for 10 years record (1997-2006) was 145.12 m^3 sec^{-1}. It was suggested that the developed model using HEC-HMS could be used as a tool for estimating peak flow in Kota Tinggi Watershed. Although, Sang (2005); Patts *et al.* (2010) and Mutie *et al.* (2006) used different models other than HEC-

HMS to simulate stream flow in Kenyan basins, their findings were similar to the findings obtained in this study. Mutie *et al.* (2006) evaluated land use change effects on river flow using USGS geospatial stream flow model in Mara River Basin. Correlation coefficient (R^2) for Amala, Nyang'ores and Mara Mines gauging stations were 0.72, 0.69 and 0.87 respectively. The model performed better for bigger areas of the Basin. The model accurately captured the hydrograph rising limbs and peaks but was unable to capture the recession limbs and low flows. Patts *et al.* (2010) used SWAT model to simulate flow in Nzoia River Catchment. The model was calibrated against stream flow data. There was good agreement between the measured and simulated daily stream flow for the calibration period and gave Nash Sutcliffe Efficiency (NSE) of 0.94. The simulation of base flow was slightly underestimated but overall, the relationship between the observed and simulated stream flow was acceptable. Model performance showed that it could be reliably used for assessing impacts of land use/cover change on stream flow.

4.5 Effect of land use/cover change on stream flow regime of River Gucha

Based on the HEC-HMS model evaluation parameters, rainfall event of 23 Jan 2010 (31 mm) and control specification period of from 0830 to 2300 h, simulated stream flow hydrographs to quantify the change in stream flow due to land use/cover change for the year 1976, 1993 and 2010 (Figure 4.6) were obtained. Change comparison of the simulated stream flow hydrographs generated using the curve number grid map for 1976, 1993 and 2010 are presented in Table 4.4. Lag time was 0.72, 0.60 and 0.50 hours, base flow was 5.0, 4.8 and 4.6 m^3/s and peak flow was 12.5, 16.30 and 17.5 m^3/s for the year 1976, 1993 and 2010 land use/cover dataset respectively (Table 4.4). Lag time decreased by 16.67 and 16.67%, base flow decreased by 4.0 and 4.17% and peak flow increased by

30.4 and 7.36% for the period between 1976-1993 and 1993-2010 respectively. The 1993 and 2010 datasets produced stream flow quicker, rising to the peak faster and receding equally faster than the 1976 data set. The simulated increase in peak flow and decrease in lag time could be either as a result of expansion of agriculture and reduction of forest cover which increased curve number of the catchment by over 25% and reduced evapotranspiration causing soils to be wetter and therefore more responsive to rainfall or lack of good land husbandry which reduce infiltrability of the soil surface or prolonged exposure of topsoil to raindrop impact. This is because crops demand less soil moisture than forests thus rainfall satisfies the soil moisture deficit in agricultural lands more quickly than in forests thereby generating more runoff.

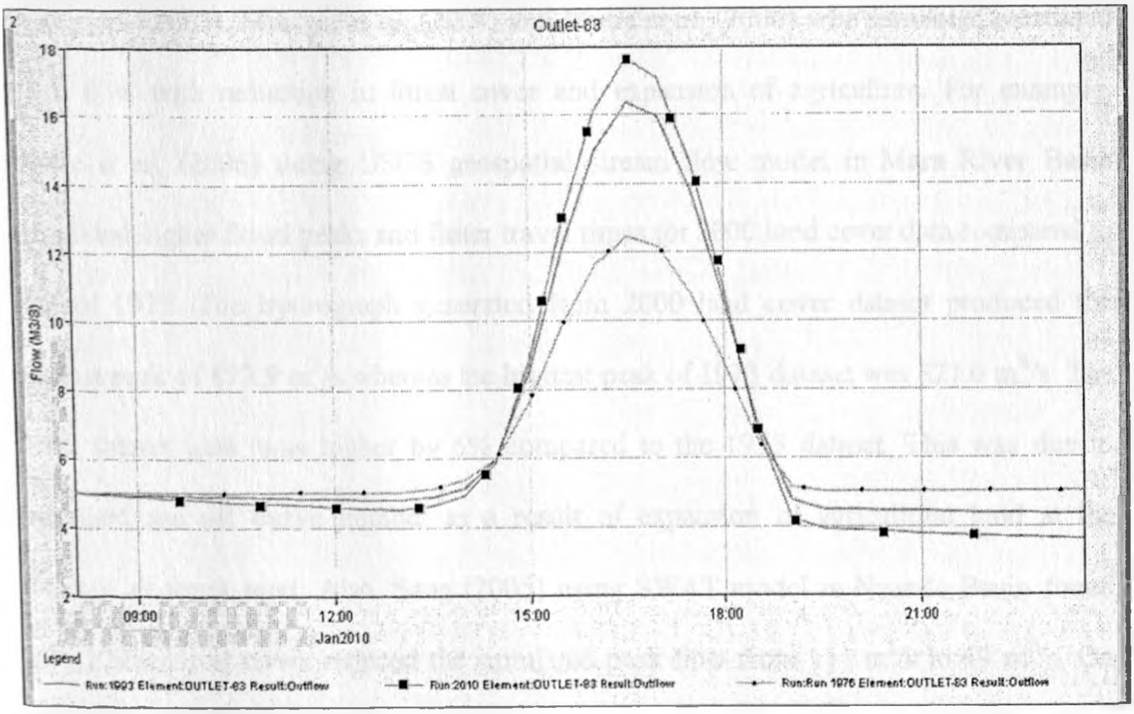


Figure 4.6: Effect of land use/cover change on stream flow regime of River Gucha

Table 4.4: Effect of land use/cover change on stream flow regime of River Gucha

Parameter	1976	1993	2010	Change (1976-1993) %	Change (1993-2010) %
Lag time (hr)	0.72	0.60	0.50	-16.67	-16.67
Base flow (m^3/s)	5.0	4.80	4.6	-4.0	-4.17
Peak flow (m^3/s)	12.5	16.30	17.5	+30.40	+7.36
Forest cover (km^2)	330.17	122.35	45.89	-62.94	-68.49
Agricultural (km^2)	677.65	883.40	949.91	+30.36	+7.53
Average CN	61	74	77	+21.31	+4.05

This was similar to the work of Alansi, *et al.* (2009); Patts *et al.* (2010); Sang (2005); Pearce *et al.* (1980); Yozop *et al.* (2007); Smith and Scott (1992); Kramer *et al.* (1999); Best *et al.* (2003); Mungai *et al.* (2004) and Mutie *et al.* (2006) who simulated increased peak flow with reduction in forest cover and expansion of agriculture. For example, Mutie *et al.* (2006) using USGS geospatial stream flow model in Mara River Basin simulated higher flood peaks and faster travel times for 2000 land cover data compared to that of 1973. The hydrograph generated from 2000 land cover dataset produced the highest peak of 877.9 m^3/s whereas the highest peak of 1973 dataset was 827.0 m^3/s. The 2000 dataset peak was higher by 6% compared to the 1973 dataset. This was due to increased run off curve number as a result of expansion of agricultural land at the expense of forest land. Also, Sang (2005) using SWAT model in Nyando Basin found that, 100% forest cover reduced the simulated peak flow from 111 m^3/s to 69 m^3/s. On the other hand 0 % forest cover increased the simulated peak flow from 111 m^3/s to 121 m^3/s. The changes indicated effects of land use pressure in the Basin. Like wise, long-term hydrological study in Upper Ewaso Ng'iro Basin by Mungai *et al.* (2004) showed that, the conversion of land use from natural forest to small-scale agriculture often practiced without adequate conservation lowered infiltration of the soils causing an increased runoff and flash floods.

The reduction of base flow from 1976 to 2010 could be either due to replacing of the natural vegetation with the exotic vegetation particularly eucalyptus (*Eucalyptus grandis*) which are allegedly voracious consumers of water hence increasing evapotranspiration which cause soils to be less wetter and therefore reducing ground water recharge or lack of good land husbandry which reduce infiltrability of the soil surface. This decrease in base flow following replacement of the natural vegetation with the exotic vegetation has also been reported by Ankeny *et al.* (1990); Logsdon *et al.* (1990); Nidal (2003); Githui (2008); Sang (2005); Patts *et al.* (2010); Zhang (1990); Bruijnzeel and Bremmer (1989); Nyangaga (2008); Smith and Scott (1992); Pearce *et al.* (1980); Meybeck *et al.* (1989 Bruijnzeel (1990); Pereira (1989); Harding *et al.* (1991); Calder (1986); Bruijnzeel (1990) and Gush and Dye (2003). Smith and Scott (1992) found that, the dry season flow was lower from forested catchments than from natural grassland. They also reported stream-flow from re-afforested areas in upland South Africa to decline faster and earlier in the case of *Eucalyptus grandis* as compared to *Pinus patula.* This is because *Eucalyptus grandis* are allegedly voracious consumers of water. Also, Githui (2008) found that when agricultural land is tilled, compaction of lower soil horizons occurs and this lowers infiltration rates and increases bulk density. This compaction decreases water retention as rainfall saturates the soil profile quicker in agricultural lands than in the forested areas thus producing more runoff.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

The hydrological response of catchment areas to rainfall depends on the interplay between climatic, soil and land use/cover variables. It is not clear whether hydrological changes are attributed to human activities or caused by natural climatic factors. Understanding how these land use activities and climatic factors influence stream flow will enable planners to formulate policies towards minimizing undesirable effects of future land-use changes on stream flow patterns. A study to assess impact of climate and land use/cover change on hydrological processes in River Gucha Catchment was conducted. Agriculture, forest and settlement covered about 92, 4 and 4% of the catchment's area respectively. Forest cover decreased by 62.94 and 68.49%, agricultural land increased by 30.36 and 7.53% and residential area increased by 7.35 and 32.89% of the original area for the period between 1976-1993 and 1993-2010 respectively. The reduction of forest cover could be attributed to clearing of forests to give room to cultivation and settlement due to high population growth rate in the area. Most of the current vegetation found in the catchment was exotic and mostly comprised of eucalyptus (*Eucalyptus grandis*) planted along the river courses.

Total annual rainfall increased by 17.9 and 212.5 mm, average annual temperature increased by 0.23 and 1.08 °C and total annual stream flow increased by 3468.51 and 670.06 m^3/s for the period between 1976-1993 and 1993-2010 respectively. The observed increase in average annual temperature could be in some part due to global warming. It was not clear whether the observed increasing stream flow and rainfall trends were attributed to human activities or whether they were caused by natural climatic factors.

More total annual rainfall was observed with increase in average annual temperatures. Stream flow versus forest cover and percentage agricultural area showed strong relationship with a coefficient of determination (R^2) of 0.9876 and 0.9928 respectively. The correlation between rainfall, temperature and percentage residential area with stream flow showed moderate coefficient of determination (R^2) of 0.4595, 0.5564 and 0.5515 respectively. Stream flow showed a higher relationship with the land use/cover change (R^2 of 0.8440) than with the temperature and rainfall in the catchment. This higher correlation of land use/cover with stream flow could be either due to expansion of agriculture and reduction of forest cover hence reducing evapotranspiration which cause soils to be wetter and therefore more responsive to rainfall or lack of good land husbandry which reduce infiltrability of the soil surface or prolonged exposure of topsoil to raindrop impact. If all other variables like rainfall and temperature were held constant, a significant increase in stream flow was expected as a consequence of expansion of agriculture and reduction of forest cover.

The shape of simulated hydrographs generally followed the observed hydrographs during calibration, validation and simulation processes of HEC-HMS model. Calibration, validation and simulation of the model against observed stream flow attained a coefficient of determination (R^2) values ranging from 0.7604 to 0.9987. The performance of HEC-HMS was considered satisfactory and can be used to simulate stream flow because the coefficient of determination (R^2) was close to 1. Lag time decreased by 16.67 and 16.67%, base flow decreased by 4.0 and 4.17% and peak flow increased by 30.4 and 7.36% for the period between 1976-1993 and 1993-2010 respectively. The 1993 and 2010 datasets produced stream flow quicker, rising to the peak faster and receding equally faster than the 1976 data set. This increased peak flow and decrease in lag time could be either as a result of expansion of agriculture and reduction of forest cover which increased curve number of the catchment by over 25% and reduced evapotranspiration causing soils to be wetter and therefore more responsive to rainfall or lack of good land husbandry which reduce infiltrability of the soil surface or prolonged exposure of topsoil to raindrop impact. The reduction of base flow from 1976 to 2010 could be either due to replacing natural vegetation with exotic vegetation particularly eucalyptus (*Eucalyptus grandis*) which are allegedly voracious consumers of water hence increasing evapotranspiration which cause soils to be less wetter and therefore reducing ground water recharge or lack of good land husbandry which reduce infiltrability of the soil surface.

Population growth control programmes need to be emphasized to reduce population growth in the area. Climate change mitigation programmes should be encouraged in the country. Historical temperature, rainfall and stream flow trend analyses should be conducted in other regions of Kenya to confirm if they are consistent with those of high agricultural potential areas. Relationship between temperature, rainfall and land use/cover with stream flow regimes need to be determined in arid and semi-arid regions of Kenya. HEC-HMS model can be used to predict effects of land use/cover on stream flow. More studies in testing the performance of HEC-HMS model in simulating run off in Kenyan basins are needed. If any control measures against increased runoff were to be applied, then clearly agricultural land has to be given priority with emphasis on proper farming practices, where less land is optimized to produce more crop yield rather than the opposite. The extra land could then be utilised to plant trees suited to the area.

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APPENDICES

Appendix A: Baseline dataset for the study area

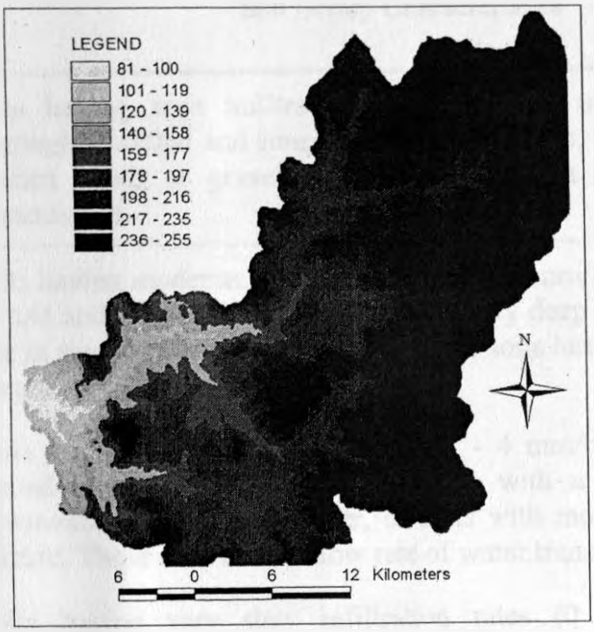

Figure A1: GDEM of the River Gucha Catchment at 15 m resolution

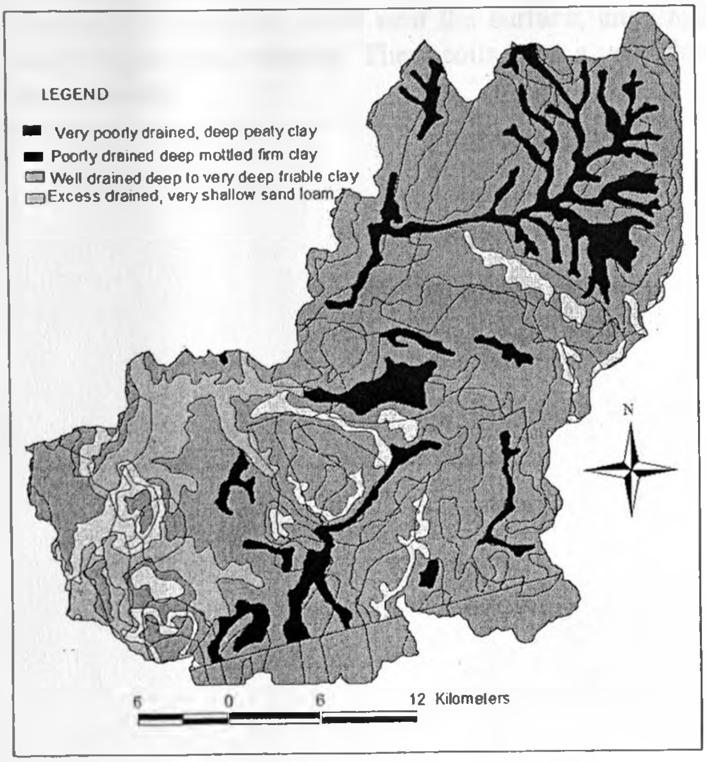

Figure A2: Soil characteristics map of the study area (Wielemaker and Boxen, 1982)

Table A1. Definition of hydrologic soil groups (NRCS, 2007)

Hydrologic Soil Group	Soil Group Characteristics
A	Soils having high infiltration rates (8 - 12 mm/hr), even when thoroughly wetted and consisting chiefly of deep, well to excessively-drained sands or gravels. These soils have a high rate of water transmission.
B	Soils having moderate infiltration rates (4 - 8 mm/hr) when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.
C	Soils having slow infiltration rates (1 - 4 mm/hr) when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water, or soils with moderately fine to fine texture. These soils have a slow rate of water transmission.
D	Soils having very slow infiltration rates (0 - 1 mm/hr) when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay pan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very slow rate of water transmission.

Appendix B:

Standard look up table and curve number grid maps for the study area

Table B1. Land use categories and associated curve numbers (SCS TR55, 1986)

Description	Average % impervious	Curve number by hydrologic soil group				Typical land uses
		A	B	C	D	
Residential (High Density)	65	77	85	90	92	Multi-family, Apartments, Condos, Trailer Parks
Residential (Med. Density)	30	57	72	81	86	Single-Family, Lot Size ¼ to 1 acre
Residential (Low Density)	15	48	66	78	83	Single-Family, Lot Size 1 acre and Greater
Commercial	85	89	92	94	95	Strip Commercial, Shopping Ctrs, Convenience Stores
Industrial	72	81	88	91	93	Light Industrial, Schools, Prisons, Treatment Plants
Disturbed/Transitional	5	76	85	89	91	Gravel Parking, Quarries, Land Under Development
Agricultural	5	67	77	83	87	Cultivated Land, Row crops, Broadcast Legumes
Open Land – Good	5	39	61	74	80	Parks, Golf Courses, Greenways, Grazed Pasture
Woods (Thick Cover)	5	30	55	70	77	Forest Litter and Brush adequately cover soil
Woods (Thin Cover)	5	43	65	76	82	Light Woods, Woods-Grass combination, Tree Farms
Impervious	95	98	98	98	98	Paved Parking, Shopping Malls, Major Roadways
Water	100	100	100	100	100	Water Bodies, Lakes, Ponds, Wetlands

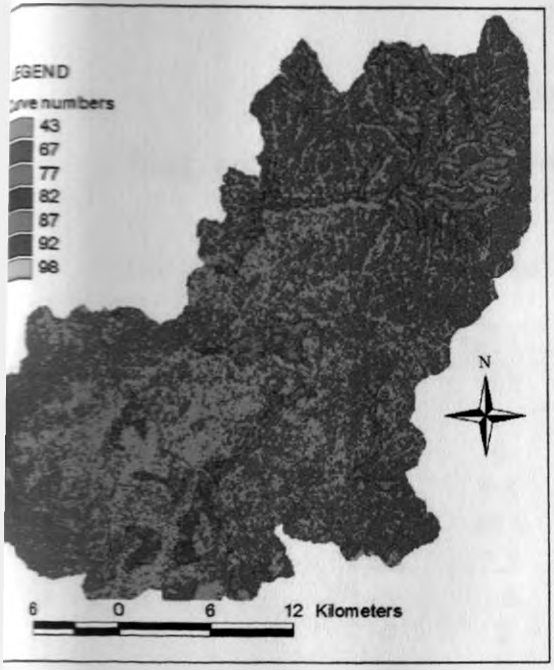

Figure B1: Curve number grid map (1976)

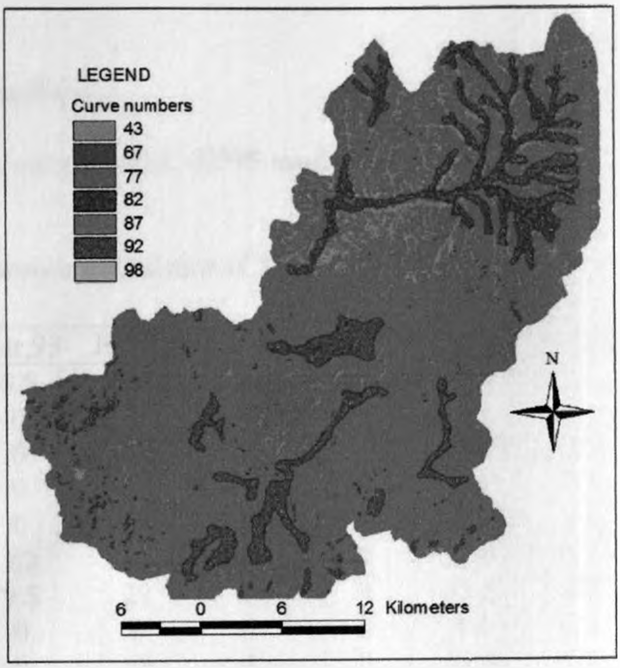

Figure B2: Curve number grid map (1993)

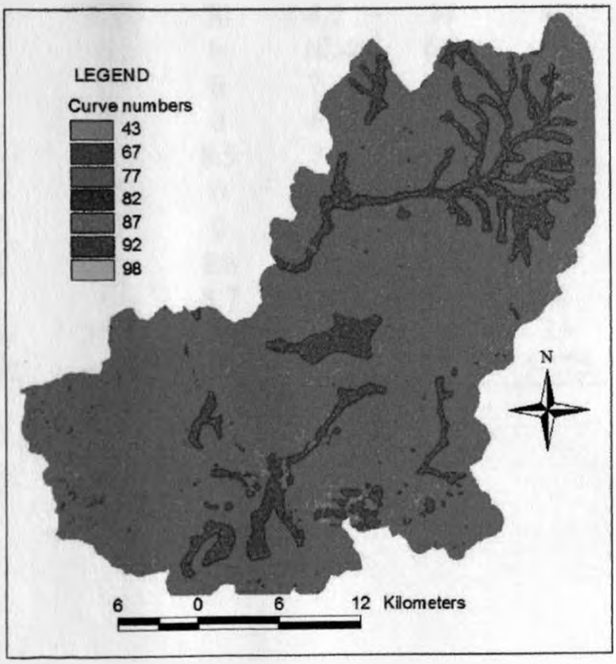

Figure B3: Curve number grid map (2010)

Appendix C:

Daily rainfall and stream flow data used in HEC-HMS model evaluation

Table C1: Rainfall events at Coffee Research Foundation (CRF) station (mm)

Date	Jan,76	May,76	Aug,76	Jan,93	Mar,93	Jun,93	Aug,93	Jan,10	Apr,10	Sep,10
8	0.2	13.9	0	15.8	0.5	3.3	5.6	0	0	2
9	2.1	12.5	0	1	0	4	6	0	0	0
10	0	32.2	8.4	0	0	13.2	5	0	15.9	11.3
11	0.2	16.9	0	9.5	0	9.8	4	0	6.8	0.3
12	2.1	0	0	45.5	0	3	3	0	0.8	3.1
13	0	20.4	5.6	3.5	20	3.5	0	0	21.9	5.5
14	0	2	0	1.6	9.5	29	0	0	11.5	0.6
15	0	2.9	0	2	0	0	6	0	4.2	0.1
16	14	7.1	1.4	0	0	0	4	0	11.4	6
17	12	13.1	0.2	18	0	7	1	0	13.2	2.2
18	0	1.1	0	1	0	37	0.15	0	22	9.3
19	0	0.9	0.5	2	2	0	0	0.4	0	7.4
20	3.4	4.4	4.3	30	4.2	17	0	0.1	22.2	1.2
21	1.7	19.3	0	0	10.4	6.8	0	0	42.2	3.8
22	1.1	0	0	0	7.1	2.1	0	0.9	7.7	1.8
23	3.6	0	0	0	6.5	3.5	0	31	18.3	0
24	0.4	0	0	8.5	7.2	0.9	0	0.6	51	1.4
25	1.7	0	2.2	0	0	5.1	5	0	35.5	0.6
26	1.1	2.5	4.1	0	0	14	0	0.5	0	11.7
27	3.6	0.4	1.6	8.8	0	1	0	0	1.4	12.4
28	0.4	0	0	8.7	0	0	0	0	1.2	1
29	0.4	38.6	20.3	0	2.5	0	15	0	2.7	0
Total	48	188.2	48.6	155.9	69.9	160.2	54.75	33.5	289.9	81.7

Table C2: Stream flow events at Kanga regular gauging station (m^3/s)

Date	Jan,76	May,76	Aug,76	Jan,93	Jun,93	Aug,93	Jan,10	Apr,10	Sep,10
8	1.50	4.03	6.67	8.52	8.14	8.52	5.86	25.34	40.23
9	1.65	5.82	4.39	12.00	8.52	12.00	6.52	17.37	42.14
10	2.97	8.08	4.87	12.48	12.00	12.48	7.21	14.79	46.64
11	2.15	9.72	5.62	70.48	12.48	70.48	7.95	15.89	45.62
12	2.33	9.29	6.26	47.15	70.48	47.15	7.21	17.03	47.67
13	2.97	10.58	6.39	33.05	47.15	33.05	6.03	25.48	53.06
14	2.65	9.36	6.13	28.97	33.05	28.97	4.96	39.34	50.32
15	1.35	9.38	5.87	58.16	28.97	58.16	3.51	26.72	57.78
16	1.20	31.80	3.40	37.50	8.20	27.00	1.40	26.30	35.50
17	1.00	30.00	3.00	35.20	5.00	20.00	0.60	30.00	36.00
18	0.70	31.00	2.00	30.00	18.00	19.00	0.70	57.00	38.00
19	0.20	32.00	2.30	23.00	17.00	16.00	0.30	42.00	45.00
20	0.40	34.00	2.00	48.00	11.00	18.00	0.70	45.00	51.00
21	0.60	37.30	2.00	47.00	14.00	20.00	0.80	135.00	54.20
22	0.10	36.40	2.00	12.00	8.00	31.00	2.00	104.00	48.00
23	0.30	37.30	2.00	9.00	3.00	43.40	3.60	55.00	43.00
24	0.20	38.20	3.40	14.00	4.00	24.40	3.40	147.00	37.00
25	0.10	38.10	4.50	12.00	3.00	12.00	1.70	186.40	36.00
26	0.50	40.10	8.00	5.00	13.00	27.00	0.40	95.00	33.00
27	0.80	43.60	10.20	12.70	9.00	36.40	0.30	50.00	28.00
28	0.40	41.10	8.00	18.40	6.00	36.00	0.20	27.00	26.00
29	0.20	44.20	6.50	15.00	5.00	32.00	0.20	21.00	21.00
Total	24.27	581.36	105.50	589.61	344.99	633.01	65.55	1202.66	915.16