جامعة أبو بكر بلقايد
UNIVERSITÉ DE TLEMCEN

Pan African University
Institute of Water
and Energy Sciences

Institute of Water and Energy Sciences (Including Climate Change)

MODELLING IMPACTS OF AGRICULTURAL LAND EXPANSION ON THE STREAMFLOW REGIME: CASE STUDY OF THIBA RIVER WATERSHED IN KENYA

Brian Omondi Oduor

Date: 06/09/2017

Master in ***Water, Engineering track***

President:	**Dr. Bernhard Tischbein**
Supervisor:	**Prof. Benedict Mwavu Mutua**
Co-Supervisor:	**Dr. Raphael M. Wambua**
External Examiner:	**Prof. Thameur Chaibi**
Internal Examiner:	**Prof. Mohamed Mazour**

Academic Year: 2016-2017

DECLARATION AND RECOMMENDATION

DECLARATION

I Brian Omondi Oduor, hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

Signature: Date: 06/09/2017

Name: **Brian Omondi Oduor**

Reg. No.: **PAUWES/302/15**

RECOMMENDATION

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

Signature: Date: 06/09/2017

Name: **Prof. Dr.-Ing. Benedict M. Mutua, Ph.D, Rer.Nat.**

DVC (Planning, Partnerships, Research and Innovation),

Kibabii University.

Signature:____________________ Date: 06/09/2017

Name: **Dr. Raphael M. Wambua, PhD, MIAgrE**

Lecturer, Grad. Engineer (EBK), Department of Agricultural Engineering

Egerton University.

ACKNOWLEDGEMENT

I would like to acknowledge the following persons for playing a vital role towards the completion of this thesis report. Firstly, I express my sincere gratitude to my supervisors Prof. Dr.-Ing. Benedict M. Mutua of Kibabii University, and Dr. Raphael Wambua of Egerton University, Department of Agricultural Engineering under whose supervision and guidance this research work was carried out. I would like to thank them for their ideas, insights, professional assistance, constructive criticism, devotion and efforts towards my work.

My gratitude also goes to the African Union Commission (AUC) and the German Ministry of Foreign Affairs through the Pan African University Institute of Water and Energy Sciences (PAUWES), for awarding me the scholarship that enabled my postgraduate studies and also the Algerian Government for facilitating my stay in Algeria. I would also like to appreciate the efforts by PAUWES Director Prof. Zerga for ensuring that all the academic and non-academic components of my stay in the institute were sorted. I also appreciate the PAUWES and GIZ/DAAD staff and my fellow colleagues in PAUWES, for the encouragement, criticism and hunt for enlightenment during these two years.

My heartfelt gratitude goes to the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) team of scientists for contributing to my research by training me on the various data analysis software that I was able to use in this research during my internship in Ouagadougou, Burkina Faso at the WASCAL Competence Centre. This was a key driving force to obtaining my results, and together with their scientific interpretations thus immensely contributing to the completion of this thesis.

ABSTRACT

The continuous increase of agricultural water demand in Thiba River Watershed as a result of the agricultural expansion especially in the Mwea Irrigation Scheme and other parts of the watershed has led to over abstraction of water from the scheme's main water supplier, Thiba River, hence reducing its flows. Thiba River supplies water to Kamburu dam, a hydroelectric dam, on its downstream and it is also depended upon by various livelihoods. This study sought to find out the potential impacts the expansion of agricultural lands would have on the streamflow regime of Thiba River and how it would affect the downstream users. The research was carried out by determining the streamflow response to agricultural water abstraction using Spearman's rank correlation method. A relationship between streamflow and rainfall variability using regression analysis was also established. In order to understand how agricultural expansion had occurred, comparison was made between the 2004 and 2014 land use maps for the watershed. The HEC-GeoHMS and HEC-HMS models were then used to model the impacts of agricultural expansion on the streamflow. Different streamflow scenarios were simulated and their effects and impacts on the downstream users assessed. The results of the study showed that there was a very significant decline in the streamflow in the drier months compared to the wetter months. The regression analysis of the variability between streamflow and rainfall provided a moderately strong but significant relationship between the two variables. In addition, results showed that agricultural area had increased by over 6% between 2004 and 2014. Results from the model calibration showed a satisfactory efficiency with an NSE value of 0.50. Simulations of three different future scenarios indicated that there would be a significant decline in the future streamflow as a result of land use and population changes due to expanded agricultural lands. The results also showed that increase in precipitation would have very little impact on the streamflow. The study therefore concluded that increased agricultural expansion would lead to a tremendous decline in the streamflow. This would therefore call for proper water management and adaptation mechanisms to be put in place in order to maintain future water supply from Thiba River. This study is useful to water professionals and managers in developing a robust integrated water and land management system. In addition, the findings from this study would inform policy makers to make informed decisions on river water resource management.

KEY WORDS: Water Abstraction, Water Demand, Irrigation, Hydrologic model, Land Use Change

RÉSUMÉ

L'augmentation continue de la demande d'eau agricole dans le bassin versant de Thiba River à la suite de l'expansion de l'agriculture, en particulier dans le système d'irrigation de Mwea et dans d'autres parties du bassin versant, a conduit à une extraction abusive de l'eau du principal fournisseur d'eau du régime, le fleuve Thiba, entraînant ainsi la réduction de l'écoulement. Cette rivière fournit un barrage hydroélectrique en aval et dépend également de divers moyens de subsistance. Cette étude a exploré les impacts potentiels de l'expansion des terres agricoles sur le régime d'écoulement du fleuve Thiba et sur la façon dont cela affecterait les utilisateurs en aval. La recherche a été réalisée en déterminant la réponse de flux au prélèvement d'eau agricole en utilisant la méthode de corrélation de rang de Spearman. Une relation entre le débit et la variabilité des précipitations en utilisant une analyse de régression a également été établie. Afin de comprendre comment l'expansion agricole s'est produite, une comparaison a été faite entre les cartes d'utilisation des terres de 2004 et 2014 pour le bassin versant. Les modèles HEC-GeoHMS et HEC-HMS ont ensuite été utilisés pour modéliser les impacts de l'expansion agricole sur l'écoulement. Différents scénarios d'écoulement ont été simulés et leurs impacts sur les utilisateurs en aval ont été évalués. Les résultats de l'étude ont montré qu'il y avait une baisse très significative du régime d'écoulement dans les mois plus secs par rapport aux mois les plus humides. L'analyse de régression de la variabilité entre flux et précipitations a donné une relation modérément forte mais significative entre les deux variables. En outre, les résultats ont montré que la superficie agricole avait augmenté de plus de 6% entre 2004 et 2014. Les résultats de l'étalonnage du modèle ont montré une efficacité satisfaisante avec une valeur NSE de 0,50. Les simulations de trois scénarios futurs différents indiquaient qu'il y aurait une diminution significative de l'écoulement futur du flux en raison de l'utilisation des terres et des changements de population en raison des terres agricoles élargies. Les résultats ont également montré que l'augmentation des précipitations aurait très peu d'impact sur le régime d'écoulement. L'étude a donc conclu que l'expansion accrue de l'agriculture entraînerait un déclin formidable du régime d'écoulement. Par conséquent, cela nécessiterait la mise en place de mécanismes adéquats de gestion de l'eau et d'adaptation afin de maintenir l'approvisionnement futur en eau du fleuve Thiba. Cette étude serait donc utile pour les professionnels et gestionnaires du secteur de l'eau pour le développement d'un système intégré de gestion de l'eau et des terres. En outre, les résultats de cette étude informent les décideurs politiques de prendre des décisions éclairées sur la gestion des ressources en eau des fleuves.

MOTS CLÉS : Abstraction de l'eau, demande d'eau, Irrigation, modèle hydrologique, changement d'affectation des terres

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AFRICOVER	Africa Land Cover
AVSWAT	Arc-View Soil Water Assessment Tool
CN	Curve Number
DHI	Danish Hydraulic Institute
DEM	Digital Elevation Model
DSS	Data Storage System
EIA	Environmental Impact Assessment
FAO	Food and Agricultural Organization
HEC-GeoHMS	Hydrologic Engineering Centre’s Geospatial Hydrologic Modelling System
HEC-HMS	Hydrologic Engineering Centre’s Hydrologic Modelling System
HEP	Hydro Electric Power
HRAP	Hydrologic Rainfall Analysis Project
GBHM	Geomorphologically Based Hydrological Model
GeoSFM	Geospatial Streamflow Model
GIS	Geographical Information System
GUI	Graphical User Interface
ILRI	International Livestock Research Institute
IPCC	Intergovernmental Panel on Climate Change
KNBS	Kenya National Bureau of Statistics
KMD	Kenya Meteorological Department
MIS	Mwea Irrigation Scheme
MMRG	Mwea Multi-Purpose Rice Growers
NIB	National Irrigation Board
NSE	Nash – Sutcliff Efficiency
PAUWES	Pan African University Institute of Water and Energy Sciences
SCS	Soil Conservation Service
SHE	Système Hydrologique Européen
SHG	Standard Hydrologic Grid
SWAT	Soil and Water Assessment Tool
USDA-ARS	United States Department of Agriculture’s Agricultural Research Service

USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
WRMA	Water Resources Management Authority
WRUA	Water Resources Users' Association
WSTF	Water Services Trust Fund

CHAPTER ONE
INTRODUCTION

1.1 Background Information

Agricultural production has continuously been increasing all over the world mainly due to increased food demand as a result of the growing population. This has prompted the expansion of agricultural lands and development of irrigation farming to supplement the unreliable and low rainfall capacities in most areas. Agriculture is the highest consumer of the global water accounting for more than 90% of the world water resources (Siebert *et al.,* 2010). Most of agricultural water demand is consumed through irrigation. According to Zeng and Cai (2014), approximately 70% of the global freshwater withdrawal is used to meet irrigation water requirements. In Kenya, just like the rest of the world, agriculture is the main water consumer accounting for 80% of the available water (Ngenoh *et al.,* 2014). Various agricultural projects, especially irrigation projects, have been initiated and promoted by the Government of Kenya so as to increase agricultural productivity and enhance food security. In spite of the many advantages of irrigation, there are some negative effects experienced in irrigation areas. These negative effects include influences on hydrological regime such as decline of the base flow and reduction in discharge of the stream caused by over-exploitation of water resources or disruption of natural hydrological regime through manmade structures; water erosion caused by inappropriate irrigation method on sloping fields and impacts of irrigation on surface and groundwater quality (Tadic and Zdecko, 2009).

Mwea irrigation scheme in Kenya for instance has both advantages and disadvantages in its environs. The irrigation scheme was established in 1950s as a resettlement scheme with the primary objective of resettling the landless and ex-detainees during the independence struggle. The scheme was managed by the government through the National Irrigation Board (NIB) until 1998 when farmers decided to form their own Cooperative Scheme to manage it. However, due to several constraints such as lack of finance, machinery and due to unskilled personnel, the farmers could not manage it alone. Thus in 2003, the farmers sought back the Kenyan Government for help in management. The scheme is currently run by both the National Irrigation Board (Government) and farmers through Water Resources Users' Association (WRUA). The NIB is responsible for technical support, infrastructure maintenance and water management in the main and secondary canals whereas the WRUA is responsible for managing the tertiary units (both water and facility maintenance). Initially all the water abstractions were monitored from a common abstraction point since cultivation was restricted within the scheme. However, since the formation of the cooperative schemes, there has been tremendous changes in the scheme such as the ‘out of scheme’ rice cultivation in stream and river valley bottoms which were formerly infested with reeds and papyrus vegetation (Ndegwa, 2014). The actual water abstractions from the river basin can thus be no longer monitored from a common abstraction point due to many private farmers pumping irrigation water directly from the stream.

Like most other irrigation schemes in Kenya, Mwea Irrigation Scheme has undergone tremendous expansion especially from 2003 after the development of the blueprint of Kenya’s Vision 2030. In accordance to the blueprint, the government has heavily invested on the expansion of irrigation with the aim of bridging the gap of 1.085 million hectares by the year 2030 so as to sustain food production (Ngenoh *et al.*, 2014).

The continued growth in population within Kenya and as such Thiba River Watershed has led to increased food demands which calls for an increase in agricultural production and thus expanding the sector.This will therefore call for more water to be aquired to meet the ever increasing agricultural water demand. Hence, if there are no proper water supply and alloction strategies, conflicts may arise among the competing water users for the diminishing water resources within the watershed. Therefore, this calls for examining how the the continuous expansion of agriculture will affect the watershed’s main water supplier,Thiba River, so as to be able to understand the situation in order to come up with proper adaptation mechanisms in case of a crisis.

Several studies done in Thiba River Watershed have focused on irrigation water efficiency use on the Mwea Irrigation Scheme (MIS) which has existed since 1956. Since 1998 to date, about 4000 acres of land has been developed by private farmers on their own for paddy cultivation. Over 26000 acres of the gazette area is currently under irrigation with only 22000 acres being part of the main scheme. This new area was not planned for and has worsened the situation in terms of water availability for the scheme (NIB, 2016). However, there is limited information on actual water abstracted from the basin and the potential impacts on streamflow associated with increased commercial agricultural activities. This study therefore focused on modelling the future impacts the continuous expansion of agricultural land, would have on the flow of Thiba River. The approach developed for obtaining future precipitation, land use changes and water demand in order to predict their impacts on the future streamflow using the three different scenarios was as simple as possible and practical. The study further examined the streamflow behavior in relation to water abstraction trends. Finally, the best practices that could be undertaken by the water management stakeholders to minimize the negative impact of the projected declining flows and increased agricultural water abstractions in the river were recommended. Furthermore, the study suggested some of the adaptation measures and legal policy framework that could be undertaken in order to maintain the future supply from Thiba River.

1.2 Statement of the Problem

The continuous agricultural land expansion in Thiba River Watershed by both the government and individual farmers has greatly increased the water demand on Thiba River. Moreover, the high population growth in this watershed would further put a lot of pressure on the watershed's diminishing water resources, which are mainly dependent on Thiba River, since there would be more water needs as well as increased food demand. Increasing agricultural productivity which would call for further expansion of agricultural lands to provide for the required food is thus inevitable. This would therefore increase the agricultural water demand and exert more pressure on Thiba River. Coupled with other domestic and industrial water demands, the ever-increasing agricultural water demand in the watershed has resulted in increased water abstractions from the Thiba River. Majorly, the bulk of the abstracted water is usually from the upstream reaches where there are higher population densities and agricultural activities thus reducing the quantity of water in the river flowing to the downstream users. Additionally, there has been very high pollution of the river water through fertilizers and chemicals from the agricultural farmlands and also sedimentation of the river from the irrigated fields thus deteriorating the quality of the river water. These circumstances have led to the declining water resources in the watershed that have resulted to conflicts over the finite water resource, environmental degradation, and reduced water head for hydropower production at Kaburu dam (Muchiri, 2013). In spite of all these problems, there seems to be very few studies, if any at all, that have attempted to examine how the continuous expansion of the agricultural lands and subsequently increased water abstraction for irrigation purposes would impact on the streamflow of Thiba River. Lack of studies have made it difficult for policy makers to design robust integrated water and land management interventions in the watershed, that could enhance sustainability and appropriateness in the water resource utilization within Thiba River Watershed. The major challenge water planners and managers are facing is to balance agricultural water requirements from streams with the various other stream water uses including sustainability of downstream aquatic ecosystems. There is also the challenge of balancing demand and supply under the scenario of declining water resources. This study therefore sought to addresses this gap in knowledge since the impact of expanding the area of agricultural land use and its irrigation on the flow regime of Thiba River in Kenya is not known.

1.3 Objectives

1.3.1 Main objective

The main objective of this research was to model the impacts of agricultural land expansion on the streamflow of Thiba River using HEC-GeoHMS and HEC-HMS models.

1.3.2 Specific objectives

To achieve the broad objective, the following specific objectives were formulated;

i) To determine the streamflow response to agricultural water abstractions in Thiba River Watershed from 2007 to 2014
ii) To determine the variability between streamflow and rainfall in Thiba River Watershed from 2000 to 2009 using regression analysis
iii) To compare the changes in land use in Thiba River Watershed between 2004 and 2014
iv) To simulate the future impacts of agricultural expansion on the streamflow of Thiba River using HEC-GeoHMS and HEC-HMS models

1.4 Research Questions

In order to achieve the specific objectives of this study, the following research questions were explored:

i) How has the streamflow been varying with agricultural water abstraction from Thiba River between 2007 to 2014?
ii) How has the rainfall variability affected the streamflow of Thiba River between 2000 and 2009?

iii) How have the changes in land use occurred in Thiba River Watershed between 2004 to 2014?

iv) How has the expansion of agricultural lands impacted on the streamflow of Thiba River based on different scenarios?

1.5 Justification

Agricultural expansion is inevitable due to the continuously increasing population and economic growth. In order to maintain the food security for the current and future generations, more agricultural land has to be utilized. To achieve this, with the inconsistent and fluctuating climatic conditions, there is need to shift to irrigated agriculture. The expansion of irrigation schemes in Kenya is thus inevitable since only 19.6% of the country's area of 539,000 ha irrigation potential has been utilized so far (WSTF, 2016). Currently, the government is expanding Mwea Irrigation Scheme by about 3,500 ha more and one of the major components of that expansion project is the construction of a dam on the Thiba River (NIB, 2016). Since Kenya is a water scarce country, it is quite evident that any agricultural lands expansion for irrigation would lead to a significant water deficit for other sectors. Yet, the current national approach is focused on exploiting the vast untapped irrigation potential, with disproportionate focus on the efficiency with which the current irrigation activities are undertaken. Increased water abstraction from Thiba River would lead to reduction in water inflow to Kaburu dam (a major hydro-electric dam in Kenya), and this would affect the electricity generation capacity. The reduction in hydroelectric power (HEP) generation could result in an overall decline of the country's economy. The findings from this study would help policy makers to make informed decisions on river water resource management. The results of the predicted streamflows could be used for setting priorities in terms of water allocations for different sectors, current and future policy considerations, research for future adaptation strategies and urban and regional planning within the Thiba River Watershed and beyond.

1.6 Scope and Limitations of Study

The study area was the Thiba River Watershed in Kenya which has an estimated surface area of 1,648km^2. Both hydrological and geophysical data were used in the study. The hydrological data included the streamflow, rainfall, evapotranspiration and water abstraction data whereas the geophysical data were the land use data, soil data, population density grid data and the Digital

Elevation Model (DEM). The rainfall and streamflow data used in this study were from 2000 to 2009 whereas the agricultural water abstraction data was from 2007 to 2014. The land use maps used were for 2004 to represent the past land use and the 2014 land use map to represent the present land use. The HEC-GeoHMS which was integrated within ArcGIS 10.2 and together with HEC-HMS models were used to simulate and model variations in streamflows as a result of changes in agricultural land use.

The main limitations of this study were that several assumptions and simplifications were made in the formulation of the streamflow behavior under different scenarios. This was to be able to develop a simple methodology that would integrate the available data and the hydrological modeling techniques in a GIS platform, so as to attain some realistic results within the provided limited time frame provided for this research. Secondly, most of the rainfall, streamflow and water abstraction data had a lot of missing data which had to be filled prior to their usage in the models. The study only focused on the impacts of agricultural lands expansion and to some extent the land use dynamics. However, the study did not consider the effects of other factors such as climate change and variability, socio-economic aspects of the area, water quality aspects and sedimentation within the watershed which also have direct impacts on the streamflow of a river.

CHAPTER TWO

LITERATURE REVIEW

2.1 Global Agricultural Water Abstraction

An estimated 250 million hectares of land are irrigated globally (Siwale, 2008). This is more than five times the area of irrigated land as at the beginning of the 20th century. According to Siebert *et al*. (2010), the agricultural sector is the highest global water consumer accounting for over 90% of water uses and almost 70% of the global freshwater withdrawal is used to satisfy irrigation needs (Zeng and Cai, 2014). Irrigation plays a vital role in global food security. Ashley and Cashman (2006) also projected an increase in global water withdrawals of up to 3200km^3 more than domestic and industrial withdrawals. These projections show that food production would be affected due to the increasing global water demand for agriculture since renewable water is a finite resource and unevenly distributed globally. The increased water abstractions resulting from increased water demand leads to reduced streamflows and, in some instances lead to drying of up of rivers with adverse effects on wildlife and amenity. Groundwater abstraction increases this problem by reducing recharge rates to rivers and other surface waters.

In a study carried out in Jaguaribe basin in Brazil, it was noted that variations in water abstractions for irrigation purposes depend on the irrigated area and irrigation water requirement per unit hectares. The results also showed that irrigation water abstraction is very sensitive to the reservoir yield and reliability since a 5% abstraction in the upstream resulted into a 10% water scarcity probability annually (Van Oel *et al.,* 2010). Changes in water abstraction also seriously had an influence on reservoir yield and reliability. Further studies have also shown that climate change significantly affect irrigation water withdrawals. Higher temperatures lead to higher crop evapotranspiration and hence increased irrigation water requirements (IPCC, 2001).

2.2 Effect of Land Use on Streamflow

Several studies have associated the heavy forest covers with the existence of water bodies and higher base flows, which is as a result of higher infiltration in these areas thus higher recharge of the sub surface storage. On the contrary, other studies have shown the heavy catchment forest covers are associated with lower base flows due to higher evapotranspiration rates in the forests. Price (2011), demonstrated that the effects of agriculture and urbanization are also inconsistent with regard to their influence on the streamflow. This was attributed to varied additions of imported water and extremely variable background conditions.

Results from a study conducted by Ngigi *et al.* (2007) in Ewaso Ng'iro River, indicated that the flow of the river has progressively been reducing since 1960 by almost 30%. This has been attributed to high water abstraction levels at the upstream of the river as a result of agricultural activities and drought cycles, despite the decline in rainfall trends in the catchment. It was observed that water abstractions increased from about 20% in the wet seasons up to almost 70% in the dry season. According to Price (2011), low streamflows in a watershed are usually caused by three main factors which are the geomorphic factors, land use management and climatic factors. The geomorphic factors include the local geological characteristics, the prevailing topography, soils and sub-subsurface-topography of the watershed. Land use management which results from human activities such as urbanization and agricultural development usually affect the streamflows. Significant land use change such as dam construction can have immediate impact on the streamflow. Similarly, the prevailing climatic conditions have their respective effects on the streamflow of the watershed. These factors can either singly or in combination impact on the streamflow of the watershed.

Land use activities such as agricultural farming usually lead to changes in vegetation of a watershed which in turn alters its hydrologic characteristics and may thus lead to changes in the streamflow. Agricultural fields may retard run off more than forests in less dense vegetation thus reducing streamflow. Different crop types will also alter the water budget of the watershed and affect streamflow during periods of low flow. For instance, Stipinovich (2005) explained that a change in land use from natural vegetation to agricultural crops often results in a drop in interception rates, a rapid delivery of storm flow to streams, and a reduction in infiltration capacity of the soils due to compaction.

The relationship between land use and streamflows is of greater interest to researchers since it can provide crucial information for water resources management actions. However, there are still uncertainties on the impact of specific land use practices to different processes of the hydrological cycle due to the complexity and specificity of catchment characteristics. Much of the present understanding of land use effects on streamflow is derived from controlled experiments and manipulations of the land surface coupled with observations of hydrological processes such as precipitation inputs and stream discharge outputs (DeFries and Eshleman, 2004).

2.3 River Flow Regime

Understanding the flow regimes in a river basin is of great importance in watershed management and sustainable water use in the catchment. Information on the surface water availability, and its seasonal variability can help towards ensuring rational water resource use for all essential activities. Streamflow regime in a river is highly dependent on different climatic factors, among which the most important is the precipitation, in terms of frequency, intensity and seasonal distribution of rainfall events. The cause effect relationship between precipitation and discharge becomes more noticeable in non-perennial rivers, where streamflow mainly relies on surface runoff (Pumo *et al.,* 2016).

The streamflow response to rainfall depends on the catchment attributes that include the physiographic, underlying geology, vegetation covers and rainfall characteristics such as amount, intensity, and frequency. The interaction between these attributes and the nature of the response are variable in space and time and present complex hydrological phenomena. River flow regime is one of the means that addresses the complexity of streamflow response through the process of systematically organizing streams, rivers or catchments into groups that are most similar with respect to their flow characteristics.

The impacts of agriculture on the river flow regime are largely dependent on the catchment characteristics and local management activities. Generally, a change in land use from natural vegetation to agricultural farming often results in a drop in the interception rates, a rapid delivery of storm flow to streams, and a reduction in infiltration capacity of the soils due to compaction (Stipinovich, 2005). Additionally, irrigation water abstraction has a direct effect of agriculture on streamflow, since large volumes of water are diverted from the river system, thus reducing the flows to downstream areas.

Water abstraction from either surface or groundwater for the different activities such as irrigation has an effect on the natural hydrological cycle of a watershed. Reduction in river discharge alters the width, depth, velocity patterns and shear stress within the river channel (Krasovskaia, 2002). Stipinovich (2005) studied the effects of change in land cover/ land use and water abstraction in the Bot River catchment in South Africa using a combination of GIS techniques and Rainfall-runoff Pitman SHELL model but the study did not make direct links between some factors and the impact in runoff due the nature of complexity that was involved in the modelling process. However, in a research conducted by Gao and Yang (2009) in the Miyun reservoir in China, a combination of various factors on the flow regime were modelled and this was based on a distributed Geomorphologically Based Hydrological Model (GBHM), capable of fixing one factor and changing the other to model its influence on regime flow separately.

2.4 Hydrological Streamflow Modelling

The various hydrological models used to simulate and predict future water resources scenarios under some projected conditions should reproduce accurately the observed streamflow through calibration (Wagener *et al.*, 2007). However, modelling in poorly gauged or ungauged river basins and watersheds creates a major challenge. Thus, satellite data on hydrological and geophysical data can be used as an alternative in overcoming this challenge. Ungauged rivers are those with inadequate records in terms of both data quality and quantity (Sivapalan *et al.*, 2003). Currently, Streamflow in ungauged and/or gauged watershed is generally forecasted using physically-based models, conceptually and semi-distributed model, and data-driven models. Some of the most commonly used hydrological models have been reviewed in the following sections. The choice of one model over the other depends on various factors which may vary from model and data availability to the complexity and expertise required by each model.

2.4.1 Soil and Water Assessment Tool (SWAT)

The Soil and Water Assessment Tool (SWAT) model is a process-based, continuous physically based, distributed parameter river basin model that simulates water, sediment and pollutant yields developed by the United States Department of Agriculture's Agricultural Research Service (USDA-ARS) to assist water resources managers' and decision or policy makers to assess the impact of land use management on water, and diffuse pollution for large ungauged catchments with different soil types, land use and management practices (Levesque *et al.,* 2008). It has the capabilities of simulating surface runoff, streamflow, percolation, return flow, erosion, nutrient loading, pesticide fate and transport, irrigation, groundwater flow, channel transmission losses, pond and reservoir storage, channel routing, field drainage, plant water use and other supporting processes from small, medium and large watersheds. Model components include weather, hydrology, erosion, soil, temperature, plant growth, nutrients, pesticides, land management, channel and reservoir routing (Rostamian *et al.,* 2008). The SWAT model can be built using the Arc-View interface called AVSWAT which provides suitable means to enter data into the SWAT code. The hydrologic model simulated by the Arc SWAT model is based on the water balance equation;

$$SW_t = SW_o + \sum_{i+1}^{t}\{R_{day} - Q_{surf} - E_a - W_{seep} - Q_{qw}\} \quad (2.1)$$

Where;

SW_t = final soil water content (mm of water),

SW_o = initial water content in day i (mm of water),

t = time (days),

R_{day} = amount of precipitation in day i (mm of water),

Q_{surf} = amount of surface runoff in day i (mm of water),

E_a = amount of evaporation in day i (mm),

W_{seep} = amount of water entering the vadose zone in day i (mm of water), and

Q_{qw} = amount of return flow in day i (mm of water).

The hydrologic cycle is climate driven and provides moisture and energy inputs, such as daily precipitation, maximum and minimum air temperature, solar radiation, wind speed, and relative humidity, that control the water balance.

2.4.2 MIKE-SHE model

MIKE-SHE is a fully-distributed, deterministic and physically-based hydrological modelling tool used for simulating almost all the important processes in the land use of the hydrological cycle (Refsgaard *et al.*, 2010). The model is a derivative of the Système Hydrologique Européen (SHE) code developed by the Danish Hydraulic Institute (DHI). The MIKE SHE model comprises a suite of pre-processing and post-processing tools, in addition to both simple and advanced complex solution techniques for hydrological processes. MIKE-SHE has been successfully used in various fields such as design of water supply systems, soil and water management, irrigation and drought management, Environmental Impact Assessments (EIA), Climate change predictions, impacts of land use, and floodplain studies (DHI, 2007). Due to its capability of providing detailed descriptions of physical hydrological processes, it has been applied in modeling catchments that focus on water resource management and hydrologic prediction under land use and climate changes. The use of MIKE-SHE for an integrated catchment modeling process is a very complex task and thus requires an experienced modeling team with multidisciplinary skills in various hydrological sciences and a with a comprehensive understanding of MIKE-SHE processes (Liang *et al.,* 2016). Moreover, the MIKE-SHE model data requirement increases the number and difficulty of investigations, which in turn increase the survey burden and the subsequent risk of waste of human resources and finances (Feyen *et al.*, 2000).

2.4.3 Geospatial Streamflow Model (GeoSFM)

The USGS Geospatial Streamflow (GeoSFM) is a physically based semi-distributed geospatial hydrologic model which operates as an extension within ArcView 3.x hence requires data in GIS formats. This model was developed to establish a common visual environment for the monitoring of hydrologic conditions over wide areas (Artan *et al.*, 2007). The models undertake monitoring activities such as data assimilation, topographic analysis, and time series processing. This model uses remotely sensed (satellite based), ground observation data (soil, land use/land cover, rainfall/precipitation and evaporation) and digital elevation data. These data sets describing the land surface are the main input required by the model to calculate the basin hydrological water cycle (Artan *et al.,* 2007). Most of these data sets used in GeoSFM are raster grids. The GeoSFM provides a continuous simulation of streamflow, on a daily time step, providing a streamflow forecasting. The model consists of two parts namely; a GIS-based module used for model data input and preparation, and the rainfall-runoff processing module (Mutie *et al.,* 2006). The GeoSFM has successfully been used in many parts of Kenya and Africa to evaluate land use/land cover. It was used by Mutie *et al.* (2006) to evaluate land use change effects on river flow in Mara River basin in Kenya. There were reports of land use changes in the upper part of the basin with far reaching consequences for the long-term sustainability of the natural resource base. Three different periods (1973, 1986 and 2000) were analyzed in order to detect changes on land use which later could allow simulating the impacts in terms of river flow. Simulation results with the model showed that land cover data from the year 2000 produced higher flood peaks and faster concentration times compared to the 1973 land cover data. The changes detected indicate the effects of land use pressure in the basin. GeoSFM was also used by Kiluva *et al.* (2011) to model rainfall-runoff in River Yala in Western Kenya. In that study, it was used together with Muskingum-Cunge to model the hydrological processes in River Yala. The study was meant to develop a flood warning system that would mitigate the effects of the downstream flood. They used data from 1975 to 2005 for calibration, verification and routing the streamflow. The study concluded that both GeoSFM and Muskingum-Cunge models were able to issue peak streamflow and flood wave travel time. The models were able to produce information that was used to issue early warning messages. The main disadvantage of GeoSFM is its lack of compatibility with the current versions of ArcGIS as it was only designed to work with ArcView 3.x version. This version is rarely used due to its incompatibility with ArcGIS 10.x.

2.4.4 Description of HEC-GeoHMS model

The HEC-GeoHMS is a free public-domain hydrological modelling software package developed by US Army Corps of Engineers for use with ArcGIS. It utilizes ArcView and Spatial Analyst tool for development of various hydrological modelling inputs. It is a physically based, lumped, semi-distributed and geospatial hydrological tool that was developed by the Hydrologic Engineering Centre's Hydrologic Modelling Systems (HEC-HMS) to process geospatial data and create their input files in ArcGIS. It can be used to analyze terrain information, streams and sub-basin delineation, and preparation of hydrologic inputs using its Graphical User Interface (GUI) (USACE, 2013). HEC-GeoHMS is used to translate GIS spatial data into model files for HEC-HMS. ArcGIS is used for data formatting, processing and coordinate transformation. HEC-GeoHMS uses Digital Elevation Models (DEM) for catchment delineation and preparation of various hydrologic inputs. HEC-GeoHMS extension is designed to extract drainage paths and the basin boundaries from the DEM so as to represent the hydrologic parameters that are used for simulating the catchment response to precipitation. In order to estimate the hydrologic parameters, tables containing physical characteristics of streams and sub-basins are generated. These physical characteristics of the catchment and the river are computed and used in estimation of the hydrologic parameters (Adnan *et al.*, 2014). The results of the delineated catchment obtained from the HEC-GeoHMS is then imported to HEC-HMS where simulations are performed. Figure 2.1 adopted from USACE (2013) shows the relationship between GIS, HEC-GeoHMS, and HEC-HMS.

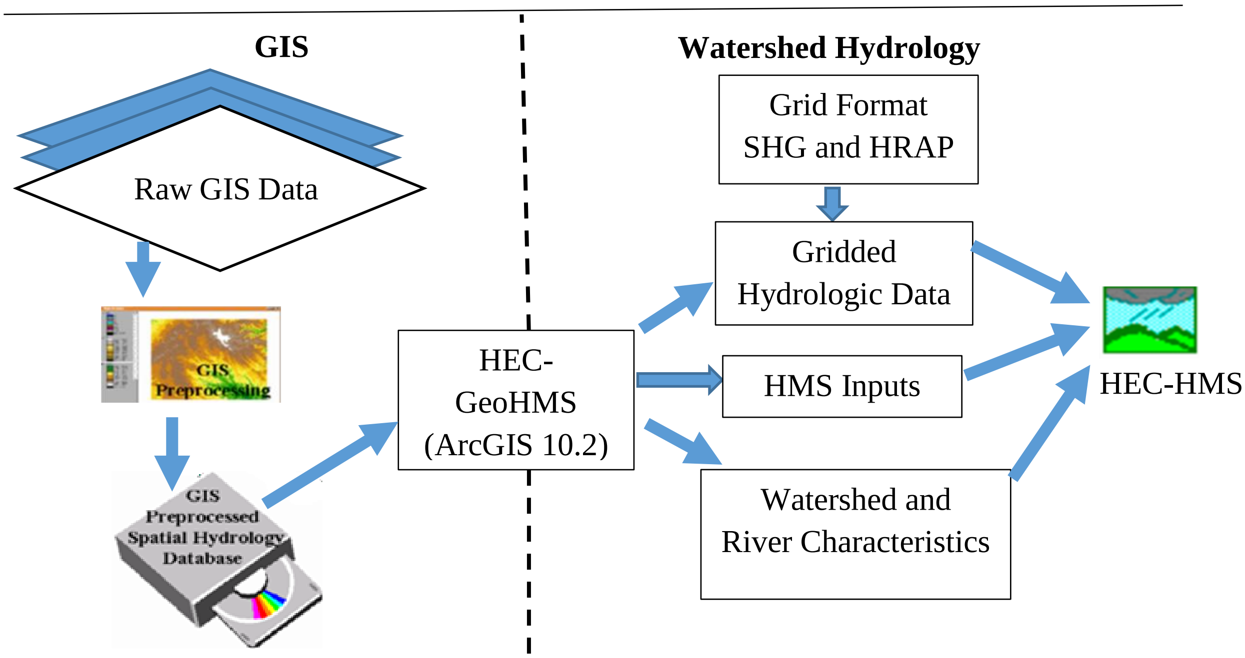


Figure 2.1: Overview of the Relationship between GIS, HEC-GeoHMS and HEC-HMS

2.4.5 Description of HEC-HMS model

The Hydrologic Modelling System HEC-HMS was designed in 1992 by the United States Hydrologic Engineering Centre to simulate precipitation runoff processes of dendritic watershed systems. This model was designed as a replacement of the HEC-1 model which was initially considered as the standard model for hydrological simulations (USACE, 2013). It was designed to be applied in large river basins water supply and also to solve flood hydrology problems. It can also be used in solving problems involving small urban and natural watershed systems. The hydrographs produced from this model can either be used directly or in conjunction with other models in studies involving water availability, flow forecasting, urban drainage, flood damage control, future impacts of urbanization, design of reservoir spillways and floodplain regulations among other hydrological uses. The model has the capability of representing various watershed systems at a given time.

The construction of the HEC-HMS model of a watershed system is done by separating the hydrological cycle into manageable pieces and dividing the watershed into smaller sub basins. The energy and mass flux balances within the cycle are then represented using mathematical equations. For simulating the precipitation runoff, the model consists of the following components: the precipitation specification option which describes the observed (historical) rainfall at a given location; the loss models which can estimate the runoff volume within the watershed given the precipitation and the watershed's characteristics; the direct runoff models which can account for the overland flow, storage and energy losses that take place as water runs off over the watershed and into the stream channels; the hydrologic routing models which account for storage and energy flux during the time water moves through the stream channels; models of naturally occurring confluences and bifurcations; and models of water control measures which include diversions and storage facilities. Additionally, the model contains a distributed runoff model which can be used with distributed precipitation data such as those obtained from the weather radar. The model also has a continuous soil moisture accounting model which is used for simulating the long-term response of the watershed to wetting and drying. The simplified representation of the rainfall-runoff process in HEC-HMS is shown in Figure 2.2 which was modified from HEC (2010a).

The HEC-HMS model contains eight hydrologic elements which include the sub basins, reach, junction, source, sink, reservoir and diversion. The sub basin is used to represent the physical outline of the watershed. For every sub basin, there should be a corresponding precipitation data. Using this precipitation data, the outflow from the sub basin element can be calculated through the subtraction of the precipitation losses. Additionally, calculation of the surface run off can be done and the base flow added. The reach element is used to convey streamflow to the basin model. The inflow into the reach is obtained from the upstream elements. This can be one or many upstream elements. In order to calculate the outflow from the reach, translation and attenuation must be accounted for. Additionally, channel losses can be included optionally in the routing. The junction element is used to combine streamflow from elements located upstream of the junction. Just like the reach, the inflow into the junction can be obtained from one or many upstream elements.

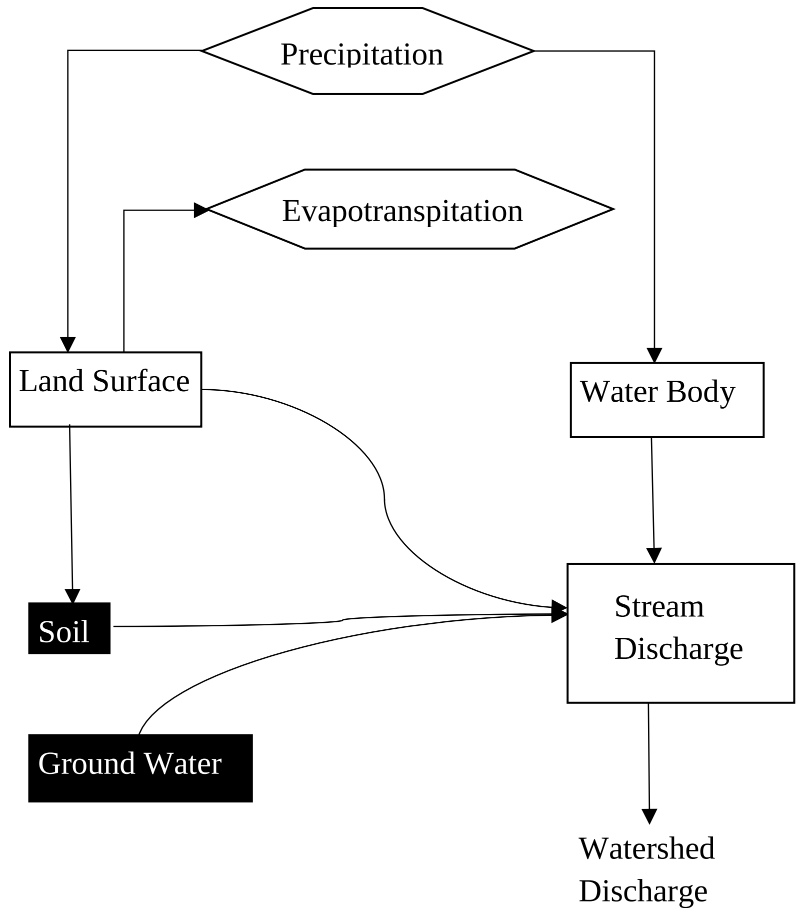


Figure 2.2: Simplified Schematic Diagram of the Rainfall-Runoff Process in HEC-HMS

To obtain the outflow from the junction, all inflow into the junction must be summed up. The source element is generally used to introduce inflow into the basin model. The source element does not have any inflow however; its outflow may be defined by the user. The sink element is used to represent the outlet of the watershed. The sink element does not have any outflow however inflow into the sink might come from one or many upstream elements. The reservoir element is used to model the hydrograph detention and attenuation as a result of reservoir or detention pond. Calculation of the outflow from the reservoir can be carried out using any of the routing methods in HEC-HMS. The inflow however, can come from one or many upstream elements. The diversion element is used to model the streamflow leaving the main channel. Its inflow can be obtained from one or many upstream channels. However, the outflow from the diversion element mainly consists of diverted and non-diverted flows. The calculation of the diverted flow can be done using the user's input. The diverted and non-diverted can be connected to other hydrologic elements located downstream of the diversion element.

2.4.6 HEC-GeoHMS and HEC-HMS model applications

The HEC-HMS and HEC-GeoHMS have been applied successfully in various studies most of which involve flood assessment and evaluation of land use changes. For instance, in a study conducted by Kawasaki *et al.* (2010) using HEC-GeoHMS to evaluate the potential impacts of precipitation and land use on streamflow in Srepok basin, Vietnam, various scenarios were developed with regard to climate change, population and socio-economic development in a GIS platform, and each scenario was estimated for streamflow for 2025 and 2050. The results show that the water demand increases due to population growth, and land development which would have a greater impact on the streamflow change as compared to precipitation in the next 50 years. The study suggested policy adjustments in land development, however it pointed out that this was very difficult due to increased expansion of agricultural land and economic investments in the region.

In another study carried out by Knebl *et al.* (2005) using HEC-HMS, NEXRAD rainfall and GIS to study the regional scale flood modelling that is related to urban development in San Antonio River Basin, Texas, it was found that an increase in the level of development led to a reduction in infiltration capacity which increased the flooding risk. The HEC-HMS has also been used by Emerson *et al.* (2005) in evaluating the effectiveness of the Valley Creek watershed's system of storm water detention basins in Pennsylvania. The study found out that the existing network of detention basins in Valley Creek watershed had very little, if any, impact on the storm water flow regime of the watershed. Significant peak flow reductions were simulated using HEC-HMS and HEC-GeoHMS by designing three different attenuated areas to detention basins. A study conducted by Hu *et al*. (2006) to determine future flood damages in the Red River, Minnesota, using HEC-GeoHMS it was suggested that in order to reduce the model's (HEC-HMS) uncertainties and improve its performance, better spatial and temporal precipitation representation was required. In a research to evaluate the impacts of land use change on streamflow in Northampton County by Lan (2012) using HEC-GeoHMS, investigations showed that further urban development in the basin would result into more runoff. The study also showed that there exists a relationship between residential development area and streamflow discharge which can also linked to the runoff volume.

HEC-GeoHMS and HEC-HMS models are thus important tools for decision support and day-to-day management. By being physically based, lumped and semi-distributed geospatial hydrologic models they can be adjusted to be applied in a number of hydrological studies with a high degree of certainty and accuracy.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of the Study Area

3.1.1 Geographical location

Thiba River Watershed is located within Kirinyaga and Embu Counties in the central region of Kenya. It is located within Latitude 0° 5´ S and 0° 47´ S, and longitude 37° 12´E and 37° 32´E which is at a distance of about 100 km North-East of Kenya's capital city, Nairobi. The Watershed (Figure 3.1) covers approximately 1648 km^2.

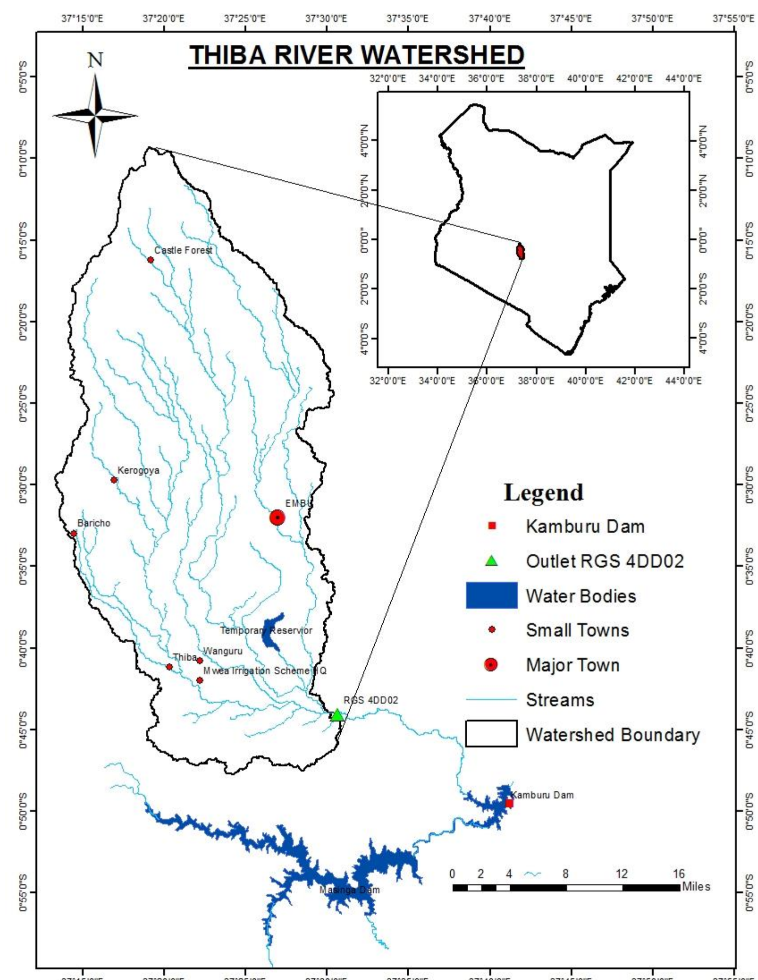


Figure 3.1: Thiba River Watershed

The watershed is located in the upper region of the Tana River basin that is drained by rivers Thiba, Nyamindi, and Rupigazi and other several smaller streams. Thiba River receives its waters from higher elevation region in Mt. Kenya. This watershed was chosen for the study since it represents one of the watersheds in Kenya where extensive water abstraction from its streams so as to satisfy irrigation water demand is taking place. The watershed has several agricultural activities taking place in both its upstream and downstream including the Mwea Irrigation Scheme (MIS) that is well known for paddy rice production in Kenya. The MIS which is of interest to this study covers about 15% of this watershed and consumes the highest irrigation water. Other agricultural practices in the watershed that also depend on irrigation include cultivation of maize and other subsistence crops. Thiba River drains its water to Kaburu hydroelectric dam which is one of the seven hydro-power stations in the Upper Tana Basin. These seven hydropower stations deliver up to 65% of the country's electricity (Bunyasi *et al.,* 2013).

3.1.2 History of Mwea Irrigation Scheme (MIS)

The Mwea Irrigation scheme was established in the 1950s by the colonial government as a resettlement camp for ex-political detainees. Prior to rice being grown in the region, the scheme was being used as a common grazing ground. However, in 1953, the first trials for rice cultivation were carried out in the region and this yielded positive results and thus led to the beginning of growing rice in this region. From 1950s to 1998, the scheme grew to become the largest and most effective rice production irrigation scheme in Kenya. Unfortunately, after 1998, the scheme underwent several institutional and management challenges that greatly impacted negatively on the output from the scheme and its efficiency in terms of water usage. Initially, the scheme was being run by the National Irrigation Board (NIB) under the care of the national government, however, in 1998, a local farmers' cooperative society, the Mwea Multi-Purpose Rice Growers (MMRG) undertook the management of the scheme. Due to lack of resources and capacity for effective management, MMRG was unable to render basic agricultural services to the farmers. This forced some farmers to start a parallel paddy rice production and marketing within the scheme which brought about a lot of pressure and competition over the irrigation water. The scheme was thus taken back by the National Irrigation Board (NIB) in 2003 so as to help to restore its past productivity.

The scheme is currently being run jointly by the NIB and the Water Resources Users' Association (WRUA). The NIB is responsible for technical support, infrastructure maintenance and water management in the main and secondary canals whereas the WRUA is responsible for managing the tertiary units (both water and facility maintenance). Despite the return of NIB in some parts of the management, proper and efficient water abstraction monitoring have proved to be impossible. This is due to the rise of many private farmers who pump water directly from the streams without regard to its multipurpose usage.

3.1.3 Climate

The climatic patterns of Thiba River Watershed range from tropical to semi-arid from upstream to downstream, and it has a bi-modal rainfall. The long rains start towards the end of March up to mid-May with its peak in April, whereas the short rains are experienced between October and November with its peak in November. The annual rainfall ranges from 400mm in the low land areas to about 2000mm in the highland areas of Mt. Kenya. The average annual rainfall varies from year to year but the overall mean annual precipitation is estimated at 944mm (FAO, 2016). Lower rainfall patterns are however mostly experienced in the months of January and February, and June to August. The monthly average rainfall for the three main weather stations within Thiba River Watershed for the period between 2000 and 2009 is as shown in Figure 3.2.

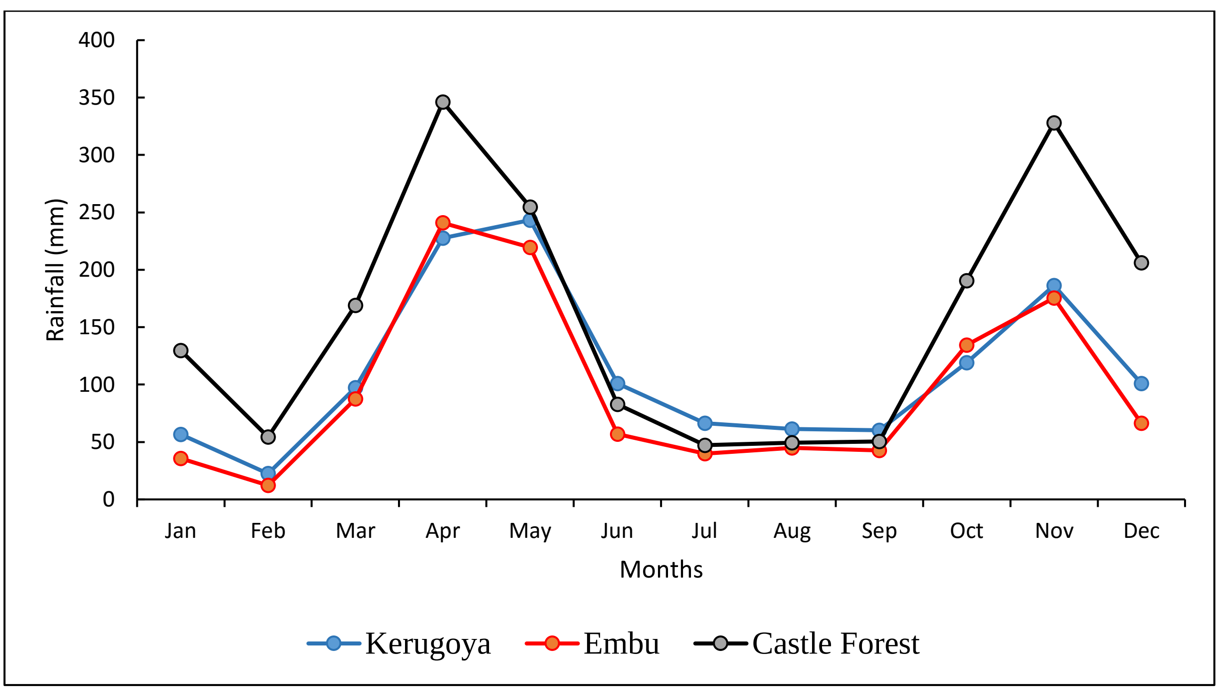


Figure 3.2: Monthly Average Rainfalls in Thiba River Watershed

The temperatures in Thiba River Watershed range from 13°C in the highland areas to almost 30°C in the lowland regions. The hottest months are between January and February whereas the coolest months are between June and July. The mean temperature for the watershed is about 23°C.

The potential evapotranspiration ranges from a mean of 1700 mm in the low elevation savannah zone to less than 500 mm annually in the summit region with an overall average of 1000mm. All areas below the forest zone have a rainfall evapotranspiration deficit. As a consequence, the high elevation forest and moorland zones provide most of the discharge of the rivers in the dry periods (Notter *et al.,* 2007).

3.1.4 Topography

The altitude of Thiba River Watershed ranges from as high as 4942m above m.s.l. in the highland region of Mt. Kenya to as low as 1051m in the lowland region. The landscape of this watershed and other topographical features are greatly influenced by the Mt. Kenya which lies on its upstream. The mountain region is characterized with high peaks and V-shaped valleys whereas the lowland area is very flat to gentle sloping. The snow melting from the top of Mt. Kenya forms a major water source for most of the rivers and streams in this watershed.

3.1.5 Soils

Thiba River Watershed is characterized by black cotton soils and volcanic soils. The high elevated regions around Mt. Kenya are characterized by histosols and nitosols which are majorly formed from volcanic ash deposits. These soils are very productive (agriculturally) than most soils in this watershed despite undergoing a series of weathering (FAO *et al.,* 2012). These soils are very deep, dark red and well drained thus favoring agricultural activities in this area such as farming of tea, coffee, and maize plantations. The histosols in this region are highly resistant to erosion thus limiting the level of soil degradation in this area (Geertsma *et al.,* 2010). In the lower elevation region, the dominant soil is the ferrasols and vertisols. These soils range from imperfectly drained to poorly drained, dark reddish brown to dark grey, and are mostly silty clay to clay (FAO *et al.*, 2012). These soils are suitable for paddy rice growing and favor the flooding irrigation system mostly adopted for rice cultivation. The spatial distribution of soil in Thiba is presented in detail using Figure 3.3.

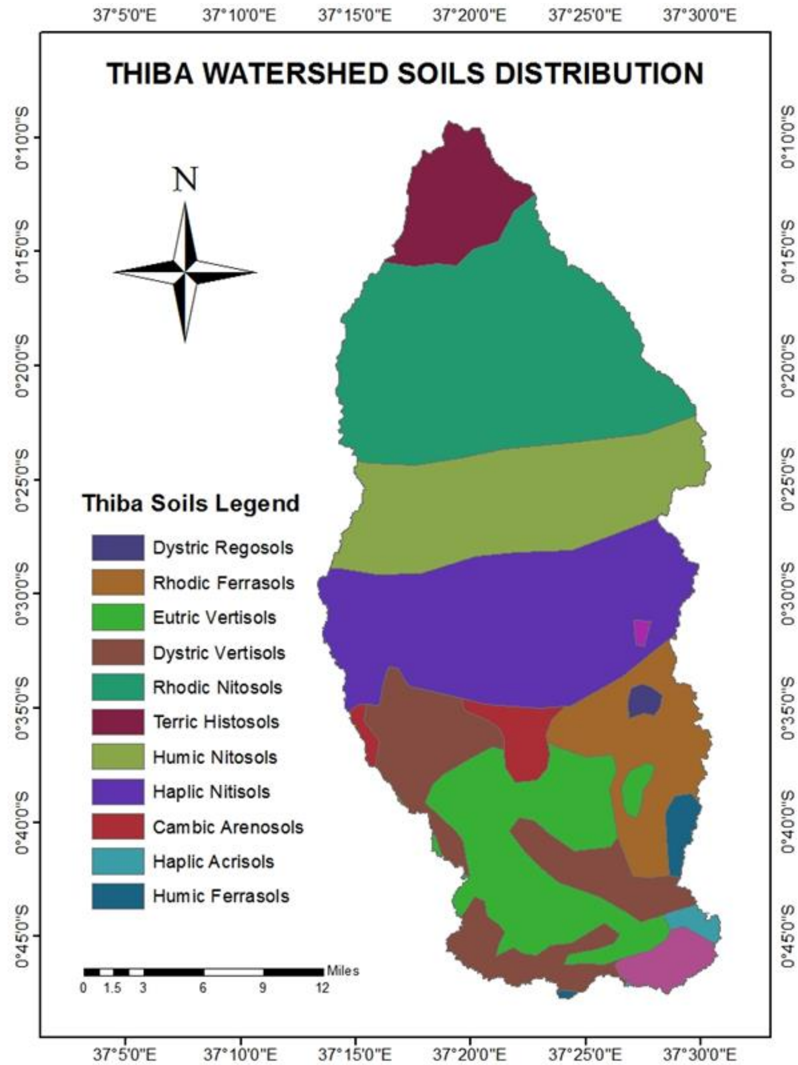


Figure 3.3: Soils Distribution in Thiba River Watershed

3.1.6 Main land use types

The predominant land-use activity in the watershed is commercial flood-irrigation of rice in the MIS. Apart from growing rice, other farmers in this watershed also practice horticultural farming whereas others are only focused on subsistence farming such as growing of maize and beans (Mati *et al*., 2011). The scheme has a gazetted area of 30,350 acres of which currently 26,000 acres are under irrigation for paddy rice production. The scheme started by growing only 65 acres of rice in Tebere section in 1954, and then picked momentum very fast and had about 2478 acres covered with rice in 1960 (NIB, 2016). Mwea Irrigation Scheme accounted for 88% produced in Kenya between 2005 and 2010 (FAO, 2016). The scheme receives over 80% of its water supply from

Nyamindi and Thiba Rivers which have a link canal joining them to transfer water from Nyamidi River to Thiba River (NIB, 2016). Irrigation water is abstracted from the rivers by gravity action through fixed intake weirs, and then conveyed and distributed in the scheme via unlined open channel systems.

3.1.7 Population and socio-economic activities

The current population density in Thiba River Watershed could be estimated at about 210 persons per square kilometer in 2017. This was estimated from the 2009 national census that estimated the population density in this region to be 183 persons per square kilometer and with an average annual growth rate of 1.7% (KNBS, 2009). Scattered settlement patterns are found mostly in the lower zones of the watershed where land sizes are large. Ecological and climatic factors influence settlement in upper zones where land is fertile and receives more rainfall. Another factor that influences settlement in this watershed is the type of farming practiced; in the upper zone where cash crops such as tea and coffee attract a high population because residents have a higher preference for cash crops farming compared to subsistence food crops. The rapid growth of Kerugoya, Sagana and Wanguru towns has also contributed to increased population in these areas since they receive many migrant workers and people interested in business opportunities in the region.

According to the county government of Kirinyaga, almost 90% of households in this watershed are involved in agriculture in one way or another with mostly those living in the highland regions of the watershed preferring cash crops whereas those in the lowland regions produce mainly food crops such as maize, beans, peas, sorghum, tomatoes and citrus fruits. Livestock farming is also starting to gain popularity in some areas in this watershed with most people in the upper part of the watershed preferring dairy farming whereas those on the low land rear indigenous breeds such as goats, cattle, sheep and chicken.

3.2 Data Collection

3.2.1 Hydrological data

The daily observed rainfall data from 2000 to 2009 for Thiba River Watershed was obtained from the Kenya Meteorological Department (KMD) in Nairobi and Embu in Kenya. The rainfall data obtained were for three stations within the watershed. The three stations were Embu, Kerugoya and Castle Forest with the station IDs of 9037202, 9037031, and 9037096 respectively. Unfortunately, there were several missing values in the observed rainfall data obtained from the meteorological department, thus satellite rainfall data was also obtained to compare with the observed data. The satellite rainfall data from 1979 to 2014 were obtained from the global cleaning weather data site. The satellite data from 2000 to 2009 was validated using the observed data and then used for this study. The average rainfall of the three stations was used to represent the rainfall for the whole watershed.

The daily observed streamflow data for Thiba River from 2000 to 2009 was obtained from the Water Resources Management Authority (WRMA) in Embu, Kenya and National Irrigation Board (NIB) in Mwea Irrigation Scheme, Kirinyaga County, Kenya. These two datasets were compared so as to validate the authenticity of the streamflow data. Statistical method of data filling was adopted so as to fill in the missing data. Due to lack of consistent data from several gauging stations within the watershed, only one gauging station was chosen to represent the whole catchment. The streamflow data was for the River Gauging Station (RGS) 4DD02 which was located at the outlet of the watershed at 0° 25’ 48’’S 37° 30’ 22’’E.

Past agricultural water abstraction data from Mwea Irrigation Scheme was obtained from NIB located at the scheme and WRMA in Embu. The data from the NIB was compared to that from the WRMA so as to validate it. The available water abstraction data obtained was from 2007 to 2014. This data was used to establish the abstraction trend as a result of agricultural activities within the watershed. The NIB measures water abstracted from the MIS daily at various locations known as checkpoints so as to ascertain the water use by different irrigation sections. In MIS there are six checkpoints, however in this study only two checkpoints were used (CP1 and CP3) to obtain the amount of water abstracted from the scheme. The other checkpoints were not used since the data available were not consistent, valid and verifiable since some of them were already faulty due lack of proper management.

The average monthly potential evapotranspiration data for Thiba River Watershed was obtained using CLIMWAT together with CROPWAT for the available stations of Embu, Mwea and

Kerugoya and then the average value for the three stations was used to represent the whole catchment. This potential evapotranspiration data was calculated according to the Penman Monteith equation in CROPWAT.

3.2.2 Digital Elevation Model (DEM)

A 30m resolution DEM for Thiba River Watershed derived from Shuttle Radar Topography Mission (SRTM) elevation data was downloaded from USGS website. The DEM described the terrain of the catchment and therefore it was very important for the watershed model. The DEM was processed using Arc Hydro and HEC-GeoHMS to obtain the stream path, watershed boundary and the basin slope as shown in Figure 3.4. The basin was then divided into several sub-basins based on the terrain and flow path. The HEC-GeoHMS was then be used to calculate the length of the stream segment and the areas of the sub-basins.

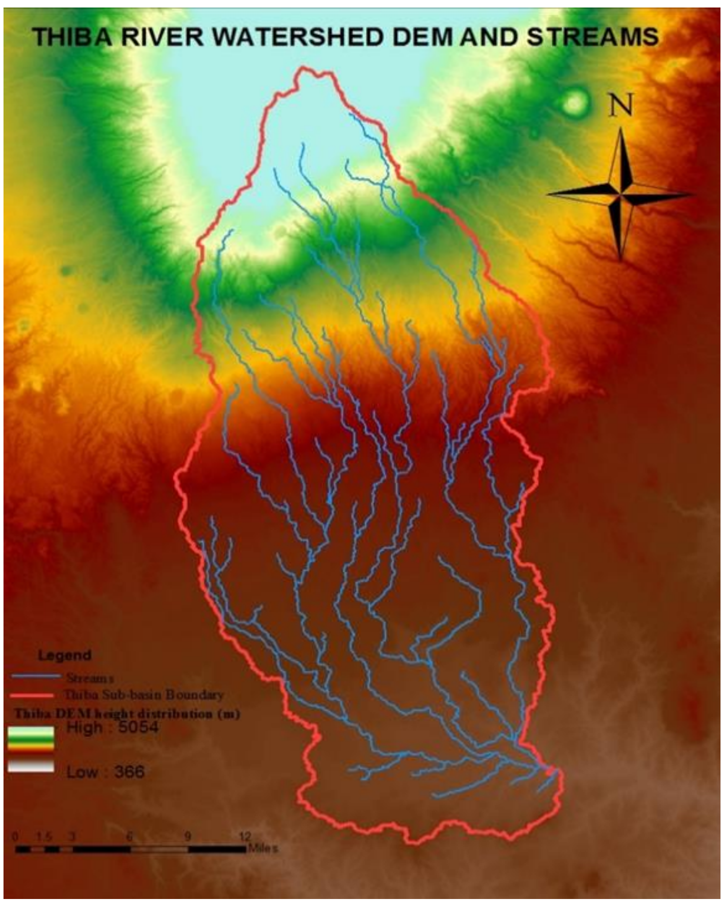


Figure 3.4: Thiba Watershed DEM and Streams

3.2.3 Soil data

The soil data map for Thiba River Watershed was downloaded from the Soil and Terrain (SOTER) database for Upper Tana Catchment (Thiba River Watershed is within Upper Tana Catchment) at the scale of 1:250,000 (Maingi *et al.*, 2010). The extracted data was used to classify the soil groups into four hydrologic groups of A, B, C, and D according to their minimum infiltration rates. This is because the rate of infiltration of a soil depends on surface intake rates and subsurface permeability (SCS, 1986). A GIS layer containing the hydrologic soil groups distribution in the basin was then created.

3.2.4 Land use data

The classified land use maps for 2004 and 2014 were downloaded from the AFRICOVER project database. The land use maps from AFRICOVER project database are produced from visual interpretation of digitally enhanced Landsat TM images (Bands 4,3,2). FAO AFRICOVER project of 2004 and 2014 designated the land use/land cover for points on an approximately 2400 x 4800 m irregular grid with an effective scale of 1:250000.

3.2.5 Population density grid data

The Kenyan population grid map from which the Thiba River Watershed population density grid was extracted using ArcGIS 10.2 was obtained from the International Livestock Research Institute (ILRI) website. The most current population density grid available was for the 2009 census, and thus it was used to produce the future population in 2030 and 2060. Generally, the population density grid maps are usually derived by dividing the total population count grids by the total land area grid. It is used to represent persons per square kilometer.

3.3 Correlation between Agricultural Water Abstractions and Streamflow

Data from the agricultural water abstraction was analyzed using Excel worksheet as the data analysis tool. Correlation methods such as Spearman's Rank, Kendall Rank and Pearson are commonly used in hydrological studies due to their relative simplicity and high validity (Fowler *et al.*, 2007). The Spearman's Rank correlation method was used to investigate the trend in water use by agriculture and streamflow data. The Spearman Rank correlation was chosen since it is a non-parametric test which does not make distributional assumptions to the population under investigation. The Spearman's rank coefficient, ρ (rho), was used to measure the linear relationship between two sets of ranked data (Blackwell, 1999). The coefficient was calculated using the relation:

$$\rho = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2-1)} \qquad (3.1)$$

Where:

ρ = Spearman's Rank correlation coefficient;

n = number of value in each dataset;

d_i = the difference between the ranks of corresponding values of X_i and Y_i

In order to under to determine the relationship between agricultural water abstraction and the streamflow, correlation was used to complement regression models in this study by measuring the strength of the relationship between the dependent and the independent variables. It provided a test of the statistical significance of the data by showing the degree with which the two variables changed together. It should be noted however, that the correlation result did not mean that a change in one variable was as a result of change in the other variable. It therefore did not give the cause of the relationship and this had to be interpreted in order to understand the causes of those changes. Since the Spearman's Rank Correlation Test only measured the relationship between the two data sets, their significance level was obtained using the values on the Spearman's Rank significance graph shown in the appendix.

3.4 Establishment of the Rainfall and Streamflow Variability

Data from both the rainfall and streamflow were analyzed using regression analysis so as to establish the relationship in their variability. Regression analysis is the quantitative expression of the basic nature of the relationship between the dependent and independent variables (Fox, 1997). It was used to measure the direction of movement of the dependent (response) variable which is streamflow to its response to changes in the independent (explanatory) variable which is rainfall. In addition, it was used to reveal the amount by which the dependent variable (streamflow) would change given a one-unit change in the independent variable (rainfall). The regression model was calculated using the function:

$$y_i = \beta_0 + \beta_1 x_i + \varepsilon_i \qquad i = 1,2,3, \dots, n \tag{3.2}$$

Where:

y_i = the i^{th} observation of the response (dependent variable)

x_i = the i^{th} observation of the explanatory (independent variable)

β_0 = intercept

β_1 = slope

ε_i= the random error or residual for the i^{th} observation and

n = sample size.

Fitting the model was done by finding values of β_0 and β_1 in such a manner that the sum of the squares of the vertical deviations was minimized. This process of minimizing is called least square regression, and was given:

$$(y_i - \hat{y}_i)^2 = (y_i - \beta_0 - \beta_1 x_i)^2 \qquad i = 1,2,3, \dots, n \tag{3.3}$$

Where;

$\hat{y}_i$ = forecasted data

y_i = observed data

The other variables were as defined in equation 3.2

3.5 Land Use Change Detection

Land use data for the Thiba River Watershed were obtained for 2004 and 2014 for comparison of the changes in land use within this watershed. The period chosen was 10 years apart so as to show the significant changes in land use in the basin as a result of increased agricultural area. Both the classified land use maps for 2004 and 2014 were downloaded from the AFRICOVER project database. The land cover/land use maps from AFRICOVER project database are produced from visual interpretation of digitally enhanced Landsat TM images (Bands 4,3,2) (Gregorio and Latham, 2015). These land use maps for 2004 and 2014 obtained from the AFRICOVER database were classified into eight classes which included irrigated agriculture, rain fed agriculture, bare land, forests, urban area, shrubs, herbaceous plants, and water. Change detection between the 2004 and 2014 land use maps was determined using comparison statistics whereby the percentage of each land use area was obtained. Thereafter, the area covered by each land use classified was compared between the two periods of 2004 and 2014 in tabular form.

3.6 Simulation of Future Agricultural Expansion on Streamflow

3.6.1 Justification for choosing HEC-GeoHMS and HEC-HMS models

The choice of HEC-GeoHMS is due to simplicity and easy approach in its application. It has the capability of analyzing watershed hydrology in both lumped and quasi-distributed forms (HEC-HMS (ModClark Method). The ModClark method allows spatially varying precipitation to be used in HEC-HMS (USACE, 2010a). In addition, the HEC-GeoHMS has a well-developed data management and visualization functions. Using the HEC-GeoHMS to perform spatial analysis when developing distributed hydrologic parameters not only saves time and costs but also helps in accuracy enhancement compared to ArcGIS alone (USACE, 2013).

The HEC-GeoHMS was designed by US Army Corps of Engineering to help and assist engineers, hydrologists or those with limited GIS experience to be able to visualize spatial information, perform spatial analysis functions, delineate catchments boundaries and streams, document watershed characteristics, prepare hydrological model inputs, and assist in preparation of hydrological reports (USACE, 2013). The main advantage of the HEC-HMS model is that it contains an automatic calibration package which can estimate certain model parameters and initial conditions when observed data of the hydro meteorological conditions are provided. The HEC-HMS model also links to a database management system known as Data Storage System (DSS) which can permit storage of data, their retrieval and connection with other analysis tools available from HEC such as HE-GeoHMS and other sources.

The limitation of the model is that when the SCS CN routing method is used, the infiltration rate will generally approach zero during a long duration storm instead of being constant as expected. Additionally, the initial abstraction of 0.2S does not depend on the storm characteristics or timing. The model sometimes underestimates the peak and low flows. This model was developed for application in mid-western US thus its application in other region is generally faced with lots of uncertainties (USCEA, 2013).

3.6.2 Hydrologic Model Development

In this study, HEC-GeoHMS 10.2 which is the ArcGIS 10.2 geo-processing extension and Arc Hydro tools were used to generate and process geospatial information of the Thiba River Watershed such as streamflow paths, sub-basins, catchment boundary, elevations, and soil type. The three main data sets that were used in this research so as to model the agricultural expansion impacts on streamflow included the Digital Elevation Map (DEM) which gave the topographic information and geologic characteristics of Thiba River Watershed, land use data, and hydrological data (rainfall, streamflow and evapotranspiration data). These data were then processed and computed using HEC-GeoHMS in ArcGIS 10.2 to generate the parameters that were required for the HEC-HMS model input that was used to generate runoff simulations.

3.6.3 Terrain processing using ArcGIS 10.2 and Arc Hydro

The downloaded DEM for the study area was used to delineate the watershed and generate its streams using ArcGIS 10.2. The boundary limit of the watershed was also developed and the resulting shape file used for clipping other GIS based raster data for the study area such as soil, land use and population density grid data. Arc Hydro tools were then used to perform the terrain processing using the DEM and stream files. The processes that were involved in the terrain processing are shown in Figure 3.5.

The terrain processing tool was used to produce the hydro DEM, flow direction grid, flow accumulation grid, stream definition grid, stream segmentation grid, and catchment grid delineation. These processes were all performed in a sequential order before the watershed processing function could be used in HEC-GeoHMS. This process was preceded by DEM reconditioning and filling of the sinks. This was done to ensure the elevation data was consistent with the vector stream network. The terrain processing was concluded by generating the slope grid for the watershed. These files were then transferred to HEC-GeoHMS in order to delineate the watershed in such a way that it could be used in HEC-HMS model.

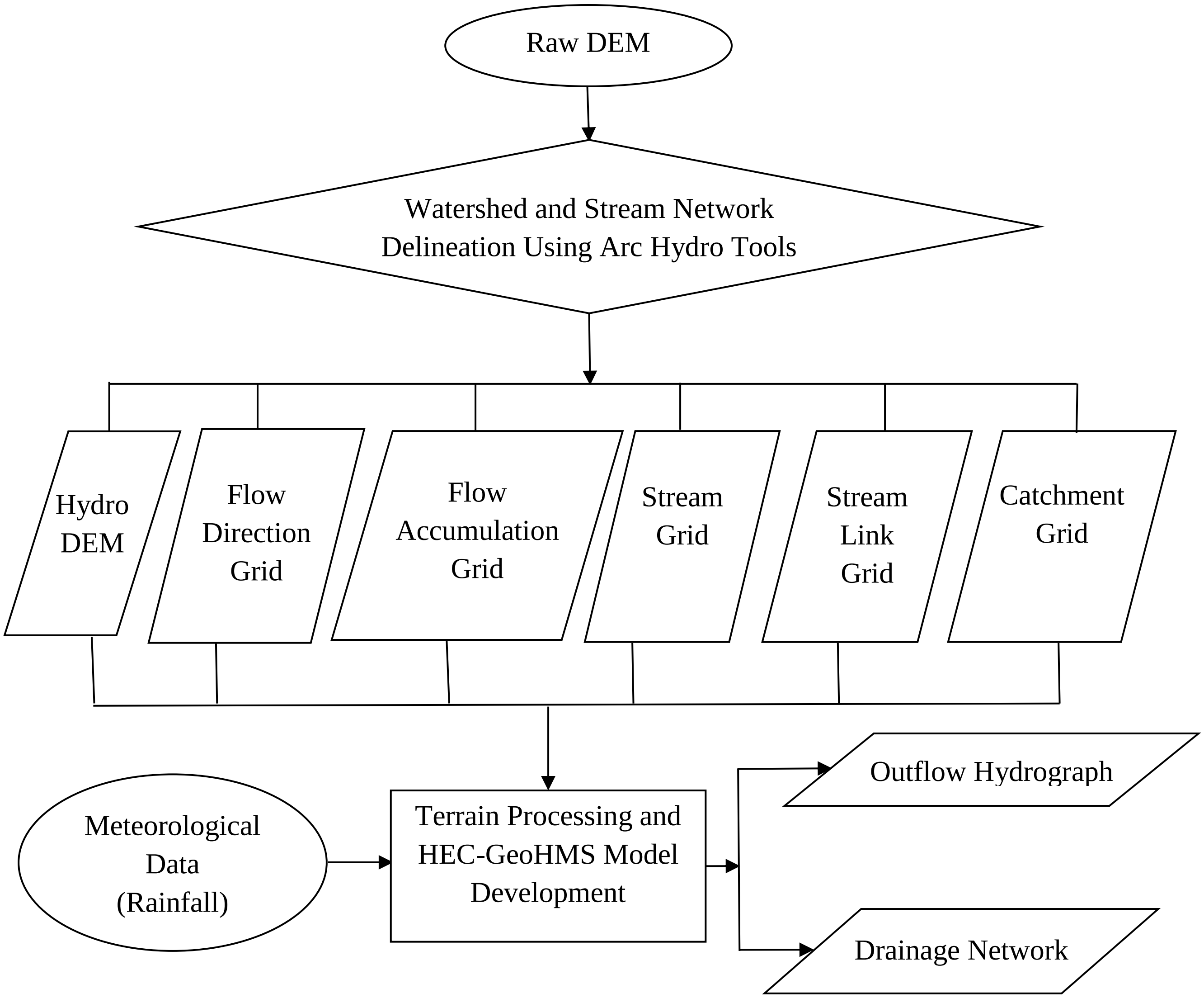


Figure 3.5: Schematic layout of the terrain processing in Arc Hydro

3.6.4 Preparing HEC-HMS model inputs using HEC-GeoHMS

The input data for the HEC-GeoHMS model included both raster and vector data sets that had been prepared in Arc hydro. The raster data included the raw DEM of Thiba River Watershed, filled DEM, flow direction grid, flow accumulation grid, stream network grid, stream link grid, catchment grid and slope grid whereas the vector data were the catchment, drainage line and the adjoint catchment. The HEC-GeoHMS project for Thiba River Watershed was set-up and the outlet point of the watershed defined. The project was started by processing the sub basins. This involved revising sub basin delineations through splitting the larger basins and merging extremely small basins so as to have sub basins of almost average areas. This was then followed by processing the river profile. In this process, the rivers could be split or merged in accordance with the newly formed sub basins. The river profile was then displayed as shown in Figure 3.6 which has a time of concentration of 5.31 hours. The basin and river characteristics that were calculated in this process included the river length, river slope, the longest flow path, basin slope, basin centroid, basin centroid elevation, and the centroidal longest flow path. The results of the delineated catchment obtained from the HEC-GeoHMS were then imported to HEC-HMS where simulations were performed.

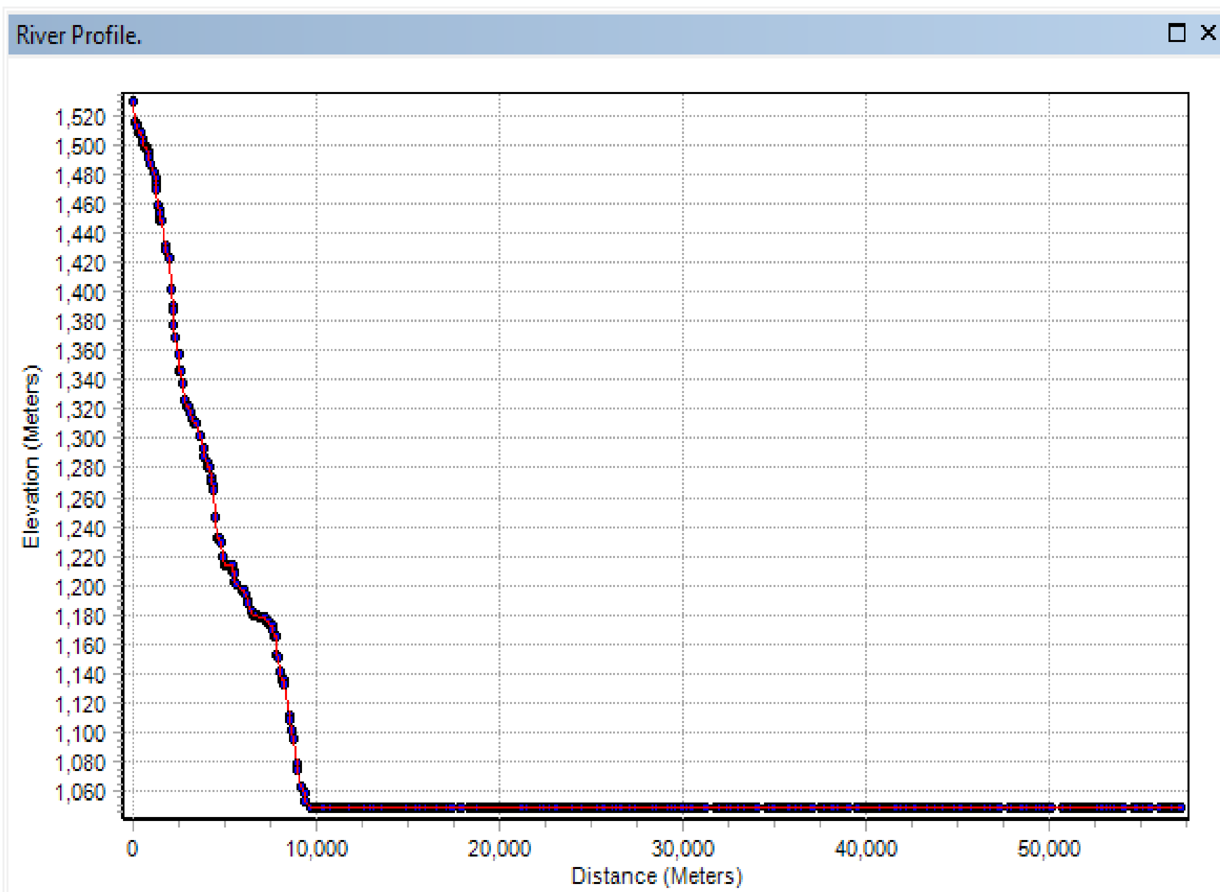


Figure 3.6: Thiba River Profile of the Longest Flow Path

3.6.5 HEC-HMS model parameters

The hydrologic parameters input for HEC-HMS model were also estimated using HEC-GeoHMS. Through the hydrologic parameter menu in HEC-GeoHMS, tools to assign and estimate various watershed and stream parameters for use in HEC-HMS were provided. These assisted in estimating the main parameters such as SCS curve number, the channel routing coefficients and the time of concentration among other parameters. For the channel routing, the Muskingum routing method was adopted in this study since it relates the amount of water stored in the river to both the inflow and outflow of the system. This Muskingum routing method was represented using the following equations:

$$S = K(xI + (1 - x)O) \tag{3.4}$$

$$O_2 = C_1I_2 + C_2I_1 + C_3I_1 \tag{3.5}$$

Where;

S = storage,

I = inflow,

O = outflow,

t = travel time, and

K and x = Muskingum parameters (constants).

The value of x was assumed to be 0.2 whereas that of K was assumed to be same as the CN lag time.

$$C_1 = \frac{0.5\Delta t - Kx}{K - Kx + 0.5\Delta t} \tag{3.6}$$

$$C_2 = \frac{0.5\Delta t + Kx}{K - Kx + 0.5\Delta t} \tag{3.7}$$

$$C_3 = \frac{K - KX - 0.5\Delta t}{K - Kx + 0.5\Delta t} \tag{3.8}$$

$$C_1 + C_2 + C_3 = 1 \tag{3.9}$$

Where;

C_1, C_2 and C_3 = Routing parameters which are obtained as using equations 3.6, 3.7, and 3.8 respectively, their sum was equal to 1 as shown in equation 3.9

The other variables of K, x, and t remained as was defined in equation 3.4 and 3.5

Land use was measured using the Soil Conservation Service (SCS) Curve Number (CN) which was the indicator of the potential of the land to generate surface runoff. The value of the CN ranges from 0 to 100 whereby a higher CN value would indicate low infiltration capacity and a lower CN would indicate a higher infiltration capacity of the soil. SCS CN was determined based on the percentage of imperviousness of the soil surface, land cover types, hydrological soil group type of the land, and the antecedent runoff conditions of the land. The SCS runoff was given by equation 3.10 (SCS, 1986).

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \tag{3.10}$$

Where;

Q = runoff (mm),

P = rainfall (mm),

S = potential maximum retention after runoff begins (mm),

I_a= initial abstraction (mm).

The initial abstraction, I_a referred to all losses before runoff began. It was highly variable, however, for data from small agricultural watershed, it was approximated using equation 3.11.

$$I_a = 0.2S \tag{3.11}$$

Through elimination of I_a as an independent parameter, this approximation allowed the use of S and P to produce some amount of runoff. Substituting equation 3.11 into equation 3.10 equation 3.12 was obtained.

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{3.12}$$

Where S was related to the soil and land use conditions of the sub-basin through the CN. The relation between S and CN was given by equation 3.13.

$$S = \frac{1000}{CN} - 10 \quad (3.13)$$

The SCS unit hydrograph was used in this study for the unit hydrograph due to its simplicity since it only has two main parameters, that is, the watershed area, A, and the lag time, t_L, as shown in equation 3.14 (Wurbs and James, 2002). The weighted time of concentration for each sub basin was computed using the CN lag method function in the HEC-GeoHMS. This function computed the basin lag time in hours as shown in equation 3.15. The CN lag value represented the time from the center mass of excess rainfall hydrograph to the peak of the hydrograph.

$$Q_p = \frac{484A}{T_p} \quad (3.14)$$

$$T_p = \frac{D}{2} + t_L \quad (3.15)$$

Where;

Q_p= peak unit hydrograph (m^3/hr.),

A = catchment area (m^2),

T_p = flow to peak; it is estimated as a function of rainfall duration, D and lag time, t_L (hrs.)

D = rainfall duration (hrs.)

t_L = lag time (hrs.)

Once all the HEC-HMS parameters were prepared and calculated in HEC-GeoHMS, they were all converted to HMS units and then the data check function was run to verify that all input parameters and data sets were in order. A log file was then created and any errors that were present in the dataset identified and corrected before the data sets were exported to HEC-HMS for simulations. A HEC-HMS schematic was then created to provide a GIS representation of the hydrologic system using a network with basin elements such as nodes/links and junctions and their respective connectivity as shown in Figure 3.7.

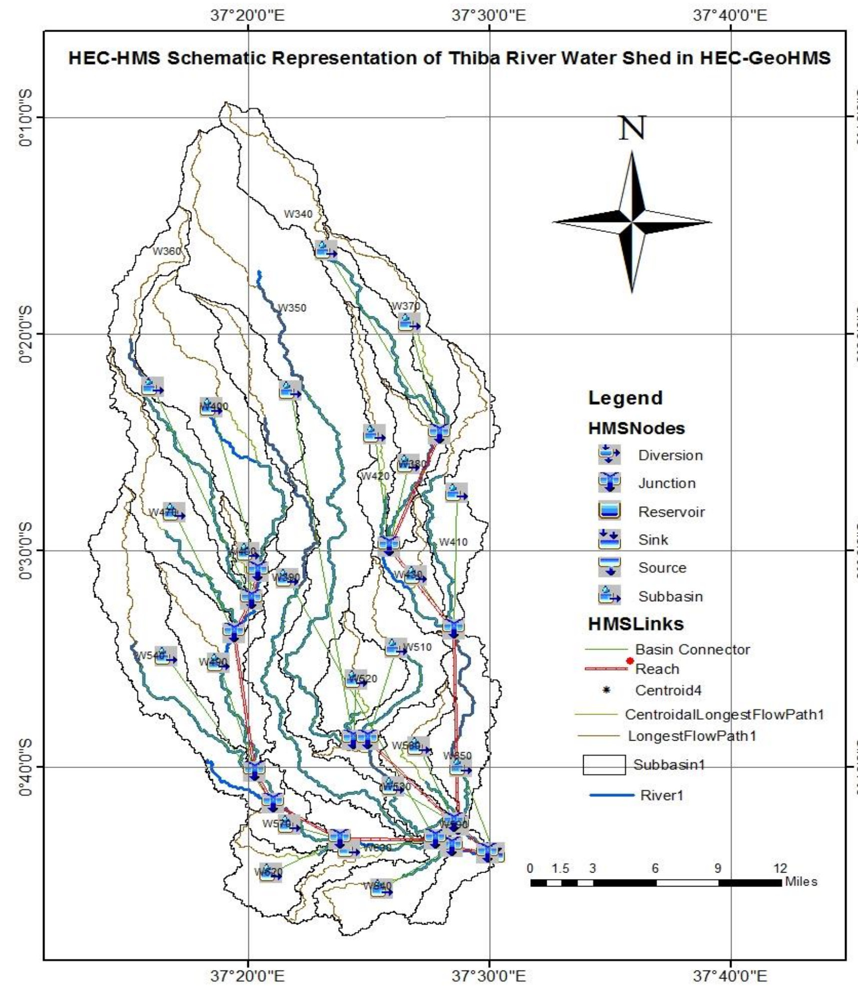


Figure 3.7: Thiba River Watershed HEC-HMS Schematic Representation in HEC-GeoHMS

Geographic coordinates were then added to the HMSLink and HMSNode feature classes so to ensure the map was exported to the HMS model without losing its geospatial information. The watershed map file of hydrologic elements (nodes and links), their connectivity and geospatial information were exported with a text file of a *.basin extension*. Other files that contained meteorological data (rainfall and temperature) and discharge data were created as empty files which were later populated in the HEC-HMS model. The meteorological file was created using a *.met extension* whereas the discharge data input file was created using a gage file. A new HMS file was created where all these project files (*.met, .map, gage file*) were stored in one directory for ease of retrieval in the HEC-HMS model. The file created had a *.hms extension*. The created HMS file was then open in the HEC-HMS model where manipulation could be carried out without any interaction with GIS.

3.6.6 Preparation of the CN grid using land use and soil data

In order to create the CN grid, the land use maps for 2004 and 2014 and soil group data were used in conjunction with the runoff curve numbers. The grid of land use map for Thiba River Watershed was added to the ArcGIS 10.2. This land use grid contained eight categories of land use classes. The grid was therefore reclassified into four classes so as to reduce the land use classes in order to make the CN preparation work easier. Most of the cells in the attribute table represented forest, agriculture, residential land and water. These formed the four main classes that were used to reclassify the land use. The process of accomplishing the land use reclassification was established as shown in Table 3.1.

Table 3.1: Reclassification of Land Use Data

Description (Original classification)	Number	Description (Reclassification)
Water	1	Water
Urban Area	2	Residential Area
Forest Herbaceous plants Shrubs	3	Forest
Rain fed Agriculture Irrigated Agriculture Bare land	4	Agricultural

Using ArcGIS 10.2, the reclassification of land use data was done and then it was converted into polygons which were then later merged with the soil data. The soil group data was also prepared into hydrological soil groups A, B, C, and D according to their minimum infiltration rates. Using the union tool in Arc Toolbox, the soil and land use shape files were combined to form one feature class. The feature class that resulted from this union had attributes from both feature classes. This resulted in the spatial data of the creating the curve number grid. The step that followed was for developing a CN Lookup table that would have the curve numbers for different combinations of land use and soil groups. This CN Lookup table was created to give an index for relating land use and soil data with CN. There was a corresponding CN value for each type of land use and hydrologic soil group. In this study, the SCS CN that were available in SCS reports and textbooks were used to populate the CN Lookup table as shown in Table 3.2.

Table 3.2: Attributes of the CN Lookup Table in Accordance to SCS CN (SCS, 1986)

LUValue	Description	A	B	C	D
1	Water	100	100	100	100
2	Residential Area	57	72	81	86
3	Forest	30	58	71	78
4	Agriculture	67	77	83	87

The combined spatial features together with the CN Lookup table were then used to prepare the CN grid in HEC-GeoHMS. The total CN for each basin was calculated using the average of area weighted CN and this was used as a parameter to characterize the land use in HEC-HMS model. The summary of the processes involved in creating the CN grid is as shown in Figure 3.8.

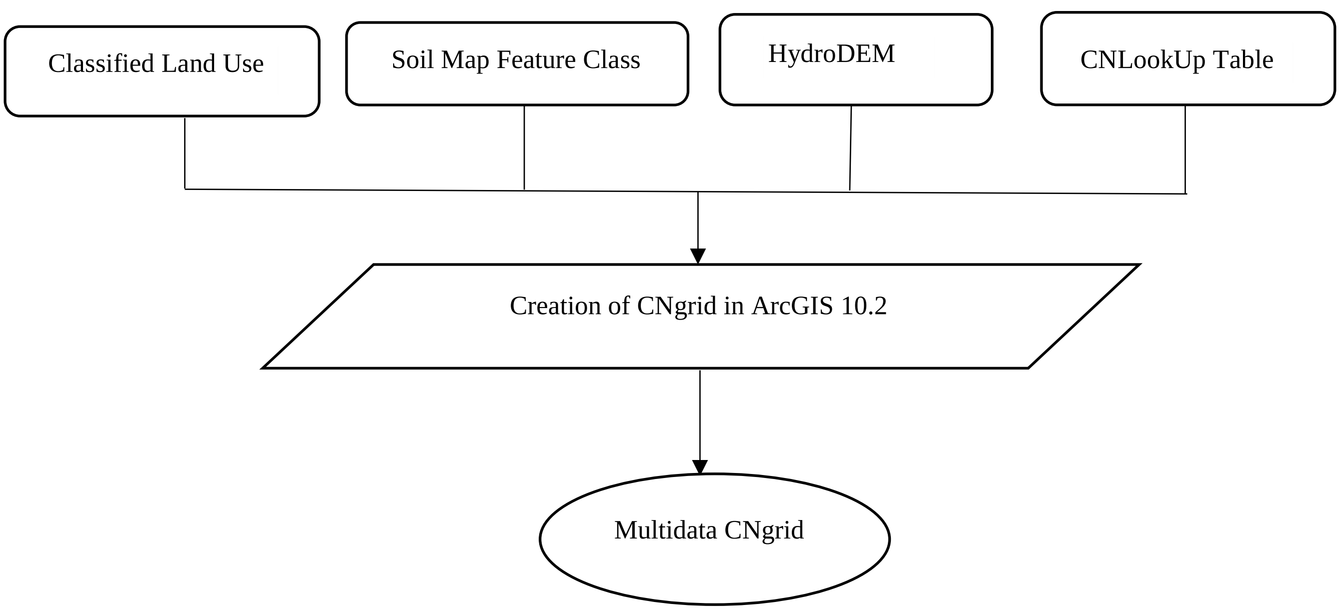


Figure 3.8: Flowchart for CN grid Map Creation in ArcGIS 10.2

3.6.7 Streamflow simulations in HEC-HMS

The data processed in HEC-GeoHMS were then integrated into HEC-HMS. The HEC-HMS version 4.2 model was opened and the exported HMS files created in the HEC-GeoHMS were added to the program. The interface of the created project in HEC-HMS was as shown in Figure 3.9.

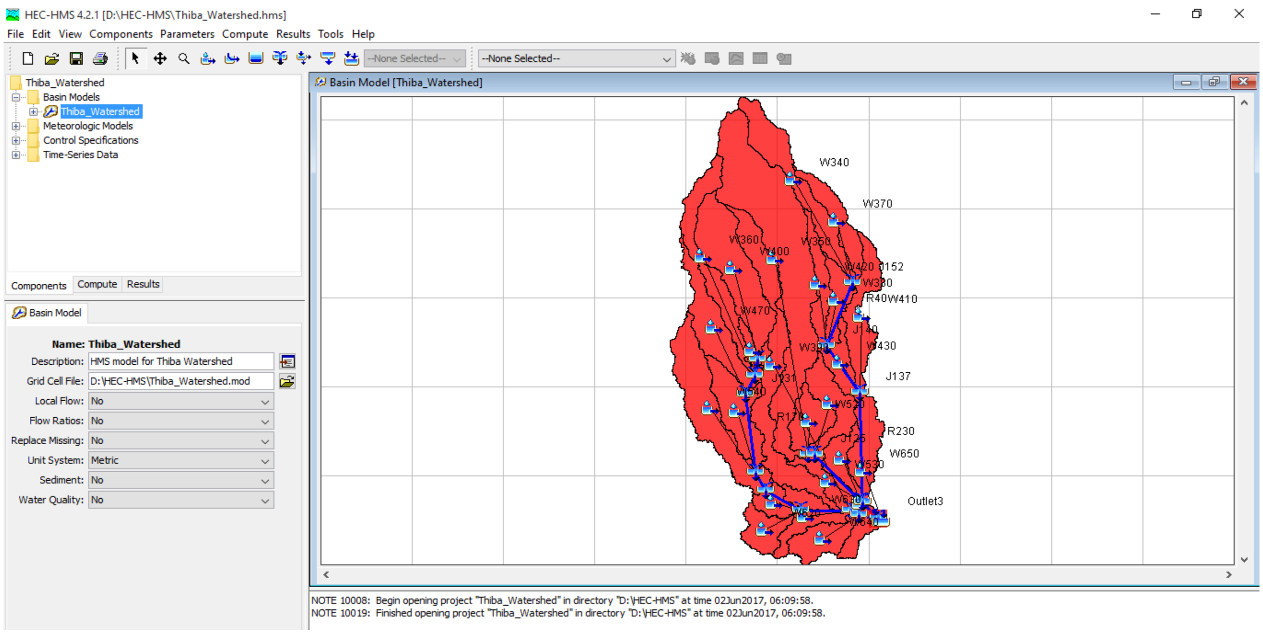


Figure 3.9: Thiba River Watershed model representation in HEC-HMS

The main component managers of the HEC-HMS model were the basin model manager, meteorological model manager, control specifications manager and time series data manager. The basin model manager contained the Thiba River Watershed map. This was the physical representation of the watershed. Initially, the map only contained the hydrologic elements which included junctions, reservoirs, reach, source, diversion and sinks after which the background map layers containing the boundaries of the watershed and its sub basins were added. The metrological manager was used to compute rainfall required by each sub basin element input the watershed. The metrological model used the watershed's average monthly evapotranspiration data to simulate the continuous hydrological response in the watershed. In order to obtain the storage-discharge relationship within the watershed, the SCS CN transformation method was applied. This method used the SCS CN by utilizing the CN grid to develop a routing method. The precipitation (rainfall) data and the Thiba River discharge data obtained at the outlet of the watershed (RGS 4DD02) was input in the time series manager so as to simulate the flow within the watershed. Each sub basin that was created had its precipitation data. A total of 24 small sub basins were created in the HEC-GeoHMS. These sub basins were based on DEM characteristics, the slope of the watershed, the length of the stream and the number of the tributaries joining Thiba River. However, due to time constraints their parameters were merged and only the average values were used to represent the whole watershed. Each of these 24 sub basins had their own parameters but for this study their averages were used in the simulation process. Additionally, due to lack of sufficient rain gauge stations within the watershed, the average rainfall data for the three stations existing within Thiba River Watershed was used. Additionally, the discharge data at the outlet watershed was assumed to represent the whole study area. The study adopted the Muskingum routing method to model the stream routing. This method used the constants K and X to solve for flow rate numerically at each node. An assumed Muskingum X value of 0.2 was used which in general is usually used to indicate a small, natural stream. The Muskingum K value was assumed to be equivalent to the basin CN lag number for each sub basin in hours as defined by the HEC-HMS 4.2 user's manual. The reach value of 2 was assumed as the initial value for conveying the streamflow within the small sub basin. The method also utilized the channel characteristics such as width, length, slope and shape to provide the channel's physical properties which included the hydrograph diffusion and dispersion.

The hydrological processes for this study was represented using the SCS Curve Number method so that when estimating the future land cover changes as a result of agricultural expansion, the curve number change would be used to represent the changes. The initial abstraction, I_a, in the SCS method was assumed to be equivalent to 0.2S where S represented the potential maximum retention capacity for the normal antecedent moisture conditions. This retention was adjusted on a 5-day antecedent rainfall (Chow *et al*., 1988).

Once all the parameters were put in place various simulations were run to show the hydrologic response of the watershed using the provided meteorological data. The simulation runs applied meteorology conditions to the watershed's land surface to estimate the runoff. Each simulation run was composed of one basin model, one meteorology model and one control specification. The computed results of the simulation runs were displayed in form of hydrographs.

3.6.8 Model calibration

Calibration of the HEC-HMS model was done using the observed streamflow data at the outlet of the watershed located at RGS 4DD02. A medium sized rainfall event of two years was chosen. Rainfall and streamflow data for the year 2000 and 2001 were chosen in this study. The average precipitation from the three rainfall stations within the watershed and the discharge data at the outlet were used. The SCS loss parameters which included the initial abstraction, the percent imperviousness and the curve number for each sub basin was calculated using equation 3.11, 3.12 and 3.13 in HEC-GeoHMS as initial values. The time of concentration, T_c, was calculated by obtaining the longest flow path in HEC-GeoHMS (Hoblit and Curtis, 2001). The model calibration was done using the model optimization feature which would automatically adjust various parameters to obtain a minimum objective function value that matched the observed values (USACE, 2013). The observed actual river flow discharges were input into the time series data manager after which the simulated flows were compared to these actual flows. Several iterations were made with each having 1000 runs until the best set of parameter values that had the highest efficiency were obtained. The parameters that were calibrated included the loss functions such as the initial abstractions and curve number (CN), transform functions such as the SCS lag, and routing functions such as the Muskingum routing parameters. The SCS lag time and the Muskingum K value were the main parameters used for calibration. The curve number values based on the land use data for 2004 and 2014 were kept as they had been initially estimated in HEC-GeoHMS. The best set of the model parameters obtained after calibration were used to run the model for the land use scenarios in the Thiba River Watershed.

3.6.9 Model validation

The verification of the model performance was done by comparing the observed and simulated streamflows at River Gauging Station 4DD02. The simulated streamflows were expected to produce a similar trend as the observed streamflows. In order to evaluate the hydrologic goodness of fit, a statistical criterion was applied on the observed (measured) streamflows and the predicted (simulated) streamflows. These results were compared using the Nash-Sutcliff Efficiency (NSE) as shown in Equation 3.16. NSE was used to indicate how well a plot of observed versus simulated values would fit the 1:1 line. According to Nash and Sutcliff (1970), the NSE represents a normalized statistic which determines the relative magnitude of the residual variance compared to the observed (measured) data variance. Its value ranges from $-\infty$ to 1, with an NSE = 1 being the optimal value. Values between 0 and 1 are generally regarded as acceptable levels of performance with values that are less than 0 being regarded as unacceptable performance levels. NSE is calculated as follows:

$$\mathrm{NSE} = 1 - \left(\frac{\sum_{i}^{n}(Q_i - Q_s)^2}{\sum_{i}^{n}(Q_i - \bar{Q})^2}\right) \quad (3.16)$$

Where;

NSE = Nash-Sutcliff Efficiency (Dimensionless)

Q_i = Observed (measured) daily streamflow (m^3/s)

Q_s = Predicted (simulated) daily streamflow (m^3/s)

$\bar{Q}$ = Mean observed (measured) daily streamflow (m^3/s)

n = Number of observations

3.6.10 Creating future land use scenarios

In order to determine the future impacts of agricultural land expansion, the study focused on examining the future land use scenarios within Thiba River Watershed. The land use data was used to determine two main factors in the future streamflow which were; the runoff and the future water demand. In this study, the future land use scenario for 2030 was used to predict the streamflow conditions in the near future whereas land use scenario for 2060 was use to predict the streamflow conditions in the far future. Many land use scenario models have been developed using GIS (Steinitz *et al*., 2005; Nagasaki *et al*., 2006; Almeida *et al*., 2008; Xia and Xiaoping, 2008), however in this study, a simple approach was developed for the scenario analysis due to limited resources and data accessibility. In order to reflect the extent of agricultural expansion and other land use developments in 2030 and 2060, the existing population density and Kenya's agricultural and irrigation policies were used to model the future land use policies. A constant average annual population growth rate of 1.7% (KNBS, 2010) according to the last census carried out in 2009, was applied in the whole watershed to generate the population density grids for 2030 and 2060. However, it must be noted that the relationship between population growth and land use changes are very complex and depends on many other factors among them urbanization and the transition stage of the region (Acharya and Nangia, 2004).

In order to create the land use and population density relationship in the Thiba River Watershed, the population density grid for 2009 was cross-related with the land use polygon for 2014. This yielded the population density ranges corresponding to each land use polygon. The land use polygon used in this case was the reclassified one that was composed of only water, forest, residential area and agricultural land due to its simplicity. The obtained ranges were then used to determine population density grids for 2030 and 2060 to predict the future land use in these regions with the basic assumption that the future land use will highly depend on population growth. Assumption was also made that the existing forested area would become more developed as the population would increase and agriculture will take a larger area of this portion. In that way, the land use maps for 2030 and 2060 were thus created. The HEC-HMS model parameters for processing runoff such as the curve numbers, lag times and the Muskingum parameters were then recalculated based on the new future land use scenarios that were developed.

3.6.11 Creating future precipitation scenarios

The input data or future prediction also required the precipitation data. In order to predict precipitation generally, the downscaled rainfall data from General Circulation Model (GCM) obtained from the IPCC were used (Kiem *et al*., 2008; Beyene *et al*., 2010). It must be noted that the GCM data are more reliable for temperature prediction than rainfall, wind and humidity prediction. However, the uncertainties could be reduced when ensemble approaches are adopted (Kundzewicz *et al*., 2007). Projections from the IPCC indicated an increase in rainfall in months of December to February and a decrease in the months of June to August. Projections also indicate future warming conditions within East African region whereby temperature will increase by 0.2°C (B1 - low scenario) to 0.5°C (A2 - higher scenario) per decade. Thus, in order to predict the future rainfall scenario for this study, a simple approach was adopted. According to IPCC reports, most global rainfall predictions indicate that there will be no change to 2.5% increase in rainfall within the next 25 years in the East African region. Similarly, in the next 50 years there will be no change to 5% increase in rainfall (Meehl *et al*., 2007). According to IPCC report, Kiem *et al.* (2008) also estimates that there will be a 6.3% to 10% increase in rainfall by 2100. Based on these estimates, this study adopted the 2.5% and 5% increase in the future rainfall for 2030 and 2060 respectively. These increases were applied uniformly to the 2009 average daily rainfall of Thiba River Watershed. Temperature change was however not considered in the scenario development since it was indirectly incorporated in the precipitation and water demand scenario development.

3.6.12 Developing future scenarios

The development of future streamflows in 2030 and 2060, projection scenarios for this study involved the use of both the projected future land use scenarios and future precipitation. The HEC-HMS model has a forecasting manager that was used to input the projected scenarios data. Streamflow forecasting in HEC-HMS involved the simulation of both past and future conditions. The future streamflows would be useful in determining future water allocation for different sectors within the watershed. Three scenarios were developed as shown in Table 3.3.

Table 3.3: Scenarios for Developing Future Streamflow in Thiba River Watershed

Scenario	Change	Description
1	Land Use Change	Daily rainfall for 2009 was used in this scenario simulation. This scenario tried to predict the future land use changes in 2030 and 2060 based on the population increase which was used to determine the future water demands. There was no precipitation change applied in this case. The changes were applied to the 2014 land use map to determine the conditions in future so as to assess the future water demand in the watershed.
2	Precipitation Change	2.5% and 5% increase in rainfall applied uniformly to the 2009 rainfall to obtain the precipitation in the years 2030 and 2060 respectively without any change in land use.
3	Combined Land Use and Precipitation Change	This scenario used the predicted 2030 and 2060 rainfalls and the future land uses to determine the future streamflow.

In creating the future Land Use for 2030 and 2060, the 2014 land use map was used as the baseline data whereby the changes made were applied to, based on the population changes in the future. According to the 2009 census the population of the region around Thiba and Embu County and its surroundings in general, was expected to grow by about 1.7% annually (KNBS, 2010).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. Agricultural Water Abstraction and Streamflow Analysis

Abstraction of water from Thiba River was considered to be one of the main drivers of changes in the flow of the river. The largest proportion of water abstraction was due to increased requirements for irrigation, occasioned by increased area of land under irrigation especially within the MIS. The data provided from NIB and WRMA showed an increasing trend of water abstraction in Thiba basin. There was an increasing trend of water abstraction for the period between 2007 and 2014 as shown in Figure 4.1. The highest abstraction of about 9.3 million m^3 happened in 2014 whereas the lowest of about 7.2 million m^3 occurred in the year 2009. This increase in abstraction in 2014 could be attributed to reduced rainfall due to the drought that was experienced in Eastern Africa in that year. Abstraction in 2009 was lower due to high rainfall in that year thus reducing the dependency on the river water.

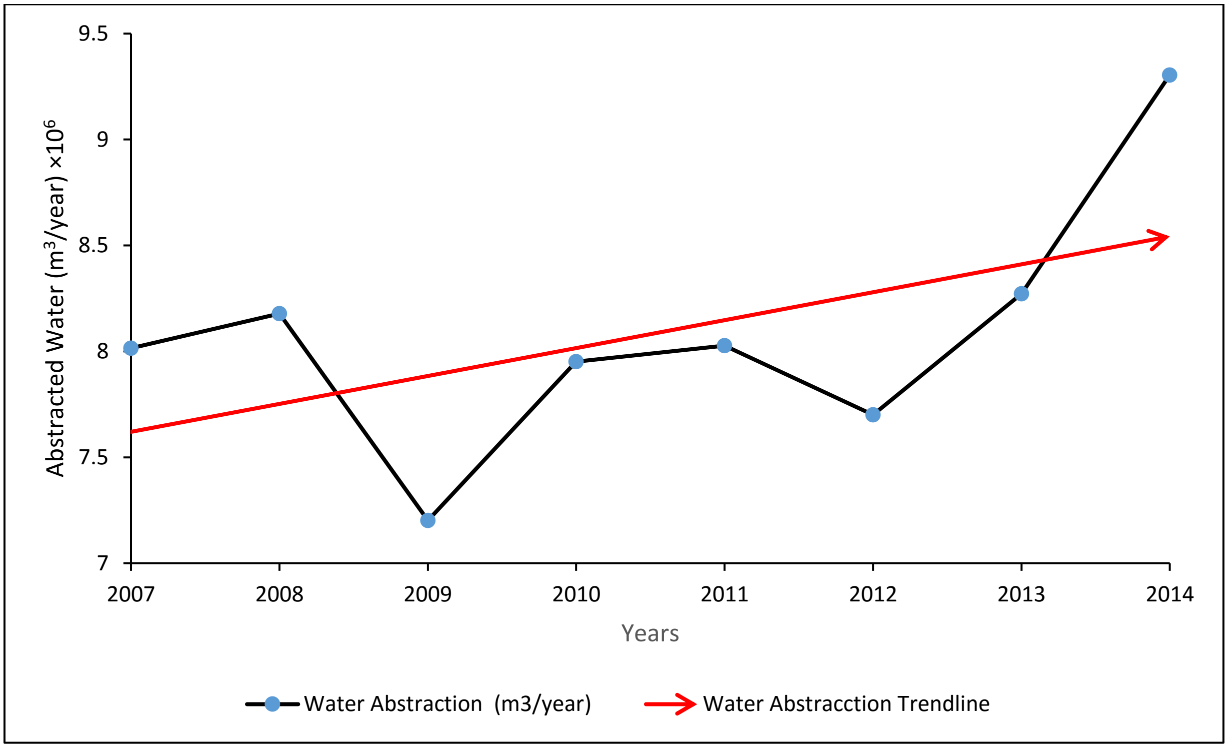


Figure 4.1: Annual Water Abstraction Trend from Thiba River between 2007 to 2014

Within the eight years under examination for this study, the water abstraction pattern indicated that the highest water abstraction was experienced in the dry months of January to February and June to October as shown in Figure 4.2 where the irrigation water demand was highest.

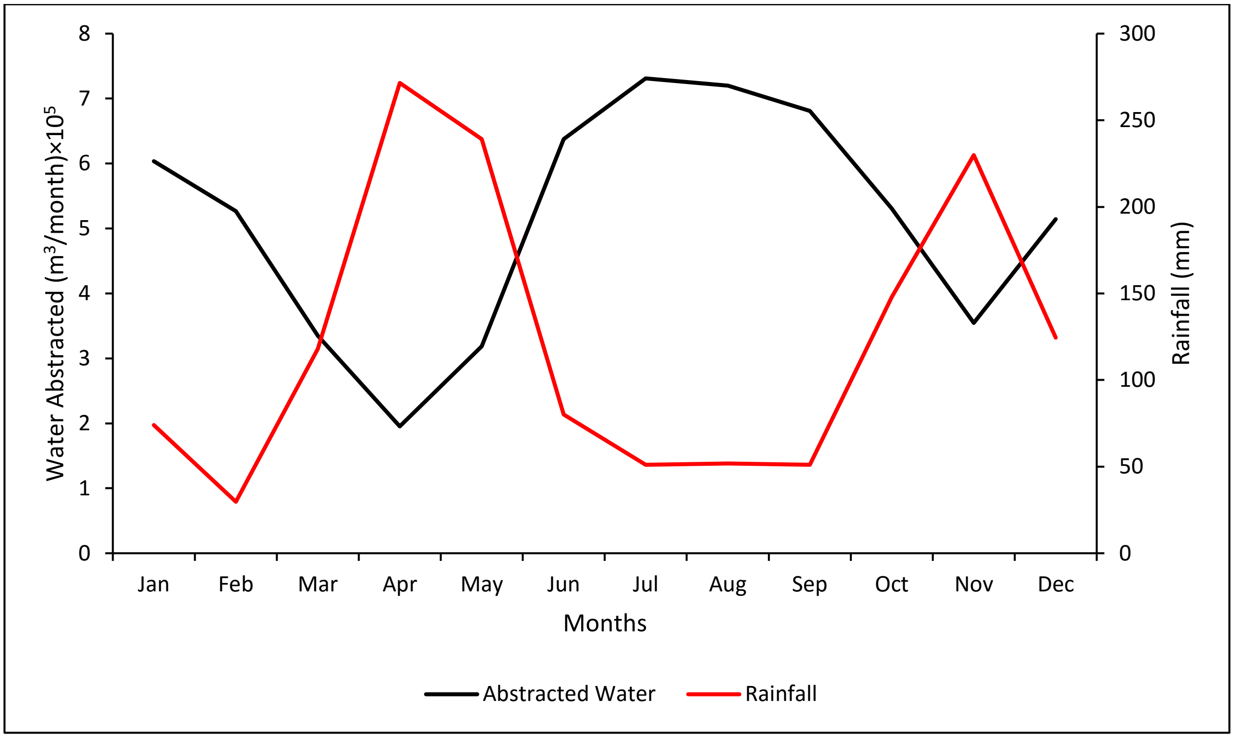


Figure 4.2: Comparison of Monthly Average Water Abstraction and Rainfall Trends from 2007 to 2014

A plot of the correlation between streamflow and Agricultural water abstraction from 2007 to 2014 gave a decreasing trend such that, as more water was abstracted, the streamflow reduced as shown in Figure 4.3. Water abstraction analysis revealed that about 0.23m^3/s (approximately 20000m^3/day) is abstracted during the dry seasons whereas 0.06m^3/s (approximately 5000m^3/day) of the river's flow is abstracted during the wet seasons. This represented about 35% of the dry season flow and only 3% of the wet season flow was abstracted from the Thiba River.

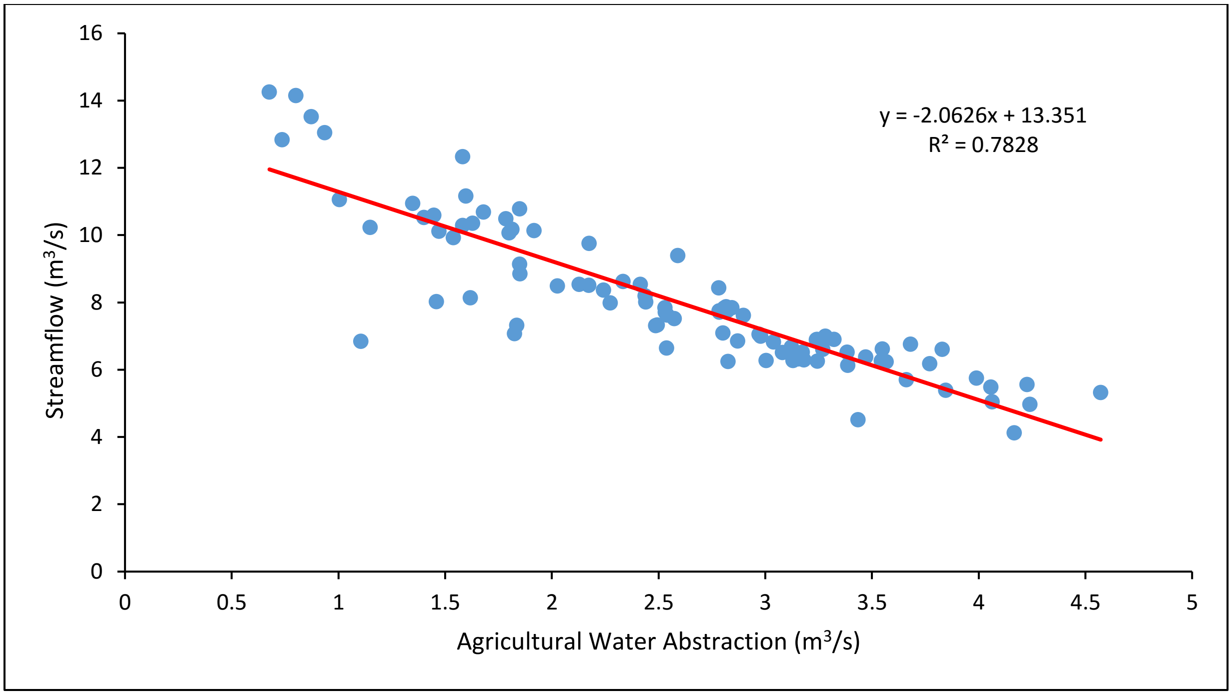


Figure 4.3: Correlation between Agricultural Water Abstraction and Streamflow

In another study carried by Ngigi *et al.* (2007) in Ewaso Ng'iro River that displayed similar agricultural water abstraction patterns as Thiba River, it was found that the dry months consisted mainly of the base flow which was derived from groundwater sources. Irrigation water abstractions have been identified as one of the main contributing factors to reduce river flows, especially during the dry periods when many farmers along the streams abstract water illegally and uncontrollably without due regard to downstream water users. Thus, the irrigation water supply in the dry seasons' river abstraction was so much increased. The situation was further aggravated by land use changes. The water abstraction resulted to decline in water flow by 30% between 1960 and 2005 (Aeschbacher *et al.*, 2005). A water assessment in the river by Ngigi *et al.* (2007) found that about 62 % of dry season flow and 43% of wet season flow is abstracted from Naro Moru river just before the confluence with Ewaso Ng'iro. These findings of this current study whereby 35% of dry season flows and 3% of wet season flows were abstracted from Thiba River basin was similar to their studies.

The correlation test of the agricultural water abstraction and streamflow of Thiba River using Spearman's Rank gave an inverse (negative) correlation with an r value of 0.88. This was a very strong and significant correlation between the two variables with a very small p-value of 0.0002. The null hypothesis was therefore rejected at a 5% confidence level, hence there existed a very significant correlation between streamflow and agricultural water abstraction. This showed that as the agricultural water abstraction increased, the streamflows reduced. The coefficient of determination R^2 was 0.78 as shown in Figure 4.3 and the regression equation of the correlation test was given by the relation:

$$y = -2.062x + 13.351 \tag{4.1}$$

It was thus concluded that agricultural water abstraction was inversely correlated to streamflow in Thiba River Watershed.

According to IFAD/UNEP/GEF (2004), the increased irrigation water demand along the slopes of Mt. Kenya was reported to be for supporting horticultural farming in the region. The increased river water usage in the upstream areas has affected the water availability in the downstream areas leading to water conflicts in the region.

4.2. Variation in Rainfall and Streamflow Results

The relationship between monthly stream discharge at the outlet of the Thiba River Watershed and average monthly rainfall was investigated to greater depth using regression analyses as shown in Figure 4.4. The results of the regression analysis gave an average but significant relationship between daily rainfall and daily streamflow. The value of R^2 which represents the coefficient of determination was 0.42. This showed that 42% of the variation between rainfall and streamflow was somehow related. This value represented a relationship that was moderately average, however the p-value was 0.008 which represents a rather significant relationship. The regression equation was given by the relation:

$$y = 1.2749x + 6.1419 \tag{4.2}$$

From the rainfall trends within the catchment represented in Figure 4.5, in all the three stations the rainfall analysis shows a decreasing trend. This decrease is however minimal but it has in some way also affected the streamflow at the Thiba River Watershed’s outlet. This declining rainfall in the region could be attributed to several factors among them climate change and land use changes that has seen majorly the forest land being converted to agricultural lands.

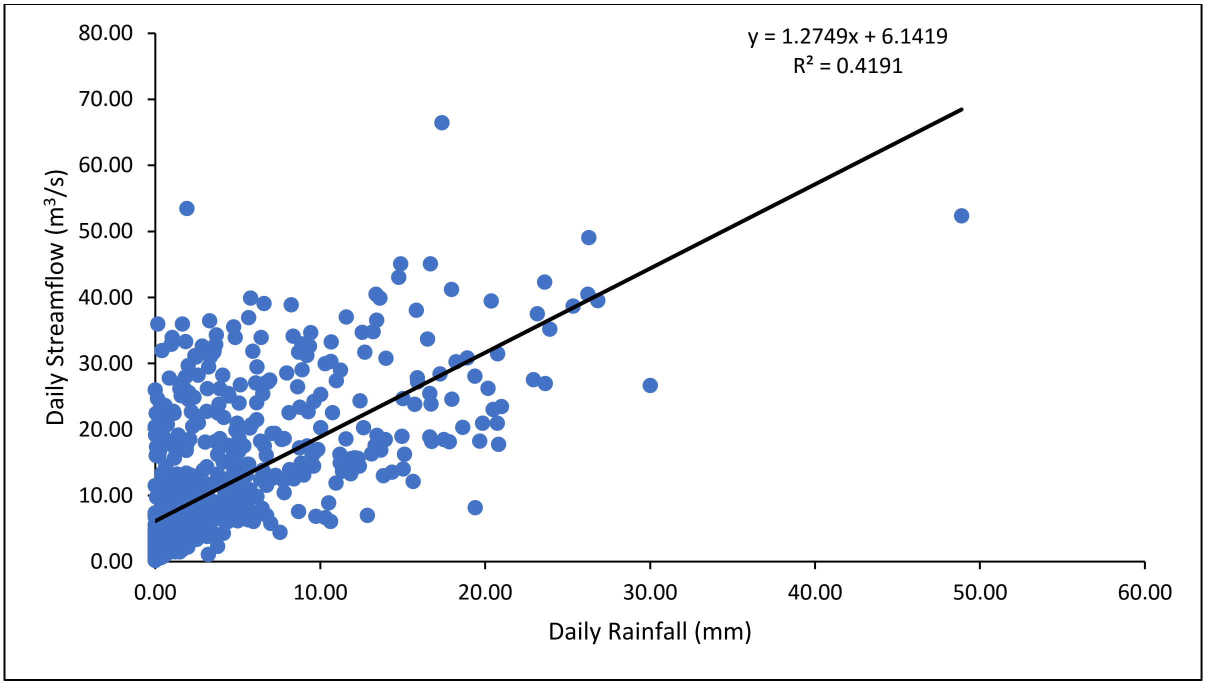


Figure 4.4: Regression Analysis Plot between the Daily Streamflows and Average Daily Rainfall Data

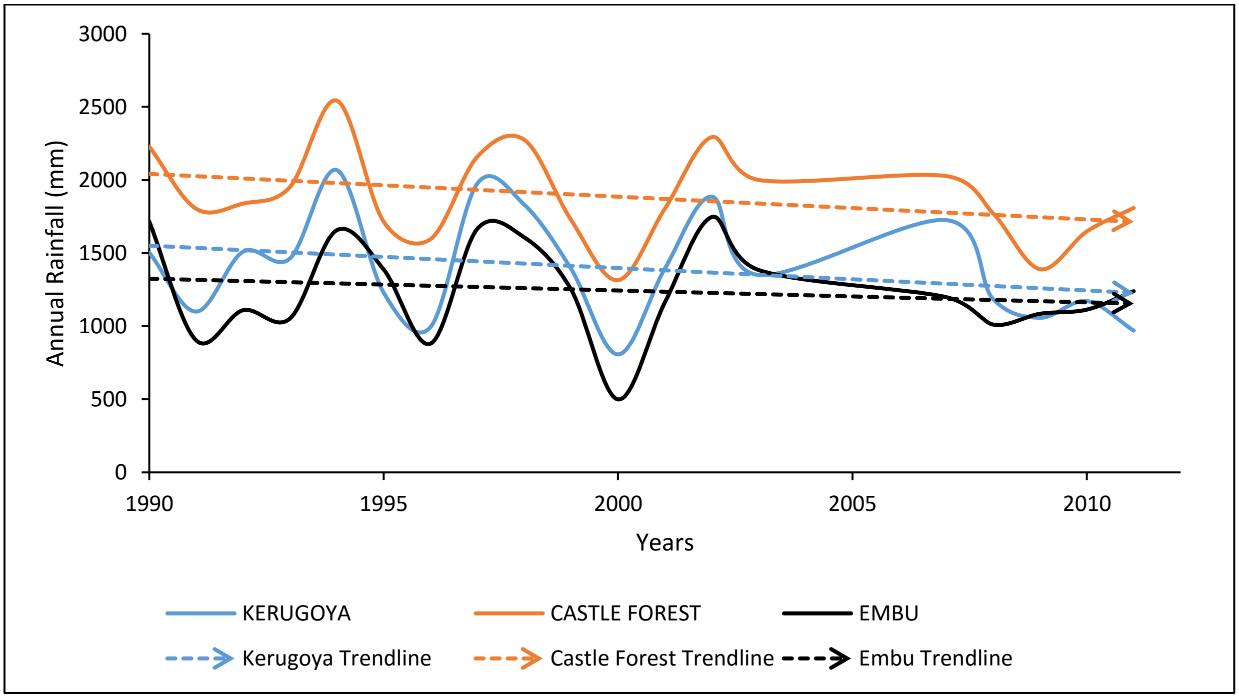


Figure 4.5: Annual rainfall trend analysis for Castle Forest, Kerugoya and Embu Rain Gauge Stations

Similarly, just as the rainfall trend analysis, the discharge trend analysis also exhibits a decreasing trend from 2000 to 2009. The regression relationship of the discharge trend is represented by the equation shown in Figure 4.6 using the relation:

$$y = -0.5542x + 30.995 \quad (4.3)$$

The decrease in discharge could be attributed to either decrease in rainfall or increased water abstraction from the river due to reduced rainfalls. However, it must be noted that despite the decreasing trend of the discharge, it also keeps on fluctuating from low to high, year to year, depending on the available rainfall for that particular year and the level of water abstraction from Thiba River.

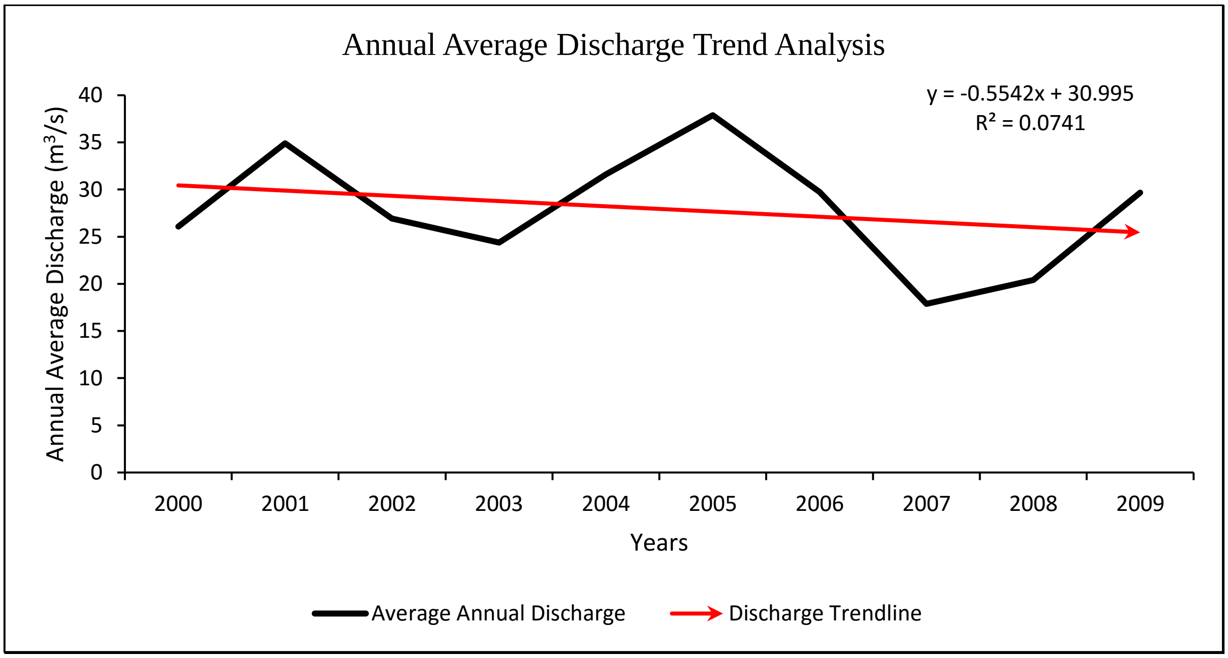


Figure 4.6: Annual Average Discharge Trend Analysis from 2000 to 2009

There is also a good agreement between observed rainfall and the simulated data that was later used in the modelling process. From the regression analyses carried out within the three station good correlation values were obtained which indicated that the data was best suited for the simulation processes. The comparison between the simulated and observed data for Castle forest, Kerugoya and Embu gave correlation values of r as 0.74, 0.71, and 0.80 respectively. The result of the regression analysis for each of the three stations is provided in Figure 4.7. The correlation values presented above were as a result of obtaining the square root of the R^2 value that was obtained during the process of carrying out regression analysis. Additionally, each of the three stations have the regression formulas that could be used to obtain future data.

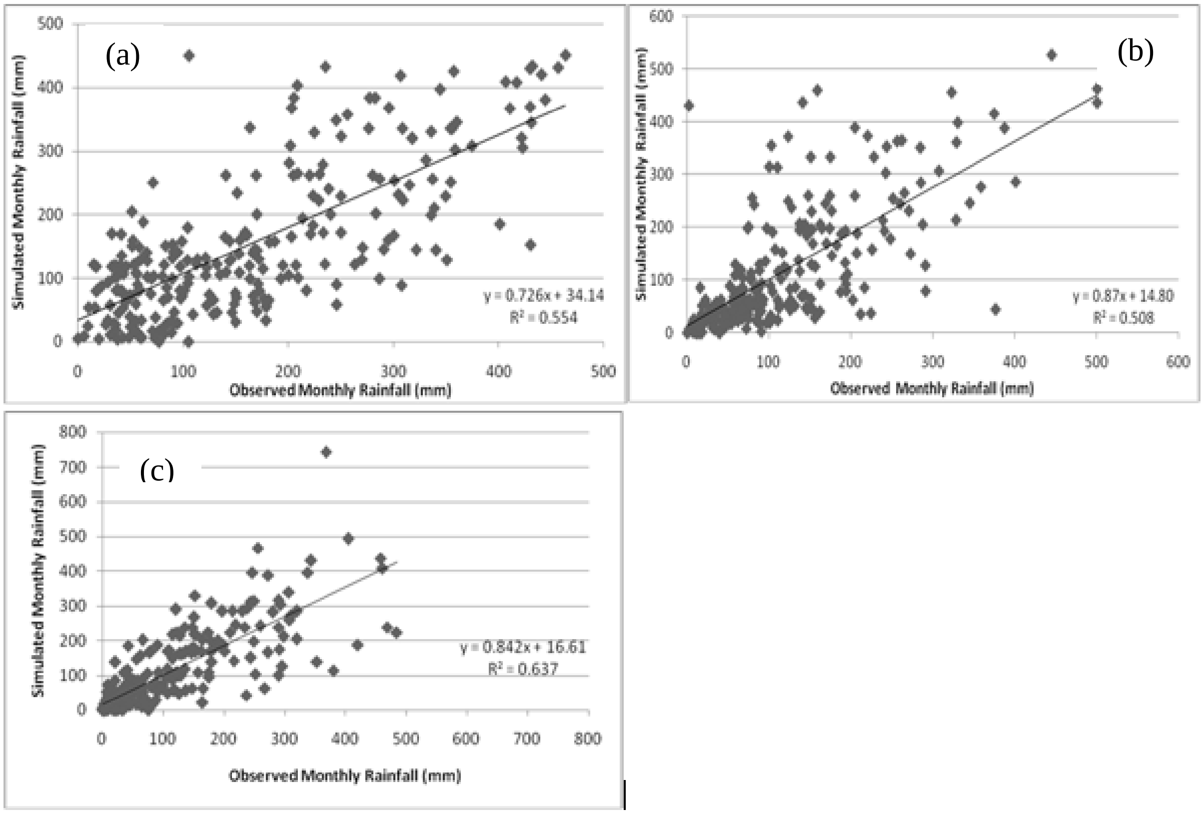


Figure 4.7: Regression Analyses of Observed and Simulated Monthly Rainfall Data for (a) Castle Forest, (b) Kerugoya and (c) Embu

4.3. Land Use Change Analysis in Thiba River Watershed

In the analysis of land use in Thiba River Watershed, the change detection was determined using the comparison statistics whereby the percentage of each land use area was obtained. Thereafter, the areal land use of each classification was compared over the set period of time. Thiba River Watershed has experienced significant spatial land use changes between 2004 and 2014. The major land use activities include agricultural activities and forest area accounting for almost 95% of the watershed. The Thiba River Watershed land uses were classified into eight categories using ArcGIS 10.2 as illustrated in Figure 4.8. The land use changes analysis in terms of percentages between 2004 to 2014 were presented in Table 4.1. Further comparison of the land use change from 2004 to 2014 were also presented as shown in Figure 4.9.

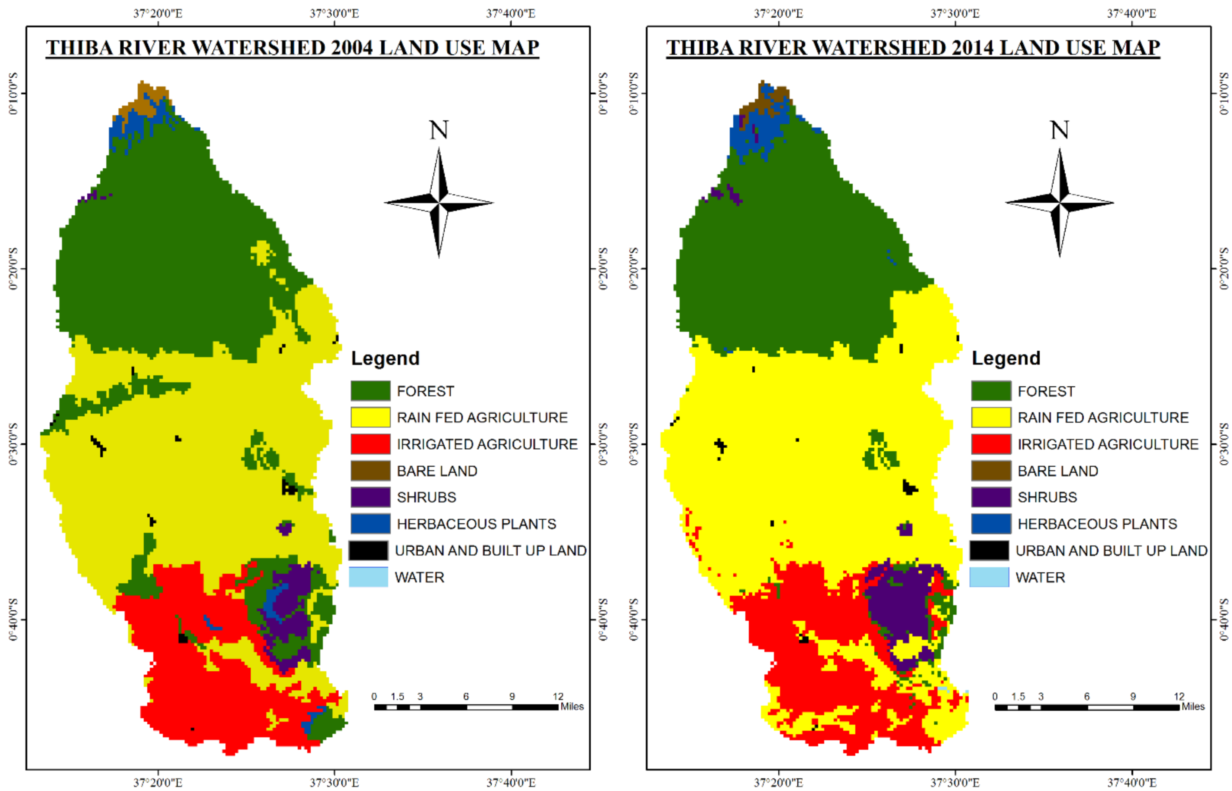


Figure 4.8: Thiba River Watershed Spatial Distribution of Land Use Maps for 2004 and 2014.

For the 2014 land use, which was used to represent the most current state of the study area, the major land use activity was rain fed agricultural farming, which included crops such as maize, coffee and tea. Around 15% of the watershed was used for irrigated agriculture of which paddy rice farming in Mwea forms a major part. Horticultural crops also form part of the irrigated crops. The forest region around Mt. Kenya covered almost a third of the watershed. This watershed could thus be rightfully categorized as an agricultural area since over 65% was agricultural land. The tabulated analysis in Table 4.1 show that between 2004 and 2014, there was a decrease in forest cover by 6.2%. This reduction in forested area could be attributed to clearing of the forests in order to create room for agricultural activities, residential areas and to some smaller extent, the increase in population that has led to increased demand of timber and fuel. Another factor that could have led to the reduction in forested land could be as a result of increase in both rain fed and irrigated agricultural land since within the same period, the rain fed agricultural land increased by almost 5% whereas the irrigated agricultural increased by slightly over 1% as it could be seen from the land use maps of 2004 and 2014.

Table 4.1: Land Use Change Analysis from 2004 to 2014 in Thiba River Watershed

Type of Land Use	Area (Ha) in 2004	%Area in 2004	Area (Ha) in 2014	% Area in 2014	2004-2014 % Change	Area Change (Ha)
FOREST	59347.49	36.01	49137.03	29.82	-6.20	-10210.46
RAIN-FED AGRICULTURE	74977.73	45.50	83199.20	50.48	4.99	8221.47
IRRIGATED AGRICULTURE	23217.75	14.09	24972.57	15.15	1.07	1754.82
BARE LAND	1064.08	0.65	923.30	0.56	-0.09	-140.78
SHRUBS	3534.56	2.14	3520.85	2.14	-0.01	-13.71
HERBACEOUS PLANTS	2083.16	1.26	2376.73	1.44	0.18	293.57
URBAN AREA	567.18	0.34	664.17	0.40	0.06	96.99
WATER	7.99	0.01	6.09	0.01	0.00	-1.90
TOTAL	164799.94	100.00	164799.94	100.00	0.00	0.00

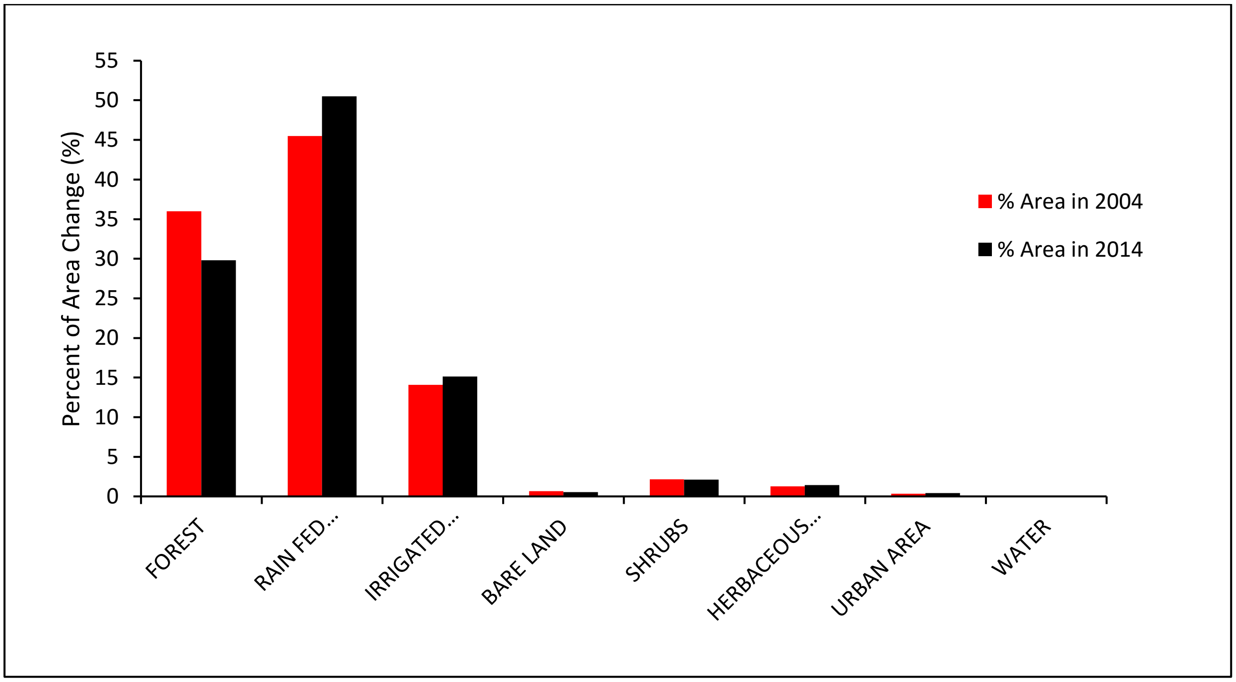


Figure 4.9: Land Use Change Detection in Thiba River Watershed from 2004 to 2014

It was also observed that the area under irrigated agriculture had increased by 1.07% between 2004 and 2014. This was most likely to be the region under which the expansion of Mwea Irrigation Scheme was done. This smaller increased area of the watershed represented over 1750 ha area of the scheme that has been expanded for paddy rice production. This increase could be attributed to a majority of the farmers at the lower elevations of the watershed turning to rice production, although initially the farmers depended on rain fed agriculture to grow maize. This is as a result of the high profitability of rice compared to maize farming. Rain fed agricultural land area was the most dominant land use within the watershed in both years accounting for about 45% in 2004 and 50% in 2014. This was as a result of high rainfall in the upper region of the study area, thus the farmers rarely depend on irrigation but receives reliable relief rainfall from Mt. Kenya throughout the year. However, those practicing rain fed agriculture in the southern region simply do it for subsistence crops only unlike those in the upper region who also plant commercial crops through rain fed agriculture.

From the analysis, the result show that there has been great conversion of forested land to give way to agricultural land since 2004. This could be attributed to the increased population growth within the rural areas of the Upper Tana Catchment of which Thiba River Watershed falls within. This has led to increased demands for agricultural lands since most of these communities rely on agriculture. Therefore, most of the forested areas were converted to small scale agricultural plots that mostly depended on rainfall for food production. In most of these areas, the farmers generally adopt unsustainable agricultural practices thus leading to lots of erosion and sedimentation of the rivers and streams. According to Kitheka and Ongwenyi (2002), some of their practices such as continuous tillage creates large bare land and thus may at times contribute to increased runoff volume.

In another study conducted by Ngigi *et al*. (2007), it was observed the agricultural intensification was increased to unprecedented rates as a result of high population growth in some parts of the Ewaso Ng'iro river basin. The same study additionally noted that land use changes led to reduced river flows, environmental degradation and a decline in agricultural production. In another study on land use land cover changes carried out by Kirui (2008) in the Upper Molo Catchment, it was found that the area covered by forested land was reduced by 48% between 1986 to 2001 due to encroachment by the local farmers in search for more agricultural land. The study concluded that the high demand for agricultural land in that area was as a result of increased population. These studies show similarities with this study as would later be discussed in the impacts of agricultural expansion on the flow of Thiba River.

4.4. Simulation of Thiba River Streamflow Using HEC-HMS

4.4.1 Model simulation results

The initial parameters that were obtained in the HEC-GeoHMS were as illustrated in Table 4.2. However, simulations carried out using these parameters did not provide a reasonable hydrograph that should have had its observed and simulated flows close to one another. This could be because of the merging of the 24 sub basins and adopting their averages for the simulation process.

Table 4.2: Initial Parameters from HEC-GeoHMS Used in the HEC-HMS Model

Parameter Name	Initial Parameters	Optimized Parameters
Curve Number (for 2004 Land Use)	67.10	35.00
SCS Lag Time	318.60 minutes	662.04
Initial Abstraction	0.10 mm	0.01mm
Muskingum X value	0.20	0.17
Muskingum K value	5.31 hours	26.77
Basin Reach	2.00	1.00
SCS CN - Curve Number Scale Factor	1.00	0.01
SCS CN - Initial Abstraction Scale Factor	0.10	100.00

The model was run based on a daily time step for the period between 01/01/2000 to 31/12/2009. The parameters obtained from the model calibration and validation were used to run the simulations. The hydrograph comparison results of the observed discharges and simulated discharges for the simulation were presented as shown in Figure 4.10

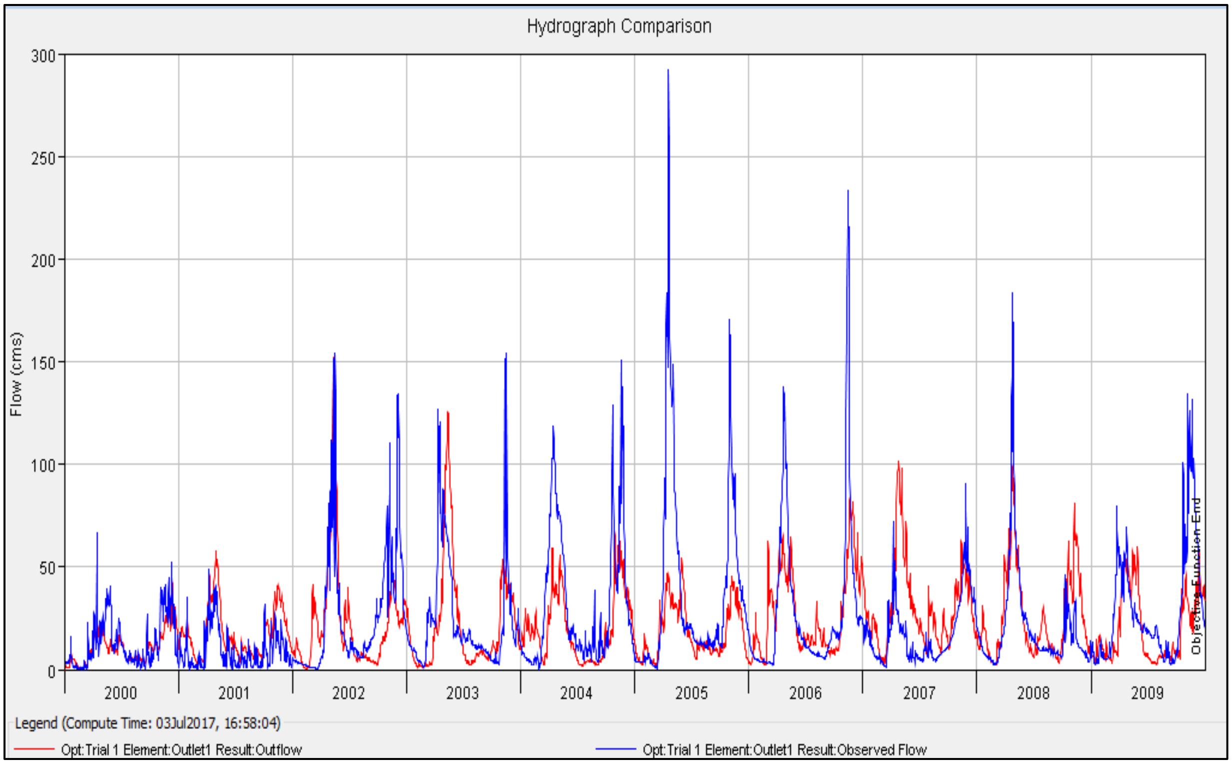


Figure 4.10: Thiba River Streamflow Simulation from 2000 to 2009

From the hydrographs, the observed values exceeded the simulated values by 7.55%. The observed discharge volume was 7058.28mm whereas the simulated discharge was 6525.38mm. This is a rather smaller margin and therefore the simulation was considered reasonable and acceptable. These results were within the permissible limits since the difference in the observed and simulated did not exceed the 10% which is acceptable. These results are close to those attained by Hashmi (2005) when studying rainfall – runoff modelling from Kaha hill torrent watershed in Pakistan where a difference of 8.2% was considered acceptable. However, as had been expected, the HEC-HMS model underestimated most of the peak flows and low flows as can be observed in Figure 4.10.

The HEC-HMS and HEC-GeoHMS modelling tools used for this study were very useful in analyzing the impacts of land use changes especially agricultural expansion within the watershed. There integration with ArcGIS provided a better platform to manipulate the various land use data for the study. The model proved to be very helpful in carrying out hydrological simulations and can thus be trusted for use in other watersheds in the region.

4.4.2 Model calibration results

Firstly, the initial parameters shown in Table 4.2 were used to calibrate the model. These parameters produced unacceptable streamflow results with a very low NSE value of -42. The best calibration result that was obtained had an NSE value of 0.5 which was considered acceptable since it lied in the range of between 0 and 1. These results were similar to those obtained by Yassin *et al*. (2015), where they were modelling hill torrents in Pakistan using HEC-GeoHMS and HEC-HMS and found a calibration value of 0.54 and considered it as being acceptable. Errors in the calibration process could be as a result of the observed data containing several missing values which had to be filled before being used in the process. It could also be due the simplification that was done on the sub basins by merging all the 24 and only using their averages. It was therefore concluded that the calibration results were acceptable since it fell within recommended range of NSE. The results of the calibration process were as shown in Figures 4.11 and 4.12.

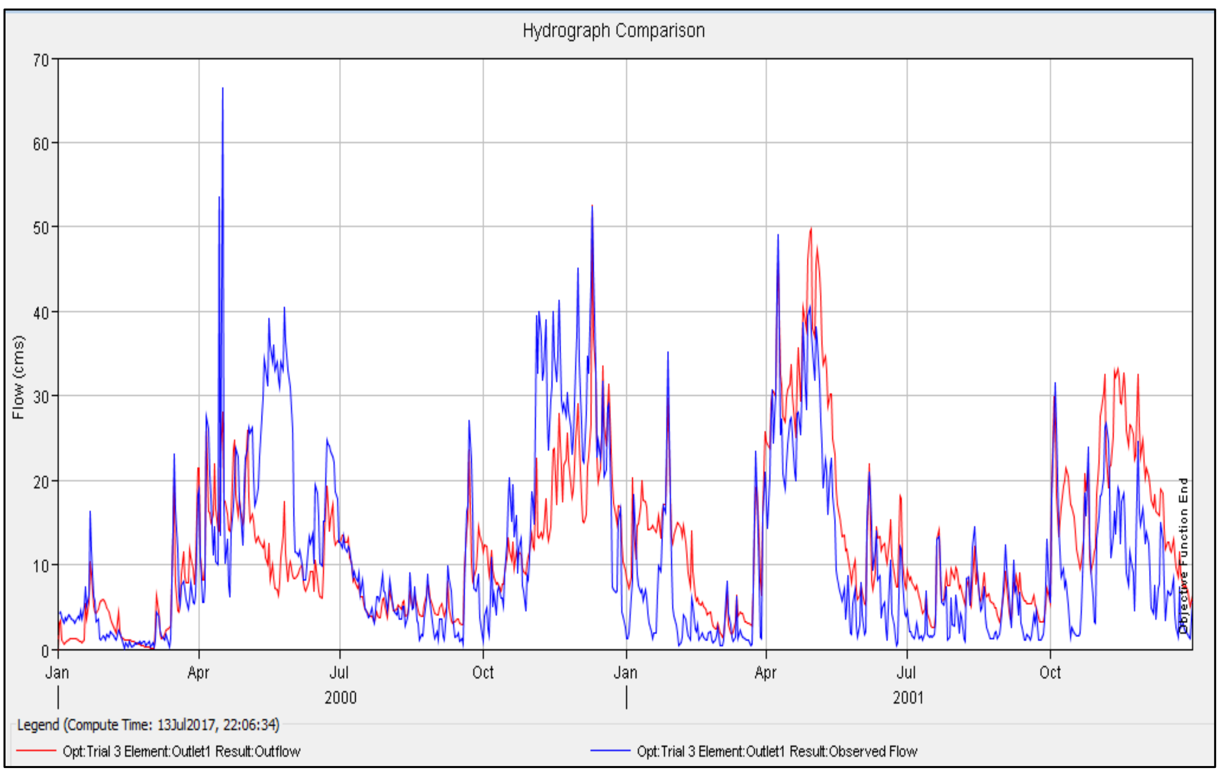
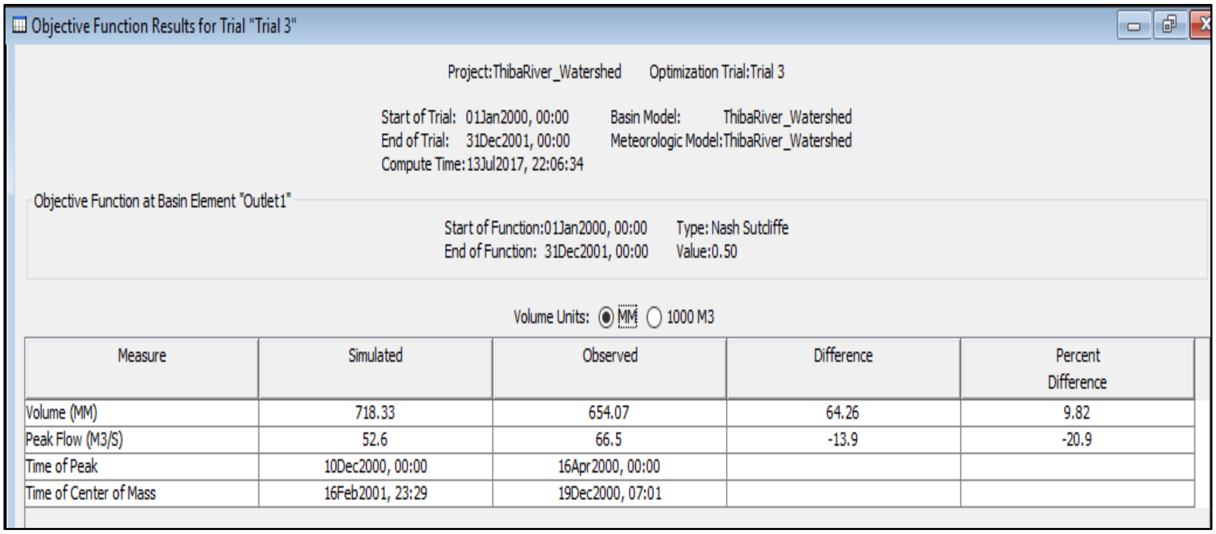


Figure 4.11: Model Calibration Hydrograph for the Period between 2000 to 2001



Objective Function Results for Trial "Trial 3"

Project:ThibaRiver_Watershed Optimization Trial:Trial 3

Start of Trial: 01Jan2000, 00:00 Basin Model: ThibaRiver_Watershed
End of Trial: 31Dec2001, 00:00 Meteorologic Model:ThibaRiver_Watershed
Compute Time:13Jul2017, 22:06:34

Objective Function at Basin Element "Outlet1"

Start of Function:01Jan2000, 00:00 Type: Nash Sutcliffe
End of Function: 31Dec2001, 00:00 Value:0.50

Volume Units: MM 1000 M3

Measure	Simulated	Observed	Difference	Percent Difference
Volume (MM)	718.33	654.07	64.26	9.82
Peak Flow (M3/S)	52.6	66.5	-13.9	-20.9
Time of Peak	10Dec2000, 00:00	16Apr2000, 00:00		
Time of Center of Mass	16Feb2001, 23:29	19Dec2000, 07:01		

Figure 4.12: Summary of the Objective Function Results for the Model Calibration

4.4.3 Model validation results

The model validation process was carried out for the period between 1/1/2002 to 31/12/2003 which was outside the period when the model was calibrated. The optimized parameters shown in Table 4.1 were used to carry out further simulations to assess the model performance. The model validation showed a good NSE value of 0.31 which was also acceptable since it was between 0 and 1. In the research carried by Yassin *et al*. (2015) in Pakistan, the validation results were also less than the calibration results with an NSE value of 0.44. This they attributed to the fact that the rainfall data did not represent the entire watershed since there was only one station. They further recommended for the installation at least 4 to 5 rain gauge stations so as to meet international standards and improve on the modelling accuracy in future. The reduction in NSE value from 0.50 to 0.31 could have been as a result of errors in the rainfall and streamflow data due to several missing data. Another factor that could have led to this reduction could be as a result of merging the sub basins in order to simplify the simulation process. The results of the model validation process were as shown in Figures 4.13 and Figure 4.14.

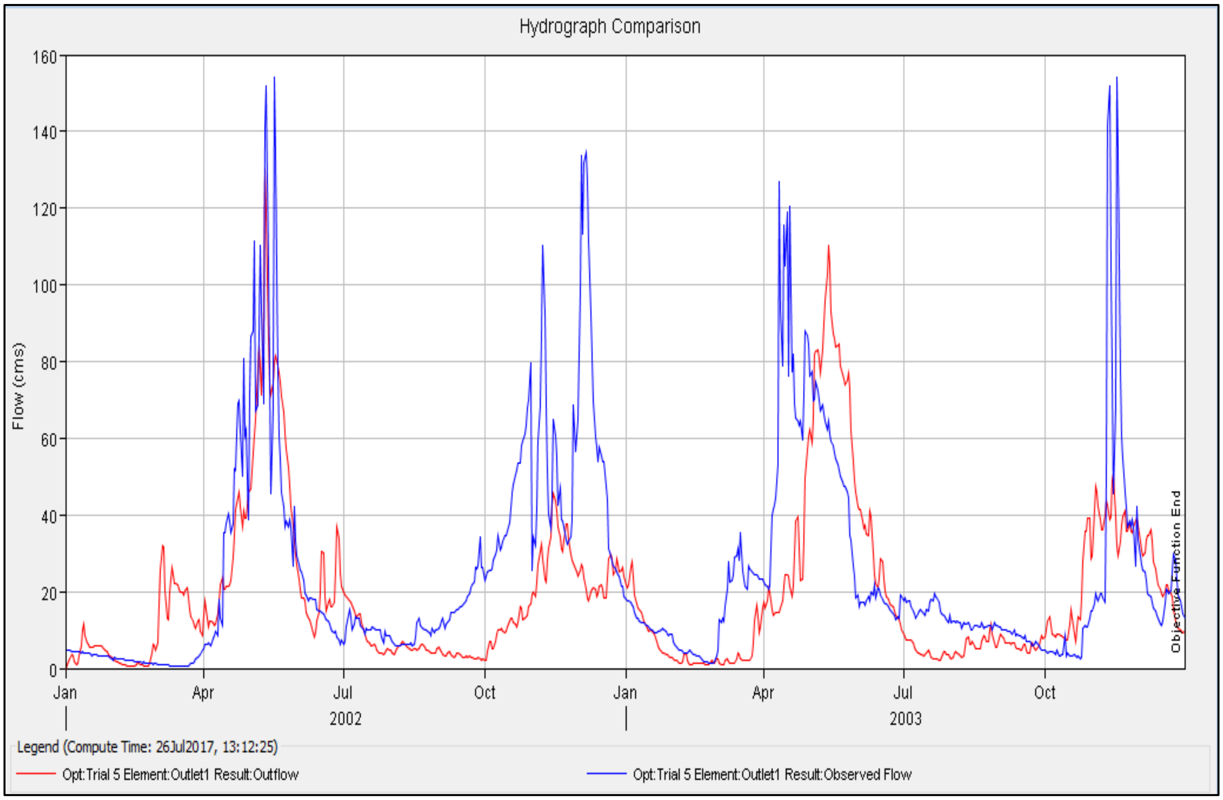


Figure 4.13: Model Validation Hydrograph for the Period between 2002 to 2003

Project:ThibaRiver_Watershed   Optimization Trial:Trial 5

Start of Trial: 01Jan2002, 00:00   Basin Model: ThibaRiver_Watershed
End of Trial: 31Dec2003, 00:00   Meteorologic Model:ThibaRiver_Watershed
Compute Time:26Jul2017, 13:12:25

Objective Function at Basin Element "Outlet1"

Start of Function:01Jan2002, 00:00   Type: Nash Sutcliffe
End of Function: 31Dec2003, 00:00   Value:0.31

Volume Units: (•) MM ( ) 1000 M3

Measure	Simulated	Observed	Difference	Percent Difference
Volume (MM)	1127.91	1501.63	-373.72	-24.89
Peak Flow (M3/S)	84.5	154.3	-69.8	-45.3
Time of Peak	13May2003, 00:00	17Nov2003, 00:00		
Time of Center of Mass	20Jan2004, 09:30	03Feb2004, 22:01		

Figure 4.14: Objective Function Summary Results for the Model Validation

4.5. Future Land Use Scenario Development Results

In the development of the first scenario, the land use map for 2014 was reclassified into four categories of water, forest, residential area and agricultural land as shown in Figure 4.15. The four land use areas and their respective population density ranges according to cross comparison of both the 2014 land use polygon and the 2009 population density grid within the study area were as shown in Table 4.3. The agricultural water demand for the region in 2009 was about 7.2 million m^3 whereas in 2014 it was about 9.3 million m^3. These values were obtained from the water abstraction data of 2009 and 2014 discussed in the section 4.1 of this chapter four (Figure 4.1). The population density ranges presented in Table 4.4 proposed for each land use in this study area showed that approximately 75% of agricultural area and 80% of forest area in the observed 2014 land use polygon lied in their proposed population density ranges thus supporting the validity of these ranges.

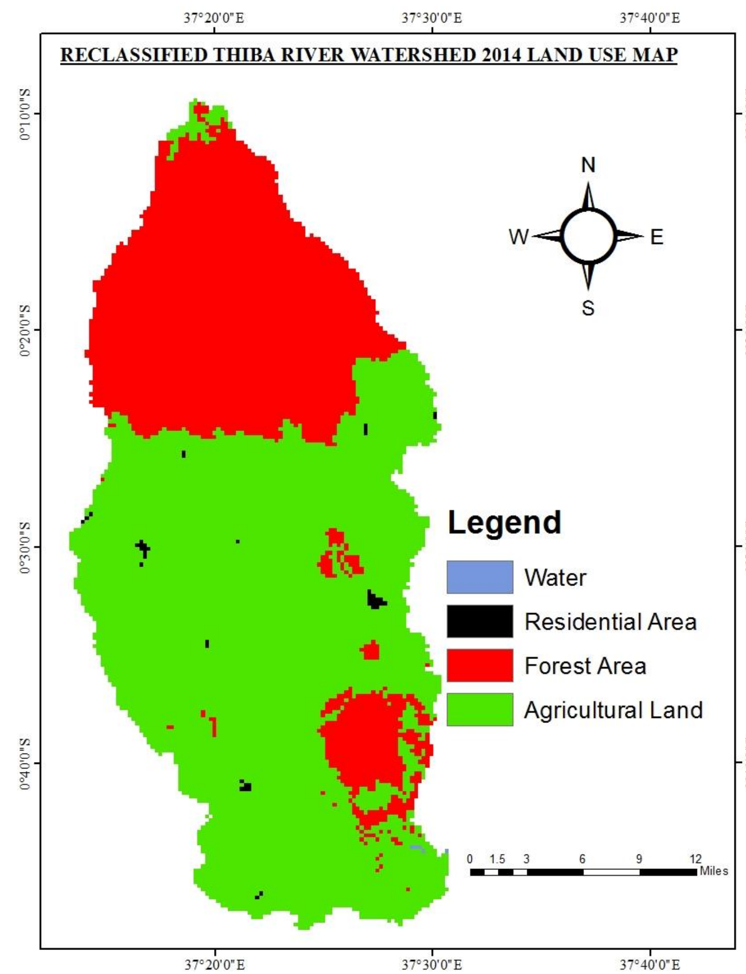


Figure 4.15: Reclassified 2014 Land Use Map for Thiba River Watershed

Table 4.3: Reclassified 2014 Land Use Areas and their respective Population Densities

Land Use Category	Land Use Areas (km^2) in 2014	Land Use Area % in 2014	Population Density Range (Persons/km^2)
Water	0.06	0.01	0
Forest	550.35	33.40	0 - 30
Residential Area	6.64	0.40	Over 300
Agricultural Land	1090.95	66.20	30 - 300

From the results given in Tables 4.3, 4.4 and 4.5, it is shown that the projected land use changes especially those related to increase in agricultural development would affect the water demand within the study area. The population of Thiba River Watershed were as presented in Table 4.4. Using the results of these population changes, the projected water demand for the watershed was determined.

Table 4.4: Past and Projected Population of Thiba River Watershed

Year	Total Population	Population density (persons/km^2)
1999	262361	159.20
2009	301584	183.00
2030	409198	248.30
2060	562956	341.60

From the agricultural water abstraction in 2014 shown in Figure 4.1 and the 2014 land use polygon shown in Figure 4.15, the future agricultural water demand in 2030 and 2060 were determined and presented as shown in Table 4.5.

Table 4.5: Projected Agricultural Water Demand based on The Future Population Increase

Year	Population density	Water Demand (Mm^3/year)
2009	183.0	7.2
2014	198.5	9.3
2030	248.3	11.6
2060	341.6	16.0

The population change analysis show that the agricultural water demand would increase to 11.6 million m^3 in 2030 and 16 million m^3 in 2060. This represented a 61% and 122% increase in agricultural water demand by 2030 and 2060 respectively compared to 2009. It also represented a 24% and 72% increase in the 2030 and 2060 agricultural water demand respectively as compared to 2014. This meant that if the water would be abstracted from the Thiba River then its flow would reduce tremendously. Efficient irrigation water usage need to be adopted or other sources of water should be developed to meet this projected increase in agricultural water demand. Additionally, it would also be expected that the water demand for other uses would also increase as the population increased and thus would create a lot of pressure on the Thiba River water if there will be no new water sources developed. This process was based on the assumption that only population would affect the future agricultural water demand. However, it must be noted that other factors including future economic growth and the climate change trends and its inter-seasonal variability would greatly influence the amount of agricultural water required especially during the dry seasons. More water consumption would be expected as the economy and living standards of people grow.

The future land use map for 2030 and 2060 that were input into the HEC-HMS model were developed by using the ranges of the population density and the areas obtained in the 2014 land use map together and then recalculated using the future population densities. The land use map created for 2030 and 2060 had the following new areas illustrated in Table 4.6.

Table 4.6: Projected Land Use Areas for 2030 and 2060 in comparison to 2014.

Land Use Category	**2014**		**2030**		**2060**	
	Areas (km^2)	**Area (%)**	**Area (km^2)**	**Area (%)**	**Area (km^2)**	**Area (%)**
Water	0.06	0.01	0.06	0.01	0.06	0.01
Forest	550.35	33.40	329.60	20.00	164.80	10.00
Residential Area	6.64	0.40	39.60	2.40	82.40	5.00
Agricultural Land	1090.95	66.20	1278.80	77.60	1400.73	85.00

Using these land use changes and the 2009 rainfall data, simulations were conducted using the calibrated model. The simulation results showed that the streamflows decreased by 18% in 2030 and 52% in 2060 as compared to the 2009 streamflows. This decrease in streamflows could be attributed to the increase in water demand due both land use changes and population increase. Increase in residential area which would increase the CN value thus increasing the surface runoff which could have also led to increase in streamflow. However, the increase in residential areas was so negligible compared to increase in agricultural water demand. Reduction of the forest land could have also contributed to an increase in streamflows since there was an increase in the bare created for agricultural purposes thus leading to an increase runoff. However, this was also outdone by the high levels of water abstraction from the river.

In second scenario that used the precipitation change, the annual streamflow increased by 3% and 6% in the year 2030 and 2060 respectively. This could be attributed to the increase in precipitation by 2.5% and 5%. The minimal increase in annual streamflow could have also been due the fact that according to IPCC, East Africa would have increased evapotranspiration rates despite the little increase in precipitation. These would therefore result to either the effects of the increased precipitation being so negligible or sometimes not even felt at all.

In the Third Scenario that combined the projected land use and precipitation changes, the results of the simulation showed almost similar results to those of the first scenario of land use change. This could be because the high increase in water demand in the first scenario overwhelmed the precipitation increase in the second scenario. The simulations showed a decrease in streamflow by 15% and 48% in 2030 and 2060 respectively.

Several assumptions had to made in the development of these scenarios so as to create a simple and practical approach. The use of the same daily distribution rainfall of 2009 to predict the future precipitation is not a realistic scenario. However, its simplification was used to help understand better how the flow changes for each scenario. Due to limited availability of spatial and temporal data in Thiba River Watershed many assumptions and simplifications had to be made. Other assumptions were in situations such as a constant linear population growth rate of 1.7% in order to calculate the future human and agricultural water demands. Based on the above analysis of the three scenarios, the effects of land use change have more impact on the streamflow compared to change in precipitation. This was clearly illustrated when the three scenarios were combined.

Despite having an increase in precipitation, increase in water demand especially agricultural water demand due to population increase have a higher effect on the streamflow since there would be increased abstractions from the river. The analysis shows that the predicted water demand due to land use changes as a result of high population growth in the watershed decreases the streamflow by up to 21% and 58% in 2030 and 2060 respectively whereas the increase in precipitation would increase the streamflow by about 3% and 4% in 2030 and 2060 respectively. The results obtained were similar to those obtained by Kawasaki *et al.* (2010) where the impacts of population growth and land development were had a greater impact on the streamflow change as compared to precipitation in the next 50 years. The graphical illustration of how each scenario responded is as shown in Figure 4.16.

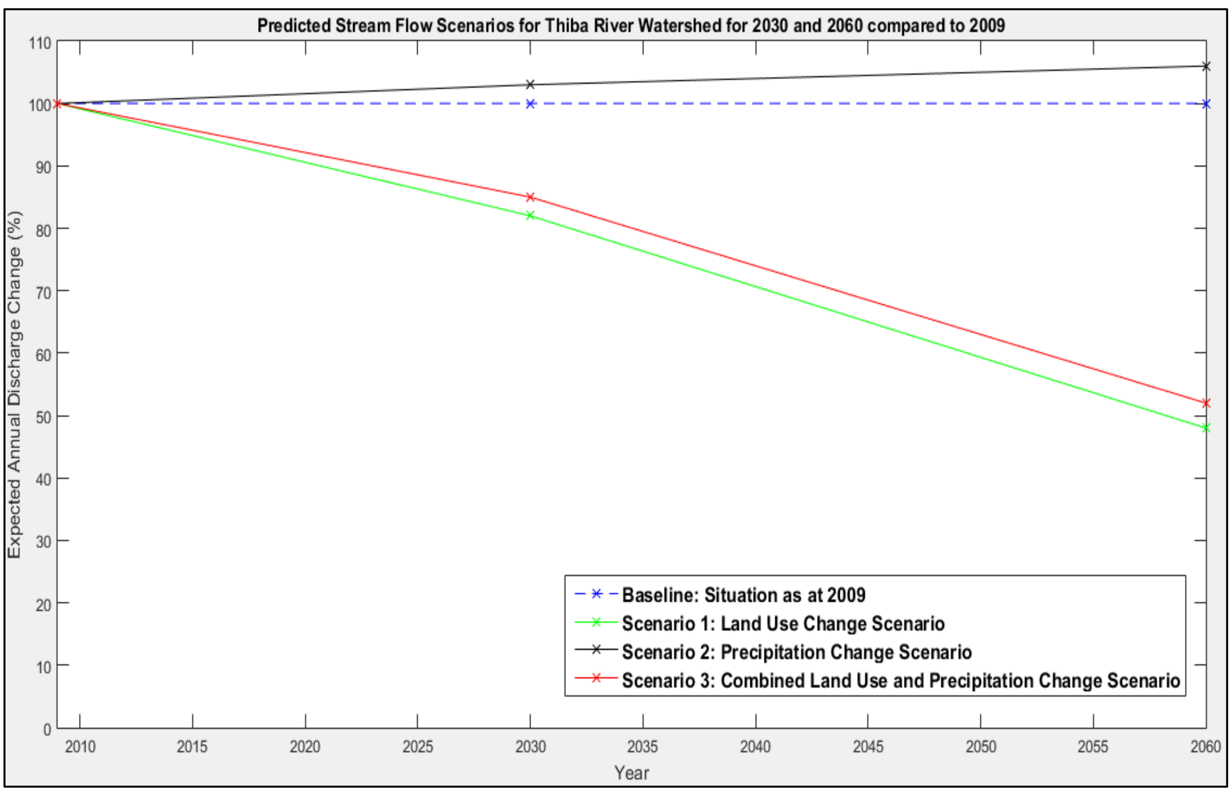


Figure 4.16: Predicted Annual Streamflow Change in Thiba River Watershed for each Scenario in 2030 and 2060 compared to 2009

4.6. Impact of Agricultural Expansion on the Flow of Thiba River

Agricultural expansion represented one of the major land use change in Thiba River watershed. Currently, it was estimated that agricultural land covered over 65% of the study area and this was likely to expand rapidly in the coming years. Firstly, there have been an increasing trend in the water abstraction of Thiba River, this was mainly attributed to the continuous increase in agricultural water demand as a result of agricultural expansion within the watershed. From the 2007 to 2014 water abstraction data analysis, the difference between the lowest abstraction year, which is 2009, and the highest abstraction year, which is 2014, is over 25%. These abstractions have caused Thiba River's streamflow decline by 35% in the dry seasons and 3% in the wet seasons. From the analysis, most abstractions and subsequently reduced flows were experienced in the dry moths of Jan to February and June to October. If these abstraction trends continued in Thiba River, then it was likely not to meet the demand for other water users especially the downstream Kamburu dam and other water users. This could lead to rise of conflicts for the river's water resources since it's the main supplier of water in the region.

In the analysis of the 2004 and 2014 land use data, there was a decline in the forest land by over 6% while the agricultural land had increased by about 5%. This simply could have implied that the forest areas were being cleared to create room for agricultural production. This could have been attributed to several factors with the main one being increasing food demand due to high population in the region. Agriculture formed the main land use activity in the watershed and thus, any significant change as a result of land use could confidently be attributed to be as a result agricultural lands expansion. The results showed that there was a very insignificant variation or even no variation at all in the flows using the two different land use maps. Both simulations had almost similar trends to one another. This could be as a result of the negligible difference in the curve numbers of the two years since the model was only using the CN value to determine the impact of land use change on the streamflow. The average value of the curve number used for the 2004 land use map was 37 whereas that of 2014 land use map was 41. All other parameters as well as the precipitation and discharge in both cases were the same.

Three future scenarios were developed and the model was simulated again using these scenarios. The first scenario involved the use of the 2014 land use map together with the 2009 population grids to try and create the future land use maps for 2030 and 2060. Future population densities were projected using the existing census information from the Kenya National Bureau of statistics (KNBS). When simulations were run using only the 2009 precipitation and the newly created land uses there was a tremendous decline in the streamflow in those future years as was shown in Figure 4.16. The agricultural water demand as a result of the projected population increase was as high as 61% in 2030 and 122% in 2060. The streamflows were projected to reduce by 18% in 2030 and up to 52% in 2060 as compared to the flows in 2009. This scenario showed that population increase played a big role in determining the future water demand. Consequently, the future agricultural water demands would increase since more agricultural areas would be needed to provide food for the increased population. The second scenario projected only the future precipitation in the watershed and used the 2014 land use map to represent the future land uses. The results from this scenario had very little variation from the 2009 baseline as shown in Figure 4.16. However, due an increase in precipitation with no change in land use the scenario projected an increase in the flow of Thiba River. It projected a 3% and 6% increase in streamflow in 2030 and 2060 respectively. These results showed that as long as there is no change in land use and especially agricultural expansion, then the streamflows were likely to either remain the same or slightly increase due to precipitation increase. The final scenario combined both the future precipitation and the future land uses. This scenario had almost similar trends to the first scenario where land use and population changes were used. The third scenario gave 15% and 48% decreases in streamflow in 2030 and 2060 respectively. This therefore demonstrated that the impacts of precipitation are very lower on the flow of a river than the land use changes especially when related to human activities such as population increase and agricultural expansion. The results obtained from the three scenarios indicated that water demands in the watershed would contribute highest to the decline of the streamflow as a result of increased population and land use changes such as agricultural expansion. Precipitation however had a rather minimal impact on the streamflow.

CHAPTER FIVE
CONLUSION AND RECOMMENDATIONS

5.1. Conclusions

Based on the four objectives of this research, the study found out that;

There were higher agricultural water abstractions in the dry seasons as compared to the wet seasons, this therefore led to reduced streamflows during the dry seasons in comparison to the wet seasons. It was thus concluded that agricultural water abstractions have significant impacts on the flow of Thiba River during the dry seasons but the impacts during the wet seasons are insignificant. There existed a strong and significant inverse correlation between agricultural water abstraction and streamflow such that increased water abstraction reduced the streamflow significantly.

Results from the regression analysis of streamflow against rainfall gave a coefficient of determination of 0.42 and correlation coefficient value of 0.65. This demonstrated a moderate but significant relationship between rainfall and streamflow. Both rainfall and streamflow trend analysis showed a decreasing trend for the period between 2000 to 2009.

The study demonstrated that there had been tremendous land use changes within the Thiba River watershed from 2004 to 2014, with the main ones being an increase in agricultural area and decrease in forested area. Land use change analysis showed that most forest lands had been converted to agricultural lands. It was thus concluded that the expansion of agricultural lands was mostly due to the high population increase within the watershed.

The model calibration results provided a reasonable and acceptable NSE value of 0.50. Likewise, the NSE value for the model validation of 0.31 was also acceptable. Simulations carried out on future land use showed that the streamflows would reduce tremendously due to increased water demands as a result of increased agricultural expansion within the watershed. Increase in water demand as a result of increased population and agricultural expansion had a significant impact on the streamflow as compared to changes in precipitation.

5.2. Recommendations

Based on this research the following recommendations were made:

The water demand in the Thiba River Watershed is highest during the dry months when streamflow is at the lowest levels as compared to the wet months. Therefore, in order to maintain the consistent water supply from Thiba river, adaptation planning is required especially during the dry seasons. This could be done by ensuring efficient and effective water use in spite of expanding irrigation and agricultural areas. These adaptation measures must involve policy adjustments such as those involving water allocation to different sectors and agricultural land development.

Data availability was one of the major challenges in this study with several missing streamflow, rainfall and agricultural water abstraction data. It is therefore recommended that the Kenyan government agencies concerned with water resources utilization and management should come together to establish a central water resources database inventory. Modern data collection and storage techniques that could be easily accessed online by any one should be put in place.

It must be noted that increasing population requires additional lands and subsequently water to produce more foods for their sustainability. Additionally, most people are pushed by economic incentives thus expanding their agricultural lands so as to better their standards of living. Better and more water infrastructure such as large reservoir for water harvesting during the rainy season should be developed. The harvested water should then be stored and only to be used during the dry season. The Kamburu hydro power plant should add more water storage infrastructures so as to avoid problems of low power production as a result of water shortages during the dry season. Farmers should also construct smaller reservoirs in their farms whereby they can store water for usage when there is shortage.

There is need to carry out future research to understand the combined effect of climate change and land use changes on the flow of Thiba River as well as their impact on the watershed’s hydrology. Future climatic predications are necessary to forecast on appropriate measures to be undertaken to prevent such effects. Therefore, there is need to carry out further and improved scenario simulations and optimization strategies that take into account upstream-downstream water users.

This could provide valuable information to devise more effective watershed management strategies to sustain the livelihoods of the population in this area. Further research could also be conducted on the possible impacts of the agricultural expansion on the water quality and river ecosystems. This is because, the expansion of agriculture is usually associated with increase in agro-chemicals and fertilizers.

REFERENCES

Acharya, A.K., and Nangia, P. (2004) Population Growth and Changing Land Use Pattern in Mumbai Metropolitan Region of India. *Caminhos de Geografia*, 11(11): 168-185.

Adnan, N., Latif, A., Basarudin, Z., Tahir, W., and Syafiqah, N. (2014). Event-Based Rainfall-Runoff Modelling of the Kelantan River Basin. *Earth and Environmental science,* 18(1): 181-192.

Aeschbacher, J., Liniger, H.P., and Weingartner, R. (2005). River Water Impacts, Shortage in a Highland–Lowland System: A Case Study of the Research, of Water Abstraction in the Mount Kenya Region. *Mountain and Development, 25*(2): 155–162.

Almeida, C.M., Gleriani, J.M., Castejon, E.F., and Soares-Filho, B.S. (2008) Using Neural Networks and Cellular Automata for Modelling Intra-Urban Land-Use Dynamics. *International Journal of Geographical Information Science,* 22(9): 943-963

Artan, B., Asante, K., Smith, J., Pervez, S., Entenmann , D., Verdin, J., and Rowland, J. (2007). Users Manual for the Geospatial Streamflow Model (GeoSFM). U.S.A.: United States Geological Survey (USGS).

ASCE. (1993). Criteria for Evaluation of Watershed Models. *Journal of Irrigation and Drainage Engineering,* 119(3): 429 - 442.

Ashley, R., and Cashman, A. (2006). The Impacts of change on the Long term Future Demands on Water Sector Infrastructure. University of Sheffield, United Kingdom: OECD.

Beyene, T., Lettenmaier, D.P., and Kabat, P. (2010) Hydrologic Impacts of Climate Change on the Nile River basin: Implications of the 2007 IPCC Climate Scenarios. *Climatic Change*, 100: 433-461.

Blackwell Science Limited. (1999). Research in brief 763. *Journal Of Clinical Nursing*,8: 762-763.

Bunyasi, M. M., Onywere, S. M., and Kigomo, M. K. (2013). Sustainable Catchment Management: Assessment of Sedimentation of Masinga Reservoir and its implications on the dam's Hydropower generation capacity. Nairobi, Kenya: Kenyatta university.

Chiew, F., and Siriwardena, L. (2005). Estimation of SIMHYD parameter values for application in ungauged catchments. Congress on Modelling and Simulation (MODSIM 2005), (pp. 2883-2889). Melbourne.

Chiew, F., Peel, M., and Western, A. (2002). Application and testing of the simple rainfall-runoff model SIMHYD in: Mathematical Models of Small Watershed Hydrology and Applications. Littleton, Colorado: Water Resources Publication.

Chow, V.T., Maidment, D.R., and Mays, L.W. (1988) Applied Hydrology. New York: McGraw-Hill.

DeFries, R., and Eshleman, K. N. (2004). Land-Use Change and Hydrologic Processes: A Major Mocus for the Future. *Journal of Hydrological Processes,* 18:2183–2186.

DHI. (2007). MIKE SHE User Manual Voume 1: User Guide. Denmark: Danish Hydraulic Institute.

Emerson, C. H., Welty, C., and Traver, R. G. (2005). Watershed-Scale Evaluation of a System of Storm Water Detention Basins. *Journal of Hydrologic Engineering,* 10(3): 237-242.

FAO. (2016, December 22). AQUASTAT Home. Retrieved from Food and Agricultural Organization of the United Nations www.fao.org/nr/water/aquastat/countries_regions/ken/index.stm

FAO, IIASA, ISRIC, ISSCAS, and JRC. (2012). Harmonized World Soil Database (version 1.2). FAO, Rome, Italy and IIASA, Laxenburg, Austria.

Feyen, L., Vázquez, R., Christiaens, K., Sels, O., and Feyen, J. (2000). Application of a Distributed Physically-Based Hydrological Model to a Medium Size Catchment. *Journal of Hydrology and Earth System Sciences,* 4: 47–63.

Fowler, H. J., Blenkinsop, S., and Tebaldi, C. (2007). Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. *International journal of climatology,* 27(12): 1547-1578.

Fox, J. (1997). Applied Regression Analysis, Linear Models, And Related Methods. Inc.: Sage Publications.

Gao, B., and Yang, D. (2009). Impacts of Climate Variation and Land-Use Change on River Discharge in the Upstream of Miyun Reservoir. Beijing, China: Tsingua University.

Geertsma, R., Wilschut, L.I., and Kauffman, J. H. (2010). Review for the Green Water Credits Pilot Operations in Kenya. Green Water Credits Report 8. ISRIC Report 2010/02. Wageningen, the Netherlands: ISRIC-World Soil Information.

Hashmi, A. K. (2005). Rainfall- Runoff modeling from Kaha Hill Torrent Watershed D. G. Khan District, M.Sc. Thesis of Centre of Excellence in Water Resources Engineering. Lahore: University of Engineering and Technology.

Hoblit, B. C., and Curtis, D. C. (2001). Integrating Radar Rainfall Estimates with Digital Elevation Models and Land Use Data to Create an Accurate Hydrologic Model. Floodplain Management Association Spring 2001 Conference, March 13-16, 2001. San Diego: CA.

Hu , H. H., Kreymborg, L. R., Doeing, B. J., Baron, K. S., and Jutila, S. A. (2006). Gridded Snowmelt and Rainfall-Runoff CWMS Hydrologic Modeling of the Red River of the North Basin. *Journal of Hydrologic Engineering,* 11(2): 91-100.

IPCC (Intergovernmental Panel on Climate Change). (2001). Climate Change 2001, Impacts, Adaption and Vulnerability, Contribution of Working Group II to the Third Assessment Report of the IPCC. ed. by J .J. McCarthy, O. Canziani, N. A. Leary, D. J. Dokken and K.S. White, 31. Cambridge, U.K.: Cambridge University Press.

Kawasaki, A., Takamatsu, M., He, J., Rogers, P., and Herath, S. (2010). An Integrated Approach to Evaluate Potential Impacts of Precipitation and Land-Use Change on Streamflow in Srepok River Basin. *Theory and Application of GIS,* 18 (2): 9-20.

Kenya National Bureau of Statistics (KNBS). (2010). 2009 Kenya Population and Housing Census, Volume 1, Population by administrative Units. Nairobi, Kenya: Kenya National Bureau of Statistics.

Kiem, A.S., Ishidaira, H., Hapuarachchi, H.P., Zhou, M.C., Hirabayashi, Y., and Takeuchi, K. (2008) Future hydro climatology of the Mekong River basin simulated using the high-resolution Japan Meteorological Agency (JMA) AGCM. *Journal of Hydrological Processes,* 22: 1382-1394.

Kiluva, V. M., Mutua, F. M., Makhanu, S. K., and Ong'or, B. I. (2011). Rainfall Runoff Modeling in Yala River basin of Western Kenya. *Journal of Meteorology and Related Sciences,* 10: 28-39.

Kirui, W. K. and M. B. M. (2008). Analysis of Catchment Hydrologic Response Under Changing Land Use : The Case of Upper Molo River Catchment , Kenya. E*uropean International Journal of Applied Science and Technology,* 1(4): 1–25.

Kitheka, J.U., and Ongwenyi, G. S. (2002). The Tana River Basin and the Opportunity for Research on the Land-Ocean Interactions in the Tana Delta. In: African Basins: LOICZ

Global Change Assessment and Synthesis of River Catchment-Coastal Sea Interaction and Human Dimensions, eds., Arthurton, R.S.: 203–209.

Knebl, M. R., Yang , Z. L., Hutchinson, K., and Maidment, D. R. (2005). Regional Scale Flood Modeling Using NEXRAD Rainfall, GIS and HEC-HMS/RAS: A Case Study for the San Antonio River Basin Summer 2002 Storm Event. *Journal of Environmental Management*, 75: 325-336.

Krasovskaia, I. (2002). River Flow Regimes in a Changing Climate. *Journal of Hydrological Sciences*, 47(4): 597-609.

Kuria, J. N., (2004). An Economic Analysis of Rice Production in Mwea Irrigation Scheme, Nairobi, Kenya: University of Nairobi.

Lan, J. (2012). "Evaluation of the Impact of Land Use Change on Streamflow of Monocacy Creek, Northampton County, PA". Dickinson College Honors Theses. Paper 32.

Levesque, E., Anctil, F., and Van Griensven, A. (2008). Evaluation of the Streamflow Simulation by SWAT Model for Two Small Watersheds Under Snowmelt and Rainfall. *Journal of Hydrological Sciences,* 53(5): 961–976.

Liang, M., Chunguang, H., Hongfeng, B., and Lianxi, S. (2016). MIKE SHE Modeling of Ecohydrological Processes: Merits, Applications, and Challenges. *Journal of Ecological Engineering*, 96: 137-149.

Macuacua, E. (2011). Impact of Land Use Change and Increased Agricultural Water Use on Incomati River Flow regime. Zimbabwe: Msc Thesis.

Maingi, P., Hutting, J., Njoroge, C., and Dijkshoorn, K. (2010). “Soil and Terrain Conditions for the Upper Tana River Catchment, Kenya. Green Water Credits Report 11 / ISRIC Report 2010/09.”. Wageningen: ISRIC – World Soil Information.

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I. G., Weaver, A.J., and Zhao, Z.C. (2007) Global Climate Projections. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York,USA.

Muchiri , M. L. (2013). Climate Change Impacts on Water Use Strategies in Mwea Irrigation Scheme,. Kirinyaga County, Kenya: MSc Thesis.

Mutie, S. M., Mati, B., Home, P., Gandain, H., and Gathenya, J. (2006). Evaluating Land Use Change Effects On River Flow Using USGS Geospatial Streamflow Model in Mara River Basin, Kenya. Bonn, Germany: Centre for Remote Sensing of Land surfaces.

Nagasaki, H., Watanabe, K., Ohgai, A., Divigalpitiya, P., and Kondo, A. (2006) Development of a Land Use Planning Support Tool in the Developing Countries. *Theory and Applications of GIS*, 14(2): 85-96.

Nash, J. E. and Sutcliffe, J. V. (1970). River Flow Forecasting Through Conceptual Models, Part I: A Discussion of Principles. *Journal of Hydrology*, 10(3): 282–290.

Ndegwa, M. W. (2014). An Assessment of the Socio- Economic Status of Rice Farmers in Mwea Irrigation Scheme. *Journal Of Advances In Management and Economics*, 3(1): 133-134.

Ngenoh, E., Chelang'a , P. K., and Kirui, L. K. (2014). A Review of Public Irrigation Schemes Funding in Kenya. *Journal of Applied Science and Technology*, 1(5): 137-138.

Ngigi, S. N., Savenije, H. H. G., and Gichuki, F. N. (2007). Land Use Changes and Hydrological Impacts Related to Up-Scaling of Rainwater Harvesting and Management in Upper Ewaso Ng'iro River Basin, Kenya. *Journal of Land Use Policy*, 24(1): 129–140.

NIB. (2016). National Irrigation Board. Retrieved from Mwea Irrigation Scheme: https://www.nib.or.ke/projects/public-irrigation-schemes/mwea-irrigation-scheme

Notter, B., Macmillan, L., Viviroli, D., Weingartner, R., and Liniger, H.-P. (2007). Impacts of Environmental Change on Water Resources in the Mt.Kenya. *Journal of Hydrology*, 343(3): 266-278.

Price, K. (2011). Effects of Watershed Topography, Soils, Land Use, and Climate on Baseflow Hydrology in Humid Regions: A Review. *Progress in Physical Geography*, *35*(4): 465–492.

Pumo, D., Caracciolo, D., Viola, F., and Noto, L. (2016). Climate Change Effects on the Hydrological Regime of Small Non-Perennial River Basins. *Science of the Total Environment*, 542: 76-92.

Razavi , T., Coulibaly, P., and Asce, M. (2013). Streamflow Prediction in Ungauged Basins : Review of Regionalization Methods. *Journal of Hydrologic Engineering*, 3: 958–975.

Refsgaard, J., Storm, B., and Clausen, T. (2010). Système Hydrologique Européen (SHE): Review and perspectives after 30 years' development in distributed physically-based hydrological modelling. *Journal of Hydrological Resources*, 41: 355–377.

Rostamian, R., Jaleh, A., Afyuni, M., Mousavi, S. F., Heidarpour, M., Jalalian, A., and Abbaspour, K. C. (2008). Application of a SWAT Model for Estimating Runoff and Sediment in two Mountainous basins in Central Iran. *Journal of Hydrological Sciences*, 53 (5): 977-98.

Siebert, S., Burke, J., Faures , J. M., Frenken, K., Hoogeveen, J., Döll, P., and Portmann, F. T. (2010). Groundwater use for Irrigation – A Global Inventory. *Journal of Hydrology and Earth Sciences*, 14(10): 1863–1880.

Sivapalan, M., Blöschl, G., Zhang, L., and Vertessy, R. (2003). Downward approach to hydrological prediction. *Journal of Hydrological Processes*, 17(11): 2101-2111.

Siwale, C. (2008). Assessing Upstream and Downstream Interactions in Chalimbana River Catchment, Zambia. University of Zimbabwe: PhD Thesis.

Soil Conservation Service (SCS). (1986). Urban Hydrology for Small Watersheds. Technical Release 55. United States Department of Agriculture Natural Resources Conservation Services Conservation Engineering Division: Washington D.C.

Steinitz, C., Faris, R., Flaxman, M., Karish, K., Mellinger, A.D., Canfield, T., and Sucre, L. (2005) A Delicate Balance: Conservation and Development Scenarios for Panama's Coiba National Park. *Journal of Environment*, 47(5): 24-39.

Stipinovich, A. (2005). Change in Land Cover and Water Abstraction: Modelling Runoff Effects in the Bot River Catchment. University of Stellenbosch.South Africa: MSc Thesis

Tadic, L., and Zdecko, T. (2009). Impacts of Irrigation on the Environment. Ohrid/Macedonia,: International Symposium on Water Management and Hydraulic Engineering.

U. S. Army Corps of Engineers (USACE). (2010a). Hydrologic Modeling System, HEC-HMS User´s Manual, Version 3.5. U.S. Army Corps of Engineers, Hydrologic Engineering Center.

U. S. Army Corps of Engineers (USACE). (2013). Hydrologic Modeling System, HEC-GeoHMS, Version 10.1, Users Guide. U. S. Army Corps of Engineers, Hydrologic Engineering Center.

USDA . (1999). Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys, 436(2). Washington, D.C.: United States Department of Agriculture, Natural Resources Conservation Service.

Van Oel, P. R., Krol, S. M., Hoekstra, A. Y., and De Araujo, C. J. (2010). The Impacts of Upstream water Abstractions on Reservoir Yield: The case of the Oros Reservoir in Brazil. *Journal of Hydrological Sciences*, 53(4): 857-867.

Vilanculos, A. (2005). Management of Olifants Basins Floods: Application of Geospatial Streamflow Model. Maputo, Mozambique.

Wagener, T., Sivapalan, M., Troch, P., and Woods, R. (2007). Catchment classification and hydrologic similarity. *Journal of Geographical Compass*, 1(4): 901–931.

Water Services Trust Fund (WSTF). (2016). Irrigation Potential and Development in Kenya. Nairobi: WSTF.

Wurbs, A., and James, W. P. (2002). Water Resources Enginnering. Prentice Hall.

Xia, L., and Xiaoping, L. (2008) Embedding Sustainable Development Strategies in Agent-Based Models for Use as a Planning Tool. *International Journal of Geographical Information Science*, 22: 21-45.

Yasin, G., Nabi, G., & Randhawa, S. M. (2015). Modeling of Hill Torrent Using HEC Geo-HMS and HEC- HMS Models: A Case Study of Mithawan Watershed. *Pakistan Journal of Meteorology*, 11 (12): 82-93.

Zeng, R., and Cai, X. (2014). Analyzing Streamflow Changes : Irrigation-Enhanced Interaction between Aquifer and Streamflow in the Republican River basin. *Journal of Hydrology and Earth System Sciences*, 18: 493–502.

APPENDIX

SIGNIFICANCE OF SPEARMAN'S RANK CORRELATION

Work out the 'degrees of freedom' you need to use. This is the number of pairs in your sample minus 2 (n-2).

- First plot the results of the obtained ρ on the table.
- If it is below the line marked 5%, then it is possible your result was the product of chance and you must reject the hypothesis.
- If it is above the 0.1% significance level, then we can be 99.9% confident the correlation has not occurred by chance.
- If it is above 1%, but below 0.1%, you can say you are 99% confident.
- If it is above 5%, but below 1%, you can say you are 95% confident (i.e. statistically there is a 5% likelihood the result occurred by chance.

Fig. 1: The significance of the Spearman's rank correlation coefficients and degrees of freedom