"COMPARISON OF THE PERFORMANCE OF RAINFALL-RUNOFF HYDROLOGICAL MODELS IN RUVUBU RIVER BASIN"

A CASE STUDY OF RUVYIRONZA-NYABIRABA CATCHMENT

A DISSERTATION SUBMITED AND PRESENTED

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IN HYDROLOGY AND WATER RESOURCES MANAGEMENT

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CERTIFICATION

I, the undersigned, certify that I have read and recommend for acceptance by the Arba Minch University a dissertation entitled: **Comparison of the Performance of Rainfall-Runoff Hydrological Models in Ruvubu river basin - A case study of Ruvyironza-Nyabiraba Catchment** in Partial fulfilment of the requirements of the degree of Masters of Science in Hydrology and Water Resources Management.

……………………………………………

Dr. Semu Ayalew Moges

Supervisor

Date……………….………..

DECLARATION AND COPY RIGHT

I, Astere Nindamutsa, 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……………………

Date………………………….

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-My classmates for their assistance in my thesis research;

Last but not least, my special thanks goes to my family, my friends, and as well as my wife, my daughter and my son for their patience and encouragement while I was too far from them.

DEDICATION

This thesis is dedicated to

My wife

Marie Rose Nshimirimana

My daughter

Breda Marie Ishimwe

And

My son

Jean Cardin Nganji.

ABSTRACT

Rainfall-runoff models have become accepted as important tools in operational hydrology for estimating information required for water resources planning, design, and operation. Specifically, rainfall-runoff models are normally useful tools where data are insufficient by simulating and by extending the time series.

This thesis work presents an appraisal study to compare the performance of four hydrological models in RVZ- Nyabiraba catchment for Ruvubu river basin and to select the best candidate model for the catchment response prediction.

In this appraisal study, to achieve our objective 2 empirical models: Simple Linear Model (SLM), Linear Perturbation Model (LPM), and 2 conceptual models: (HBV) and Soil Moisture Accounting and Routing (SMAR) were tested in Ruvyironza-Nyabiraba catchment.

Parameter optimization is carried out by trial and error, ordinary least squares, Rosenbrok, Simplex and generic algorithm. The parameter set that gave the best objective function value over the calibration period in the ranges of the parameters was used for validation. The visual comparisons were also made for the low and high flow fit of the hydrographs. The comparison was also made on the basis of the relative error of peak (RE) criteria and the index of volumetric fit (IVF).

From the models comparison performance criteria, it is shown that the Simple linear model (SLM) and HBV are not adequate in modelling the rainfall runoff transformation. However, the RVZ-Nyabiraba catchments exhibit marked seasonal behaviour and good results was also obtained with Linear Perturbation model (LPM) which involves the assumption of linearity between the departures from seasonal expectations in input and output series. Within the range (0.5-0.9) of the tested models performance, in the RVZ-Nyabiraba catchment, out of the four models, SMAR was found to be the best candidate model that can simulate the flows. Hence, SMAR is adequate in modelling the rainfall runoff transformation. Further investigation should be made to generalize the applicability of this model to all Ruvubu river basins.

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LIST OF ABBREVIATIONS AND ACRONYMS

ATP: Applied Training Project

^{O}C: Degree centigrade

ET_o: Reference Evapotranspiration

FAO: Food Agricultural Organization

GFMFS: Galway River Flow Modelling and Forecasting System

HBV: **H**ydrologiska **B**yrans avdeling for **V**attenbalans model

IGEBU: Geographic Institute of Burundi

IVF: Index of Volumetric Fit

Km^2: Kilometers square

LPM: Linear Perturbation Model

M: Meter

M^3/s: Meter cube per second

mm: Millimeter

NBI: Nile Basin Initiative

NWS: National Weather Service.

RE: Relative Error of Peak

RVZ: Ruvyironza

SAC-SMA: Sacramento Soil Moisture Accounting and Routing model

SHE: Système Hydrologique Européen

SLM: Simple Linear Model

SMAR: Soil Moisture Accounting and Routing

CHAPTER ONE

INTRODUCTION AND BACKGROUND

1.1 General

Many scientific disciplines use models to describe systems in simpler terms and to predict system response. In general, the purpose of the development of these models is first to advance our understanding and state of knowledge about the hydrological processes involved in the rainfall-runoff transformation. The second is to provide practical solutions to many of the related environmental and water resources management problems. Rainfall-runoff models are normally used as components in river flow forecasting systems. The efficient forecasting of river flows is beneficial in many aspects for the prosperity of those societies living in river basins.

During the last three decades rainfall-runoff models have become accepted as an important tools in operational hydrology for estimating information required for water resources planning, design, and operation.

It is become increasingly obvious that the social and economic planning in all parts of the world and in Burundi in particular must seriously considered the management of water as a priority. An integral part of any water management program must be the ability to predict river flows.

To develop these rivers for irrigation, hydropower or water supply purposes, the river flow characteristics have to be known. To know their flow characteristics, there has to be optimum river gauges in the river catchments.

But, concerning hydrological data of the rivers, there is missing data because of insufficient observations; instrument failure etc. and a large number of gauging stations on each river are not working.

In such situation, using a hydrological model which requires two essential components, one to determine how much of a rainfall becomes part of the storm hydrograph (the runoff production component), second to take account of the distribution of that runoff in time, to form the shape of storm hydrograph (the runoff routing component) are helpful in generating runoff from the rainfall (Genene Abera Nigatu, 2006).

In fact, there is a need of study which solves the above problems by testing hydrological models which are not requiring very much details data in different drainage area of the country.

The aim of this study is to test some Linear and Conceptual hydrological rainfall-runoff models on a specific catchment located in Ruvubu drainage (one of the 2 tributaries of the Nile basin) in Burundi on Ruvyironza(RVZ)-Nyabiraba catchment.

This catchment is selected according to the data availability and its proximity.

The purpose of the application of the models is also to calibrate each model and compare the performance of each hydrological rainfall-runoff models with respect to the efficiency and consistency.

To achieve the objective of the study, 2 empirical models: Simple Linear Model (SLM), Linear Perturbation Model (LPM), and 2 conceptual models: (HBV) and Soil Moisture Accounting and Routing (SMAR) are tested.

1.2 Description of the study area

Burundi has 2 major watersheds: one of Congo-Nile crest basin and another of the Nile Basin. The Ruvubu river basin is one of the sub basin of Burundian Nile Basins. The density of the hydrographical network varies from low to high river tributaries. The Ruvubu river basin drains a basin area of 9432 km^2 and its length of 265 km inside Burundi, is the most important river. It exits Burundi through the northeast at the border with Tanzania.

One catchment of RVZ-Nyabiraba in Ruvubu River basin is selected for this study.

In fact, RVZ-Nyabiraba is one of the catchment which collects tributaries contributing flow into the Nile River through Ruvubu River inside Burundi.

The catchment of RVZ-Nyabiraba is located in the central plateau of Burundi which occupies the South-East part of Kirimiro natural region and at the East part of the Congo Nile crest. It regroups 2 provinces and 6 communes:

-Gitega: Buraza, Gishubi, Makebuko and Ryansoro;

-Bururi: Matana and Rutovu.

The catchment of RVZ-Nyabiraba lies between $3^{0}30'$ N and $3^{0}55'$S of latitude and $29^{0}40'$ W- $30^{0}00'$ E of longitude, it ranges in elevation up to 1610 m above sea level at Ruvyironza, up to 1770 m above sea level at Nyabiraba, up to 1735m above sea level at Mweya meteorological stations and up to 1578 m above sea level at RVZ-Nyabiraba hydrological station.

RVZ-Nyabiraba catchment has 2 mains important sources. One of the 2 sources constitutes the longest source of the Nile river basin in the region.

The borders of the watershed are:

- North catchment: ranges in elevation from 1600 to 1900m;

- West catchment: ranges in elevation from 1600 to 2300m;

- South catchment: ranges in elevation from 2000 to 2200m;

- South-East and East catchment: Narrow old pen plains; the altitude of 1250m to 1500m resulting in the valleys of Eastern Ruvubu river basin(ranges in elevation from 1200 to 1600m).

This study considers only the upper part of the basin above the RVZ-Nyabiraba gauging station with a drainage area of 751.8 Km^2, the length of 68 km and the width of 11 km.

The study area has the characteristics of plateau. It has a tropical climate but moderate by altitude.

The following are the climate characteristics:

-Ruvyironza river has a mean daily flow of $10m^3/s$ at Nyabiraba gauging station as shown in Figure 1.1).

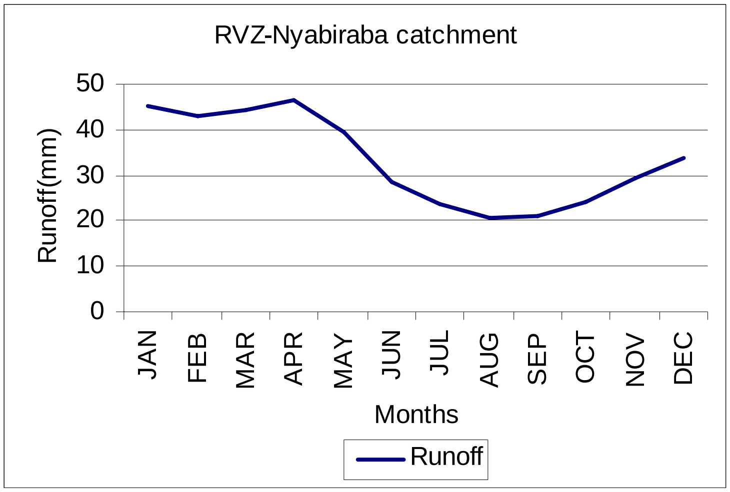


Figure 1.1 The mean daily flow at Nyabiraba gauging station

-The mean temperature is a function of topography and lies between 15^0C and 20^0C as shown in Figure 1.2).

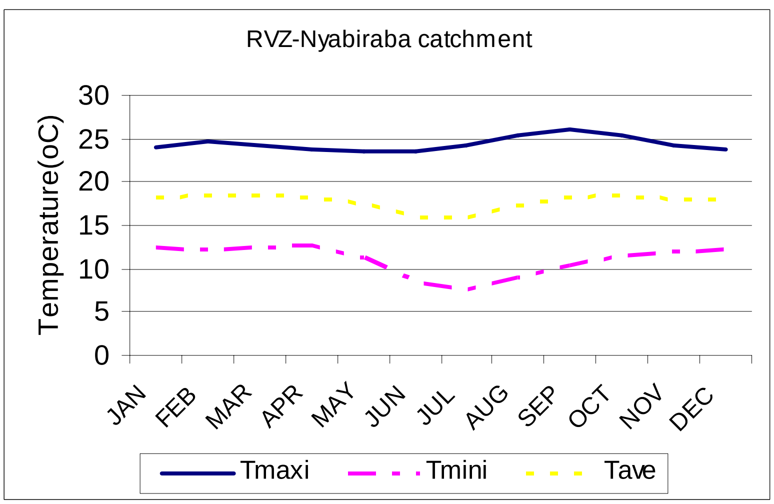


Figure 1.2 The monthly temperature of RVZ-Nyabiraba catchment

-The total rainfall amounts vary from about 1000 to 1200mm, of which 70% falls between November and April as shown in Figure 1.3).

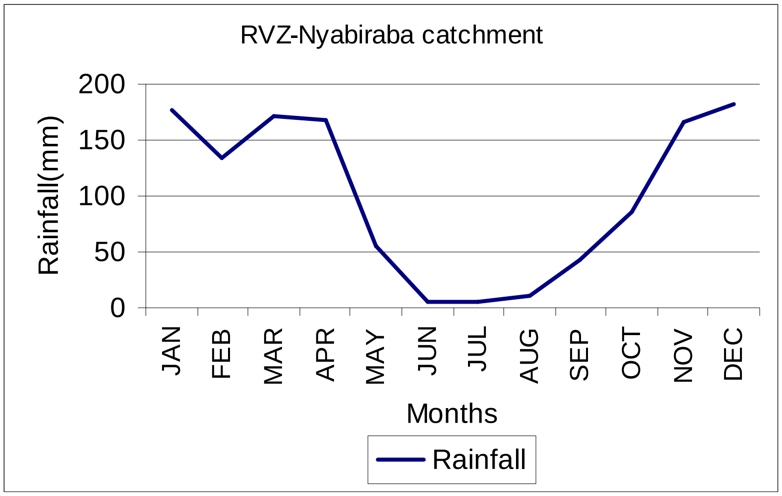


Figure 1.3 The rainfall regime of RVZ-Nyabiraba catchment

The rainfall regime is characterized by two rainy seasons, the short rainy season and the long rainy season. The short rainy season starts from mid-September to December immediately followed by January which is generally a small dry season.

The long rainy season starts in February to May followed by a long dry season from June to August.

The total potential evapotranspiration varies from 1100mm to 1500mm as shown in Figure 1.4).

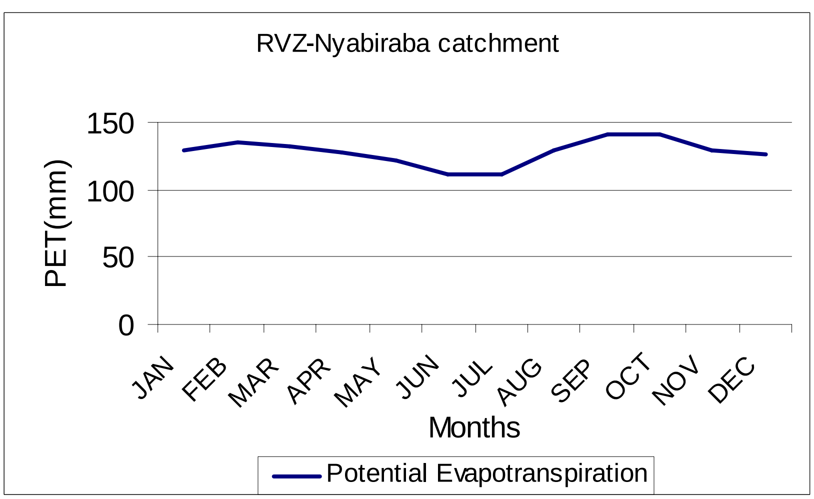


Figure1.4 The monthly potential evapotranspiration of RVZ-Nyabiraba catchment

The soils are either, clay or sandy. The schist-quartz rocks are his characteristic. The RVZ-Nyabiraba catchment occupies the South-East part of Kirimiro region and is characterized by the presence of wood savannas. Most of these soils are favourable to agriculture. The main crops growing are, among others, maize, beans, bananas, manioc, collocate, potato, tomato, peanuts, rice etc…

In 1998, Burundi population was around 6.1 million of peoples, the population density being 220 peoples per square km. The population growth is 3.2%. The population growth is unequal in different parts of the country. The population density in the study area varies from 150 to 250 peoples per square km (people/km^2) at the south-east of the catchment in the communes of Buraza, Gishubi, Makebuko and Ryansoro; the population density is low at the extreme south-west of the catchment: below 150 peoples per square km (people/km^2) in the communes of Matana and Rutovu. The population density is founded in areas with fertile soils.

During the dry season, the population practices farming activities in the wetlands to get subsistence food and other needs. Bananas, local brew and coffee are the essential sources of population income.

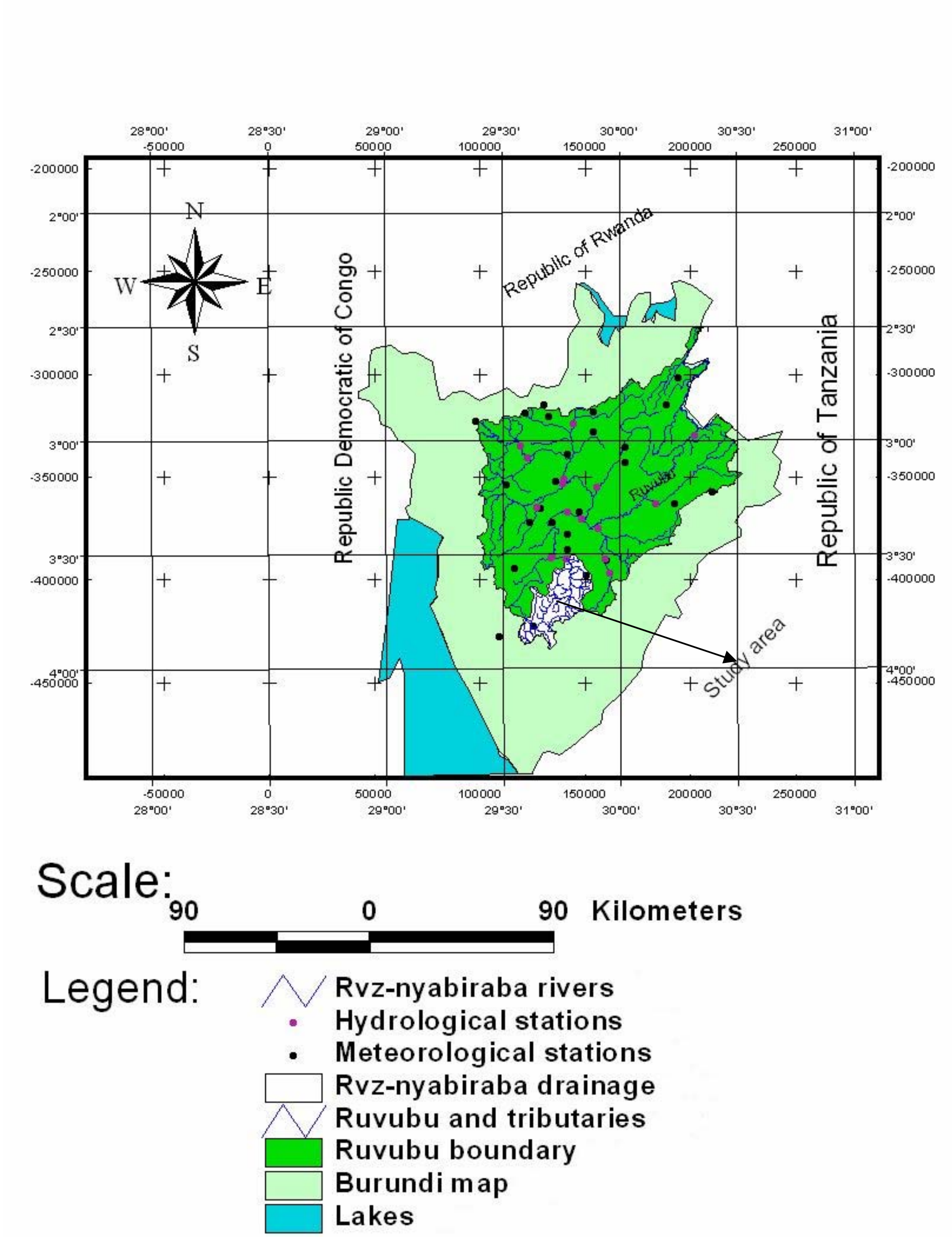


Figure 1.5 Location map of the selected study area

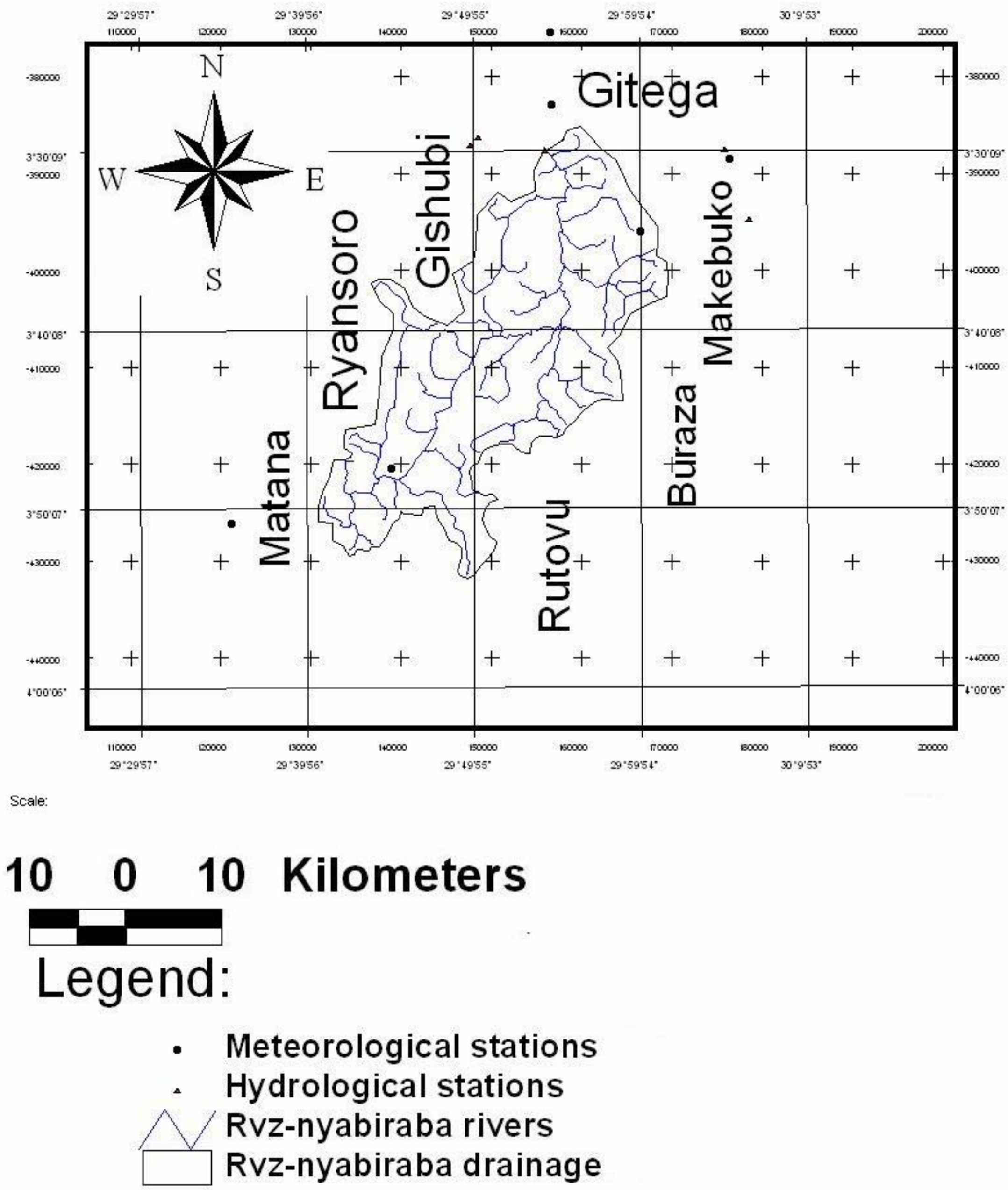


Figure 1.6 Map of the selected study area

1.3 Problem statement

Rainfall-runoff models are useful tools where data are scarce and resources are under development. It is possible to generate runoff from rainfall and meteorological data where river gauge is not available (Keith, 2002). The main problem in Burundi is that, most of the rivers did not have any flow records. Even those gauged rivers did not have sufficient data, the gauging stations are at the minimum and consistency is always at stake.

Hence, hydrological rainfall- runoff models are appropriate operational tools to simulate and extend the time series. It is also necessary to adopt different hydrological rainfall-runoff models in different catchments and basin in Burundi in order to develop characteristic curves and parameters that are applicable to un gauged catchments. The models will help also to improve the consistencies usually observed in the observed discharge.

1.4 Objective of the study

1.4.1 General objective

The objective of this study is to define the best hydrological rainfall-runoff model between black-box and conceptual which is suitable for use within the country, to test the calibration and parameter interdependence in the catchments.

1.4.2 Specific objectives

-To assess and select the models to be used for the application;

-Data preparation according to the models input format;

-Calibration and verification of certain data to be ready for application;

-Sensitivity analysis of parameters for better evaluation and application;

-Model application according to the target conditions;

-Model evaluation and validation which can be done for necessary model modification;

-Analysis of the performance of two linear models (Black-Box) and two conceptual models;

-Comparison of the results of the models in the catchments;

-To investigate the rainfall and runoff characteristics of the catchments.

-To propose appropriate models which are suitable for use within the country.

1.5 Thesis organization

The chapter one concentrates the introduction and background where the importance, the purpose of the application of rainfall-runoff models and how the comparison of the performance of each model in operational hydrology is described. In this chapter also, the study of the selected area, the problem statement, the objective of the study including general and specific objective are described in details.

The chapter two deals in details with the literature review on rainfall-runoff modelling, where the models selected (SLM, LPM, SMAR and HBV) are classified and described with respect to the experience of other works.

In chapter three, the work includes all the estimated and analysed of hydrological characteristics of RVZ-Nyabiraba catchment.

The chapter four tries to show the model results and analysis in which each model selected for the performance comparison is analysed by using different techniques by detecting which model improve well than others in modelling the rainfall-runoff transformation.

The last chapter include the summary, the conclusion and recommendation in which all procedures regarding the comparison of the performance of rainfall-runoff models in the selected catchment is summarised; and where the proposed future work are recommended.

Further informations are appendices included in the thesis work for good clearance.

CHAPTER TWO

LITERATURE REVIEW ON RAINFALL RUNOFF MODELLING

2.1 Hydrologic processes

The central focus of any hydro meteorological study is the hydrological cycle. The hydrological cycle has no beginning or end and its many processes occur continuously (Chow et al, 1988).

In describing the cycle, the water evaporates from ocean and land surface to become part of atmosphere; water vapour is transported and lifted in the atmosphere until it condenses and precipitates on the land or the oceans. Precipitated water may be intercepted by vegetation, becomes overland flow over the ground surface, infiltrate into the ground, flow through the soil as subsurface flow and discharges into streams as surface runoff. The infiltrated water may percolate deeper to recharge groundwater, later emerging as spring and seeping into streams to form surface runoff and finally flowing into the sea or evaporating into the atmosphere as the hydrological cycle continues.

It is noted that through the concept of the cycle seems simple, the phenomena are enormously complex and intricate. It is not just one large cycle but it is rather composed of many interrelated cycles of continental, regional and local extent.

The major achievement and objectives of the rainfall runoff modelling is thus to study a part of the hydrological cycle namely the land phase of the hydrological cycle on a catchments scale. Then the problem becomes to express the runoff from the catchments as a function of the rainfall and other catchments characteristics.

Considering the land phase of the hydrological cycle, any empirical, conceptual or distributed model predicts its effort on an expansion of the basic water balance or continuity equation that is

$$I - O = \frac{ds}{dt} \qquad \text{.......... 2.1}$$

Where

I is the input to the system (rainfall),

O is output from the system (evaporation, stream and groundwater flow)

ds/dt is the change in soil moisture.

The main processes encompassed are precipitation, evapotranspiration, interception, infiltration, subsurface flow and stream flow.

It is evident that before any modelling effort can be performed, one has to understand the above physical processes, their extent of effect on the abstraction from or addition of water to a catchment.

2. 2 Hydrological modelling

There are many different reasons why we need to model the rainfall-runoff process of hydrology. The main reason is however, a result of the limitations of hydrological measurement techniques. We are not able to measure every thing we would like to know about hydrological systems. We have in fact, only a limited range of measurement techniques and a limited range of measurements in space and time. Therefore there is a means of extrapolating from those available measurements in both space and time. Particularly to un gauged catchments and in to the future(where measurements are not possible) to assess the likely impact of future hydrological change, models of different types provide a means of quantitative extrapolation or predication that will hopefully be helpful in decision making(Keith, 2002).

During the early part of the 20th century there were two strands of modeling developed by engineers as pragmatic tools for hydrological/hydraulic design.

One stochastic for determining the probability those extreme events might occur, investigated by Gumbel (1941).

The other was deterministic and was again aimed at hydrological/hydraulic design.

These deterministic models were typified by the unit hydrograph (Sherman, 1932) which was intended to characterize the shape of the hydrograph in a river in response to an extreme rainfall event.

Until very recently, these two modeling techniques have remained the standard modeling tools for practicing engineers;

The modeling alternative to the unit hydrograph and extreme value analysis emerged out of research institutions during the late 1960s.

These models are normally classed as being Lumped conceptual models.

Increasing availability of computing power, coupled with a desire to simulate sediment and chemical transport pathways within a catchment, led to the development of more "physically based" and spatially distributed models, such as the Système Hydrologique Européen(SHE) model(Abbot et al., 1986).

However, in hydrological forecasting, this approach tends to break down due to the complexity of the boundary conditions rather than any essential difficult in the physical laws (Nash and Sutcliffe, 1970).

Hydrologists have long recognized the complexity of the problem and hence resorted to the use of simplified hydrological models.

Such models may be broadly described as conceptual or empirical according to whether they are, or are not, capable of physical interpretation;

With such models, attention centre on identifying a relationship between rainfall or inflow as input and stream flow as output, without attempting to describe any of the internal mechanisms whereby this transformation takes place.

2.3 Hydrological Models Classification

Hydrological models can be classified in different ways. Broadly many of the models presented in the literature can be divided into deterministic and stochastic categories. A deterministic model is one in which the processes are modelled based on definite physical laws and no uncertainties in prediction are admitted. It has no component with stochastic behaviour i.e. the variables are free from random variation and have no distribution in probability.

2.3.1 Deterministic Models

Deterministic means that a given set of parameters and inputs exactly determine the output. In other words there is no stochastic or random element in the model.

Deterministic models can be further classified according to whether the model gives a spatially lumped or distributed description of the catchment area, and whether the description of the hydrological processes is empirical, Conceptual or fully physically based.

The familiar classification of model classification is to classify them in three categories:

a) Black box models,

b) Conceptual models,

c) Distributed physically based models.

a) **Black box models**

Black box models are based on transfer functions which relate inputs with outputs. These models, as the name suggests, generally do not have any physical basis.

b) Conceptual Models

Lumped conceptual models occupy an intermediate position between the fully physically- based approach and empirical black box analysis. Conceptual implies that the modeller has a conceptual picture of the physical processes that are occurring in the catchment. Lumped infers some sort of averaging process. For example, 'lumped models' will normally simulate spatially averaged soil moisture, rather than attempting to simulate the spatial distribution of soil moisture across the catchment.

In essence conceptual hydrological models can be described as those that retain some of the physical laws (e.g. conservation of mass) in their mathematical formulation, without trying to exactly model reality. They are commonly based on analogies of catchments or river networks as a set of storage reservoirs with different properties.

c) Distributed Physically Based Models

The physically based models are based on our understanding of the physics of the hydrological processes which control the catchment response and use physically based equations to describe these processes. Also, these models are spatially distributed since the equations from which they are formed generally involve one or more space coordinates.

A discretization of spatial and temporal coordinates is made and the solution is obtained at the node points of this discretized representation. This implies that these models can be used for forecasting the spatial as well temporal pattern of more than one hydrological variable. Such models require much of computational time and also require advanced computers as well as a broad data base.

Physically based distributed models do not consider the transfer of water in a catchment to take place in a few defined storage as in case of lumped conceptual models. From their physical basis such models can simulate the complete runoff regime, providing multiple outputs (e.g. river discharge, phreatic surface level and evaporation loss) while black box models can offer only one output. In these models transfer of mass, momentum and energy are calculated directly from the governing partial differential equations which are solved using numerical methods, for example the St. Venant equations for surface flow, the Richards equation for unsaturated zone flow and the Boussinesq equation for ground water flow.

As the input data and computational requirements are enormous, the use of these models for real-time forecasting has not reached the ‘production stage’ so far, particularly for data availability situations prevalent in developing countries like.

2.3.2 Stochastic Models

The model becomes stochastic when probabilistic laws are being used and stochastic elements, with known or determinable distribution, occur in the model.

Stochastic models may be divided into:

-Models for frequency analysis (statistic repartitions).

-Regression models.

-Stochastic models.

-Models with random coefficients.

-Models with constraints expressed in probability (chance constrained models).

The frequency analysis models are generally used in hydrology to evaluate the values characterized by a given exceedance probability (or by the corresponding return period). For dimensioning the spillways of a dam, exceptional high floods with rare frequency are being used. To obtain the maximum discharge with a given exceeding probability, a statistic processing of maximum yearly discharges is necessary, extrapolating the empiric repartition through theoretical repartitions.

Regression models are used for checking the dependency or independency of two or more statistic variables. If the variables are independent, they may be analysed separately as one-dimensional repartitions. If the variables are dependent, it is important to evaluate the influence of a variable (or of a group of variables) over the explained variable. This statistic processing of a special practical importance is known as correlation or regression analyses.

Regression curves between two variables have the significance of some conditioned average values. The intensity of the statistical dependence between variables is expressed by the correlation coefficient in the case of a linear correlation and by the correlation ratio for a non-linear correlation.

The correlations have a special importance in hydrology; one may give as examples:

the rating curve (the H-Q correlation);

the correlation between the evaporation coefficient and the altitude;

the correlation between a high flood's time of increase and the aggregated variable $L/\sqrt{I_r}$, where I_r is the river's slope;

the correlation between a high flood's total duration and one of the following variables (simple or aggregated): L , $F/\sqrt{I_b I_r}$ or $L/\sqrt{I_b}$

(Where L is the river's length, I_b is the river basin's slope, F is the basin surface, etc.).

The values of the explained variable present deviations compared to the average values represented by the correlation curve; the more the respective values are closer to the curve, the more the dependency between the variables. At the limit, if all the values are situated on the curve, the link between the variables is deterministic.

A stochastic process represents an infinite row of statistic variables; a finite sample of this row is called a time series and constitutes in fact a multidimensional statistic variable.

If all the statistic variables which form the series have the same distribution, the respective time series constitutes a sample of a stationary stochastic process; if the components of the time series have the same distribution law, but with different parameters (average value, dispersion); the respective stochastic process is non-stationary.

Observations concerning a stochastic process may underline a general evolution tendency, representing the series' deterministic component (also called systematic component or tendency) to which a statistic component, due to some factors with random influence, is added.

The deterministic component is generally formed by a polynomial tendency, slowly variable in time, over which come seasonal components, which manifest themselves periodically; this period is usually the day, month, season, year, but could also be groups of years or centuries.

The statistic component of the process is analysed after subtracting the determinist component from the initial series; the residuals (the differences between the initial series and the determinist component) are interpreted like a time series, extracted from a stationary stochastic process.

Stochastic processes generally and time series especially are largely used in hydrology. Thus, the discharges may be interpreted as a Markov process; the artificial generation of hydrological values has actually been used for a long time in practice based on the Markov model.

The hydrological data sequences registered in the past do not offer all possible cases for dimensioning or establishing the operation rules for the water management works. The extension of available data by artificial generation using Markov models or time series (respecting the basic characteristics of the initial data: average value, coefficient of variation and asymmetry) is largely practiced. These techniques do not lead to new information concerning the river's hydrology; they only allow obtaining different scenarios of the discharges, keeping the initial information or its greatest part.

The models with random coefficients are used when certain coefficients of the mathematical models do not have a unique value, but take a range of values with different probabilities. Thus, the values obtained from measurements are subject to errors; on the other hand, by their own nature (discharges, costs, etc.) some variables have a stochastic character. By taking it into account, the model becomes more realistic, but also more difficult to solve.

The models with constraints expressed in probability impose themselves when certain constraints cannot be always satisfied. Such situations are frequently encountered in the waters management field. Some objectives (water supply for users, flood control, protection of water's quality) may not be always realized with certitude, but with a certain probability. From this point of view, a deterministic model can be seen as a probabilistic model, whose relations are satisfied with a probability of 100 %.

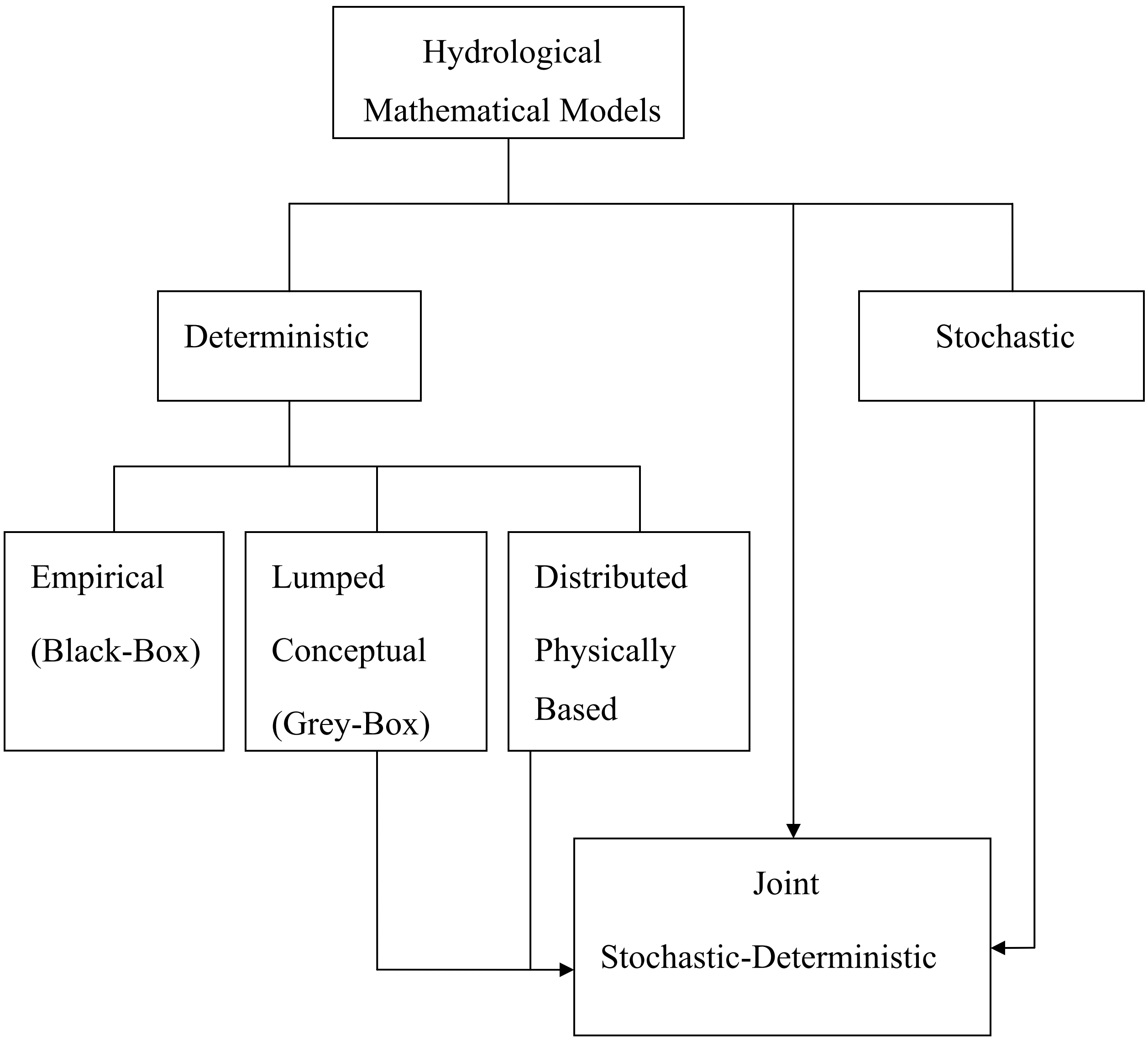


Figure 2.7 Classification of hydrological models according to process Description

2.4 Model calibration and validation

Model calibration and validation are necessary and critical steps in any model application. For most all watershed models, calibration is an iterative procedure of parameter evaluation and refinement, as a result of comparing simulated and observed values of interest.

Model validation is in reality an extension of the calibration process. Its purpose is to assure that the calibrated model properly assesses all the variables and conditions which can affect model results, and demonstrate the ability to predict field observations for periods separate from the calibration effort.

While there are several approaches to validating a model, perhaps the most

effective procedure is to use only a portion of the available record of observed values for calibration; once the final parameter values are developed through calibration, simulation is performed for the remaining period of observed values and goodness-of-fit between recorded and simulated values is reassessed.

This type of split-sample calibration/validation procedure is commonly used, and recommended, for many watershed modelling studies. Model credibility is based on the ability of a single set of parameters to represent the entire range of observed data.

If a single parameter set can reasonably represent a wide range of events,

then this is a form of validation.

In practice, the model calibration/validation process can be viewed as a systematic analysis of errors or differences between model predictions and field observations.

2.4.1 Manual calibration methods

The development of hydrological rainfall–runoff models, such us conceptual, for use in hydrologic predictions has been driven by several needs, one of which is operational flood forecasting (Sorooshian, 1997). These conceptual models vary in complexity, but nearly all have parameters for which values must be estimated. In spite of the advances in “physically” based modelling, there is general agreement among scientists and practicing hydrologists that a certain level of calibration is required to obtain successful stream flow predictions. Although some parameters can be derived directly from knowledge of physical watershed characteristics, others must be adjusted or “tuned” to get acceptable simulations of observed stream flows.

The traditional and most widespread approach to model calibration involves “manual” (also called “expert”) adjustment of the parameter values to improve the model response, based on visual inspection of the observed and simulated hydrographs. The hydrologist will typically attempt to reproduce the hydrograph peaks (amount and timing), flood volumes, recession slopes, and base flow. However, for models such as the Sacramento Soil Moisture Accounting Model (SAC-SMA; Burnash 1995) and “SNOW-17” (Anderson 1973, 1978), used by the National Weather Service (NWS) for flood forecasting, this approach requires considerable training and experience. Further, it is typically laborious and time consuming, particularly when numerous parameters with interacting effects must be adjusted.

2.4.2 Automatic calibration methods

During the past three decades, considerable research has been performed on the development of automated methods to aid the model calibration process. The classical single-objective automatic approach, based on optimization theory, requires the definition of a mathematical measure (an objective function such as least squares or maximum likelihood) of the differences between the observed and simulated hydrograph. An optimization algorithm is then used to adjust the parameters toward values that minimize (or maximize, if appropriate) this function. Although the method is fast and objective, it has not received widespread acceptance among operational hydrologists. For example, NWS personnel have explored the use of automatic calibration methods (with various single-objective functions) but found that visual inspection of the hydrograph reveals areas of concern, such as poor matching of recessions and unacceptable flow biases. Use of different objective functions has not helped to resolve this problem. Therefore, poor confidence in the capabilities of automatic methods has inhibited their usage at RFCs for speeding model calibration.

Automatic calibration methods have evolved significantly since early endeavours reported Nash and Sutcliffe (1970), Monroe (1971), and Johnston and Pilgrim (1976).

During the last two decades, the evolution of these methods has been motivated by 1) the need to simplify and speed up the calibration process, 2) the need to assign some objectivity and confidence to the calibration process (and hence, model predictions), and 3) the lack of numerous expert calibrators available for each watershed model (Sorooshian and Gupta 1995).

Various issues that have arisen in the context of research into automatic calibration methods have included conceptually unrealistic parameter values, poor model performance on validation period (vs calibration period), and the inability of the algorithms to find a “single” best parameter set

2.5 Model performance

Model performance, i.e. the ability to reproduce field observations, and calibration/validation are most often evaluated through both qualitative and quantitative measures, involving both graphical comparisons and statistical tests. For flow simulations where continuous records are available, all these techniques will be employed, and the same comparisons will be performed, during both the calibration and validation phases. Comparisons of simulated and observed state variables will be performed for daily, monthly, and annual values. Statistical procedures include error statistics, correlation and model-fit efficiency coefficients, and goodness-of-fit tests.

2.5.1 Objective methods

When using an objective method, an error function has to be defined, to uniquely (objectively) define the goodness of fit. Several types of error functions are used in model calibration all based on a function of type f (Q_o-Q_s). Widely used in eqn. 2.1 below that is based on the explained variance as a criterion:

$$R^2 = \frac{\sum (Q_o - Q_{oav})^2 - \sum (Q_s - Q_o)^2}{\sum (Q_o - Q_{oav})^2} \qquad \text{.....................................2.2}$$

or

$$R^2 = 1 - \frac{MSE\,(Q)}{VAR\,(Q_o)} \qquad \text{.....................................2.3}$$

Where :

-Q_o is the observed daily runoff;

-Q_{oav} is the average daily runoff;

-Q_s is the simulated daily runoff;

-R^2 is often termed the Nash efficiency Criterion.

-MSE(Q): the mean square error between simulated and observed runoff,

-VAR: the statistical variance,

The numerical value of the error function uniquely defines the goodness of fit for the model, hence the term objective. The higher the value of R^2 the better the model fit. If the model fits perfectly Q_s always will be equal to Q_o and from Eqn 2.2, it is easily seen that R^2 will equals to 1.0.

In addition to the R^2 criterion three other types of error functions are commonly used:

- Cumulative difference(water balance)

$$\sum (Q_o - Q_s) \qquad \text{.....................................2.4}$$

- Cumulative squared difference

$$\sum (Q_o - Q_s)^2 \qquad \text{.....................................2.5}$$

- Cumulative absolute difference

$$\sum / Q_o - Q_s / \qquad \text{.....................................2.6}$$

2.5.2 The index of volumetric fit, IVF and the relative error of peak, RE

IVF is the ratio of the total volume of estimated to the total volume of observed.

$$IVF = \sum_{i=1}^{N} \frac{(Q_e)_i}{(Q_o)_i} \quad \text{...} 2.7$$

Where:

-Q_e is the estimated discharges,

-Q_o is the observed discharges

-N is the total number of discharge values.

The relative error of the peak is defined as

$$RE = \frac{/(Q_p)e - (Q_p)o\ /}{(Q_p)_o} \quad \text{...} 2.8$$

Where:

- $(Q_p)_o$ is the observed peak flows,

- $(Q_p)_e$ is the estimated peak flows.

2.6 Description of the Models selected

2.6.1 Linear Models

Since Sherman(1932) introduced the concept of the unit hydrograph, linear systems analysis has played an important role in applied hydrology, in rainfall-runoff modelling and in flood routing. The unit hydrograph hypothesis, which is based on the assumptions of proportionality and superposition of time-invariant responses, expresses the operation of a system in converting the precipitation excess x(t) to direct storm runoff y(t) by the "Convolution" or "Duhamel" integral i.e.

$$y(t) = \int_{\tau=0}^{\tau=1} x(\tau)h(t-\tau)d\tau \text{ ……………………………………………………………2.9}$$

Where

h (t) is the system weighting function= unit impulse response function or "instantaneous unit hydrograph" ordinate at time t.

τ is the dummy variable of integration

In dealing with continuous functions, the input-output relationship for a lumped, linear, time-invariant, system expressed in terms of the impulse response function is given by the convolution integral, eqn. 2.9.

When the input function is expressed as a series of pulses or mean values over successive short intervals T, the response to a unit pulse of duration T is more convenient expression of the operation of the system than the impulse response.

Incorporating a model error term, the discrete linear input-output relationship is expressed in terms of the sampled pulse response by the equation

$Y_i = x_i h_1 + x_{i-1} h_2 + x_{i-2} h_3 + \ldots + x_{i-m+1} h_m + e_i$ for i = 1, 2, 3……………………………………2.10

or

$$Y_i = \sum_{i=1}^{m} x_{i-j+1} h_j + e_i \text{ ………………………………………………………………………2.11}$$

Where

y_i is the i^{th} output,

x_i is the estimate of the i^{th} input

e_i is a disturbance/model error term or residual all at the i^{th} time interval;

h_j is the estimate of the j_{th} ordinate of the unit hydrograph/pulse response ;

m is the memory length which implies that the effect of any input x will lasts only through m intervals of duration T.

A more drastic constraint to the shape and volume of the estimated pulse response functions is obtained by parametric modelling, wherein a solution is sought within the constraint of an assumed model form. Based on prior knowledge of the system behaviour, the response function is represented by a suitable mathematical equation involving only a few parameters. This must, however, be estimated by optimization, through a search in the space of reasonable parameter values, rather than by a direct algebraic method such as that of ordinary least squares. If the input x (t) is related to the output y (t) by a differential equation of the form

$$y(t) = \frac{1}{(1+KD)^n} x(t) \quad \text{..........} 2.12$$

Where

k is a constant having the dimension of time,

n is a numerical constant and D is the differential operator.

The corresponding impulse response function is given by

$$h(t) = \frac{1}{\Gamma(n)} e^{-\frac{t}{k}} \left(\frac{t}{k}\right)^{n-1} \quad \text{..........} 2.13$$

Where $\Gamma(n) = \int_0^\infty e^{-x} x^{n-1} dx$ is the gamma function of n.

If n is a positive integer, the system corresponds exactly to a series of n equal linear reservoirs each of storage S equal to the product k_y.

The parameters of the model must be estimated by optimization, implying a search in the n, k and G_g is fixed to its desired value and the search conducted in the n, k space.

The parameter pair, n and the product nk, should, however, be chosen for optimization, rather than n and K separately, because n is a ''shape'' parameter and the product nk is a ''scale'' parameter. Expressed in this way, the two parameters are likely to be more independent than would n and k separately, both of which contribute to the scale and to the shape, although in different ways (K.M. O'CONNOR, 1992).

Equation 2.13 written out for each output ordinate y_1 to y_n yields n linear equations

$$\begin{bmatrix} y_1 \\ y_2 \\ . \\ . \\ y_m \\ y_{m+1} \\ . \\ . \\ y_n \end{bmatrix} = \begin{bmatrix} x_1 & 0 \ldots\ldots & \ldots & 0 \\ x_2 & x_1 \ldots\ldots & & ..0 \\ . & \ldots\ldots & \ldots\ldots & \\ . & \ldots\ldots & \ldots\ldots & \\ x_m & x_{m-1} \ldots\ldots & & x_1 \\ x_{m+1} & x_m \ldots\ldots & & \cdot x_2 \\ . & \ldots\ldots & \ldots\ldots & \\ . & \ldots\ldots & \ldots\ldots & \\ x_n & x_{n-1} \ldots\ldots & & x_{n-m+1} \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \\ . \\ . \\ h_m \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ . \\ . \\ e_m \\ . \\ . \\ . \\ e_n \end{bmatrix} \ldots\ldots\ldots\ldots 2.14$$

Where

m is the memory length

n is the number of observations of y.

In the above formulation, it is assumed that the x values over the memory length prior to x_1 are also zero. When this is not so, e.g. when the x and y series are simultaneous observations of input and output at equal time intervals beginning and ending at arbitrary times, then the first m-1 equations of the set (eqn.2.14) would not valid, as not all the relevant x values would be known.

The useful set of equations would, therefore, begin at y_m and extend to y_n, i.e. below the dotted horizontal line in eqn. 2.14. This is the situation which commonly exists when a linear relationship is assumed to relate long synchronous input and output series, for example, several years of daily values.

Equation 2.14 can be rewritten in matrix/vector form as

$$\{Y\}=[X]\{H\} + E \qquad 2.15$$

Or

$$Y=XH+E \qquad 2.16$$

Where

{Y} or Y is a (n, 1) column vector of the output series,

[X] or X is a (n,m) matrix of the input series,

{H} or H is a (m, 1) column vector of the pulse response ordinates,

E is an (n, 1) column vector of the model errors.

The solution H to this set of equations is generally found by the least-squares estimation method (minimizing the scalar sum of squares of the errors/residuals).

2.6.1.1 The Simple Linear Model (SLM)

Nash and Foley (1982) introduced the **S**imple **L**inear **M**odel (SLM) not as a substantive rainfall-runoff model in its own right but rather as a naïve black-box model to be used mainly for the purpose of model efficiency comparisons. The intrinsic hypothesis of the naïve SLM is the assumption of a linear time-invariant relationship between the total rainfall R_i and the total discharge Q_i.

In its discrete form, the SLM, is expressed by the convolution summation relation (Kachroo and Liang, 1992),

$$Q_i = \sum_{j=1}^{m} R_{i-j+1} h_j + e_i \qquad \text{..........2.17}$$

where

Q_i and R_i are the discharge and rainfall respectively at the i^{th} time-step,

h_j is the j^{th} discrete pulse response ordinate or weight,

m is the memory length of the system,

e_i is the forecast error term.

The model requires daily rainfall and daily discharge input data and calibrated on daily data by ordinary least square method.

2.6.1.2. The Linear Perturbation Model (LPM)

This model exploits the seasonal information inherent in the observed rainfall and discharge series. It was originally introduced in the context of rainfall-runoff modelling by Nash and Barsi (1983). Initially referred to as the hybrid model, in a series of subsequent publications it is referred to as the **L**inear **P**erturbation **M**odel(LPM) (e.g. Kachroo et al., 1988; Kachroo, 1992a; Kachroo et al., 1992b; Liang et al.,1992; Liang and Guo, 1994; Elmahi and O'Connor, 1996; Shamseldin et al., 1997).

In the LPM, it is assumed that, during a year in which the rainfall is identical to its seasonal expectation, the corresponding discharge hydrograph is also identical to its seasonal expectation. However, in all other years, when the rainfall and the discharge values depart from their respective seasonal expectations, these departures series are assumed to be related by a linear time invariant system.

Hence, the LPM structure reduces reliance on the linearity assumption of the SLM and gives substantial weight to the observed seasonal behaviour of the catchment).

The relation between the departure (i.e. perturbation) series, for a single –input series of the LPM has the Convolution summation form as

$$Q_i = \sum_{j=1}^{m} R_{i-j+1} h_j + e_i \qquad \text{...2.18}$$

Where

R_i and Q_i are the respective departures of rainfall and discharge from their seasonal expectations

$Q_i = y_i - y_d$ and $R_i = x_i - x_d$

x_d and y_d are the expected values of rainfall and discharge respectively on each date d.

e_i is the error output term.

Model-estimated departure values are added to the seasonal expectation to give the estimated discharge series. Linear perturbation model is a combination of the seasonal and the linear components. It improves the results of efficiency for the catchment which exhibit marked seasonality. The following steps are how the LPM is applicable (GFMFS):

-Seasonal mean rainfall and discharge are calculated for the periods of calibration,

-The smoothed seasonal mean(Fourier analysis) values, X_d and Y_d are then subtracted from the corresponding observed rainfall and discharge series for the periods of calibration, to yields the time series of the perturbation R and Q,

-The pulse response function for the catchment is estimated by the method of ordinary least square method,

-The resulting pulse response for the catchment is convoluted with the corresponding rainfall perturbation to obtain the estimated outflow perturbation series,

-The final estimated discharge series of the LPM is calculated by adding seasonal mean discharge to estimated outflow perturbation series,

-The difference between observed and computed discharge is squared and summed and the usual measure of efficiency R^2 is calculated for the catchment for the pulse response function derived. The model requires daily rainfall and daily discharge input data and calibrated on daily data by ordinary least square method.

2.7 Conceptual Models

The deficiency in models of the systems analysis type (e.g. the Simple Linear or the Linear Perturbation Models) seems to lie in their failure to take adequate account of the effect of evaporation in determining the volumes of runoff which, unlike that of rainfall, is not immediate.

Over a period of time, evaporation may create a soil-moisture deficit, thus controlling the generation of runoff from a subsequent storm. This variably delayed effect cannot be allowed for by the assumption of a linear relation between the discharge series as dependent variable and series of rainfall and potential evaporation as independent inputs. It can, however, be included in a conceptual model where the generation of runoff is expressed by a series of prescribed operations.

2.7.1 The Soil Moisture Accounting and Routing (SMAR) Model

The SMAR Model is a development of the' Layers' conceptual rainfall-runoff model introduced by O'Connell et al. (1970), its water-balance component having been proposed in 1969 by Nash and Sutcliffe (Clarke, pp.307, 1994).Using a number of empirical and assumed relations, which are considered to be at least physically plausible, the non-linear water balance (i.e. soil moisture accounting) component ensures satisfaction of the continuity equation, over each time-step.

The routing component, on the other hand, simulates the attenuation and the diffusive effects of the catchment by routing the various generated runoff components through conservative linear time-invariant storage elements. For each time-step, the combined output of the two routing elements adopted (i.e. one for generated 'surface runoff' as input and the other for generated 'groundwater runoff' as input) becomes the simulated discharge forecast.

Parameter description

The water balance component operates in a manner analogous to a vertical stack of horizontal soil layers. Each layer can contain water up to a field capacity. Evaporation (E) occurs at potential rate from top layer. From the 2nd, 3rd, etc layer, upon exhaustion from the first layer E occurs at rate of evaporation decay coefficient c, c^2, etc times E (where c is less than unity). A constant amount of evaporation applied reduces the soil moisture in exponential manner. The capacity of each layer is taken as 25 mm (except the lower layer).The soil moisture storage capacity Z (mm) is a parameter to be optimized.

When rainfall exceeds evaporation, a fraction H' of the excess(x) generates to direct runoff (H). Of the remainder (1-H')*x, anything exceeding the maximum infiltration capacity(Y) of the soil also contributes to runoff. Note that H' is taken proportional to the available soil moisture of the first five layers.

H'=H*(available soil moisture per 125 mm of water). H is to be optimized.

The remaining moisture restores each layer from top to bottom to field capacity until the surplus rainfall exhausts or until all layers are at field capacity. Any surplus rainfall remaining after restoring all layers to field capacity generates runoff. The runoff is generated as soil moisture.

The potential evaporation (PE) is also estimated because it contributes in the process.

PE= T* E pan.

T: is the potential evaporation conversion coefficient

n :is the shape parameter of the Nash gamma function 'surface runoff'

routing element; a routing parameter.

nk :is the scale (lag) parameter of the Nash gamma function 'surface

runoff' routing element; a routing parameter

G: is the weighting parameter, determining the amount of generated

'Groundwater' used as input to the 'groundwater' routing element.

Kg: is the time lag parameter for groundwater storage

F: is the coefficient for loss to/ gain from groundwater reservoir

In the SMAR routing component, it is provided by linear time invariant. It can be the expression in the form of pulse response related the generated runoff (say x) to observed discharge y.

$$y_i = \sum_{j=1}^{m} x_{i-j+1} h_j + e_i \qquad \ldots\ldots\ldots\ldots 2.19$$

Where

The pulse response ordinates h_j express uniquely the transformation of the system.

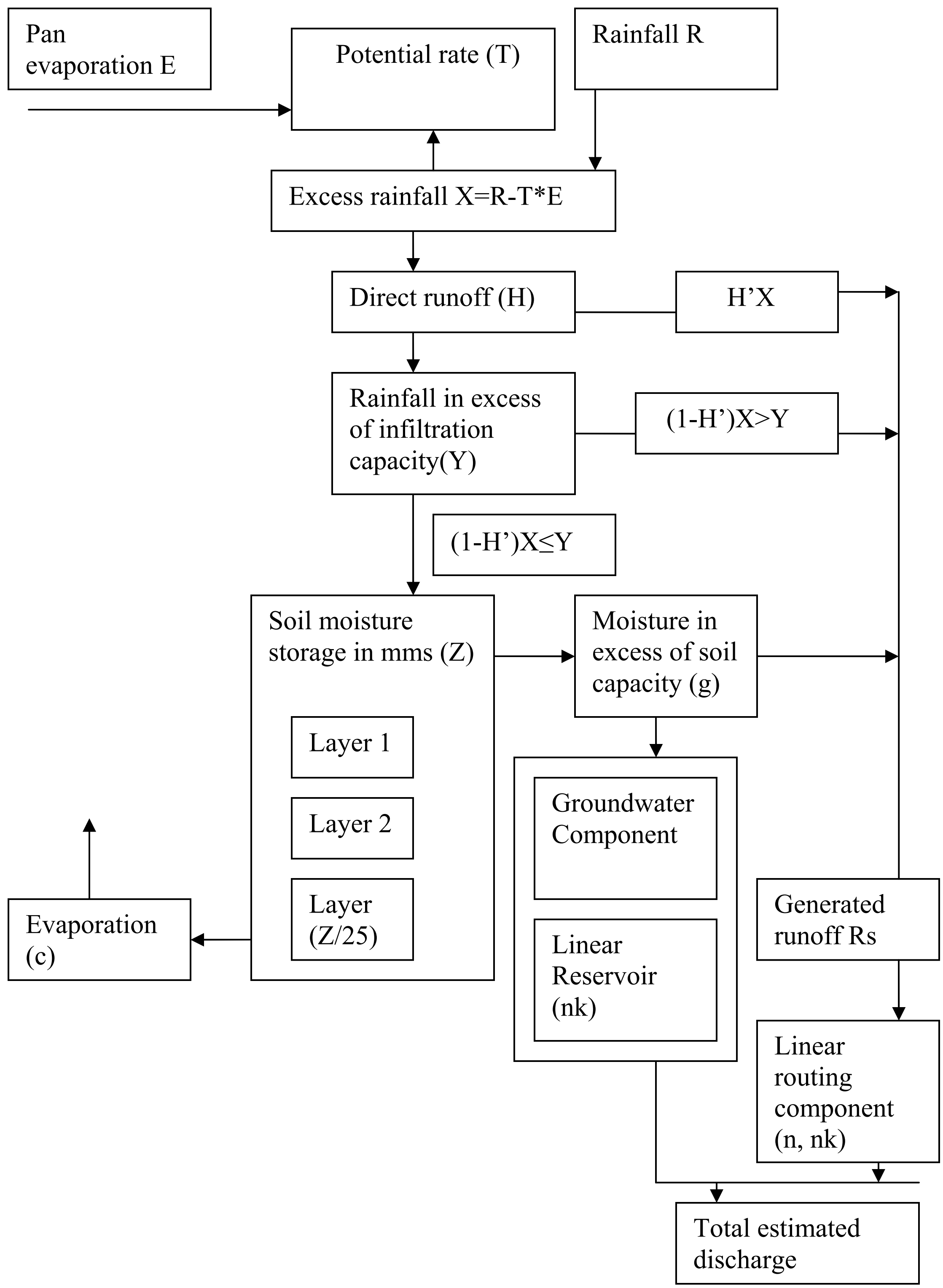


Figure 2.8 Schematic diagram of the Liang (1992) version of SMAR Model

2.7.1.1 Calibration and optimization of SMAR Model

The calibration procedures involves successive choices of combinations of the water balance parameters H,T,Y,C, or Z, calculation of the series generated runoff(x), subsequent estimation of the pulse responses by the method of ordinary least squares G and u_i, where G is the corresponding gain factor which is equal to the sum of the ordinates h_j and u_i the standardized pulse response series and finally calculation of the computed discharge(y^) and determination of the values of the objective function F,

Where,

F= f (H, T, Y, C, Z, and also G and U) =$\sum (y_i - y_{jav})$

Optimization on the above lines would allow a gain factor G in the routing component to assume values other than unity, thus failing to maintain the distinction between the roles of the water balance and the routing component. To avoid this, the generic algorithm, the Rosen Brock and simplex optimization routine must be carried out with G constrained least squares instead of that of ordinary least squares.

If the derived pulse response exhibits physically unrealistic oscillation or has negative ordinates, further constraints such as the non-negative constraints or some form of shape constraints must also be imposed on the estimation procedure.

This may be achieved by quadratic programs or a combination of ridge regression and constrained least squares, or simply by assuming a parameter form such as the gamma function or the differential equation (transfer function) pulse responses.

2.7.2 HBV Model

The HBV model (Bergström, 1976, 1992) is a conceptual rainfall-runoff model, which is used to simulate the runoff process in the catchment based on data for precipitation, air temperature and potential evapotranspiration. The model computes snow accumulation and melt, actual evapotranspiration, storage in soil moisture and groundwater and runoff from the catchment.

The HBV (**H**ydrologiska **B**yråns avdeling for **V**attenbalans)-model is basically a lumped model, where the catchment under consideration is treated as one unit without any considerations to the spatial distribution within the catchments. It is a deterministic type model, where two equal sets of inputs will always yield the same output, given identical start conditions and identical model parameters.

The model is normally run on daily values of rainfall, air temperature and daily or monthly estimates of potential evaporation.

The HBV-model has to be calibrated for catchments before it can be used for practical applications.

The model has a fixed structure, but contains a number of parameters that need to be given values before it can be applied.

2.7.2.1 The model structure

The HBV model, like many other precipitation-runoff model is based on a conceptual representation of a few main components in the land phase of the hydrological cycle. Runoff from a catchment is computed from climatic data precipitation, air temperature and potential evapotranspiration.

To accomplish this, the model compute water balance for the main storage types in the catchment, and show how these storages change dynamically in response to the varying meteorological inputs.

The standard version of the HBV model uses the four main storage components shown in Figure 2.9: Snow storage, soil moisture, upper zone and lower zone. In addition, a separate river and lake storage may be used when needed.

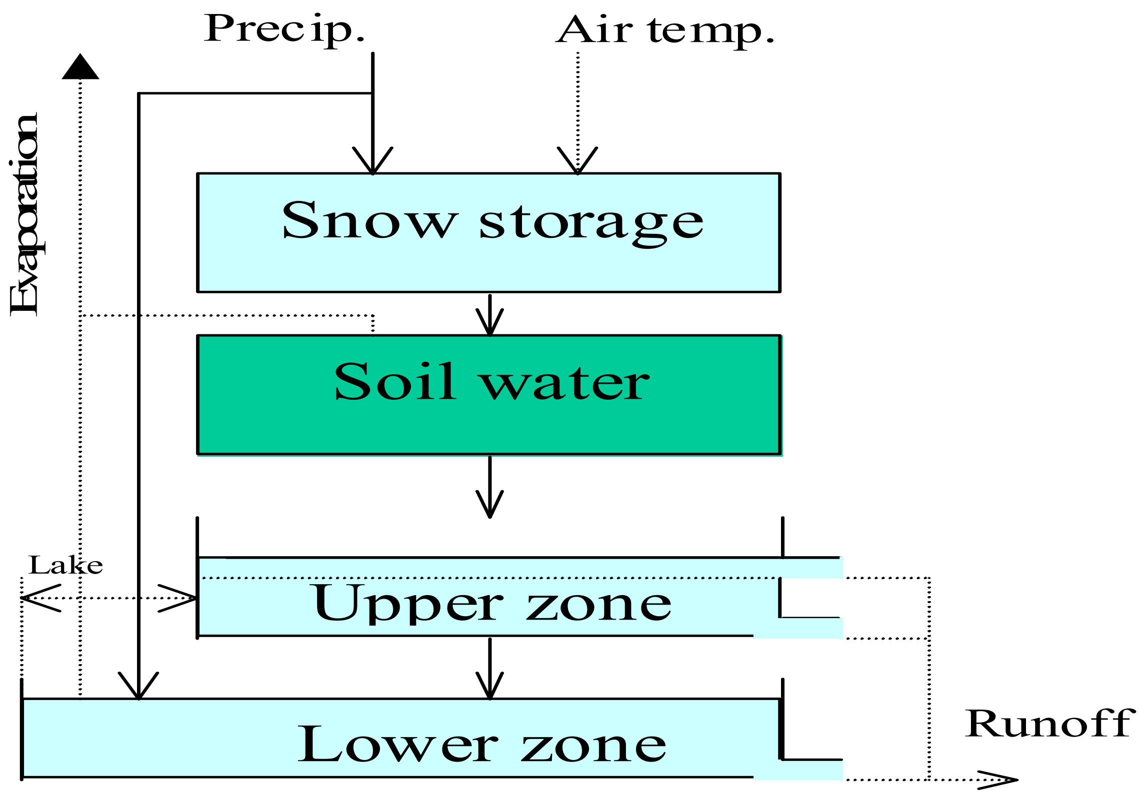


Figure 2.9 Structure of the HBV- model (Killingtveit and Saelthum, 1992)

2.7.2.2 Soil Moisture routine

The soil moisture accounting of the HBV model receives rainfall or snow melt as input from the snow routine, and computes the storage of water in soil moisture, actual evapotranspiration and what may be called the net runoff generating precipitation as output to the runoff response routine.

This routine is based on two simple equations with three parameters, BETA (β), LP and FC, as shown in the Figure 2.10. BETA controls the contribution to the runoff response routine (dvz) and the increase in soil moisture storage (dSM) from each millimeter of rainfall or snow melt. This structure results in a small percentage contribution to runoff (small net precipitation) when the soil moisture is low, and a high contribution when the soil moisture is high.

LP is a soil moisture value above which evapotranspiration reaches its potential value, and FC is the maximum soil moisture storage in the model. The parameter LP is given as a fraction of FC. If the soil moisture storage is filled up to FC no more precipitation or snow melt can be stored as soil moisture, and all input to soil moisture storage will be transformed directly to runoff. This may lead to high runoff even from moderate rain.

The soil moisture storage is depleted by evapotranspiration. The computation of actual evapotranspiration (EA) is a function of potential evapotranspiration (EP) and relative soil moisture storage(SM/FC). If the soil moisture exceeds a threshold value (LP) the actual evapotranspiration equals the potential value. If soil moisture is below LP the actual evapotranspiration decreases linearly with the decrease in storage as shown in Figure 2.10. Evapotranspiration in the model is only computed from the snow-free part of a catchment.

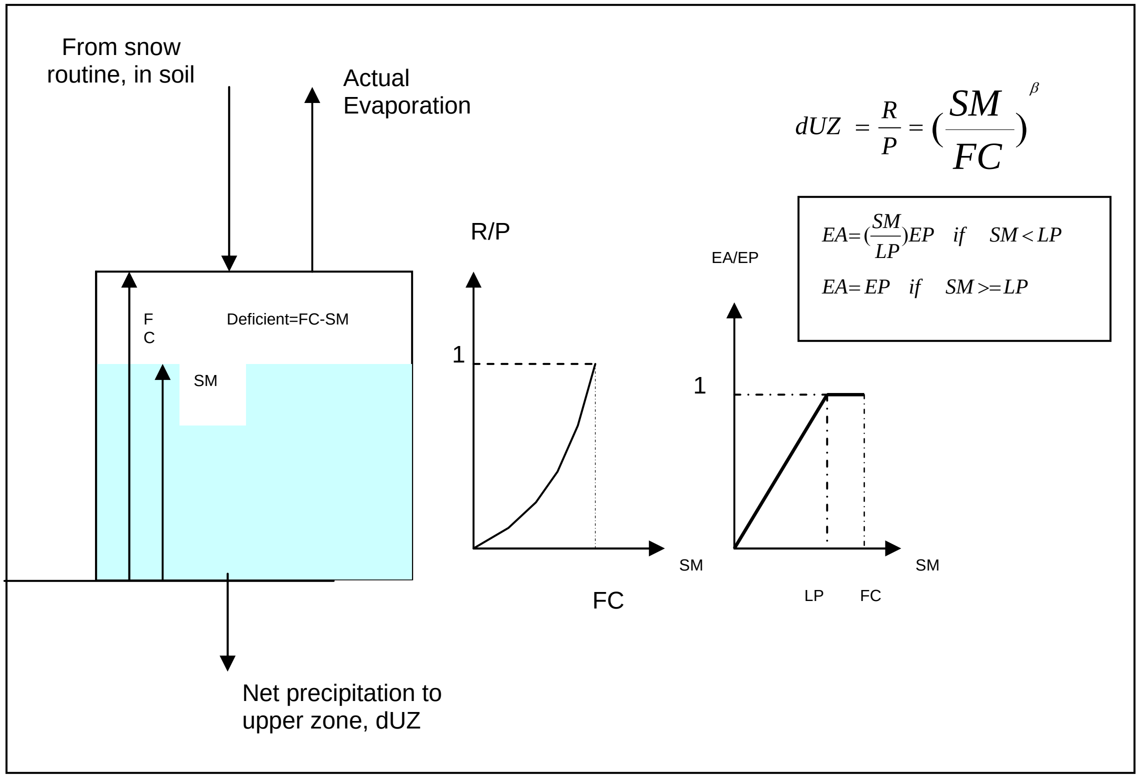


Figure 2.10 The soil moisture routine in the HBV-model

Both β, LP and FC are free parameters and must be determined by model calibration. In some versions of the model an additional parameter controls the infiltration of water into the soil moisture routine. If the intensity of rainfall or snow melt exceeds infiltration capacity the excess water is transferred directly to the runoff response function.

2.7.2.3 Runoff response routine

The runoff generation routine is the response function which transforms excess water from the soil moisture zone to runoff. It also includes the effect of direct precipitation and evaporation on a part which represents lakes, rivers and other wet areas. The function consists of one upper, non-linear, and one lower, linear, reservoir. These are the origin of the quick (superficial channels) and slow (base-flow) runoff components of the hydrograph.

The upper zone conceptually represents the quick runoff components, both from overland flow and from groundwater drained through more superficial channels, interflow. When the input of net precipitation from soil moisture zone exceeds a percolation capacity (PERC), the storage in upper zone will start to fill and simultaneously be trained through the lower outlet. The speed of drainage is determined by the recession coefficient for the lower outlet (KUZ). If the storage exceeds a threshold (UZ1), an even quicker drainage will start through the upper outlet; the drainage speed is controlled by the upper recession coefficient (KUZ1).

In some implementation of the model even an additional threshold and recession coefficient is used for still higher storage and quicker runoff components as shown in Figure 2.11. The combined effect of the upper zone is a variable response which can be adjusted to fit the observed quick runoff response in a catchment.

The lower zone conceptually represents the groundwater and lake storage that contributes to base flow in the catchment. The drainage speed is controlled by only one recession parameter (KLZ). The lower zone gets water input by percolation from upper zone and by direct precipitation on lakes and rivers. The lower is depleted through base flow runoff and also through evaporation from lakes and rivers. This evaporation always equals the potential as long as there is water in the lower zone storage.

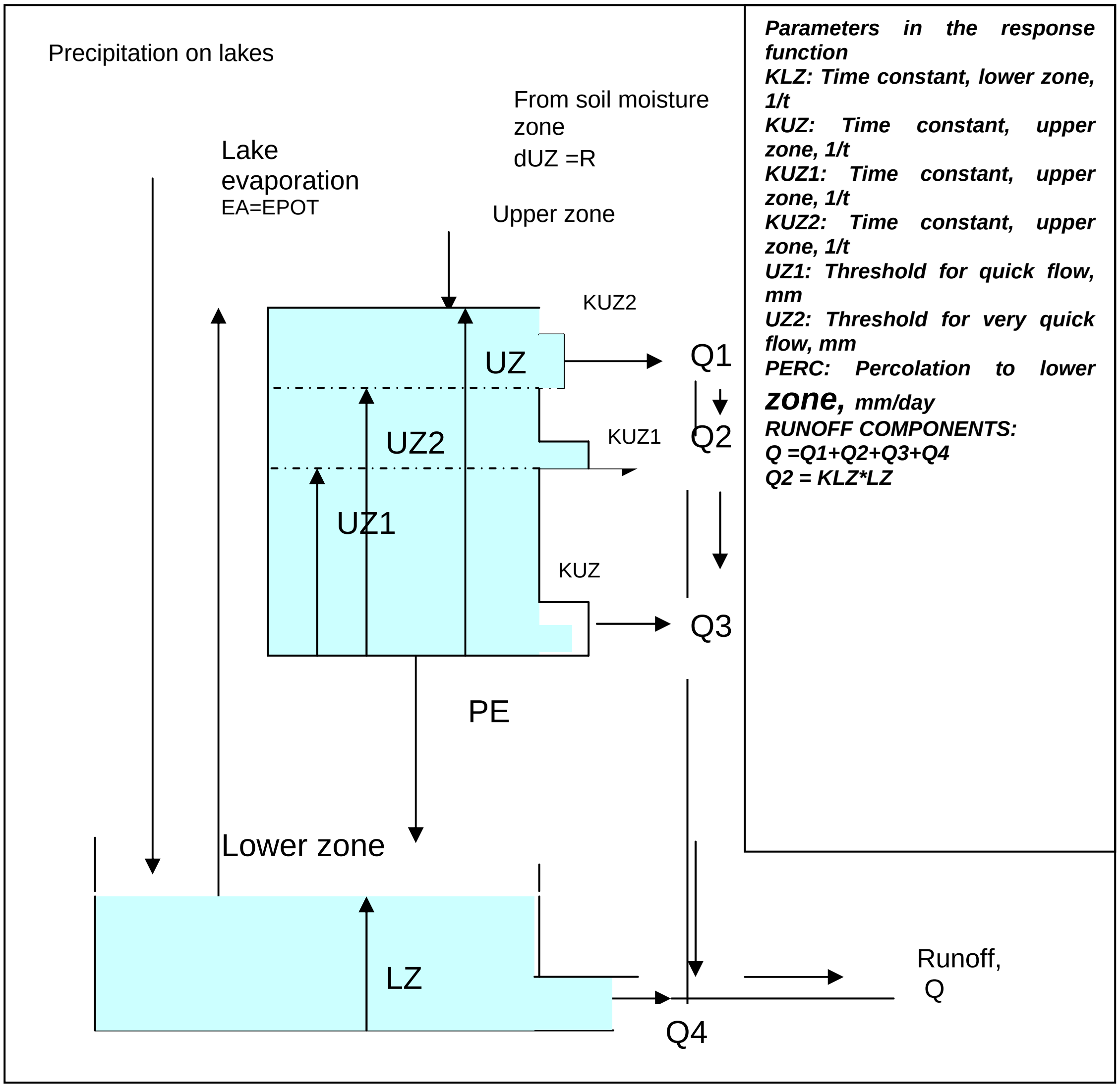


Figure 2.11 The runoff response routine in the HBV-model

CHAPTER THREE

METHODOLOGY AND DATA ANALYSIS

3.1 Procedure

Generally, the study involves the following procedures:

-collection of hydrological and meteorological data, topographical map and digitized map of the basin,

-filling and extension of data,

-checking of data for consistency,

3.2 Source and availability of data

For the purpose of this work, ten years of climate and hydrological data have been selected such as daily rainfall; daily temperature and evaporation for 4 stations and daily discharge of Ruvyironza-Nyabiraba River were collected from the Geographic Institute of Burundi (IGEBU). The summary information is shown in table 3.1. The topographical maps of the basin were collected also in the same Institute.

Table 3.1 Summary information of hydrometeorrological stations in RVZ-Nyabiraba catchment

Nº	Stations name	Location			Type of data	Annual values	Period	% of missing data	Remark
		Elevation (m)	Latitude (degree)	Longitude (degree)					
1	MWEYA	1735	-3.48	29.92	Rainfall(mm)	950	1976-2005	0.0	Ordinary
					Air temperature(^{o}C)	18.2	1985-2005	3.3	
					Relative humidity (%)	-	-	-	
					Sunshine(hour)	-	-	-	
					Wind speed(m/s)	-	-	-	
2	GISOZI	2097	-3.57	29.68	Rainfall(mm)	1000	1931-2005	0.05	Principal
					Air temperature(oC)	16.8	1975-2005	1.45	
					Relative humidity (%)	70	1991-1999	0.16	
					Sunshine(hour)	5.0	1977-1999	0.4	
					Wind speed(m/s)	0.9	1991-1999	0.18	

Table 3.1 Summary information of hydrometeorrological stations in RVZ-Nyabiraba catchment… (Cont'd)

3	RUVYIRONZA	1822	-3.82	29.77	Rainfall(mm)	1100	1960-2005	0.0	Principal
					Air temperature(oC)	17.6	1974-2005	1.4	
					Relative humidity (%)	72	1991-1999	0.25	
					Sunshine(hour)	5.5	1977-1996	0.13	
					Wind speed(m/s)	-	-	-	
4	MAKEBUKO	1770	-3.60	30.00	Rainfall(mm)	900	1934-2005	0.6	Ordinary
					Air temperature(oC)	17.8	1976-2005	3.9	
					Relative humidity (%)	-	-	-	
					Sunshine(hour)	-	-	-	
					Wind speed(m/s)	-	-	-	
5	NYABIRABA	1770	-3.53	29.31	Discharge	12.25	1988-2005	0.55	

3. 3 Filling in missing data

In the catchment, the percentage of missing data is described in table 3.1 and the results show that the missing data percentage is very less as compared to the availability of year's data.

To estimate the areal rainfall for RVZ-Nyabiraba catchment different stations were selected, which are inside and outside of the catchment. Inside the catchment we find only 2 stations (Ruvyironza and Makebuko). So, it was necessary to include from outside the catchment, Gisozi and Mweya which are the surroundings stations.

The missing flow records in the catchment are estimated from rainfall and runoff analysis and seasonal mean of all years. Locclim software was used also to process the raw data and in estimating the missing data applied in the models. The missing data was also estimated using the normal ratio method of average annual values from the record of surrounding stations.

Hence, for example, the missing precipitation data P_x, will be given by

$$P_x = \frac{1}{M}[P_1 \frac{N_x}{N_1} + P_2 \frac{N_x}{N_2} + P_3 \frac{N_x}{N_3}]$$

Where

N_1, N_2, N_3 and N_x representing the average annual rainfalls at stations1, 2, 3 and X respectively; P_1, P_2, P_3 and P_x representing their respective precipitation data of the day for which the data is missing at station X; M is the number of surrounding stations.

3. 4 Consistency of data

Double mass curve analysis was used to check the consistency of average annual rainfall data for selected meteorological stations as shown in Figure 3.1).

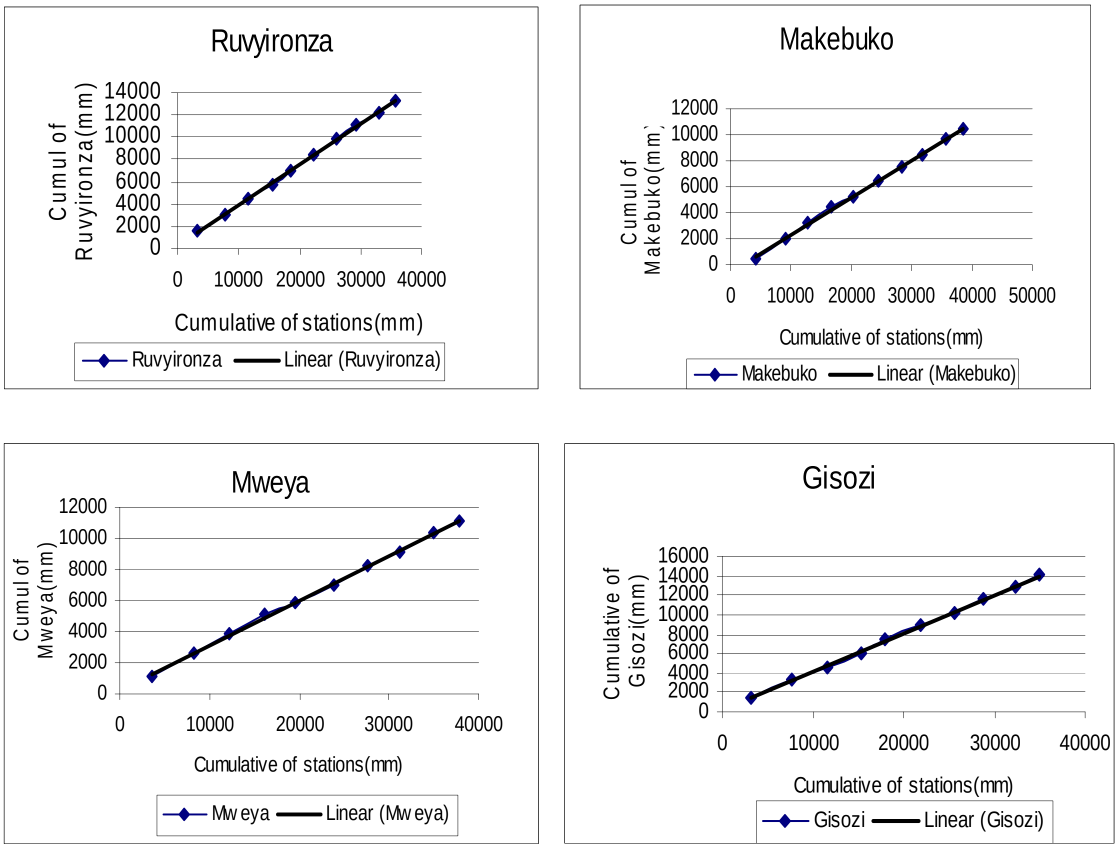


Figure 3.1 Double mass analysis of rainfall data on stations for RVZ-Nyabiraba catchment

As seen from double mass curves of each station all the stations have slight deviations.

3.5 Estimation of areal rainfall of RVZ-Nyabiraba catchment

The table 3.2 show the rainfall stations of the catchment with their main characteristics.

For the selected stations the rainfall data range varies from 1996 to 2005. The average annual rainfall varies with elevation variation in the range of 1000mm and 1500mm.

Table 3.2 Rainfall stations

N°	Stations	Altitude (m)	Latitude (degree)	Longitude (degree)	Average Annual rainfall	Period
1	MWEYA	1735	-3.48	29.92	1115	1996-2005
2	GISOZI	2097	-3.57	29.68	1405	1996-2005
3	RUVYIRONZA	1822	-3.82	29.77	1330	1996-2005
4	MAKEBUKO	1770	-3.60	30.00	1054	1996-2005

Mean precipitation over an area

The point sampling of the areal distribution of a storm is represented by the rain gauges.

In general, for engineering purposes, knowledge is required of the average rainfall depth over a certain area: the areal rainfall. Some cases where the areal rainfall is required are: design of a culvert or bridge draining a certain catchment area, design of a pumping station to drain an urbanized area; design of a structure to drain a polder, ect. In order to convert the point rainfall value at various stations into an average value over the catchment, various methods are proposed. In this study, the most method of mean areal precipitation computation used for analysis is by the Thiessen polygon. In this method, lines are drawn to connect reliable rainfall stations, including those just outside the area. The connecting lines are bisected perpendicularly to form a polygon around each station. To determine the mean, the rainfall amount of each station is multiplied by the area of its polygon and the sum of the products is divided by the total area. If P_1, P_2….P_n are the rainfall magnitudes recorded by the stations 1, 2... n respectively and A_1, A_2…., A_n are the respective areas of Thiessen polygon, then the average rainfall over the catchment P is given by:

$$P = \frac{P_1 A_1 + P_2 A_2 + ... + P_n A_n}{A_1 + A_2 + ... + A_n} \quad ....3.1$$

$$P = \sum_{i=1}^{m} P_i \frac{A_i}{A} \quad ....3.2$$

Where

m is the number of station.

The ratio A_i/A is called the weighting factor for each station and is given in table 3.3.

The Thiessen polygon constructed by Arcview software is presented in Figure 3.2.

Table 3.3 Thiessen coefficients for RVZ-Nyabiraba catchment

N^o	Stations	Thiessen polygon	Area of Polygon (km^2) (A_i)	Total Area (km^2) (A)	Weighting Factor A_i/A
1	MWEYA	1	57.37	751.75	0.0763
2	GISOZI	2=2+3	12.85	751.75	0.0171
3	RUVYIRONZA	4	374.16	751.75	0.4977
4	MAKEBUKO	5	307.37	751.75	0.4089

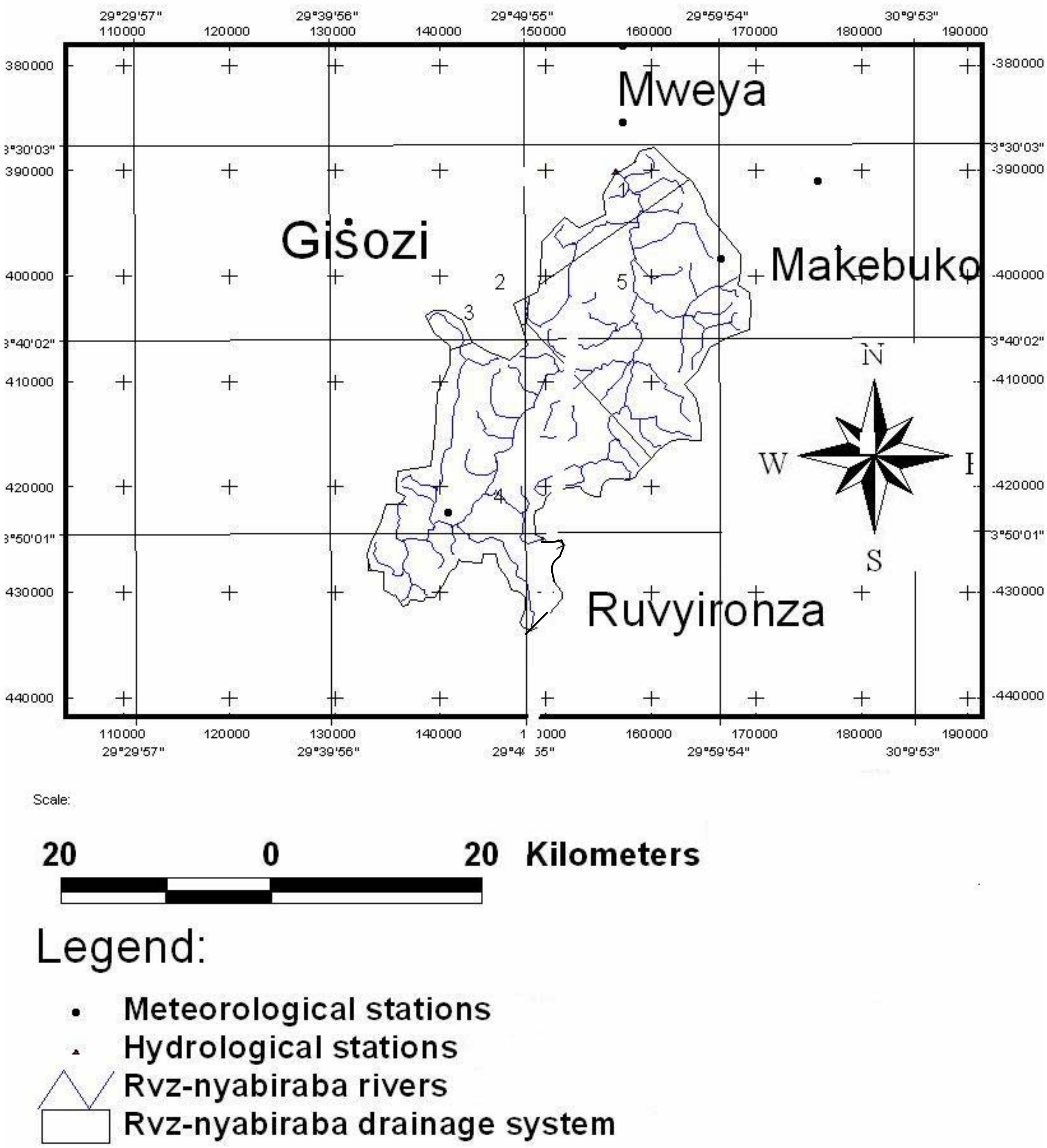


Figure 3.2 Thiessen polygons for RVZ-Nyabiraba catchment

The monthly areal rainfall distribution is shown in Figure 3.3.

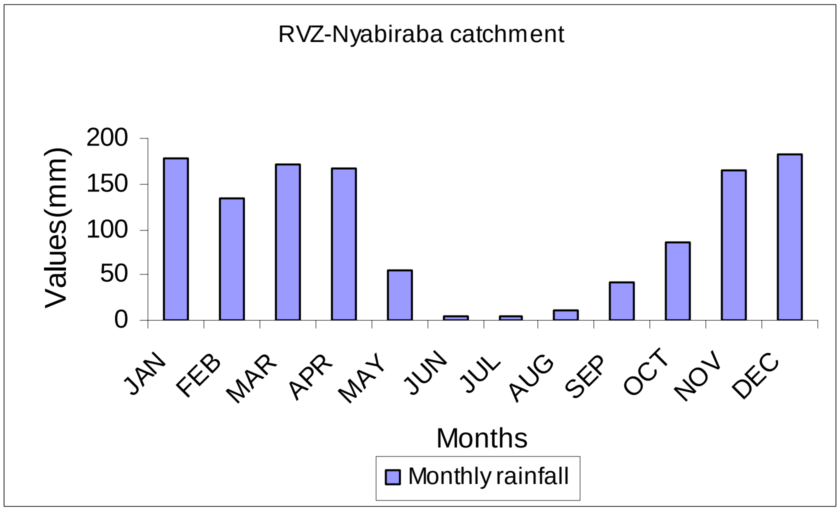


Figure 3.3 Monthly areal rainfall distributions

The mean daily flow distribution per month is also shown in Figure 3.4

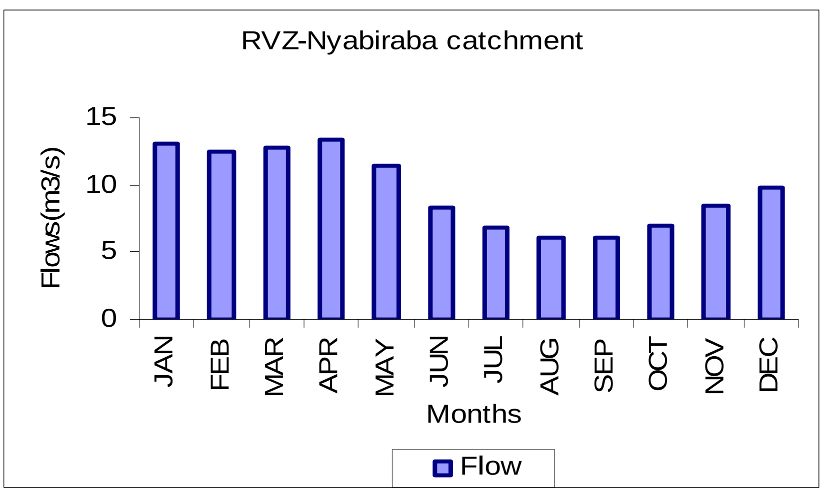


Figure 3.4 The mean flow distribution

3.6 Estimation of areal potential evapotranspiration of the catchment

The process by which water is evaporated from the wet surface and transpired by plants together is called evapotranspiration. The concept of Potential Evapotranspiration was introduced to study the maximum atmospheric demand of water. Potential Evapotranspiration is a climate parameter and can be computed from weather data.

The FAO Penman Monteith method is recommended as the sole method for determining the reference evapotranspiration of the area where measured data on temperature, humidity, wind speed and sunshine duration or radiation are available, (Crop water requirements, FAO Irrigation and Drainage paper, 24, Rome, 1992).

Often, in the study area, humidity data are not available in some selected meteorological stations in order to predict the potential evapotranspiration of the catchment by FAO Penman Monteith.

For those conditions, other empirical methods which require the limited weather data can be used. Hence, the Hargreaves method is selected to estimate potential evapotranspiration of the catchment(Hargreaves, and Samani, 1982).

Hargreaves method

The Hargreaves method (Hargreaves, and Samani, 1985) of computing daily grass reference evapotranspiration is the empirical approach that has been used in cases where the availability of weather data is limited.

The original Hargreaves formula calculates reference evapotranspiration with solar radiation and temperature data.

$$ET_o = 0.0135 \frac{R_s}{\lambda}(T + 17.8) \quad \text{..........} 3.3$$

Where

ET_0= Reference evapotranspiration, mm/day

λ= Latent heat of vaporization, MJ/Kg (2.45 MJ/Kg)

R_s= Solar radiation, $MJ/M^2/d$,

T= Mean air temperature, ^0C

Often, solar radiation data are not available. Therefore, an alternative approach available that requires only measurement of minimum and maximum temperature, with extraterrestrial radiation (R_a). Ra is determined from the latitude and the month of the year.

The working Hargreaves equation for an interior region is given here below as:

$$ET_o = 0.0023\,(T + 17.8)(T_{max} - T_{min})^{0.5} R_a \quad \text{...3.4}$$

Where R_a is the extraterrestrial radiation (mm/day)

Radiation (mm/day) = 0.408 Radiation (MJ/m^2 day)

T_{max}= Mean monthly maximum temperature, ^0C

T_{min}= Mean monthly minimum temperature, ^0C

The monthly areal potential evapotranspiration distribution is shown in Figure 3.5.

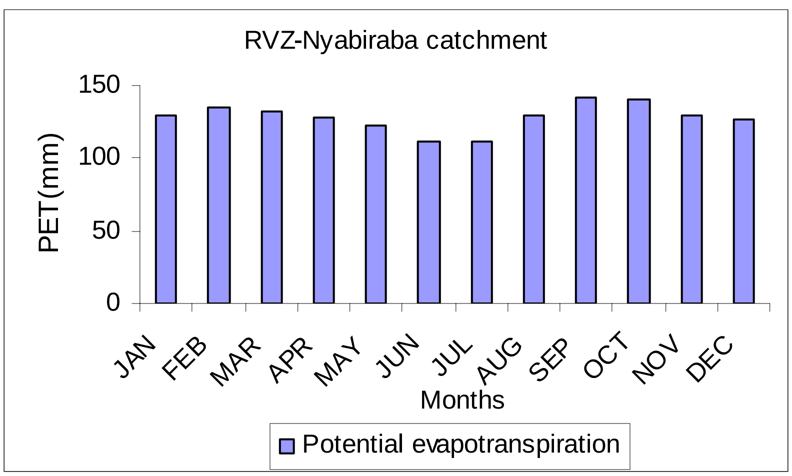


Figure 3.5 Monthly areal Potential evapotranspiration distribution

3.7 Estimation of Areal temperature of the catchment

The minimum and the maximum temperature of 10 years data was collected from the national meteorological service and the average mean temperature was computed at each station. The stations which do not have any maximum and minimum temperature data, the average mean temperature was estimated from the surrounding stations using LocClim software.

The values of areal monthly minimum and maximum temperature for the RVZ-Nyabiraba catchment is shown in Appendix I table 3.2 to 3.3 and the monthly areal minimum and maximum temperature distributions are shown in figure 3.6.

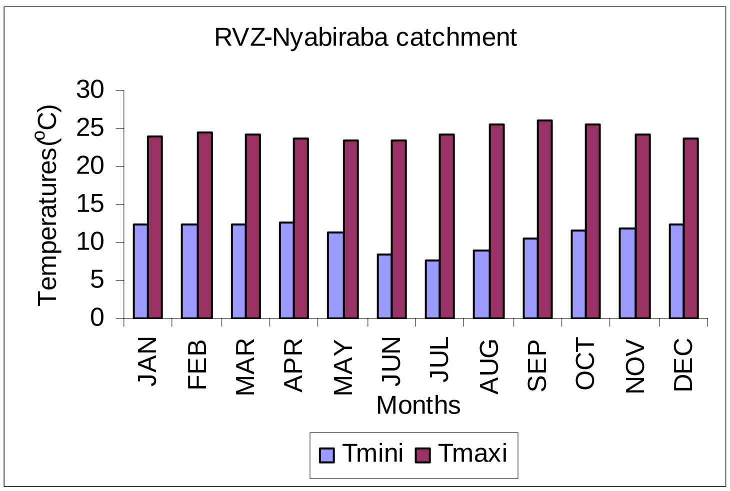


Figure 3.6 Monthly areal temperature distributions

From those computed values, the potential evapotranspiration from each station was calculated.

3.8 Hydrometeorological characteristics of RVZ-Nyabiraba catchment

The hydrometeorological characteristics of RVZ-Nyabiraba catchment are shown in Figure 3.7 to express how the areal rainfall, runoff and potential evapotranspiration vary through out the year. In the catchment, we can observe two seasons, the first appears during March and April and the second around November and December. The seasonal precipitation and runoff diagram for RVZ-Nyabiraba catchment(Figure3.7) shows that in some cases the amount of precipitation is lost through evaporation.

The mean areal rainfall and the mean monthly runoff of the catchment are given in Appendix I tables 3.4 to 3.5.

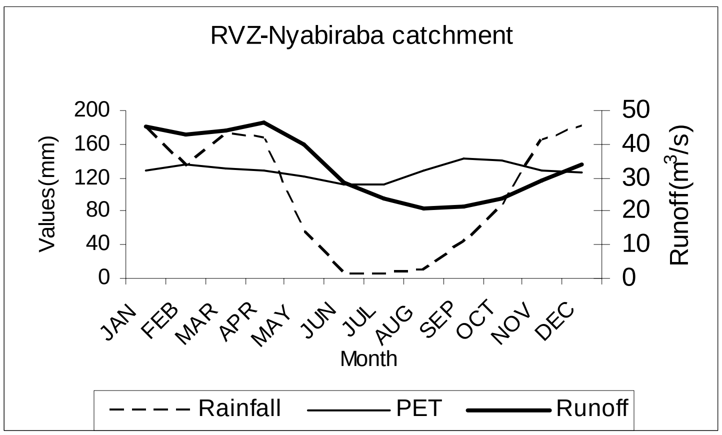


Figure 3.7 Monthly mean values of rainfall, potential evapotranspiration and runoff of RVZ-Nyabiraba catchment

CHAPTER FOUR

MODEL RESULTS AND ANALYSIS

4.1 Introduction

The Simple Linear Model (SLM), the Linear Perturbation Model (LPM), Soil Moisture Accounting and Routing (SMAR) and **H**ydrologiska **B**yråns avdeling for **V**attenbalans (HBV) are applied to the RVZ-Nyabiraba catchment. The available 10 years daily data are divided into two parts: five years (1996-2000) for calibration and five years (2001-2005) for verification was used as dictated from experience of other works (R.Lidén, J. Harlin, 2000). The calibration and verification periods are shown in table 4.1.

Table 4.1 Calibration and verification periods of RVZ-Nyabiraba catchment

Models	Number of years	Number of data points	Starting date	Calibration period	Verification period
SLM	10	3653	1/1/1996	1996-2000	2001-2005
LPM	10	3653	1/1/1996	1996-2000	2001-2005
SMAR	10	3653	1/1/1996	1996-2000	2001-2005
HBV	10	3653	1/1/1996	1996-2000	2001-2005

Automatic calibration procedures on the basis of Least Square solution have been followed for SLM and LPM models.

In the case of SMAR, automatic search algorithms of Rosen Brock, Simplex and generic algorithm have been used and the best algorithm that gave better efficiency criteria was used to estimate parameters.

For HBV model, the manual calibration of trial and error procedure has been used. The parameter set that gave the best objective function value over the calibration period was used for validation.

4.2 Simple Linear Model (SLM)

SLM was applied to RVZ-Nyabiraba catchment and different methods are applied to compare the model performance.

The data is available for the 10 years of rainfall and discharge. The first five years were used for calibration and the remaining five years for verification. Automatic calibration procedures on the basis of Least Square solution have been followed for SLM.

After exhaustive search, a memory length of 17 days has been found to give reasonable pulse response function. No further improvement in shape was possible in this regard.

The Figure 4.1 shows the simulated pulse response functions simulated by the method of Ordinary Least Squares for RVZ-Nyabiraba catchment.

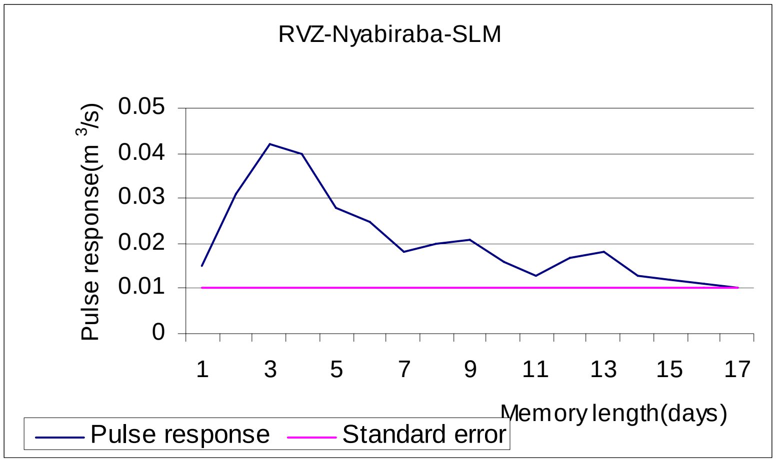


Figure 4.1 The pulse response derived by ordinary least squares of

RVZ- Nyabiraba catchment for SLM

The SLM graphical representation of the simulated and observed flows are given in figures 4.2 for Calibration (left) and verification (right) periods.

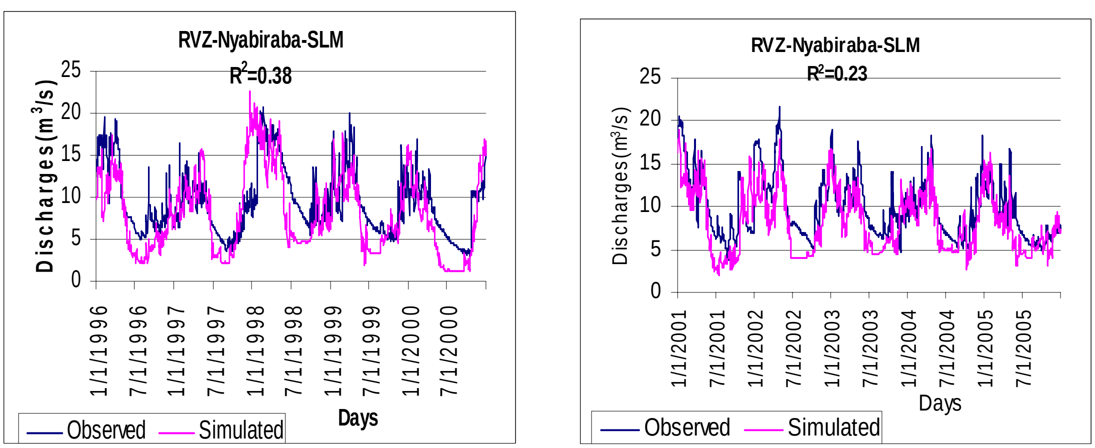


Figure 4.2 Graphical results of the simulated and observed hydrographs

for calibration (left) and verification (right) period

The graphical representation between simulated and measured low and high flows do not show a good agreement both in calibration and verification periods. It shows that the SLM under simulates the low and high flows both in calibration and verification periods. Therefore all the peak flows were not well simulated both in calibration and verification periods.

On this catchment of RVZ-Nyabiraba, the model efficiency of SLM is 0.38 for the calibration period and 0.23 for the verification period. This result of SLM indicates the model efficiency which is very poor. Also, these results confirm that SLM alone is inadequate for modelling the rainfall-runoff transformation.

Residual analysis

In general, the residuals are the differences between the simulated and the observed discharge.

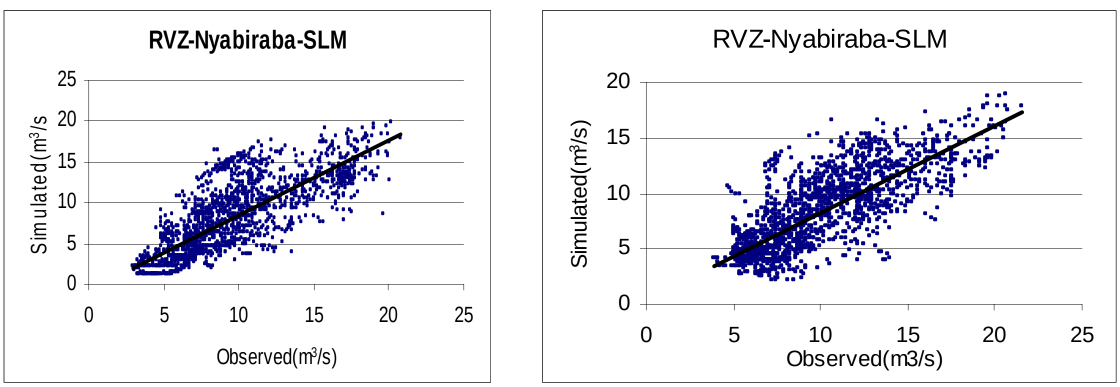


Figure 4.3 Scatter diagrams of SLM for calibration (left) and verification (right) periods for RVZ-Nyabiraba catchment

By considering the simulated versus observed scatter diagrams, presented here above in Figure 4.3, it is noted that values are appear to be equally above and below the 45-degree line in the model.

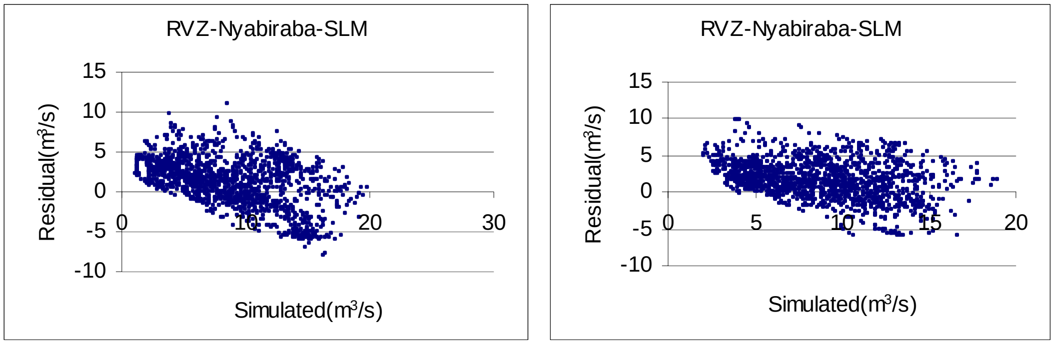


Figure 4.4 Residual versus computed scatter diagrams using SLM for

Calibration (left) and verification (right) periods

The residual plots for SLM in the RVZ-Nyabiraba catchment shows that the values are converging to the x-axis with more positive values for both calibration and verification periods indicating that the model under simulates the flows.

4.3 Linear Perturbation Model (LPM)

LPM was applied to RVZ-Nyabiraba catchment and different methods are applied to compare the model performance. The Fourier coefficient and the linear model parameters are given here below in table 4.2 and 4.3.

Table 4.2 Estimated parameter values of the linear model under the constraints of the gamma function

Catchment	RVZ-Nyabiraba			
Memory length	22			
Estimated gamma function model parameter	n	k	nk(days)	Gg
	0.807	11.169	9.009	0.639

Table 4.3 Fourier coefficients for smoothing the seasonal mean rainfall and discharge of RVZ-Nyabiraba catchment

	Seasonal mean rainfall			Seasonal mean discharge		
Number of Harmonics	Fourier coefficients		Variance accounted by the j^{th} harmonics %	Fourier coefficients		Variance accounted by the j^{th} harmonics %
	a(j)	b(j)	c(j)	a(j)	b(j)	c(j)
1	3.15	1.12	50.34	1.66	3.82	93.43
2	-0.35	-0.46	1.49	-0.49	0.15	1.43
3	0.06	-0.89	3.53	0.05	-0.31	0.52
4	0.1	0.18	0.19	-0.05	0.07	0.05

In both rainfall and discharge, more than 50 and 93 % respectively of the information can be explained by the first harmonic alone. This indicates a highly seasonal nature of the rainfall and runoff in this catchment.

The figure 4.5 shows the simulated pulse response functions simulated by the method of Ordinary Least Squares for RVZ-Nyabiraba catchment. It indicates from the plots that better shape is obtained by LPM for the selected memory lengths (22days).

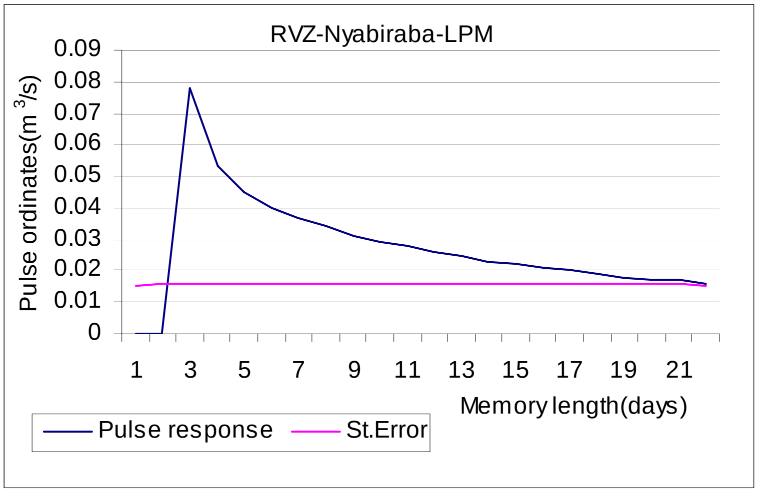
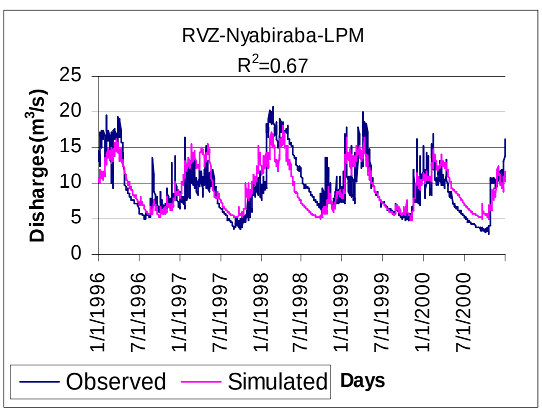


Figure 4.5 The pulse responses derived by ordinary least squares of LPM

The LPM model graphical results are given in figure 4.6 for calibration and for verification periods.



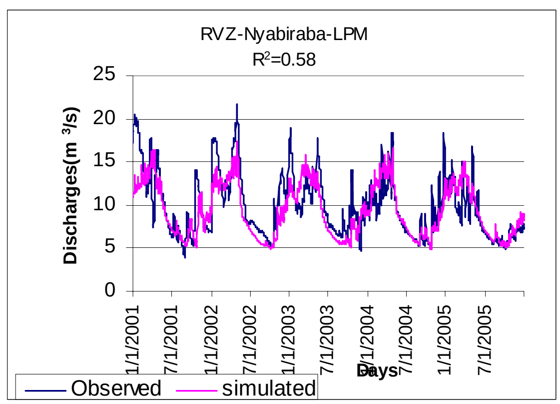


Figure 4.6 Graphical results of the observed and simulated hydrographs

for LPM for calibration (left) and verification (right) periods.

It shows that the graphical representation of measured and simulated low flows matched well for both calibration and verification periods. For the high flows, no agreement between measured and simulated flows in some years for both calibration and verification periods. Hence all the peak flows were not well simulated both in calibration and verification periods. Then, the LPM under simulated the high flows both in calibration and verification periods in some years.

As compared to SLM, the hydrograph fit is better in LPM. The hydrograph in SLM is different to the LPM.

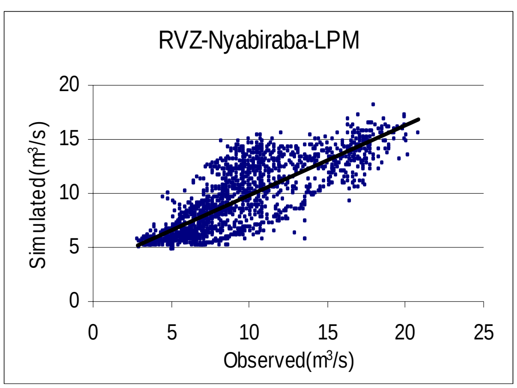
On this catchment of RVZ-Nyabiraba, the corresponding efficiency result by LPM is 0.67 for calibration and 0.58 for the verification periods. These results of LPM indicate the model efficiency which is satisfactory. Also, these results confirm the adequacy of LPM for modelling the rainfall-runoff transformation.

When compared with the results of the SLM, the LPM is significantly better. The combination of the seasonal and linear components of the LPM improves the results significantly.

Hence, between the two models (SLM and LPM), LPM is selected as the best model to simulate the flows for RVZ-Nyabiraba catchment.

Residual analysis

In general, the residuals are the differences between the simulated and the observed discharge.



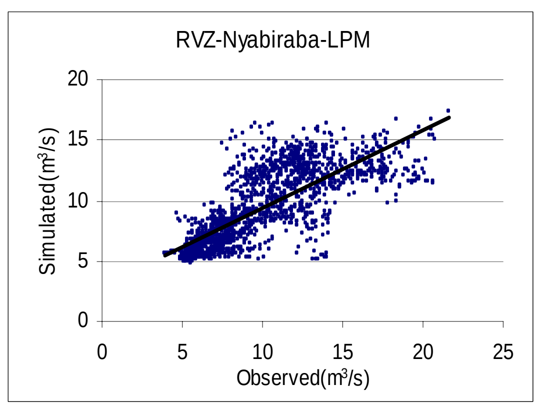
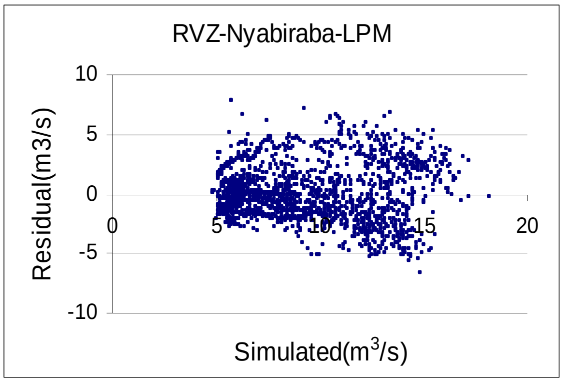


Figure 4.7 Scatter diagrams of LPM for calibration (left) and verification (right) periods

By considering the simulated versus observed scatter diagrams, it is noted that values are appear to be equally above and below the 45-degree line in the model.

The scatter diagrams are presented here above in Figure 4.7.



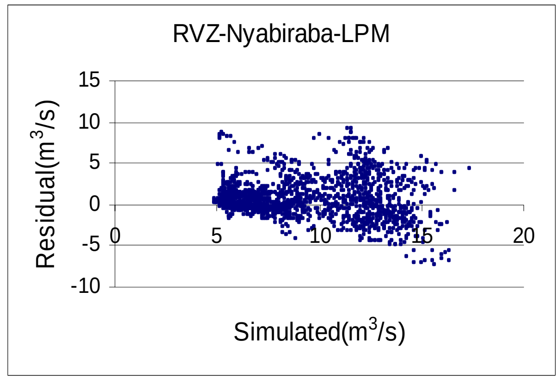


Figure 4.8 Residual versus simulated scatter diagrams using LPM for calibration (left) and verification (right) periods

The residual plots for LPM in the RVZ-Nyabiraba catchment shows that the values are converging to the x-axis with half negative and positive values for both calibration and verification periods indicating that for some years the model over simulates the flows.

4.4 Soil Moisture Accounting and Routing Model (SMAR)

RVZ-Nyabiraba catchment was chosen for examination with SMAR model. For SMAR, calibration and verification used is the same as those described before. The data is available for the 10 years of rainfall, discharge and evaporation data.

For SMAR, the first five years were used for calibration and the remaining five years for verification. The Generic algorithm, the Rosen Brock and the Simplex optimization routine were used for estimating the parameters of the water balance component(C, Y, H, T, and Z) and the pulse response function of the routing component was estimated by the method of constrained least squares(G). In the first trial (1), only T was allowed to be optimized the remaining four parameters (C, Y, H, and Z) were fixed at their inoperative values. In trial 6, parameters C and H were optimized keeping the remaining three inoperative values and in trial 15, parameters Z, Y, and T were optimized and the remaining two parameters fixed at inoperative values. The other parameters combinations were also tried to find optimum values for all parameters which minimizes the objective function F. A selection of the sub model forms used and the results obtained in model efficiency over the calibration periods for the catchment is described in table 4.4. From table 4.4 trial 15 with parameter combination ZYT result are better in Model efficiency (R^2=0.72).The parameter combination ZYT show a good fit for the simulated to observed discharge (ratio) than other combinations. Hence, the parameter combination ZYT was selected for SMAR model.

Table 4.4 Test results of the calibration period of RVZ-Nyabiraba catchment

Trial	Model	Optimum parameter values					Ratio	F(mm^2/day)	R^2 (%)
		T	H	Y	Z	C			
1	T	0.87					0.986	0.61	72.0
2	H		0.038				0.975	0.61	68.8
3	Y			140.75			0.976	0.64	68.9
4	Z				161.51		0.976	0.63	68.9
5	C					0.99	0.976	0.64	68.7
6	HC		0.02			0.962	0.974	0.63	68.9
7	YC			69.16		0.995	0.973	0.65	68.9

Table 4.4 Test results of the calibration period of RVZ-Nyabiraba catchment... (Cont'd)

8	ZC				67.74	0.989	0.976	0.62	68.9
9	TC	0.70				0.994	0.972	0.62	67.2
10	YZ			135.36	121.7		0.975	0.60	68.6
11	TZ	0.81			51.9		0.971	0.61	66.3
12	TZC	0.76			60.07	0.82	0.972	0.63	66.3
13	TYC	0.77		155.43		0.975	0.973	0.625	67.1
14	THC	0.87	0.054			0.95	0.986	0.61	71.0
15	TYZ	0.52		142.61	196.04		0.984	0.66	72.2
16	THZ	0.74	0.011		146.72		0.977	0.61	69.4
All							0.975	0.61	68.9

The TYZ sub model combination is selected for optimized parameters.

The parameter Z is greater than 125mm in RVZ-Nyabiraba in which = H*

(available soil-moisture content per 125 of water).

The nine SMAR model parameters values are given in table 4.5.

Table 4.5 The nine optimized parameter of SMAR model for RVZ-Nyabiraba catchment

N^o	Parameter	Optimized value
1	T	0.87
2	H	0.054
3	Y	142.61
4	Z	196.04
5	C	0.95
6	F	0.66
7	G	0.996
8	N	1.62
9	NK	4.35
10	KG	140.67

4.4.1 Model parameters

The figure 4.9 shows the simulated pulse response functions simulated by the method of Ordinary Least Squares for RVZ-Nyabiraba catchment. It indicates from the plots that better shape is obtained by SMAR for the selected memory lengths (13 days) as shown in Figure 4.9.

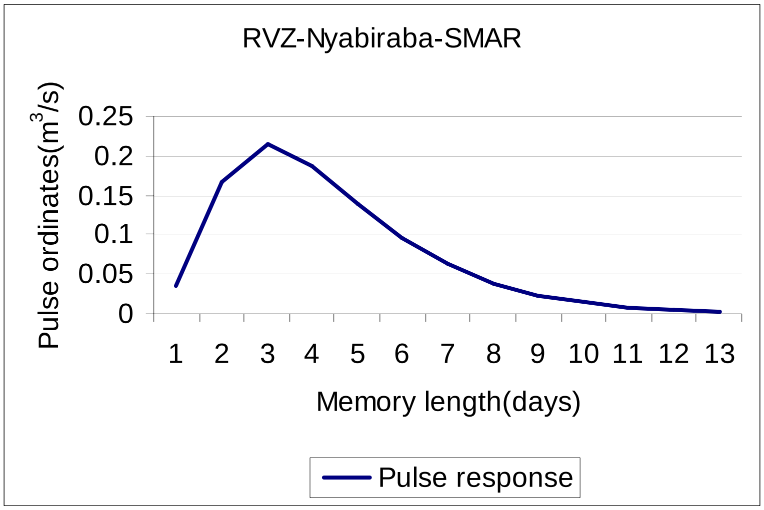
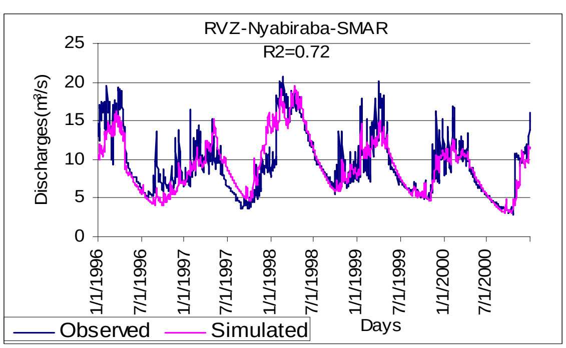


Figure 4.9 The pulse response of RVZ-Nyabiraba catchment after SMAR model

From the figure 4.10 below, it shows a good agreement between observed and simulated low flows both in calibration and verification periods. Also, the graphical representation between simulated and observed high flows match well in calibration periods for some years. Hence, the model under simulate the high flows for verification and for calibration periods in some years. The model fit better the simulated low flows than the high flows.

As compared to the previous models (SLM, LPM), the hydrograph fit between simulated and observed flows is better in SMAR model both in calibration and verification periods for RVZ-Nyabiraba catchment. Therefore all the high flows were not well simulated both in calibration and verification periods. The results of the graphs are given here below.



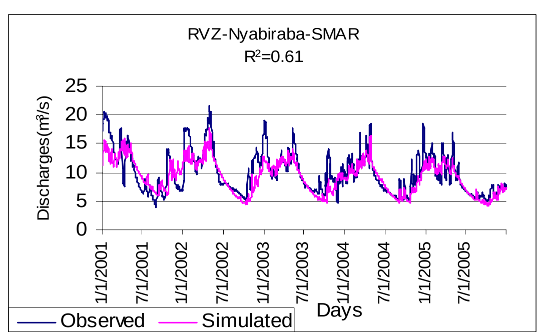


Figure 4.10 Graphical results of the simulated and observed hydrographs

for calibration (left) and verification(right)period .

Hence, a good result seems to be obtained also on wet catchments as the characteristic of the model's non-linear soil moisture formulation.

On this catchment of RVZ-Nyabiraba, the corresponding efficiency result by SMAR is 0.72 for the calibration and 0.61 for the verification period. These results of SMAR indicate the good performance. Also, these results confirm the adequacy of SMAR for modelling the rainfall-runoff transformation.

As compared with the results obtained from the SLM and LPM, SMAR is significantly better. Hence, between the three models discussed, SMAR is selected as the best model to simulate the flows for RVZ-Nyabiraba catchment.

Residual analysis

By considering the simulated versus observed scatter diagrams, it is noted that values are appear to be equally above and below the 45-degree line in the model.

The results show a good volumetric fit .The scatter diagrams are presented here below in Figure 4.11.

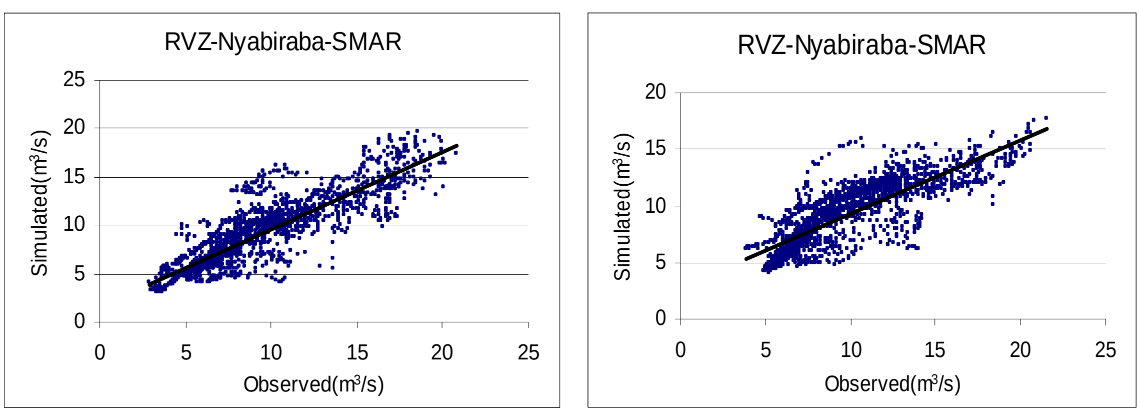


Figure 4.11 Scatter diagrams using SMAR model for calibration (left)

and verification (right) period

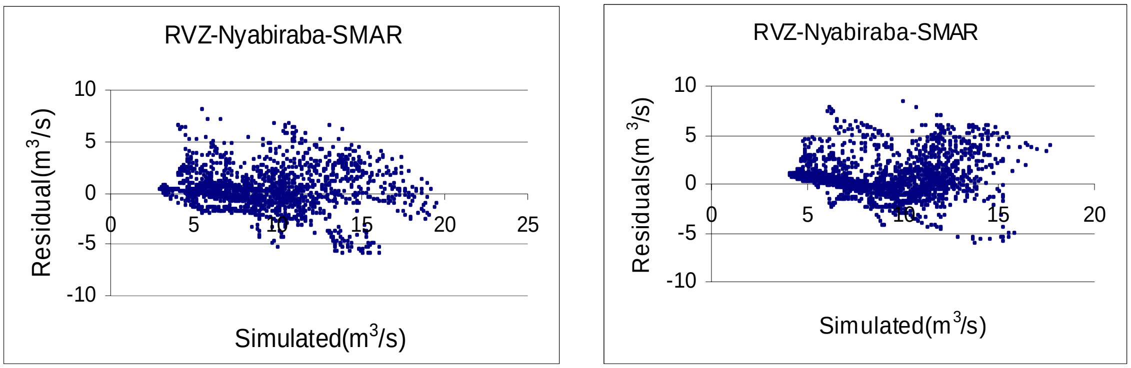
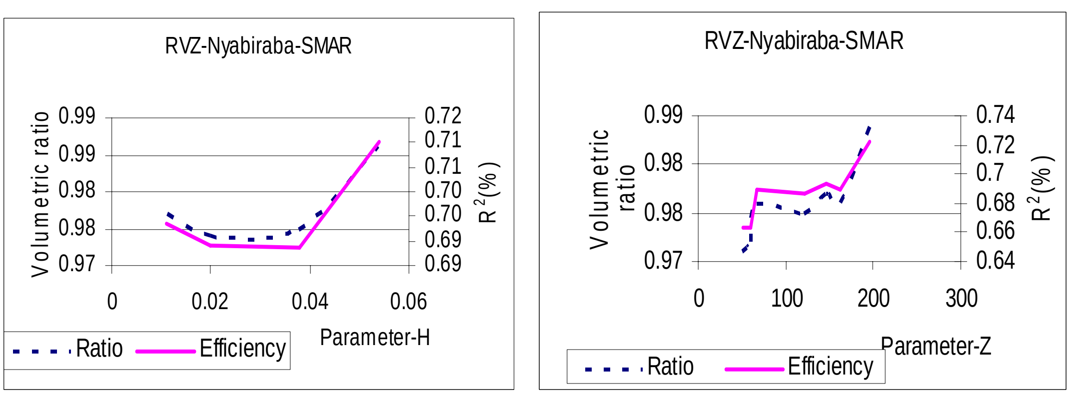


Figure 4.12 Residual versus simulated discharge plots using SMAR model for calibration (left) and verification (right) period

The residual plots for SMAR in the RVZ-Nyabiraba catchment shows in figure 4.12 that the residual values deviates towards half along the x-axis both for calibration and verification periods. Therefore, the model has the tendency to under simulate the flows.

4.4.2 Sensitivity of parameters in SMAR model

The influence of parameters on the objective functions and on the ratio of the observed and the simulated mean discharge is given in figure 4.13.



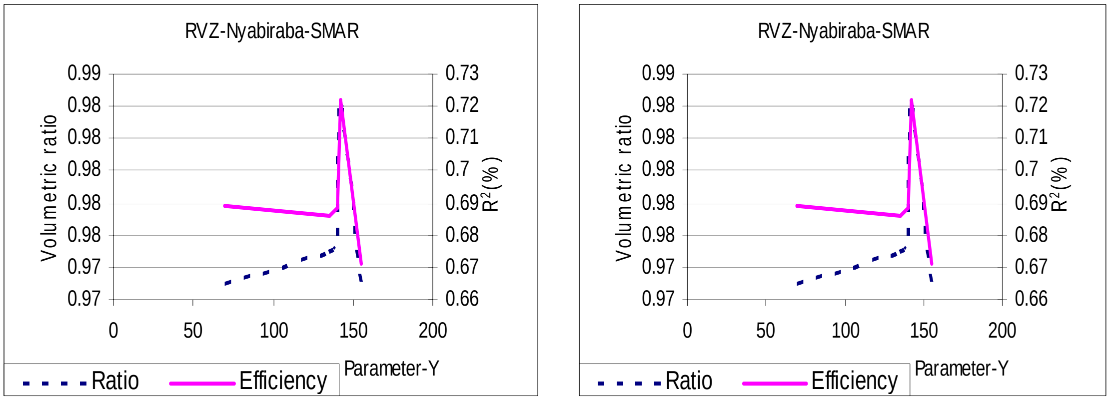


Figure 4.13 The effect of SMAR model parameters on model efficiency and volumetric ratio-RVZ-Nyabiraba catchment

For RVZ-Nyabiraba catchment the all four selected parameters appears to be sensitive, for slight change of both parameters, the volumetric ratio and model efficiency changes in the same direction in increasing or decreasing (Figure 4.13).

Hence, there appear to be upper limit for parameters Z and Y. Concerning Z parameter values beyond 160 and Y beyond 140 the volumetric ratio and efficiency continue to increase and decrease respectively indicating that both parameters cannot be fixed at their upper limit. The optimized parameter value C approaches to unit, it indicates that the actual evaporation rate seems to be close to the potential rate. This is common in wet catchments.

4.5 HBV model.

RVZ-Nyabiraba catchment was also chosen for examination with HBV model. For HBV, calibration and verification used is the same as those described before. The data is available for 10 years of rainfall, discharge and evaporation data. For HBV, the first five years were used for calibration and the remaining five for verification.

The optimized parameters after manual calibration of trial and error procedure have been used for estimating the parameters: FC, LP, and β, KUZ1, KUZ2, UZ1, KLZ and PERC. See the parameters description in appendix III: Table 4.2.

4.5.1 Model parameters

The experience from the graphical representation between observed and simulated river flows allows a hydrologist to accept or reject a model.

Figure 4.14 shows the time series of simulated and the observed flows after testing the model and optimizing the parameters.

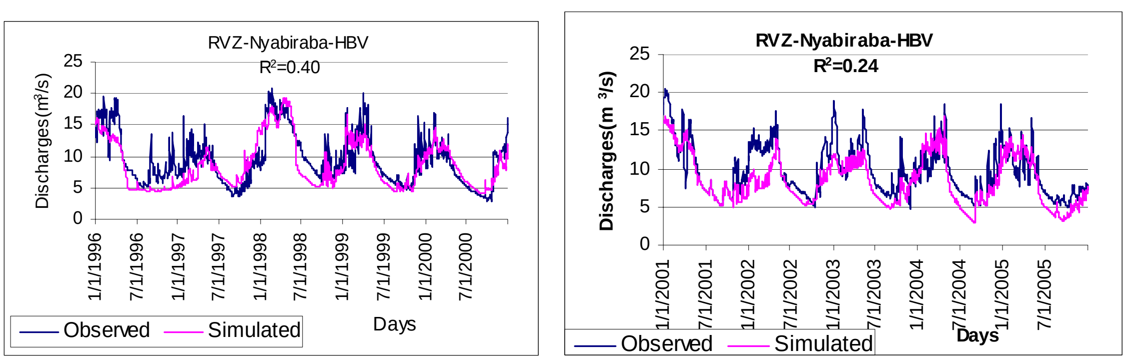


Figure 4.14 Graphical results of observed and simulated discharge with HBV model for calibration (left) and verification (right) period

Based on the standard parameter range given for HBV model (Appendix III table 4.2) the RVZ-Nyabiraba catchment was tested.

From the hydrographs fit between simulated and observed discharges, the model do not match well the low and high flows both in calibration and verification periods. The HBV model resulted with low satisfaction between observed and simulated discharges on the catchment in both calibration and verification periods. Therefore, it is noted that the model over simulates the low flows in some years during calibration period and under simulates the low flows during verification periods. Then all the high flows were not well simulated both in calibration and verification periods in the catchment.

To fit the model, the test was investigated by taking some parameters out of the range given. The parameter PERC (mm/day) which controls the percolation rate was taken as 3.4 mm/day out of the range given as (0.5-1.0).

The result obtained after optimizing all parameters is displayed on figure 4.14.

The efficiency was adjusted up to 0.40. The high value of PERC parameter may indicate that the major portion of the catchment may have coarse soils which may contribute to high percolation.

In fact, the range of parameters of PERC of HBV model has to be extended from 0.5-3.4.

The optimized parameters after manual calibration are shown in table 4.6.

About RVZ-Nyabiraba catchment, the efficiency is 0.40 for calibration and 0.24 for verification periods. These results of HBV indicate the model efficiency which is very poor.

Also, these results confirm that HBV is inadequate for modelling the rainfall-runoff transformation. When compared with the results of the SLM, the LPM and SMAR, HBV model performance is a little better than SLM.

Hence, between the four models in study, SMAR is found to be the best candidate model that can simulate the flows for RVZ-Nyabiraba catchment.

Residual analysis

The scatter diagrams are a little better distributed along the 45-degree line for calibration and verification periods. Seasonality is observed in the study catchment as shown from the time series graph of residual. See in appendix II figure 4.5.

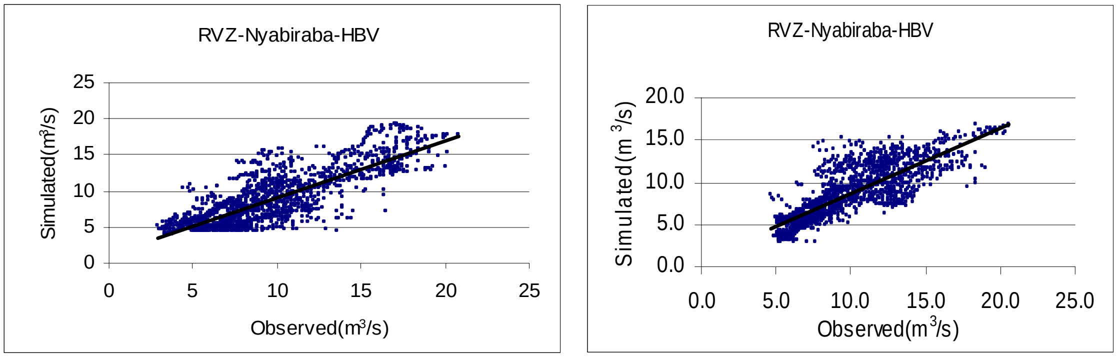


Figure 4.15 Observed and simulated scatter diagrams with HBV model for calibration (left) and verification (right) period

As shown the residual graphs in figure 4.16 the points are converging along the x-axis line with more positive values both in calibration and verification period, which indicate that the model under simulates the outputs discharges.

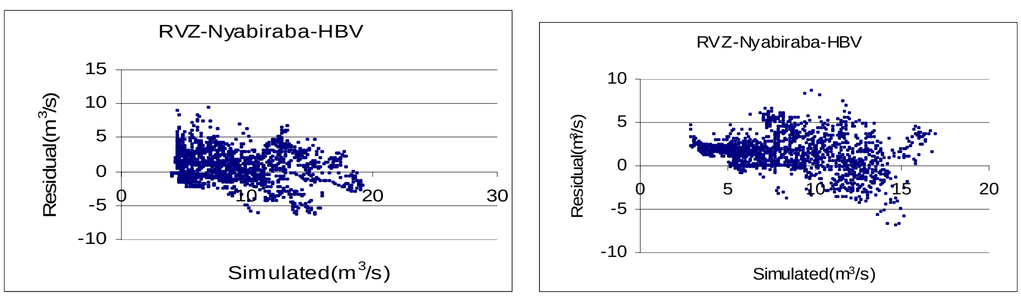


Figure 4.16 Residual and simulated scatter diagrams with HBV model for calibration (left) and verification (right) period

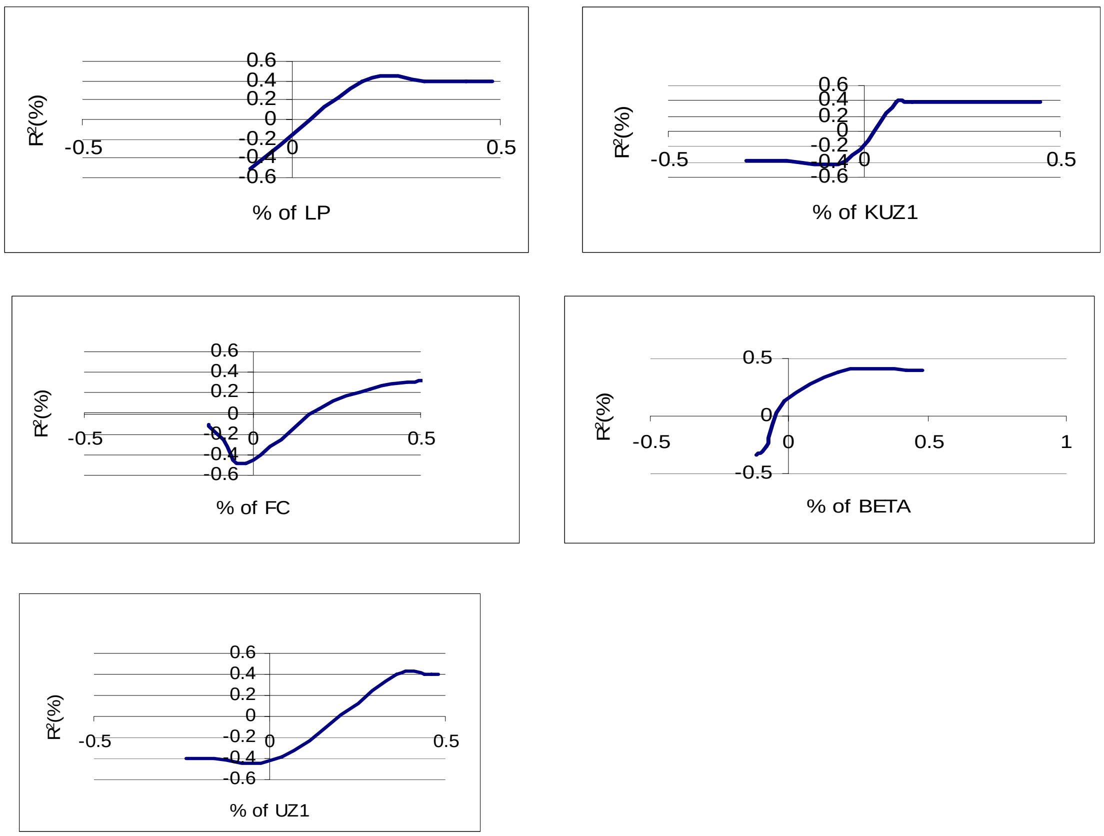
Table 4.6 Optimized HBV model parameters for RVZ-Nyabiraba catchment

Soil zone	Description	Symbol	Range	Optimized value	Unit	Remark
Soil	Field capacity:	FC	75-300	220	mm	
	BETA:	β	1.0-6.0	2		
	Threshold evaporation:	LP	70%-100% FC	210	mm	
Upper zone	Fast drainage coefficient:	KUZ2	0.1-0.5	1	1/day	
	Slow drainage coefficient:	KUZ1	0.05-0.15	0.05	1/day	
	Threshold:	UZ1	10-40	10	mm	
	Percolation:	PERC	0.5-1.0	3.4	mm/day	Out of range
Lower zone	Drainage coefficient:	KLZ	0.0005-0.002	0.001	1/day	

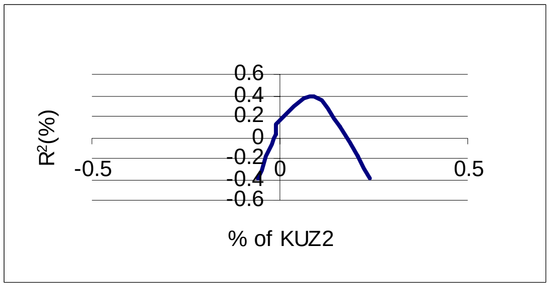
4.5.2 Parameters Sensitivity analysis of HBV model

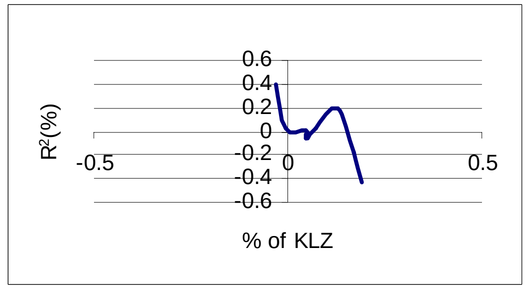
The analysis of parameter sensitivity using manual calibration was done by increasing and decreasing the value of each parameter. See the optimized value on table 4.6. The values obtained by increasing and decreasing -10% up to 40% of the sensitive parameters is plotted with the efficiency obtained. See the results on figure 4.16. The percent increase for FC, BETA, LP, KUZ1 and UZ1 doesn't significantly vary the model performance, but decreasing from optimized value in both parameters may result less efficiency showing that the five parameters may be set at higher values. There are two types of categories noted in RVZ-Nyabiraba catchment:

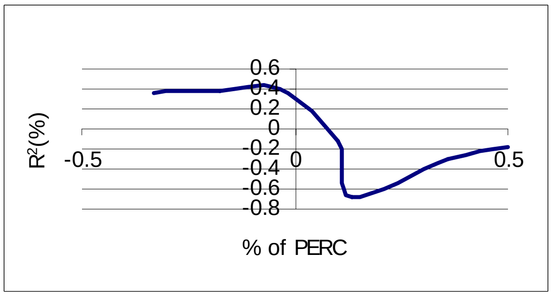
In category I the parameters FC, BETA, LP, KUZ1 and UZ1 are not sensitive in increasing the efficiency of the model. In category II all parameters (KUZ1, KLZ and PERC) show marked sensitivity when the parameter values are increasing or decreasing, this influences greatly the performance of the model.



a) Category I







b) Category II

Figure 4.17 Parameters Sensitivity of HBV model in RVZ-Nyabiraba Catchment

4.6 General comparison of model performance results and discussion

In RVZ-Nyabiraba catchment, the SMAR model performance result is better than other models applied in the area of study both in calibration (R^2= 0.72) and verification (R^2= 0.61) periods and has good hydrological fit. These results confirm the adequacy of SMAR for modelling the rainfall-runoff transformation. The results of calibration and verification from the rainfall-runoff models considered in the study are shown in table 4.7. The RVZ-Nyabiraba catchments exhibit marked seasonal behaviour and good results was also obtained with Linear Perturbation model (LPM) which involves the assumption of linearity between the departures from seasonal expectations in input and output series. In verification period SMAR and LPM has also better performance. In SLM and HBV models it is observed from the hydrographs that the models under simulates the high flows and low flows in calibration and verification period; in LPM and SMAR, the measured and simulated low flows hydrograph matched well for both calibration and verification periods .It is observed from the hydrographs that the models under simulates the high flows in calibration and verification period .The residual plots indicate that the flows from the models is under simulated for SLM and HBV and over simulated for LPM and under simulated for SMAR. Normally, the expected residual values should be close to the x-axis. It can be noted from the hydrograph that SLM and HBV model resulted with very poor satisfaction between observed and simulated discharges on the catchment in both calibration and verification periods.

Then, LPM and SMAR models resulted with good satisfaction between observed and simulated discharges on the catchment in both calibration and verification periods.

The Index of volumetric fit (IVF) and the relative error of peak (RE) are the evaluation criteria when the performances are indistinguishable on the basis of R^2. Hence, LPM, SMAR and HBV models present good fit regarding the ratio between simulated and observed discharge in calibration period; LPM and SMAR have good outputs in verification period.

On the basis of the hydrograph fit, all the models could not well simulate the peak discharges or the high flows. This might be due to the areal rainfall distribution taken for simulation which is averaged over the catchment or the high spatial variation of rainfall over the basin. The other reason is the under simulation of the low flows in HBV and SLM which might be due to the lumped models consider the catchment as one homogeneous zone and they did not consider the spatial variations of the catchment and some looses such as evaporation and data inconsistency.

Table 4.7 Calibration and verification results from different rainfall- Runoff models considered in the study area

Model	RVZ-Nyabiraba (751.8Km^2)			
	R^2	Index of Volumetric Fit(IVF)	Relative error of peak(RE)	Rank
Calibration				
SLM	0.38	0.85	0.05	4
LPM	0.67	1.00	0.13	2
SMAR	0.72	0.93	0.06	1
HBV	0.40	0.91	0.07	3
Verification				
SLM	0.23	0.82	0.12	4
LPM	0.58	0.94	0.20	2
SMAR	0.61	0.93	0.18	1
HBV	0.24	0.86	0.20	3

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATION

5.1 Summary and conclusion

Two linear (SLM, LPM) and two non-linear (SMAR, HBV) rainfall-runoff models were selected and used in this thesis research. The inputs data of the models were daily precipitation, discharge and evapotranspiration from 1996 to 2005 for RVZ-Nyabiraba catchment. These available 10 years daily data were divided into two parts: five years (1996-2000) for calibration and five years (2001-2005) for verification.

The objective of the research was to compare the performance of four hydrological models in RVZ-Nyabiraba catchment for Ruvubu river basin and to select the best candidate model for the catchment response prediction. From the calibration period of each model the optimized parameters which give the good performance result were determined. From the calibration optimized parameters obtained, the verification has been made. Automatic calibration procedures on the basis of Least Square solution have been followed for SLM and LPM models.

In the case of SMAR, automatic search algorithms of Rosen Brock, Simplex and generic algorithm have been used and the best algorithm (Simplex) that gave better efficiency criteria was used to estimate parameters. For HBV model, the manual calibration of trial and error procedure has been used for estimating parameters. The parameter set that gave the best objective function value over the calibration period in the ranges of the parameters was used for validation. PERC parameter was optimized out of the parameter range for HBV model set up. From the simulated pulse response functions, further improvement in shape was noted in SMAR followed by LPM. No further improvement in shape was possible in SLM.

The SMAR model perform well than the other models followed by LPM model both in calibration and verification periods in terms of the Nash-Sutcliffe model forecast efficiency index R^2. The performances of SLM and HBV are very poor than all of the other models applied. Hence, the SMAR model is selected to be the best to simulate the discharge in RVZ-Nyabiraba catchment. LPM can also be adequate to simulate the discharge in RVZ-Nyabiraba catchment. Further investigation should be made to generalize the applicability of this model to all Ruvubu river basins.

The visual comparisons were also made for the low and high flow fit of the hydrographs.

Consequently, SMAR model which has R^2 value of 72% showed good fit even though it under simulates the high flows for some years and it is selected for the catchment.

The comparison was also made on the basis of the relative error of peak (RE) criteria and the index of volumetric fit (IVF), i.e. the ratio between the total observed discharges to the total simulated discharge. The ratio is near to unity for SMAR and HBV models and equal to unity for LPM for calibration, showing that the three models volumetric fit are not compromised.

It is noted from the hydrographs that the SLM and HBV under simulates the low flows and high flows in calibration and verification period; in LPM and SMAR, the measured and simulated low flows hydrograph matched well for both calibration and verification periods .

It is observed from the hydrographs that the models under simulates the high flows in calibration and verification period .Hence, from the hydrograph, SLM and HBV model resulted with very poor satisfaction between observed and simulated discharges on the catchment in both calibration and verification periods.

Then, LPM and SMAR models resulted with good satisfaction between observed and simulated discharges on the catchment in both calibration and verification periods.

In general, on the basis of the hydrograph fit, all the models could not well simulate the peak discharges on the catchment in both calibration and verification periods.

5.2 Recommendation

- The selected models should be tested with more case studies with good data quality in order to use the models for Burundi catchments;

-The model structure and parameter ranges of some models, like HBV have to be modified to some extent for Burundi standards because the models are developed according to other countries standards as seen from parameter PERC in HBV model;

- Calibrating using models without having good quality data leads to poor model outputs and inappropriate conclusion;

- The catchment characteristics must be reasonably known to apply the appropriate hydrological model;

- Results obtained by application to gauged catchment can be regionalized to form a conception of the hydrological system in ungauged catchments;

-These models can be tested in several gauged catchment to derive homogeneous response units that could be applied to generate flow in ungauged catchments.

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APPENDIX

APPENDIX I HYDROMETEOROLOGICAL DATA

Table 3.1 Mean monthly minimum temperature (in ^{o}C) of meteorological stations in RVZ-Nyabiraba catchment

Months/Stations	Mweya	Makebuko	Gisozi	Ruvyironza
Jan	12.6	12.1	12.2	12.6
Feb	12.8	12.3	12.0	12.1
Mar	12.8	12.3	12.0	12.6
Apr	12.9	12.4	12.5	12.8
May	12.2	11.3	11.6	11.3
Jun	9.7	8.5	9.3	8.4
Jul	9.2	7.9	8.8	7.2
Aug	10.4	9.3	10.1	8.7
Sep	11.4	10.5	11.2	10.2
Oct	12.2	11.6	11.9	11.4
Nov	12.5	11.9	12.2	11.8
Dec	12.7	12.3	12.0	12.2

Table 3.2 Mean monthly maximum temperature(in ^{o}C) of meteorological stations in RVZ-Nyabiraba catchment

Months/Stations	Mweya	Makebuko	Gisozi	Ruvyironza
Jan	24.2	24.2	22.0	23.8
Feb	24.4	24.4	22.8	24.8
Mar	24.3	24.3	22.2	24.2
Apr	23.9	23.9	21.6	23.8
May	23.7	23.7	21.3	23.5
Jun	23.6	23.6	21.3	23.5
Jul	24.3	24.2	22.0	24.2
Aug	25.7	25.7	23.1	25.3
Sep	26.4	26.6	23.9	25.9
Oct	25.7	25.9	23.1	25.2
Nov	24.5	24.7	21.7	23.8
Dec	23.9	23.8	21.8	23.6

Table 3.3 Average Areal Rainfall (in mm) of the RVZ-Nyabiraba River catchment above the gauging station at Nyabiraba after Thiessen polygon

Days/Year	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
1	2.7	4.4	10.0	8.6	0.0	8.1	0.6	2.1	9.4	18.6
2	0.8	3.8	0.9	8.5	15.6	10.6	11.4	24.1	2.4	7.0
3	0.7	0.0	2.1	5.4	2.4	3.7	27.9	4.9	0.0	15.3
4	4.1	5.0	7.5	0.3	1.7	6.8	10.2	0.5	4.0	1.2
5	12.8	2.8	10.5	2.1	0.3	13.1	0.1	2.1	5.2	3.9
6	21.0	0.9	0.7	2.2	0.0	1.9	11.6	13.4	0.0	7.2
7	8.2	9.8	9.3	0.0	8.6	2.7	8.3	9.9	2.8	0.0
8	0.0	10.0	6.1	0.0	7.3	5.3	5.6	0.0	2.1	6.7
9	1.3	4.3	23.9	7.5	2.5	26.7	1.7	5.9	0.3	0.9
10	11.0	8.5	27.0	2.1	7.8	0.3	0.0	7.5	0.3	2.5
11	0.4	0.4	0.1	4.6	10.7	5.3	10.2	6.1	8.3	3.0
12	12.1	5.7	6.1	33.6	1.0	1.1	11.8	2.1	0.5	1.6
13	0.7	10.0	2.6	15.7	13.0	8.6	15.6	2.4	3.5	6.6
14	0.7	1.6	3.1	31.8	5.4	4.2	15.0	0.0	1.3	8.2
15	3.6	3.9	9.6	1.2	1.4	0.0	0.1	0.0	0.5	25.5
16	0.5	0.2	15.7	9.5	0.0	6.8	1.6	5.5	2.1	8.9
17	0.1	13.5	0.1	23.3	0.0	2.0	0.7	5.1	11.2	0.3
18	1.5	4.1	7.8	34.1	3.6	4.7	0.0	9.9	30.5	0.0
19	0.8	6.3	18.3	0.1	1.1	8.9	9.7	4.5	4.2	0.4
20	9.0	0.0	16.4	0.0	2.0	9.9	12.3	1.5	0.0	0.0
21	5.0	0.2	2.5	2.9	1.6	4.5	20.7	2.7	0.2	0.0
22	3.5	0.0	0.1	7.1	1.9	18.2	15.5	6.6	13.1	15.9
23	0.0	18.1	0.8	3.6	9.8	2.3	0.0	0.0	0.4	2.4
24	11.8	19.2	0.6	1.3	1.3	3.2	5.3	0.0	1.7	11.9
25	4.2	1.9	3.7	6.6	1.4	3.7	1.3	0.0	4.4	0.1
26	0.6	3.8	0.3	0.0	2.4	0.0	0.1	1.0	11.9	17.3
27	19.5	0.2	1.4	2.1	0.9	0.0	0.2	0.2	0.1	0.0
28	23.7	0.7	5.5	0.0	1.4	9.4	1.5	4.5	4.9	15.3
29	7.5	0.0	15.3	0.0	0.0	11.1	1.7	0.9	0.1	0.0
30	5.0	12.5	0.1	11.5	0.9	4.6	12.2	1.7	6.2	6.1
31	7.1	0.0	10.8	19.5	0.0	0.6	0.0	0.0	28.1	0.0
32	3.0	1.4	1.7	0.4	11.0	4.4	1.1	0.0	1.2	8.1
33	0.5	9.4	0.0	0.0	10.5	0.6	0.0	0.0	3.9	12.5
34	13.9	2.7	27.7	7.6	13.4	6.4	0.0	0.0	1.1	9.3
35	3.6	8.0	1.5	0.0	14.6	4.1	4.1	0.0	0.0	0.0
36	1.7	7.0	14.8	0.0	0.0	0.4	2.4	0.9	0.2	0.0
37	2.2	7.4	7.9	0.0	5.4	19.8	3.8	0.0	3.5	4.7
38	13.8	4.2	16.4	0.0	0.2	7.3	14.5	2.3	13.9	0.8

39	17.0	12.5	11.6	12.2	7.2	20.8	0.1	9.3	0.0	7.9
40	0.3	0.1	24.0	0.8	21.1	7.3	0.0	15.4	5.6	0.3
41	0.2	1.1	15.5	28.2	1.7	3.0	2.4	0.0	0.0	0.0
42	10.4	0.4	22.6	1.1	19.7	0.4	7.6	9.8	0.8	0.0
43	11.1	2.3	2.1	0.0	0.0	4.9	20.6	2.5	4.6	0.0
44	5.5	2.9	2.9	14.1	1.8	1.7	6.0	1.1	0.0	0.0
45	0.1	0.5	6.2	0.0	0.0	0.0	2.1	1.2	1.0	0.0
46	2.4	5.6	10.0	0.0	0.4	0.0	0.0	6.9	7.7	0.0
47	13.5	3.5	3.0	5.0	6.7	1.4	2.7	9.0	0.2	0.0
48	3.9	5.3	0.9	0.3	6.7	0.0	6.7	4.7	0.2	0.0
49	8.5	6.7	1.0	0.0	0.1	1.8	3.9	0.0	2.5	0.0
50	3.0	26.1	16.6	0.0	10.8	0.0	3.8	0.0	12.3	13.6
51	0.0	0.9	2.1	10.0	0.0	2.7	0.3	0.0	0.4	0.0
52	0.6	23.8	6.3	0.1	0.0	2.6	0.0	0.0	2.3	0.5
53	2.1	0.0	22.9	0.5	0.0	30.8	0.0	0.0	2.1	0.0
54	7.8	1.7	5.7	5.5	0.0	4.2	0.1	0.0	0.6	0.0
55	0.8	4.7	0.0	0.0	0.0	5.2	0.0	0.0	0.1	0.0
56	1.4	3.6	5.5	1.0	0.5	0.0	0.0	14.2	36.1	0.7
57	0.9	2.5	4.8	6.8	2.4	0.0	0.0	26.2	4.7	8.5
58	15.5	0.0	6.1	16.3	0.0	16.7	0.0	5.9	7.4	3.5
59	22.7	1.4	1.0	2.0	0.0	1.8	0.0	0.0	8.8	5.9
60	0.0	1.0	2.3	0.1	2.5	0.2	4.9	5.2	3.1	12.2
61	0.2	5.0	0.0	22.2	5.4	0.2	8.7	9.4	8.2	6.1
62	5.6	12.2	0.6	0.1	6.8	0.0	0.7	10.9	0.5	3.3
63	0.1	2.8	0.0	23.7	2.1	0.0	1.5	0.0	0.0	0.0
64	3.7	0.0	0.0	0.1	0.0	1.0	12.2	0.0	0.0	0.0
65	3.3	4.9	0.6	0.1	2.2	1.5	4.8	0.0	0.0	15.3
66	0.0	0.0	0.3	10.1	8.4	4.2	1.6	3.0	9.0	0.6
67	6.0	17.5	11.0	4.0	3.0	14.3	0.2	23.1	10.7	0.2
68	22.5	4.7	5.1	8.7	0.4	16.9	0.9	0.0	3.4	0.0
69	11.8	0.0	5.0	6.6	7.1	0.0	6.0	0.0	6.6	0.0
70	2.5	0.0	0.0	1.9	0.8	12.0	5.3	12.2	10.5	0.1
71	2.9	0.0	2.6	2.9	1.6	10.3	0.7	0.0	0.7	0.0
72	1.3	0.0	0.1	8.2	7.7	0.2	17.6	1.5	11.3	0.5
73	27.3	0.0	0.0	15.9	2.3	0.0	3.8	0.0	6.7	6.5
74	5.4	4.8	0.1	0.9	1.3	0.0	0.0	6.6	9.7	0.3
75	13.3	1.3	3.5	3.6	15.2	8.6	1.1	28.2	0.3	5.5
76	6.4	0.6	17.2	0.2	0.6	13.5	10.4	0.1	0.0	26.5
77	15.3	4.6	0.1	3.4	0.0	3.1	4.0	6.7	1.7	3.4
78	2.9	2.8	0.0	0.2	19.3	9.3	3.3	0.0	3.4	0.2
79	2.2	0.0	25.6	15.0	2.2	6.8	9.8	0.0	3.2	6.0
80	13.1	6.2	1.7	13.9	0.9	0.2	6.4	13.5	23.1	19.5

81	1.9	7.7	11.3	0.0	1.1	26.7	0.4	0.3	25.9	4.3
82	0.0	4.6	5.1	0.4	0.1	0.1	0.9	2.0	0.0	0.6
83	2.0	1.8	7.9	0.0	7.0	6.7	0.3	1.7	0.1	22.3
84	2.8	3.2	25.1	4.4	5.3	1.8	18.2	17.7	0.0	0.0
85	20.5	6.1	17.7	16.6	2.3	22.4	0.7	0.0	0.1	5.3
86	2.1	3.9	9.1	12.0	2.0	16.8	1.7	4.9	0.7	18.3
87	14.7	4.8	17.4	0.5	0.2	10.3	6.0	18.4	14.6	0.0
88	11.3	1.7	2.0	2.8	11.2	0.0	4.1	3.3	0.7	0.3
89	1.3	0.0	9.3	7.8	1.8	19.6	0.2	0.5	0.0	3.8
90	0.0	22.0	6.9	17.3	3.3	4.0	0.4	1.4	0.7	1.5
91	10.4	17.5	7.2	9.5	5.1	19.7	14.9	5.9	20.8	0.0
92	2.7	10.8	0.0	4.3	0.2	0.5	19.1	0.5	0.4	6.7
93	6.6	10.0	7.9	12.8	1.5	0.7	23.6	3.8	0.6	0.0
94	0.1	5.2	15.8	5.6	9.5	3.3	12.2	1.3	2.8	1.8
95	0.0	6.9	10.2	28.7	0.0	2.1	9.0	19.3	39.7	0.4
96	19.9	15.0	8.2	3.9	0.9	2.2	1.3	3.3	1.9	4.3
97	1.9	2.8	18.5	0.0	6.3	21.8	0.0	0.0	3.3	4.8
98	20.6	8.1	28.4	8.2	2.0	16.8	0.0	2.4	14.6	1.9
99	0.7	2.4	0.0	0.2	8.3	11.7	0.0	2.4	7.2	0.6
100	3.5	3.6	7.3	9.8	0.0	13.8	1.5	0.0	0.9	20.0
101	5.9	5.3	1.9	7.6	12.3	0.9	1.5	8.9	13.9	8.1
102	0.8	5.4	23.7	0.2	0.6	2.5	31.8	0.0	0.9	1.2
103	2.2	16.7	9.3	0.0	1.6	0.4	2.8	0.0	1.0	9.9
104	0.0	9.3	6.9	0.0	0.0	0.0	5.3	7.2	5.4	0.1
105	1.7	1.7	3.6	0.0	2.6	0.4	17.1	6.1	14.5	0.0
106	1.0	0.9	1.1	0.0	0.0	0.3	8.6	5.6	0.1	0.3
107	10.8	1.4	8.8	0.0	5.0	0.0	17.3	21.9	0.0	0.0
108	1.1	8.0	8.8	14.4	0.0	0.0	6.7	17.5	0.2	0.0
109	16.9	2.8	3.6	16.4	0.0	0.0	6.8	0.1	0.0	0.0
110	2.2	5.6	3.0	9.2	0.0	1.0	11.9	0.2	3.4	0.0
111	6.7	4.5	0.0	3.1	0.0	12.5	2.7	8.7	2.8	0.0
112	0.0	0.0	5.3	0.0	0.0	13.3	2.3	14.1	1.6	0.0
113	0.6	0.7	0.0	0.8	0.0	6.3	15.0	2.1	0.6	0.0
114	1.6	25.8	0.0	0.0	0.0	7.7	0.0	0.0	24.9	0.0
115	0.0	8.0	28.5	0.0	0.1	8.0	2.7	0.0	51.6	0.0
116	2.2	16.6	16.8	0.0	1.6	1.1	0.4	0.0	2.5	0.0
117	3.8	2.4	0.2	1.2	1.4	2.4	29.6	0.1	0.4	0.0
118	5.7	0.0	2.9	0.6	0.7	0.0	9.2	0.9	1.5	7.9
119	3.5	3.6	2.1	0.1	2.0	0.4	37.0	24.5	6.7	5.3
120	0.0	21.3	3.5	0.0	0.2	12.9	8.8	1.7	0.0	2.2
121	0.0	9.4	5.0	1.5	0.0	6.9	0.2	4.9	0.5	29.5

122	0.0	6.7	3.8	11.6	0.0	0.5	6.7	0.5	0.0	5.9
123	0.0	29.2	4.5	16.4	0.0	0.0	16.5	0.5	0.0	6.1
124	0.1	8.2	0.6	3.4	0.0	1.6	2.1	6.5	0.0	0.0
125	0.1	13.8	2.4	0.2	0.0	3.6	2.7	8.1	0.0	1.2
126	4.3	4.7	12.2	0.0	0.0	26.3	1.3	0.0	0.0	3.3
127	0.2	5.6	8.0	0.0	1.5	4.8	1.1	2.8	0.0	8.2
128	0.0	2.8	14.4	0.0	0.0	4.6	0.8	13.1	0.0	0.0
129	0.0	11.1	7.1	2.5	0.0	0.0	0.8	2.0	0.0	10.1
130	0.0	3.6	0.9	0.0	0.0	0.0	0.0	28.9	0.0	0.0
131	3.7	4.2	1.9	0.1	0.0	0.0	0.4	0.0	0.0	0.0
132	0.0	5.2	0.8	0.0	0.0	0.0	0.0	2.4	0.0	0.0
133	4.9	3.8	0.2	0.0	0.0	0.0	0.0	3.0	0.0	0.0
134	0.0	5.4	6.9	0.0	0.0	0.6	0.0	9.4	0.1	0.0
135	0.0	1.8	0.7	3.1	0.0	0.2	0.0	1.7	0.0	0.0
136	8.2	0.3	0.0	0.0	0.0	0.0	0.0	2.1	0.0	0.0
137	0.5	1.8	0.0	0.0	0.0	1.0	0.0	3.0	0.0	0.0
138	0.2	0.3	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
139	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0
140	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.8	0.0
141	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.8	0.0	1.9
142	0.4	0.0	0.0	5.0	0.0	7.7	0.0	7.1	0.0	0.1
143	4.2	0.9	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0
144	0.5	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	1.3
145	0.6	0.0	6.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
146	0.0	0.0	3.0	0.5	0.0	0.0	0.0	1.0	0.0	0.0
147	1.5	0.0	0.1	0.0	0.7	0.0	0.0	7.6	0.0	2.2
148	0.1	0.0	0.0	0.0	0.1	2.4	0.0	4.8	0.0	4.6
149	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9
150	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	1.1
151	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
152	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4
153	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
154	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
155	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
156	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
157	0.0	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
158	0.0	0.0	3.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
159	0.0	0.0	1.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
160	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
161	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0

162	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
163	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
164	4.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
165	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
166	0.0	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
167	0.0	7.1	0.0	0.0	0.0	0.0	0.0	0.0	8.4	0.0
168	0.0	7.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
169	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
170	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
171	0.0	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
172	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
173	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
174	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
175	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
176	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
177	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
178	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
179	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
180	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
181	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
182	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
183	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
184	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
185	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
186	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
187	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
188	16.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
189	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
190	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
191	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
192	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
193	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
194	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
195	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
196	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
197	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
198	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
199	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0
200	0.0	0.0	0.0	0.0	0.0	8.7	0.0	0.0	0.0	0.0
201	0.0	0.0	0.1	0.0	0.0	7.5	0.0	0.0	0.0	0.0

202	0.0	0.0	0.7	0.0	0.0	12.8	0.0	0.0	0.0	0.0
203	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.0
204	0.0	0.0	0.0	0.0	0.0	2.8	0.0	0.0	0.0	0.0
205	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
206	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
207	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
208	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
209	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
210	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
211	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
212	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
213	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
214	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
215	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0
216	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0
217	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
218	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
219	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
220	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
221	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
222	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
223	0.0	0.0	0.0	0.0	0.0	7.3	0.0	0.0	0.0	0.0
224	0.0	0.0	0.0	0.0	0.0	2.3	0.0	0.0	1.0	0.0
225	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
226	1.3	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0
227	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.0
228	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	5.8
229	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.1
230	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.0
231	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.4
232	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	1.0
233	1.8	0.2	0.0	0.0	0.0	0.0	0.0	3.2	0.0	0.0
234	12.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
235	0.0	0.5	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0
236	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0
237	0.0	0.0	0.2	16.6	0.0	0.0	0.0	0.0	0.0	0.0
238	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.0	0.0	0.0
239	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0
240	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
241	0.0	0.0	0.0	2.8	0.0	0.0	0.0	0.0	0.0	0.0

242	0.0	0.0	0.0	2.7	0.0	0.0	0.0	0.0	0.0	0.0
243	0.0	0.0	0.0	4.8	0.0	0.0	0.0	0.0	0.0	0.0
244	0.5	0.0	0.0	5.3	0.0	0.0	0.0	0.0	0.0	0.0
245	22.1	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
246	2.8	0.0	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0
247	11.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.8	0.0
248	0.0	0.0	0.0	0.0	0.0	1.6	0.0	1.6	8.0	0.1
249	1.0	0.0	0.0	0.0	0.0	0.2	0.0	6.3	7.3	1.2
250	0.0	0.0	0.0	0.0	0.0	0.1	0.5	1.6	8.2	0.1
251	1.4	0.0	0.0	0.0	0.0	0.0	0.5	0.0	1.4	0.0
252	0.7	0.0	0.0	0.0	0.1	0.0	0.0	0.0	4.2	0.0
253	0.0	0.0	0.0	0.0	0.0	0.2	6.0	0.1	0.0	0.0
254	0.0	0.0	0.0	0.0	0.0	15.0	0.0	0.0	0.0	0.0
255	0.0	0.0	0.2	9.1	0.0	0.0	3.9	3.9	0.0	0.0
256	3.3	0.0	0.0	3.7	0.0	0.0	0.0	0.6	0.0	0.0
257	0.3	0.0	0.0	0.0	0.0	16.2	0.0	0.1	0.0	0.0
258	6.6	0.0	0.0	0.0	0.0	7.0	0.0	0.0	0.0	0.0
259	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
260	0.0	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3
261	0.1	17.9	0.0	0.0	0.0	1.5	0.0	0.3	0.0	8.1
262	0.0	2.0	2.3	3.2	0.0	6.9	0.0	0.5	0.0	0.7
263	3.5	0.0	0.0	0.0	24.2	12.7	0.0	12.7	0.1	0.2
264	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	9.2	0.0
265	0.0	0.0	0.0	1.3	0.0	15.1	0.0	5.4	1.3	0.2
266	0.0	0.0	0.0	0.3	0.0	0.0	0.0	2.1	0.0	0.0
267	0.0	0.0	0.0	2.7	0.0	3.7	0.0	0.8	0.0	0.0
268	0.3	0.0	0.0	0.0	0.0	8.8	0.0	0.0	5.7	0.0
269	0.0	0.0	3.5	1.8	0.0	4.2	0.0	0.0	6.4	0.0
270	0.0	0.0	0.0	0.3	0.0	7.5	0.0	0.0	16.7	0.1
271	0.0	0.0	0.0	4.3	0.0	6.0	0.0	2.0	4.6	0.0
272	0.0	0.0	1.2	10.0	0.2	0.5	0.0	0.0	4.7	1.0
273	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	7.8
274	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
275	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0
276	7.6	0.0	12.6	0.0	3.4	1.1	0.0	1.1	0.0	0.0
277	2.0	0.0	10.7	0.0	0.0	0.2	0.1	0.0	0.0	0.0
278	2.6	0.0	0.0	0.6	0.8	1.6	0.3	6.1	0.0	0.0
279	15.1	1.4	0.0	0.0	2.8	0.5	0.0	0.0	0.0	0.0
280	0.7	3.6	0.0	0.6	0.1	0.8	0.0	0.0	0.1	0.0
281	0.6	8.0	0.0	2.1	1.3	5.5	4.9	0.2	0.0	0.0

282	0.0	6.1	0.0	0.5	0.0	1.7	3.0	0.1	0.0	0.0
283	0.0	0.0	0.0	1.2	0.0	0.2	0.0	0.0	0.0	0.4
284	3.2	0.5	0.0	0.5	1.2	0.0	0.0	0.0	0.1	0.0
285	0.0	0.1	0.0	10.1	0.7	0.0	0.0	0.0	0.0	5.4
286	0.0	0.8	2.1	20.0	0.1	3.5	0.0	0.0	0.0	2.9
287	0.9	0.0	2.1	0.0	0.0	0.1	0.0	0.0	0.0	2.3
288	0.0	0.1	11.1	0.0	0.0	0.0	0.0	19.0	2.1	1.8
289	0.4	11.0	0.2	0.0	0.0	0.0	1.0	14.1	0.6	0.1
290	6.3	4.0	8.1	0.0	0.0	0.2	2.4	18.7	0.0	0.0
291	0.0	7.8	0.0	0.0	7.6	0.1	0.1	11.3	0.0	0.0
292	0.0	4.0	0.0	0.0	5.9	0.2	20.3	7.7	0.0	0.1
293	3.8	33.8	0.0	0.0	5.6	0.0	4.0	0.0	0.0	18.7
294	6.7	23.2	0.0	0.0	12.0	0.0	1.6	3.1	0.0	0.0
295	3.2	5.8	0.3	0.0	1.5	0.0	0.0	0.3	0.0	0.0
296	6.3	9.2	0.0	0.0	1.1	9.5	0.0	0.0	5.0	0.0
297	0.0	0.8	25.0	1.1	0.5	1.3	0.0	2.2	14.5	0.2
298	1.3	0.3	11.9	0.0	11.0	19.4	0.0	17.0	0.5	0.1
299	0.4	0.2	0.0	0.0	2.3	0.7	0.2	0.3	3.3	11.2
300	0.0	2.8	18.0	0.1	0.2	5.9	4.1	9.4	2.2	2.9
301	2.9	7.0	22.1	0.1	0.0	16.8	0.6	1.6	3.0	0.0
302	0.0	0.0	3.1	1.5	0.0	26.2	1.5	0.0	19.7	0.0
303	2.8	4.6	1.4	0.0	0.0	3.1	0.9	0.0	1.3	0.0
304	17.0	0.1	0.1	0.0	6.5	21.7	4.1	0.9	10.2	6.1
305	6.7	0.7	1.0	0.0	4.0	17.3	7.4	1.2	2.1	8.8
306	5.5	1.3	0.0	0.0	7.7	10.2	2.0	1.4	0.0	0.3
307	14.6	5.1	0.0	0.6	14.3	17.1	6.1	2.5	2.1	3.0
308	0.0	29.2	0.0	0.5	17.6	9.1	38.5	4.3	3.7	4.0
309	0.3	2.4	1.8	0.0	11.1	14.0	16.4	0.2	2.8	8.1
310	0.3	5.8	5.4	9.7	0.0	0.8	9.7	3.1	5.5	8.9
311	2.3	6.6	18.0	3.0	0.0	0.3	5.5	2.6	0.1	3.2
312	1.1	6.6	0.0	2.6	1.2	0.0	1.1	0.0	8.2	6.2
313	0.0	5.8	0.0	0.0	14.2	0.0	0.0	1.0	3.7	3.0
314	9.5	12.0	0.0	6.8	17.7	0.0	5.8	0.0	8.9	0.7
315	2.9	3.6	0.0	5.3	1.5	2.0	0.0	0.3	6.6	6.3
316	1.0	5.1	0.0	17.9	0.0	0.2	2.8	0.1	3.1	0.0
317	4.4	4.5	10.4	8.6	4.9	35.2	5.9	9.1	0.7	3.1
318	2.5	1.6	1.3	0.0	2.1	19.4	2.8	20.3	0.2	0.0
319	4.1	8.5	0.1	8.8	7.0	2.5	0.1	0.6	2.3	0.7
320	1.5	13.7	0.0	4.2	5.1	6.6	0.4	10.8	1.1	9.8
321	0.3	21.1	0.0	4.9	10.0	0.4	7.0	0.0	6.0	1.4

322	0.0	2.4	0.0	7.9	7.0	1.9	21.3	6.1	3.5	0.5
323	1.5	0.5	3.3	5.0	0.3	4.9	1.8	0.0	3.4	0.5
324	2.1	12.5	3.0	8.6	5.8	0.1	16.1	0.0	4.4	0.1
325	0.5	11.1	0.1	10.3	18.4	3.4	0.6	4.1	1.9	0.3
326	3.5	7.0	2.8	7.9	26.1	0.0	0.7	5.8	3.6	1.6
327	4.8	23.2	8.9	6.7	8.4	1.5	18.3	6.1	15.8	2.4
328	0.9	2.0	0.8	9.9	22.5	1.3	15.0	13.5	0.3	9.0
329	4.2	12.0	0.0	10.8	7.0	0.3	0.6	10.7	10.8	11.9
330	0.8	7.3	3.7	9.2	6.7	1.8	8.7	3.1	8.2	14.9
331	0.1	4.0	15.5	11.9	21.3	0.0	1.8	6.3	13.5	3.9
332	12.4	11.1	2.8	11.9	17.8	0.0	0.8	10.5	15.4	0.4
333	1.2	18.1	0.9	12.6	1.8	0.0	5.5	7.9	1.9	5.1
334	0.0	2.2	0.0	17.4	7.2	0.0	0.0	0.0	2.7	4.4
335	2.9	7.7	1.5	7.1	15.4	6.3	0.0	3.7	9.7	0.8
336	0.1	3.5	24.7	6.9	6.5	2.4	1.4	11.0	4.4	0.6
337	10.8	0.0	0.8	9.6	3.5	24.2	11.2	11.5	0.3	3.6
338	4.5	4.7	11.7	9.4	10.2	1.6	0.3	2.4	2.8	1.0
339	10.2	12.9	0.1	0.0	3.9	12.1	4.4	18.0	1.9	4.2
340	7.0	17.0	9.0	3.5	2.0	18.3	4.9	1.2	1.7	11.7
341	0.1	3.6	3.3	1.3	5.1	4.4	0.3	0.1	1.4	8.2
342	32.1	12.9	0.3	8.4	0.0	6.0	28.7	6.6	14.0	0.7
343	15.8	6.0	11.3	0.0	2.0	0.6	9.8	4.5	6.9	1.2
344	0.3	27.4	3.6	0.1	5.5	3.7	2.0	7.1	4.4	8.1
345	0.0	9.5	0.5	4.7	12.4	1.8	17.2	1.5	0.0	13.9
346	0.2	14.7	3.2	1.6	0.7	0.3	3.7	11.3	15.5	3.0
347	1.2	14.1	8.6	18.1	6.6	4.4	0.7	15.4	4.3	6.5
348	0.1	3.4	0.0	13.2	12.2	0.0	6.2	0.0	0.0	0.0
349	3.1	3.6	1.7	4.9	0.5	0.0	2.6	1.9	5.4	0.9
350	4.7	14.1	0.3	6.8	2.2	0.1	21.9	0.0	12.3	0.0
351	2.4	6.1	5.9	5.6	10.8	8.5	0.0	1.7	24.3	0.1
352	3.2	8.5	0.7	5.2	3.8	4.6	0.7	1.6	1.7	0.4
353	0.3	16.2	13.5	13.0	6.6	1.0	6.0	8.5	2.4	3.8
354	0.9	47.9	2.5	4.9	2.9	9.3	0.0	15.6	13.9	0.6
355	7.5	0.3	1.5	3.1	0.0	0.1	12.1	6.7	8.3	15.2
356	0.6	9.8	0.0	7.1	2.8	0.1	8.4	0.2	0.7	0.0
357	4.6	6.5	8.7	6.7	21.5	0.0	17.0	5.3	0.0	4.6
358	0.0	13.7	0.0	8.2	17.7	3.9	1.8	2.2	43.4	0.1
359	2.0	2.6	1.9	11.6	4.5	23.0	10.9	0.0	1.8	2.2
360	11.9	21.6	0.0	10.0	10.2	1.1	21.1	0.0	3.0	2.8
361	0.1	0.1	1.0	2.1	0.1	1.2	1.7	6.6	0.0	1.6
362	0.5	1.7	0.0	5.2	12.4	1.1	28.4	0.0	9.6	10.2
363	1.5	2.9	0.3	14.7	8.3	7.9	0.6	6.1	0.8	0.1
364	0.0	3.7	1.1	0.0	11.1	8.6	9.2	3.9	0.6	0.4
365	1.0	1.6	0.0	3.3	0.6	20.8	4.2	0.0	16.5	10.0
366	0.4				5.4				2.2	

Table 3.4 Daily outlet discharge (in m^3/s) at Nyabiraba gauging station of the RVZ-Nyabiraba river catchment

Days/Year	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
1	14.61	6.99	7.70	8.29	11.90	17.22	7.39	16.83	9.94	13.24
2	13.85	7.17	8.11	7.42	11.37	18.64	8.54	17.43	10.20	12.84
3	13.14	8.51	8.99	11.70	11.64	18.57	13.19	17.54	10.26	12.64
4	14.61	8.88	9.04	8.66	12.00	19.36	17.19	18.04	9.62	12.77
5	14.06	8.29	8.63	8.73	11.44	19.36	17.61	19.00	9.23	12.91
6	12.84	8.13	9.84	7.73	7.95	19.58	17.50	18.75	8.98	13.04
7	12.37	7.85	8.85	8.16	9.84	19.58	17.50	18.04	8.60	12.64
8	16.17	7.36	8.54	7.73	8.66	20.34	17.29	17.29	8.47	12.44
9	16.73	7.36	9.46	7.24	8.13	20.59	17.08	16.87	8.29	12.30
10	17.15	8.16	10.88	10.91	8.98	20.56	17.50	16.48	8.16	12.10
11	16.73	8.16	10.36	8.35	10.00	20.19	17.57	16.03	8.22	12.10
12	16.34	7.73	9.62	7.73	10.95	19.98	17.72	15.96	9.11	11.77
13	15.99	7.14	9.49	16.41	10.20	20.12	17.54	16.13	11.18	11.50
14	15.64	7.11	10.00	16.90	10.36	19.72	17.72	16.03	12.44	11.37
15	15.09	7.42	9.27	16.13	11.91	19.65	17.61	15.54	10.78	11.84
16	16.69	8.07	9.74	10.91	14.33	19.76	17.47	15.12	10.07	12.97
17	17.26	7.73	9.14	10.91	12.24	20.23	17.57	14.57	12.10	13.45
18	17.43	7.45	8.98	14.13	10.65	19.79	17.43	13.85	12.91	12.44
19	17.01	7.11	9.17	17.75	10.92	19.47	17.50	13.34	12.30	11.24
20	16.80	6.90	10.33	16.34	13.68	19.07	17.54	12.80	11.97	11.04
21	16.41	6.69	10.18	14.47	12.77	19.51	17.75	12.40	12.23	11.04
22	16.06	6.51	9.27	10.91	11.64	19.11	17.61	12.07	11.84	11.31
23	16.34	6.48	9.61	10.91	10.49	19.58	17.36	11.64	11.57	10.98
24	16.76	9.11	18.32	10.46	10.10	19.79	17.29	11.37	11.57	11.24
25	17.26	14.54	18.04	10.91	10.01	19.47	17.40	11.08	10.98	11.64
26	17.43	16.52	17.54	10.26	11.02	18.86	17.26	10.75	10.39	12.50
27	16.66	14.23	17.19	10.46	9.33	18.39	16.94	10.65	10.00	12.91
28	15.96	11.04	17.26	9.87	8.92	18.29	16.66	10.49	9.94	13.79
29	15.44	9.97	17.33	9.23	8.51	18.21	16.45	10.55	10.33	14.88
30	15.02	9.20	17.33	8.66	8.29	17.75	16.20	10.36	11.04	15.23
31	14.47	8.04	17.47	8.29	8.79	17.36	16.03	9.97	12.17	15.02
32	14.09	8.07	17.75	9.62	9.36	17.04	15.75	9.74	12.57	14.47
33	13.68	7.73	17.33	10.91	8.26	16.94	15.50	9.55	13.38	13.65
34	13.31	7.67	16.48	9.17	9.17	16.59	15.30	9.39	12.03	13.58
35	13.45	8.07	18.32	8.79	11.31	16.41	15.05	9.27	10.91	13.38
36	15.30	8.32	19.04	9.55	13.08	16.03	14.61	9.42	10.13	13.04
37	15.71	8.69	20.19	8.47	15.47	16.20	14.43	9.39	10.00	12.77
38	17.04	11.58	19.04	8.66	14.50	16.41	14.19	9.14	10.33	12.64
39	19.58	10.26	18.82	8.41	13.62	16.27	13.96	8.92	11.18	12.37
40	17.47	11.01	18.68	8.35	13.75	16.06	14.13	10.36	11.37	12.91

41	17.40	12.77	18.61	8.04	14.26	16.31	14.06	10.52	10.65	13.24
42	17.04	11.80	19.90	15.23	16.94	16.52	13.79	10.33	9.94	13.31
43	16.62	10.95	19.54	10.91	16.84	16.34	13.48	10.10	9.04	12.77
44	16.48	9.75	20.05	10.26	16.73	15.96	13.28	9.87	8.47	12.03
45	16.03	9.20	19.98	10.91	14.68	15.75	13.04	9.71	8.35	11.24
46	16.03	8.92	19.33	10.46	12.80	15.61	12.87	9.55	9.62	10.52
47	16.73	8.32	19.25	9.17	12.00	15.23	12.67	9.46	10.13	10.07
48	17.50	7.85	18.82	8.54	11.77	14.88	12.47	10.03	9.62	9.68
49	16.62	12.44	18.32	8.22	12.91	14.57	12.27	10.16	9.30	9.49
50	16.34	11.90	19.25	7.97	12.00	14.26	12.13	9.87	8.98	9.42
51	15.71	11.34	19.98	7.73	12.74	13.99	11.90	9.81	9.36	9.62
52	15.05	10.52	19.90	7.60	11.94	13.68	11.64	9.49	9.74	9.49
53	14.47	10.07	20.12	7.85	11.11	13.51	11.37	9.27	9.36	9.23
54	14.26	13.92	20.77	7.42	10.52	13.21	11.14	9.14	8.98	9.11
55	13.31	13.92	19.98	7.24	10.23	12.97	10.81	9.01	9.42	9.11
56	12.84	12.74	18.89	7.60	10.00	13.11	10.62	8.85	10.07	8.92
57	13.92	11.64	18.39	9.62	9.75	13.07	10.42	8.66	10.39	8.73
58	10.59	10.33	18.46	10.26	10.59	13.07	10.20	8.60	10.85	8.98
59	10.26	10.52	18.04	14.33	10.46	12.74	10.00	8.95	11.84	9.36
60	10.00	14.40	17.75	11.57	10.00	12.37	9.84	9.49	12.23	10.39
61	17.15	13.70	17.54	12.23	10.33	12.04	9.68	9.30	12.23	10.00
62	16.48	11.94	17.19	12.64	9.94	11.64	10.03	10.13	12.10	10.07
63	14.85	9.78	17.75	12.17	9.75	11.31	10.75	10.26	11.57	10.07
64	9.36	10.63	17.11	12.84	10.59	11.04	11.11	10.42	10.72	9.74
65	15.47	12.07	16.55	14.88	10.52	10.95	12.10	10.68	10.07	9.36
66	15.09	13.60	18.46	12.30	10.85	11.21	12.17	10.49	10.00	9.17
67	15.23	11.52	17.82	10.33	11.41	11.47	12.84	10.29	10.26	8.85
68	15.92	9.68	17.04	13.11	11.24	11.41	12.74	10.36	12.97	8.60
69	16.76	9.17	17.04	14.95	12.30	11.97	12.80	11.51	16.97	8.35
70	17.26	9.65	18.04	14.40	11.91	12.30	12.60	12.30	15.64	8.22
71	17.61	9.55	16.97	14.74	12.07	12.23	12.34	12.13	12.30	7.97
72	16.13	9.71	16.34	13.11	11.14	12.07	12.27	11.74	12.03	7.85
73	16.45	10.59	15.71	14.13	13.07	12.44	12.30	11.87	13.04	7.67
74	16.83	10.33	15.44	17.75	12.00	12.67	12.17	12.04	12.84	8.10
75	16.76	9.74	15.30	16.69	10.33	12.54	11.94	12.00	11.77	9.94
76	17.26	9.36	15.09	14.61	10.36	12.60	12.37	12.00	10.91	13.31
77	17.29	9.42	15.50	13.99	10.13	12.47	12.47	13.55	10.78	14.95
78	17.04	8.79	15.37	15.02	10.29	13.14	12.47	13.75	11.37	14.47
79	16.69	8.38	14.88	14.33	9.81	14.54	12.20	13.85	11.24	14.54
80	16.34	8.73	15.44	14.26	10.43	15.75	11.97	13.62	11.11	14.88

81	16.03	8.88	16.27	16.97	12.27	16.90	11.67	13.34	12.84	14.95
82	15.75	9.68	16.69	14.33	10.55	17.47	11.31	13.01	13.18	14.33
83	15.44	9.78	16.34	13.24	10.00	17.82	10.98	12.87	12.64	13.85
84	15.02	10.03	15.85	12.10	9.74	17.68	10.68	12.57	12.23	13.38
85	15.57	10.21	17.75	13.58	9.84	17.22	10.55	12.30	11.57	12.84
86	16.13	10.55	18.46	12.91	11.08	16.48	10.95	11.97	11.37	12.10
87	16.66	11.89	18.97	14.26	11.04	15.12	11.57	11.90	12.03	11.18
88	19.29	11.57	18.54	13.65	10.78	14.02	11.97	12.13	12.37	10.39
89	18.97	10.68	17.89	13.24	10.23	13.48	12.37	12.47	11.31	10.07
90	19.22	9.52	17.89	12.77	10.46	10.78	12.34	12.10	11.24	9.68
91	18.82	11.34	17.75	12.46	10.65	10.36	12.34	11.84	11.24	9.23
92	17.61	12.13	17.54	17.12	10.29	10.03	12.47	12.30	11.50	8.85
93	17.26	11.21	17.19	20.09	10.29	9.58	12.94	12.30	12.03	8.47
94	17.11	11.31	17.75	17.01	10.13	8.82	13.31	12.04	12.03	8.79
95	16.87	11.41	17.11	16.59	9.78	8.41	13.92	11.67	12.44	9.49
96	16.41	10.72	16.55	16.80	9.62	8.01	14.16	11.47	12.84	10.46
97	16.76	10.75	18.46	18.07	9.20	7.51	14.40	11.27	13.45	11.70
98	19.04	10.72	18.46	18.47	10.13	7.82	14.71	11.41	14.40	12.10
99	18.89	11.60	18.61	17.47	11.14	8.22	15.96	11.21	15.71	12.44
100	17.33	10.03	17.96	17.26	11.47	9.39	16.55	10.95	16.27	12.44
101	17.04	9.17	17.82	16.94	13.25	9.91	16.41	10.78	15.16	12.97
102	16.94	9.14	17.61	16.70	13.45	10.65	16.69	10.49	13.99	12.97
103	16.83	8.88	17.04	17.75	12.74	12.04	17.54	10.49	13.45	12.44
104	16.41	8.92	17.04	16.34	12.04	12.80	17.08	10.16	14.47	12.03
105	15.99	8.22	16.27	15.12	11.27	13.45	17.22	10.10	14.54	11.31
106	15.64	10.88	16.27	14.54	10.36	12.87	17.50	10.07	14.88	10.59
107	15.57	10.62	16.83	13.79	9.68	13.92	17.15	10.68	13.99	9.87
108	15.40	9.97	17.40	13.24	10.00	14.44	17.68	11.47	12.91	9.04
109	15.02	9.84	17.40	13.14	9.75	14.68	17.61	12.57	12.10	8.54
110	14.68	11.21	17.47	13.89	9.20	15.26	17.43	13.75	11.50	8.35
111	13.42	11.47	17.61	18.32	9.07	15.12	19.54	14.43	11.44	8.22
112	14.33	11.41	17.61	17.11	8.79	14.99	19.65	14.16	11.50	7.85
113	13.99	11.50	17.54	16.20	8.69	15.75	19.15	14.09	10.85	7.79
114	12.84	12.03	17.40	14.44	8.60	16.48	19.07	13.82	11.77	8.10
115	11.70	10.75	17.40	13.55	8.26	15.92	19.11	13.51	14.61	8.41
116	11.37	15.23	17.19	12.94	8.10	16.41	18.61	13.38	18.32	8.73
117	11.31	13.24	16.85	12.57	8.41	16.06	18.71	13.31	18.39	10.00
118	10.68	12.50	17.10	12.34	8.57	15.40	19.61	13.01	17.04	10.33
119	10.42	10.63	17.82	12.10	8.69	14.68	20.63	12.67	17.40	11.04
120	9.94	10.91	17.96	11.90	8.44	14.47	20.77	12.50	16.48	12.30

121	9.75	9.39	17.36	11.74	8.63	14.26	21.62	11.51	15.92	12.97
122	9.62	12.08	16.78	11.84	8.29	14.06	20.52	12.54	14.95	13.92
123	9.62	12.96	16.38	11.84	8.07	13.79	20.52	12.54	13.31	14.40
124	9.49	13.04	16.29	13.79	7.94	13.89	20.37	12.87	12.30	15.64
125	9.49	12.13	16.17	14.81	7.76	13.75	19.83	12.70	11.84	16.76
126	9.42	11.47	15.97	12.97	8.87	13.51	19.33	13.38	11.77	16.34
127	9.36	10.72	15.87	12.27	8.77	13.18	18.82	13.31	11.50	15.64
128	8.98	9.97	15.78	11.57	8.68	14.34	18.36	13.85	10.98	14.95
129	9.11	9.27	15.64	11.31	7.42	12.60	17.89	16.03	10.78	14.47
130	9.36	8.73	15.50	10.98	7.36	12.37	16.87	17.72	10.59	13.85
131	9.11	10.16	15.49	10.72	7.20	12.13	16.48	17.47	10.46	13.18
132	8.98	9.74	15.38	9.38	7.20	12.50	16.10	17.11	10.52	12.30
133	8.73	9.36	15.66	10.36	7.08	12.44	15.61	16.76	10.39	11.57
134	8.73	9.23	15.52	10.00	7.30	12.20	15.16	16.69	10.13	10.85
135	8.73	9.17	15.44	10.10	7.11	11.84	14.61	16.27	9.81	10.07
136	8.60	10.98	15.31	10.59	7.02	11.44	14.16	15.92	9.42	9.49
137	8.60	11.47	15.24	10.36	6.90	11.21	13.82	15.61	9.42	9.11
138	8.35	11.62	15.23	10.00	7.08	10.95	13.48	15.37	9.30	8.79
139	8.35	10.36	15.16	9.94	6.90	11.41	15.36	15.40	9.36	8.73
140	8.35	10.03	15.09	9.84	6.90	11.21	13.04	15.19	9.23	8.79
141	8.35	9.65	14.85	9.65	6.69	10.88	12.84	14.92	9.23	8.79
142	8.16	9.49	14.59	9.39	6.81	10.75	12.54	14.78	9.11	9.04
143	8.10	10.33	14.50	8.76	6.72	10.55	12.40	14.47	8.98	8.85
144	8.04	10.42	14.28	8.82	6.60	10.49	12.27	14.19	8.92	8.60
145	7.97	9.91	14.11	9.14	6.51	10.33	12.00	14.02	8.79	8.92
146	7.73	9.55	14.01	9.01	6.39	10.26	11.80	13.58	8.66	9.23
147	7.73	10.59	13.82	8.92	6.72	10.03	11.64	13.31	8.73	9.87
148	7.73	10.46	13.72	8.88	6.75	9.78	11.31	12.97	8.60	10.91
149	7.73	9.91	13.63	8.85	6.72	9.65	11.11	12.74	8.66	11.50
150	7.73	9.87	13.65	8.76	6.63	9.55	10.95	12.50	8.66	11.70
151	7.73	11.84	13.51	8.82	6.66	9.42	10.88	12.20	8.60	11.50
152	7.73	10.55	13.58	8.69	6.54	9.33	10.75	12.40	8.54	11.31
153	7.73	10.23	13.60	8.63	6.45	9.20	10.72	12.10	8.54	10.52
154	7.73	9.42	13.36	8.54	6.42	9.04	10.65	11.94	8.41	9.94
155	7.73	9.07	13.41	8.44	6.30	8.92	10.52	11.67	8.29	9.23
156	7.73	8.57	13.50	8.38	6.21	8.88	10.16	11.44	8.16	8.73
157	7.73	8.19	13.28	8.57	6.18	8.73	9.94	11.24	8.10	8.35
158	7.73	8.01	13.14	8.76	6.24	8.63	9.74	10.98	8.10	8.35
159	7.73	8.04	12.91	8.47	6.18	8.38	9.49	10.78	8.04	8.10
160	7.73	9.46	12.69	8.29	6.03	8.26	9.23	10.52	7.91	7.97

161	7.73	8.88	12.45	8.19	6.03	8.19	9.04	10.23	7.79	8.10
162	7.73	8.51	12.37	8.13	6.03	8.13	8.85	10.00	7.91	7.97
163	7.11	8.29	12.44	8.10	5.94	8.01	8.63	9.78	7.85	7.79
164	7.11	8.10	12.40	8.01	5.94	7.85	8.41	9.49	7.67	7.79
165	7.11	8.04	12.34	8.01	5.97	7.70	8.29	9.23	7.60	7.60
166	7.11	7.97	12.28	7.97	5.97	7.70	8.07	9.39	7.54	7.67
167	7.11	7.91	12.10	7.94	6.09	7.51	7.94	9.27	7.67	7.60
168	7.11	7.88	11.84	7.82	6.00	7.42	7.88	9.23	7.60	7.48
169	7.11	7.91	11.72	7.88	6.03	7.30	7.88	9.20	7.79	7.42
170	7.11	7.85	11.60	7.73	5.94	7.20	8.04	9.23	7.67	7.42
171	7.11	7.60	11.65	7.67	5.82	7.14	7.94	9.07	7.48	7.42
172	7.11	7.36	11.97	7.57	5.79	7.05	8.07	8.88	7.42	7.17
173	7.11	7.17	12.35	7.57	5.71	7.02	7.97	8.82	7.30	6.99
174	6.99	7.14	12.49	6.70	5.65	6.96	7.88	8.82	7.30	6.99
175	6.99	7.11	12.35	7.51	5.50	6.84	7.85	8.69	7.36	7.24
176	6.93	6.96	12.17	7.45	5.59	6.75	7.85	8.69	7.24	7.24
177	6.96	6.93	11.97	7.45	5.59	6.66	7.76	8.73	7.11	7.17
178	6.99	6.78	11.90	7.39	5.47	6.63	7.91	8.85	6.93	6.99
179	6.96	6.63	11.79	7.27	5.38	6.60	7.82	8.76	6.93	6.93
180	6.87	6.57	11.54	7.33	5.38	6.51	7.79	8.63	7.05	7.11
181	6.51	6.57	11.26	7.36	5.47	6.42	7.79	8.44	6.99	7.11
182	6.39	6.51	11.01	7.27	5.47	6.39	8.07	8.32	6.87	6.93
183	5.91	6.51	10.81	7.27	5.35	6.30	8.04	8.04	6.93	6.87
184	5.91	6.51	10.65	7.17	5.30	6.36	8.13	7.76	7.05	6.81
185	5.82	6.51	10.52	7.27	5.21	6.33	8.07	7.63	7.05	6.75
186	5.79	6.51	10.46	7.14	5.18	6.54	8.19	7.51	6.87	6.63
187	5.79	6.51	10.36	7.11	5.12	6.39	8.10	7.60	6.81	6.75
188	5.79	6.39	10.13	7.08	5.15	6.51	8.01	7.39	6.75	6.81
189	5.76	6.39	9.97	7.05	5.07	7.02	8.26	7.63	6.81	6.63
190	5.73	6.36	9.87	7.02	5.12	7.88	8.29	7.85	6.87	6.57
191	5.73	6.27	9.81	6.93	5.24	8.47	8.16	7.76	6.69	6.57
192	5.68	6.21	9.78	7.02	5.27	8.95	8.16	7.67	6.63	6.51
193	5.62	6.21	9.71	6.90	5.18	8.47	8.13	7.70	6.63	6.57
194	5.59	6.09	9.62	6.81	5.12	8.13	8.04	7.79	6.75	6.45
195	5.62	6.03	9.52	6.72	5.07	7.63	8.04	7.76	6.63	6.33
196	5.62	6.03	9.49	6.66	5.01	7.57	8.13	7.63	6.57	6.27
197	5.59	6.03	9.42	6.66	4.89	7.51	8.07	7.60	6.57	6.33
198	5.56	5.97	9.33	6.66	4.84	7.42	7.94	7.57	6.57	6.21
199	5.47	5.85	9.55	6.60	4.78	7.20	8.07	7.51	6.45	6.15
200	5.44	5.85	9.81	6.63	4.69	7.05	8.01	7.45	6.51	6.15

201	5.44	5.79	9.74	6.57	4.64	6.90	7.91	7.33	6.57	6.33
202	5.44	5.79	9.68	6.45	4.66	6.81	7.97	7.51	6.45	6.33
203	5.38	5.76	9.68	6.42	4.61	6.54	7.82	7.57	6.45	6.21
204	5.33	5.73	9.58	6.33	4.58	6.33	7.70	7.42	6.45	6.15
205	5.21	5.68	9.47	6.42	4.52	6.48	7.60	7.33	6.39	6.15
206	5.21	5.68	9.46	6.45	4.52	6.18	7.60	7.39	6.33	6.03
207	5.18	5.62	9.42	6.51	4.49	6.12	7.57	7.27	6.33	6.09
208	5.15	5.53	9.39	6.39	4.47	5.97	7.51	7.20	6.45	6.15
209	5.09	5.50	9.34	6.39	4.47	5.73	7.54	7.05	6.33	6.21
210	5.09	5.50	9.27	6.33	4.55	6.33	7.51	7.17	6.27	6.03
211	5.09	5.44	9.20	6.27	4.52	6.81	7.39	7.17	6.21	5.97
212	5.09	5.44	9.17	6.21	4.49	7.30	7.54	7.02	6.21	5.97
213	4.98	5.38	9.17	6.12	4.47	7.67	7.51	6.96	6.21	5.85
214	4.98	5.35	9.11	6.09	4.47	7.42	7.42	7.14	6.27	5.79
215	5.45	5.04	9.04	6.03	4.44	7.20	7.33	7.02	6.21	5.79
216	5.91	4.98	8.92	6.12	4.41	7.08	7.27	6.93	6.15	5.68
217	5.79	4.84	8.79	6.21	4.38	6.96	7.39	6.87	6.09	5.62
218	5.68	4.89	8.79	6.36	4.33	6.84	7.45	6.78	6.09	5.62
219	5.68	4.81	8.73	6.36	4.30	6.66	7.27	6.78	6.09	5.56
220	5.62	4.69	8.66	6.36	4.30	6.54	7.20	6.66	6.15	5.50
221	5.56	5.12	8.66	6.30	4.35	6.48	7.08	6.66	6.03	5.56
222	5.56	4.89	8.60	6.21	4.35	6.39	7.02	6.75	5.97	5.62
223	5.44	4.81	8.54	6.12	4.33	6.30	7.17	6.60	6.03	5.62
224	5.44	4.78	8.54	6.09	4.30	6.12	7.17	6.57	6.03	5.50
225	5.38	4.69	8.47	6.03	4.24	6.09	7.02	6.60	6.03	5.44
226	5.33	4.69	8.38	5.97	4.30	6.00	6.90	6.72	6.15	5.38
227	5.33	4.61	8.35	5.88	4.24	5.91	6.96	6.66	6.15	5.44
228	5.33	4.69	8.32	5.82	4.24	5.82	6.84	6.57	6.09	5.62
229	5.33	4.66	8.26	5.82	4.19	5.62	6.87	6.48	6.09	5.79
230	5.33	4.69	8.19	5.79	4.16	5.41	6.78	6.39	5.97	5.97
231	5.21	4.58	8.16	5.88	4.10	5.30	6.96	6.48	5.91	6.09
232	5.21	4.58	8.16	5.71	4.07	5.24	7.02	6.66	5.91	6.15
233	5.15	4.52	8.10	5.65	4.05	5.15	7.02	6.96	5.79	6.33
234	7.91	4.52	8.01	5.59	3.96	5.01	6.90	6.87	5.73	6.27
235	7.85	4.52	7.97	5.65	3.94	4.89	6.84	6.96	5.68	6.39
236	7.36	4.41	7.94	5.82	3.94	4.61	6.90	6.81	5.56	6.27
237	7.11	4.33	7.88	5.97	3.91	4.52	6.81	6.84	5.50	6.57
238	6.99	4.05	7.85	6.33	3.91	4.33	6.96	6.84	5.38	6.33
239	6.63	4.05	7.82	6.96	3.85	4.44	6.90	6.72	5.50	6.03
240	6.51	3.80	7.76	6.93	3.83	4.07	6.87	6.66	5.38	5.68

241	6.39	3.80	7.73	7.11	3.80	4.02	6.81	6.60	5.21	5.68
242	5.97	3.69	7.73	6.72	3.85	3.88	6.84	6.48	5.21	5.85
243	5.91	3.63	7.67	6.63	3.77	4.10	6.93	6.57	5.27	5.91
244	5.68	3.55	7.67	6.63	3.74	4.55	6.84	6.42	5.21	5.62
245	9.81	3.69	7.48	6.57	3.74	5.07	6.75	6.36	5.27	5.44
246	13.58	3.74	7.36	6.63	3.69	5.76	6.75	6.30	6.15	5.27
247	11.18	3.85	7.73	6.69	3.80	6.06	6.69	6.30	7.05	5.50
248	10.46	3.83	7.60	6.99	3.74	6.18	6.63	6.18	7.67	5.56
249	9.84	3.85	7.48	6.63	3.74	6.42	6.60	6.18	8.35	5.68
250	9.49	4.10	7.36	6.15	3.69	7.33	6.48	6.66	8.92	5.68
251	9.11	4.30	7.24	5.97	3.66	8.19	6.54	9.52	8.66	5.91
252	9.11	4.13	7.11	6.03	3.72	8.60	6.36	9.27	8.60	5.97
253	8.79	4.75	7.17	5.91	3.63	9.14	6.24	8.76	8.60	6.15
254	8.35	5.01	7.05	5.73	3.74	9.01	6.30	8.38	7.85	6.15
255	8.16	4.81	6.93	5.56	3.66	9.20	6.18	8.26	6.87	5.97
256	7.73	4.49	6.99	5.38	3.77	8.88	6.18	8.01	6.15	5.85
257	7.67	4.10	7.11	5.73	3.69	8.60	6.33	7.88	6.03	5.85
258	7.30	5.01	6.99	5.97	3.55	8.13	6.30	7.76	5.85	5.97
259	7.11	5.18	7.11	5.62	3.44	7.85	6.21	7.63	5.68	5.79
260	7.91	4.30	6.99	5.68	3.44	7.94	6.12	7.39	5.68	5.91
261	8.22	4.07	6.69	5.44	3.36	7.60	6.12	7.14	5.62	6.45
262	7.97	4.49	6.63	5.33	3.34	7.57	6.06	7.02	5.56	6.27
263	7.67	4.72	6.81	5.44	3.34	7.45	6.00	6.90	5.50	6.09
264	7.48	4.49	6.93	5.38	3.58	7.30	6.06	6.78	5.44	5.91
265	7.11	3.96	6.81	5.38	3.85	7.02	6.00	6.66	5.44	5.73
266	7.11	3.85	6.87	5.15	3.69	6.84	5.88	6.54	5.27	5.68
267	7.05	3.83	6.69	5.04	3.53	6.63	5.94	6.45	5.27	5.56
268	6.93	3.74	6.45	5.09	3.47	6.48	5.79	6.33	5.21	5.44
269	6.75	3.69	6.57	5.21	3.47	6.33	5.79	6.21	5.73	5.38
270	6.51	3.63	8.47	5.33	3.36	6.27	5.71	6.21	6.39	5.50
271	6.51	3.69	7.54	5.27	3.36	6.06	5.56	6.09	7.24	5.38
272	6.39	3.63	5.50	5.09	3.44	5.88	5.50	6.03	8.92	5.27
273	6.33	3.63	7.24	5.56	3.36	5.73	5.41	5.97	8.35	5.15
274	6.03	4.49	7.11	5.38	3.28	5.88	5.53	5.91	7.30	5.09
275	5.91	5.07	6.99	5.44	3.18	5.71	5.65	5.91	6.63	5.15
276	5.85	5.01	6.87	5.73	3.10	5.56	5.59	5.91	6.39	5.09
277	8.66	4.30	8.10	5.56	2.99	5.44	5.47	7.67	6.15	5.04
278	8.73	4.02	9.42	5.38	3.20	5.65	5.35	7.48	5.97	5.04
279	8.35	5.88	8.85	5.21	3.23	5.56	5.24	8.10	6.03	5.09
280	8.16	4.92	8.16	5.33	3.50	5.47	5.12	9.94	5.85	5.04

281	7.67	4.02	7.11	5.21	3.47	5.30	5.18	9.23	5.91	4.98
282	7.54	3.80	6.87	5.09	3.36	5.65	5.12	8.73	5.73	4.86
283	7.67	4.05	6.69	5.38	3.36	6.06	5.35	8.22	5.50	4.92
284	7.73	4.84	6.45	4.75	3.50	6.30	5.33	7.85	5.38	5.15
285	7.30	5.35	6.51	5.44	3.69	6.36	5.41	7.36	5.38	5.33
286	7.11	5.15	6.45	5.62	3.88	6.96	5.35	7.05	5.38	5.62
287	7.05	4.66	6.51	6.21	3.69	7.05	5.09	6.87	5.56	5.85
288	6.93	4.58	10.91	7.42	3.50	7.45	5.01	6.75	5.50	5.73
289	6.63	4.52	13.58	7.05	3.39	7.91	4.98	9.83	5.44	5.50
290	6.51	5.73	11.57	6.39	3.44	12.20	5.56	12.84	5.38	5.33
291	6.63	5.44	9.62	5.91	3.31	13.72	5.79	14.13	5.27	5.21
292	6.81	4.84	8.79	5.68	3.04	13.79	7.91	14.06	5.21	5.33
293	6.63	5.38	7.73	5.27	2.86	14.02	10.07	12.64	5.15	5.38
294	6.45	5.21	7.24	4.98	3.28	13.89	10.75	14.06	5.15	5.79
295	6.39	5.09	7.05	4.92	3.50	13.41	10.39	13.79	5.09	6.21
296	6.27	4.84	6.81	4.92	3.99	13.48	10.23	13.45	5.27	6.81
297	6.21	4.78	6.63	4.81	4.10	13.21	9.91	12.91	5.50	6.81
298	5.91	4.47	6.69	4.86	4.41	13.34	9.65	12.50	6.03	6.99
299	5.91	6.12	13.58	4.75	4.41	14.02	9.42	8.79	6.45	7.42
300	5.79	5.94	10.91	4.86	4.66	13.82	9.07	11.51	6.63	7.85
301	5.79	5.27	10.91	4.75	10.78	13.38	8.76	10.20	7.60	7.60
302	6.69	5.97	12.03	5.68	10.72	12.97	8.32	9.42	10.39	7.36
303	7.05	5.56	12.23	5.56	10.62	12.80	7.79	9.17	12.30	7.24
304	7.11	5.56	10.39	5.33	10.52	12.60	7.54	9.04	11.50	7.54
305	7.11	5.85	8.92	5.09	10.29	12.67	7.27	8.92	10.59	7.42
306	6.93	9.44	8.79	4.86	10.13	12.54	7.08	9.42	9.62	7.79
307	6.81	6.87	7.97	4.92	10.29	12.23	6.90	9.36	8.79	7.36
308	6.51	5.56	7.60	4.98	10.81	12.30	6.78	9.42	8.22	7.11
309	6.51	5.07	7.36	5.09	10.72	12.07	6.57	9.23	7.79	6.81
310	9.23	4.84	7.11	5.21	10.52	11.84	6.42	9.11	7.42	6.69
311	9.11	6.66	9.42	5.04	10.49	11.44	6.78	8.98	7.24	6.51
312	8.54	6.36	9.87	6.03	10.75	11.37	8.21	8.85	6.87	6.33
313	8.10	5.62	8.66	5.85	10.42	11.04	9.52	8.85	7.54	6.27
314	7.60	5.27	7.85	6.75	10.16	10.72	12.00	8.66	8.73	6.33
315	7.67	8.19	7.42	6.63	9.94	10.55	12.17	8.54	9.74	6.45
316	7.54	7.79	7.11	5.62	10.00	10.39	11.18	8.35	9.42	6.33
317	7.24	7.60	6.93	7.11	10.10	10.29	9.97	8.60	8.29	6.57
318	7.11	7.82	7.11	8.16	10.59	10.10	10.20	8.66	8.10	6.45
319	7.05	6.87	6.93	12.03	10.39	9.91	10.85	9.23	7.85	6.15
320	7.05	6.45	6.81	8.35	10.13	9.74	11.78	8.92	7.73	6.21

321	6.81	6.27	6.63	7.17	10.13	9.58	12.17	8.66	7.97	6.39
322	6.51	6.09	6.51	8.10	10.07	9.42	12.77	8.29	7.91	6.15
323	6.45	5.85	6.45	7.60	9.97	9.27	12.74	7.91	8.73	6.03
324	7.79	6.36	6.63	11.18	9.71	9.07	12.54	7.67	8.60	5.91
325	7.60	6.30	6.69	8.98	9.46	8.95	12.67	7.36	8.35	5.79
326	7.30	9.97	6.51	8.16	9.23	8.73	12.50	6.75	7.60	6.03
327	7.24	10.26	6.51	8.35	9.46	8.57	12.50	6.39	8.16	6.33
328	7.11	9.84	6.69	7.36	9.84	8.44	12.84	5.97	9.55	6.27
329	6.99	9.55	7.85	7.67	9.62	8.19	13.45	5.73	11.37	6.15
330	12.91	9.27	7.48	7.54	10.07	8.07	13.96	5.38	13.11	6.57
331	10.98	9.11	8.29	7.48	10.03	7.85	14.23	5.15	13.31	7.05
332	9.81	9.27	8.04	7.54	10.00	7.67	14.23	4.92	13.24	7.60
333	9.11	8.32	8.66	8.66	10.13	7.54	14.09	4.75	13.11	7.73
334	8.41	9.36	7.67	9.23	10.36	7.45	13.96	4.69	12.97	7.54
335	7.73	9.14	7.11	10.07	10.62	7.27	13.79	8.85	13.04	7.17
336	7.67	9.07	6.87	16.34	10.72	7.20	13.45	8.57	13.85	7.30
337	7.91	8.57	7.73	12.50	10.81	7.20	13.07	8.44	13.85	7.48
338	8.22	8.51	10.91	10.91	11.04	7.08	12.77	9.01	12.77	7.24
339	8.54	8.19	8.60	8.98	10.95	7.39	12.67	8.76	11.37	6.99
340	8.35	8.44	7.60	8.47	10.78	7.27	12.20	8.41	10.33	7.11
341	8.04	9.04	8.60	7.85	10.65	7.45	11.84	8.22	9.62	7.73
342	8.01	9.27	8.47	7.30	10.81	7.45	11.60	8.41	9.11	7.73
343	7.73	10.16	7.60	7.11	10.88	7.51	11.70	8.76	9.17	7.54
344	13.92	10.68	7.11	7.73	11.04	7.67	11.41	8.63	9.23	7.36
345	12.50	9.68	7.73	7.42	11.08	7.57	11.37	8.41	9.04	7.17
346	11.04	9.42	7.36	7.30	11.27	7.63	11.14	8.16	9.81	6.99
347	10.36	9.58	7.11	6.99	11.47	7.51	10.81	8.86	9.94	7.42
348	10.20	8.88	8.98	8.54	11.57	7.33	10.72	10.88	10.33	7.42
349	10.07	8.76	8.29	8.47	11.84	7.17	11.24	10.59	10.39	7.30
350	9.62	8.38	8.04	13.85	11.87	7.20	11.80	9.87	10.13	7.36
351	9.17	8.63	7.97	12.77	11.18	7.05	11.84	9.46	10.26	7.11
352	8.79	8.79	9.74	11.31	10.46	6.90	11.44	9.11	11.18	6.99
353	8.35	8.88	9.55	11.18	9.97	6.87	11.18	9.11	14.81	6.87
354	8.29	8.73	8.92	11.11	9.68	7.08	11.34	10.10	13.58	6.87
355	7.85	9.01	10.91	10.65	10.10	7.06	12.44	7.57	14.61	7.17
356	7.73	10.49	8.73	10.26	10.72	7.05	12.80	11.27	15.78	7.36
357	7.54	10.85	7.48	10.07	11.14	7.04	13.31	11.51	18.39	7.36
358	7.33	10.81	10.91	9.87	11.67	7.03	13.41	10.98	18.39	6.87
359	7.11	11.03	9.55	10.07	12.07	7.02	13.38	10.23	17.82	6.87
360	7.11	11.31	9.62	11.24	12.47	7.01	13.38	9.68	16.62	7.73
361	6.99	11.55	9.11	11.57	12.87	7.00	14.47	9.36	15.37	8.04
362	6.81	9.49	7.85	15.30	13.07	6.99	14.78	9.01	14.81	7.85
363	6.75	8.57	7.36	13.92	13.75	6.97	16.52	8.98	14.33	7.60
364	6.63	8.01	7.36	12.77	14.81	6.95	16.66	9.39	13.65	7.30
365	6.51	7.76	8.35	12.77	15.12	6.93	16.76	9.39	13.58	7.54
366	6.51				16.13				13.31	

Table 3.5 Mean monthly Rainfall (mm) of RVZ-Nyabiraba catchment

YEAR	MONTH												An. Ave.
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
1996	180.1	166.3	212.9	122.7	29.6	4.5	16.4	16.5	53.7	90.5	85.1	126.9	1105
1997	151.7	145.9	124.2	222.4	118.7	24.1	0.1	0.7	23.2	135.3	246.8	296.7	1490
1998	218.7	240.9	187.7	233.4	80.2	6.3	0.8	0.9	7.6	128.9	79.9	117.3	1303
1999	245.4	111.8	203.5	136.9	44.9	0.0	0.0	32.8	42.7	38.5	203.3	196.2	1256
2000	105.9	136.9	126.9	56.7	2.4	0.0	0.0	0.0	24.5	68.7	280.2	192.0	994
2001	188.1	148.3	210.7	162.9	60.7	0.5	34.4	10.0	108.2	120.4	150.2	177.2	1371
2002	212.8	82.2	136.9	299.1	32.8	0.0	0.0	0.0	10.9	49.7	202.5	237.5	1264
2003	124.8	109.6	170.5	158.3	110.8	0.0	0.0	3.9	38.1	113.1	131.7	154.7	1116
2004	159.8	124.4	172.8	204.0	0.9	8.4	0.0	2.0	93.7	64.9	149.7	204.5	1185
2005	186.9	76.2	162.7	75.6	77.5	2.5	0.0	37.2	20.8	52.4	122.6	116.6	931
Ave	177.4	134.3	170.9	167.2	55.8	4.6	5.2	10.4	42.3	86.2	165.2	182.0	1202
St.dev	43.0	47.2	33.4	74.4	41.2	7.5	11.5	14.0	34.1	36.0	66.5	57.1	
Cv	0.2	0.4	0.2	0.4	0.7	1.6	2.2	1.3	0.8	0.4	0.4	0.3	

Table 3.6.Mean monthly Annual runoffs (m^3/s) of RVZ-Nyabiraba catchment

YEAR	MONTH												An. Ave.
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
1996	15.8	15.1	16.4	14.9	8.6	7.2	5.5	5.9	8.1	6.9	7.9	8.4	10.1
1997	8.6	10.4	10.4	10.9	10.4	8.0	6.0	4.6	4.1	5.0	7.4	9.3	7.9
1998	11.5	19.0	16.9	17.4	15.2	12.4	9.8	8.3	7.1	8.7	7.5	8.4	11.9
1999	10.9	9.3	13.8	15.5	10.4	7.9	6.7	6.1	5.8	5.4	7.2	10.5	9.1
2000	10.5	12.3	10.8	9.9	7.2	5.9	4.9	4.1	3.6	4.7	10.1	11.7	8.0
2001	19.3	15.1	13.4	12.4	11.8	7.7	7.0	5.7	7.1	9.6	9.9	7.2	10.5
2002	16.6	12.9	11.7	16.9	15.2	8.7	7.9	7.0	6.2	7.0	10.9	12.8	11.2
2003	14.4	9.5	11.8	12.1	14.4	9.8	7.5	6.7	7.1	9.7	7.8	9.3	10.0
2004	10.5	10.3	12.0	14.0	10.0	7.6	6.6	5.8	6.7	6.5	9.3	12.8	9.3
2005	12.5	11.2	10.9	10.2	11.6	7.9	6.4	5.8	5.7	5.9	6.6	7.3	8.5
Ave	13.0	12.5	12.8	13.4	11.5	8.3	6.8	6.0	6.1	6.9	8.5	9.8	9.6
St.dev	3.3	3.1	2.3	2.7	2.7	1.7	1.4	1.2	1.4	1.8	1.5	2.1	1.3
Cv	0.26	0.25	0.18	0.20	0.24	0.21	0.20	0.20	0.23	0.27	0.17	0.21	0.14
Run.(mm)	1.87	1.80	1.84	1.93	1.65	1.20	0.98	0.87	0.88	1.00	1.22	1.40	1.39

APPENDIX-II FIGURES

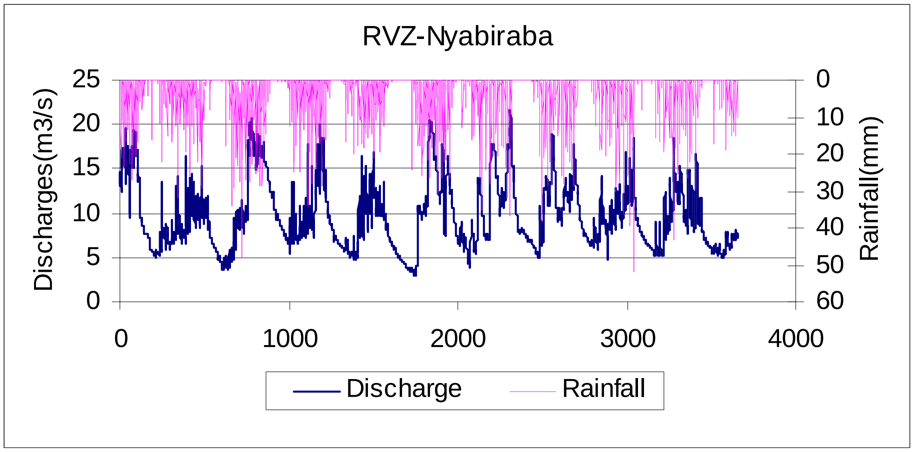
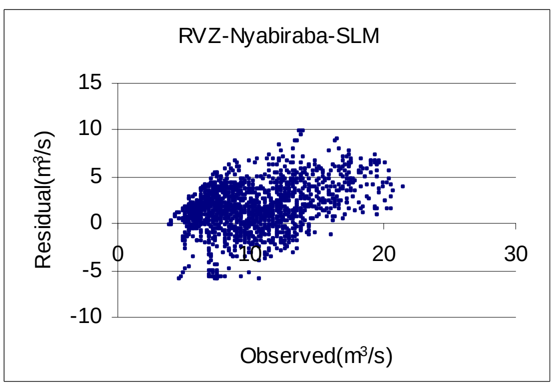
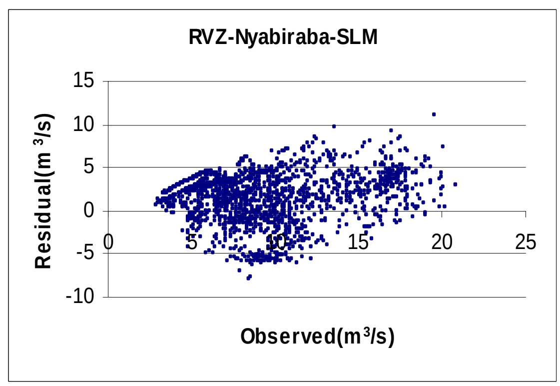
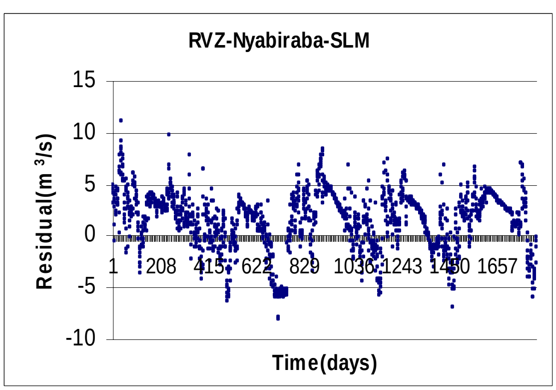


Figure 4.1 Rainfall (mm) and discharge (m^3/s) hydrograph of RVZ-Nyabiraba Catchment







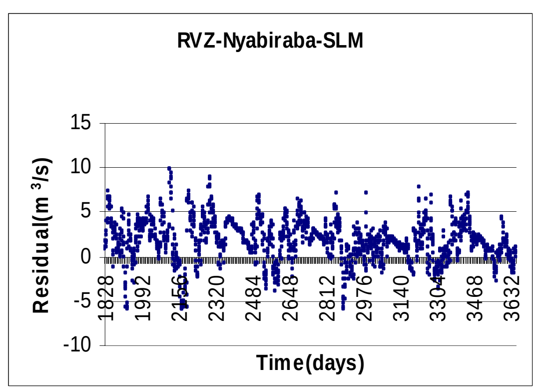


Figure 4.2 Scatter diagrams using SLM for calibration (left) and verification (right) period

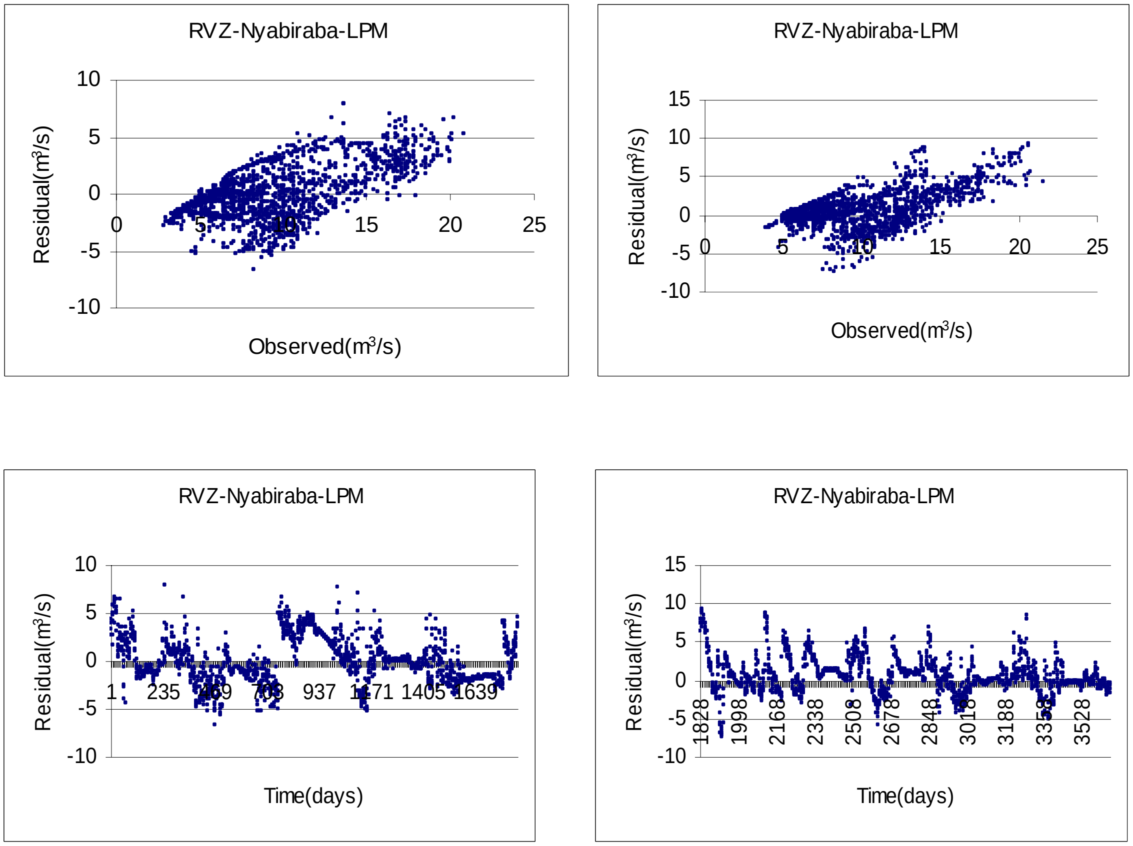
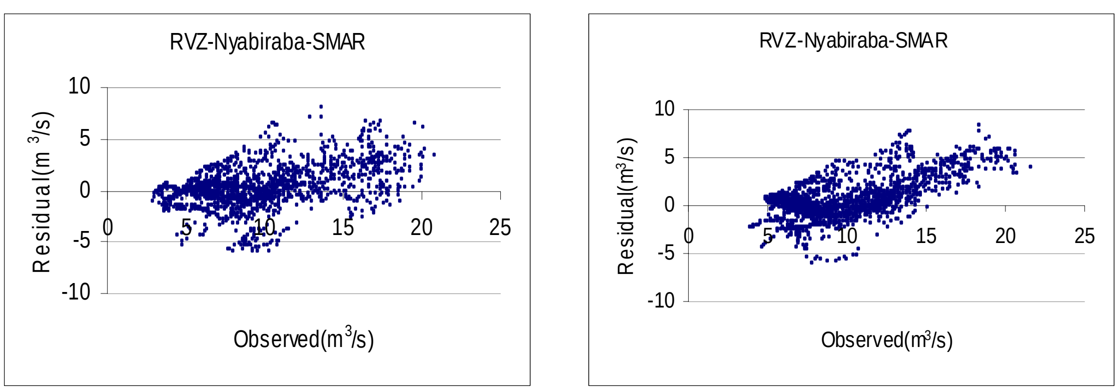


Figure 4.3 Scatter diagrams using LPM for calibration (left) and verification (right) period



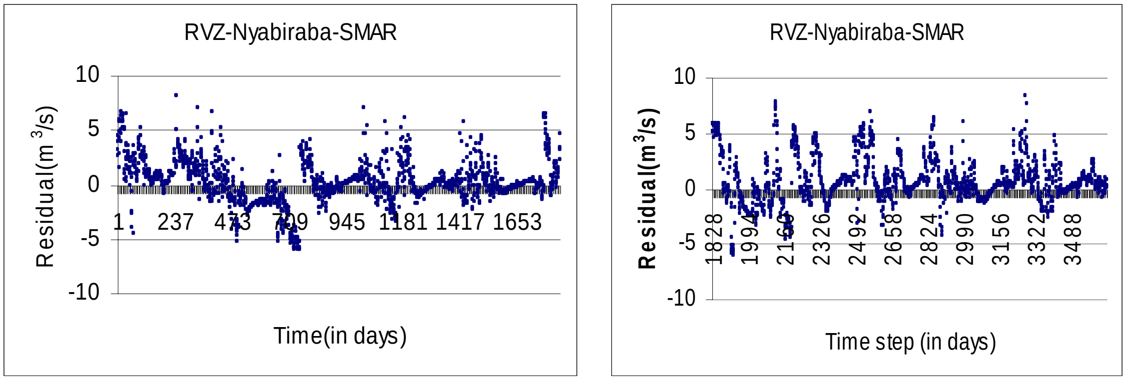


Figure 4.4 Scatter plots using SMAR model for calibration (left) and verification (right) period

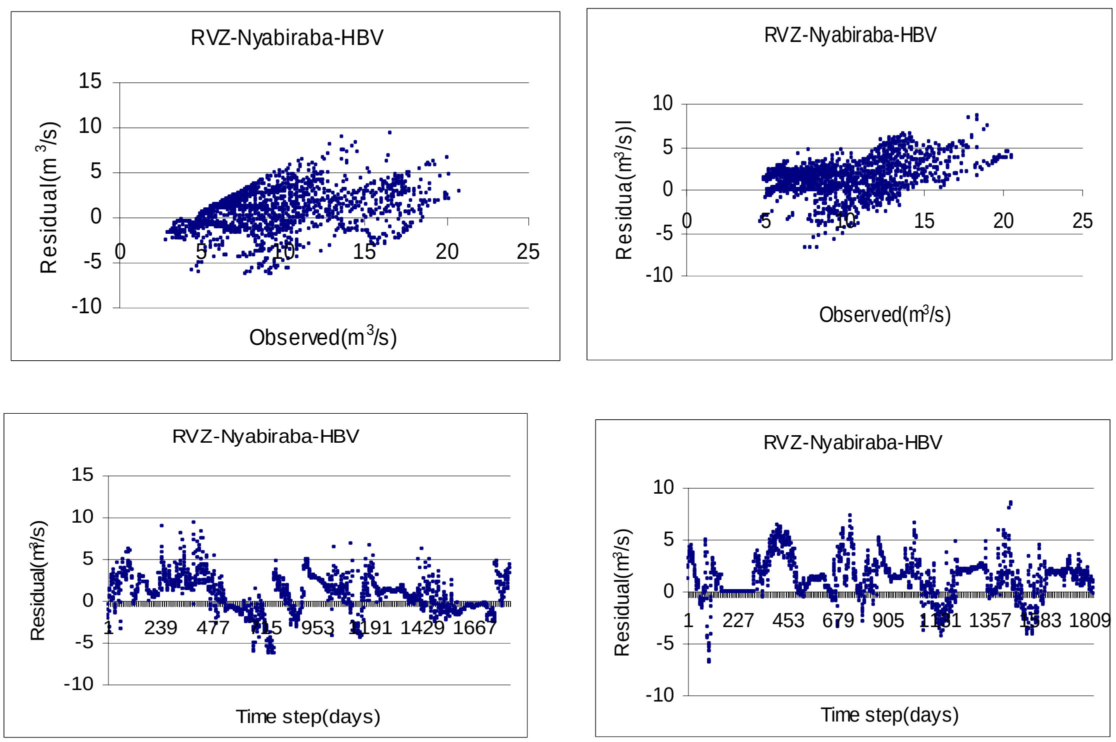


Figure 4.5 Scatter diagrams using HBV model for calibration (left) and verification (right) period for RVZ-Nyabiraba catchment

APPENDIX-III MODEL PARAMETERS

Table 4.1 Parameters of the SMAR model and their description

Starting parameter	Lower parameter	Upper limit	Symbols	Description
0.71	0	1	T	Potential evaporation conversion coefficient
0.41	0	1	H	Direct runoff separation coefficient
100	10	100	Y	Soil moisture infiltration rate(mm/time step
200	100	200	Z	Soil moisture storage capacity(mm)
0.75	0.5	1	C	Evaporation decay coefficient
0.75	0	1	G	Groundwater separation coefficient
1	1	10	N	Parameter n of Nash model
5	1	10	NK	Time lag parameter for Nash cascade routing
100	1	200	Kg	Time lag parameter for groundwater storage
0.75	0	1	F	Coefficient for loss to gain from groundwater reservoir
25			CAP	Soil moisture capacity depth of each layer(mm)

Initial conditions of the catchment		
QG(mms/T.S)	n warm(warm up periods)	m(memory length)
0	60	36

Parameters of the generic algorithm optimization						
NVAR	NPOP	NEVA	PM	CM	ISEED	

10	100	5000	0.001	2	-1	GA2 parameter

Parameters of Rosen Brock optimization for further turning					
1	0.00001	0.000001	5000	0	(If 'IOPRSB' = 0, then no Rosen. Opt.)
Parameters of Simplex Optimization for further turning					
IOPSMP	ATOL	TOLF	ITMXRS	IPRT	
1	0.00001	0.000001	5000	0	(If 'IOPSMP' = 0, then no Simplex Opt.)

Table 4.2 Free parameters in the HBV model

Name	Meaning	Value range	Default value	Units
T_x	Threshold temperature Rain/Snow	From -1.0-2.0	1	^oC
T_s	Threshold temperature for snowmelts	From -1.0-2.0	0	^oC
C_x	Degree-day factor	From 3.0-6.0	4	mm/^oC*Day
CFR	Re-freezing efficiency in snow	From 0.0-0.01	0.005	
PKORR	Precipitation correction Rainfall	From 1.05-1.2	1.05	
SKORR	Precipitation correction Snowfall	1.15-1.5	1.2	
TTGRAD	Temperature lapse rate for clear days	From -0.6 to -1.0	-1	^oC/100 m
TVGRAD	Temperature lapse rate during precipitation	From -0.4 to -0.6	-0.4	^oC/100 m
PGRAD	Precipitation lapse rate	From 1.0 to 1.10	1.05	
FC	Field capacity in soil moisture zone	From 75 to 300	150	mm
LP	Threshold value for potential evapotranspira-tion in soil moisture	70%-100%	100	% of FC
β	Parameter in soil moisture routine	From 1.0 to 4.0	2	
UZL	Threshold level for quick runoff in Upper zone	From 10 to 40	20	mm
KUZ1	Recession constant in Upper zone	From 0.1 to 0.5	0.3	1/day
KUZ2	Recession constant in Upper zone	From 0.05 to 0.15	0.1	1/day
PERC	Percolation from upper to Lower zone	From 0.5 to 1.0	0.6	mm/day
KLZ	Recession constant	From 0.0005 to 0.001	0.001	1/day