CORRELATION ANALYSIS BETWEEN THE PHYSICAL CATCHMENT DESCRIPTORS (PCD’s) AND THE IHACRES RAINFALL - RUNOFF MODEL PARAMETERS

A Case of Kasese Catchments, Uganda

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Master (IWRM) Dissertation
University of Dar es Salaam
July 2008

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By

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A Dissertation Submitted in Partial Fulfilment of the Requirement for the Degree of Masters in Integrated Water Resources Management of the University of Dar es Salaam

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CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance by the University of Dar es Salaam a dissertation entitled: ***Correlation Analysis Between the Physical Catchment Descriptors (PCD'S) and the IHACRES Rainfall Runoff Model Parameters,*** in partial fulfilment of the requirements for the degree of Masters in Integrated Water Resources Management of the University of Dar es salaam.

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DECLARATION
AND
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I, **Busingye Evelyne**, declare that this dissertation is my own original work and that it has not been presented and will not be presented to any other University for similar or any other degree award.

Signature …………………………….

ACKNOWLEDGEMENTS

It is by God's grace that I have made it through this project successfully. Thank you Lord for your unending mercy, forgiveness and protection given to me throughout my entire life.

I would like to offer my heartfelt gratitude to my supervisors; Dr. Nobert, J. and Dr. Mkhandi, S. for your guidance, dedicated supervision, constructive criticism, and tireless support you gave me to accomplish this project.

This dissertation would not have been possible without the kind support of my sponsors, WaterNet, thank you for offering me this immeasurable opportunity of acquiring a Masters in water resource management.

I thank the staff for Directorate of Water Resources Management (DWD) most especially Mr.Twinomuhangi Maximo for the flow data. Thanks also go to Mr.Callist Tindimugaya who is the Ag. Commissioner for DWD.

Special regards to my love Gumisiriza Esau who left no stone un turned to see me finish this project successfully. I appreciate all your care and support you offered me.

I wish to express my appreciation to Lubang Ben and Sudi, who I consulted several times. You helped me overcome my doubts in doing this dissertation and thank you for your generosity.

DEDICATION

To My Dear Parents Mr and Mrs Twinomugisha Apollo, Brothers and Sisters

ABSTRACT

The purpose of this study was to analyze the correlation between the Physical catchment descriptors (PCD's) and the IHACRES Rainfall Runoff model parameters for the Kasese catchments. Future researchers can base on the output of this study for regionalisation of Kasese catchments. The model was calibrated for four(4) catchments to obtain a set of dynamic response characteristics (DRCs) describing the hydrological behaviour within the region. For the four catchments, Mubuku, Rwimi, Nyamugasani and Chambura, IHACRES model calibrated with an R^2 of 0.12, 0.25, 0.38 and 0.51 respectively. It was concluded that the poor measures of fit between observed and modelled stream flow (R^2) could have been due to lack of good-quality time series of rainfall data representative of the whole basin and influence of snow melt for especially Mubuku, Rwimi and Nyamugasani. Physical Catchment Descriptors (PCDs) indexing Topography, Soil type, land cover, length of main channel, drainage density, and basin area were correlated to the hydrological model parameters, from which a set of DRC–PCD relationship results indicate that strongest correlations were found with the quickflow proportion (Vq), catchment storage index (1/c), catchment drying constant (TauW) and the temperature modulation factor (f) with the PCD's. It was then concluded that IHACRES model is applicable to Kasese catchment but further work is necessary to correlate the records from river flow measurement stations and rain gauges to facilitate better modelling results when using this model.

TABLE OF CONTENTS

Page

Page

Page

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND ANNOTATIONS

ARPE	Average Relative Parameter Error
CRR	Conceptual Rainfall Runoff Model
DRC’s	Dynamic Response Characteristics
DWD	Directorate of Water Department
GIS	Geographical Information System
IHACRES	Identification of Unit Hydrograph And Component Flows from Rainfall, Evaporation and Stream flows
IWRM	Integrated Water Resources Management
PCD’s	Physical Catchment Descriptors
SLM	Simple Linear Model
UCG	University College of Galway
UH	Unit Hydrograph

CHAPTER ONE

INTRODUCTION

1.1 Background

Accurate estimation of stream flow is essential for engineering design, water resources management and planning, pollution control, conservation and recreational use. However, even though there are several gauging stations in most of the catchments, data are not always available where a need exists. Given that rainfall data are usually available, rainfall-runoff models provide a technique for the simulation of flows given a set of model parameters. In the case of ungauged basins, such direct measurements of stream flow are never available and prediction in those basins requires alternative approaches. A major difficulty in predicting hydrology of ungauged basins is that the watershed response is governed uniquely by interactions of climate, topography, geology, and vegetation.

Assessment of water resources in ungauged locations is difficult due to lack of hydrological data required for estimating runoff. Efforts to estimate runoff data through computational methods have been made using empirical methods and rainfall-runoff models. These rainfall-runoff models have been developed using simulations in the form of mathematical equations that require the use of several parameters (Kokkonen *et al*, 2003).

One approach is to use information from models derived at gauged locations as a basis for such modelling based upon watershed attributes. Statistical relations between calibrated model parameters and watershed characteristics may capture information about the governing hydrologic processes and serve to develop a classification system useful for reducing predictive uncertainty at ungauged locations (Whitfield *et al*., 2006).

In this study therefore, IHACRES model which has successfully been used to model the pluvial watersheds in other mountainous regions, is better placed to be used in the Kasese district basin that is also mountainous in nature. IHACRES is a relatively simple form of model based upon excess precipitation (Jakeman *et al*., 1990, Littlewood and Jakeman, 1994; Littlewood *et al*., 1997).

Despite the simple formulation, IHACRES has been shown to be suitable in a wide range of rainfall-runoff catchments (Wagener and Wheater, 2002). Regionalization Approaches to Daily Streamflow Predictions using the IHACRES model have been previously reported (Kokkonen *et al*., 2003) for the Coweeta watershed, Sefton and Howarth (1998) for the United Kingdom. Kokkonen *et al*. (2003) considered thirteen (13) catchments within a 16-km^2 watershed.

In order to predict flows at ungauged sites using calibrated rainfall-runoff models, a method of estimating a parameter set is needed. A number of techniques (e.g. Merz and Blöschl, 2004) have been employed including:

1. Determining regression relationships between model parameter values and catchment's attributes

2. Adopting a parameter set from a nearby, catchment that is expected to have sufficiently similar response characteristics, Interpolation schemes (e.g. kriging) of parameter values from nearby catchments.

3. Methods based on estimating parameter sets rather than individual parameter values have a considerable advantage due to the highly nonlinear nature of catchment responses and the correlations that typically exist in rainfall-runoff models Croke and Norton (2004).

4. Application of regression relationships between catchment attributes and individual parameters requires parsimonious models that have strong relationships between parameters and catchment attributes as well as little correlation between different parameters**.**

While IHACRES (Jakeman, *et al*., 1990) has been used in previous regionalisation studies (e.g. Post and Jakeman 1996 and 1999, Post *et al*. 1998, Sefton & Howarth (1998), and Kokkonen *et al*. (2003), the CMD version of the non-linear loss module has a potentially better structure for regionalization (Jakeman & Hornberger, 1993).

Regionalisation by describing these hydrological characteristics in terms of physical descriptors then allows estimation of the unit hydrograph for any catchment in the region.

Application of this methodology allows flow series to be constructed and the sensitivity of flow to the hydrological characteristics and to physical descriptors to be investigated.

The objective of this paper is to determine the relationship between model parameters and catchment physical descriptors. The ultimate goal is to provide guidance to water resource practitioners to reduce predictive uncertainty at ungauged locations in Kasese Catchments.

1.2 Description of the Study Area

1.2.1 Location

Kasese District is located in the Western Region of Uganda. It lies between latitudes 0^{o}12'S and 0^{o}26'N longitudes 29^{o}42'E and 30^{o}18'E. The District is bordered to the north by the district of Bundibugyo, the north east by Kabarole, to the south by Bushenyi and to the west by the Republic of Zaire, (Kasese District Profile, 1998). Figure 1.1 represents the location of Kasese District while Figure 1.2 represents the location of catchments in Kasese District.

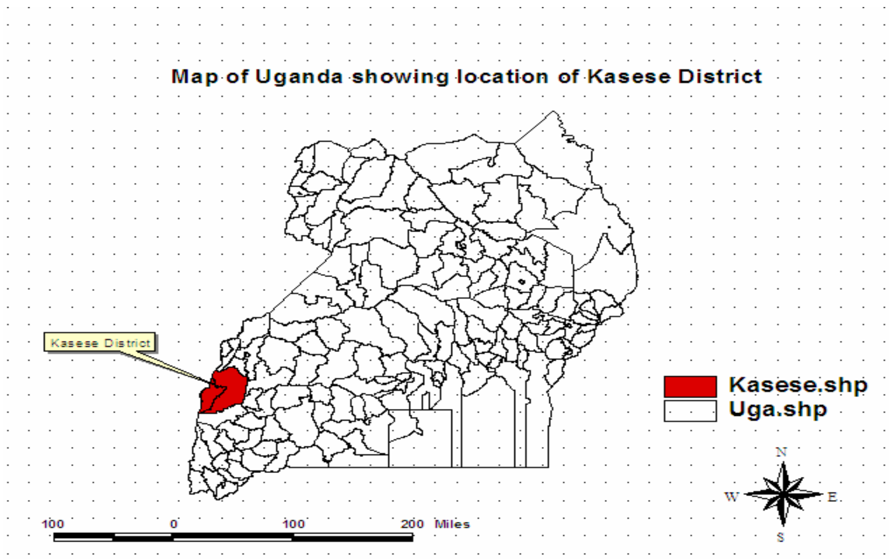

Figure 1.1: Showing location of Kasese District

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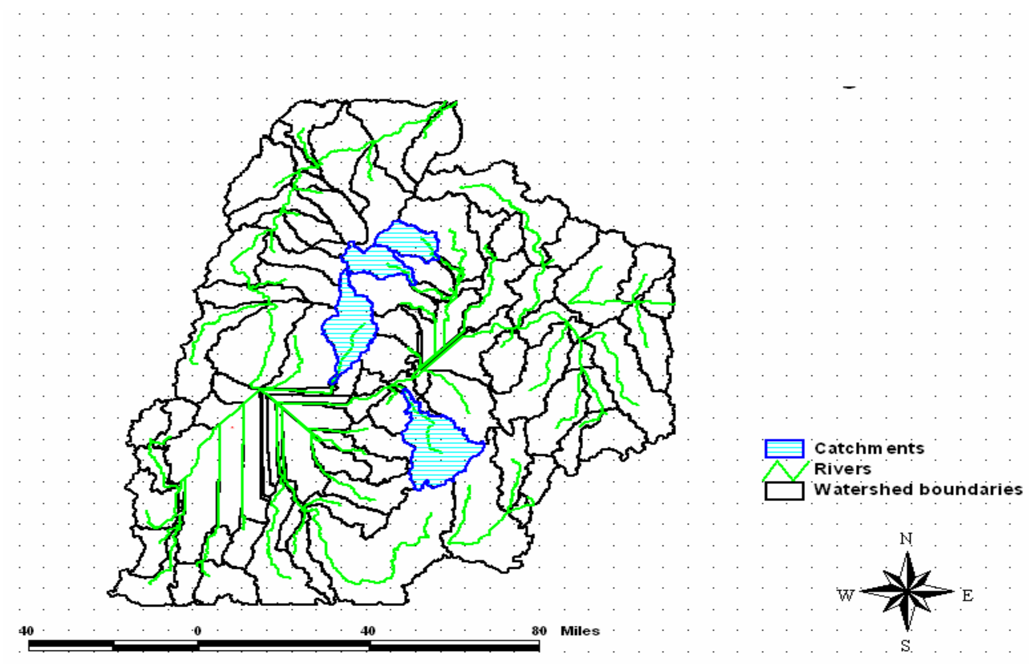

Figure 1.2: Showing location of Catchments in Kasese under Study

1.2.2 Size

The total land area of the district is 2724 Km^2 while the area covered by water bodies is 461 Km^2. Of the total area of the district, Queen Elizabeth National Park covers 885 Km^2 and Rwenzori National Park covers an area of 652 Km^2. This leaves only 1647 Km^2 for human settlement.

1.2.3 Population

Presently the population of the district is estimated at 360,000 (assuming an annual growth rate of about 2.1% for 1991-1995 period) this gives an average land density of about 220 people per square kilometre for the settled areas, (Kasese District profile, 1998)

1.2.4 Climate

a) Rainfall

The district experiences bimodal rainfall pattern. The first rains are short and occur during March- May, and the longer rains from August-November. Annual rainfall ranges from less than 800 mm-1600 mm, and is greatly influenced by altitude. In terms of total annual rainfall, the extreme southern to the south-eastern part of the district receives slightly less than 800 mm. The savannah area is especially covered by the Queen Elizabeth National park and lakes George and Edward, receive 800-1000 mm. For the central part of the district stretching diagonally in the south-west to the north-east direction, annual rainfall ranges from 1000-1200 mm. At the foothills of the Rwenzori Mountains, the amount is 1200-1400 mm. From the foothills to the mid slopes, rainfall received is 1400-1600 mm, and for the mid slopes to summit, 1600 mm.

b) Temperature

Due to the wide temperature variations influenced by altitude, temperature can be extreme, from very high (at the plains) to below zero at the summit. In the 1964-1970 period average annual temperature was 26.5 ^{0}C.

From 1991- 1995 annual average temperature were 23.9 ^{0}C, with minimum and maximum averages of 17.7 and 30.2 ^{0}C, respectively.

1.2.5 Hydrology

Major rivers in Kasese District include Nyamugasani which transverses Kyondo, kyarumba, Kisinga and Katwe sub-counties. Lhubiriha River forms the border between Uganda and Zaire. Nyamwamba River flows through Kilembe and Rukooki sub counties, and Kasese Town council and into Lake George swamp system. Sebwe (Isebo) River supplies water for Mubuku Irrigation Scheme, and traverses Bugoye and Rukooki sub-counties. Mubuku River passes through Bugoye, Maliba and Karusandara sub-counties, and then drains into the Lake George swamp system.

Most of the rivers in the northern part of Kasese originate in the Rwenzori Mountains, which lie along the western border of Uganda and rise to a height of 5,100 metres.

Here are the legendary 'Mountains of the Moon where snows fed the lakes, sources of the Nile.

In the centre of the range, some of the peaks carry permanent snow and glaciers, while the lower slopes are covered with dense forests. The Highest Mountain in the range, Mt. Stanley, is the third highest in Africa after Mt. Kilimanjaro and Mt. Kenya. Its highest peak, Margharita, rises 5109 m above sea level. Bamutaze & Mwanjaliwa (2008).

1.2.6 Soils

The soils found in Kasese District include organic, ferrosols, podsols/eutrophic, and hydromophic.

Organic Soils

Organic soils (non-hydromophic): these are found on high altitude and are almost entirely organic soils of the mountain at an altitude of about 3,000 m up to the summit. They are acidic and have an upper layer, which contains slightly more than 20% organic matter. Their productivity is low but support timber trees. The dominant soils being peaty loam over dark brown sandy clay loam.

Ferrosols Soils

Ferrosols soils are humic and of high altitude (2400-3000 m) and possesses better agronomic qualities. The clay fraction consists mainly of kaoline minerals, free iron oxides, amorphous gels and some times small amounts of 2:1 lattice clay. The dominant soils being brown gritty clay loams, and sandy loams.

Podsolic Soils

Podsolic soils are at an altitude of 1200-2400 m. They are not differentiated and are highly leached, in which translocation of iron and aluminium has taken place. They are characterized by an ash-coloured bleached horizon immediately below a very acidic, peaty top soils and rusty coloured b-horizon.

These soils are of little agricultural value being used occasionally for grazing and any cultivation (coffee growing) which is confined to small valleys and pediments.

Eutrophic Soils

Eutrophic soils are developed on the rift valley flat and are recent rift valley deposits. Brown sandy loams and sandy clay loams, and parent material in rift valley sediments dominate them. They are developed on sandy and gravel which is water worn. North of Lake George are large spreads of sands, ravel and clays brought down by rivers draining from Rwenzori Mountains.

Hydromophic Soils

The development and characteristics of these soils are influenced by permanent or seasonal logging. Some of the soils are locally saline. The dominant soil is peaty sands and clays whose parent material is papyrus residues and river alluvium. Productivity is medium to high, and suitable for sweet potato growing.

1.2.7 The People

The district has an approximate total population of 530,000 people. Kasese is a multi-ethnic district with many people of different ethnic backgrounds. Like most districts in Uganda, Kasese district is predominantly agricultural, relying on farming for employment and income.

1.3 Problem Statement

Most of the river catchments located in Kasese District is currently under intensive utilisation with many water consumption uses, which include Mubuku rice scheme, Hima cement factory, Prisons, Barracks, Kilembe mines, Domestic (Urban) water supply, and other developments like H.E.P plants are yet to start operating. Therefore, the driving factor for this study is the socioeconomic development and its consequences on the Kasese district water resources. The pressure on the natural resources will have negative impact on the river flow and consequently on the water uses earlier mentioned.

There is therefore a need for an efficient utilisation of water resources potential, a good planning and designing of water resource projects and an efficient river flow analysis. The lack of long series of discharge data and modelling exercises for the catchments is still evident. Thus, the study was to explore the possibility of transferring model parameters between gauged and ungauged catchments based up on similarities in physical catchment descriptors (PCD'S).

1.4 Objectives

1.4.1 Overall Objective

The purpose of this study was to analyze the correlation between the Physical catchment descriptors (PCD's) and the IHACRES Rainfall Runoff model parameters for the catchments.

1.4.2 Specific Objectives

The specific objectives of the study are:

1) To carry out an optimization of the parameters of the model.
2) To determine the physical characteristics of the catchments in study.
3) To analyse the relationship between the Physical catchment descriptors and the optimized model parameters.

1.5 Significance of the Study

Researchers are usually faced by challenges in modelling catchment behaviour due to the unavailability of observed data of sufficient quality and quantity, therefore this study is meant to explore transferability of model parameters between catchments, based upon catchment characteristics. This will give guidance to water resource practitioners in reducing predictive uncertainty at ungauged locations.

Assessment of the water resources potential of the basin like estimating irrigation potential areas within the basin, assessing the hydropower potential of the basin, design of hydraulic structures, flood forecasting and others.

1.6 Layout of the Dissertation

The first chapter of this work presents the general framework, motivations of this research and briefly describes the study area by its location, topography, climate other physical characteristics, and hydrology of the catchments in study.

Chapter Two covers literature review, which presents the review of past studies done, hydrological, and modelling in general including the purpose of hydrological modelling, classification of rainfall runoff models, descriptions of the different types of rainfall runoff models and the type of data required for the study.

Chapter Three presents data processing and analysis, methodologies used while chapter Four outlines the results and discussions; the IHACRES model application results, the derived physical catchment descriptors, and the correlation between the model parameters and the catchment descriptors.

Chapter Five concludes the study by presenting summary, conclusions and recommendations.

CHAPTER TWO

LITERATURE REVIEW

2.1 Review of Past Studies Done

Physically based distributed rainfall-runoff models were recognized recently as a powerful tool to proper reconstruction of watershed discharge distribution based on detailed GIS maps of the region. Additionally, these kinds of models seem to give good calculation results even in situations where no historical discharge observations are available and thus no calibration is possible that is in ungauged basins as observed by Boyko, (2006).

On the other hand, these models usually have a high complexity and are computationally demanding. Since the creation of complex distributed models, the work on their simplification has been conducted. IHACRES model can be mentioned as good examples of simplified models, which still provide proper simulation results.

Several previous studies have integrated application of IHACRES model in studying the rainfall- Runoff modelling of their catchments in study. One of the studies was done in England and Wales headed “Relationships between dynamic response characteristics and physical descriptors of catchments in England and Wales” by Sefton *et al*, (1998). They applied a regionalization methodology to the catchments in England and Wales to enable estimation of daily flow for any catchment in the region for which physical data and records of rainfall and temperature are available.

In the previous studies of IHACRES model, Post and Jakeman (1996, 1999) used relationship between catchment characteristics and model parameter to find out initial six model parameters in IHACRES model that can be used to define the daily stream flow. The time constant governing quickly flow recession of stream flow from catchment (τ_q) is influenced by the drainage network and catchment area. The time constant governing the slow flow rate of recession of the stream flow (τ_s) is controlled by the slope and shape of catchment. The peak of the unit hydrograph (h) resulting from a unit input of the effective rainfall is a function of area and catchment gradient. The parameter modulating catchment losses in response to temperature (f) is governed by catchment gradient. Finally, the parameter defining the maximum volume of the non-linear store (c) and governing actual rate of water loss in the catchment (τ_w) are relative to the drainage density and basin length.

IHACRES model was also applied to 60 catchments to obtain a set of dynamic response characteristics (DRC's) describing the hydrological behaviour within the region. Relationships were derived to describe the DRC's in terms of the Physical Catchment Descriptors so that the model may be used to simulate flow for any catchment in the region, given the driving variables, that is rainfall and temperature. The relationship derived was satisfactory validated on two additional catchments within the region.

Another study was done in Canada, Italy. Titled "Transferability of Conceptual Model Parameters in Mountainous Rainfall- Driven Catchments" by David *et al*, 2006. They emphasized the fact that The IHACRES model has been widely shown to be successful in modelling rainfall-runoff processes in a variety of environments. The objective of this paper was to examine the utility of physical catchment descriptors (PCD's) to predict model parameters priori.

Results from calibrated model parameters from a variety of catchments in mountainous pluvial regimes were compared to basin area, drainage density and other attributes derived from digital elevation models. The results indicated that some model parameters were significantly correlated to PCD's. Significant correlations at 5% level were found between several of the PCD's and IHACRES model parameters strongest correlations were found with the quick flow proportion(Vq), Catchment storage index (1/c) and catchment drying constant (TauW).

The limitation of model structures and the data availability on parameter values will make it difficult to apply a hydrological model without calibration. Tingsanchali *et al*., (2005) argues that in very few cases reported in the literature, models have been applied using only parameter values measured or estimated but prior to using it the parameters values are adjusted to get better fit with the observed data as. However, in most of the cases the models cannot estimate the parameters by either measurement or prior estimation. Furthermore, studies have found in general that, even after using intensive series of measurement of parameter values, results have not been fully satisfactory. Prior estimation of feasible ranges of parameters also often results in ranges of predictions that are wide and may still not include the measured responses all of the time.

A rainfall-runoff model, IHACRES, which calculates component unit hydrographs using an estimate of excess rainfall, is employed to characterise the streamflow regime of individual catchments, Sefton and Howarth (1998). Regionalisation by describing these hydrological characteristics in terms of physical descriptors then allows estimation of the unit hydrograph for any catchment in the region. The standard method of regionalisation uses gauged catchments to identify a relationship between model parameters and catchment descriptors as applied by Lee *et al.,* (2006), Wagener and Wheater (2006), so then ungauged catchment model parameters can be estimated. Application of this methodology allows flow series to be constructed and the sensitivity of flow to the hydrological characteristics and to physical descriptors to be investigated.

Furthermore, given the future climate and a set of physical descriptors, it is possible to derive continuous flows for any of the ungauged catchment within the region. Along with the development of rainfall-runoff models in gauged catchments, regionalisation methods have been used to predict flows in ungauged locations (Croke and Jakeman, 2004; Croke and Norton, 2004). Geographic Information Systems (GIS) have been used to investigate catchment characteristics using digital terrain analysis derived from a Digital Elevation Model (DEM). By using GIS and Digital terrain analysis, catchment regions and model parameters can be generated and used to calculate empirical relationships between streamflow and terrain attributes in gauged sub-catchments (Newham *et al*., 2002). This approach can provide an effective way to extrapolate and apply the hydrological rainfall-runoff models to ungauged sub-catchments.

More recently, focus has been on estimation of water balance model parameters aimed at simulation of continuous records. Bergmann *et al*., (1990) presented a distributed model describing the interaction between flood hydrographs and basin parameters. Combining loss estimates with modelling in a physically based stochastic monthly water balance model, Vandewieel and Elias., (1995) simulated monthly time series.

A next step is the estimation of daily hydrological model parameters, a task begun by Seton *et al*., (1995), Post, and Jakeman, (1996) with the potential for reconstruction of daily flow records. The application presented is therefore a harsh test for the methodology; the estimation of daily flows for ungauged catchments within a large basin and with different flow regimes for the different sub catchments.

Other recent developments of IHACRES include UH identification using only streamflow data for situations where rainfall data are sparse or unavailable and the use of groundwater level and/or evapotranspiration data as additional exogenous variables for model calibration (Croke *et al*., 2002). Another important aspect of improving methods to regionalize hydrological response is by understanding the influence of land-use variations on streamflow regimes (Croke and Jakeman, 2001). Most progress has been made with small experimental catchments subject to comprehensive land-use changes (Post *et al*., 1998; Kokkonen & Jakeman, 2002; Dye & Croke, 2003). The effect of mosaic patterns of land-use on hydrology remains a problem.

In this study a rainfall-runoff model, IHACRES, which calculates component unit hydrographs using an estimate of excess rainfall, was employed to characterise the streamflow regime of individual catchments, a method used by Sefton and Howarth (1998). In addition, describing these hydrological characteristics in terms of physical descriptors then allows estimation of the unit hydrograph for any catchment in the region that was recommended for further studies.

2.2 General Aspects of Hydrologic Models

A hydrological model may be defined as a set of mathematical relations describing the various components of the hydrological cycle, with the aim of simulating the result of the hydrological cycle, which is runoff.

In the hydrological cycle, the transformation of input (rainfall) into output (runoff) involves a number of interrelated processes. In hydrological models, attempts are made to duplicate this transformation of rainfall into runoff (Pitman, 1973), albeit with varying degrees of simplification and generality. The model is said to be physically relevant if an improved understanding of the hydrologic cycle and its processes is achieved (Pitman, 1973). According to Pitman (1973), a practical hydrologic model should meet the following requirements:

a) Represent to an acceptable degree of accuracy, the hydrologic regimes of a wide variety of catchments

b) It should be easily applied with existing hydrologic data to different catchments.

c) The model should be physically relevant so that, in addition to stream flow, estimates of other useful components such as actual evaporation or soil moisture state can be made.

2.3 Purpose of Hydrological Modelling

Physically based or theoretical models are often used in research purpose to gain a better understanding of the hydrologic phenomena operating in a catchment and of how changes in the catchment may affect these phenomena. However, some of the general purposes emphasise that:-

a) Hydrological models are largely applied to predict extreme events, such as flood and low flows,

b) Hydrological models may be used in interpolation and extrapolation of hydrological data series, i.e. it can be used in filling and replacing of the missing records,

c) A well-structured hydrological model promotes an improved understanding of biological processes occurring in hydrological system (Fleming, 1975),

d) A well-structured hydrological model merges the component of the system, resulting in a coherent view on the behaviour of the entire system (De Coursey, 1991),

e) Hydrological models are applied to make decision in relation to design, planning, operation and management of water related structures (Schulze, 1998).

2.4 Classifications of Rainfall-Runoff Models

2.4.1 Empirical "Black Box" Model

Empirical "black box" models or sometimes referred to as system type of models, simply attempt to relate rainfall as input to runoff as an output with little or no attempt to simulate the individual hydrological processes involved.

Example of the black box models include the unit hydrograph method, the simple linear reservoir model, linear difference equation models (Box and Jenkins, 1976), the Constrained Linear System Models (Todini, 2003) and the Linear Perturbation Model (Nash and Barsi, 1983)

2.4.2 Conceptual Models

Conceptual Rainfall-Runoff (CRR) models were introduced in hydrology to improve the black box system model theoretical approach, which depend mainly on some general, yet flexible relationship between input and output data without much physics in the system. CRR models have generally been very useful and successful approach in simulating runoff from catchments in different parts of the world for the last three decades (WMO, 1975).

However, because of basin scale hydrologic processes are lumped at a point, CRR ignores the spatial variability of meteorological variable. Therefore, CRR models are limited in assessing the effect of land use and other changes in basin hydrology (Biftu, 1998). Examples of this class of models include Soil Moisture Accounting and Routing Model (SMAR), NAM, Xinanjiang, HBV etc. (Biftu, 1998).

2.4.3 Physical Based Distributed Hydrologic Models

With Physical based distributed hydrologic models, model calibration is less dependent on the existence of the past data records. Basin response is represented on both a spatially and temporal distributed basis and in terms of multiple variables outputs.

2.5 General Classification of Rainfall Runoff Models

Rainfall runoff models may be grouped in two general classifications according to Alan A.Smith (2008) as illustrated in Figure 2.1 and Figure 2.2.

The first approach uses the concept of effective rainfall in which a loss model is assumed which divides the rainfall intensity into losses and an effective rainfall hyetograph. The effective rainfall is then used as input to a catchment model to produce the runoff hydrograph. It follows from the approach that the infiltration process ceases at the end of the storm duration.

An alternative approach that might be termed a surface water budget model incorporates the loss mechanism into the catchment model. In this way, the incident rainfall hyetograph is used as input and the estimation of infiltration and other losses is made as an integral part of the calculation of runoff.

This approach implies that infiltration will continue to occur as long as the average depth of excess water on the surface is finite. Clearly, this may continue after the cessation of rainfall.

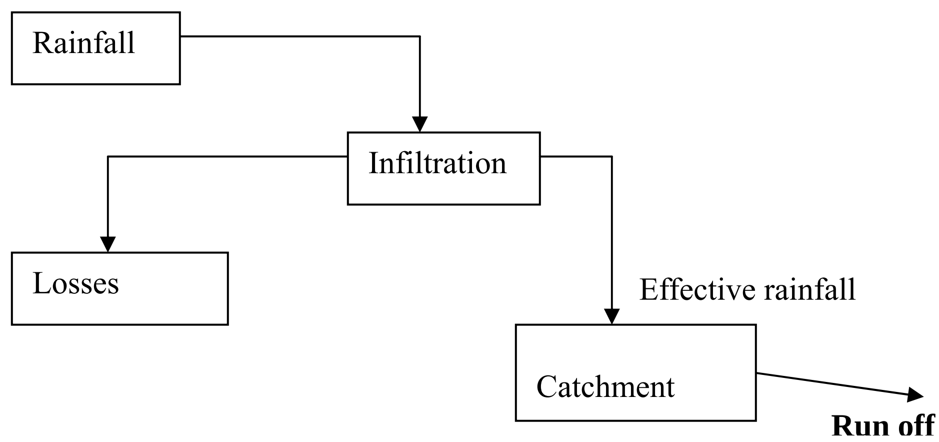

Figure 2.1: A Rainfall-Runoff Model using Effective Rainfall

Source: Alan A. Smith, 2008

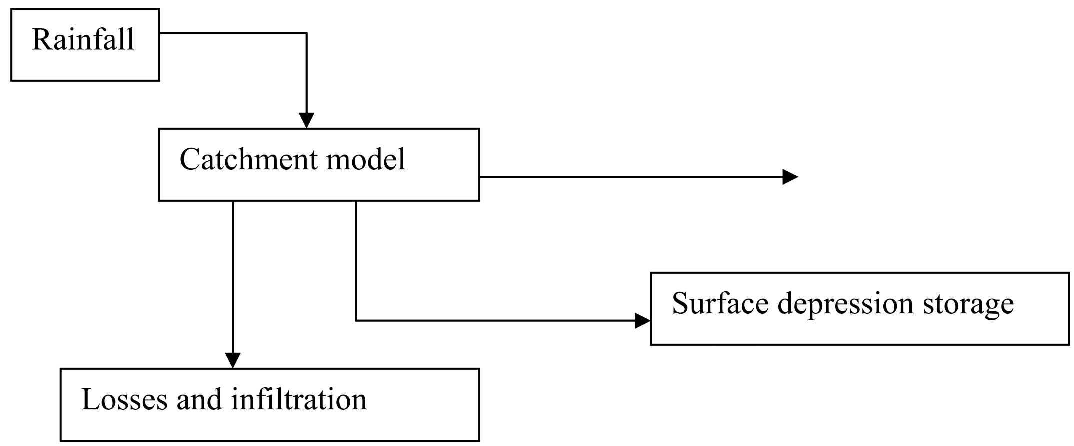

Figure 2.2: A Rainfall-Runoff Model Using a Surface Water Budget

Source: Allan A. Smith, 2008

2.6 Model Choice for the Study

In this study, IHACRES model, a conceptual Rainfall Runoff model was chosen to model a number of watersheds in the mountainous areas of Kasese District in Uganda due to a number of reasons as explained below:

IHACRES is a relatively simple form of model based upon excess precipitation (Jake man *et al*., 1990, Littlewood and Jakeman, 1994; Littlewood *et al*., 1997).

The model is very simple and parametrically parsimonious (Jakeman and Hornberger, 1993), but despite the simple formulation, IHACRES has been shown to be suitable in a wide range of rainfall-runoff catchments (Wagener and Wheater, 2002).

Regionalization approaches to daily streamflow predictions using the IHACRES model have been previously reported (Kokkonen *et al*., 2003) for the Coweeta watershed, Sefton, and Howarth (1998) for the United Kingdom. IHACRES model provides a simulation of slow and quick flow at gauged sites.

The model is easy to understand with low computational-mathematical demands and simulations are quickly set up. In addition, It allows one to filter the major climatic factors (precipitation and temperature) affecting stream flows. It has been successfully tested for streamflow prediction in Australian catchments and worldwide in a range of catchment hydroclimatologies, including those producing ephemeral, low-yielding streamflows.

It has few parameters allowing it to be calibrated in a shorter period than most conceptual models. It is relatively easy to use especially for calibration and simulation of different time periods; the model prepares a unique identification of system response even with only a few years of input data set (Newham *et al*, 2002);

The parameters of IHACRES are designed to be climate independent but are intended to reflect also the landscape and landuse characteristics for the period of calibration of the catchment considered (Jakeman and Hornberger, 1993; schreider *et al*.,1997).

2.6.1 IHACRES Model Description

The rainfall-runoff model (IHACRES) used in this research is based on the catchment moisture deficit (CMD) model of Croke and Jakeman., (2004).

The IHACRES (Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Stream flow data) model is a simple lumped (integrated) catchment scale rainfall-stream flow model. It is an approach which attempts to capture identifiable catchment-scale dynamic response characteristics (DRCs) from such data because the DRCs can be used to discriminate between the behaviour of catchments, an important application of IHACRES is assisting with regionalization (information transfer from gauged to ungauged basins) (Jakeman *et al*., 1992; Littlewood & Jakeman, 1994).

Its purpose is to assist the hydrologists or water resources engineers to characterize the dynamic relationship between basin rainfall and stream flow. This model applies a transfer function/unit hydrograph approach to relate total rainfall to total discharge in two stages. It is composed of two parts, i.e., the linear and non-linear models.

In the first part is a non-linear loss model: an evaporation loss module to calculate effective rainfall: this computes the amount of rainfall that does not contribute to direct runoff (i.e., lost due to evapotranspiration or held in soil storage) through continuous update of an index representing catchment soil moisture. Rainfall excess is computed as a direct function of the soil moisture index and is routed to the catchment outlet via two parallel linear reservoirs representing quick and slow stream flow response (Kokkonen *et al*., 2003).

The second part is the linear module (a unit hydrograph module) defined as a recursive relation at a given time step (daily for this study) for modelled flow, calculated as a linear combination of antecedent flow values and effective rainfall (Jakeman and Hornberger, 1993). The effective rainfall output from the first step generates the necessary input to the unit hydrograph module. The linear module, representing the transformation of excess rainfall to flow discharge, allows very flexible configuration of linear stores connected in parallel and or series (Kokkonen *et al*., 2003).

The total number of parameters for IHACRES model are six and they include (1/c, TauW, f, Vs, Tq and Ts) as represented in (Table 2.1)

Table 2.1: The Parameters Describing the IHACRES Model

Parameters	**Description**
f	Temperature modulation factor (f) in 1/ ^{o}C
TauW	Catchment drying time constant (TauW) in days
Tq	Quick flow reservoir time constant (Tq) in days
Ts	Slow flow reservoir time constant (Ts) in days
1/c	Catchment storage index/Volume-forcing constant (1/c) in 1/mm
Vq	Proportion of effective rainfall which becomes quick flow Vq

Source: Hutchinson et al., (2006)

A conceptual diagram of the structure of the IHACRES model is shown in Figure 2.3 as given by Evans and Jakeman, (1998).

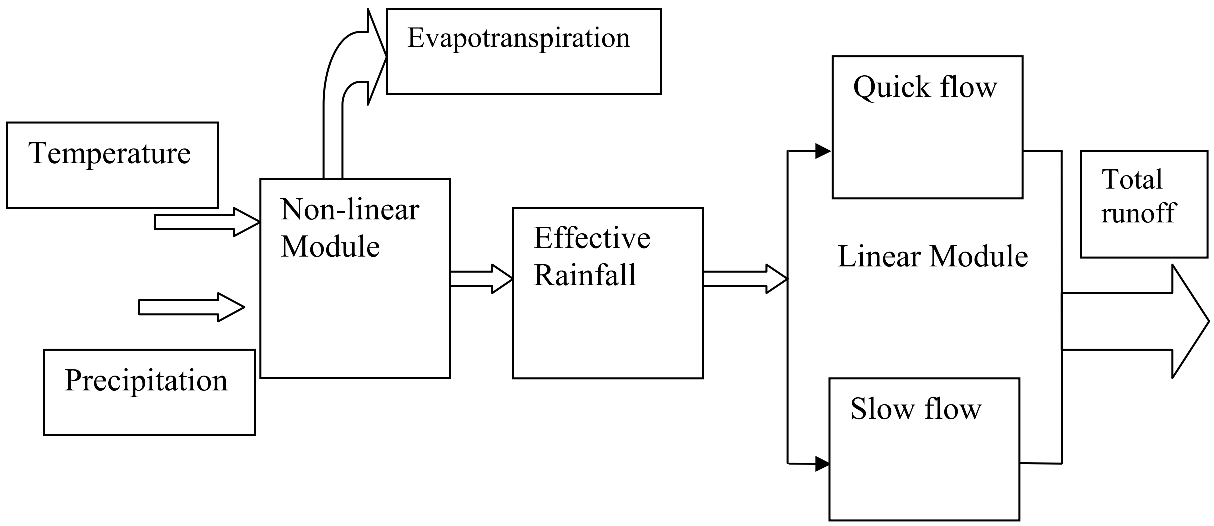

Figure 2.3: Structure of CMD-IHACRES *Source: Evans and Jake man, 1998*

The IHACRES model was selected following the methodology of Jakeman *et al*. (1990) which has been previously applied in the US, Australia and the UK. The model comprises of two components: a loss module and a routing module.

The rainfall filtering, or loss module, calculates effective rainfall which contributes directly to stream flow, given time series of rainfall and temperature. A catchment storage index, s_k, is calculated at each time step, k, as;

$$s_k = cr_k + \left(-\frac{1}{\tau_w(t_k)}\right) s_{k-1} \quad \text{.......} \quad (2.1)$$

Where c determines the proportion of rainfall, r_k, contributing to catchment storage, and $\tau_w(t_k)$ is the time constant of catchment wetness decline, dependent on temperature t_k given by;

$$\tau_w(t_k)=\tau_w \exp(10f-t_k f) \quad (2.2)$$

Where τ_w and f are model parameters. In Equation (2.2) τ_w is the time constant of catchment wetness decline at 10°C and f is a factor describing the effect of a unit change in temperature on the loss rate. The reference temperature of 10°C is considered appropriate for conditions in England and Wales. The effective rainfall u_k is then calculated as

$$u_k = \frac{1}{2}(s_k + s_{k-1})r_k \quad (2.3)$$

Secondly, a linear routing module converts rainfall excess into streamflow, x_k, using a parametric unit hydrograph approach in which streamflow separation is achieved by convoluting effective rainfall with identified components of the unit hydrograph;

$$x_k = \left[\frac{b_0 + b_1 z^{-1} + \cdots}{1 + \alpha_1 z^{-1} + a_2 z^{-2} + \cdots}\right] u_k \quad (2.4)$$

Where a_i and b_i are termed transfer function parameters and z^{-1} is a backward shift operator ($z^{-1}x_k=x_{k-1}$). In this application, a two-component system is selected, representing quick and slow pathways which are parameterised and summed such that

$$x_k = \left[\frac{\beta_q}{1 + \alpha_q z^{-1}}\right] u_k + \left[\frac{\beta_s}{1 + \alpha_s z^{-1}}\right] u_k \quad (2.5)$$

Where α describes the rate of decay and β describes the peak of the unit hydrograph component. Solving Equation (2.4) and Equation (2.5) to describe a and b in terms of α and β gives:

$$a_1=\alpha_q+\alpha_s \quad (2.6)$$

$$a_2=\alpha_q\alpha_s \quad (2.7)$$

$$b_0=\beta_q+\beta_s \quad (2.8)$$

$$b_1=\beta_q\alpha_s+\beta_s\alpha_q \quad (2.9)$$

For the quick (q) and slow (s) components, time of decay and relative volumetric throughput are defined respectively as

$$\tau_{q,s} = -\frac{1}{\ln(-\alpha_{q,s})} \quad (2.10)$$

$$v_{q,s} = \frac{\beta_{q,s}}{v_T(1+\alpha_{q,s})} \quad (2.11)$$

with the total volumetric throughput

$$v_T = \frac{\beta_q}{1+\alpha_q} + \frac{\beta_s}{1+\alpha_s} \quad (2.12)$$

v_T is also an approximation of the steady state gain of the system which is quantified by the conversion factor between the units of rainfall and streamflow. Each catchment therefore has its dynamic response characterised by catchment area and a total of six DRCs; three from the loss module (c, τ_w and f), and three from the routing module (τ_q,τ_s and v_s).

The linear module allows any configuration of stores in parallel or series. From the application of CMD-IHACRES to many catchments, it has been found that the best configuration is generally two stores in parallel.

2.7 Development of Regional Landscape Hydrologic Parameters Relationships

Regression approaches that have been applied to cross-sectional data to relate catchment characteristics to model parameters typically apply the following general steps (e.g., Kokkonen et al. 2003, Wagener and Wheater 2005):

(1) Establish an expectation of which landscape or climate variables could yield strong statistical relationships with each calibrated model parameter.

(2) Use linear regressions to formulate and assess these relationships.

(3) Validate linear regressions by predicting model parameters for each catchment based on a regression assessed without including the particular catchment.

In this study the above steps were followed but focused on step (1) and (2).Table 4.1 and 4.2 lists calibrated model parameters and attributes respectively for the four catchments. Landscape attributes and hydrometerological data sources are described based on Anderson et al. (2005) approach. While there are many additional candidate landscape attributes, there is a high prior probability that many of these might be suitable based on previous reported studies with IHACRES model e.g., Sefton and Howarth.,(1998), Post and Jakeman.,(1999).

2.8 Type of Data Required

IHACRES requires three sets of time series data. These are Observed Rainfall (in millimetres or inches), Temperature (in degrees Celsius, Fahrenheit, or Kelvin) or evapo-transpiration (in millimetres or inches) Observed Streamflow (in cubic metres per second, megalitres per time step, millimeters per time step, litres per second, or cubic feet per second), Barry *et al.,* (2005).These data must be in delimited ASCII text format. Depending on the measurements units used for the above datasets, catchment area (in Km^2) may be required, Barry *et al.,* (2005).

2.8.1 Time Series Data

2.8.1.1 Rainfall Data

The observed Rainfall data required should be (in millimetres or inches) as required by the IHARES operation (Croke and Jakeman, 2004).

Areal Rainfall Measurement

Rainfall measured at a rain gauge is known as point rainfall. For hydrological modelling or water balance consideration however, one must consider areal rainfall, i.e. average rainfall over entire catchment. In order to obtain areal rainfall from point rainfall, one must have a hypothesis about the spatial rainfall pattern between gauges.

Such hypothesis can be in the form of isohyets, i.e. lines of equal rainfall. Several methods are used to estimate areal rainfall from point measurements. Such measurements are made over a catchment area or drainage basin and the total quantity of water falling on the catchment is evaluated.

The three common methods used in determining the areal precipitation over a catchment from point rain gauges measurement are:-

i) The Arithmetic Mean Method

This is the simplest method of calculating the average rainfall over an area. It involves taking the arithmetic mean of the rainfall stations within the catchment.

The rainfall stations used in the calculations are usually those inside the catchment area, but neighbouring gauges outside the boundary may be included if it is considered that the measurements are representative of the nearby parts of the catchment.

It is given by:-

$$\overline{P} = \frac{1}{N}\sum_{t-1}^{N} P_t^j \qquad (2.13)$$

Where $\overline{P}$ - is the areal rainfall is the rainfall depth on day j and in gauge i within the topographic basin and N is the total number of rain gauging stations within the topographic basin. The arithmetic mean method gives a satisfactory measure of the areal rainfall, if the catchment is sampled by many uniformly spaced rain gauges or when the area has no marked diversity in surface characteristics, so that the range in altitude is small and hence the variation in rainfall amounts is minimum.

ii) Thiessen Polygon Method

The method attempts to allow for non-uniform distribution of gauges by providing a weighting factor for each gage. The stations are plotted on a map, and connecting lines are drawn. Perpendicular bisectors of these connecting lines form polygons around each station. The sides of each polygon are the boundaries of the effective area assumed for the station. The area of each polygon is determined by planimeter and is expressed as a percentage of the total area.

Weighted average rainfall for the total area is computed by multiplying the precipitation at each station by its assigned percentage of area and totalling.

The results are usually more accurate than those obtained by simple arithmetical averaging. The greatest limitation of the thiessen polygon method is its inflexibility; a new thiessen diagram is being required every time there is a change in the gage network. In addition, the method does not allow for orographic influences. It simply assumes linear variation of precipitation between stations and assigns each segment of area to the nearest station. In a catchment where the rain gauges network is fixed, this procedure is convenient. This method gives good results if there is a good network of representative rain gauges.

Once the areas of the polygons are determined, the average precipitation using the thiessen polygonal method is determined as follows:-

$$\overline{P} = \sum_{t-1}^{n} W_t P_i \qquad \text{.......} (2.14)$$

Where:-

P_t = the average precipitation

P_i = the gauge precipitation for polygon i

W_i = the weighted area ($\frac{P_A}{P}$)

A_p = the area of the polygon within the topographic basin in km^2

A = the total area in km^2

n = the total number of polygons

iii) The Isohyetal Method

This method when used by an experienced analyst is the most accurate method of averaging precipitation over an area. Station locations and amounts are plotted on a suitable map, and contours of equal precipitation (Isohyetal) are then drawn.

The average precipitation for an area is computed by weighting the average between successive isohyets (usually taken as the average of the two Isohyetal values) by the area between isohyets, totalling these products, and dividing by the total area.

The isohyetal method permits the use and interpretation of all available data and is well adapted to display and discussion. In constructing an isohyetal map, analyst can make full use of their knowledge of orographic effects and storm morphology, and in this case, the final map should represent a more realistic precipitation pattern than could be obtained from the gauged amounts alone.

If linear interpolation between stations is used, the results will be essentially the same as those obtain with Thiessen method. The average precipitation by isohyetal method is determined as follows:-

$$\overline{P} = \sum_{t-1}^{n} W_t P_i \quad \ldots\ldots (2.15)$$

Where:-

P = the isohyetal average precipitation

P_i = the average precipitation between contours

W_t = the weighted area ($\frac{A_t}{A}$)

A_t = the sub area between contours in km^2

A = the total area in km^2

n = the total number of sub areas

2.8.1.2 Flow Data

The flow data required should be in either cumecs (m^3 /sec), mega litres per time step, millimetres per time step, litres per second, or cubic feet per second as required by the IHARES operation (Croke and Jakeman, 2004).

2.8.1.3 Temperature Data

The daily temperature is another necessary data variable used for calibration, simulation and regionalization. The average of the Maximum and Minimum temperature as used by Chow *et al,* (1964) is good enough for as long as a temperature station is comprehensive enough, and therefore can be used as a base station without necessarily considering all the temperature stations in the study area.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

Advances in scientific hydrology and in the practice of engineering hydrology are dependent on good, reliable and continuous measurements of hydrological variables. The measurements are recorded by a wide range of methods, from simple writing down of number by a single observer to invisible making of electronic impulses on a magnetic tape. However, scarcities of these variables are the major setbacks in hydrological modelling and due to difficulties in techniques and methods used in collecting data from the field there is need to verify the data.

In most cases the quality of the data collected are of poor, in that it contains missing values and even the available data are inconsistence and of very short period which are not suitable for hydrological modelling. Therefore, there is need for data preparation and processing to obtain better output results.

3.2 Data Preparation

The temporal and spatial databases for Kasese district basin as a whole already exist and this can help in the modelling efforts. These databases provide both the position (longitude and latitude) and the elevation of each of the metrological gauged stations used in this chapter.

The meteological stations used for this study those that are located within the Kasese basin. The measured daily stream flow database, climate data (daily temperature and rainfall) and a number of ancillary data sets discussed below were obtained from a number of sources as shown in Table 3.1 below. A Digital Elevation Model of 90 X 90 m resolution together with ancillary spatial data layers, were used in the program to generate summary statistics of catchment attributes.

Table 3.1: Maps and Data Sources Required for the Study

No.	Data	Type	Office/ Institute
1	Digital Elevation Model(DEM) of 90X90m resolution	Map and Numerical	Online global data source, ftp://e0srp01u.ecs.nasa.gov/srtm/version1/africa/
2	Land cover and vegetation map(1992)	Map and Numerical	National Forest Authority, GIS and RS Section (1992)
3	Gauge stations and data (Stream flow)	Numerical (daily time series)	Ministry of water and environment, Directorate of water resources management, Entebbe.
4	Gauge stations and data (rainfall and temperature)	Numerical(daily time series)	Ministry of water and environment, department of meteorology.

3.2.1 Rainfall Data

Rainfall data were collected for rain gauge stations within the Kasese basin. (Figure 3.1 showing the distribution of the rain gauges within the Basin). This flow data was in millimetre per second and of a period of ten (10) years ,i.e., from 1964 to 1974 for six station namely 89300800, 89300360, 89300610, 89300330, 89300620 and 90290210 for Mubuku, Kilembe mines, Rwimi, Isunga, Mweya and Kiburara respectively.

1. The rainfall data was prepared using FORTRAN program to transfer the free format of the rainfall data into UCG format and to determine the percentage of the missing data.

2. All the missing values and all the outliers were removed and replaced by -9.9. The table below shows the percentage of the missing values. Table 3.2 shows the percentage of the missing rainfall data.

3. Filling of the missing values were done by inverse distance square method expressed as-

$$P = \frac{\sum_{t-1}^{n} \frac{P_t}{D_t^2}}{\sum_{t-1}^{n} \frac{1}{D_t^2}} \qquad \textbf{(3.1)}$$

Where:-

P_A is the estimated rainfall at station A

P_t is the observed rainfall at stations I

D_i is the distance between the point to be estimated and the other stations.

The inverse distance method, one of the commonly used methods for analyzing spatial variation of rainfall, is flexible if the order of distances in the method is adjustable. By applying the genetic algorithm (GA), the optimal order of distances can be found to minimize the difference between estimated and measured precipitation data. The results of a case study of the Feitsui reservoir watershed in Taiwan showed that the variability of the order of distances is small when the topography of rainfall stations is uniform.

The results also verified that the variable-order inverse distance method is more suitable than the arithmetic average method and the Thiessen Polygons method in describing the spatial variation of rainfall. The efficiency and reliability of hydrologic modelling and hence of general water resource management can be significantly improved by more accurate rainfall data interpolated by the variable-order inverse distance method. So based on the above findings, the inverse distance method was used in this study.

4. FORTRAN program was used to determine mean daily rainfall for the catchments from the available data.

5. Areal rainfall for the catchments were obtained by using arithmetic mean method. Daily rainfall series for the catchments were based on the rainfall stations located near the relevant sub-catchments for the specified period (1964-1974).

6. The final predicted rainfall for each cells in the catchment were averaged for each gauge of this study (for this study at least three-rainfall gauge stations were used to calculate the final result for each flow station location).

Table 3.2: Percentage of Missing Rainfall Data

Stations	From	To	Years	No. of data Points	% Missing data
Kasese	1/1/1964	31/12/1974	11	4018	1.79
Mweya	1/1/1964	31/12/1974	11	4018	2.22
Kilembe	1/1/1964	31/12/1974	11	4018	0.05
Kiburara	1/1/1964	31/12/1974	11	4018	0.80
Rwimi	1/1/1964	31/12/1974	11	4018	0.00
Isunga	1/1/1964	31/12/1974	11	4018	0.00

3.2.2 Stream Flow

This flow data was in Cumecs and of a period of ten (10) years, i.e., from 1964 to 1974 for four station namely 84221, 84222, 84227 and 84228, for, Rwimi, Mubuku, Chambura and Nyamugasani respectively.

(i) The streamflow data was prepared using FORTRAN program to transfer the free format of the data into UCG format and to determine the percentage of the missing data. Table 3.3 shows the percentage of the missing stream flow data.

(ii) All the missing values and all the outliers were removed and replaced by -9.9. Table 3.2 below shows the percentage of the missing values.

(iii) Filling of the missing values was done by seasonal mean method.

Table 3.3: Percentage of Missing Flow Data for Kasese Catchments

Station	From	To	Years	No. Points	% age Missing data
Mubuku	1/1/1964	31/12/1971	8	2922	0.99
Chambura	1/1/1964	31/12/1974	11	4018	0.77
Rwimi	1/1/1964	31/12/1974	11	4018	0.75
Nyamugasani	1/1/1964	31/12/1974	11	4018	27.6

The flow measurements were obtained from the four gauging stations as represented by red triangular symbols in Figure 3.1 below. The rainfall measurements were obtained from the seven rainfall stations as represented by the brown circles symbols in Figure 3.1 below.

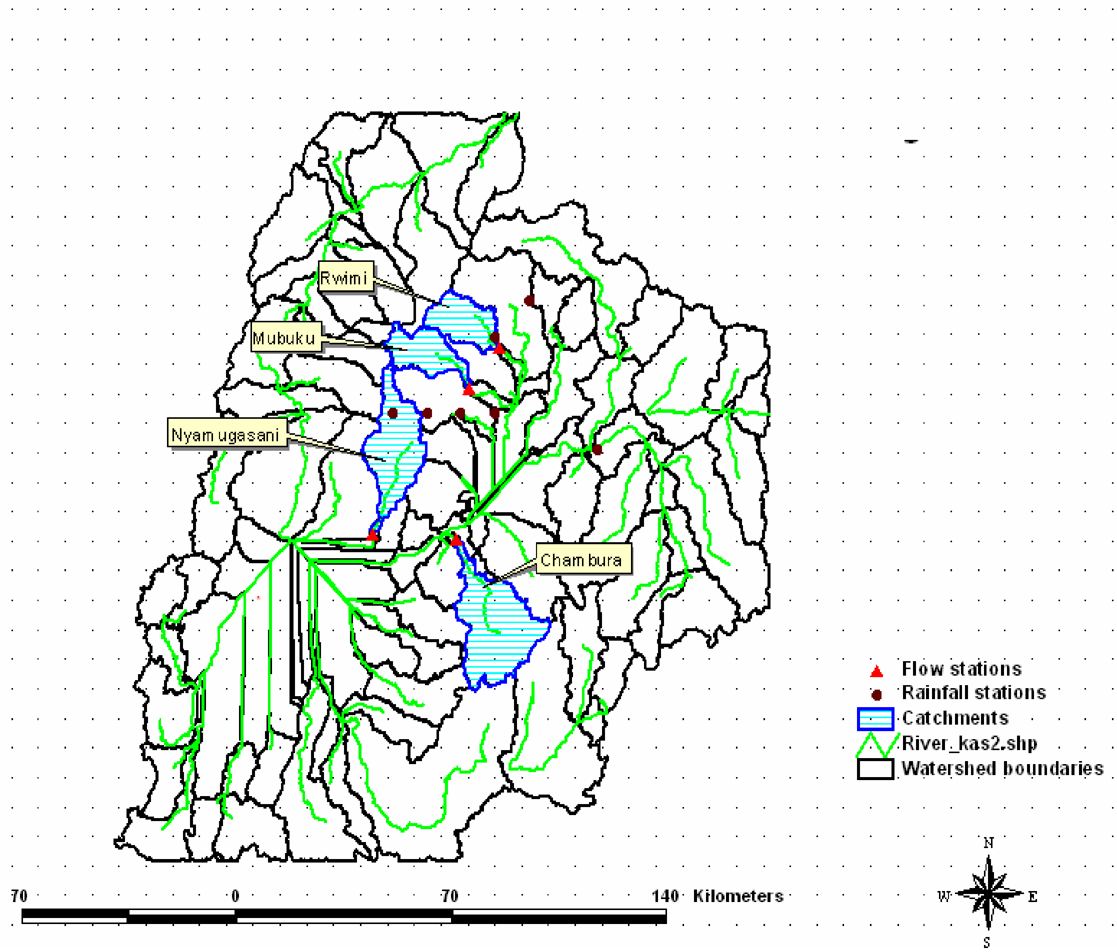

Figure 3.1: Rainfall and Flow Gauging Stations Distribution

3.2.3 Temperature

The average of the maximum and minimum daily temperature is another necessary data variable used for calibration, simulation and regionalization. For this study, one representative station (Kasese station) with maximum and minimum temperature data was used.

The maximum and minimum temperature data were averaged to calculate the results to be used in calibrating and simulating the rainfall-runoff model. This was based on the method used by Kokkonen *et al*., (2003). Below is Table 3.4 showing the basic catchment details.

Table 3.4: Basic Catchment Details

River	Area (Km^2)	Mean %age run-off coefficient.
Mubuku	256	1.37
Rwimi	266	0.75
Chambura	507	0.41
Nyamugasani	660	0.46

3.3 Model Parameter Optimisation

This section describes the data processing procedures used in this case study and consists of mainly hydrological analysis.

3.3.1 Hydrological Analysis

The hydrological analysis involved, tabulation of hydrological data, determination of unit hydrograph, duration curve and runoff coefficient. The hydrological analysis was carried out as preparation for running the IHACRES model and subsequent optimisation of the model parameters. The determination of unit hydrograph, duration curve, runoff coefficient and optimisation of the model parameters are discussed in section 3.3.2.

3.3.2 Operation of the IHACRES Model

There are three modes of the IHACRES package and they include data, calibration and simulation.

i) Data Mode

Each component has its own set of tabs to provide navigation. The data component has three tabs that provide access to

a) A summary of the data currently loaded. This data loaded included observed rainfall (in millimetres), temperature (in ^{o}C) and Stream flow data (in m^3).The data was in delimited ASCII text format (white space was ignored) Barry *et al*.,(2005). All the data for this study was for a period of 10 years, i.e., from 1964-1974 and for all the four catchments (see section.

b) An import tool was used to load in the required input time series data that have specified above.

c) Views tools were used to interrogate the loaded data searching it for any queries.

ii) Calibration Mode

Calibration mode has two tabs that allow one to define the calibration periods. In this study, the calibration period was three years based on Jakeman et al., (1993) methodology for all the catchments as explained in section 4.2.1.

It also helps in build the model (the linear and non-linear modules) which involves running the modules. The general order of operation in calibrating the model

Step 1- Setting the calibration periods. For this study, the calibration period found to give a good output of hydrograph for stream flow and rainfall was 1971 to 1974 for three catchments except for Mubuku catchment (See details in section 4.2.1).

Step 2- Setting the linear module calibration. This was set by performing a cross correlation to calculate the delay between rainfall and stream flow data. This step was carried out for all the catchments (See details in Chapter four)

The Instrumental Variable function was activated (by checking) of the fixed Transfer Function to control the linear module calibration.

Step 3- Setting the Non-linear Module calibration. This was set by selecting the classic Module. Several grid searches were performed to search through parameter space to obtain a good parameter set. Details of process and results are given in Chapter four, section 4.2.

In calibrating the IHACRES model, values for the catchment drying time constant (TauW) and the temperature modulation factor (f) governing the non-linear module were selected manually. Parameter values in the linear routing module and the parameter 1/c (catchment storage index/volume-forcing constant) in the non-linear module were calculated automatically by the program.

The coefficient of determination (R^2) and a percentage 'average relative parameter error' (% ARPE) for the parameters in the linear module are program outputs. The criteria that a good model is one that has a high value for R^2 and a low value for % ARPE, was used. The transfer function parameters are optimised using an instrumental variable procedure (Jakeman et al., 1990).

The model was calibrated using selected ranges for the parameters (TauW and f) in the non-linear loss module. In a single run of the program, R^2 and % ARPE are then tabulated by the program for each pair TauW-f that enabled scanning of the results in search of the best pair. Ideally, the maximum R^2 and the minimum for % ARPE would occur for a single pair; in practice, the maximum R^2 and minimum % ARPE will define ranges of the catchment drying time constant and the temperature modulation factor.

iii) Simulation Mode

This step follows the calibration of the model, and it provides access to extensive analytical tools to explore the predicted streamflow time series.

3.4 Statistics Used

Throughout IHACRES, various statistics are used. These are described in the Table 3.5 below: Qo is an observed flow value, Q_o is a modelled flow value and Σ is the 90th percentile of observed non-zero flows.

Table 3.5: Statistics Used in IHACRES Model

Name	Description	Formula
Bias	overall error in flow volume, in mm per year (difference between Observed and modelled flows)	$\frac{\sum (Q_o - Q_m)}{n}$
Relative Bias		$\frac{\sum (Q_o - Q_m)}{\sum Q_o}$
R Squared	Measure of fit between observed and Modelled stream flow	$1 - \frac{\sum (Q_o - Q_m)^2}{\sum (Q_0 - \overline{Q_m})^2}$
R2_sqrt	Variation of R Squared, giving less Weight to peak flows	$1 - \frac{\sum (\sqrt{Q_o} - \sqrt{Q_m})^2}{\sum (\sqrt{Q_o} - \sqrt{Q_o})^2}$
R2_Log	Variation of R Squared, giving equal Weight to all flow percentiles.	$1 - \frac{\sum (\ln(Q_o + \varepsilon) - \ln(Q_m + \varepsilon))^2}{\sum (\ln(Q_o + \varepsilon) - \overline{\ln(Q_o + \varepsilon)})^2}$
R2_inv	Variation of R Squared, giving more More weight to low flows	$1 - \frac{\sum \left[\frac{1}{Q_o + \varepsilon} - \frac{1}{Q_m + \varepsilon} \right]^2}{\sum \left[\frac{1}{Q_o + \varepsilon} - \overline{\frac{1}{Q_o + \varepsilon}} \right]^2}$
U1	Auto-correlation of stream flow	
X1	Cross correlation	

Source: Table Showing statistics used in IHACRES, IHACRES user guide (2005)

3.5 Spatial Analysis

Watershed characteristics and catchment attributes relevant to hydrologic investigation can be easily generated and stored using GIS and spatial analysis (Cazorzi *et al*., 2000). The spatial analysis consists of; DEM depressions filling, calculating flow direction and flow accumulation, delineating streams with an accumulation threshold, defining streams, segmenting streams, delineating watersheds, processing watershed polygons, processing streams, and aggregating watersheds(Cazorzi *et al*., 2000; Newham *et al*., 2002; kokkonen *et al*., 2003). In this study, the spatial process framework used to derive catchment attributes in the Kasese basin catchments is as shown in Figure 3.2.

3.5.1 DEM Processing

Before the extraction of hydrological attributes, the DEM should be manipulated to produce a depression less DEM (Maidment, 1996). This procedure was carried out ARC-GIS version 9.2. Following this step, the hydrological attributes of slope low direction and streamline were then obtained (Cazorzi *et al*., 2000).

The DEM processing involved digital terrain analysis using the DEM to obtain the river network. This included the determination of cell grid dimension, computation of the slope of each cell, flow direction, and delineation of catchment boundaries (Maidment, 1996). The hydrological parameters slope, aspect, flow direction, drainage network with area, perimeter, elevation, circularity, were extracted from the DEM as represented by the Simplified spatial data process framework (see Figure 3.2).

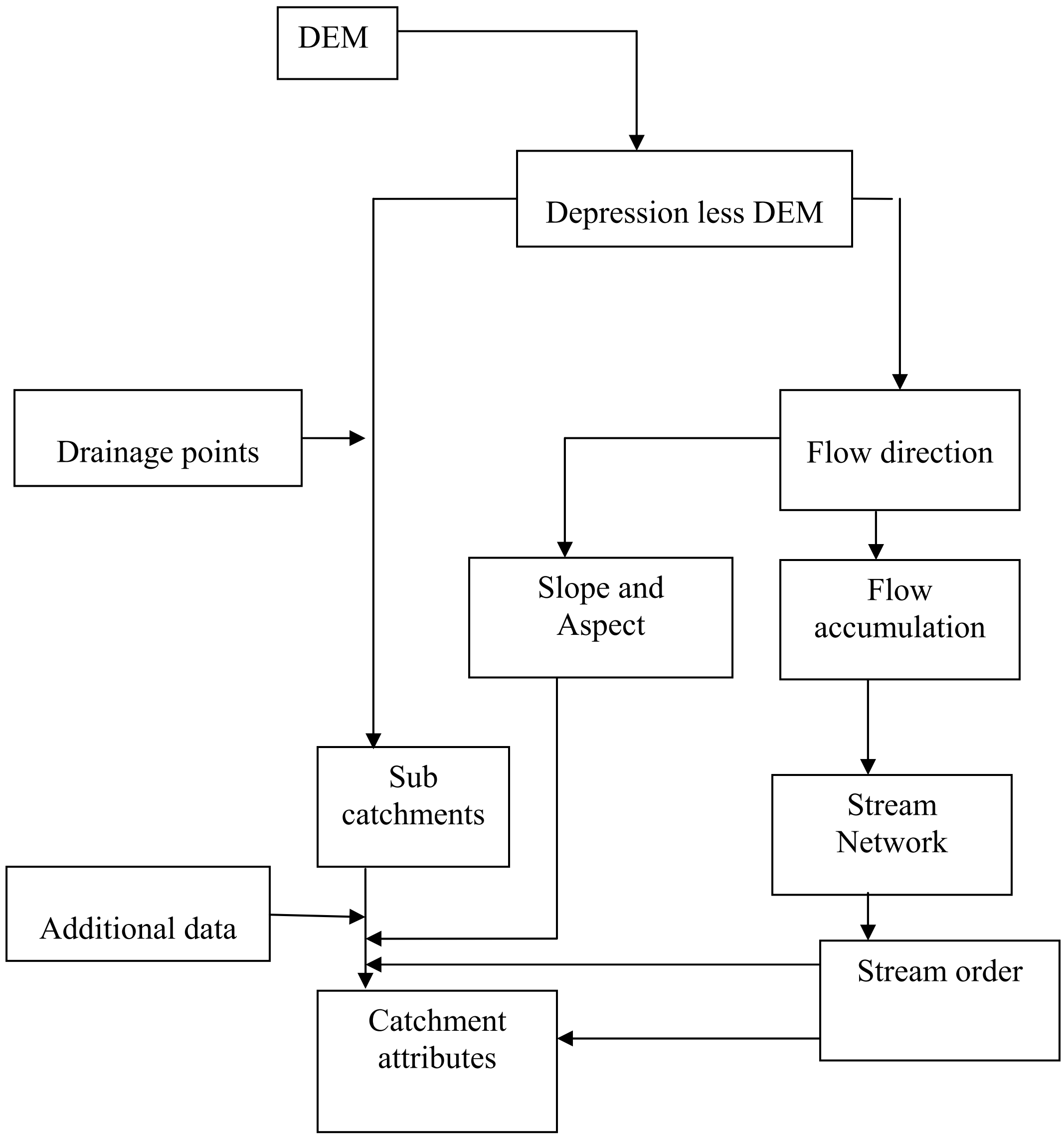

Figure 3.2: Simplified Spatial Data Process Framework

In addition, through DEM processing, sub-catchments, basin boundaries and drainage network and streamline were determined (Kokkonen *et al*., 2003).

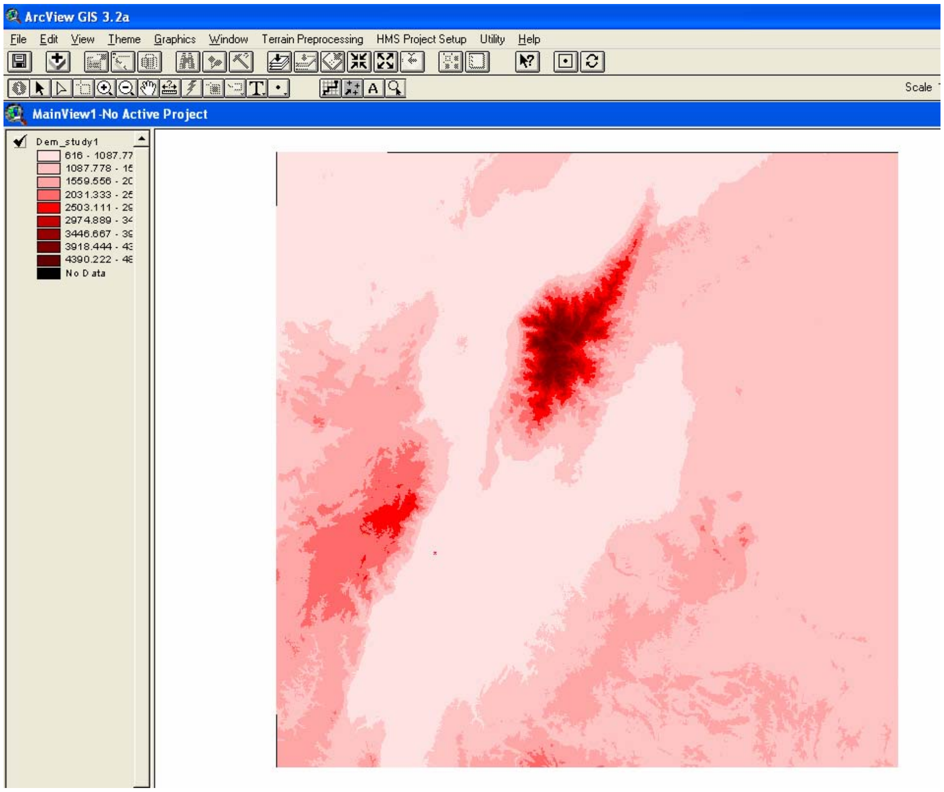

Figure 3.3: 90mx90m DEM Data in Degrees

3.5.2 Slope and Flow Direction

Topographic differences affect the hydrological response of a catchment (Newham *et al*., 2002). Hence, to predict the hydrological response of a catchment, the spatial variability of the hydrologic processes should be considered as was recommended by Moore *et al*., (1993); Maidment., (1996). The algorithm used in this study was able to extract the topographical structure from a DEM.

Slope is the elevation difference per horizontal distance and was used to estimate the flow direction.

The other important attribute to derive for hydrological modelling is flow accumulation; that was also extracted using DEM. The value of this parameter (flow accumulation) reveals the total flows from the surrounding cells that run in the selected direction (Cazorzi *et al*., 2000)

3.5.3 Catchment Delineation and Extraction of PCDs

The catchment region is defined as the area that drains to a point in the landscape. Consequently, the catchment contains within it hydrological properties, described by stream network, slopes, rainfall, runoff coefficient and unit hydrograph. The procedure to identify the stream flow network and sub catchments is shown in Figure 3.4. Two main data inputs were required for this step: The 90m resolution DEM (Digital Elevation Model) and drainage points that define the catchments of interest.

Catchment boundaries and other physical characteristics like flow direction, stream density, basin area, basin slope, hill slope length, longest drainage path were generated using step by step procedure under geographic user interface of HEC-GeoHMS extension as shown in Figure 3.4 below.

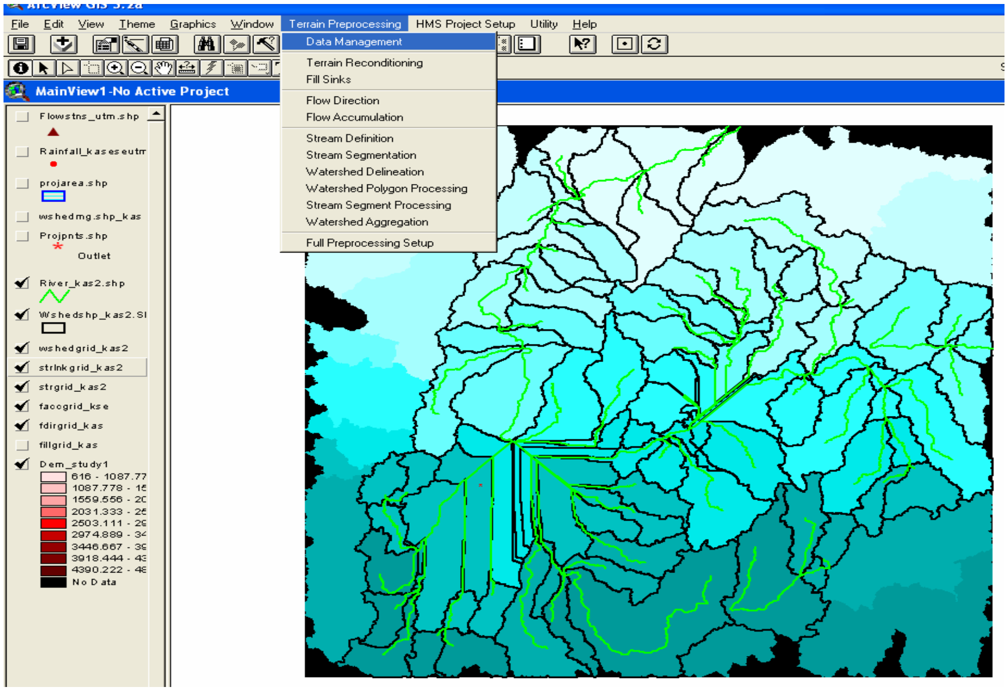

Figure 3.4: Process of Watershed Delineation

After watershed delineation, the gauging stations locations in degrees were added as a theme into the main view of the ArcView GIS.

From the HMS Project setup menu, the new project started and the various gauge stations were the output points. From HMS Project set up menu, the new project generated using the original stream definition.

It is from the project view that the different physical catchment descriptors for the respective catchments were extracted and saved in the attribute tables.

This was done by selecting the basin characteristics menu to obtain the river length, river slope and basin centroid.

Figure 3.5 also shows the four catchment areas generated by the spatial analysis. As noted earlier. Four streamflow gauged sites were considered for this study. Hence, the number of catchment areas generated was four.

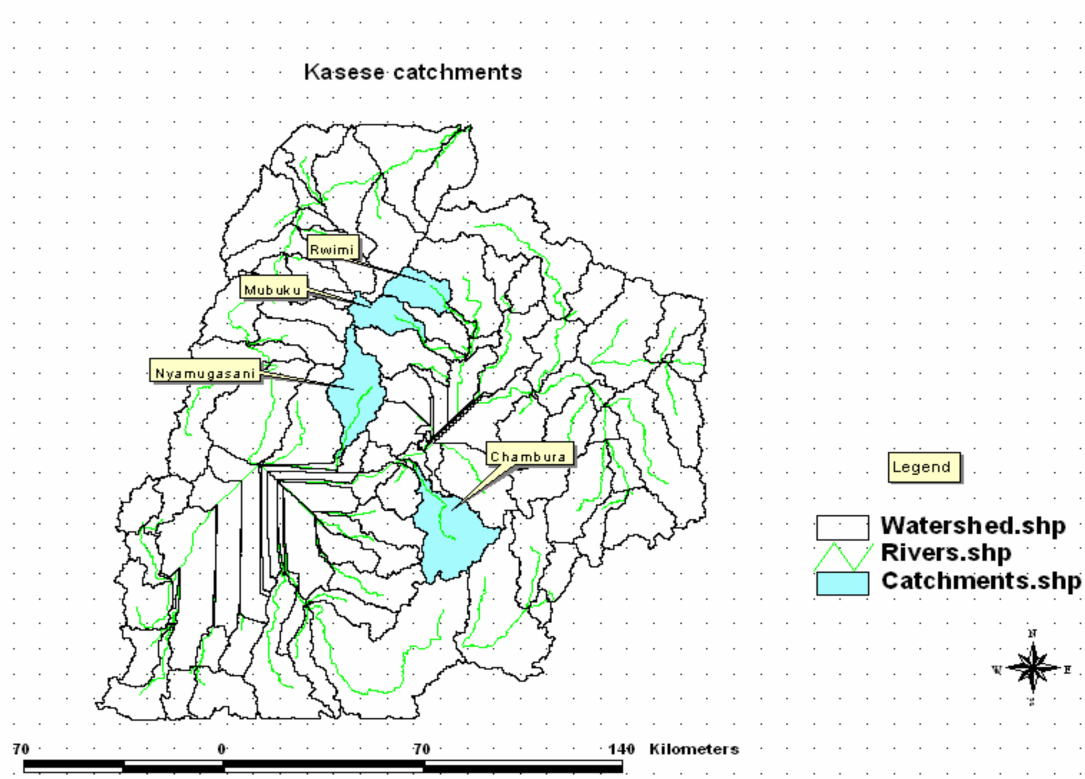

Figure 3.5: Showing the Extracted Catchments

It can be observed that in Figure 3.5, Nyamugasani, Rwimi and Mubuku catchments originate from the same region, which is the Rwenzori Mountains while Chambura originates far south of Kasese and flows into Kazinga channel that joins Lake George and Lake Edward.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter covers the results and discussion. The results discussed here were obtained based on the methodologies described in chapter three. The discussions in this chapter were based on the results obtained from the analysis done in chapter Three.

4.2 IHACRES Model Parameter Results

Finding a good model fit was not straightforward for any of the four Kasese catchments in study. A provisional 'best' model fit was obtained in the IHACRES methodology by repeatedly calibrating the unit hydrograph module using different values of the loss module parameters (τ_w and f), searching for a good model-fit and good precision on the unit hydrograph parameters. For each gauged catchment, use the data to estimate the calibration parameters for the selected rainfall-runoff model was done. For each of the four Kasese catchments convergence of the unit hydrograph parameters was not well behaved. However, details of the provisional 'best' model fits for these four catchments are listed in Table 4.1 below.

Table 4.1: Derived "Best" Model Fit Parameters for each Catchment

IHACRES model Parameters	Watersheds(Catchments)			
	Mubuku	Rwimi	Nyamugasani	Chambura
Temperature modulation factor (f)	0.0	0.0	0.0	6.0
Proportion of effective rainfall which becomes quick flow (Vq)	0.215	0.12	0.264	0.663
Quick flow reservoir time constant (Ts)	115.050	17.097	78.832	430.256
Slow flow reservoir time constant(Tq)	2.626	3.101	3.408	11.821
Catchment storage index/volume forcing constant (1/c)	1.0	1.0	1.0	1.0
Catchment drying time constant (Tw)	5.0	997	572.0	305

4.2.1 Model Calibration Results

A selection of a 3-year calibration period after (Jakeman *et al*., 1993) helps to balance problems of variance and bias; shorter periods tend to give high variance in DRCs whilst longer periods may include changes in the system for example in land-use or rating curves.

For a subset of four (4) catchments, IHACRES model was calibrated for three periods of 3 years in length within the 11year period and as well as on the whole 11-year period.

Each period started and ended with no flows because the model assumes an initial S_k of zero (Refer to Equation 2.2). Three parameters were used in evaluating model performance: R^2, a measure of goodness of fit; bias (the difference between mean observed and modelled flow), indicating where there is systematic over estimation or under estimation of flow; and ARPE, the average relative parameter error (Jakeman *et al*., 1990) combining the efficiency of the parameterisation and goodness of fit.

The third sub period, 1971–1974, was found to give the best calibrations though not a good simulation of the full 11 years. Models were therefore calibrated over the 3-year period 1971–1974 except for Mubuku catchment, which was from calibrated for the period of 1964-1967.

For each catchment, the optimal combination of loss characteristics was chosen using objective guidelines based on maximising R^2 and minimising ARPE and bias. The transfer function parameters were optimised using an instrumental variable procedure. (Jakeman *et al*., 1990).

In calibrating the IHACRES model, values for the catchment drying time constant (TauW) and the temperature modulation factor (f) governing the non-linear module were selected manually. Parameter values in the linear routing module and the parameter 1/c (catchment storage index/volume-forcing constant) in the non-linear module were calculated automatically by the program.

The coefficient of determination (R^2) and a percentage average relative parameter error' (%ARPE) for the parameters in the linear module are program outputs. We used the criteria that a good model is one that has a high value for R^2 and a low value for %ARPE. We calibrated the model using selected ranges for the parameters (TauW and f) in the non-linear loss module.

In a single run of the program, R^2 and % ARPE were then tabulated by the program for each pair of (TauW) and (f) to enable the scanning of the results in search of the best pair. Ideally, the maximum R^2 and the minimum for %ARPE would occur for a single pair; in practice, the maximum R^2 and minimum %ARPE define ranges of the catchment drying time constant and the temperature modulation factor.

The results of the calibration are as shown in the Table 4.2 below. See Figure 4.1, 4.2 and 4.3 for the graphical representation of the model fits (best and worst) for observed and modelled stream flow. The mean calibration R^2 obtained was 0.35 and the mean simulation R^2 was 0.31.

For the three catchments, IHACRES calibrated with an R^2 lower than 0.5 except Chambura with 0.51, and on all the simulation over 10 years; all the catchments had R^2 still less than 0.5.

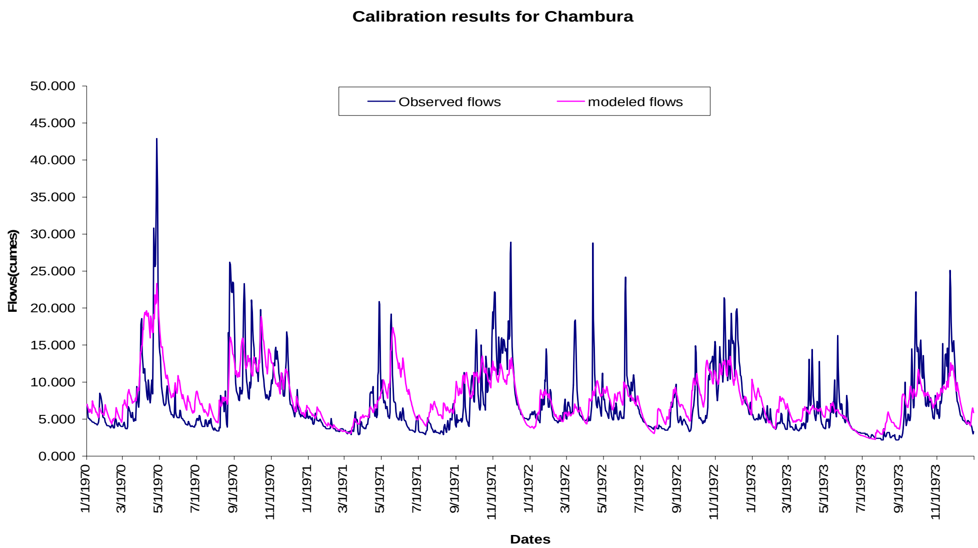

Figure 4.1: “Best” Fit of the Observed and Modelled Flows of Chambura

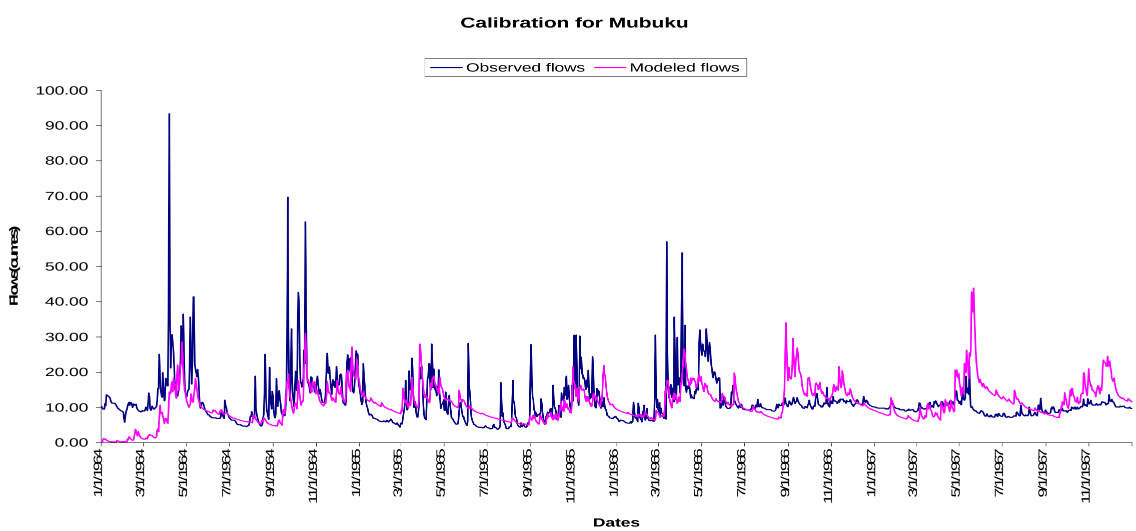

Figure 4.2: “Worst” Fit of the Observed and Modelled Flows of Mubuku

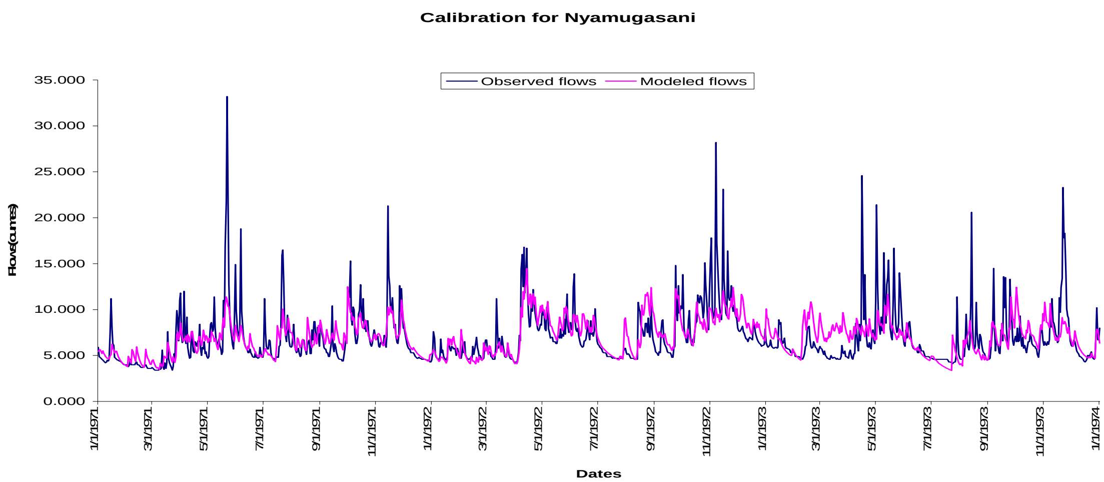

Figure 4.3: “Best” Fit of the Observed and Modelled Flows of Nyamugasani

From the graphs, generally the modelled runoff graphs do not capture the peak flows. There is a *considerable* elevation of the low flows for Mubuku catchment as observed, but when in actual sense, it is not a strong base flow catchment. The calibrated DRC’s are summarised in Table 4.2 below.

Calibration of the IHACRES model was not very good basing on the results in Table 4.2 below. Resulting calibrations had an average coefficient of determination (R^2) of 0.31, with a range from 0.12 to 0.51. Lack of success in calibrating the model in the catchment may be due lack of representativeness of climate input most especially temperature and rainfall.

Table 4.2: Calibration Results for "Best" Fit for Kasese Catchments.

	Model Parameters			
Name of Catchment	t_w	f	R^2	% ARPE
Mubuku	1.0 - 70.0	1.0 - 6.0	0.12	0.019
Rwimi	2.0 - 1000	1.0 – 7.0	0.25	0.007
Nyamugasani	1.0 - 1000	1.0 – 7.0	0.38	0.001
Chambura	1.0 - 1000	0.0 – 4.0	0.51	0.004

From the results, three catchments namely Mubuku, Rwimi and Nyamugasani with R^2 of 0.12, 0.25 and 0.38 respectively gave the poorest R^2 unlike Chambura with 0.51, which is fair. This could be because the headwaters of the three catchments are from the Rwenzori Mountains glaciers and snowmelt from snow capped peaks, unlike for Chambura, which is far south.

This could be further explained basing on the runoff coefficient results in Table 3.3, where Mubuku, Rwimi, Nyamugasani, Chambura are 1.37, 0.75, 0.46, and 0.41 respectively. This is extremely too high most especially for Mubuku. The absolute maximum is 1 and likely maximum is 0.7 for very wet catchments down to less than 0.1 for dry catchments. Unfortunately, these are not very wet catchments, so there could be a component of ice melt contributing to stream flow apart from rainfall.

4.3 Results for the Derived PCD's

After delineating the catchments, projects were created for each catchment, and the corresponding results obtained from the theme tables of the respective themes. The derived PCDs are as represented in Table 4.3 below.

Table 4.3: Derived PCD's for each Catchment

PCD's (Physical catchment descriptors)	Watersheds (Catchments)			
	Mubuku	Rwimi	Nyamugasani	Chambura
Length of main channel(km)	17.45	14.94	35.29	43.34
Average hill slope length (km)	42.14	30.10	24.92	18.92
Basin elevation(m)	2360	1704	1440.0	1491.0
Basin area(Km^2)	261	265	495	674
Longest drainage path(km)	38.85	39.28	65.44	67.61
Drainage density(km/$km^{2)}$	0.149	0.148	0.132	0.100
Major land use (%)	22.42	41.53	31.84	48.07
Major Soil types (%)	45.96	45.87	57.89	43.37

4.4 Results for the Correlation Matrix for Calibrated DRCs and Key PCDs

Microsoft -Excel software (CORREL work sheet function) was used to correlate derived key PCD's and the IHACRES model calibrated results, and the output is as shown in Table 4.4. Significant correlations at the 5% and above level were found between several PCDs and IHACRES model parameters.

4.4.1 Temperature Modulation Factor (f)

It is helpful at this stage to consider what dependencies we should be expecting for the IHACRES parameters with the Physical catchment descriptors. Beginning with the loss module parameters, since (f) moderates the sensitivity of wetness decline to temperature (refer to Equation ii), it may be expected to be influenced by factors affecting seasonal variation in evapotranspiration, for example land use/ land cover and climatic variables, and this is why it is correlating highly with the major landuse and basin area .

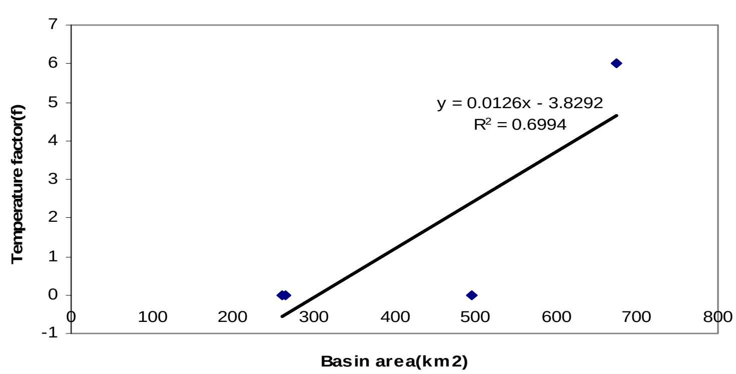

Figure 4.4: Temperature Factor Vs Basin Area

Since (τ_w) is the inverse of the rate of loss to evapotranspiration and to stream at 10°C (Equation i) governing the reduction of s_k through time and c is the contribution of unit rainfall to s_k land-use may be expected to be the dominant driver. (Post and Jakeman, 1996).

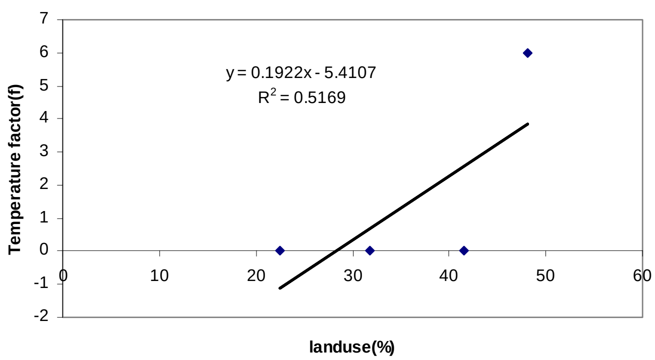

Figure 4.5: Temperature Factor Vs Landuse

4.4.2 Catchment storage index (1/c)

The larger the value of (1/c) mm, the greater the catchment storage capacity, and the lower the streamflow. Thus it should vary directly with landscape attributes that slow flow delivery to stream channels.

And this is the case for this study where 1/c is significantly correlated to the catchment size, the length of the main channel and the major landuse (small scale farming and forested areas) of the catchments. Post et al. (1996) found a dramatic reduction as a result of the reduction in transpiration following clear felling (85% removal of tree cover).

Wagener and Wheater (2005) suggest that a better fit could be derived from attributes that measure physical characteristics of soil such as porosity. The major soil type in these catchments is sandy clay loams and sandy loams to a small extent. These are characterized with high porosity there high flow delivery to stream channels. This can also explain the reason for high runoff coefficient values as seen in Table 3.4 section 3.2.

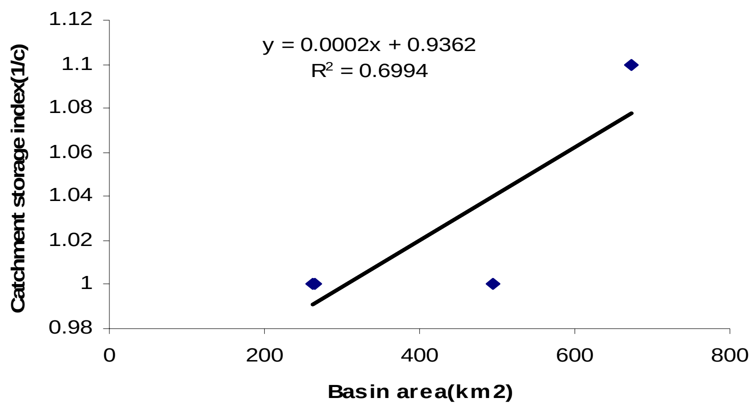

Figure 4.6: Catchment Storage Index Vs Basin Area

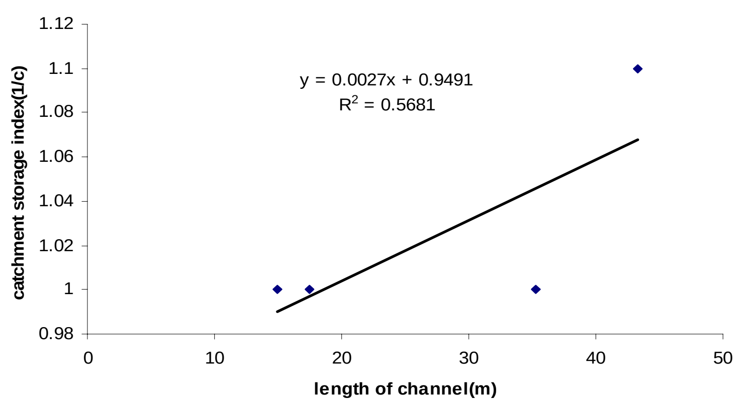

Figure 4.7: Catchment Storage Index Vs Length of Channel

4.4.3 Quick Flow Reservoir Time Constant (Ts)

Although the hydrograph separation into quick and slow response components is purely mathematical, according to Sefton *et al*., (1998) it is not unreasonable to link the quick component to surface and subsurface flow. Post and Jakeman (1999) assumed that surface and shallow subsurface flow delivery times, such as characterized by t_s, are likely to be related to size and shape of the catchment and stream network densities. In this study a positive relationship with catchment area was identified which is also significant statistically (R^2=0.59), it shows the right physical trend.

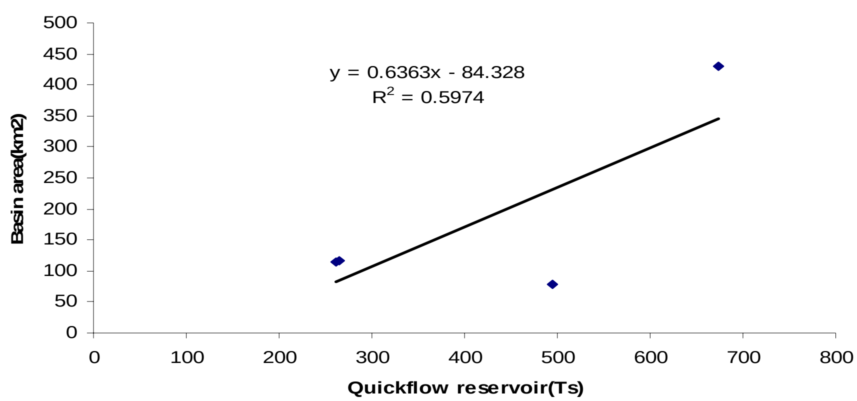

Figure 4.8: Quick Flow Reservoir Constant Vs Basin Area

4.4.4 Catchment Drying Time Constant (t_w)

Land use/land cover, soil drainage and infiltration rates, or some aspect of hydrogeology (e.g., soil or aquifer depths) should drive variations in the catchment drying time constant. Anderson et al. (2005) reported a relationship with *g100* (R^2= 0.64), the extent of drift thicknesses greater than 100 ft in depth. The prevalence of very deep soils and/or associated aquifers leads to longer soil drying times, which would produce more runoff. In this study a positive relationship of t_w with major soil type (sand clay loams) was identified which is also significant statistically (R^2=0.66) which is in line with Anderson et al. (2005) findings as already noted.

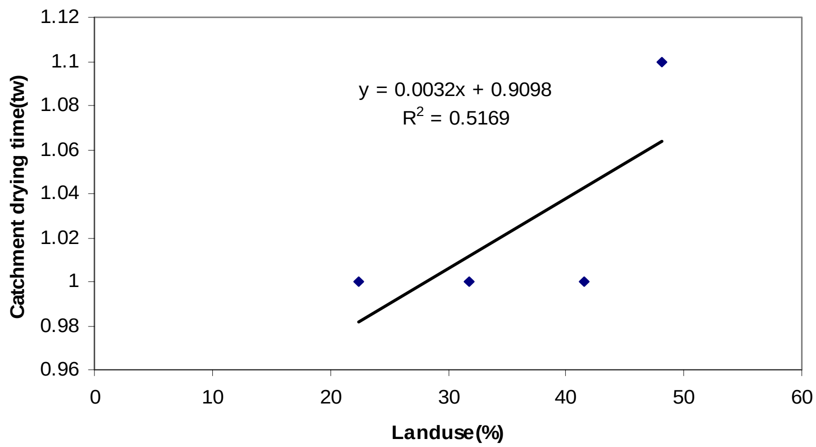

Figure 4.9: Catchment Drying Time (tw) Vs Landuse

4.4.5 Proportion of Effective Rainfall that becomes Quickflow (Vq)

Soil depths or geology would control the split between shallow and deeper flow pathways. Sefton and Howarth (1998) identified a strong relationship (R^2 = 0.59) between v_s and percent catchment containing a groundwater or aquifer component. Wagener and Wheater (2005) suggested that improvement over the traditional approach of seeking correlations between model parameters and landscape attributes could be obtained by weighted regression in which more weight is given to parameters that are better identified in the calibration process. In this study, v_q is strongly related to catchment size (R^2=0.81) and the major landuse (R^2=0.50) which logical to expect. For example under normal circumstance, the lager the catchment size, the less the v_q.

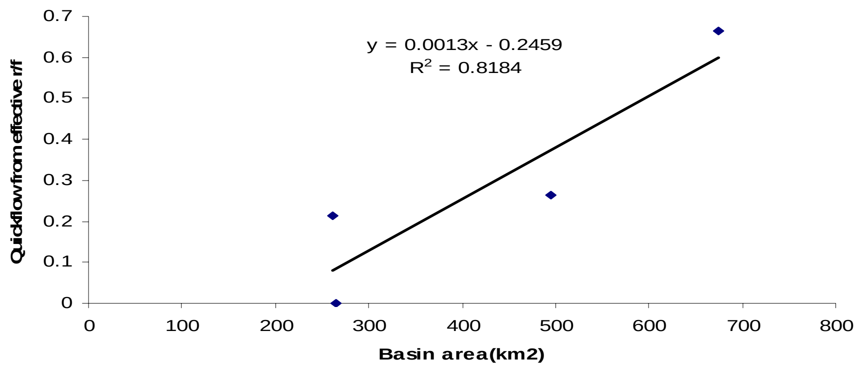

Figure 4.10: Quickflow Vs Basin Area

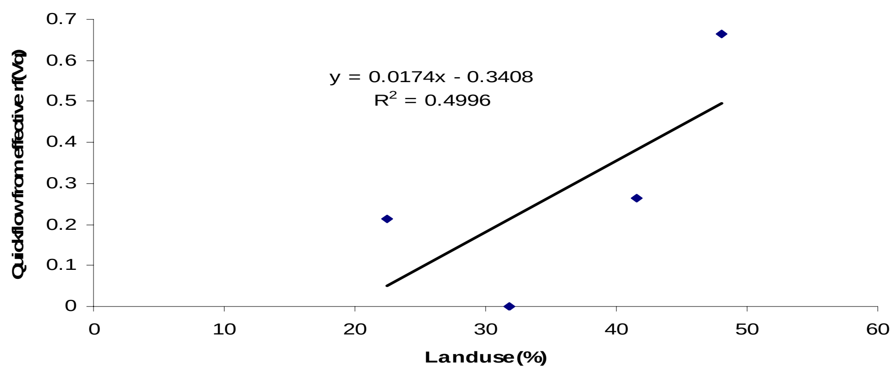

Figure 4.11: Quickflow Vs Landuse

4.4.6 Slow Flow Reservoir Time Constant (Tq)

Wagener and Wheater (2005) argue that calibrations to identify the slow reservoir time constant tq based on the entire hydrograph will tend to be unsuccessful because this parameter is related to the low flow periods. This is a possible reason for the weak relationship obtained by Sefton and Howarth (1998) (R^2 = 0.14) though it was not the case in this study. This could be due to the influence of snowmelt contributing to the flows thus altering the sequence of the hydrographs.

Littlewood (2003) proposed an augmented calibration scheme to re-adjust the temperature modulation parameter after initial calibration in order to improve the fit at low flows, but did not obtain stronger statistical relationships between f, tq and catchment attributes. The summary of the obtained relationship between the calibrated DRCs and key PCDs is as shown in Table 4.4.

Table 4.4: Correlation Matrix for Calibrated DRCs and Key PCDs

PCD's	Model parameters					
	f	Vq	Ts	Tq	1/c	tw
Basin area	0.69	0.81	0.59	0.70	0.69	-0.03
Longest drainage path	0.39	0.59	0.29	0.39	0.38	-0.008
Length of main channel	0.57	0.78	0.46	0.56	0.57	0.05
Drainage density	-0.88	-0.88	-0.81	-0.89	-0.88	-0.04
Basin elevation	-0.16	-0.12	-0.11	-0.21	-0.17	-0.31
Average hill slope length	-0.47	-0.37	-0.39	-0.52	-0.47	-0.12
Major land use	0.52	0.50	0.43	0.56	0.52	0.04
Major Soil type	-0.25	-0.66	-0.20	-0.20	-0.25	0.66

Table 4.4 illustrates the correlation matrix between calibrated model parameters and PCDs. Strongest correlations were found with the quickflow proportion (Vq), catchment storage index (1/c), catchment drying constant (TauW) and the temperature modulation factor (f). No significant correlations were found between the drying rate at reference temperature (t_w) and PCD's except soil type.

Correlations of model parameters with length of main channel, longest drainage path, and drainage area were very similar indicating that no 'new' information may be obtained from computing catchment descriptors beyond catchment area.

The lack of an observed relation between PCDs and the Drying rate at reference temperature (t_w) may be related to the seasonal variability in climate of these mountain regions. Observed climate records, typically representative of valley-bottom climates, may not be expected to represent the seasonal variability of basin-averaged temperature and precipitation assumed by the model. It is not to my surprise that there was no significant positive correlation between drainage density and the quick and slow reservoir coefficients. This is obvious that increasing drainage density would reduce the reservoir time constants (, i.e., quicker runoff response).

Despite these shortcomings, at the scales we have considered there is evidence that basin attributes might be used to estimate the range of model parameters that might be applied in ungauged basins for Kasese catchments.

A strong positive correlation between t_w and $1/c$, which is implicit in the model, enables estimation of one from the other. When a large proportion of unit rainfall contributes to the soil moisture index (high c, low $1/c$) this results in wet soil (high s_k) with rapid rate of change in soil moisture (low τ_w) and this is in agreement with Post and Jakeman, (1996) findings.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

IHACRES model was used for this study to examine the utility of the physical catchment descriptors (PCD's) to predict model parameters to explore transferability of model parameters between catchments, based upon physical catchment characteristics. The model was calibrated for four catchments and the results for R^2 were 0.12, 0.25, 0.38 and 0.51 for Mubuku, Rwimi, Nyamugasani and Chambura catchments respectively. It was concluded that the poor measures of fit between observed and modelled stream flow (R^2) could have been due to lack of good-quality time series of rainfall data representative of the whole basin and influence of snow melt for especially Mubuku, Rwimi and Nyamugasani. Physical catchment descriptors (PCDs) indexing topography, soil type, land cover, length of main channel, drainage density, and basin area were correlated to the hydrological model parameters from which a set of DRC–PCD relationship results indicate that strongest correlations were found with the quickflow proportion (Vq), catchment storage index (1/c), catchment drying constant (TauW) and the temperature modulation factor (f) with the PCD's. It was then concluded that IHACRES model, despite the low results of R^2 is applicable to Kasese catchment.

5.2 Conclusions

The loss module DRCs are described in terms of land cover, soil and climatic variables, and the routing module DRCs in terms of topographical and soil variables. The modelling of streamflow discharge of the Kasese catchments was constrained by: Inadequate rainfall, streamflow and temeperature input data, highlighting that good quality data are essential for understanding how streamflow responds to climate forcing. In this study, daily data sets were available for rainfall and temeperature. However, daily streamflow data could not be obtained for all the stations.

Lack of an appropriate number of streamflow and climatic stations across the catchments with sufficiently long records of onsite measurements of variables for model calibration. The number of stations available for running the IHACRES model were very small. Karim,(2005) recommended atleast thirty (30) streamflow and climatic stations are needed for an optimal calibration program.

The Generally the model calibration results for the Kasese catchments were poor. This could be due to lack of representativeness of climate input data most especially temperature and rainfall. This could also be due to the fact that the three catchment's (Mubuku, Rwimi and Nyamugasani) headwaters are from the Rwenzori Mountains glaciers and snow melt from snow capped peaks, unlike for Chambura which is far south.

As observed by Sefton *et al.,* 1998), catchments influenced by snow melt do not give good calibration results and the fact that IHACRES model version doesnot cater for the snow melt, then good results could not be expected.

Strongest correlations were found with the quickflow proportion (Vq), catchment storage index (1/c), catchment drying constant (TauW) and the temperature modulation factor (f). No significant correlations were found between the drying rate at reference temperature (t_w) and PCD's except soil type.

The poor correlations obtained could have been because of bias introduced into parameter values due to the choice of climate stations to pair with the hydrometric station. The climate station may be an inappropriate distance away to assume it representative of basin climate conditions.

From the results above, it can be concluded that generally IHACRES model results is satisfactory and the calibrated models were able to reproduce the observed temporal variations in stream flow in the catchment and therefore applicable to Kasese basin and most especially catchments that are far from the influence of snow melt in Rwenzori Mountains can give good results.

5.3 Recommendations

There was lack of good-quality time series of rainfall data that is representative for the whole basin. Further work should endeavour to improve the Kasese hydrometric network for basic hydrological survey and modelling purposes, and to systematically correlate the records from river flow measurement stations and rain gauges to facilitate better modelling results when using IHACRES model.

Though generally the model calibration results for the Kasese catchments were poor, they could be improved considering atleast thirty (30) streamflow and climatic stations for an optimal calibration program. This will improve the bias in the results.

An alternative to minimise the bias in the results could be by using either a reanalysis model approach or a regional climate model to derive basin-wide proxy climate records Gridded daily climate products, such as DAYMET could provide better forcing inputs to hydrological models in complex terrain than individual climate stations.

Although the IHACRES model is parsimonious in structure, there are likely several alternative parameter sets that perform as nearly as well as the optimally chosen parameter set in this study. These could include the percentage of lakes and rivers in the catchment therefore future work could look into this for possibly better results.

After deriving the DRC–PCD relationships, the relationships should have been validated by simulation of flow and sensitivity analysis at least two or more additional catchments which unfortunately was not done in this study.

So further studies need look into that, to give a more realistic recommendation of the use of the IHACRES model in Kasese catchments.

Previous work has developed the IHACRES approach for application to snow-affected catchments in Australia and Scotland. Results presented and discussed in this paper show that similar work is required to develop IHACRES for application to Kasese catchments affected by snowmelt from the Rwenzori mountain peaks.

The IHACRES model results presented and discussed here, should be regarded as a bench mark for modeling exercises and therefore future work with spatially distributed models (using long warm-up periods) may provide insights to help model the catchments by the IHACRES approach.

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APPENDIX I

List of Flow Gauge Stations and their Details

Number	Latitude	Longitude	Elevation (m)	Catchment size Km^2	Name of station
84221	0:22: 0 N	30:12: 0 E	0.0	266.0	R. Rwimi at Fort Portal - Kasese Road
84222	0:16: 0 N	30: 7: 0 E	0.0	256.0	R. Mubuku at Fort Portal - Kasese Road
84227	0: 7:22 S	30: 6:24 E	1028.0	660.0	R. Chambura at Kichwamba
84228	0: 7:24 S	29:50:34 E	930.0	507.0	R. Nyamugasani at Katwe - Zaire Road

Source: Directorate of Water Department, Entebbe –Uganda

APPENDIX II

List of Rainfall Gauge Stations and their Details

Station No.	Name of stations	Latitude	Longitude	Altitude (Ft)
89300800	MUBUKU	0 13'N	30 09'E	4250
89300360	KILEMBE MINES	0 12'25"N	30 00 15E	4500
89300610	RWIMI	0 23N	30 13'E	5000
89300330	ISUNGA	0 30'N	30 20'E	4700
90290210	MWEYA INST ECOLOGY	0 12'S	29 54 'E	3150
89300620	KIBURARA PRISON	0 05'N	30 28E	4050

Source: Department of Meteology, Kampala-Uganda

APPENDIX III

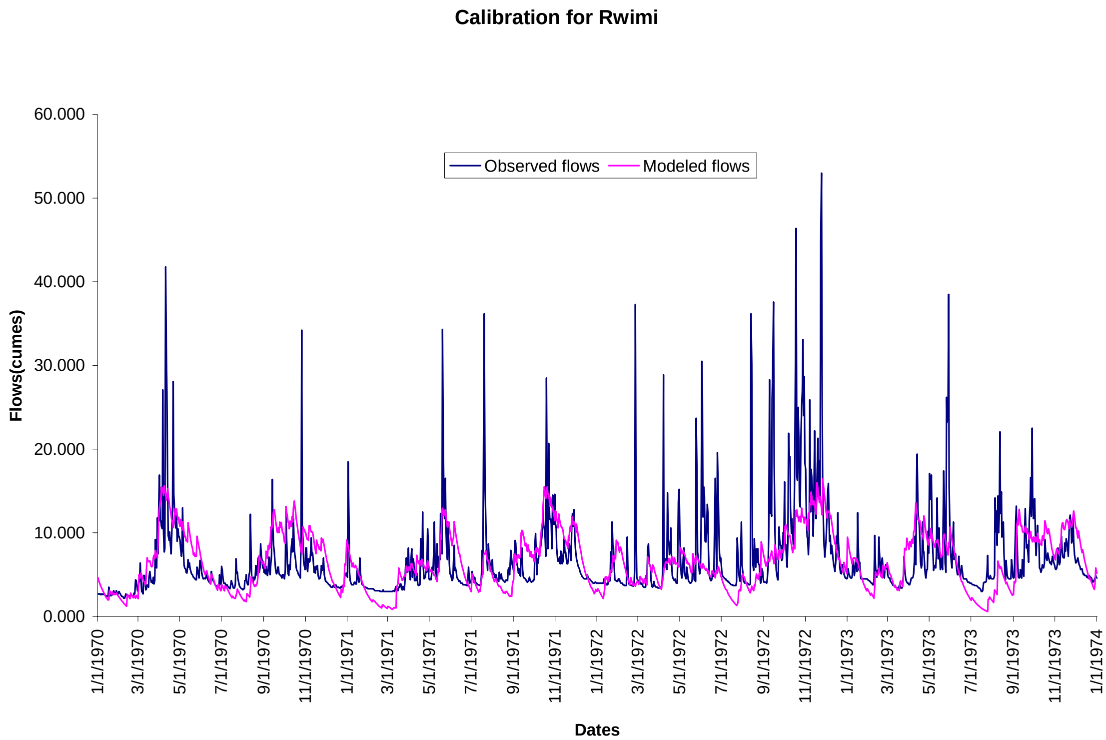

Figure 5.1: **Observed and Modelled flows of Rwimi Catchment**

APPENDIX IV

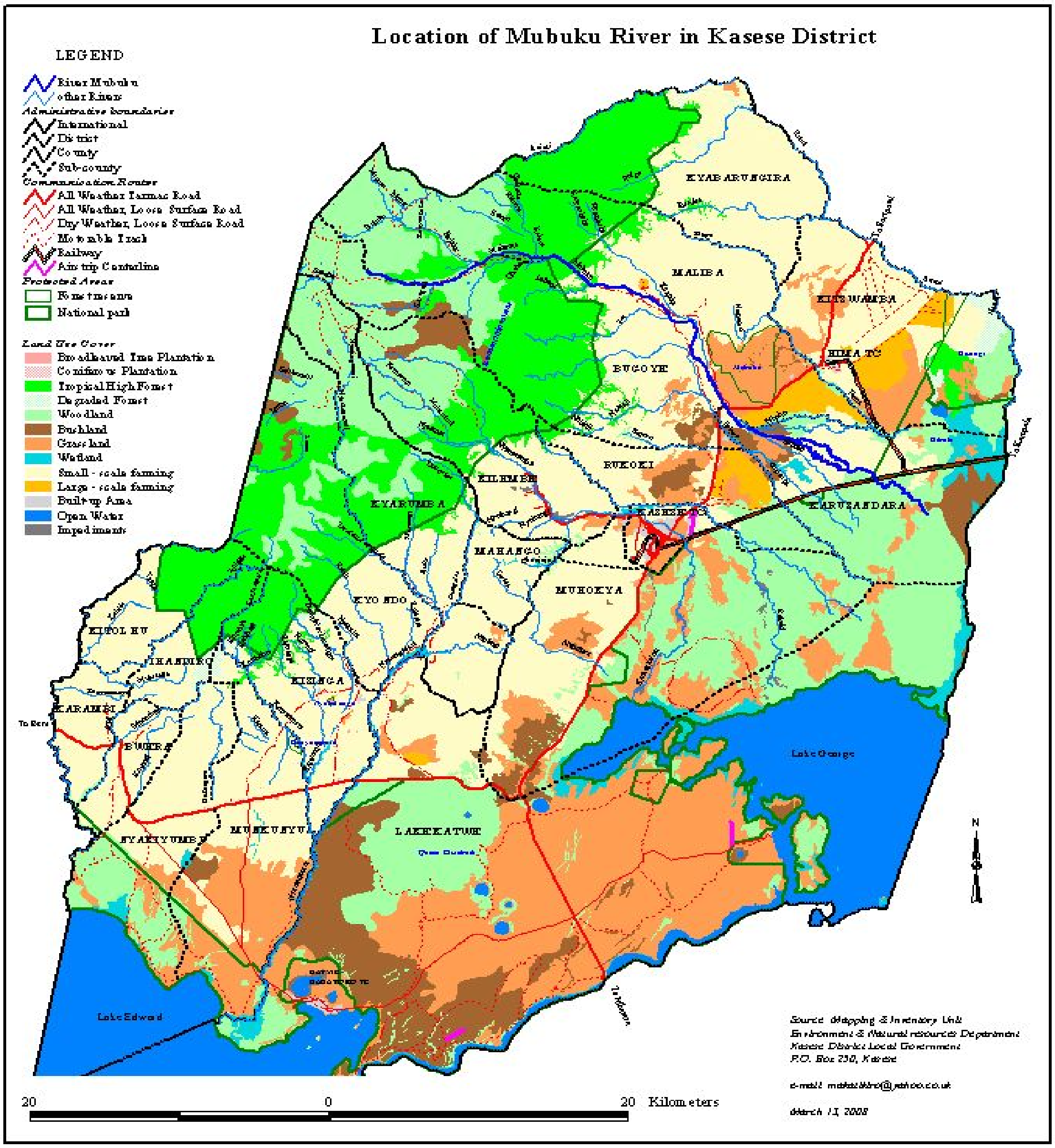

Figure 5.2: Major landuse Cover Types *Source: Mapping & Inventory Unit, Env't and Natural Resource Dept-Kasese District. March, 2008*