HYDROLOGICAL MODELING OF RAINFALL-RUNOFF FOR NYANDO RIVER BASIN

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DECLARATION

I hereby declare that this thesis is my original work and has not been presented for a degree in any other university. All sources of information have been acknowledged.

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This thesis has been submitted for examination with our approval as University supervisors.

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DEDICATION

This work is dedicated to my father Philip Kuria Wainaina for all the support and encouragement he accorded to me as I pursued my studies.

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ABSTRACT

River flooding has been associated with severe social and economic problems throughout the world. While deaths from most natural disasters have declined over the past two decades, loss of lives and property from flooding has increased. Floods occasionally cause disasters in Kenya and the Nyando River basin is among the areas adversely affected. In hydrology, rainfall-runoff models enable users the ability to forecast the runoff from a catchment from the amount of precipitation received by that catchment. This study was conducted with the aim of establishing a hydrological model that can reasonably depict the relationship between rainfall and runoff as a first step to establishing a flood early warning system for the Nyando basin. The study involved the selection of a hydrological model that could be suitably domesticated to the Nyando river basin characteristics to simulate discharge for flood management. The main criteria for the model selection were the nature of basic algorithms, process-based and deterministic approach to input or parameter specification and the spatial representation was to be semi-distributed. In addition, the availability of the required input data and the suitability to flood modelling were considered. HEC-GeoHMS software was used to delineate the Nyando catchment from a 90 m Shuttle Radar Telegraphic Mission DEM and to expediently create hydrological inputs that were used directly with the selected model, HEC-HMS Version 3.1 to model the catchment. The HEC-HMS model was calibrated and validated for the Nyando catchment in the period 1980 to 1983 and 1984 to 1991 respectively. In the calibration of the model, correlation coefficient and the Nush-Sutcliffe efficiencies were same and equal to 0.64 while the BIAS efficiency was 0.002. In validation the correlation coefficient and Nush-Sutcliffe efficiency were equal to 0.66 and the BIAS efficiency was 0.051, values indicating that the model was well optimized. To demonstrate the application of the model, it was used to asses the effects created by the inclusion of two proposed reservoirs on peak discharges for the period 1984 to 1991. The peak outflow which was predicted to be on 01 May 1988 at 104.8m^3/sec was reduced to 91.0 m^3/sec by the inclusion of the two dams. This translated to a reduction of the peak discharge by 13.2%. From the modeling efficiency values, it can be concluded that HEC-HMS model was successfully adapted to the Nyando catchment and can be accepted as an important tool in operational hydrology for estimating information required for water resources planning, design, and operation and for flood control and monitoring.

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LIST OF ABBREVIATIONS

ASL	Above Sea Level
CN	Curve Number
DEM	Digital Elevation Map
DOI	Digital Object Identifier
DSS	Data Storage Systems
EM-DAT	Emergency Disasters Database
ET	Evapotranspiration
FEWS	Flood Early Warning System
GIS	Geographical Information Systems
GIS	Global Information Systems
GPS	Global Positioning Systems
GUI	Graphical User Interface
HEC	Hydrological Engineering Centre
HMS	Hydrological Modeling System
LAM	Limited Area Model
LVSCRO	Lake Victoria South Catchment Regional Office
MWRMD	Ministry of Water Resources Management and Development
NIB	National Irrigation Board
NWP	Numerical Weather Predictions
O	Observed Discharge
P	Predicted Discharge
QPFs	Quantitative Precipitation Forecasts
$\mathbf{R^2}$	Coefficient of Linear Regression
RS	Remote Sensing
SCS	Soil Conservation Service
SIU	Standard International Units
SMA	Soil Moisture Accounting Model
SRTM	Shuttle Radar Topography Mission
SWAT	Soil and Water Assessment Tool
US-ACE	US Army Corp of Engineers
WMS	Water Management Systems

CHAPTER 1

1.0 GENERAL INTRODUCTION

1.1 MODELING AND HYDROLOGY

Many scientific disciplines use models to describe systems in simpler terms and to predict system response. In hydrology, rainfall-runoff models enable users the ability to forecast the runoff from a catchment from the amount of precipitation received by that catchment. During the last three decades rainfall-runoff models have become accepted and important tools in operational hydrology for estimating information required for water resources planning, design and operation e.g. river water level gauging data. Rainfall-runoff models are important to researchers in gaining a better understanding of the processes involved within a hydrologic system (Luijten et al, 2000).

1.2 BACKGROUND

Floods are the most common of all environmental hazards. Every year, floods claim over 20,000 lives and adversely affect around 75 million people worldwide. The reason lies in the wide spread geographical distribution of river flood plains and low-lying coasts, together with their long-standing attractions for human settlement (Smith, 2001). Floods are recurring phenomena which form a necessary and enduring feature of all river basin and low land coastal system. Major floods are the largest source of economical losses from natural disasters mainly in developed countries, and they are also a major cause of disaster related deaths, mainly in the less developed countries. Despite recent advances in the understanding of the relevant climatologically, fluvial and marine mechanisms and a greater investment in flood reduction measures, floods take a large number of lives and damage more property each year, mainly because of unwise land management practices and growing human vulnerability (Brooks et al, 1997).

Flooding has occurred throughout recorded history and as a natural phenomenon have no regard for mankind and its activities (Walsh et al, 1990). Evidence of this is that while deaths from most natural disasters have declined over the past two decades, loss of life from flooding has increased (Grentfest and Huber, 1989).

The flood is at the present time only fifth place as an agent responsible for loss of life. It has, however, the fastest growth rate in terms of frequency and number of human lives affected (Watanabe, 1988).

Floods only become a hazard when they affect human activities adversely and often go unrecorded or even unnoticed if they occur in uninhabited areas (Ward, 1978). However, it is generally assumed that floods are one of the most serious natural disasters and can cause much more damage than a tropical cyclone or earthquake.

As the risk of flooding is a severe hazard to human life, activities and structures, there is need for prevention and protection policies, which aim at reducing the vulnerability of people and property. Though the solution for flood mitigation and prevention seems simple, it involves a vast amount of data and knowledge about the causes and influencing factors of floods and their resulting damage.

The improvements in technology, particularly in the hydrological and meteorological fields, have increased the availability of facilities for accurate collection, storage and processing of data. This data can be channeled into forecasting systems and warning networks to provide optimum protection to man, structures, communication networks and agricultural activities so as to minimize the loss of life and property. An accurate prediction and prior warning greatly reduce the damage cost and loss of life due to flood disaster.

As the world population is ever increasing, the critical demand for living space is becoming more apparent. The demand has led to the encroachment and development of high risk-areas such as floodplains. The inhabitants of these floodplains often disregard the risk of flooding, either due to a genuine ignorance or the danger of a false sense of security provided by structural designs constructed to control floods.

The degree of personal protection adopted by inhabitants in flood risk areas is usually proportional to the level of their flood experience. A person who has experienced many floods will often be well prepared. However, such experiences are naturally associated with fear, which causes panic and delayed evacuations in emergency situations. A reluctance to abandon possessions can further increase the delays and risk to life. Major environmental disasters in Africa are recurrent droughts and floods (UNEP, 2000). Their social-economic and ecological impacts are devastating to African countries, because most of them do not have real time forecasting technology, or resources for post-disaster rehabilitation. In addition to droughts and floods, tropical cyclones, cause havoc, especially in West Indian ocean Islands and coastal states.

1.3 FLOOD CONTROL MEASURES AND STRUCTURES IN KENYA

Floods occasionally cause disasters in Kenya. Areas of Kano plains in Nyanza Province, Budalangi in Western province and lower parts of Tana River are susceptible to floods. Arid and semi-arid areas of the country also experience flash floods. In 1997/98 the El Nino phenomenon affected many parts of Kenya causing damages and destruction to property, loss of lives, famine and waterborne disease epidemics. With inadequate preparations for El Nino floods national resources were over-stretched in the response phase. The El Nino induced floods of 1997-1998 caused some US$ 151.4 million in public and private property damage (MWRMD, 2003). This figure does not include the number of people who lost family members, savings, property and economic opportunities.

Flooding arises as a result of the river flows overtopping the banks and inundating the adjacent low-lying areas. This condition causes a lot of damage to property and crops and may result in loss of life and disruption of human settlement/comfort. In Kenya, flooding occurs frequently especially in the Lake Victoria basin. River Nyando is characterized by flooding in its lower reaches. The river floods frequently. This is due to the large cathment area versus one river outlet that discharges the water into the lake. There is intense erosion in the up stream region due to deforestation. The soil blocks the channel or fills it, hindering the free flow of water. Deposition of the material eroded upstream areas takes place in the downstream stretches of the river. The deposition is intensive due to the low gradient of the river bed in the lower areas. The deposition reduces the depth and thus the capacity of the river, which eventually results into flooding. On river Nyando only 4 km of dykes have been constructed from Ahero town down stream and stops a few kilometers before entering into Lake Victoria.

The flood control measures that are in use in the Nyando basins can be classified as structural. Of these measures only small stretches of dykes have been implemented and there has not been much success to mitigate the flood impacts in the lower parts of the Nyando river.

1.4 PROBLEM STATEMENT AND JUSTIFICATION

Floods are unusually high rates of discharge and/or water levels, often leading to inundation of land adjacent to rivers and streams. They are mainly as a result of high-flow rather than base-flow, and are usually caused by intense or prolonged rainfall, snow melt or combination of these factors. Other causes are increased rainfall intensity or duration, reduced infiltration capacity and increased runoff due to deforestation, or change in the efficiency of drainage networks.

Flooding is becoming increasingly a major contributor to personal and property damage worldwide and in many places strikes without warning. Increasing population pressure and economic activities has led to the development of extensive infrastructures near the rivers. These economic activities and changing land use increase the risk of future inundations. The changing climatic behavior of extreme rainfall, typhoon and hurricane contribute extensively to this problem. The existing disaster mechanism in Kenya is primarily geared towards strengthening rescue and relief arrangements during and after the major flood disasters rather than minimizing the incidence and extent of flood damage. Problems related to flooding have greatly increased and there is need for effective studies and understanding of the problem to help mitigate the worst effects of flood disasters and the need for development of a system to understand the threatened areas. There are basically two flood mitigation measures and strategy, structural and non structural. Structural flood control measures attempt to decrease the flow and /or decrease the flooding depth. Measures that decrease the flow include reservoirs and diversions while measures that decrease flooding depth include channel alterations, levees, and floodwalls. A flood early warning system is one way of non-structural and non-physical mitigation measure.

Flood Early Warning Systems (FEWS) are used for predicting water levels and discharges at specific locations along a river network. Flood early warning systems have three aspects, the technical part which involves the predictions, dissemination of warnings based on these predictions and response to the warnings or how people respond to this information.

Due to scientific and technological advancement in recent decades, the researcher's capability to predict flood events in the affected basins is of paramount importance. Various hydrological and river flow models exists which can be used to develop a basin FEWS.

In the Kano plains rains are not abnormally high i.e. (annual average rainfall 1219mm) but drainage is impended due to poorly drained soils (black cotton), flat gradient of the land and siltation. River Nyando has its source in the highlands of Kericho and Nandi districts where there is a lot of rain throughout the year. This means that the river has a high stream discharge throughout the year. This high stream discharge combined with the fact that the soils are impermeable and the poor surface drainage create ideal situation for flooding.

Nyando river basin has suffered destructive floods without any serious mitigation action which is a clear indication of neglecting the importance of the problem.

1.5 OBJECTIVES

1.5.1 Overall Objective

To establish a hydrological model for the Nyando River catchment that can reasonably depict the relation between rainfall and runoff to aid in Planning and decision making in response to floods from the catchment.

1.5.2 Specific Objectives;

1. To domesticate a selected hydrologic model (HEC-HMS) for flow estimation in the Nyando River basin, Kenya.
2. To simulate discharge for flood management and to evaluate the effects created by inclusion of two proposed dams along the Nyando River on peak discharge.

1.5.4 Limitations of the Study

The model will be established using historic and flood events associated data. In order to develop and operate a flood forecasting and warning system, real time data collection is crucial.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 ENVIRONMENTAL DEGRADATION AND DISASTERS

Developing countries are vulnerable to disasters as a result of poverty and population growth. The continued uncontrolled alterations of environmental systems weaken the defences of many countries to natural hazards. Vulnerability and poverty go hand in hand.

One disaster often leads to another. High wind storms are often followed by floods and land slides, Floods are followed by drought and drought by pest epidemics and famine (see Table 2.1 indicating flood related disasters in Kenya). Such chain of disasters result partially from the tendency of natural disasters to deliberate the environment, they are aided in this by some human activities. The same cycle results whether the cause of the cycle is natural or spring from human effort. However, environmental degradation intensifies the effects of disasters.

Drought is too little water. Humans cause land to be more drought prone by removing the vegetation and soil systems which absorb and stores water in ways that are beneficial to humans. Floods are increasingly faster in frequency, while drought affects the largest number of people. Flood is too much water. Humans make land prone to flooding by removing the trees and other vegetation which absorb this water. Floods are generally considered to be first on-set disasters but their root cause may be partly a history of progressive environmental degradation. Floods are generally triggered not by exaggerated rainfall but by the silting of the rivers, the reduced absorption capacity of the soils, flawed infrastructure planning and inadequate maintenance of existing facilities.

Poor countries which suffer flood disasters are the same countries in which environmental degradation is proceeding most rapidly. Countries with severe deforestation, erosion, over-cultivation and overgrazing tend to be hardest hit by disasters.

There are two ways in which human can make natural disasters more frequent and dangerous; First by altering the environment to make it more prone to certain disaster triggers, mainly to droughts and floods. Secondly, people (especially the poor) can leave in dangerous structures on dangerous grounds, making themselves more exposed and more vulnerable to disaster trigger mechanisms.

In the case of Kano plains people live in the flood plains of a river that is prone to flooding thus making themselves more vulnerable to floods.

Table 2.1: A Summary of Natural Disasters in Kenya 1964 to 2007

		No of events	killed	Injured	Homeless	Affected	Total Affected	Damage US $ (000's)
Drought	Avg/event	9	114	0	0	29,552,000	29,552,000	1,500
		13	13	0	0	3,283,556	3,283,556	167
Earthquake		1	0	0	0	0	0	0
	Avg/event		0	0	0	0	0	0
Epidemic		24	3,059	0	0	6,842,728	6,842,728	0
	Avg/event		127	0	0	285,114	285,114	0
Flood		24	766	8	200	2,020,800	2,021,008	22,388
	Avg/event		32	0	8	84,200	84,209	933
Slides		2	32	0	0	0	0	0
	Avg/event		16	0	0	0	0	0
Wave/Surge		1	1	0	0	0	0	0
	Avg/event		1	0	0	0	0	0
Wind Storm		1	50	0	0	0	0	0
	Avg/event		50	0	0	0	0	0

Source: "The OFDA/CRED International Disaster Database

NB: In order for a disaster to be entered into the database at least one of the criteria has to be fulfilled:

- 10 or more people reported killed
- 100 people reported affected
- a call for international assistance
- declaration of a state of emergency

2.2 FOREST COVER EFFECT ON FLOODS

Until rain reaches the ground, human beings have little influence over it. But whether water, once on the ground, becomes "a productive resource or destructive/hazardous depends very largely on man's management on vegetation and soils" (UNESCO, 1974).

A key driving force in the yearly increases in flood disasters is the rapid rate of deforestation in the tropics. An American environmentalist Erik Eckholm wrote in "Down to Earth" (Pluto Press; Norton, 1982): "Decades of research have proved that the deforestation of watersheds, especially around smaller rivers and streams can increase the severity of flooding, reduce stream flows and dry up springs during dry seasons and increase the load of sediments entering the water ways. Yet most efforts to combat such problems have entailed engineering measures – dams, embankments, dredging – that addresses symptoms and not their causes. The exact contribution of deforestation to flood trends is probably impossible to pin point but as flooding worsens in country after country new attention is being given to watersheds. The felling of forest stands and the consequent reducing evapo-transpiration alone can significantly increase flood volumes.

The Nyando river watershed is in Kericho and Nandi districts where trees are continuously being cleared to give room for human settlement and agriculture. It would therefore follow that this deforestation has led to an increase in the sediment load of the river (Onyango, 2001).

2.3 HAZARDS ASSOCIATED WITH FLOODING

Hazards associated with flooding can be divided into primary hazards that occur due to contact with water; secondary effects that occur because of the flooding, such as disruption of services, health impacts such as famine and disease, and tertiary effects such as changes in position of river channels. Throughout the last century flooding has been one of the most costly disasters in terms of both property damage and human casualties. Major floods in China, for example killed 2 million people in 1887, nearly 4 million in 1931 and about 1 million in 1938. The 1993 flood of the upper Mississippi River and Midwest killed only 47 people, but the U.S. Army corps of

Engineers estimates the total economic loss at between 15 and 20 billion dollars (Nelson, 2001).

2.3.1 Primary Effects of Flooding

Primary effects of floods are those due to direct contact with the flood waters (Stephen, 2001). Water velocities tend to be high in floods and as discharge increases velocity increases.

- With higher velocities, streams are able to transport larger particles as suspended load. Such large particles include not only rocks and sediment, but, during a flood, could include such large objects as automobiles, houses and bridges.
- Massive amounts of erosion can be accomplished by flood waters. Such erosion can undermine bridge structures, Levees, and buildings causing their collapse.
- Water entering human built structures cause water damage. Even with minor flooding of homes, furniture is ruined, floors and walls are damaged, and anything that comes into contact with the water is likely to be damaged or lost. Flooding of automobiles usually results in damage that cannot easily be repaired.
- The high velocity of flood waters allows the water to carry more sediment as suspended load. When the flood waters retreat, velocity is generally much lower and sediment is deposited. After retreat of the flood waters everything is usually covered with a thick layer of stream deposited mud, including the interior of buildings.
- Flooding of farmlands usually results in crop loss. Livestock, pets, and other animals are often carried away and drown.
- Humans who get caught in the high velocity flood waters are often drowned by the water.
- Flood waters can concentrate garbage, debris, and toxic pollutants that can cause the secondary effects of health hazards.

2.3.2 Secondary and Tertiary Effects of Floods

Secondary effects are those that occur because of the primary effects and tertiary effects are the long term changes that take place. Among the secondary effects of a flood are:

- Disruption of services-
  -Drinking water supplies may become polluted, especially if treatment plants are flooded. This may result in disease and other health effects, especially in under developed countries.
  -Petroleum and electrical services may be disrupted.
  -Transportation systems may be disrupted, resulting in shortages of food and clean-up supplies. In under developed countries food shortages often lead to starvation.
- Long-term effects (tertiary effects)-
  -Location of river channels may change as the result of flooding, new channels develop, leaving the old channels dry.
  -Sediment deposited by flooding may destroy farm land (although silt deposited by the flood waters could also help to increase agricultural productivity)
  -Jobs may be lost due to disruption of services, destruction of business, etc. (although jobs may be gained in the construction industry to help rebuild or repair flood damage).
  -Insurance rates may increase.
  -Corruption may result from misuse of relief funds.
  -Destruction of wildlife habitat may occur.

2.4 DISASTER PREPAREDNESS

Disasters preparedness where flooding is a hazard requires essentially three elements:

- An effective forecasting service, linked to
- An effective warning system, backed up by
- A well equipped flood fighting organization, and all of these should form part of a national or region disaster emergency organization.

2.4.1 River Flood Forecasting and Warning

The duty of a forecasting service is to indicate in advance the likely stages or levels to which a river will rise at a particular time and place.

Early flood warning systems allow time for people to leave low- lying areas and to move personal property, livestock and mobile equipment to high ground. Sometimes valuable crop can be harvested in advance of destructive floods, emergency evacuation and relief organization.

2.4.2 Disaster Prevention and Mitigation

Prevention does not mean halting such trigger events as earthquakes and cyclone but rather minimizing their impact on our environment. Disaster prevention and elimination of poverty are closely linked, just as poverty and environmental degradation.

People are changing their environment thus making it more prone to disasters and thereby exposing themselves to be more vulnerable to those hazards (Leah, 2001). Most of scientific effort and money devoted to manage natural disaster has been spent on studying climatological and geological triggers (over which humans have very little control), rather than studying the wide range of human actions (over which humans do have some control).

A strong earthquake in an occupied desert area which affects no one is hardly a disaster. On the other hand a mild earthquake in a shantytown of heavy mud brick houses on the slope of a steep ravine may seem to be disaster in terms of human deaths and suffering. But is the disaster more as a result of the earthquake or the fact that people were leaving in such dangerous conditions? Is it easier to prevent the earth shocks or improve the housing condition?

Disaster prevention and mitigation are closely linked with poverty. Most disaster problems in the third world are unsolved development problems. Disaster prevention and mitigation is primarily an aspect of development. It can be argued that as people develop economically and politically they become less vulnerable to natural disasters.

- Organizations concerned with disaster must be concerned with development. A case in point is the comparison between Tokyo in Japan and Managua in Nicaragua. These are two towns which are prone to earthquakes. The people in Tokyo are far less vulnerable to injury by earthquakes because Tokyo has strictly enforced building codes, zoning regulations and earthquake training and communication systems. In Managua there are still many people living in top-heavy, mud-brick houses on hillsides. They are vulnerable. Japan is a developed country; Nicaragua is not (Leah, 2000).

Similarly, a flood in an undeveloped country would have more devastating effects than floods in the developed world. Current trends of disaster prevention and mitigation put emphasis on preparedness and development before disasters occur rather than providing relief efforts after the event.

2.5 PREDICTING RIVER FLOODING

Floods can be such devastating disasters that anyone can be affected at almost any time. When water falls on the surface of the earth, it has to go somewhere. In order to reduce the risks due to floods, three main approaches are taken to flood prediction. Statistical studies can be undertaken to attempt to determine the probability and frequency of high discharges of streams that cause flooding. Floods can be modeled and maps can be made to determine the extent of possible flooding when it occurs in the future. And, since the main causes of flooding are abnormal amounts of rainfall and sudden thawing of snow or ice, storms and snow levels can be monitored to provide short-term flood prediction (Stephen, 2001). This study will focus mainly on the monitoring of storms

2.6 MONITORING THE PROGRESS OF STORMS

If factors such as amount of rainfall, degree of ground saturation, degree of permeable soil, and amount of vegetation can be determined, then these can be correlated to give short-term prediction, in this case called a forecast, of possible floods (Michael H.G. 2004). If a forecast is issued, then a flood warning can be communicated to warn the public about possible extent of the flood, and to give people time to move out of the area. Such forecasts are very useful for flooding that has a long lag time between the storm and the peak discharge. Flash floods, which characteristically have short lag times, are more problematic. Thus, in some areas known to be susceptible to flash floods, a flash flood warning is often issued any time heavy rainfall is expected because there is always the chance of a flash flood accompanying heavy rainfall.

River Nyando has a stretch of 142 kilometers and with most of the rain occurring in the upper areas of the catchment (Kericho and Nandi districts), a FEWS would give ample lead time to the residents in the lower areas which are susceptible to flooding

2.7 INFORMATION NEEDED FOR FLOOD ASSESSMENT

Flood risk assessment process requires up-to-date and accurate information on the terrain topography and the use of land. Remotely sensed images from satellites and aircrafts are often the only source that can provide this information for large areas at acceptable costs. Digital elevation models can be constructed quickly. Furthermore all kinds of parameters that are important to hydrological modeling is related to the land cover, e.g. permeability, interception, evapo-transpiration, surface roughness, etc. Seven indicator maps that characterize the various aspects of a flood hazard include: maximum water depth, maximum flow velocity, maximum impulse (amount of moving water), maximum speed of the raising of the water level, duration, arrival time of the first floodwaters, sedimentation and erosion (Alkema, 2004).

2.8 STORM WATER COMPUTER MODELS

In storm water management there are typically three types of models commonly used: hydrologic, hydraulic and water quality models. There are also a number of other speciality models to simulate ancillary issues (some of which are sub-sets of the three main categories) such as sediment transport, channel stability, lake quality, dissolved oxygen and evapotranspiration. They have been used in urban drainage studies, reservoir simulation studies, watershed management studies, flood control studies, pollution control studies among other field of hydrology (Luijten et al, 2000). Hydrologic and hydraulic modeling, which is basically used in flood early warning systems, is discussed below.

2.8.1 Hydrologic models

Hydrological modeling refers to the application of models in the study of environmental hydrology which have contributed much to hydrology (Luijten et al, 2000). Hydrologic models attempt to simulate the rainfall-runoff process to tell us "how much water, how often". They use rainfall information or simulate ons to provide runoff characteristics including peak flow, flood hydrograph and flood frequencies.

Hydrologic models can be:

- Deterministic – giving one answer for a specific input set, or
- Stochastic – involving random inputs giving any number of responses for a given set of parameters.
- Continuous – simulating many storm events, or
- Single event – simulating one storm event.
- Lumped – representing a large area of land use by a single set of parameters,
- Distributed – land areas are broken into many small homogeneous areas each of which has a complete hydrological calculation made on it.

2.8.2 Hydraulic models

Hydraulic models take a known flow amount (typically the output of a hydrologic model) and provide information about flow height, location, velocity, direction and pressure.

Hydraulic models share some of the differing characteristics of hydrologic models (continuous vs. single event) and add:

- One – dimensional – calculating flow information in one direction (e.g. downstream) only, or
- Multi – dimensional – calculating flow information in several dimensions (e.g. in and out of the channel and down stream).
- Steady – having a single unchanging flow velocity value at a point in the system, or
- Unsteady – having changing flow velocities with time.
- Uniform – assuming the channel slope and energy slope are equal, or

- Non-uniform – solving a more complex formulation of the energy and momentum equations to account for the dynamic nature of flows.

For most problems encountered in hydraulics, a simple one dimensional, steady model will work well. But if the volume and time distribution of flow are important (for example, in a steeper stream with storage behind a series of high culvert embankments) an unsteady model is needed. If there is a need to predict with accuracy the ebb and flow of floodwater out of a channel (for example in a wide, flat floodplain where there are relief openings under a road) a two dimensional model becomes necessary. If pressure flows and the accurate computation of a hydraulic grade line are important an unsteady, non-uniform model with pressure flow calculating capabilities is needed.

The initial stage of the establishment of a FEWS will attempt to simulate the rainfall-runoff process which is the purpose of this study. However, a model combining both hydrologic and hydraulic modeling is best for the full establishment of a FEWS.

2.9 THE MODELING PROCESS

The overall modeling process involves: (1) development of study or model objectives, (2) identification of resources and constraints, and finally, (3) the selection and the implementation of the model itself.

2.9.1 Setting up of Model objectives

It is important to know specifically what answers are needed, to what accuracy, and in what format. Requiring a simple peak flow is far different from needing to know the timing of peaks from several different interesting watersheds. Estimating future floodplain elevations along a reach is a fundamentally different problem than finding the probability of roadway overtopping (NBCBN-RE, 2005).

A review of the problem begins with the process of determining the model objectives. These objectives also establish a performance or design criteria for the model. Questions to be considered include; Must the system handle the 25 year storm? Are

Which pollutants? Those aspects of the system to be modeled will dictate what models are appropriate for use. For example, if storm sewers are present then open channel model can be ruled out as an appropriate model for the entire system. If a specific type of hydraulic structure is present that a standard model cannot handle, an alternative way to simulate that structure will be necessary.

Model objectives also explain how the numbers generated from the model will relate to the needs of the study. For example, if a cost benefit analysis is required, the model results must be interpreted in terms of overall life-cycle cost and not simply in terms of discharge rate.

2.9.2 Constraints to Modeling

Availability of data, funds, time and user ability can potentially constrain modeling solutions. The goal of any modeling effort is to develop an approach that stays within the constraints dictated while addressing the needs of the study identified in the previous step. Data collection/availability and costs are usually the chief constraints.

Sources of existing available data should be researched. Seek for data that tends to "ground truth" model outputs. Even partial data can be useful if it helps to validate the model or modeling results. After existing data sources have been identified, the need to gather additional data is assessed. Automated processes and systems such as GIS and GPS can reduce both cost and human error. A consideration of the long term use of data and its maintenance is necessary. For example, if the model is to eventually become an operational model, the ability to maintain the data in a cost effective way is of paramount importance (Zahidul and Islam, 1996).

Accuracy and the corresponding necessary level of detail are of overriding importance. Accuracy depend both on the accuracy of the input data and the degree to which the model adequately represent the hydrologic, hydraulic or water quality processes being modeled. For example, if lumped hydrologic parameters are adequate, then the cost of modeling effort can be reduced. However, the ability to determine information within the sub-basin represented by a single parameter is lost. Changing model needs from an average 500-acre sub-basin size to a 50-acre size can determine information within the sub-basin represented by a single parameter is lost. Changing model needs from an average 500-acre sub-basin size to a 50-acre size can increase the cost of a model almost ten fold. Is the information derived worth the cost?

Both risk and the uncertainty affect the modeler's ability to predict the results accurately. Risk is an estimated chance of occurrence, such as flooding. Uncertainty is the error associated with measuring or estimating key parameters or functions. Uncertainties arise due to errors in sampling, measurement, estimation and forecasting, and modeling. For hydrologic and hydraulic analysis, stage and discharge are of prime importance. Uncertainty if discharge is due to short or nonexistent flood records, inaccurate rainfall-runoff modeling, and inaccuracy in known flood flow regulation where it exists. Stage uncertainty comes from errors and unknowns in roughness, geometry, debris accumulation, sediment effects and other factors (WMO, 1994).

Accuracy developed in one area can be impacted by rough estimates in another, and the technological gains lost. For example the gains in accuracy from very precise field surveys of cross sections can be lost if the estimates of roughness coefficients or discharge rates are very approximate.

Sensitivity analysis involves holding all parameters constant except one and assessing the change in output variable of concern with a certain percentage change with the input variable. Those variables that are amplified in the output should be estimated with higher accuracy and with a more detailed consideration of the potential range of values and the need for conservative design. The modeler must try to assess how accurate estimates are and to account for risk and uncertainty through estimating the range of potential error and choosing values that balance conservative engineering with cost consciousness. The designer typically develops a "most likely" estimate of a certain design parameter (for example, ten-year storm rainfall or Manning's roughness coefficient) and then uses sensitivity analysis to test the impact of variability in the parameter estimate on the final solution.

2.10 SELECTION AND IMPLEMENTATION OF MODELS

Considerations should be based on:

1. The fundamental differences in models, particularly in the spatial and temporal scales at which they operate and the processes they are designed to represent and
2. Practically the knowledge, amount of time and data needed in modeling.

To achieve these, the researcher should evaluate the different fundamental approaches to modeling, the balance between data, model complexity and predictive performance, and general classification of models, highlighting key features that indicate the likely applicability to a particular study.

In practice, pragmatic choices will have to be made regarding the appropriate level of model complexity and the consequences of those choices. A conceptual relationship between model complexity, the availability of data for model testing, and predictive performance of the model will have to be evaluated. The term "data availability" means the amount, quality and information content of the available data for model testing. The term "model complexity" means the detail of process representation. Complex models simulate more physical processes and so are likely to have more parameters. "Predictive performance" means how much confidence we can have in the model outputs when used to predict future events. This confidence has to be as high as possible, given the model and/or data available (Mwakalila et al.,2001).

Once the model objectives and constraints have been evaluated, the model (or models) is selected and the design is implemented. Typical steps in model implementation include validation, calibration, verification and production.

Validation involves a determination that the model is structured and coded as intended for the range of variables to be encountered in the study. Validation tests key algorithms for accuracy. For example, if a hydrologic model cannot handle short time steps or long time periods it cannot be used without modification. If a certain model begins to lose accuracy at high or low imperviousness or cannot accurately handle back water situations, and these will be encountered in practice the model cannot be used. Often validation is one-time effort, after which the modeler is comfortable with the model's "quirks" and knows how to deal with them. Validation often involves pushing parameters to the limit of reasonable extent to test an algorithm. For example in a hydrologic model infiltration can be reduced to zero to test if the input and output hydrographs are equal. Or the model can be run with small rainfalls using porous soils to determine if no runoff is generated, or only runoff from directly connected impervious areas.

Calibration is the comparison of a model to field measurements, other known estimates of output (e.g. regression equations), or another model known to be accurate, and the subsequent adjustment of the model to best fit those measurements. Verification then tests the calibrated model against another set of data not used in the calibration. This step is not always possible due to the general shortage of data of any sort in storm water management. Goodness of prediction is done through a simple comparison of the difference in observed and predicted peaks, pollution loads, flood elevations or volumes divided by the observed values and expressed as a percentage, or as simple ratio. Assessing the goodness of fit of a hydrograph is done by calculating the sum of the squares of the difference between observed and predicted values at discreet time steps (Toolkit, 2007).

Once the model is prepared for use, attention shifts to efficient production methods that minimize the potential for errors while maximizing efficiency. Often "production line"-type efforts are used for large modeling projects. However, constant attention must be paid to ensure the execution of correct procedures, detailed documentation of efforts and input/output data sets, and recognition of anomalies that would invalidate a particular model run.

While there is much to be gained from simple user interfaces and black box approaches that simplify the input and output processes, there is an inherent danger that the modeler will not be aware of errors or problems in the modeling process. For example, in hydraulic modeling, shifts from super to sub-critical flow happens at a sharp break points and are reflected in a jump in water surface. If not caught, a model will under predict flow elevation. Numeric instability in mathematical algorithms may give oscillating answers that have nothing to do with reality. A structure review process must be established to ensure reasonableness of output and accuracy of input values has been used. Labeling of data sets should be systematic and exact. Out flow and observed stream flow at the selected element (Berihun, 2003).

2.11 BASIC FEATURES FOR MODEL CLASSIFICATION

There are several criteria used in the classification of hydrological models. In many cases these classification represent the needs of a particular discipline. Based on their nature, models may be physical, analog or mathematical. Physical models are miniature representation of the real world system. Analog models represent the flow of water with flow of electricity in a circuit. Mathematical models are equations or a set of equations that represents the response of a hydrologic system component to a change in hydro meteorological conditions (ASCE Task Committee, 1999).

Computer models can be simple, representing only a very few measured or estimated input parameters or can be very complex involving twenty times the number of input parameters. The right model is the one that: (1) the user thoroughly understands, (2) gives adequately accurate and clearly displayed answers to the key questions, (3) minimizes time and cost, and (4) uses readily available or collected information. Complex models used to answer simple questions are not an advantage. However, simple models that do not model key necessary physical processes are useless.

A general classification of models will be useful for giving an indication of model structure or complexity. (Sing, 1995) discusses classifications in terms of how processes are represented, what time and space scales are used and what methods of solution to equations are used. Here three basic features, useful for distinguishing approaches to modeling in catchments hydrology will be focused on.

1. The nature of the basic algorithms (empirical, conceptual or process-based),
2. Whether a statistical or deterministic approach is taken to input or parameter specification, and
3. Whether the spatial representation is lumped or distributed.

2.11.1 Empirical, Regression or "Black-Box" models

The first step in classification will be to make attempts to represent the basic process. Models that simply calibrate a relationship between inputs and outputs are known as empirical, regression or "black-box" models. They are based on input-output relationships without any attempt to describe the behavior caused by individual processes. An example is:

$$\textbf{Runoff} = \textbf{a (rainfall)}^{\textbf{b}}$$

Where we derive the parameters "a" and "b" via a regression between measured rainfall and runoff.

2.11.2 Conceptual-Empirical Models

The next step in complexity is conceptual-empirical models where, in the case of catchments modeling, the basic processes such as interception, infiltration, evaporation, surface and subsurface runoff etc. are separated to some extent. However, the equations that are used to describe the processes are essentially calibrated input-output relationships, formulated to mimic the function behavior of the processes in question (Crawford and Linsley, 1966).

2.11.3 Physically-Based or Process-Based Models-Complex Conceptual Models

As the quest for deeper understanding of hydrological processes has progressed, models based on fundamental physics and governing equations of water flow over and through soil and vegetation have been developed (Catchword, 2004). These are often called physically-based or process-based models. They are intended to minimize the need for calibration by using relationships in which parameters are, in principle, measurable physical quantities. In practice these parameters can be difficult to measure (At least everywhere that is needed for modeling and at the right scale) so these models are best thought of as complex conceptual models (Beven, 1989).

2.11.4 Stochastic or Deterministic Representations

Another basic distinction between models is whether stochastic or deterministic representations and inputs are used. Most models are deterministic, meaning that a single set of input values and a single parameter is used to generate a single set of output. In stochastic models, some or all of the inputs and parameters are represented by statistical distributions, rather than single values. Stochastic is very useful, particularly when one is uncertain about the exact values of model parameters. From the above descriptions a deterministic model will be appropriate for this study. The choice of this model type will enable varying of one parameter value while holding the other parameter values constant to establish its most optimal value.

2.11.5 Representing Spatial Detail

Finally, models differ in how they represent the spatial detail. Spatially lumped models treat the modeled area (e.g. a sub-catchment) as a single unit and average the effects of variability over that unit. Spatially distributed models separate the region to be modeled into discrete units, enabling different model inputs or parameters to be used to represent spatial variability. These notions of "lumped" or "distributed" do not indicate anything particular about the methods used for presenting individual processes, but simply indicate the approach to spatial representation (Toolkit, 2007).

2.11.6 Representing Timing Variations

The distinction between lumped and distributed catchment models can also be made in the time domain. Some models can be designed to give output that represents "average" or "long term" values, whereas others are "time stepping" models where output is produced hourly, daily, monthly etc. The simplest models are lumped in both time and space while the more complex models tend to be distributed in both time and space (Toolkit, 2007).

2.12 HEC-GeoHMS SOFTWARE

HEC-GeoHMS software was developed as a geospatial hydrology tool kit for engineers and hydrologists with limited GIS experience. The program allows users to visualize spatial information, document watershed characteristics, perform spatial analysis, delineate sub basins and streams, construct inputs to hydrologic models, and assist with report preparation. This software allows the user to expediently create hydrological inputs that can be used directly with Hydrological Modeling Systems, HEC-HMS.

2.13 HEC-HMS MODEL

2.13.1 Model Overview

The Hydrologic Modeling system (HMS), developed by the Hydrologic Engineering Center (HEC) of the United States Army Corps of Engineers (USACE), is a software package for simulating precipitation-runoff processes of a watersheds (HEC, 2001). It is designed to be applicable to a wide range of geographic areas to solve the widest range of problems. This includes large river basin water supply and flood hydrology, and small urban or natural watershed runoff. Hydrographs produced by the model are used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, flood plain regulation and system operation (HEC, 2000). For precipitation-runoff simulation, the model requires three model components; a basin component, a meteorological component and a control specification.

The physical representation of the watershed is accomplished with a basin model. Hydrologic elements are connected in a network to simulate runoff processes. Available elements are; sub-basin, reach, junction, reservoir, diversion, source and sink. An element uses a mathematical model to describe the physical process. Computation proceeds from upstream elements in a down stream direction.

Meteorological data analysis is performed by the meteorological model and includes precipitation, evaporation and snow melt.

The time span of a simulation is controlled by control specifications. Control specifications include a starting date and time, ending data and time, and a time interval.

A simulation run is created by combining a basin model, meteorological model and control specifications.

HEC-HMS has long been one of the industry-programs for hydrologic analysis (HEC, 2001). It can model both continuous and single storm event, a choice can be made between lumped or distributed model parameters and includes several different options for modeling rainfall, losses, unit hydrographs and stream routing. The HEC-

HMS interface contained within WMS makes it simple to enter and manage input data and display analysis results. Precipitation and discharge gage information can be entered manually within the program or can be loaded from previously created DSS files. Computation results are viewed from basin model schematics. Results of wide implementation of this package show its good performance for hydrologic simulation and prediction (Morid et al., 2001).

2.13.2 Models Included In HEC-HMS

HEC-HMS uses separate model to represent each component of the runoff process including:

1. Models that compute runoff volume;
2. Models of direct runoff;
3. Models of base flow;
4. Models of channel flow.

Runoff volume models address questions about the volume of precipitation that falls on the watershed: How much infiltrates on pervious surface? How much runs off of previous surfaces? How much runs off the impervious surfaces? When does it run off? HEC-HMS consists of various choices in each category of the models mentioned above which can be selected according to the intended purpose. Only selected models for the purpose of this study are discussed below;

Deficit and constant loss is a continuous, lumped, empirical, fitted parameter model. It uses a single soil layer to account for continuous changes in moisture content (HEC, 2001). It should be used in combination with a meteorologic model that computes evapotranspiration. The potential evapotranspiration computed by the meteorologic model is used to dry out the soil layer between precipitation events. Infiltration only occurs when the soil layer is saturated. Parameters included in this model are:

1. Initial deficit; It indicates the amount of water that is required to saturate the soil layer to the maximum storage.
2. The maximum storage; Specifies the amount of water that the soil layer can hold, specified as a depth. An upper bound would be the depth of active soil layer multiplied by porosity. However, in most cases such an estimate has to

be reduced by the permanent wilting point and for other conditions that reduce the holding capacity of the soil.

3. The constant rate defines the infiltration rate when the soil layer is saturated. A good approximation is to use the saturated hydraulic conductivity.
4. The percentage of subbasin which is directly connected to the impervious area can be specified. No loss calculations are carried out on the impervious area; all precipitation on that portion of the subbasin becomes direct runoff.

Clark's UH is an event, lumped, empirical, fitted parameter model. It represents translation and attenuation of excess precipitation as it moves across the subbasin to the outlet (HEC, 2001). The model is based on the linear reservoir model. The traditional formulation of kinematic wave theory assumes the kinematic wave friction relationship parameter to be constant. Parameters included are;

1. The time of concentration; defines the maximum travel time in the subbasin. It is used in the development of translation hydrographs.
2. The storage coefficient is used in the linear reservoir that accounts for storage effects. Many studies have found that the storage coefficient, divided by the sum of time of concentration and storage coefficient, is reasonably constant over a region.

Baseflow Recession method is designed to approximate the typical behavior observed in watersheds when channel flow recedes exponentially after an event. However, it does have the ability to automatically reset after each storm event and consequently may be used for continuous simulation. It defines the relationship of Q_t, the base flow at any time t, to an initial value as:

$$Q_t = Q_0 K^t$$

Where Q_0 = initial baseflow (at time zero); and K = an exponential decay constant. Parameters included are;

1. The initial baseflow at the beginning of a simulation must be specified through either of the two methods available as required; initial discharge and initial discharge per unit area.

2. The recession constant describes the rate at which baseflow recedes between storm events. It is defined as the ratio of baseflow at the current time, to the baseflow one day earlier.
3. There are two methods for determining how to reset the base flow during a storm event; ratio to peak and threshold flow.
4. You must specify ratio to the peak when the base flow is set.

2.14 ESTIMATION OF MODEL PARAMETERS BY OPTIMIZATION TRIALS

Parameter optimization is the process of adapting a general model to a specific watershed (HEC, 2001). Some parameters can be estimated directly from field measurements e.g. area. Other parameters can be estimated indirectly from field measurements. In this case, the field measurement does not result in a value that can be input directly to the model. However, the field measurement can provide strong recommendations for a parameter in a model based on previous experience e.g. measurements of soil texture are highly correlated with parameters such as hydraulic conductivity.

Finally there are parameters that can only be estimated by comparing computed results to observed results such as observed stream flow. Even for parameters of the first two types, there is often enough uncertainty in the true parameter value to require some adjustment of the estimates in order for the model to closely follow the observed stream flow.

The quantative measure of goodness of-fit between the computed result from the model and the observed flow is called the objective function. An objective function measures the degree of variation between computed and observed hydrographs. It is equal to zero if the hydrographs are exactly identical. A minimum objective function is obtained when the parameter values best able to reproduce the observed hydrograph are found. Constraints should be set to ensure that unreasonable parameter values are not used. The iterative parameter estimation procedure used by a model is often called optimization. Initial values of all parameters are required at the start of the optimization trial. A hydrograph is computed at a target element by computing all of the upstream elements. The target must have an observed hydrograph for the time period over which the objective function will be evaluated. Only parameters of upstream elements can be estimated.

The value of the objective function is computed at the target element using the computed and observed hydrographs. Parameter values are adjusted by a search method and the hydrograph and objective function for the target element are recomputed. This process is repeated until the value of the objective function is sufficiently small, or the minimum number of iterations is exceeded. Results can be viewed after the optimization trial is complete. The objective function measures the goodness of-fit between the computed and the measured values.

2.15 ESTIMATION OF AREAL RAINFALL BY THIESSEN POLYGONS

Thiessen polygons were suggested by Thiessen as a way of interpolating rainfall estimates from a few rain gauges to obtain estimates at other locations where rainfall had not been measured. The method is very simple: to estimate rainfall at any point, take the rainfall measured at the closet gauge. This leads to a map in which rainfall is constant within polygons surrounding each gauge, and changes sharply as polygon boundaries are crossed. These polygons have many other uses besides spatial information:

- Thiessen polygons can be used to estimate the trade areas of each of a set of retail stores or shopping centers.
- They are used internally in the GIS as a means of speeding up certain geometric operations, such as search for nearest neighbor.
- They are the basis of some of the more powerful methods for generalization vector data bases.

As a method of spatial interpolation they leave something to be desired, however, because the sharp changes in interpolated values at polygon boundaries is often implausible (Albert, 2007).

2.16 EVALUATION OF HYDROLOGICAL MODEL BEHAVIOR AND PERFOMANCE

This is commonly made and reported through comparisons of simulated and observed variables. Frequently, comparisons are made between simulated and measured stream flow at the catchment outlet (Krause et, al., 2005). There are a number of reasons why hydrologists need to evaluate model performance:

1. To provide a quantitative estimate of the model's ability to produce historic and future watershed behavior;
2. To provide a means of evaluating improvements to the modeling approach through adjustment of model parameter values, model structure modifications, the inclusion of additional observation information and representation of important spatial and temporal characteristics of the water shed;
3. To compare modeling efforts with previous study results.

The process of assessing the performance of a hydrologic model requires the hydrologist to make subjective and/or objective estimates of the "closeness" of the simulated behavior of the model to observations (typically of stream flow) made within the watershed. The most fundamental approach to assessing model performance in terms of behaviors is through visual inspection of the simulated and observed hydrographs. In this approach, a hydrologist may formulate subjective assessments of the model behavior that are generally related to the systematic (e.g., timing, rising limb, falling limb, and base flow) behavior of the model. Objective assessment, however, generally requires the use of mathematical estimate of the error between the simulated and observed hydrologic variable(s) – i.e. objective or efficiency criteria.

Efficiency criteria are defined as mathematical measures of how well a model simulation fits the available observations (Beven, 2001). In general, many efficiency criteria contain a summation of the error term (difference between the simulated and the observed variable at each time step) normalized by a measure of the variability in the observations. To avoid the canceling of errors of opposite sign, the summation of absolute or squared errors is often used for many efficiency criteria. As a result, an emphasis is placed on larger errors while smaller errors tend to be neglected. Since errors associated with high stream flow values tend to be larger than those values associated with errors for lower values, calibration (both manual and automatic) attempts aimed at minimizing these types of criteria often lead to fitting the higher portions of the hydrograph (e.g., peak flows) at the expense of the lower portions (e.g., base flow). Further, different efficiency criterion may place emphasis on different systematic and/or dynamic behavioral errors making it difficult for a hydrologist to clearly assess model performance.

There have been several studies (e.g., Batidas et al., 1999; Boyle et al., 2000; Yapo et al., 1998) aimed at utilizing efficiency measures to closely estimate the subjective processes of visually inspecting the hydrograph.

2.16.1 Efficiency Criteria

There are several criteria used for evaluating model efficiency e.g. Nash-Sutcliffe efficiency, Nash-Sutcliffe efficiency with logarithmic values, index of agreement or the BIAS statistics of residuals regression analysis among others. The three criterions used for this study are discussed below:

2.16.2 Nash-Suticliff Efficiency, the Bias Statistics of the Residuals and Regression Analysis

As mentioned previously Model performance is usually evaluated by considering one or more objective statistics or functions of the residuals between models' simulated output and observed catchments' output. The objective functions used in this study were the Nash-Sutcliffe and bias statistics of residuals, which are poorly correlated. The Nash-Sutcliffe efficiency criterion measures the fraction of the variance of the observations explained by the model, while bias (relative volume error) measures the tendency of the model-simulated values to be larger or smaller than their observed counterpart (Weglarczyk, 1998). The Nash-Sutcliffe efficiency criterion ranges from minus infinity to one with higher values indicating better agreement. It measures the fraction of the variance of observed values explained by the model: It is calculated as:

$$NS = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} \left(O_i - \overline{O}\right)^2}$$

While the Bias (relative volume error) is calculated as:

$$BIAS = \frac{\sum_{t=1}^{n} (P_i - O_i)}{\sum_{t=1}^{n} O_i}$$

Where ***Oi*** is observed catchment output at discrete time ***t***, ***Pi*** is the corresponding model simulations, $\bar{o}$ is the mean of the observed values, and ***n*** is the number of data points to be matched. Bias (relative volume error) measures the tendency of the model simulated values to be larger or smaller than their observed counterpart:

Although the Nash-Sutcliffe efficiency criterion is frequently used for evaluating the performance of hydrological models, it favors a good match between observed and modeled high flows, while sacrificing to some extent matching of below-mean flows (Houghton-Carr, 1999). It was for this reason that the two different measures of model performance were considered.

Regression analysis is the method used for estimating the unknown values of one variable corresponding to the unknown value of another variable. When the curve is a straight line, it is called a line of regression. A line of regression is the straight line which gives the best fit in the least square sense to the given frequency.

CHAPTER 3

3.0 METHODOLOGY

3.1 DESCRIPTION OF THE PROJECT AREA.

3.1.1 Nyando Basin

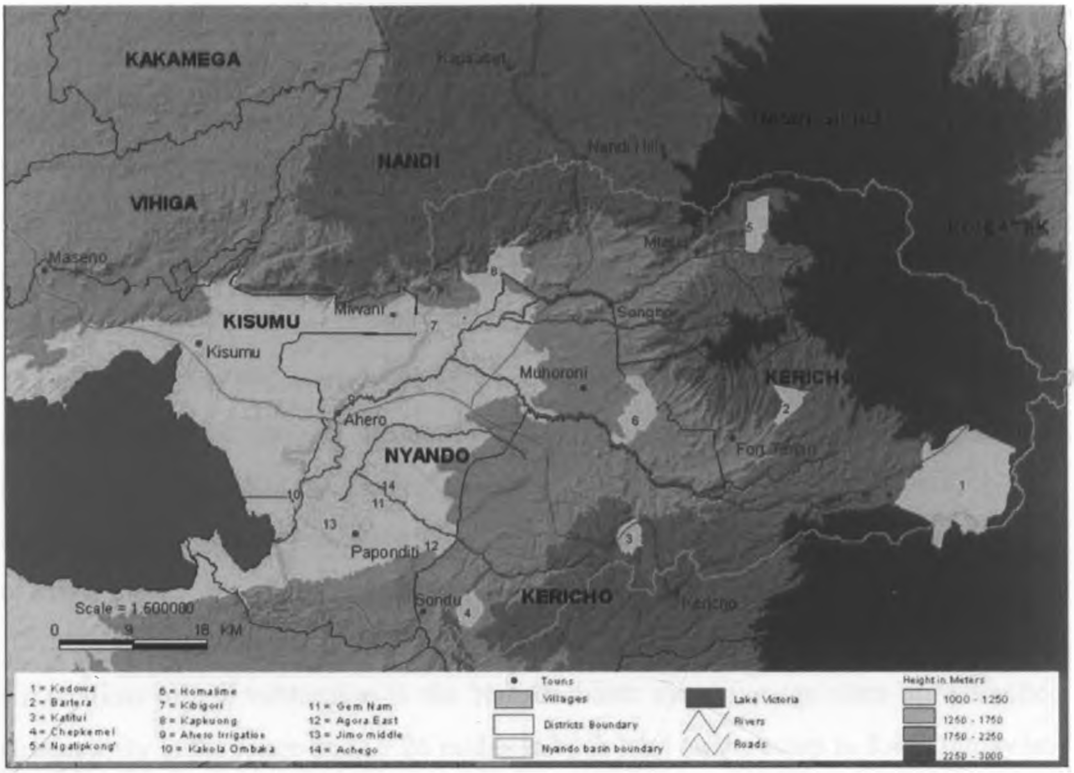
The catchment of the Nyando basin (Figure 3.1) is situated in Nyando, Nandi and Kericho Districts, with a mean annual rainfall, varying between 1,200 mm and 2,000 mm. The basin covers an area of about 3,600 km^2, and has within it some of the most severe problems of agricultural stagnation, environmental degradation and deepening poverty found anywhere in Kenya. The Nyando River discharges about 15m^3/s (World Agroforestry Center, 2003) and drains into the Winam Gulf of Lake Victoria and is a major contributor of sediment, nitrogen and phosphorus to Lake Victoria. About 750 000 people reside within the Nyando basin, most of whom live in Nyando District in Nyanza Province and Nandi and Kericho districts in Rift Valley Province.

The average population density is 214 persons per km^2, with some areas of the basin having over 1,200 people per km^2. The incidence of consumption poverty is high, ranging from an average of 58 percent in Kericho District, to 63 percent in Nandi District and 66 percent in Nyando District. At the administrative location level, the locations of Nyando District include both those with the lowest poverty rate in the sugar belt of Muhoroni Division (36 percent) and those with the highest poverty rate in Upper Nyakach Division (80 percent) for the entire basin (Central Bureau of Statistics, 2003).

3.1.2 Hydrology and Climate

The main rivers in the lower plains are the Kibos and Nyando. Other smaller rivers are Luanda, Nyaidho, Miriu and Awach. The length of the Nyando River is estimated to be 142 km and its discharge ranges from a minimum of 2m^3/s to the extreme flood of 850 m^3/s, which occurred in 1961. The river has a relatively high silt load.

The lower plains experience a mean annual rainfall of 1,260 mm, most of it falling between March and May and a small peak between September and November. Severe convectional rains occur near the shores of Lake Victoria and the highest recorded intensity has been 23 mm during a five-minute period in 1961. The mean annual maximum temperature ranges between 25 and 30°C while the minimum is between 9 and 18°C.



Source: JICA Study Team

Figure 3.1: Nyando River Basin

3.1.3 Soils & Land use

Various types of soils are found in the basin. The soils of the mountains, hills, plateaus and slopes range from excessively drained to well drained, very shallow to shallow, dark reddish brown, stony and rocky, sandy clay loam to clay, in places with an acid humic topsoil and/or moderately deep to deep, (Phaeozems, Lithosols, Regosols and Cambisols). Most parts of the government protected natural forest (conservation forestry) falls under these areas and acts as stabilizers of the thin soil layers and also for protecting the water catchments (KARI, 2004).

The soils of the uplands are well drained, deep to very deep and in some cases shallow to moderately deep, dark reddish brown to dark brown, friable to firm clay, with thick acid humic topsoil (Acrisols, Nitosols, Cambisols, and Ferralsols). The dominant land use is tea growing (both estate and small scale). Tea is deep-rooted crop that requires a lot of rainfall and well-drained acidic soils. Other crops found in this unit and also requiring well-drained soils are maize, potatoes, pyrethrum, wheat and cabbages. The government protected planted forests (production forestry) falls under these areas. Most of the planted tree species are exotic and requires deep soils, which are well drained (KARI, 2004).

The soils of the plains are moderately well to imperfectly drained, deep to very deep, brown to black, in places saline and sodic sandy clay loam to cracking clay (Vertisols, Planosols, Gleysols and Fluvisols). The dominant land use in this unit is sugarcane growing (both estate and small scale) (KARI, 2004).

The soils found in the swamps are very poorly drained, deep to very deep, dark grey to black, half ripe clay; in many places peaty (Gleysols, Histsols). Rice growing (irrigated) is practiced here. During the dry season crops like maize, tomatoes, onions and kales are grown. Other major activities is harvesting of papyrus and other species of making mats, seats, fish traps and thatching material (KARI, 2004).

An analysis of soil infiltration in the Nyando basin show average rates of hydraulic conductivity in the range from 7.26 m/day in bush land on the scarp to 5.445 m/day in the bush land in the hills to 0.359 m/day in the piedmont plains. A rate of only 0.029 meters per day was found for sub-surface soils in the piedmont plains. The infiltration rates for cropland are higher than grassland or grazing lands in the piedmont plains. This low permeability explains the occurrence of inundations in these plains as the flood waters are impeded from infiltrating into the ground.

3.2 FRAME WORK FOR MODEL SELECTION

The frame work was necessary to give the guideline on selection of the model. The following considerations were made:

1) A general review of the existing hydrological and hydraulic models to be adopted for flood forecasting applications;

2) The selection criteria for choosing the most appropriate hydrological tools for achieving the goals set in the project.

3.2.1 General Review of Existing Hydrological and Hydraulic models

The review of the models considered their classification mainly on the basis of the schematization of the basin and the representation of the physical processes, introducing the basic terminology related to hydrologic models. The choice of a significant simplification in the representation of both the basin elements and the involved physical processes as well as the use of an adaptive component for adjusting forecasts in real time was taken into account.

Also considered in the review of the models was the classification in terms of how processes were represented, the time and space scale that were used and what methods of solution to equations were used. The main features for distinguishing the approaches were: the nature of basic algorithms to be conceptual, a deterministic approach was favoured for input or parameter specification and the spatial representation was semi distributed.

The first feature defined whether the model was based on a simple mathematical link between input and output variables of the catchment or if it included the description, even if in a simplified way, of the basic processes involved in the runoff formation and development. Generally, when the observations were reliable and adequate, extremely simple statistical or parametric models were used. For this reason conceptual models were generally preferred.

Another basic distinction that was considered in the modelling was on whether stochastic or deterministic representations and inputs were to be used. Deterministic models were best suited in evaluating experimental results. Most models that were deterministic generated a single set of output. For this reason a deterministic model was selected

On the basis of the spatial representation, the hydrological models can be classified into three main categories: lumped models, semi-distributed models, distributed models. In lumped models which treat catchments as a single unit, the parameters and the input do not vary spatially within the basin and the basin response is evaluated only at the outlet. Parameters do not represent physical features of hydrological processes and the impact of spatial variability is evaluated by using certain procedures for calculating effective values for the whole basin. It can be expected that their use in basins characterized by a complex topography which can enhance the rainfall amount in some parts of the basin, do not furnish an adequate level of forecast reliability. However, other factors e.g. data availability and the duration of the study contributed in the selection of such model as discussed later.

The semi-distributed and distributed models take an explicit account of spatial variability of processes, input, boundary conditions, and/or watershed characteristics. Of course, a lack of data prevents such a general formulation of distributed models that is these models can not be considered fully distributed. In particular, in the semi-distributed model the above quantities are partially allowed to vary in space by dividing the basin into a number of smaller sub-basins which in turn are treated as a single unit (Boyle *et al*, 2001; Corradini *et al.* 2002; Todini, 1996). Whereas distributed models represent spatial heterogeneity with a resolution usually chosen by the user. The widespread availability of digital terrain data and the significance of topography have meant that the choice of element size and type is often dictated by the way in which (and the scale at which) the topography is represented. By far, the most common form of model construction is based on square elements especially for real-time applications where the data and computing requirements should not be very high.

Most of the river discharge gauges in the Nyando basin lacked data especially in the period considered for modelling (1980-1991). However, the critical gauge below which flooding occurs (Gage 1GD03) contained most of the data in this period. A semi distributed model which would treat the sub catchments as a single heterogeneous unit with parameter changes being observed at this gauge was therefore required.

Finally, according to the hydrological processes modelled, hydrological models can be further divided into event-driven models, continuous-process models, or models capable of simulating both short-term and continuous events. The first are designed to simulate individual precipitation-runoff events and their emphasis is placed on infiltration and surface runoff. The major limit to the use of event type models is the problem of unknown initial soil moisture conditions that can not be measured and may heavily condition the forecasts in real time. Continuous-process models, on the other hand, take explicitly account of all runoff components with provision for soil moisture redistribution between storm events. They are based upon equations representing the storage and the movement of water in the soil and on the surface and their parameters are related to information provided in the form of Digital Elevation Maps (DEM), soil maps and land use maps. Generally, these models have a spatial resolution finer than the sub-catchment and so they can incorporate the spatial distribution of rainfall as furnished by RADAR images and/or from high-resolution Limited Area Models (LAMs). Due to the long period of time considered in this study (1980-1991), continuous-process models were required.

In many situations the desired forecast lead time is longer than the time that flow takes to cover the distance between the ground impact location and the flood-prone channel reaches. In basins with size ranging from several tens to hundreds km^2, very short response times (up to a few hours) are encountered. It is therefore necessary to find alternative forcing functions for catchment hydrology models other than observed rainfall as this may not allow for adequate emergency planning. This additional gain in lead time can only be achieved by including precipitation information ahead of its occurrence. The use of now casting techniques, based on radar and satellite sensors, and/or Quantitative Precipitation Forecasts (QPFs) was an obvious advantage.

3.2.2 Model Selection Process and Criteria

First the four basic considerations in choosing the right model for this study were made:

1. Objectives of the study: The selected model was one that would satisfy the required objectives of the study i.e. one that would give the needed output data within the specified time. For example some models would take a longer time to compute results which was not good in the establishment of a flood early warning system.
2. Access to data: Data requirement for each model was compared with the available data. In the case of the Nyando river catchment most of the meteorological daily data and river discharge daily data were missing in the period 1980 to 2003. The selected model was one that could give good

predictions with the available data. Other data e.g. real time forecasting data was expensive to purchase or unavailable.

3. Access to expertise: people with experience in working with a model can provide useful information on the experience they have on the model and can easily advice on the suitability of the selected model to meet the objectives of the study.
4. Availability of resources: Some models even though found to be suitable to the objectives of the study could be very expensive and difficult to acquire.

These were considered iteratively, since limitations in one of the four areas could restrict choices and so require a re-evaluation of the objectives, the personnel involved, cost of the study etc.

Hierarchical approach to modeling was applied i.e. started with simple and got more complex as required. Further considerations were based on the following factors;

1. The time step for the model; models with shorter time steps gave more realistic/precise predictions. Once fed with real time data a FEWS should be able to give predictions within a reasonable time to ensure enough lead time for the warning. The model was therefore supposed to give quick results normally in a day or less than a day. The model selected was the one that struck a balance between these considerations as explained later.
2. Further considerations were made based on the model recommended applications and the intended applications for this study. Models recommended for modeling rainfall runoff relationships got an upper consideration on other model applications.

3.3 DATA BASE PREPARATION

Reliable results could only be achieved if sufficient data of good quality were available. This was achieved through preparation of a good data base. The data that was required for this study were;

- Digital elevation map (DEM) for the Nyando River basin and
- Long time series of evaporation, precipitation and river discharge data.

A 90m resolution shuttle radar topographic mission (SRTM) digital elevation map (DEM) was used to delineate the Nyando catchment. The shuttle radar topographic mission obtained elevation data on a near global scale to generate the most complete high resolution digital topographic data base of the Earth. SRTM consisted of a specially modified radar system that flew on board the space shuttle Endeavour during an eleven day mission in February of 2000. The DEM is the version 2 of the shuttle radar topographic mission digital data (also known as the “finished” version).

Hydrological models often require time-series of precipitation data for estimating basin rainfall. A time series of flow data often called observed flow or observed discharge is helpful for calibrating a model and is required for optimization. Hydrological models also require the use of paired data to describe inputs that are functional in form. Functional data defines a dependent variable in terms of an independent variable. Examples of paired data include unit hydrographs and stage discharge curves. Some of the methods included in a program operate on a grid cell basis. This means the parameters must be entered for each grid cell. It also means that boundary conditions like precipitation must be available for each grid cell. Meteorological (precipitation and Evaporation) data was acquired from the Kenya meteorological department. Nyando river discharge data was acquired from the Water Resources Management Authority (WRMA) Kisumu office.

3.3.1 Choice of Modeling Period

To determine data availability for each rainfall station, tabulation was done to establish short records, gaps in the data and the number of variables for which records were available. The stations with most data were selected and a method of estimating any missing data was decided. Regression analysis was done to select the station with highest correlation with the gauge in use so that its data will be used when gaps occur. Data for rainfall which is the major source of runoff in Nyando catchment was provided from at least fifteen measuring points fairly distributed within the catchment and all other necessary meteorological data from four meteorological stations within the catchment.

Most data from 1990 to 2007 which would have been most appropriate for this modeling was missing or was in hard copy form. This gave the only alternative to use data from 1980 to 1991.

Further criterion for the selection of the critical river gauging stations was based on the Eastings and Nothings i.e. the X and Y coordinates. An overlay of the gauging stations layer and the catchment map was done to establish the location of each station. Only gauge stations in the areas above the flood prone parts of the catchment were selected.

3.3.2 Variables for which data was prepared

This depended on the requirements of the selected model. However, the rainfall, meteorological and the river gauging data were rearranged and stored in software and in the form which was accepted by the model input.

3.4 DELINEATION OF NYANDO RIVER BASIN

HEC-GeoHMS, a geospatial hydrology tool kit was necessary in computing basin parameters. The program allows users to visualize spatial information, document watershed characteristics, perform spatial analysis, delineate subbasins and streams, construct inputs to hydrological models, and assist in report preparation. HEC-GeoHMS was downloaded from the public domain and was used as an extension to the ARC View GIS and spatial analyst extension to delineate the Nyando river catcment. The following functions were performed with this software:

- Data management; thematic GIS data layers were tracked together with their names as provided by the user.
- Terrain processing; step-by-step terrain processing was performed with the software where the researcher had the opportunity to examine the outputs and made corrections to data sets as needed.
- Basin processing; this involved sub-basin delineation and processing. The Nyando basin was subdivided into several sub-basins or sub-basins were merged as desired with the results of the operations being displayed immediately to be confirmed. Data availability and the published sub-basins guided on how the subdivisions were done.
- HMS model support; the software was used to produce a number of hydrological inputs that were used directly in HEC-HMS. In addition the program supported the estimation of hydrological parameters by providing tables of physical characteristics of the streams and watersheds. While

working with HEC-GeoHMS the researcher could toggle HEC-GeoHMS in order to bring in other Arc View extension programs to perform spatial operations and develop additional parameters for populating the hydrological model.

3.5 CALIBRATION AND VALIDATION OF THE MODEL

The first step was to subdivide the data for calibration and validation. Generally shorter period is used in calibration than in validation (usually one third of the available data for calibration and two thirds for validation). Calibration is done for a shorter period because the parameters have some significance to the actual condition while in validation we want to expose the model to variable and extreme climatic conditions and also because the floods return period is longer than one year. Hence, the period with best data coverage was subdivided into two. A third of the available data i.e. from1980 to 1983 was used for calibration while two thirds of the data that is from 1984 to1991 was used for validation.

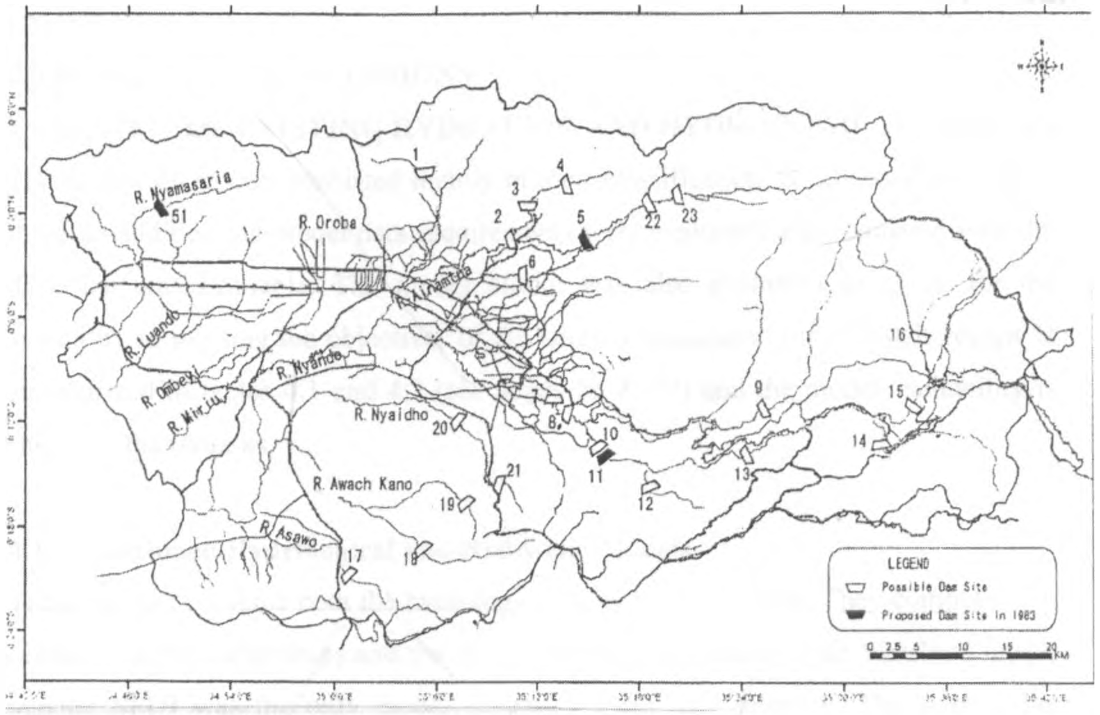
- The initial first period data was used to calibrate the model.
- The following period data was used to validate the model.

The parameters that were varied included; (1) transform method – storage coefficient, (2) loss method- maximum storage, constant rate and impervious layers (3) routing method - Muskingum (k), Muskingum (x) (4) loss method – flow rate & fraction (5) transform method – storage coefficient (6) loss gain flow rate (7) maximum infiltration (8) surface storage (9) impervious percentage (10) canopy percentage (11) canopy storage (12) base flow (13) recession constant (14) threshold R (15) Tension zone capacity and (16) surface capacity. In the calibration of the model, manual trial and error method was used. This involved varying one parameter while holding other parameters constant and observing the effect on agreement between observed and calculated discharges at the critical gauging station below which flooding occurs in the Nyando catchment. Each time the parameter value was adjusted Nash-Sutcliffe and the bias statistics of residuals values were calculated to establish the model performance and the way forward. Parameter value with highest correlation between observed and calculated discharges was picked for that varied parameter. Same procedure was repeated for all the parameters in one sub-basin. When all parameters were optimized in one sub-basin same procedure was repeated in the next sub-basin until all were manually optimized. This ensured that a minimum objective function for all the parameters in all the sub-basins were established which could best reproduce the observed hydrograph. This provided initial values for all the parameters which were required at the start of an optimization trial. When the most significant values for all the parameters were established automatic calibration provided for in the model as optimization trials were done to ensure that reasonable parameter values were used (Parameter optimization is the process of adapting a general model to a specific watershed).

The degree of agreement on the observed and calculated hydrographs was determined using some agreed scientific function correlation coefficient, the Nash-Sutcliffe efficiency criterion and bias statistics of residuals. The parameters were then varied over a reasonable range to establish the variation on the agreement. The parameter value's which gave the best agreement between the observed and calculated values were selected. In the validation of the calibrated model, a run for another later period (subdivided as indicated above) this time with no adjustment on the parameter values was done and the agreement between the calculated and observed data was expected to be the same as in the calibration period or better. Same rainfall gauging stations used in the calibration of the model were used in its validation.

3.6 MODEL APPLICATION: EVALUATION ON EFFECTS OF DAMMING AT TWO PROPOSED DAM SITES

Previous studies in the Nyando River catchment proposed 24 locations in the catchment as possible sites for dam construction. Two dam sites, one in the upper Ainamatua River (a tributary of the Nyando River) i.e. Dam number 5 and another in the upper Nyando River i.e. Dam number 11 (see Fig. 3.2) were proposed as prospective dams that could cause significant reduction in peak discharge for the Nyando River. In the application of this model, the effects on peak discharge caused by inclusion of these two reservoirs were evaluated. This was achieved by including the two reservoirs in the model and a run was done for the period 1984 to 1991. The two hydrographs predicted by the model i.e. one with the dams and the other without the dam options were the compared. Effects on the peak discharges were then evaluated.



Source: JICA Study Team

Figure 3.2 Locations of proposed and candidate Dam sites

CHAPTER 4

4.0 RESULTS AND DISCUSSIONS

4.1 REVIEW OF EXISTING HYDRAULIC AND HYDROLOGICAL MODELS

The review of models consisted mainly in their classification as described in chapter three. In addition the model data requirements were evaluated and compared with the data that was available. The model output was also evaluated to check for the suitability in meeting the objectives of the study. Consequently the models review is summarized in tables 4.1 and 4.2 (see pages 56 & 57) and the models suitability is shown in the remarks.

4.1.1. Combined Hydrological and Hydraulic Models.

These models combine both the hydrologic and hydraulic models. They compute both rainfall runoff relationships and the flow in rivers and channels. The Watflood model version SPL9 was the only model reviewed under this category. The cost of the model, running systems requirements and the required input data limited the use of the model.

4.1.2. Hydrologic Models

These are models that compute rainfall runoff relationships and their output is normally used as the input to a Hydraulic model for the full establishment of a flood early warning system. Five models were evaluated under this category; HEC-HMS version 3.1, rrl (rainfall runoff library) version 1.0.5, NAM model, TOPKAPI (TOPographic Kinematics Approximations and Integration) model and CHYM (Cetemps HYdrological Model). With all determining factors taken into care off, HEC-HMS Version 3.1 model was selected for the study. This model does not have the capacity to delineate a catchment or to generate a basin model and was therefore coupled with HEC-GeoHMS software for these purposes. The choice of this model created a desire to evaluate hydraulic models which could use the model's output to compute down stream flows and show the extent of inundations which was necessary for the development of a flood early warning system.

Table4.1: Models Reviewed

Model	Year of release	Type	Sub-Type	Input Data Requirements	Available Data	Model Output	Remarks
Hydrologic and Hydraulic Model							
1. Watflood Version SPL9	July 2007	Deterministic	Distributed	→Grid data: Georeferenced data,channel elevation. All basin and rainfall data is based on coordinate system. UTM or LAT-LONG coordinates convinient →Rainfall data →Meteolorogical data. →Snow data. →Climatic data eg temperature, radiation. →Watershed data eg basin outline reservoirs,raingauge stations, grid size and drainage directions,drainage area. →Radar data →Contour density →Routing reach number (IREACH) →Land cover classes (IAK) eg glaciers, wetlands, water interventions, bare ground, forests, fields with crops or low vegetation. →Optional-Stage hydrographs →Optional-Stage discharge curves for lakes and reservoirs	√ √ √ √ √ √ √	→A summary of precipitation and flow. →Parameter values and errors. →Reservior information. →Streamflow data (m3/sec) and gridded information about initialization of stream flow. →Animation maps. →Diagnostic data for the melt routines. →Flow hydrographs (0bserved/computed). →Stage plot hydrogaraphs. →Import files to other programs. →Gridded initial flow data. →Spreed sheets and graphs. →Sediment routine output. →Reach inflows. →Land cover class. →Water balance calculations.	→This model runs on DOS,SUN solaris, SGI& linux systems. →The model is expensive.
Hydrologic Model							
1. HEC-HMS Version 3.1	November 2006	Deterministic	semi-distributed	→Digital elevation model (DEM) ranging from meters to kilometerscell size. →Hydrological init code (HUC)-contains major watershed boundaries. →Digital line graphs (DLG)-eg streets and railways, water surface features eg stream networks and irrigation ditches. →Stream flow gauge dat and locations (longitude and latitude coordinates. →Digital aerial photos with colors can be used as a background base map. →Drainage facilities photographs. →Soil types data. →Land use/land cover data.	√ √ √ √ √ √ √ √	→Objective function table-provides summary information about the objective of the evaluation location.it gives volume,peakflow,time of peakflows,& time to the center of mass of the computed and observed hydrographs, volume & peakflow difference between the computed and observed hydrographs. →Optimized parameter table-in tabular form it lists the parameters that were selected for optimization with one row for each parameter. →Hydrograph comparizion graphs-shows the computed outflow & observed stremflow at the objective function elevation location. →Flow comparision graphs-Shows the computed flow plotted againist the observed flow. →Flow residual graphs-Shows the difference between computed and observed flow for each time step. →Objective function graph-shows the value of the objective function at each iteration of the search method. →Element summary table-each element upstream of the objective function evaluation location is shown. →Element time series review graph-all time series data computed by an individual element are available for viewing. →Time series tables and graphs-graphs of selected time series data can be opened as graphs or time series tables.	→It is a good model for modelling Rainfall-Runoff relationship. →Requires moderate training needs. →All the required input data can be sourced easily.
2. rrl (rainfall runoff library) Version 1.0.5	June 2004	Stochastic	Lumped	→Rainfal - A continous time series of rainfall data that represents the rainfall across the catchment (mm/day). →Evaporation - A continous time series of potential evaporation or actual evapotranspiration data that represent evapotranspiration across the catchment (mm/day). →Flow gaugings - Daily runoff values for the gauging station that is to be modelled (mm/day or m3/sec). →Catchment area - This is used to convert inputs and outputs between	√ √ √	→The model outputs dailly and monthly flow or depth of runoff. →Time series data. →Soil moisture content. →Effective rinfall.	→The model is restricted to daily data input. But usually flooding occurs in less than a day after precipitation. Hourly data is therefore more convinient for a flood early warning system.
3.NAM MODEL (precipitation run-off model)	1995	Stochastic (conceptual)	Lumped	→The nine Model parameters as describe →Initial conditions. →Meteorological data: • Rainfall $ • Potential evapotranspiration. →Stream flow data	√ √ √ √ √	→Cacthment run-off hydrographs at the basin outlet or outlet of the subbasins which furnish the input to the hydrodynamic model. →Other components of the hydrological cycle such as: • Evapotranspiration, • Soil moisture content & →Ground water level.	Can either be applied independently or used to represent one or more contributing catchments that generate lateral inflow to a river network.
4. TOPKAPI Topagrafic Kinematic Aproximation & Integretion	2002	Deterministic	semi-distributed	→Soil compents that include saturated hydrsulic conductivity,saturated & residual soil water content,thickness of surface soil layer & component of transmissivity. →Mannings roughness coefficient for overland flow and for channel flow. →Evapotranspiration component. →DEM or terrian data. →Land use data →Geographical coordinates and measurement of precipitation. →Meorological data →Precipitation data.	√ √ √ √ √	Model output are discharges at control river sections. Evapotranspiration. Soil moisture &. Infiltration in evry grid cell	Applied in FEWS for various rivers in Europe Difficult to aquiring all the input data.

Model	Year of release	Type	Sub-Type	Input Data Requirements	Available Data	Model Output	Remarks
5. CHYM Model (The Cetemps Hydrological Model)	2002	Deterministic	Lumped	→Raster Digital Elevation Model. →Land use map. →MM5 simulation output files. →Radar rainfall estimates. →Satellite rainfall estimate. →Raingauge observations.	√ √ √ √ √	→Sequence of dynamic fields simulated by the model. →Rain. →Dischrge. →Wetted perimeter.	Recommended in places where the technological tools as well as geomorphological and hydrometereological information available are not so advanced.
HYDRAULIC MODELS							
1. RAP (River Analysis Package) Version 1.1	November 2003	1-D model (one Dimensional model)		→Reach geometry data- A file containing information about the shape of each cross-section and the position of the cross-sections relative to each other (or some specified datum in space). →A flow profile summary Table or output table- A file containing tables that relate the flow through the reach to the water surface level at each cross-section. →Time series flow data. →A rating curve of the hydraulic parameter- That is, combine daily discharge with a rating curve of average depth versus discharge to create a time series of daily depth.	√ √ √	→Water level at each cross-section. →Time series data. →River or channel discherge in cubic meters per second. →Rating curves. →Annual, seasonal and monthly flood frequency curves. →Annual, seasonal and monthly duration curves.	Applicable in: • Hydraulic analysis. • Time series analysis. • Ecological response analysis. • Time series manupulation.
2. LISFLOOD-FP Version 2.6.2	June 2005	1-D & 2-D Model (One dimensional & 2 dimensional model)		→Raster digital elevation map. →Boundary conditions: • Inflow discharge hydrographs-from gauging station records. •Flow across the domain edge- • Point source within the domain (this two can be based on gauging station records, spot water elevation or flux measurements, tidal curve or tide/flood frequency). →Channel slope- Taken from dem or surved cross-sections. →Channel width- " " " " " " " →Bankfull depth- " " " " " " " →Model time step- user defined. →Inflow discharge into the river or channel	√ √ √ √ √ √ √ √ √	→Mass balance output files. →Water depths. →Channel water surface profile. →Synoptic water dfepth & water surface elevation files. →Maximum water surface elvation. →Time of initial inudation, maximum depth & total time of innundation.	Recommended applications includes fluvial & plain flood applications.
3. MIKE 11 hydrodynamic module (HD)		2D (a quasi two-dimensional approach)		→Plenitary of the investigated river reaches. →Geometry characteristics of the involved hydraulic structures. →Geometry characteristics of the river bed. →Initial conditions. →Upstream and downstream boundary conditions. →Roughness parameters of the river bed and the flood plains.		Furnishes with a user deffined time step: →Water level and discharge values at the computational grid points. →Discharge velocity. →Wetted cross sectional area. →Hyadraulic radious. →Water volume and energy level.	Describes both steady and unsteady flood wave propagation.

Table 4.2: Model Requirements and Classification

MODEL TYPE	DATA NEEDS			OUTPUTS				VISUALISATION	SYSTEM REQUIREMENTS			AVAILABILITY		FLEXIBILI	TRAINING NEEDS	APPLICATIONS
	CHARACTERS	RESOLUTION		PARAMETERS					MEMORY	CONECTIVITY	SOFT WARE	FREE	LICENSED			
		TMPL	SPTL	A	B	C	D									
1. HEC-HMS Version 3.10 (Nov. 2006) Use with HEC-GeoHMS	20 to 30	1 minute to 24 hours	From 30M DEM	Graphics	Tabular	Basin Model Maps			128MB memory operation 24MB installation 17" SVGA monitor 1GB physical memory HEC-GeoHMS CPU pentium iii 500MHZ Memory 256MB	HEC Geo HMS ArcView GIS 3.2 or latter Spatial analyst 1.1 or latter	1. Microsoft Windows 2. Sun microsystems Solaris	YES YES	YES YES	YES	Minimal	→Planning & desisgning new flood damage reduction facilities. →Operating & or evaluating existing hydraulic conveyance and water control facilities →Preparing for and responding to floods. →Regulating floodplain activities. →Restoring and enhancing the environment. →Have facilities for innundation mapping. →HEC-GeoHMS Provides the connection for translating GIS spatial information into hydrologic models →It creates hydrological inputs that can be used directly with the hydrological model system, HEC-HMS →It allows users to analyse DEMS in a number of coordinate systems and projections
2. LISFLOOD-FP Version 2.6.2 (June 2005)	22	Seconds	From 100M DEM 250-500m gives good innundation	Stage & Discharge Hydrographs	Water Depth, Time step &water surface profile	Raster Maps	mass balance	ARC-View or windows visuali-zation & animati-on programme	Pentium 4 PC 1 Ghz processor 128 Mb of RAM 5Gb hard disk	Arc-view or Arc-Info or 2D raster array	Windows NT,98,2000	YES	YES	Adaptive	Moderate	→Fluvial applications. →plain flood applications. ***NB*** →Setting too large a time step can result in "chequerboard" oscillations in the solution which rapidally spreads and amplify, rendering the simulation useless.The recommended time step is between 2-20 secnds. →The model input is the inflow discharge hydrograph.It does not therefore have the capacity to generate the rainfall-runoff relationship.
3. River Analysis package Version 1.1 (Nov. 2003)	Must be gap free (fill gaps with -9999)	Basically Daily but can also handle Sub-daily, Monthly, Seasonal & Annual	DEM Not Required	HA gives TSA.	TSA gives tabulated numeric output.			TSA has its input screen	133 Intel Pentium Hard disk 10MB, RAM-256.	HECRAS or Spreadsheet Net framework	Microsoft Windows XP,2000, Mellinium Edition,98 & NT. memory-128MB,		YES	YES	Recommended	Interactively compare pre- and post-regulation flow regimes. →To calculate discharge for design floods less than 10yr ARI. →Assess the likely habitat limitations imposed by hydrologic regime. →Quantify the flow regime. →Create one dimensional hydraulic model of a river reach & calculate a time series of geomorphically relevant hydraulic parameters. NB RAP will not allow you to specify a reporting period outside the concurent period of input time series
4. rrl Rainfall Runoff Library Version 1.0.5 (5 models)	Approximately 55	Strictly Daily	DEM Not Required		Tabular			rrl has its input screen	133 Intel Pentium Hard disk 10MB, RAM-256.	Net framework version 1 1 or later	Microsoft Windows XP,2000, Mellinium Edition,98 & NT. memory-128MB,		YES	NO		
5. HEC-RAS versions 4.0 (Nov 2006) Use with HEC-GeoRAS	99		High resolution DTM that can show channel X-sectional data	plots for: X-section, Rating curve, X-Y-Z, Hydrograph plots	Tabular output	Raster Maps	Summary of errors, warnings & notes	Recommended Arc GIS model	Pentium processor or higher Hard disk 100MB,RAM-256 A mouse A CD rom drive Color Video Display	ARC GIS	Microsoft Windows XP,2000, Mellinium Edition,98 & NT. memory-128MB, HEC-GeoRAS Arc GIS 8.3 for version 4.0 & Arc GIS 9.1 for version 4.1 Both 3D & spatial analyst. Mcrosoft XML 4.0, ESRI AP frame work & AP ultilities, ESRI XML data exchange	YES YES	YES YES		Although minimum training is recommended its manual is abit long with 687 pages.	Capable of performing: →Steady and unsteady flow water surface profile calculations. →Sediment transpoort/movable boundary computations. →Water quality analysis and saveral hydraulic design computations. →Gives water surface profiles. ***NB*** Performs one dimensional hydraulic analysis HEC-GeoRAS →Creates files of geometric data for import into HEC-RAS →Import data extraced from data sets (ARC GIS layer) and Digital Terrian Model (DTM) and complemetary data sets. →It also processes and enables viewing of results exported from HEC-RAS
6. Hec-ResSim Reservior System simulation. Version 3.0 (April 2007) use with HEC-DSS (Data Storage System)		Not specified			Tabular output	Hydrograph plots			Not specified		Microsoft windows	YES	YES		Although minimum training is recommended its manual is abit long with 512 pages.	ResSim is comprised of a graphical user interface (GUI): →A computational program to simulate reservior operation, →Data storage and management capabilities, and →Graphics and reporting activities.
7. WRAM Water allocation model (Version 2.3)			Dem not required	Graphics	Tabular output			Has a visualisation Window	Pentium processor or higher Hard disk 10MB,RAM-256 A mouse	Microsoft Net framework	Microsoft Windows XP,2000, Mellinium Edition,98 & NT. memory-128MB,	YES	YES	NO	Minimal	→WRAM was developed to simulate water trading on a temporary and permanent basis, and →To be used as a tool to evaluate the impacts on regional economies. →In addition, WRAM provides the necessary link to hydrological net work models such as IQQM and REALM

4.1.3. Hydraulic Models

These are the models that compute flows along a river or in channels. 1D model indicates the depth of flow in the river channel; 2D models indicate both the flow depth and the extent of the inundations while 3D models indicate the depth, extent of the inundations and the volume. A 2D model was found sufficient to meet the objectives of this study. Three models were evaluated in this category; RAP (River Analysis Package) Version 1.1, LISFLOOD-FP Version 2.6.2 and MKE 11 hydrodynamic module (HD). Most input data for LISFLOOD-FP model can be provided from the output of a HEC-HMS model. The model is available free from the public domain and its recommended applications include fluvial and plain flood applications.

Further classification on the models was done to asses;

- The output parameters for each model like graphics, tables or maps
- How to view the results
- Operational systems requirements like the memory, processor or RAM.
- The model availability and flexibility
- Training needs and
- The recommended model applications (Table 4.2).

4.2 DATA BASE PREPARATION

This was commenced with an assessment of the available recorded historical data especially rainfall. There are a large number of rainfall observation stations in the Nyando river basin. There exist 40 working rainfall stations including adjacent ones that can be used to provide reliable precipitation characteristics for the catchment. The available records of rainfall data in some stations are summarized in Table 4.3 indicating also the period for which the data was recorded.

Table 4.3: Available Recorded Measurement Rainfall Data

Station	No	Deg.	Min.	Deg.	Min.	Year Opened	Year Closed	Drainage
Murogosi Estate, Turbo	8934012	0	40N	34	59E	1925	1964	1C
Kabagendui Kibet Farm	8935001	0	2N	35	18E	1920	xxxxx	1G
Hoeey's Bridge, Brindley Park	8935005	0	47N	35	3E	1923	1965	1B
Nandi, Koisagat Tea Estate	8935013	0	5N	35	16E	1921	xxxxx	1G
Nandi Hills, Savani Estate	8935033	0	3N	35	6E	1929	xxxxx	1G
El Lahre S.F.T. Farm	8935042	0	52N	35	7E	1936	1973	1B
Kimugul Primary School	8935050	0	2N	35	20E	1937	xxxxx	1B
Siret Tea Co. Ltd., Nandi	8935071	0	4N	35	14E	1944	xxxxx	1G
Nandi Tea Factory	8935095	0	6N	35	11E	1947	xxxxx	1G
Narasha Forest Station	8935109	0	2N	35	41E	1950	xxxxx	2E
Nandi Forest Station	8935112	0	12N	35	4E	1950	xxxxx	1F
Kibabet Estate Ltd.	8935120	0	8N	35	17E	1952	xxxxx	1F
Kapsiwoni Nandi Tea Estate Ltd.	8935130	0	7N	35	11E	1954	xxxxx	1F
Kassup Forest Reserve, Elgeyo	8935134	0	39N	35	31E	1955	xxxxx	2C
Timboroa Forest Station	8935137	0	4N	35	32E	1954	xxxxx	2E
Tenges Intermediate School	8935142	0	20N	35	48E	xxxxx	xxxxx	2E
Kipkurere Forest Station	8935148	0	5N	35	24E	1959	xxxxx	1G
Nandi Hills Agricultural Office	8935152	0	7N	35	11E	1962	xxxxx	1F
Nandi Hills, Kibweri Tea Estate	8935161	0	5N	35	9E	1958	xxxxx	1G
Miwani Sugar The Hill	9034008	0	3S	34	59E	1924	xxxxx	1G
Miwani Sugar Section I	9034012	0	3S	34	57E	1934	xxxxx	1H
Kibos National-Fiber Research Center	9034081	0	04S	34	49E	1952	xxxxx	1H
Lambwe Forest station	9034087	0	39S	34	21E	1958	xxxxx	1H
Papondit Chief's Camp	9034118	0	19S	34	56E	1908	xxxxx	1G
Kericho District Office	9035008	0	3S	34	59E	1924	xxxxx	1G
Kipkelion Railway Station	9035020	0	12S	35	28E	1904	xxxxx	2G
Equator Barguat Estate	9035042	0	1S	35	24E	1932	xxxxx	1G
Chemelil Plantation	9035046	0	4S	35	9E	1932	xxxxx	1G
Londiani Braeside	9035049	0	11S	35	37E	1933	1981	1G
Kipkelion Moran Company Ltd.	9035068	0	08S	35	27E	1938	xxxxx	1G
C.D. Cullen, Equator	9035069	0	0S	35	33E	1938	1976	2E
Kaisugu House, Kericho	9035075	0	19S	35	22E	1939	xxxxx	1G
Hundreds Acres, Londiani	9035078	0	12S	35	35E	1939	1981	1G
Itiok Farm Co. Ltd., Londiani	9035084	0	07S	35	35E	1941	1977	1G
Sorget Forest Station	9035128	0	10S	35	35E	2001	xxxxx	1G
Nyabondo Water Supply	9035142	0	23S	35	01E	1954	xxxxx	1J
Makutano Forest Station Londiani	9035155	0	03S	35	37E	1955	xxxxx	1G
Tinga Kipkelion Monastery	9035188	0	5S	35	27E	1959	xxxxx	1G
Ainamoi Chiefs Camp, Kericho	9035199	0	18S	35	16E	1960	xxxxx	1L
Kericho Laliat Farm, Ainamoi	9035200	0	16S	35	15E	1959	xxxxx	1L
Kipkorech Estate	9035201	0	19S	35	20E	1939	xxxxx	1G
Kenya Forestry College, Londiani	9035226	0	09S	35	35E	1957	xxxxx	1G
Coffee Board Sub-station, Koru	9035230	0	08S	35	17E	1959	xxxxx	1G
Kericho Chagaik Estate	9035235	0	20S	35	20E	1954	xxxxx	1G
Keresoi Forest Station, Londiani	9035240	0	17S	35	32E	1961	xxxxx	1J
Kipsitet Chief's Office KE	9035269	0	13S	35	10E	1968	xxxxx	1G
Chemelil Sugar Scheme	9035274	0	4S	35	8E	1970	xxxxx	1G

4.2.1. Precipitation Data

Precipitation data was provided as daily values and was analyzed from twenty eight rain gauging stations. Fifteen of these stations which were fairly distributed within the basin were used as the precipitation input for the catchment while the extra thirteen were used to estimate missing data in the key stations. Most of the rain gauge stations were concentrated in the highland areas of the catchment i.e. Nandi and Kericho Districts where most of the rainfall for the catchment was experienced. Location of the rain gage stations was established using their Latitude and Longitude coordinates. Their distribution over the catchment is shown in Fig. 4.1 and Table 4.3.

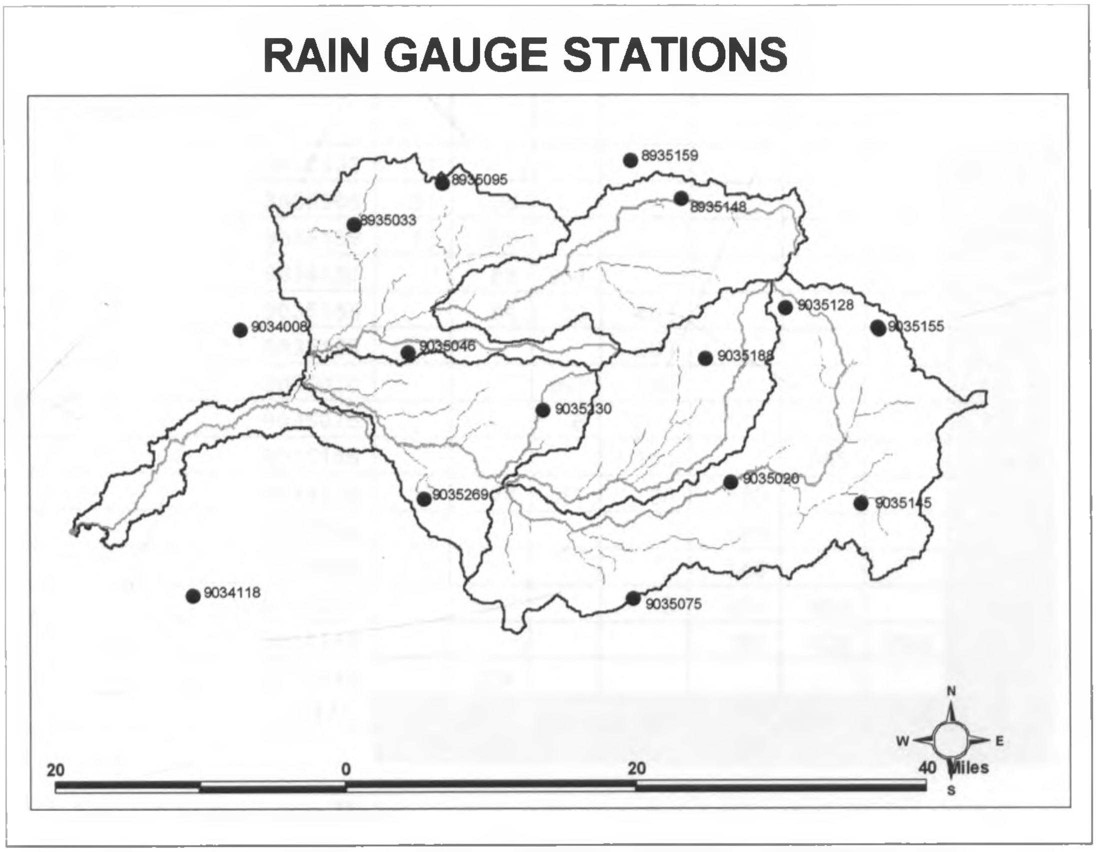


Figure 4.1: Locations of rain gauges used to provide precipitation input to the Nyando catchment

A correlation was done to establish how closely data from one station was related to the other and the results from regression analysis on twenty eight of the rain gauge stations and the numbers of data considered in each analysis were as indicated in Appendix I. Although the correlation between the gauge stations was low, the highest two stations data were used to fill gaps in the selected stations, as HEC-HMS model could not work with gaps in between the data. Data for the fifteen rain gauge stations for the period from 1970 to 1991 with gaps filled is provided in a software form. Input from each rain gauge station in the six sub-catchments delineated in the Nyando basin model was computed by Thiessen polygons and the results were as tabulated in Table 4.4. This gave a reliable representation of the precipitation characteristics for the catchment. Consequently areal rainfall for each sub-catchment was computed and stored in the model input.

Table 4.4: Ratio of the Area under Each Rain Gauge Station by Thiessen polygons

SUB-CAHMENT GAUGING STATION	1	2	3	4	5	6	7	TOTAL
8935033	111							111
8935095	87	58						145
8935159	13	106						119
9035188		68	354					422
9035155		64	12	463				539
9035128				803				803
9035020			463	152				615
9035075			6	272				278
9035145				140		865		1005
9035230	27	28	111	88	580			834
9035046					865			865
9034008					145			145
9035269				8	505	684		1197
9034118					130	420	1064	1614
8935148		224						224
TOTAL	238	548	946	1926	2225	1969	1064	8916

4.2.2. Evapotranspiration Data

Four meteorological stations (Kano, Tinderet, Kericho Timbili and Koru), all strategically located within the Nyando catchment were used to account for regional trend in monthly average evapotranspiration and this data was provided as a 24 hour measurement value. Monthly average evapotranpiration for each met station was then calculated (see section 4.6 for the computation procedure) using recorded data for the period 1970 to 1991 (The results are shown in Table 4.5).

Table 4.5: Gauging Stations Monthly average ET

Month	Station			
	Kano Irrigation	Tinderet	Kericho Timbili	Koru
Jan	138.4	132.0	121.9	114.9
Feb	114.5	106.4	99.2	94.4
Mar	79.6	73.3	67.6	64.1
Apr	83.2	77.7	72.2	68.0
May	81.3	76.4	72.4	68.4
Jun	86.0	80.9	77.0	72.5
Jul	87.2	82.3	77.1	72.7
Aug	97.1	91.9	87.6	82.6
Sep	104.8	98.8	94.7	89.4
Oct	107.9	101.8	95.3	89.9
Nov	130.4	121.0	113.5	107.0
Dec	0.0	0.0	0.0	0.0

Area contribution from each meteorological station was computed using Thiessen polygons method and the results were as indicated in (Table 4.6). Consequently expected evapotranspiration from each sub-basin was computed (Table 4.7) and fed manually to the model input.

Table 4.6: Results on meteorological stations contribution

SUB-BASIN	1	2	3	4	5	6	7	TOTAL
MET. STATION								
Kano irrigation Ahero	62				630	546	994	2232
Tindaret Tea Estate	133	482	1092	1092	45			2844
Kericho Timbili				872	55	606	70	1603
Koru Cotton Exp.Station	95	18	186	116	1280	192		1887
TOTAL	290	500	1278	2080	2010	1344	1064	8566

Table 4.7: Expected evapotranspiration from sub-basins

MONTH	SUB-CATCHMENT 1	2	3	4	5	6
Jan	173.8	168.1	166.8	153.3	173.5	168.3
Feb	160.1	149.8	149.8	142.2	164.4	161.2
Mar	170.8	132.8	139.4	139.9	199.4	184.6
Apr	128.3	94.1	99.7	97.3	153.2	138.7
May	122.3	95.6	99.7	94.7	141.1	127.6
Jun	117.7	94.6	98.6	95.0	134.8	121.6
Jul	119.9	98.2	101.7	95.7	135.3	121.6
Aug	123.6	98.1	102.3	98.2	142.2	128.7
Sep	131.3	107.6	111.1	105.9	147.9	135.7
Oct	147.1	118.6	123.3	114.4	167.7	148.0
Nov	138.9	120.9	123.4	113.9	150.7	136.7
Dec	165.1	144.9	148.5	136.8	179.7	159.4

4.2.3 Water Level at Gauging Stations

Water level stations existed in various locations along the Nyando River and on its main tributaries which was provided from WRMA Offices - Kisumu. Lake Victoria South Catchment Regional Office (LVSCRO) is responsible for water quality and sediment measurements in the rivers flowing into Lake Victoria. However, the water level measurements has been terminated or abandoned at more than half of the stations due to financial constraints. The availability of recorded data on water levels is summarized in Table 4.8. The critical gauging station for the Nyando catchment below which flooding occurs i.e. gauge 1GD03 had recorded data for the period 1969 to 2004 however most data for the period from 1990 to 2002 was missing.

Table 4.8: Availability of Recorded Data on Water Levels

	River	Station Name	Coordinates		Catchment Area (km^2)	Data Collection Period
		description of location	Latitude	Longitude		
1GB03	AINAMATUA	at Kibigori	S 0 04.553"	E 35 03.353"	1300	1968 - 1990
1GB05	AINAMATUA	at bridge after confluence	S 0 01.724"	E 35 10.452"	606	1965 - 1999
1GBO6A	MBOGO	at Chem-ker. Bridge	S 0 03.653"	E 35 08.866"	67	1973 - 1980
1GD10	KAPCHORE				158	
1GB11	AINAPSIWA	before meeting Ainopongetury	S 0 01.695"	E 35 10.478"	142	1965 - 1980
1GC01	MASAITA	at Londiani w/s dam	S 0 08.121"	E 35 36.109"	48	
1GC03	NYANDO (KIPCHORIAN)	at confl. With Kimoson	S 0 12.406"	E 35 27.708"	523	
1GC04	TUGUNON	at Tugunon bridge	S 0 15.276"	E 35 24.914"	47	1965 - 1980
1GC05	NYANDO (KIPCHORIAN)	at Lambel Farm Bridge	S 0 11.822"	E 35 32.126"	251	1965 - 1980
1GC03	NYANDO (KIPCHORIAN)	at Kikelion w/s	S 0 11.940"	E 35 28.355"	546	1967 - 1980
1GEO1	CHERONGIT					
1GDO2	NYANDO	at Ahero Bridge			1375	
1GDO3	NYANDO		S 0 07.511"	E 35 00.061"	2625	1969 - 2004
1GDO4	NYANDO				2520	1965 - 1980
1GDO7	NYANDO		S 0 0 30'50"	E 35 09'50"	1419	1963 - 1994
1GGO1	NAMUTING	(Paraaget) at Bridge	S 0 12.256"	E 35 20.844"	298	1965 - 1980
1GGO2	NAMUTING				386	
1HA01	OROBA (GREAT)		S 0 03.306"	E 35 00.119"	62	
1HA02	OROBA (LITTLE)		S 0 03.257"	E 35 58.890"	10	
1HA11	OROBA (GREAT)				72	
1HA14	AWACH (NYANGORI)		S 0 02.880"	E 35 48.340"	104	

4.3 DIGITAL ELEVATION MAP AND MODEL DEVELOPMENT

SRTM 90m DEM's have a resolution of 90m at the equator, and are provided in mosaiced 5deg X 5deg tiles for easy down load and use. All are produced from seamless dataset to allow easy mosaicing. This DEM is distributed free of charge by USGS and is available for download from the National Map seamless Data Distribution System. From the Longitudinal location of the Nyando basin, it was found to be located within two of these tiles. IDRIS Kilimanjaro image processing GIS applications were then used to join the two tiles to produce the Nyando DEM, it lies between latitude 1° and -1° 50', and longitude 34° 50' and 36° 50'. Figure 4.2 shows Nyando basin slopes grid delineated from the DEM.

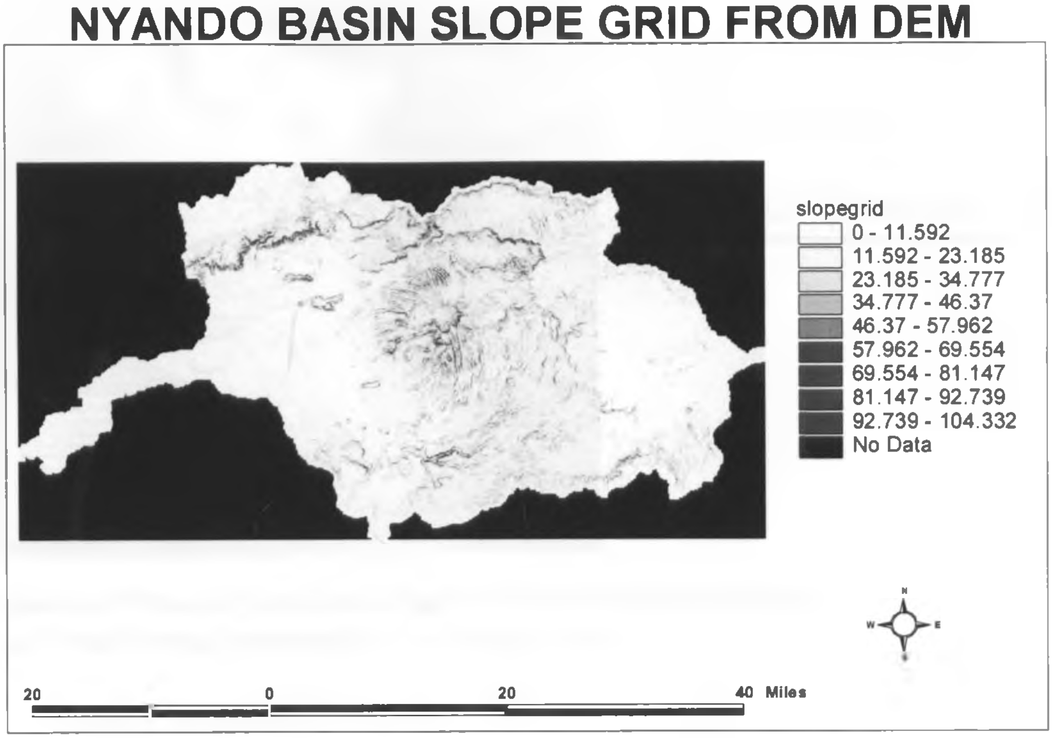


Figure 4.2: Nyando basin slopes grid from the DEM

4.4 DELINEATED NYANDO RIVER BASIN

The delineated Nyando river basin was as shown in **Figure 4.3**. The total delineated area for the basin model was 2803 km^2 compared with the published 3,600km^2. The area for the Awach River basin was not included in the delineated area which explain the difference. The two rivers join in the swampy areas next to L. Victoria and can only be modeled separately. However, the published catchment area at the key water level gauging station i.e. gauge 1GD03 was 2,625 km^2 (JICA study team, 2007) compared with the delineated area of 2,647 km^2 which indicates an error of less than 0.5% at the critical gauging station below which flooding occurs along the Nyando river catchment.

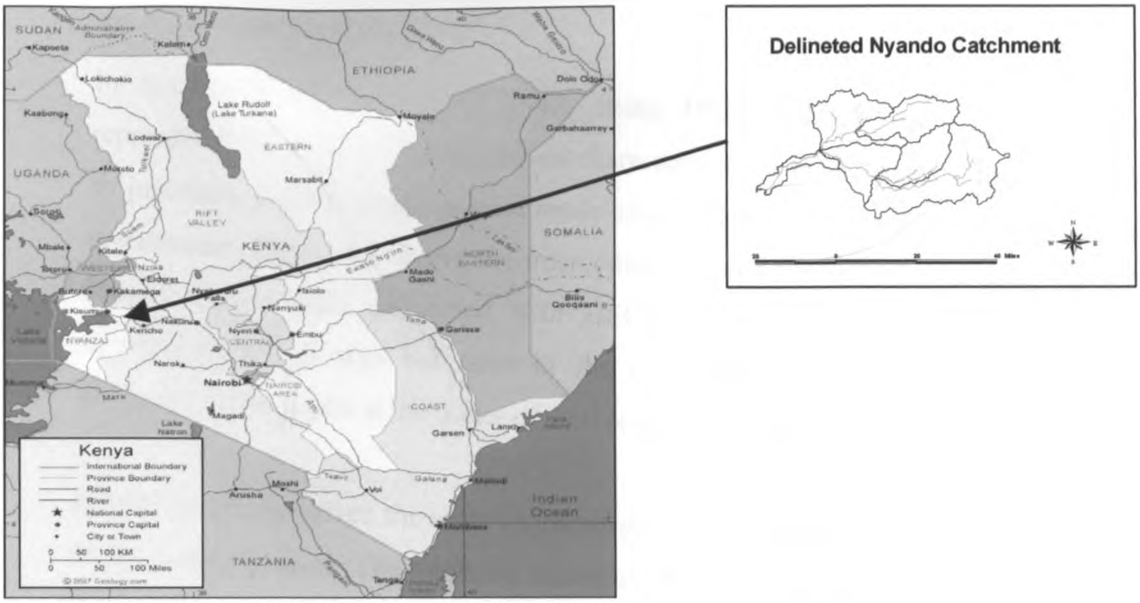


Figure 4.3: Map of Kenya showing the Location of Nyando Basin

(Source:http://geology.com/world/kenya-satellite-image.shtml)

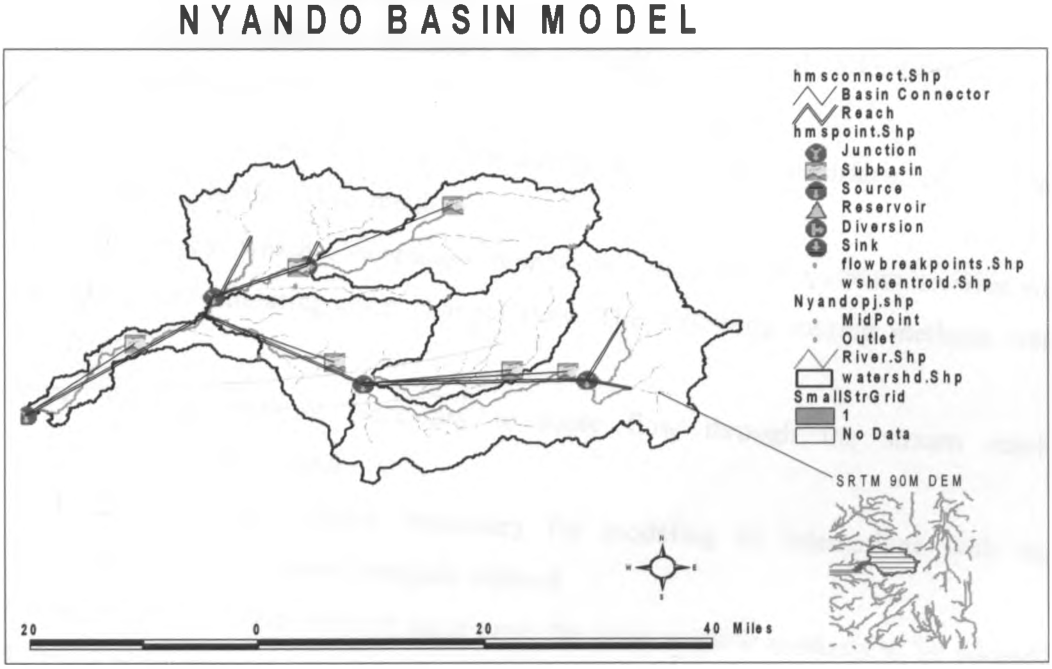


Figure 4.4: A figure showing Nyando River with its sub-basins and their connectivity

4.5 THE BASIN MODEL

In setting up the hydrologic model using HEC-GeoHMS each subbasin was represented as an element with various characteristics. The subbasins were connected by junctions, and the channels were modeled as reaches, where water could be routed downstream. Figure 4.4 shows the interconnectivity of the various subbasins for the Nyando River basin delineated with HEC-GeoHMS. A map file was used as background but it was not used in the computations. The Subbasin produced discharge hydrographs at the outlet of their respective areas.

Each subbasin was given the same characteristics which lumped the model parameters at the subbasin level. The subbasin characteristics required by the model included precipitation, evaporation, physical characteristics like slope, manning roughness and channel length. The following methods were selected for the sub-basins;

- Loss method; Necessary to perform the actual infiltration calculations; Soil moisture accounting method.
- Transform method; Necessary for calculating the actual surface runoff; Clark unit hydrograph.
- Base flow method; for calculating the actual subsurface calculations; Recession base flow method.

A reach element which conceptually represents a segment of a stream or river was necessary for simulating open channel flow. The following routing methods were selected;

- Routing method; Necessary to route flow through the stream reach; Muskingum routing
- A Loss/Gain method; Necessary for modeling of interactions with the subsurface; Constant loss/gain method.

According to the model manual these were the most suitable methods to be adopted for tropical catchments.

4.6 THE METEOROLOGIC MODEL

A meteorologic model was required to introduce meteorological inputs in to the model. The model required precipitation which was to be in the form of either rainfall or snow melt. In the case of Nyando basin, the only source of precipitation was through rainfall. Measured precipitation was provided into the model and the gage weighting method was used to compute the areal distribution.

The monthly average evapotranspiration method was used to estimate the average depth of evaporated water each month. The monthly average evapotranspiration was obtained from sumation of daily evapotranspiration for each month averaged over a number of years. Evapotranspiration rate was entered for each month through trial and error from observation on the trend on the pan evaporation. Evapotranspiration (ET) is the loss of water from canopy interception, surface depression, and soil profile storage. In the soil moisture accounting (SMA) model which was used in this study, potential ET demand was computed from monthly pan evaporation depths, multiplied by monthly-varying pan correction coefficients, and scaled to the time interval.

When ET is from interception storage, surface storage, or the upper zone of the soil profile, Actual ET is equivalent to potential ET. When potential ET is drawn from the tension zone, the actual ET is a percentage of the potential, computed as;

ActEvapSoil = PotEvaSoil.f (CurSoilStore, MaxTenStore)

Where;

ActEvapSoil = the actual ET from soil storage,

PotEvaSoil = the calculated maximum potential ET and

MaxTenStore = the user specified maximum storage in the tension zone of soil storage.

4.7 CONTROL SPECIFICATIONS

Their principle purpose was to control when simulations start and stop, and what time interval was used in the simulation. Two control specifications were set, one for the calibration period and the other for the validation period. The time window was specified for each by using a separate start date, start time, end date and end time. The start and end date for the calibration period was set as 1st January 1980 and 31st December 1983 and for the validation as 1st January 1984 and 31st December 1991 respectively. In Kenya normally, river discharge data are collected at 9.00am, which was used as the start and end time in both cases. All data were collected on daily basis and a time interval for one day was therefore adopted. The time interval for one day was also found to be satisfactory lead time for a flood early warning system for the Nyando catchment.

4.8 MODEL CALIBRATION AND VALIDATION

Model performance is usually evaluated by considering one or more objective statistics or functions of the residuals between model simulated output and observed catchment output. In calibrating the rainfall runoff model, one discharge station within the basin was used where observed flow was provided (gauge 1GD03). This is the critical gauging station below which flooding occurs along the Nyando river basin. Its location was identified using its Latitude and Longitude coordinates i.e. latitude -1.25, and longitude 34.96. Manual calibration and preliminary estimates from field measurements were utilized to minimize the search range in the optimization trials. The objective functions used in this study were the Nash-Sutcliffe and the BIAS statistics of residuals, which are poorly correlated (see typical results provided in Table 4.9).

Table 4.9: Evaluation on modeling efficiency

Optimized parameter (Transform Method; Storage Coefficient)				
Sub-basin	Parameter value (Storage coefficient)	Modeling Efficiency (E)		
		Nash-Sutcliffe	BIAS	Remarks
R5W5	13	0.607	0.02	Critical Parameter
	20	0.613	0.008	
	24	0.61	-0.019	
	23	0.61	-0.011	
	22	0.613	-0.008	
	21	0.613	0.00001	
	15	0.602	0.028	
	18	0.604	-0.0002	
R4W4	13	0.0613	0.00001	
	15	0.606	-0.002	
	18	0.605	-0.01	
	21	0.603	-0.015	
	10	0.605	-0.003	
	11	0.605	-0.003	
	12	0.614	-0.003	
R3W3	13	0.614	-0.003	
	12	0.614	-0.007	
	17	0.611	-0.0011	
	20	0.611	-0.02	
R2W2	12	0.614	-0.008	
	13	0.614	-0.007	
	14	0.614	-0.008	
R1W1	12	0.616	-0.039	
	13	0.616	-0.007	
	15	0.613	-0.008	
	18	0.611	-0.025	

Although the Nash-Sutcliffe efficiency criterion is frequently used for evaluating the performance of hydrological models, it favors a good match between observed and modeled high flows, while sacrificing to some extent matching of below-mean flows (Houghton-Carr, 1999). It was for this reason that two different measures of model performance were considered. These results were then plotted and the most optimal values were derived from the graph.

Parameter optimization was done on the critical parameters i.e. those that created a significant change on the modeling efficiencies (see sample results in Table 4.10). Soil parameters were adjusted until a best fit was found that matched the observed runoff from the sub-catchment.

Table 4.10: Sample results on Parameter optimization

ELEMENT	PARAMETER	UNITS	INITIAL VALUE	OPTIMIZED VALUE	OBJECTIVE FUNCTION SENSITIVITY
R3W3	Base flow initial flow	m3/sec	5.1251	7.8409	0.00
	threshold R.	mm	1.127	1.1479	0.00
	Canopy capacity	%	20.403	18.819	0.00
	Recession constant		0.92	0.95579	0.00
	Soil initial rate	mm/Hr	2.8704	2.9062	0.00
	Soil initial storage	%	85	36.282	0.00
	Soil percolation rate	mm/Hr	1.5	1.6905	0.00
	Surface capacity	mm	0.204	0.3106	0.00
	Surface initial storage	%	10	6.2746	0.00
	Tension zone capacity	mm	216	215.02	0.05

The calibration resulted in a hydrograph that was somehow similar in shape as the observed hydrograph. Figure 4.5 shows observed and simulated daily discharges from five sub-basins in Nyando catchment considered for the calibration. The simulated and observed hydrograph peaks were realized on 28th November 1982 and 29th November 1982 at 9.00 am respectively as $94.8m^3/s$ and $108.00m^3/s$. The total simulated outflow was 707.80 mm while the observed outflow was 709.99 mm. The Nash-Sutcliffe efficiency for calibration was 0.64 while Bias efficiency was 0.002. These results indicated a good adaptability of the HEC-HMS model to the Nyando river catchment.

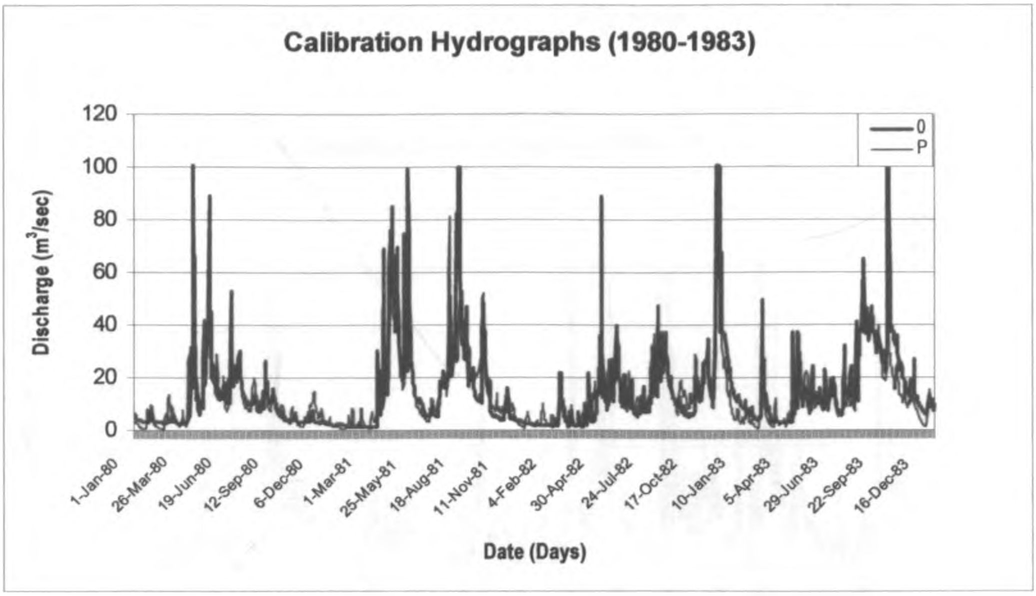


Figure 4.5: Calibration results for river gauging station 1GD03 (Nash-Sutcliffe =0.64 BIAS = 0.002)

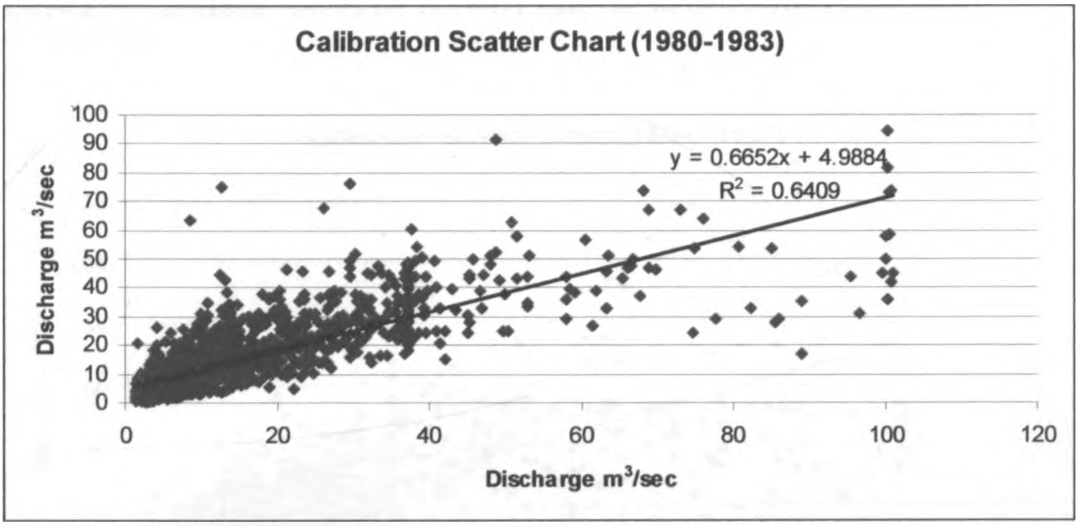


Figure 4.6: A figure showing the correlation coefficient of the simulated and observed values in Nyando River at gauging station 1GD03 (Calibration)

A correlation was done to establish how closely the observed data was related to the simulated data which gave a figure of 0.64 (see Figure 4.6) also indicating good relation. Results from the simulated and observed daily discharge for the five sub-basins used in the validation are presented in Figure 4.7. Nash-Sutcliffe efficiency was 0.66, a deserved higher figure than during calibration while the bias method was 0.051. The correlation coefficient was 0.66 as indicated in Figure 4.8. In the modeling practice the validation should give similar or better results to the calibration, in this case better results were noted.

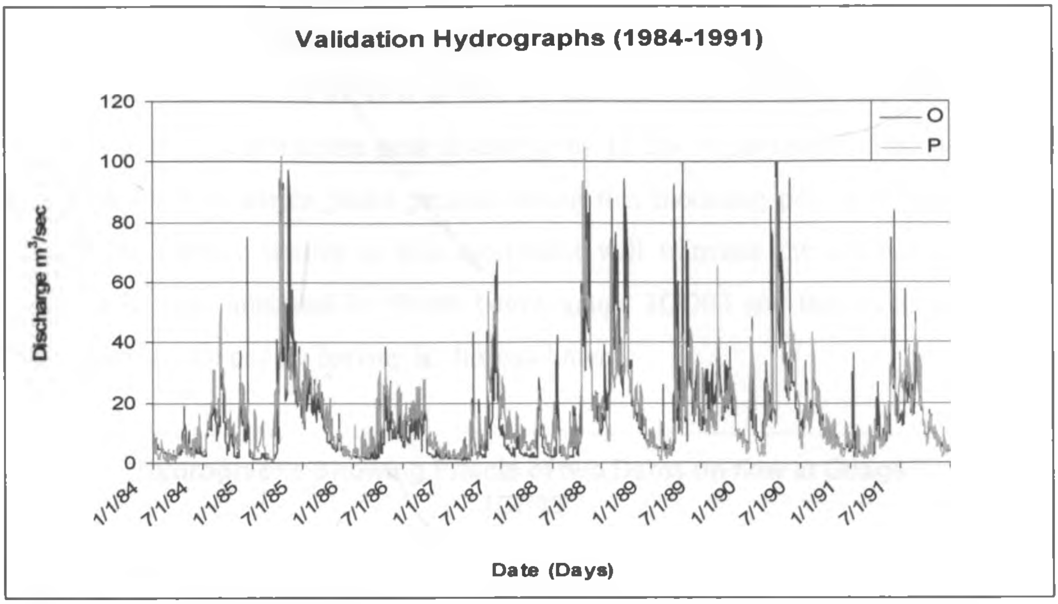


Figure 4.7: Validation results for the river gauging station 1GD03 **(Nash-Sutcliffe =0.66 BIAS = 0.051)**

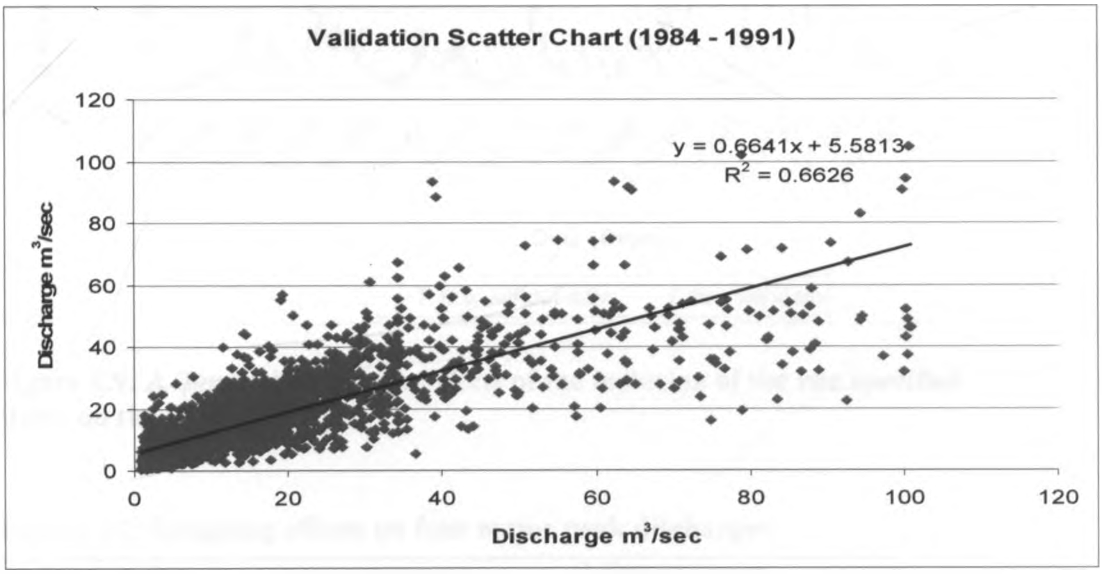


Figure 4.8: A figure showing the correlation coefficient of the simulated and observed values in Nyando River at gauging station 1GD03 (Validation)

4.9 EVALUATION ON EFFECTS OF DAMMING AT TWO PROPOSED DAM SITES

Figure 4.9 compares predicted hydrographs with and without the dams for the period 1984 to 1991. The peak outflow which was predicted to be on 01 May 1988 at 104.8m^3/sec was reduced to 91.0 m^3/sec by the inclusion of these two dams. This translates to a reduction of the peak discharge by 13.2%. A summary of the damming effects on the four major peaks present during this modeling period is provided in Table 4.11. Further studies in this catchment will translate these findings in the reduction in area inundated by floods below gauge 1GD03 and the social economic implications to the people leaving in this catchment.

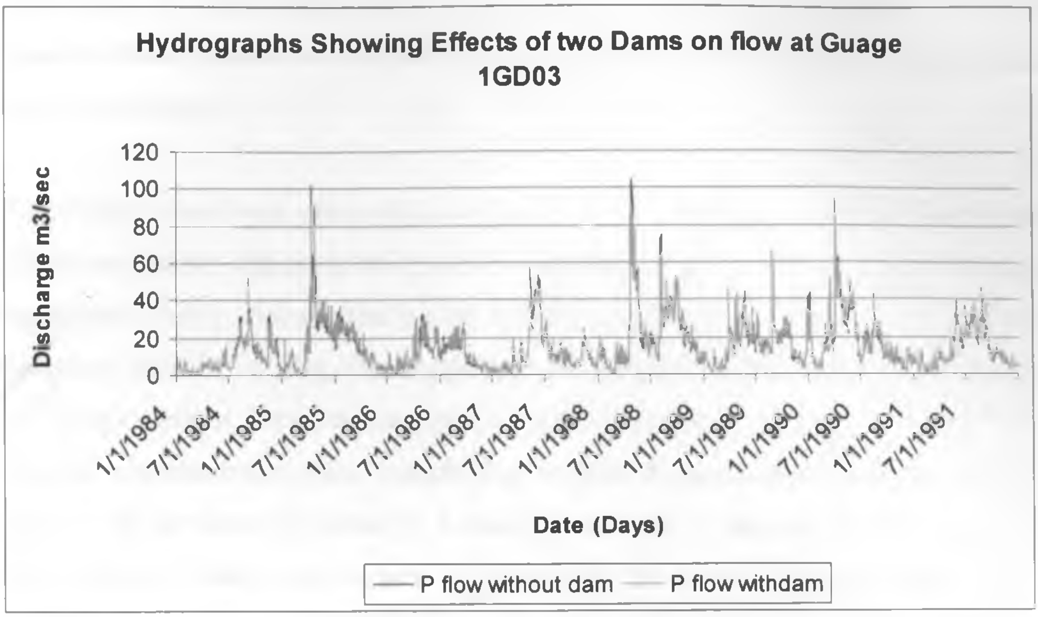


Figure 4.9: A figure showing the effects of the inclusion of the two specified Dams on the flow

Table 4.11: Damming effects on four major peak discharges

DATE	PEAK DISCHARGES		REDUCTION VOL. M^3/SEC	PERCENTAGE
	WITHOUT DAMS	WITH DAMS		
15/4/1985	101.9	91	10.9	10.7
24/4/85	90.7	80.6	10.1	11.1
1/5/1988	104.8	91	13.8	13.2
6/4/1990	94.4	85.7	8.7	9.2

CHAPTER 5

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

This research contributed to the attempt to understand how extreme flood events are generated, propagate and inundate rivers and their flood plains. Based on the model, it was possible to predict peak flows from Nyando River. In the application of the study, an evaluation on the effects created on the flow from the inclusion of two proposed dams in the Nyando catchment was done.

A procedure was followed for selecting a model which was based on model suitability, its cost, input data requirement, systems requirement and the recommended applications of the model. Based on this HEC-HMS hydrological model was selected.

HEC-HMS model was successfully set up with the aid of HEC-GeoHMS software which was used to delineate the Nyando catchment from a 90 m SRTM DEM and to expediently create hydrological inputs that were used directly with the model. The necessary data for running the model was also prepared which consisted of fifteen rain gauge stations, four meteorological stations and one river gauging station. The physical representation of the Nyando river watershed was accomplished with a basin model with elements connected in a dendritic network to simulate runoff processes. Meteorological data analysis was performed by the meteorological model which included precipitation and evapotranspiration. Control specifications included starting date and time, ending date and time for the historical precipitation data for the Nyando watershed.

From the results, in the calibration of the model the total simulated outflow was 707.8 mm compared to the observed outflow at 709.99 mm which indicates an error of 0.3%, a small variance. Also in the calibration of the model, Nash-Sutcliffe efficiency was 0.64 and the Bias efficiency was 0.002, while in the validation of the model Nash-Sutcliffe efficiency was 0.66 and the Bias efficiency was 0.015. These figures indicated a good adaptability of the HEC-HMS model to the Nyando catchment. The simulated peak outflow was 94.8m^3/s compared to the observed outflow at 108.0m^3/s occurring on 28th and 29th November 1982 respectively, figures also showing close relationship. The peak outflow which was predicted to be on 01 May 1988 at 104.8m^3/sec was reduced to 91.0 m^3/sec by the inclusion of the two proposed dams, one in the Ainamatua tributary and the other in upper Nyando river. This translated to a reduction of the peak discharge by 13.2%. A summary of the damming effects on four major peak discharges in the river were evaluated. Further studies in this catchment will translate these findings in the reduction in area inundated by floods below gauge 1GD03 and the social economic implications to the people leaving in this catchment. These results indicated the potential of the HEC-HMS model to be used in future planning and development of other proposed candidate dams in the Nyando catchment.

It can therefore be concluded that the HEC-HMS model version 3.1 was well adapted to the Nyando River watershed and gave good predictions on how rainfall is turned into runoff and can be effectively used to provide useful information that aid in decision making in the equitable management of the watershed. It can aid in: planning and designing new flood damage reduction facilities, operating and or evaluating existing hydraulic conveyance and water control facilities, preparing and responding to floods, regulating flood plain activities, restoring and enhancing the environment and inundation mapping.

5.2 RECOMMENDATIONS

Based on this study the following recommendations were made:

1. In further development for the establishment of a flood early warning system for the Nyando river basin, the data generated by HEC-HMS model can be used as an input to a hydraulic model which is intended to provide information on the extent of inundations and all other river hydraulic characteristics.
2. Awach River joins the Nyando River in the swampy areas of the Winam Gulf of Lake Victoria. In order to establish back water effects caused by flooding from the Awach River on the Nyando River, it is necessary to conduct a hydrological modeling of the Awach River basin. This will establish the combined effects by flooding from these two rivers which naturally can flood at the same time.

3. To increase the reliability of the precipitation estimates, techniques based on weather radar and satellite observations (or combinations of those) should be considered to provide accurate forecast before storms.
4. To increase the reliability of flood early warning systems, real time weather forecasting is needed.

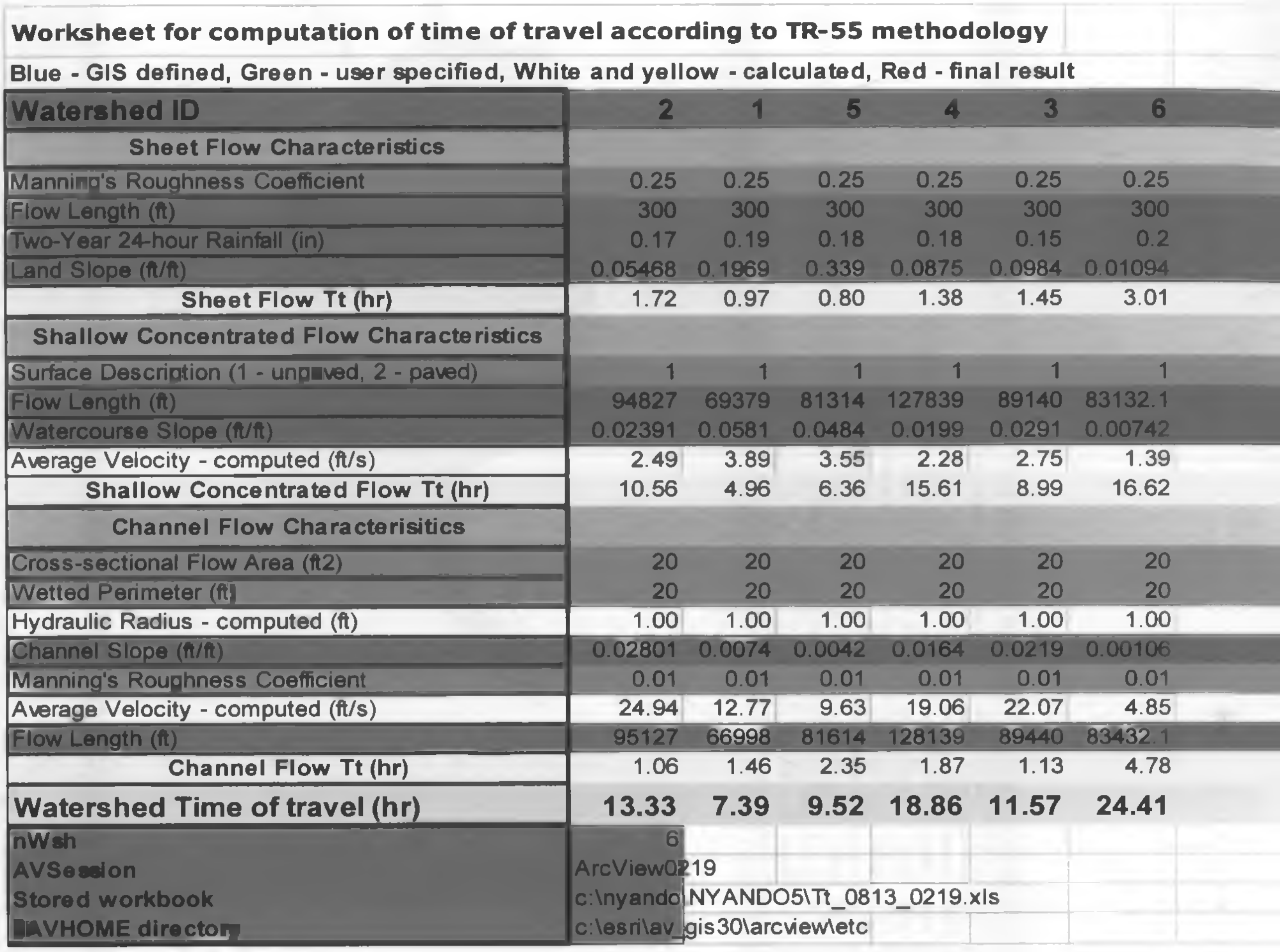
APPENDIX 1: MATRIX OF COEFFICIENT CORRELATION - r^2

	8935033	8935095	8935159	9035188	9035155	9035128	9035020	9035075	9035145	9035230	9035046	9034008	9035269	9034118	8935148	8935001	8935013	9035002	9035201	9035266	9035180	9034086	9034009	9034007	8935161	9034025	9035301	9034023
8935033	**********	0.331	0.014	-0.252	-0.252	-0.24	-0.236	-0.354	-0.422	-0.266	0.238	0.245	0.17	0.112	0.198	0.184	0.616	0.229	0.201	0.223	0.176	0.184	-0.222	0.24	0.377	0.192	0.206	0.13
8935095	0.331	**********	0.017	0.208	0.164	0.187	0.166	0.157	0.182	0.159	0.157	0.191	0.168	0.087	0.275	0.209	0.328	0.176	0.206	0.262	0.163	0.121	0.162	0.173	0.282	0.155	0.194	0.118
8935159	0.014	0.017	**********	0.01	0.014	0.33	0.024	0.017	0.28	0.014	0.02	0.009	0.028	0.026	0.017	0.032	0.01	0.009	0.022	0.003	0.009	0.03	0.004	0.017	0.007	0.014	0.007	0.026
9035188	-0.252	0.208	0.01	**********	0.359	0.315	0.319	0.314	0.294	0.3	0.218	0.175	0.166	0.129	0.288	0.154	0.277	0.348	0.208	0.306	0.359	0.192	0.127	0.158	0.28	0.171	0.337	0.148
9035155	-0.24	0.187	0.033	0.315	**********	0.32	0.299	0.289	0.248	0.275	0.256	0.136	0.185	0.158	0.2621	0.157	0.249	0.378	0.202	0.303	0.365	0.205	0.107	0.132	0.235	0.169	0.277	0.16
9035128	-0.236	0.168	0.024	0.319	0.299	**********	0.235	0.255	0.241	0.208	0.19	0.126	0.15	0.122	0.261	0.16	0.201	0.333	0.228	0.306	0.327	0.162	0.096	0.118	0.196	0.136	0.251	0.151
9035020	-0.236	0.168	0.024	0.319	0.299	0.235	**********	0.333	0.275	0.277	0.219	0.169	0.166	0.143	0.239	0.139	0.225	0.308	0.179	0.214	0.277	0.2	0.141	0.166	0.257	0.171	0.29	0.165
9035075	-0.354	0.157	0.017	0.314	0.289	0.255	0.333	**********	0.435	0.342	0.245	0.204	0.202	0.162	0.208	0.15	0.2	0.273	0.287	0.226	0.275	0.252	0.161	0.167	0.272	0.205	0.412	0.195
9035145	-0.422	0.182	0.028	0.294	0.248	0.241	0.275	0.435	**********	0.454	0.24	0.172	0.22	0.175	0.238	0.172	0.219	0.273	0.287	0.23	0.274	0.207	0.145	0.152	0.247	0.194	0.608	0.202
9035230	-0.266	0.159	0.014	0.3	0.275	0.208	0.277	0.342	0.454	**********	0.326	0.212	0.274	0.142	0.197	0.143	0.235	0.253	0.179	0.168	0.265	0.261	0.198	0.201	0.256	0.2	0.259	0.242
9035046	0.238	0.157	0.02	0.218	0.256	0.19	0.219	0.245	0.24	0.326	**********	0.239	0.216	0.17	0.188	0.144	0.216	0.217	0.129	0.164	0.21	0.38	0.177	0.22	0.252	0.298	0.273	0.15
9034008	0.245	0.191	0.009	0.175	0.136	0.126	0.169	0.204	0.172	0.212	0.239	**********	0.158	0.13	0.142	0.102	0.217	0.13	0.134	0.133	0.132	0.287	0.6	0.682	0.292	0.246	0.2	0.117
9035269	0.17	0.168	0.028	0.166	0.185	0.15	0.166	0.202	0.22	0.274	0.216	0.158	**********	0.129	0.171	0.13	0.213	0.196	0.189	0.164	0.186	0.186	0.137	0.16	0.172	0.183	0.21	0.144
9034118	0.112	0.087	0.026	0.129	0.158	0.122	0.143	0.162	0.175	0.142	0.17	0.13	0.129	**********	0.1	0.182	0.137	0.084	0.181	0.085	0.114	0.188	0.098	0.098	0.2	0.164	0.162	0.136
8935148	0.198	0.275	0.017	0.288	0.262	0.261	0.239	0.208	0.238	0.197	0.188	0.142	0.171	0.1	**********	0.166	0.248	0.263	0.241	0.325	0.268	0.153	0.126	0.107	0.232	0.138	0.257	0.144

NO OF DAYS CONSINDERED IN EACH REGRESSION

	8935033	8935095	8935159	9035188	9035155	9035128	9035020	9035075	9035145	9035230	9035046	9034008	9035269	9034118	8935148	8935001	8935013	9035002	9035201	9035266	9035180	9034086	9034009	9034007	8935161	9034025	9035301	9034023
8935033	**********	7241	6807	7206	7023	7205	6931	7235	7266	7390	6505	6138	7148	5019	7209	6902	6755	6171	6141	6632	7173	7269	6257	6110	7239	7390	7389	7930
8935095	7241	**********	7215	7611	7554	7642	7089	7641	7640	7795	6848	6296	7523	5269	7340	7276	5605	6515	7028	7671	7516	7458	6446	6268	7122	7795	7794	7795
8935159	6808	7215	**********	7240	7269	7272	6903	7359	7299	7454	6541	5893	7182	4929	7300	6905	6203	6385	6753	7330	7175	7088	6196	5956	7083	7454	7454	7454
9035188	7206	7611	7240	**********	7641	7699	7116	7669	7699	7823	6907	6322	7582	5361	7670	7274	6665	6543	7087	7730	7544	7484	6473	6325	7452	7823	7822	7823
9035155	7023	7554	7269	7641	**********	7642	7119	7642	7672	7796	6910	6266	7555	5240	7642	7216	6245	6515	7030	7703	7517	7458	6415	6266	7424	7796	7795	7796
9035128	6931	7089	6903	7116	7119	**********	7146	7698	7728	7852	6936	6322	7612	5358	7640	7272	7852	7335	7852	7852	7852	7821	7271	6510	7821	7852	7851	7852
9035020	6931	7089	6903	7116	7119	7146	**********	7238	7299	7299	7056	6261	7299	4777	7240	7299	6141	6660	6782	7299	7268	7270	6841	6384	7299	7299	7298	7299
9035075	7235	7641	7359	7669	7642	7698	7238	**********	7883	7883	7883	7852	7855	7459	7823	7822	7852	6970	7172	7883	7604	7852	7702	6921	7852	7883	7883	7883
9035145	7266	7640	7299	7699	7672	7728	7299	7883	**********	7882	7027	6318	7671	5357	7669	7731	7791	6633	7177	7850	7634	7544	6440	6323	7511	7876	7881	7882
9035230	7390	7795	7454	7823	7796	7852	7299	7883	7882	**********	7086	7975	7765	5450	7824	7458	6755	6695	7240	7913	7728	7668	6416	6420	7510	7880	7890	7890
9035046	6505	6848	6541	6907	6910	6936	7056	7883	7027	7086	**********	5588	6879	4626	6908	6540	5869	5566	6263	7058	6810	6843	5709	5562	6749	7085	7088	7089
9034008	6138	6296	5893	6322	6266	6322	6261	7852	6318	7975	5588	**********	6411	4437	6260	5923	5650	5221	5985	6349	6194	6351	6196	6291	6319	6411	6410	6411
9035269	7148	7523	7182	7582	7555	7612	7299	7855	7671	7765	6879	6411	**********	5271	7552	7185	6543	6512	7029	7703	7486	7427	6383	6235	7394	7789	7764	7765
9034118	5019	5269	4929	5361	5240	5358	4777	7459	5357	5450	4626	4437	5271	**********	5237	5085	4898	4324	4747	5387	5294	5236	4560	4381	5264	5444	5450	5450
8935148	7209	7340	7300	7670	7642	7640	7240	7823	7669	7824	6908	6260	7552	5237	**********	7274	6604	6635	7057	7730	7514	7455	6443	6295	7484	7819	7824	7824

APPENDIX 2: Worksheet for Computation of Time of Travel Interval According To TR-55

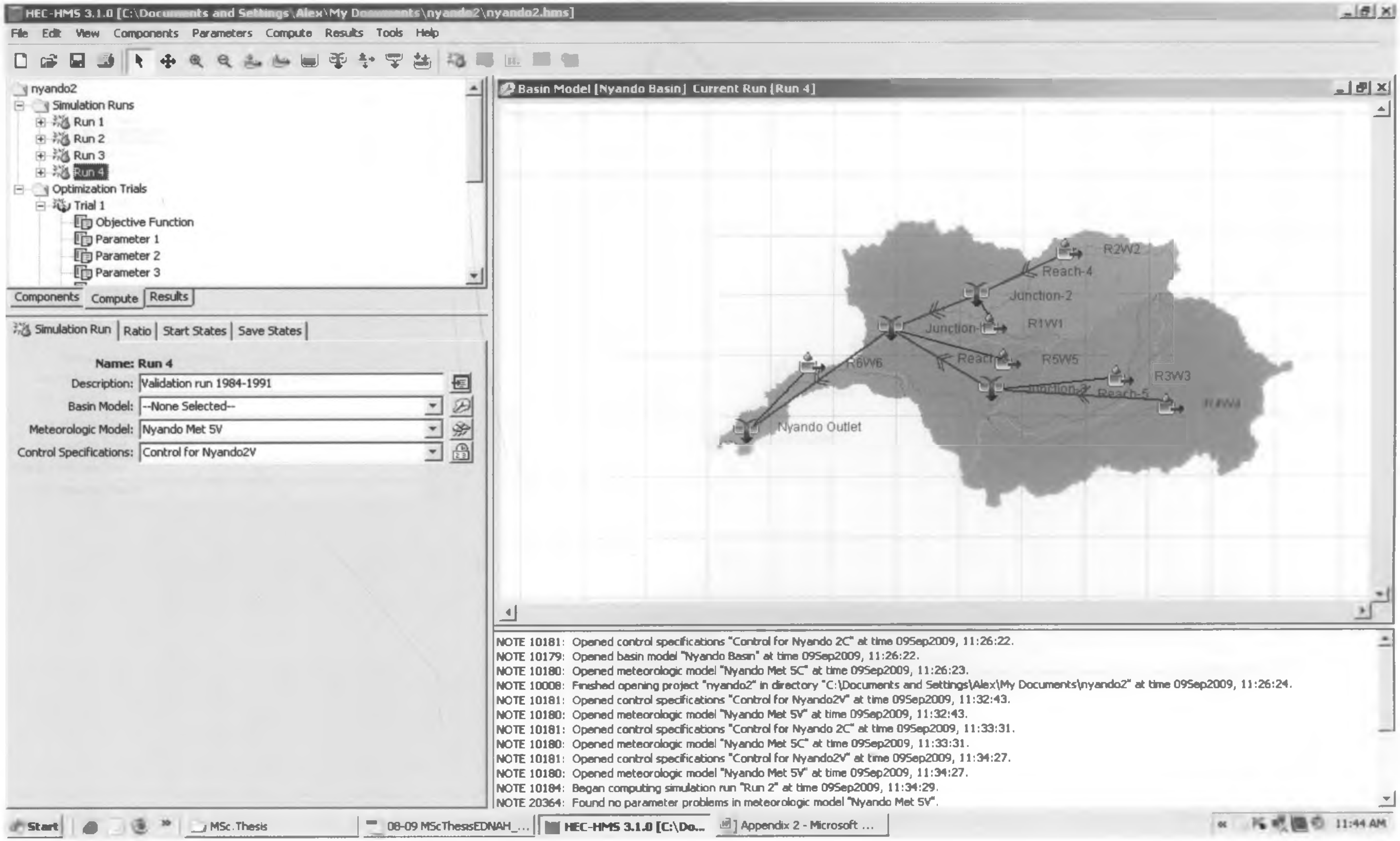


Worksheet for computation of time of travel according to TR-55 methodology

Blue - GIS defined, Green - user specified, White and yellow - calculated, Red - final result

Watershed ID	**2**	**1**	**5**	**4**	**3**	**6**
Sheet Flow Characteristics						
Manning's Roughness Coefficient	0.25	0.25	0.25	0.25	0.25	0.25
Flow Length (ft)	300	300	300	300	300	300
Two-Year 24-hour Rainfall (in)	0.17	0.19	0.18	0.18	0.15	0.2
Land Slope (ft/ft)	0.05468	0.1969	0.339	0.0875	0.0984	0.01094
Sheet Flow Tt (hr)	1.72	0.97	0.80	1.38	1.45	3.01
Shallow Concentrated Flow Characteristics						
Surface Description (1 - unpaved, 2 - paved)	1	1	1	1	1	1
Flow Length (ft)	94827	69379	81314	127839	89140	83132.1
Watercourse Slope (ft/ft)	0.02391	0.0581	0.0484	0.0199	0.0291	0.00742
Average Velocity - computed (ft/s)	2.49	3.89	3.55	2.28	2.75	1.39
Shallow Concentrated Flow Tt (hr)	10.56	4.96	6.36	15.61	8.99	16.62
Channel Flow Characterisitics						
Cross-sectional Flow Area (ft2)	20	20	20	20	20	20
Wetted Perimeter (ft)	20	20	20	20	20	20
Hydraulic Radius - computed (ft)	1.00	1.00	1.00	1.00	1.00	1.00
Channel Slope (ft/ft)	0.02801	0.0074	0.0042	0.0164	0.0219	0.00106
Manning's Roughness Coefficient	0.01	0.01	0.01	0.01	0.01	0.01
Average Velocity - computed (ft/s)	24.94	12.77	9.63	19.06	22.07	4.85
Flow Length (ft)	95127	66998	81614	128139	89440	83432.1
Channel Flow Tt (hr)	1.06	1.46	2.35	1.87	1.13	4.78
Watershed Time of travel (hr)	**13.33**	**7.39**	**9.52**	**18.86**	**11.57**	**24.41**
nWsh	6					
AVSession	ArcView0219					
Stored workbook	c:\nyando\NYANDO5\Tt_0813_0219.xls					
AVHOME directory	c:\esri\av_gis30\arcview\etc					

APPENDIX 3: NYANDO BASIN MODEL



Name: Run 4

Description: Validation run 1984-1991

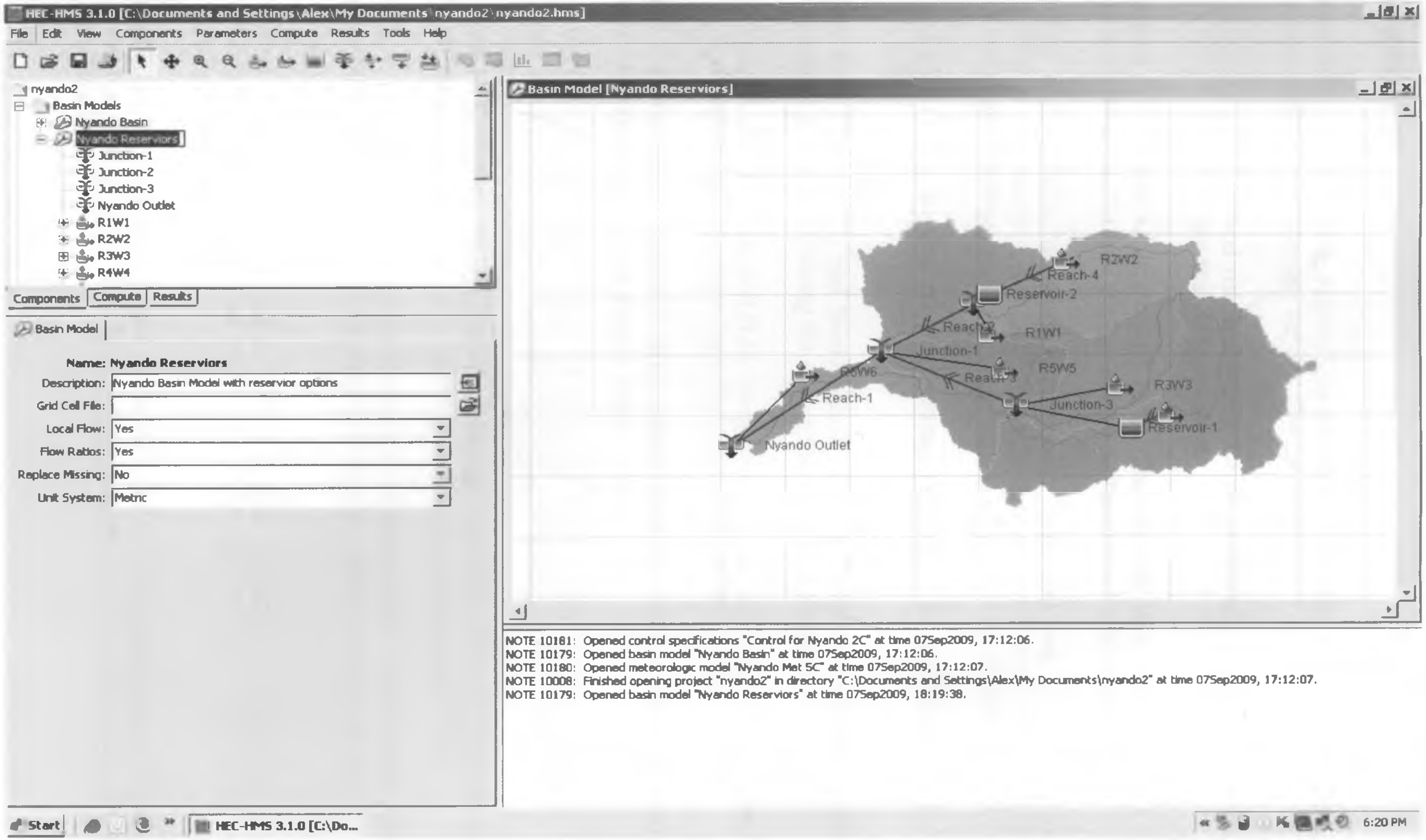
Basin Model: --None Selected--

Meteorologic Model: Nyando Met 5V

Control Specifications: Control for Nyando2V

```
NOTE 10181:  Opened control specifications "Control for Nyando 2C" at time 09Sep2009, 11:26:22.
NOTE 10179:  Opened basin model "Nyando Basin" at time 09Sep2009, 11:26:22.
NOTE 10180:  Opened meteorologic model "Nyando Met 5C" at time 09Sep2009, 11:26:23.
NOTE 10008:  Finished opening project "nyando2" in directory "C:\Documents and Settings\Alex\My Documents\nyando2" at time 09Sep2009, 11:26:24.
NOTE 10181:  Opened control specifications "Control for Nyando2V" at time 09Sep2009, 11:32:43.
NOTE 10180:  Opened meteorologic model "Nyando Met 5V" at time 09Sep2009, 11:32:43.
NOTE 10181:  Opened control specifications "Control for Nyando 2C" at time 09Sep2009, 11:33:31.
NOTE 10180:  Opened meteorologic model "Nyando Met 5C" at time 09Sep2009, 11:33:31.
NOTE 10181:  Opened control specifications "Control for Nyando2V" at time 09Sep2009, 11:34:27.
NOTE 10180:  Opened meteorologic model "Nyando Met 5V" at time 09Sep2009, 11:34:27.
NOTE 10184:  Began computing simulation run "Run 2" at time 09Sep2009, 11:34:29.
NOTE 20364:  Found no parameter problems in meteorologic model "Nyando Met 5V".
```

APPENDIX 4: NYANDO BASIN MODEL WITH RESERVOIRS



Name: Nyando Reservoirs

Description: Nyando Basin Model with reservior options

Grid Cell File:

Local Flow: Yes

Flow Ratios: Yes

Replace Missing: No

Unit System: Metric

```
NOTE 10181:  Opened control specifications "Control for Nyando 2C" at time 07Sep2009, 17:12:06.
NOTE 10179:  Opened basin model "Nyando Basin" at time 07Sep2009, 17:12:06.
NOTE 10180:  Opened meteorologic model "Nyando Met 5C" at time 07Sep2009, 17:12:07.
NOTE 10008:  Finished opening project "nyando2" in directory "C:\Documents and Settings\Alex\My Documents\nyando2" at time 07Sep2009, 17:12:07.
NOTE 10179:  Opened basin model "Nyando Reserviors" at time 07Sep2009, 18:19:38.
```

REFERENCES

Albert C.P.L., K.W.Yeung, (2007). Concepts and techniques in geographical information systems, University of Georgia Athens, Georgia, U.S.A.

Alkema D., (2004). Flood risk assessment for environmental impact assessment (EIA): An example of motor way near Trenton, Italy.

Bastidas L.A., Gupta H.V., Sorooshian S., Shuttleworth W.J., and Yong Z.l., (1999). Sensitivity analysis of a land surface scheme using multi-criteria methods.

Berihun A.T., (2003). Modeling water quality using soil and water assessment tool (SWAT), A case study in the Lake Naivasha Basin, Kenya, International Institute for Geo-Information Science and Earth Observations (ITC), Enachede, The Netherlands.

Beven J.K., (1989). Rainfall runoff modeling, The primer, John Wiles and sons ltd, New York, USA.

Boyle D.P., Gupta H.V., and Sorooshian S., (2000). Towards improved calibration of hydrological models, combining the strength of manual and automatic methods.

Brooks K.N., P.F. Flolliott, and H.M. Gregersen, (1997). Hydrology and the management of agricultural watersheds, Iowa State University Press, Chelsea, MI.

CEIWR-HEC, (1991). Missouri River system analysis model – Phase 1, Institute for Water Resources Engineering Center, Davis, USA.

CEIWR-HEC, (1993). Assessment of structural flood-control measures on alluvial fans, Institute for Water Resources Engineering Center, Washington D.C. USA.

CEIWR-HEC, (1996). Analysis of flood damage reduction measures Napa River, Napa CA, Institute for Water Resources Engineering Center, Sacramental, USA.

Chow, V.T., (1983). Open Channel Hydraulics. McGraw-Hill. Auckland New Zealand Cooperative research center for catchment hydrology: series on model choices.

Crawford N.H., and Linsle R.K., (1996). Digital simulation in hydrology, Stanford watershed model IV, Technical report 39, department of civil engineering, Stanford University, California, USA.

Daniel K.., Troy N., John C.P. and Arlen D.F., (1996). Pilot application of weather radar – Based runoff forecasting Salt River basin, Institute for Water Resources Engineering Center, Davis, USA.

De Roo, A. and G. Schmuck, (2003). European flood alert system; Joint research center, Institute for Environmental and Sustainability. European commission.

Deliverable report 7.1 Contract no. EVGI-CT-1999-00011, (1999). A European flood forecasting system, Institute of Environmental and Sustainability of the European Commission Joint Research Center.

Dinand A., (2004). RS and GIS Applications in flood forecasting, Department of Earth Systems Analysis, International Institute for Geo-Information Science and Earth Observations (ITC), Enschede, The Netherlands.

EM – DAT (Emergency database), www.em-dat.net-

Erik Eckholm, (1982). Down to Earth, Pluto Press; Norton.

Gary W.B., Mark R.J., Cameron T.A., Jason N. and Chris N.D., (2003). Susquehanna River flood warning and response system; Institute for Water Resources Engineering Center, Davis, USA.

Georgia storm-water management manual: Volume 2, (2001). Technical Handbook.

GLCF: AVHRR, (2008). Global land cover classification Data, Department of geography, Institute for advanced computer studies, University of Maryland, U.S.A.

Helmet J.G., and Eric F.L., (2001). What drives tropical deforestation, LUCC report series No.4, University of Louvain, Belgium.

Houghton-Carr, (1999). Assessment criteria for simple conceptual daily rainfall-runoff models, Institute of Hydrology, Wallingford, Oxford shire, UK.

JICA study team, (2008). The study on integrated flood management for Nyando River basin.

JICA study team, (1992). Study on national water plan. Progress report No.1.

Jason N. and David W., (1999). Analysis of flood control operation of Iowa/Des Moines River reservoir system using linear programming techniques; Institute for Water Resources Engineering Center, Rock Island, USA.

Jennifer, A.O., (2004). Scenario study for flood hazard assessment in the lower Bicol flood plain Philippine using a 2D flood model; Based on the 1988 flood event caused by typhoon Yonning; A case study for flood hazard assessment WR 4500 SLARIM an ITC research project in strengthening local authority in risk management.

Karen P.B., Robe M., Francois P.B., and Clande M., (2001). The impact of climate change on seasonal floods of a Southern Quebec River basin.

Krause P., D.P. Boyle, and F. Base, (2005). Comparison of different efficiency criteria for hydrological model assessment. Department for geoinformatics, Hydrology and Modeling, Friedrich-Schiller-University, Jena, Germany.

Leo R.B., William, K.J., Harold, E.K., Edward, C.M. and Arthur F.P., (1977). Reservoir systems analysis for conservation Hydrological engineering methods for water resources development, Volume 9, US-ACE, HEC, Institute for Water Resources Engineering Center, Davis, USA.

Linhua X., Shenglian G., (2003). A two – parameter monthly water balance model and its application.

Longley P.A., Michael F.G., D.J. Maguire and D.W. Rhind, (2005). Geographical Information Systems and Science.

Luijten J.C., J.W. Jones, and E.B. Knapp, (2000). Dynamic modeling of strategic water availability in Cabuyal River, Colombia. The impacts of land cover change on hydrologic balance. Advances in environmental monitoring and modeling (1). Gainesville, Florida.

Manuela G.M., (2004). Flood hazard assessment and Zonation in the lower Limpopo, Mozambique, International Institute for Geo-Information Science and Earth Observations (ITC), Enachede, The Netherlands.

Michael H.G., (2004). Usable science 8, Early warning systems: Do's and Don'ts. National Center for Atmospheric Research, Colorado, USA.

Michael W.B., and Thomas B.J., (1992). Flood damage analysis within the readiness management system, Institute for Water Resources Engineering Center, Davis, USA.

Moore R.J., Jones D.A., Black K.B., Austin R.M., Carrington D.S., Tinnion, M.A., Akhondi R.F.S., and Hyrad, (1914). Integrated systems for rainfall and river flow forecasting in Real-time and their application in Yorkshire; BHS Occasional paper No.4, 12.

Morid S., H. Ghaemi, H. Mir-Abolghasemi and M. Abeding, (2001). Evaluation of the HEC-1 model for flood forecasting and simulation in the Hormozgan province, Iran.

Mwakalila S., P.Campling, J.Feyyen, G. Wyseure, and K. Beven, (2001). Application of a data based mechanistic modeling (DBM) approach for predicting runoff generation in semi – arid region.

Nash, J.E. and J.V. Sutcliffe, (1970). River flow forecasting through conceptual models.
National Weather Service (NWS) (1994). The great flood of 1993. Natural disaster survey report.

National workshop on Flood Disaster Management-space inputs, (2004). NRSA, Hyderabad, India.

Grentfest and Hubber, (1989 & 2005). Nile Basin Capacity Building Network "NBCBN-RE". Flood and catchment management, Group 1&2.

Nippon Koei co. Ltd., (2007). The study on integrated flood management for Nyando river basin in the republic of Kenya.

Norton, (1982). Industrial and engineering chemistry fundamentals, Volumes 24-25, American Chemistry Society.

Onyango L.A., (2001). Ahero Dykes, Department of Engineering, University of Nairobi.

Ralph G., Mastomonaco P.E., (2004). The contribution of small storms to annual runoff volume evaluated in a sample watershed using the curve number method. Denver, Colorado.

Series on model choice, cooperative research centre for catchment hydrology (www.toolkit.net.au/ modelchoice).

Sing V.P., (1995). Waste water treatment and waste management.

Smith K., (2001). Digital Surface Model (DSM) construction and flood hazard. defra/environmental agency, flood and coastal defense R&D programme. Defra-Flood management division, London.

Smith K., and Ward R., (1998). Floods physical processes and human impacts, India.

Stein B., Kolbjorn E., L.A.Roald, Nils R.S., and Astrid V., (2003). Estimation of Parameters in a distributed precipitation-runoff model for Norway, Hydrological earth systems sciences, Norwegian Institute for Water Research, Oslo, Norway.

Stephen T.L., Lancaster, and Raphael L.B., (2001). A simple model of river meandering and its comparison to natural channels, Oregon State University, USA.

Stewart, J., (1991). Evaporation from Wet Canopy of Pine Forest. Canada Water Resources Journal, Vol. 13, No6.

The CGIAR Coansortium for Spatial Information, (2007). Applying GeoSpatial Science for a Sustainable future. Europa Technologies Image, TerraMatrics.

The International DOI Foundation (IDF), (2008). The digital object identifier system news.

The OFDA/CRED International Disaster Database, www.em-dat.net-Universite catholique de Louvain – Brussels – Belgium"

Toolkit, (2007). Engineering interactive systems, joint working conference, Salamanca, Spain.

Turner B.L. and S. Meyer, (1991). Population and Land Cover Change Interrelationship. American Society of Civil Engineers, U.S.

UNEP, (2000). Global environmental outlook 3, past, present and future perspectives.

UNEP, (2000). Human impact on erosion and sedimentation, proceedings of Rabal Symposium S6, Hebrew University, Jerusalem, Israel.

U.S. Bureau of Reclamation, (1984). Runoff Measurement using weirs. US Department of Agriculture, US.

US-ACE, HEC, (2006). Hydrological Modeling Systems HEC-HMS Release notes, Version 3.1.0; Hydrological modeling center.

US-ACE, HEC (2003). Susquehanna River flood warning and response system.

Walsh P.D., and Brasington F.C., (1990). Application of weather forecasts and meteorological products for river management.

Ward, (1978). Flooding in South Dakota, Northern Star University, USA.

Watanabe, (1998). Nile Basin Capacity Building Network "NBCBN-RE". Flood and catchment management, Group 1&2.

WMO, (1994). Guide to Hydrological Practices: Vol 1: Data Acquisition and Processing. Report no.186. World Meteorological Organization, Geneva, Switzerland.

Weglarczyk, (1998). The interdependence and applicability of some statistical quality measure for hydrological models, Journal of Hydrology, Volume 206.

Western, Van Ceese, and Farifteh, J., (1997). ILWIS for windows, Users Guide. ILWIS Department, International Institute for Aerospace Survey and Earth Sciences, Enschende, The Netherlands.

World Agroforestry Center, (2003). Proceedings of a workshop on reversing environmental and agricultural decline in the Nyando basin.

Yapo P.O., Gupta H.V., and Soroosian S., (1998). Multi-objective global optimization for hydrological models.

Zahidul, and Islam, (1996). A Numerical Study on Flood Routing by Kinematic Wave Model, Bangladesh University of Engineering and Technology (BUET), Dhaka.