KYAMBOGO UNIVERSITY

FACULTY OF ENGINEERING

DEPARTMENT OF CIVIL AND BUILDING ENGINEERING

COMPARING PERFORMANCE OF DIFFERENT LUMPED CONCEPTUAL HYDROLOGICAL MODELS: A CASE STUDY OF RIVER KAFU CATCHMENT

BY

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A RESEARCH THESIS SUBMITTED TO KYAMBOGO UNIVERSITY GRADUATE SCHOOL IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF SCIENCE IN WATER AND SANITATION ENGINEERING OF KYAMBOGO UNIVERSITY

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DECLARATION

I, Amollo Carolyne Judith, hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree of the university or other institute of higher learning, except where due acknowledgement has been made in the text and reference list.

Name………………………………………………………………………………

Sign…………………………………………….....Date……………………………

APPROVAL

The undersigned certify that they have read and hereby recommend for acceptance by Kyambogo University a research thesis entitled “Comparing the Performance of Different Lumped Conceptual Hydrological Models: Case Study of River Kafu Catchment”, in fulfillment of the requirements for the award of a Master of Science in Water and Sanitation Engineering of Kyambogo University.

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LIST OF ABBREVIATIONS/ACRONYMS

AWBM:	Australian Water Balance Model
CPG:	Catchment Planning Guidelines
DHI:	Danish Hydraulic Institute
FAN – Stat:	Frequency Analyses considering Non – Stationarity
HBV:	Hydrologiska Byr˚ans Vattenavdelning
HMSV:	Hydrological Model Focusing on Sub Flows' Variation
IWRM:	Integrated Water Resource Management
MAB:	Model Average Bias
MWEJSR:	Ministry of Water and Environment Joint Sector review
NAM:	Nedbør-Afstrømnings Model
NSE:	Nash – Sutcliffe Efficiency
PDM:	Probability Distribution Model
PET:	Potential Evapotranspiration
POT:	Peak Over threshold
PRMS:	Precipitation Runoff Modeling System
RMSE:	Root Mean Squared Error
RRL:	Rainfall Runoff Library
SMAR:	Soil Moisture Accountability and Routing

T_{max}:	Maximum Temperature
T_{min}:	Minimum Temperature
UNWWDR:	United Nation Water Development Report
MAAIF	Ministry of Agriculture, Animal Industry and Fishery
NEMA	National Environmental Management Authority

ABSTRACT

Planning for water resources management can be supported by hydrological modeling. In a typical data scarce region, the compatibility of structures of various models with the limited data can greatly affect results of modeling. In this study, performance of six conceptual hydrological models was tested based on hydro-meteorological data from River Kafu catchment. These models included the Australian Water Balance Model (AWBM), SACRAMENTO, Soil Moisture Accounting and Routing (SMAR), TANK, SIMHYD, and Hydrological Model focusing on Sub-flows' Variation (HMSV). The models were calibrated and validated over the periods 1952-1961 and 1962-1981, respectively. HMSV was calibrated based on conventional and case-specific frameworks for which it was hereinafter denoted as HMSV (1) and HMSV (2), respectively. Optimal parameters of each model was obtained based on automatic calibration strategy with performance assessed under both moderate and extreme hydrological conditions. Considering the full time series, the NSE values for AWBM, HMSV (1), SACRAMENTO, SIMHYD, SMAR, TANK and HMSV (2) were 0.70, 0.67, 0.35, 0.56, 0.41, 0.14, 0.53 respectively. It was found that each model performed better for high flow than low flow. Among these models, HMSV has a particular calibration framework to capture extreme hydrological conditions. To test this framework, case-specific calibration of the HMSV to capture, say, high flow or low flow, performance for extreme hydrological conditions were noted to be highly enhanced. This meant that calibration of models could be done based on a particular purpose of a study, for instance, planning of risk-based applications such as floods or drought. Under moderate hydrological conditions, the best and worst model was AWBM and SAC, respectively. For high and low flow conditions, the best model

under conventional calibration was HMSV (2) and worse was SAC. This study showed that the selection of a model under data scarcity depends on the purpose for which the modeling exercise is to be done.

Keywords: Rainfall-runoff model, Hydrological extremes, high flows, low flows

CHAPTER ONE: INTRODUCTION

1.1 Background

Due to the changing climate, many locations of the world especially those in arid environments are faced with the challenge of water insecurity. This affects various aspects of water resources management something which requires careful planning. The global demand and competition for water has continuously grown at a rate of about 1% yearly as a function of population, all this came as a result of developing world - grappling with poverty, growing population, increasing urbanization and industrialization and this has increased the need for information, assessment and monitoring of global water resources (UNWWDR, 2018).

Global Water Partnership (2005) proposed the Integrated Water Resources Management (IWRM) as a concept that can be used to optimize water resources management when accomplished within a spatial unit called a catchment. Within the framework of the Integrated Water Resources Management, modeling can be used to understand the hydrological functioning of a catchment with possible analyses of scenarios related to planning and operation of water resources management applications. Some of these applications involve reservoir operation, irrigation, hydropower generation and ecological management practices.

For hydrological modeling, both physically or process-based and conceptual lumped models exist Physical models consider the use of several parameters, multiple input data and treat the catchment as independent cells thus complicating calibration and analyses. A conceptual model on the other hands requires few input data and further treat the catchment as a single unit and simpler in their structure to use and are mostly designed to simulate lumped runoff especially at the catchment exit. Conceptual models have been mostly used in several studies (Onyutha, 2016; Tegegne et al., 2017; Clanor, et al., 2015), in modelling the hydrological behavior of various catchments. Examples of the rainfall runoff models used were Hydrologiska Byr˚ans Vattenavdelning (Berstrom and Forsman, 1973; Bergstrom, 1995), Nedbør-Afstrømnings Model (NAM) (Nielsen and Hansen, 1973; Havno et al., 1995); Danish Hydraulic Institute DHI, (1964), Hydrological Model focusing on sub flows variation (HMSV), (Onyutha, 2019), Australian Water Balance Model (AWBM) (Boughton, 2004), TANK model (Sugawara and Funiyuki, 1956), Sacramento model (Burnash, et al., 1973), All these models performed differently under various hydro-meteorological conditions and thus calls for more study to ascertain their suitability in a data scarce catchment.

An important note is that, data availability does not only limit calibration, but also contributes to uncertainty in the entire rainfall-runoff generation process. Lack of data that exist due to short historical and spatially insufficient observations fully affects application of hydrological models (Grayson et al., 2002). In addition, data limitation is a serious drawback to scientific study in hydrological processes especially in Sub-Sahara Africa in which Uganda is located and this is because investment in data collection and monitoring is limited.

The aim of this study was to evaluate the suitability of lumped conceptual models in a data scarce catchment. Data scarcity or limited data simply means weather stations are far apart, not evenly distributed, stations are not continuously operational thus, data are characterized by gaps of missing records. Access to data was also very limited as a researcher was meant to pay to acquire data for the research study.

In a bid to understand the catchment characteristic of River Kafu, a study was conducted considering the entire catchment with aim of having comprehensive information that could further guide the water resources management in making decision concerning the catchment in the near future like, flood warning and mitigation, adaptation to climate change impacts on hydrology and land use impacts among others. Six models; HMSV, SIMHYD, SACRAMENTO, AWBM, TANK and SMAR were applied and using their different structures, various parameters were set and calibrated before coming up with models best suited for extreme conditions of the study area. Important to note is the uniqueness of the HMSV in capturing the extreme condition in its re calibration framework which no other models among the six can do. HMSV in this study considered calibration in its two fold as conventional and framework denoted as HMSV (1) and HMSV (2) respectively.

1.2 Statement of the problem

River Kafu catchment is primarily a range land supporting vast herds of livestock especially in the dry season. In addition, it provides water for other domestic purposes and major economic activities like fishing and agriculture. The catchment has been affected by the potential impacts of climate change and variability. Furthermore, the catchment also experiences alteration due to the natural or anthropogenic activities and is continuously being faced with water scarcity, deteriorating water quality, floods and droughts, issues which are all negatively impacting Uganda's quest for economic and social development.

Different Models have different structures and variations in concept of different models leads to different equations which have implication on the compatibility of the model structure to a given data. For a data scarce regions like Uganda, it is important that before any model is applied to a catchment, comparison needs to be done in order to be able to choose the right model for the intended purpose.

The 2005 Water Sector Reform Study and the 2006 Joint Sector Review (JSR) both recommended the implementation of the Integrated Water Resource Management at catchment level and this is reflected under the Catchment Planning Guidelines (CPG 2014) and this study will contribute to the good management of the water resources.

It is also key to note that due to lack of hydrological study within Kafu catchment, many challenges affecting the catchment in relation to catchment management and further decision making by the different ministries (MWE, MAAIF, NEMA etc) continued to exist. For example, the flooding that has been happening within the catchment leading to submerging of bridges and displacement of people shall continue to exist if no study is undertaken to help in decision making such as having the catchment reclaiming its vegetation cover, tree planting among others. Having this study done shall greatly improve ways of working within the different ministries.

1.3 Objectives of the study

1.3.1 Main objective

The overall objective of the study was to compare the performance of different lumped conceptual hydrological models in simulation of hydrological conditions of River Kafu catchment.

1.3.2 Specific objectives

a) To apply selected models (SMAR, TANK, SACRAMENTO, SIMHYD, HMSV and AWBM) as lumped conceptual hydrological models to River Kafu catchment.

b) To generate the daily catchment runoffs using the selected models with respect to moderate and extreme hydrological conditions.

c) To determine the best model that can be used as a tool to support River Kafu catchment risk-based management plan.

d) To use output of the best model for extreme value analyses

1.4 Research Questions

a) Can the various lumped conceptual models be applied in simulation of run off at River Kafu Catchment?

b) Can the various models adequately reproduce flow variability in respect to both moderate and extreme conditions?

c) Which Hydrological Model performed best under moderate and extreme conditions

d) Can the output of the selected models be reliable for extreme value analysis?

1.5 Research Justification

Lumped conceptual models are preferred as compared to fully distributed models when hydrological models are considered. Taking into account East Africa where this study is undertaken from, there were several lumped conceptual models that were applied in several studies (Ebrahim et al. 2013; Easton et al. 2010; Legesse et al. 2003; Betrie et al. 2011; Bitew and Gebremichael 2011). The results from the studies revealed they all applied a single hydrological models. According to Onyutha (2016), large bias in reproducing observed extreme hydrological events can be reached by choice and use of particular models among others. It is only through the use of several models that can help in reducing such possible bias required to support decisions related to management of water resource applications.

At the time this project commences, there were no studies in relation to hydrological models in respect to variation of flow of River Kafu catchment conducted and tailored towards hydrological extremes. The purpose of this study conducted between January 2019 and April 2020 at Kyambogo University, Kampala, Uganda was to compare the performance of several lumped conceptual models in the simulation of daily River Kafu flow. The study was conducted while taking into account how the six models could capture flow variations and frequency of the observed hydrological extremes within the study periods. The performance of models places them in their different ranks on how suitable they can be useful for proper management of the catchment.

1.6 Significance/Importance of the Study

Comparison of performance of different lumped conceptual hydrological models in River Kafu catchment was conducted in both moderate and extreme conditions. The result from the study can be used for proper management of the Catchment by the different ministries (MWE, MAAIF, NEMA). This will then bring out the component of proper planning and management in terms of water management applications such as Reservoirs operations, hydro power generation, irrigation, Bridges, etc. Knowing that the catchment is dominated by agriculturalist and pastoralist, the study can as well be used for predictive planning and advising MAAIF on the zones within the catchment that can be used for either irrigation or bound from irrigation. For the NEMA, the study can help in reclaiming the vegetation within the catchment by planting more trees. Given that no hydrological study was conducted in River Kafu catchment before, this study shall act as a baseline information for any future research that shall be undertaken within the catchment especially when effect of land use modelling is undertaken.

1.7 Conceptual Framework

The study looked at simulation of river flow upon application of six different models under moderate and extreme conditions (Dependent Variables). The simulated river flow is a component that is derived upon interactions of climatic variables – Rainfall and evapotranspiration (Independent variables). However, there are factors that indirectly influence the climatic variables such as temperature and land cover (Moderating variables) and can greatly impact on the simulated flows at any point within the catchment. The simulated flows can further be use for proper management of the catchment and this benefits the different ministries (MWE, MAAIF, NEMA). Taking into consideration the catchment policy guidelines also influence the hydrological characteristics of the catchment.

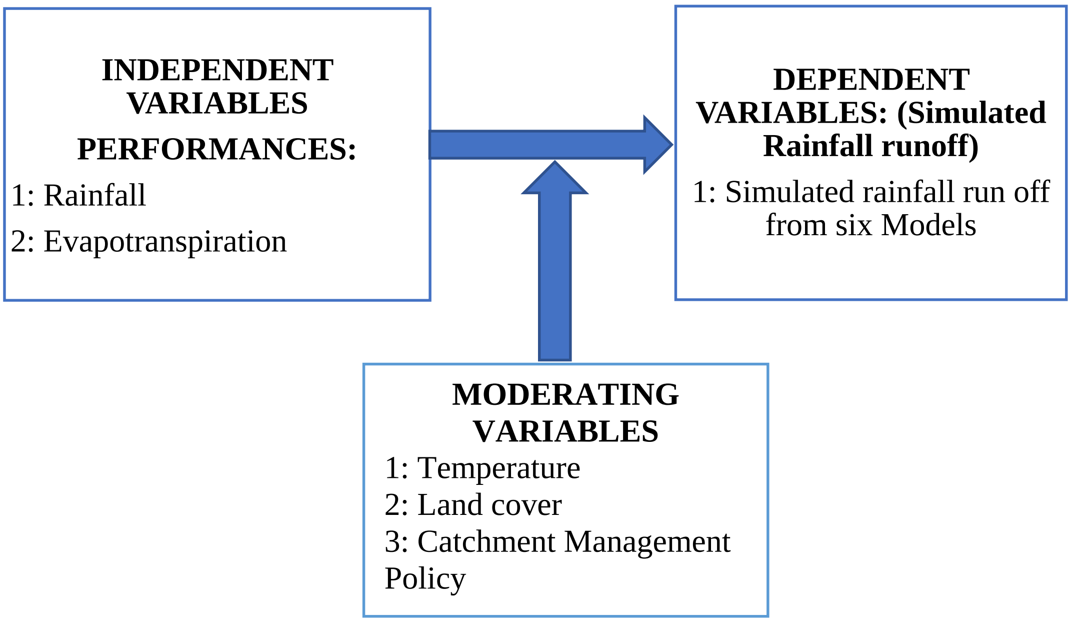


Figure 1. 1 Conceptual Framework

1.8 Chapter Summary

This chapter looked at the problem faced by Kafu Catchment and how best the problem can be solved through application of the different models to further help in decision making by the different ministry body (MWE, MAAIF, NEMA). It furthers explained the practical application of the models deployed in the study with the current life context.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

Computer based lumped conceptual rainfall runoff models have been widely applied in hydrological modelling since they were first introduced in the late 1960s and early 1970s. The common examples of the models which are being used are; Sacramento model (Bergstrom et al., 1973), the HBV model (Berstrom and Forsman, 1973; Bergstrom, 1995), and NAM model (Nielsen and Hansen, 1973; Havno et al., 1995). Models are computer programs consisting of sets of interlinked equations to permit the representation of a real world in a simplified form. Rainfall runoff models are useful in areas like infilling river flow data gaps, prediction of future events, and ungauged catchments.

However, the investigation of the rainfall runoff processes especially in the absence of data or /and presence of limited data was speeded up in the 1960’s by the growth in the speed and capacity of the digital computing equipment. Further, hydrological models are used for research purposes in enhancement of knowledge about hydrological systems (Beven, 2001).

2.2 Hydrological modeling

Hydrological models are simplified, conceptual representations of a part of the hydrological, or water cycle. They are primarily used for hydrological prediction and for understanding hydrological processes. The best model is the one which gives results close to reality with the use of least parameters and model complexity. A model consists of various parameters that are used in defining the characteristics of the model. A runoff model can be defined as a set of equations that helps in the estimation of runoff as a function of various parameters used for describing watershed characteristics. The most important inputs used for hydrological models are meteorological data (Rainfall, temperature, Evaporation, sun shine) and Hydrological data or watershed characteristics like soil properties, vegetation cover, watershed topography, soil moisture content, characteristics of groundwater aquifer are also considered. Hydrological models are very much considered as an important and necessary tool for water and environment resource management that needs to be undertaken for all the streams, rivers, lakes and many others.

A parsimonious modeling approach has been proposed to model dominant hydrological processes in data scarce regions in past studies (Pande et al., 2012). In addition, various investigations were conducted on distributed and lumped hydrologic models (Boyle et al., 2001; Koren et al., 2004; Krajewski et al., 1991; Carpenter and Georgakakos, 2006; Reed et al., 2004; Refsgaard, 1997; Shah et al., 1996; Smith et al., 2004; Refsgaard and Knudsen, 1996; Zhang et al., 2004).

2.3 Types of Rainfall runoff models

Rainfall-runoff models are best classified according to input and parameters required by the model and extend to which is applied. It can be classified as a lumped and distributed model based on the model parameters which have a function of space and time. In lumped models, the entire catchment or river basin is taken as a single unit with averaged input considered hence outputs generated without considering the spatial processes while a distributed model makes predictions that are distributed by dividing the entire catchment in to small cell, usually square cells or triangulated irregular network, with parameters, inputs and outputs varying spatially. Secondly it can further be classified as deterministic and stochastic models based on the other criteria and assumptions deployed. Deterministic models give the same output for a single set of input values while in stochastic models, different values of output are produced for a single set of inputs.

Another classification is static and dynamic models based on time factor. Static models exclude time while dynamic models include time.

The most important and commonly used classifications are empirical models, conceptual models and physically based models.

2.3.1 Conceptual models

A conceptual model describes hydrological processes and looks at actual representation of the catchment putting in consideration the parameters and contributing factors. Semi empirical equations are used in conceptual models and the model parameters are assessed not only from field data but also through calibration. Many conceptual models have been developed in different studies with varying assumptions and considerations.

2.3.2 Physically-based model

This model represents hydrological systems using physical laws that have been obtained using the scientific method. In other words, it is the mathematical representation of real phenomena which works majorly with mathematical relationships. It uses variables which are measurable and are functions of both time and space. The hydrological processes of water movement are represented by finite differential equations. It does not require extensive hydrological and meteorological data for their calibration but the evaluation of a large number of parameters describing the physical characteristics of the catchment are required (Abbott et al., 1986a; 1986b). In this method, huge amounts of data such as soil moisture content, initial water depth, topography, topology, dimensions of river network and many others are required. It can provide a large amount of information even outside the boundary and can be applied for a wide range of situations, MIKE SHE model is an example (Abbott et al., 1986a; 1986b).

2.4 Hydrological model selection

Model selection is a very important aspect to be taken by researchers. Key to note is, not all models are suitable for application in all range of hydrological conditions and characteristics. The aim of the study/modeling, timeline required to apply the model, the level of accuracy basing on the previous studies and above all the outcome of the study will greatly contribute to model selection. In order to achieve the intended objective of the model, the selection stage is very vital. Beven (2001) proposes several procedures to be followed during model selection and these include; reliability based on time and money, intended output of the project, assumptions and limitations, and availability of the model inputs.

This study was able to deploy five internationally well-known models (AWBM, TANK, SAC, SIMHYD and SMAR) with the newly introduced model HMSV. The first five models used were picked from eWater toolkit of the cooperative Research Centre for catchment Hydrology in Australia via link http://www.toolkit.net.au/ (accessed: 28th April, 2019). The details of these models can be obtained from Rainfall Runoff Library RRL (Podger, 2004).

The newly introduced model HMSV published by Onyutha (2019) was obtained online via link https://sites.google.com/site/conyutha/tools-to-download (accessed: 8th May 2019). All the applied models were selected because they are freely available online, easy to learn and apply, applicable mostly in modeling runoff in a lumped conceptual way which is directly linked to the project title and the objective, availability of the input parameters and the past studies done by different researchers.

A model transforms inputs into outputs, though it requires the modeler to have a clear understanding of classification of models. Categorization of models is important in applying the specific models to specific uses. For example, if the goal is to create a model for predicting runoff from un-gauge watersheds, parametric models that require unavailable data for parameter estimation are not recommended. Understanding runoff generation has a significant role in catchment hydrology. Some of the tasks envisioned for rainfall runoff models are of a purely hydrological nature, such as real time flood forecasting, design flood estimation, and assessment of the reliability of natural water resources. However, increasingly, outputs of hydrological models are used to investigate wider environmental problems. These include water quality issues in surface and groundwater, ecological studies and providing boundary conditions for models dealing with atmospheric general circulation.

2.5 Review of the hydrological models for the study

The study considered the use of six conceptual hydrological models using the same river catchment data set. The models deployed were SMAR, HMSV, SACRAMENTO, SIMHYD, TANK and AWBM. Each model performed differently based on their structures as discussed under this chapter.

2.5.1 Hydrological model focusing on sub-flows' variation – HMSV

This is a recently introduced hydrological model focusing on the separation of flows into sub flows. The Model splits the runoff flows into base flow (Q_{bf}), inter flow (Q_{if}) and over land flow (Q_{of}). The input parameters are Potential Evapotranspiration (E_{Pet}), River flow (Q) and precipitation (P). The model focuses on realizing excess runoff after the evapotranspiration needs and soil moisture threshold absorption needs are met. The output of the HMSV is the total simulated runoff (Q_{sim}) from the three different sub flows. HMSV has a calibration strategy in two fold as conventional and framework. For the purpose of this study, the conventional and framework was denoted as HMSV (1) and HMSV (2) respectively. The HMSV (1) in its conventional approach deployed the same approach during calibration just like other five traditional models in this study. The calibration is done basing on the overall water balance without focus to extreme conditions. On the other hand, HMSV (2) has a calibration strategy tailored in capturing the extremes conditions. The mismatch between high flows and low flows are deduced iteratively as detailed by Onyutha (2019).

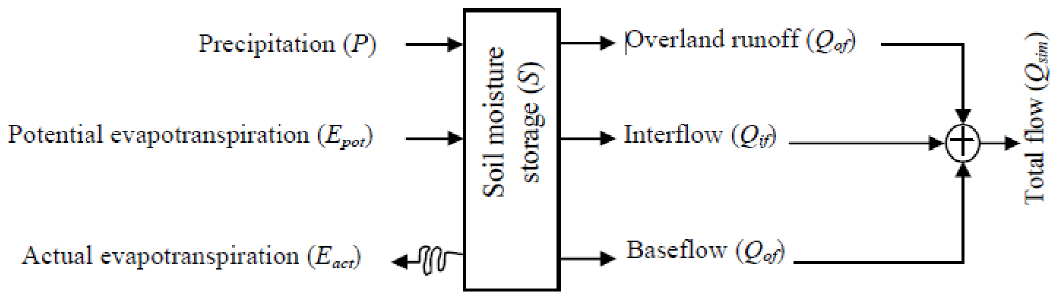


Figure 2. 1 The HMSV (Source: Onyutha, 2019)

2.5.2 Australian Water Balance Model - AWBM

This application of model is deployed at catchment to calculate runoff from rainfall on daily and hourly time increments. The daily time session is used to determine the water yield and water management studies whereas the hourly time session helps in design of flood estimation. An important feature of the AWBM is the development of model-specific calibration procedures which is based on the model structure, including a graphical analysis of rainfall and runoff data, multiple linear regression and an automatic self-calibrating procedure.

2.5.2.1 The structure of Australian Water Balance Model

The AWBM for the catchment water balance takes rainfall to three surface water stores based on their moisture contents. Each surface water store is considered independently of the others. Evaporation is subtracted from each of the stores. The moisture in excess of the storage capacity becomes either the surface runoff or recharge into the groundwater. The base flow and the surface runoff are routed separately and later combined into the total flow at the outlet of the catchment.

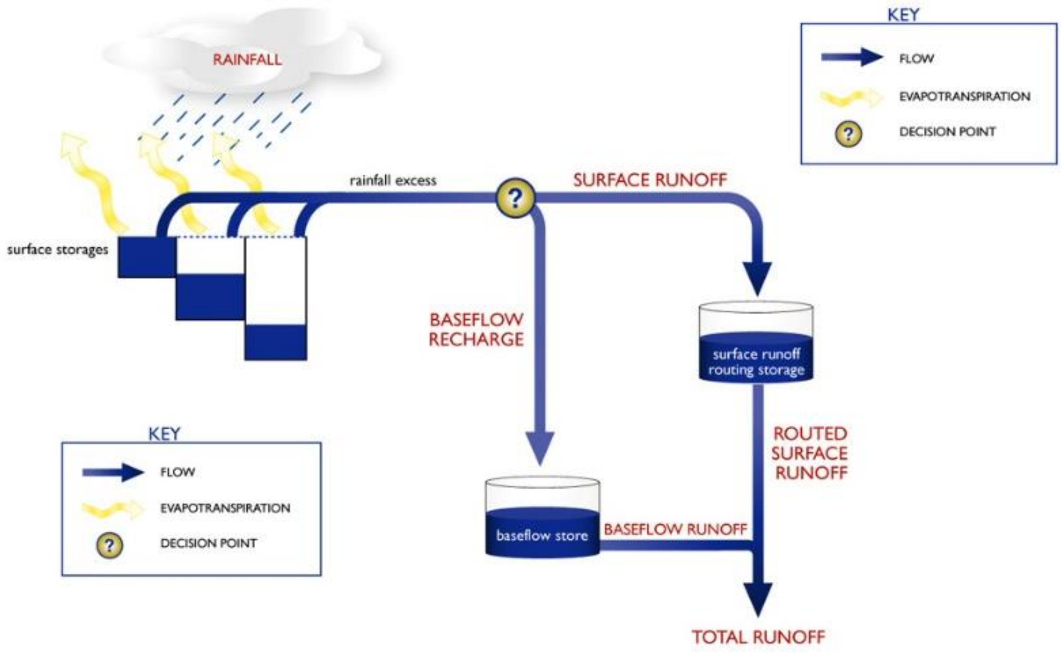


Figure 2. 2 The AWBM (Source: Podger, 2004)

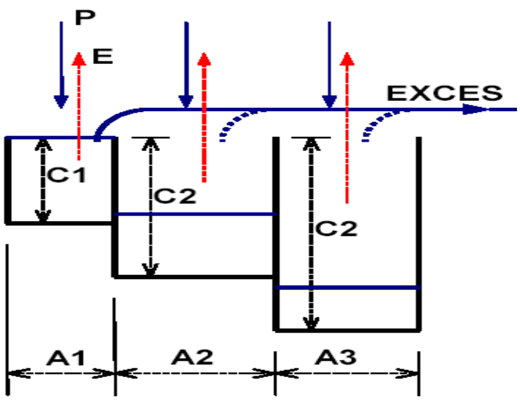


Figure 2. 3 Illustration of surface water storage for the AWBM (Source: Podger, 2004)

2.5.3 Tank

This model was developed in Japan and was among the successful models applied to many river basins in Africa, Asia, Europe and the United States. It’s a conceptual rainfall runoff model developed by Sugawara and Funiyuki (1956) and consists of a set of linear storages in series or parallel with sides and bottom outlets leading to subsequent tanks connected together. It has demonstrated satisfactory performance in depicting characteristics and vertical and horizontal groundwater movement for watershed, sub watershed and wet rice field (Setiawan et al., 2003). The TANK Model is designed with ease and uses simple software that can model water distribution in different four categories such as run off, subsurface flow intermediate flow, sub base flow and base flow, vertical water flow distribution of every watershed layer hence horizontal and vertical distribution can be well modeled (Sugawara and Funiyuki 1956)

2.5.3.1 Structure of Tank

The TANK model has four tanks arranged vertically in series. The rainfall is fed into the top tank. The rainfall is lost by evaporation from the top tank downwards in a sequential way. The outlets at the sides of the tanks generate different components of the total runoff, that is, surface runoff, intermediate runoff, subbase runoff, and base flow from the first through to the fourth tank, respectively.

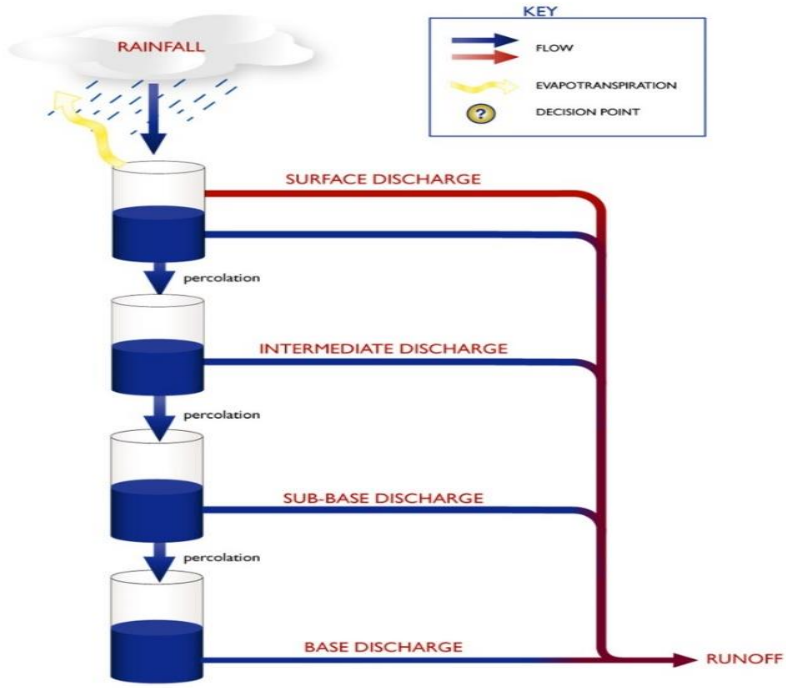


Figure 2. 4 The TANK (Source: Podger, 2004)

2.5.4 Soil moisture accounting and routing - SMAR

Soil Moisture Accounting and Routing (SMAR) model is one of the common model deployed in the hydrological modeling of the catchment. It's a lumped conceptual model introduced by (Connell et al., 1970). The model works in two splited mode with Soil Moisture Accounting component being responsible in having the continuity equation catered for as time moves on. In other words, the ability to have all the input parameters works concurrently without compromising the effectiveness of one another including the changes in the soil moisture storage. The routing part handles the runoff component through simulation effect of the catchment. In addition, the two generated runoff (surface runoff and groundwater runoff) are treated as the total simulated discharge from the model. SMAR has got nine parameters that control the entire routing component.

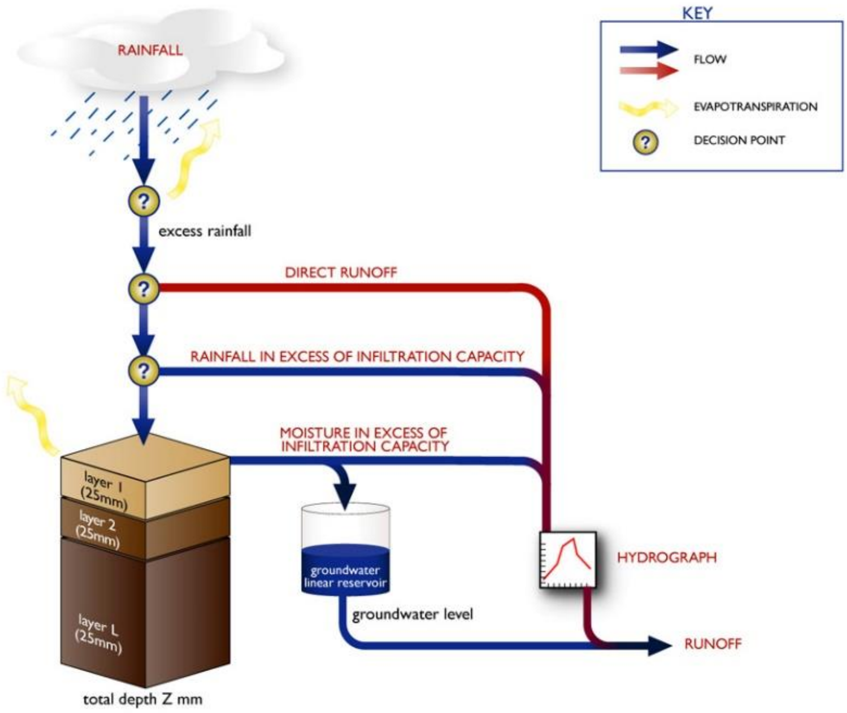


Figure 2. 5 The SMAR (Source: Podger, 2004)

2.5.5 Sacramento

This model demonstrates how moisture distribution in a physically realistic manner within hypothetical zones of soil columns is presented. The model works in a way that percolation characteristics are maintained to simulate the streamflow conditions from the catchment under study. The key components are tension water, free water, surface flow, lateral drainage, Evapotranspiration and vertical drainage.

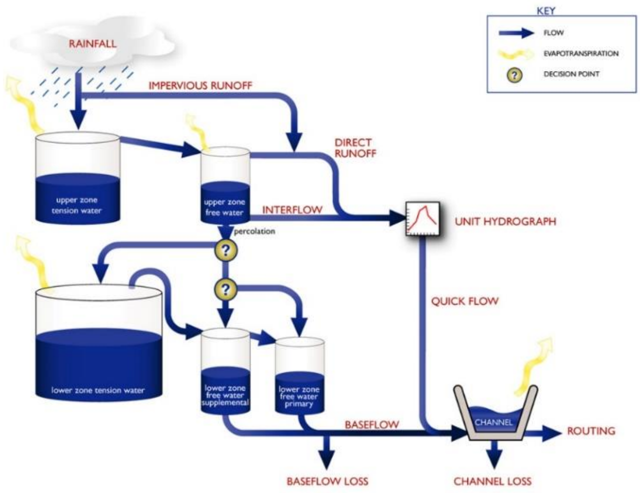


Figure 2. 6 The SACRAMENTO (Source: Podger, 2004)

2.5.6 SIMHYD – Simplified form as HYDROLOG

This is a simplified version of the daily conceptual rainfall runoff model known as HYDROLOG and was developed in 1972 (Porter, 1972; Porter and McMahon,1975) and the MODHYDROLOG (Chiew and McMahon, 1991). It is one of the conceptual rainfall runoff models that deals with estimation of daily rainfall data and that of real potential evapotranspiration. The model has seven parameters as will be discussed in chapter three of the study. In this model, the daily rainfall fills the interception store which gets emptied every day through evaporation while the excess rain articulates to an infiltration function which later determines the infiltration capacity and further has excess that exceeds the infiltration capacity as infiltration excess runoff. The infiltrated moisture component subjected to soil moisture function is responsible for diverting water to stream (interflow), groundwater store (recharge) and soil moisture store.

Interflow is estimated as the linear function of the soil wetness (soil moisture level divided by soil moisture capacity) and ground water recharge is estimated as the linear function of the soil wetness with remaining moisture flowing to the soil moisture store. It is also noted that evaporation from the soil moisture store is estimated as a linear function of the soil wetness and cannot exceed the atmospheric controlled rate of real potential evapotranspiration. SIMHYD estimates runoff generated from infiltration, excess runoff, interflow and base flow.

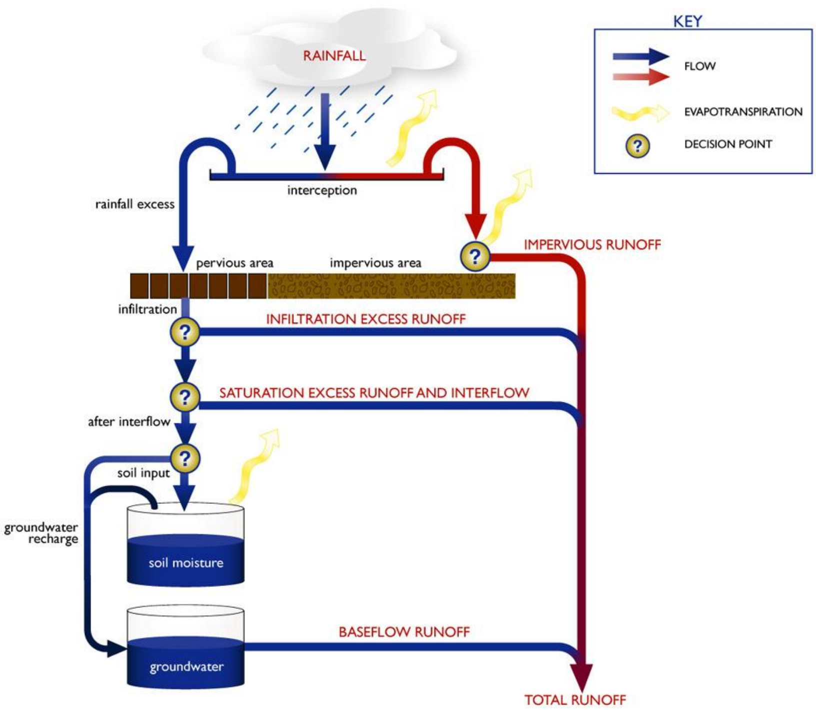


Figure 2. 7 The SIMHYD (Source: Podger, 2004)

2.6 Chapter Summary

The chapter described the current literature related to models in the different catchment within the world. It also looked at the model classification with more focus on conceptual hydrological models. The selected models for the study was fully described in terms of its structure. Gaps identified in the literature was linked to the model structure in relation to calibration strategy where all the five international well known models obtained from Rainfall Runoff Library (RRL) of the “eWater Toolkit,” only most deployed in overall water balance. However, the HMSV newly introduced by Onyutha (2019) was noted in its literature to have a calibration strategy tailored towards capturing the extreme conditions which none of the other models described talked of. Future model structures needs to be revised to be able to handle calibration strategy in twofold just like HMSV

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Introduction:

This chapter covers the methods and tools deployed for the study. The methods looked at the application of the different six models deployed in capturing the flow variability both in moderate and extreme conditions. The extreme conditions were analyzed in terms of return periods considering the study periods of thirty (30) years.

3.2 Research Design:

The research was based on the secondary data sets (Rainfall and River flows) and was collected from the meteorological and water resources departments respectively. Experimental data sets (Temperatures from PGF) were downloaded online via the link http://hydrology.princeton.edu/data/pgf/0.5deg (accessed 12 May 2019). The data were used for modelling the catchment using the different six models applied. Figure 3.1 shows the research design followed by the study.

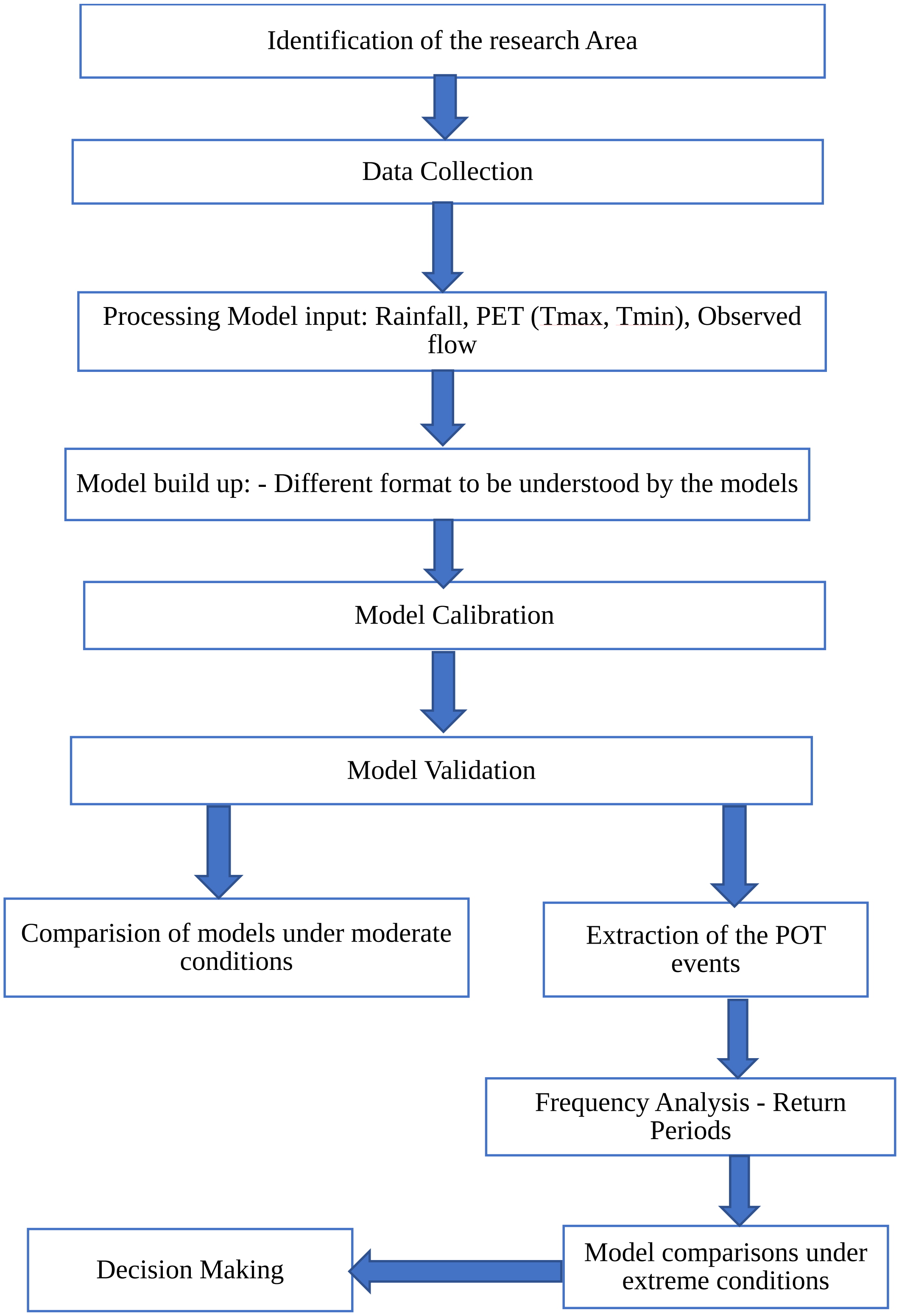


Figure 3. 1 Research design

3.3 Research approach:

A quantitative research approach was adopted for the study. Climatic variables were used to obtain the simulated flows in both moderate and extreme conditions. Comparison of how the different conceptual hydrological models performed in flow variability was assessed. All the findings were used to come up with model performance evaluation.

3.4 The study area

The catchment of River Kafu is located in western part of Uganda and falls within the Albertine region. River Kafu has a catchment area of 15,983 km^2 which extends longitudinally from 31°10' E to 32°41' E and between 0°11' N and 1°56' N in the North South direction. The catchment of River Kafu is in the western part of Uganda and comprises areas from a number of districts including Hoima, Kibale, Kyankwanzi, Luwero, Masindi, Nakasongola and Nakaseke. River Nkusi passes via the swamp from which River Kafu emanates. River Kafu has two tributaries including River Mayanja and River Lugogo. River Kafu empties into the Victoria Nile at the location with longitude = 32.095 and latitude = 1.647. River Kafu catchment is surrounded by a number of lakes including Kyoga, Victoria, Albert, Wamala, Edward, and George. There are also a number of mountains in between which River Kafu catchment is located including Rwenzori, Elgon, and Moroto. Figure 3.2 comprises the Digital Elevation Model (DEM) as the background map. The hole-filled DEM derived from the USGS/NASA (Jarvis et al. 2008) and processed by the International Centre for Tropical Agriculture (CIAT-CSI-SRTM) using interpolation methods described by Reuter et al. (2007) was downloaded online via the link http://srtm.csi.cgiar.org (accessed 03 December 2019). It is noticeable that the altitude is higher in the southern than northern part of the catchment.

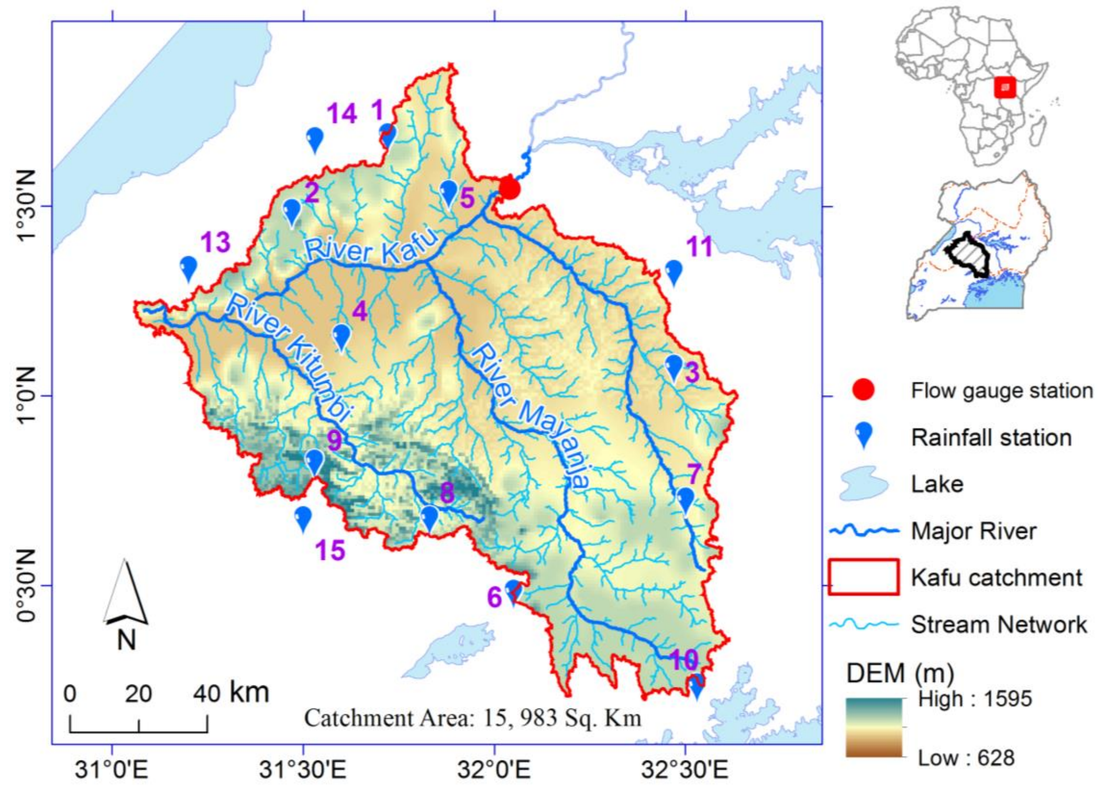


Figure 3. 2 Delineated map showing Kafu Catchment.

3.5 Criteria of Research area selection

The research area was selected based on two major concerns. By the time the study was proposed to be undertaken, no hydrological research was conducted within the catchment. Secondly, River Kafu catchment experiences a bimodal rainfall pattern with March-April-May and September-October-November (SON) rainy seasons. Rainfall of large intensities tends to occur during the SON season. Due to the increasing rainfall, there are a number of bridges on River Kafu which have recently been often submerged by the flooding water thereby hampering movement of vehicles.

Several homes and agricultural fields have also been inundated thereby leading to loss of property and displacements of large number of local population in the River Kafu catchment

3.6 Research Data

Model inputs including temperature, rainfall, and river flow were obtained from various sources as described next.

3.6.1 River flow

Daily River Kafu flow data observed at the main hydrological station (with station ID 83213) along Gulu-Kampala highway (32.04°N; 1.55°E: 1035meters above sea level) just before it pours into Kyoga basin. The river flow data from 1952–1981were collected from the Ministry of Water and Environment under the Department of Water Resources Management. Hydrological data after 1981 was characterized by large blocks of missing records and therefore not considered for modeling. Another reason why the data after 1981 was not considered was because the rainfall data had significant missing records which would not support a careful hydrological modeling as undertaken in this study.

3.6.2 Rainfall

Daily rainfall data from a number of gauge stations were collected from the Uganda National Meteorological Authority in Uganda. Daily data were obtained from a total of thirty-four rainfall stations. However, only 15 stations (see Table 3.1) within and around the catchment were considered for rainfall-runoff modeling. The data from these selected rainfall stations covered the period 1952-1981. The 15 stations with their locations shown in Figure 3.2 were selected because their percentages of missing records were less than 25%. The missing data records were in-filled using the inverse distance weighted interpolation technique.

Table 3. 1 Location of selected Rainfall stations

SNo	Latitude (°)	Longitude (°)	Station ID	Description	Missing record (%)
1	1.68	31.72	88310030	Masindi Met.	5.2
2	1.48	31.47	88310060	Bulindi	2.7
3	1.07	32.47	88310180	Kakoge Gombola	2.4
4	1.15	31.6	88310190	Butembe	16.4
5	1.53	31.88	88310280	Namyekudo	21.6
6	0.477	32.05	89320610	Bakijulula	4.1
7	0.72	32.5	89320010	Bukalasa Agric.	13.2
8	0.67	31.83	89310100	Bukuya Gombolola	15.8
9	0.82	31.53	89310210	Buta – Mubende	8.9
10	0.23	32.53	89320760	Kajjansi Fish Farm	10.8
11	1.32	32.47	88310020	Nakasongola	17.5
12	1.23	30.82	88310020	Kyangwali	20.8
13	1.33	31.2	88310170	Kiziranfumbi	22.8
14	1.67	31.53	88310240	Nyabyeya	1.6
15	0.67	31.5	89310200	Namungo	14.1

3.6.3 Temperature

To compute Potential Evapotranspiration (PET) required for hydrological modeling, the minimum (T_{min}) and maximum (T_{max}) temperature were required. Due to unavailability of observed temperature data for the study area, freely available daily data (T_{min} and T_{max}) of the Princeton Global Forcing (PGF) were downloaded from internet link http://hydrology.princeton.edu/data/pgf/0.5deg (accessed: 12th/5/2019). Although the PGF data runs from 1948 to 2008, the T_{min} and T_{max} over the period 1951-1981 as that for river flow were used to compute daily PET.

3.6.4 Computation of PET

The daily time step series PET was computed using Hargreaves formula (Hargreaves and Allen, 2003). The Hargreaves method of estimating the Potential Evapotranspiration is based on maximum and minimum air temperature.

$$ET_o = 0.0023\, R_a(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5} \qquad (3.1)$$

Where;

ET_o: Potential Evapotranspiration

T_{mean}: Mean temperature (˚C)

T_{max}: Maximum air temperature (˚C)

T_{min}: Minimum air temperature (˚C)

R_a: Measured incoming radiation in mm/day. It is estimated based on the location's latitude and the calendar day of the year

3.7 Rainfall Run off modeling

3.7.1 Model build-up

Catchment-wide daily rainfall and PET were computed using the method of Thiessen Polygon (Thiessen, 1911). The daily catchment-wide PET and rainfall were converted in the format required by each hydrological model and used as the model input. The initial conditions and parameters for each model were set.

All the six models deployed for the study used catchment – averaged Rainfall, Potential Evapotranspiration and river flow as input data for the period of 30 years. HMSV model newly introduced considered splitting of flows into base flow, interflow and overland flows which then is followed by Calibration of each flow division while adjusting the required parameters according to the model until a judgemental decision was reached by the modeller. The calibration was done for the general condition for both conventional and framework using the optimization objective function Nash-Sutcliffe efficiency and for the extreme condition, the model was recalibrated using conventional and framework strategy. The other five models were obtained from Rainfall Runoff Library (RRL) of the “eWater Toolkit,” that is AWBM, TANK, SIMHYD, SAC and SMAR. They were automatically calibrated using a number of optimizers such as Rosenbrock Multistart Search, Rosenbrock single start search, Multistart Pattern Search, Uniform Random Search, Single Start Pattern Search, Generic Algorithm. These optimizers were used to safeguard the changing of manual parameters at the onset of the calibration. This was chosen for the study because it has been used by various researchers for different studies in calibration of models. In addition to that its being deployed quiet often by many researchers in calibration of rainfall- runoff and a case example is the study on influence of Hydrological Model Selection on Simulation of Moderate and Extreme Flow events of Blue Nile basin used the same principle during calibration of Rainfall-runoff using AWBM, TANK, SAC and SIMHYD which all proved to produce good values of NSE.

3.7.2 Model Calibration

Calibration involves modification of the model parameter values until a defined function is achieved. Calibration involves reducing the mismatch between simulated and observed flow. Calibration can be done automatically or manually. However, the manual approach would be subjective in this study since the various models were being compared in terms of their performance. Therefore, to eliminate subjectively, the parameters of all the models were changed using automatic calibration strategies. Calibration was done from the period between 1st January,1952 to 31st December, 1961 and Nash – Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970) was used as optimization objective function in each of the models.

3.7.3 Model Validation

Validation is normally done after calibration. In validation, the parameters are kept constant as those obtained during the calibration. However, for validation, data sets outside the calibration period are used. It is also used to further identify vibrant limitations and assumptions in the model inclusive of the impact.

3.8 Extraction of the peak over thresh hold values for extreme condition

To generate the hydrological extreme values for both low and high condition and with respect to observed and simulated flows, the procedure of extracting Peak Over Thres-hold (POT) events developed by Onyutha (2019) was used. This procedure is incorporated in a tool called FAN-Stat (Onyutha, 2017) which stands for Frequency Analyses considering Non–Stationarity. The FAN-Stat tool was employed to analyze frequency analyses of extremes in both flood and drought conditions.

While extracting the extremes, the modeler judgment and decision for the peak values should take into consideration the purpose and objective for which the study is being carried. This will then lead to the fixing of the parameters in the extracting tool. Note that the high flows were extracted from the simulated datasets for each set of the model while on the other hand of the low flows, the reciprocal of the discharge was taken into consideration with graphical representation superimposed onto the logarithm scale graph. Very key to consider was that the same parameters fixed in each extreme condition were used for both observed and simulated flows for all the models.

3.9 Model comparison criteria

The performance of a model is evaluated on the extent of its accuracy, consistency and adaptability. Assessing the model performance requires a critical understanding to be able to estimate the closeness of the simulated behaviors (through the model) to the observed. For this study, NSE was used during calibration and validation periods to assess the statistical goodness-of-fit while adjusting the model parameters. It is noted that the NSE values range from $-\infty$ to positive one ($^{+}1$) and the best model is one with the highest NSE value. The model with the lowest NSE was ranked as the last model in performance. In addition to the NSE under the statistical measures, other statistical goodness-of-fit were as well deployed for high flows and low flows. These goodness-of-fit included Model Average Bias (MAB) and Root mean square error (RMSE). The value for MAB and RMSE should be 0% and 0m3/s respectively. The best model is preferred to have zero (0) values but since this is very difficult to achieve, the closer the values of MAB and RMSE to zero (0), the better the model. In further comparison of the MAB and RMSE under extreme conditions, decision matrix ranking was undertaken and because both statistical measures were meant for the same purpose, they were given the same weight during normalization of the values. The assigning of weights makes it easier to have the models ranked with the two different statistical measures deployed for the extremes condition. Lastly the graphical representation and comparison of the observed and simulated flows. The best model was considered with the smallest mismatched as compared to the observed flow. The degree of mismatch therefore placed the different models in their preferred ranks. The graphical presentation was done for both moderate and extreme conditions. The equations for the statistical goodness-of-fit were;

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Q_{\text{mod},i} - X_{o,i}\right)^2}{\sum_{i=1}^{n}\left(X_{o,i} - \bar{X}_o\right)^2} \tag{3.2}$$

where

$Q_{mod,i}$= Modeled Flow,X_o = Observed Flow

$\bar{X}_o$= the mean of the X_o's and

n = The sample size

$$RMSE\left(m^3/s\right) = \sqrt{\sum_{i=1}^{n}\left(Q_{\text{mod},i} - X_{o,i}\right)^2} \tag{3.3}$$

$$MAB(\%) = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{Q_{\mathrm{mod},i} - X_{o,i}}{X_{o,i}} \times 100\right) \tag{3.4}$$

3.10 Chapter Summary

This chapter described the research approaches and design deployed for the study. It looked at the quantitative data used for model calibration and validation deployed on River catchment. Criteria for the catchment selection was well stated and this further informed the data acquisition from the different ministry and Authorities. Further procedure of extraction of the nearly independent over thresh hold values was as well discussed. Model performance using the different selected criteria was briefly mentioned as more is discussed in the next chapter.

CHAPTER FOUR: PRESENTATION OF RESULTS, ANALYSIS, AND DISCUSSION

4.1 Introduction:

This chapter explains how the six conceptual hydrological models performed under moderate and extreme conditions in capturing the river flow variability. The chapter also ranked the models performance under the different model comparison undertaken in the study.

4.2 Application of hydrological models

4.2.1 AWBM

Figure 4.1 shows observed verses simulated flows for both calibration and validation periods under moderate condition. Graphically, it was visually noticed that the model captured the overall variation in the flow with time after running of the model (both calibration and validation). The mismatch between the observed and simulated flows is small as noticed. While capturing the extremes, few peaks of high flows were underestimated (1960 – 1968) while on the other hand of the low flows, the visual look of the hydrographs shows the model captured low flows much better.

The optimal parameters used to obtain the simulated results of AWBM presented in Figure 4.1 can be found in Table 4.1. The best performance of a hydrological model would be indicated by the NSE of 1. However, in this study, the calibration results considering the overall water balance places AWBM with a NSE values of 0.52 and considering the full time series, the NSE values was 0.70. The NSE values were calculated using equation (3.2).

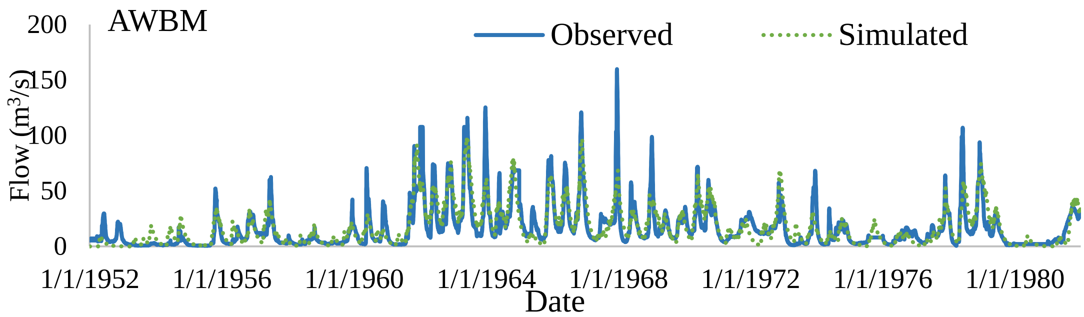


Figure 4. 1 Observed versus AWBM – based simulated flows

Table 4. 1 Optimal parameters for AWBM

S/No	Parameter description	Unit	Value
1	Partial area (A1)	(-)	0.910
2	Partial area (A2)	(-)	0.030
3	Base Flow Index (BFI)	(-)	0.85
4	Capacities (C1)	(mm)	43.8
5	Capacities (C2)	(mm)	447.3
6	Capacities (C3)	(mm)	850.5
7	Base flow recession constant (K_{base})	(day)	0.930
8	Surface flow recession constant (K_{surf})	(day)	1.000

In a similar past, Ayushi et al., (2018) applied AWBM and SMAR in catchments of Upper Awash Sub Basin in Addis Ababa and AWBM model performed well with NSE of 0.6. The researcher acknowledges the model is suitable for application to other catchments with similar characteristics. It was however a challenge in predicting the runoff for the future planning while applying the model. This therefore calls for different models to be applied so as to select the best model that can predict future runoff appropriately.

AWBM was applied in simulation of moderate and extreme flows on Blue Nile Basin by Onyutha (2016) and was the best model compared to other models (TANK, SAC, SIMHYD, SMAR) applied in the study. Zhang et al., (2016) applied AWBM to simulate variation in stream flows of Poyang Lake basin in China caused as a result of influence of human activities and climate change and the model performed very well with NSE larger than 0.842. The researcher confirmed the model for satisfactory performance in the simulation of the stream flow for the study. Ankit and Tiwari (2015) in the application of rainfall runoff estimation using RRL toolkit for Rahatgarh sub basin also confirmed good performance of AWBM with good NSE and good correlation between observed and simulated flow. The study later recommended the AWBM to be used for further water resource planning and management of the Rahatgarh basin. Same model was also applied by Yu and Zhu (2015) in a comparative assessment for forested watersheds and AWBM performed better than SIMHYD.

In relation to good performance of AWBM across the different catchment, Yu and Zhu (2015) in a comparative assessment for forested watersheds showed that AWBM worked marginally better than SIMHYD for forest watershed where forest clearing, application of herbicide and changes in species composition had occurred. This was the same scenario with Kafu catchment where AWBM performed better that all the applied models. The catchment has undergone massive clearance of the forest and vegetation in search of land for agriculture and wood for firewood. In addition to that, massive sugar plantation within the catchment including other farming practices greatly consider usage of herbicides while farming. The result from the two different studies demonstrated similarity in the catchment characteristic that eventually has interference with the catchment hydrology hence reflected in the model results.

Considering application of AWMB and SMAR by Ayushi et al., (2018) on Upper Awash Sub Basin in Addis Ababa, the performance of AWMB was better than that of SMAR and this was the same situation as of Kafu catchment. In both studies, daily rainfall-runoff modeling by using daily time series rainfall and evapotranspiration data for the catchments were considered. In terms of the catchment characteristic, The Awash Basin is the most utilized in Ethiopia with 70% of the irrigate agriculture and 90% of the nations irrigated cotton production. Similar to Kafu catchment where the catchment is dominated by farming and pastoralist. With this activities, utilization of farm inputs like agro chemicals, fertilizers and herbicides can never be abolished and all these greatly impact differently on the catchment hydrology which further is revealed in the model performance. However, for all the citation under discussions, the daily rainfall and evapotranspiration for the respective catchment were used for the specific study. It has been noticed that some researchers do apply hourly or monthly catchment input data while carrying on modelling. All this can impact differently on the models deployed.

4.2.2 TANK MODEL

Figure 4.2 shows observed verses simulated flows for both calibration and validation periods. Visual look at the hydrographs shows the model’s inability in capturing the peaks flows with respect to time. The mismatch between the observed and simulated flows is bigger especially when it comes to estimating high flows, it was noted that high flows were overestimated in most of the period (1952 – 1962 and 1971 -1982) leaving few periods with underestimation.

On the other hand, low flows were as well overestimated in most of the model period. Yun-Kyung et al., (2004) applied TANK model to predict time series of daily rainfall-runoff of Soyang Dam and Young cheon Dam watershed while considering Nash-Sutcliffe coefficient as the best optimizer and TANK model performed better than SIMHYD. Also according to Clanor, et al., (2015) application of TANK in modeling Molawin watershed yielded better result of NSE 0.98 as compared to other models used. The big variation with this study could be related to data quality and catchment characteristics that change according to climate and human activities along the catchment. This therefore call for researchers to be vigilant while deploying models in data scarce regions before any water resource management is made.

The optimal parameters used to obtain the simulated results of TANK as presented in Figure 4.2 can be found in Table 4.2. The calibration results considering the overall water balance places TANK with a NSE values of 0.10 and considering the full time series, the NSE values was 0.14.

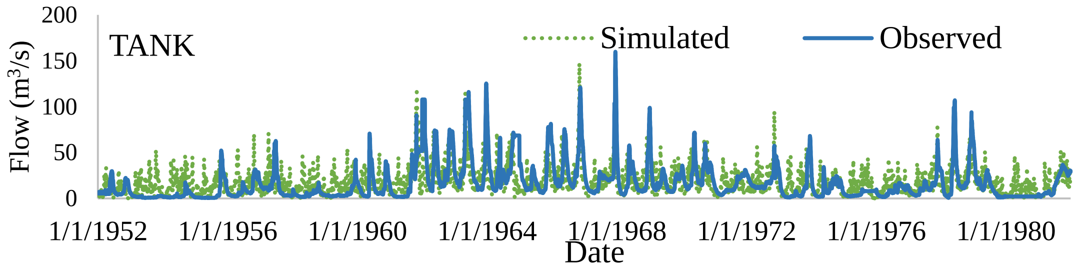


Figure 4. 2 Observed versus TANK – based simulated flows

Table 4. 2 Optimal parameters for TANK

S/No	Parameter Description	Unit	Value
1	Overland runoff from the top outlet of first tank (a11)	(m^3/s)	0.190
2	Overland runoff from the lower outlet of first tank (a12)	(m^3/s)	0.020
3	Intermediate runoff (a21)	(m^3/s)	0.060
4	Subbase runoff (a31)	(m^3/s)	0.521
5	Base flow (a41)	(m^3/s)	0.001
6	Alpha (α)	(-)	2.000
7	Outflow from the bottom of the first Tank (b1)	(m^3/s)	0.410
8	Outflow from the bottom of the second tank (b2)	(m^3/s)	0.355
9	Outflow from the bottom of the third tank (b3)	(m^3/s)	0.738
10	Water depth in the first tank (C1)	(mm)	5.000
11	Water depth in the second tank (C2)	(mm)	3.000
12	Water depth in the third tank (C3)	(mm)	7.000
13	Water depth in the fourth tank (C4)	(mm)	11.000
14	Depth below the top outlet of the first tank (H11)	(mm)	477.000
15	Depth below the lower outlet of the first tank (H12) (<H11)	(mm)	0.001
16	Depth below the outlet of the second tank (H21)	(mm)	67.000
17	Depth below the outlet of the third tank (H31)	(mm)	15.000
18	Depth below the outlet of the fourth tank (H41)	(mm)	25.000

4.2.3 HMSV

Figure 4.3 shows the split of flows into base flow, interflow and overland flows and figure 4.4 shows observed verses simulated flows for both calibration and validation periods. HMSV (1) captured the peaks much better as compared to HMSV (2). The mismatch between the observed and simulated flows is generally average for both, the model averagely captured high flows with some periods overestimated by HMSV (2) (1961 - 1980) and other periods under estimated by HMSV (1) (1961 - 1980). For the low flows, visual look at the hydrographs shows that the model was able to capture low flows much better throughout the simulation period for both HMSV (1) and HMSV (2).

The optimal parameters used to obtain the simulated results of HMSV presented in figure 4.4 a & b can be found in Table 4.3. The calibration results considering the overall water balance places HMSV (1) and HMSV (2) with a NSE values of 0.58 and 0.48 respectively. On the other side, full time series yielded NSE values 0.67 and 0.53 for HMSV (1) and HMSV (2) respectively.

This newly introduced model was applied by Onyutha (2019) in simulation of runoff along the Blue Nile basin and emerged to be the best model among SMAR, AWBM, SIMHYD, NAM, SACRAMENTO, TANK, PRMS, and PDM. The consistency realized especially in capturing the extreme condition makes HMSV one of the model to be adopted when conducting rainfall run off modeling in both data scarce region and region with available data. This is based on the discussion that they are specifically good at capturing extreme conditions as compared to other models

Note that for proper visualization of the graph, the period shown is from 1952 to 1962

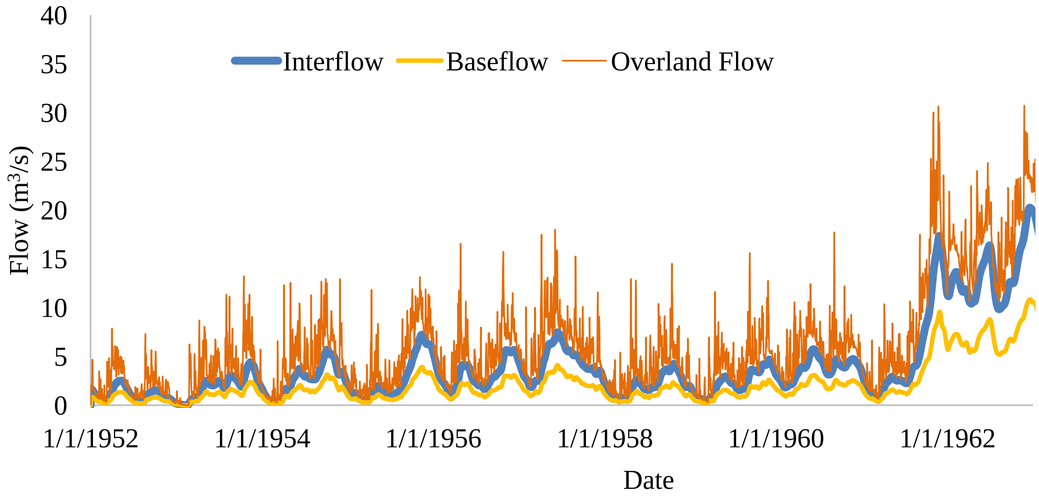


Figure 4. 3 Flow separation using HMSV model

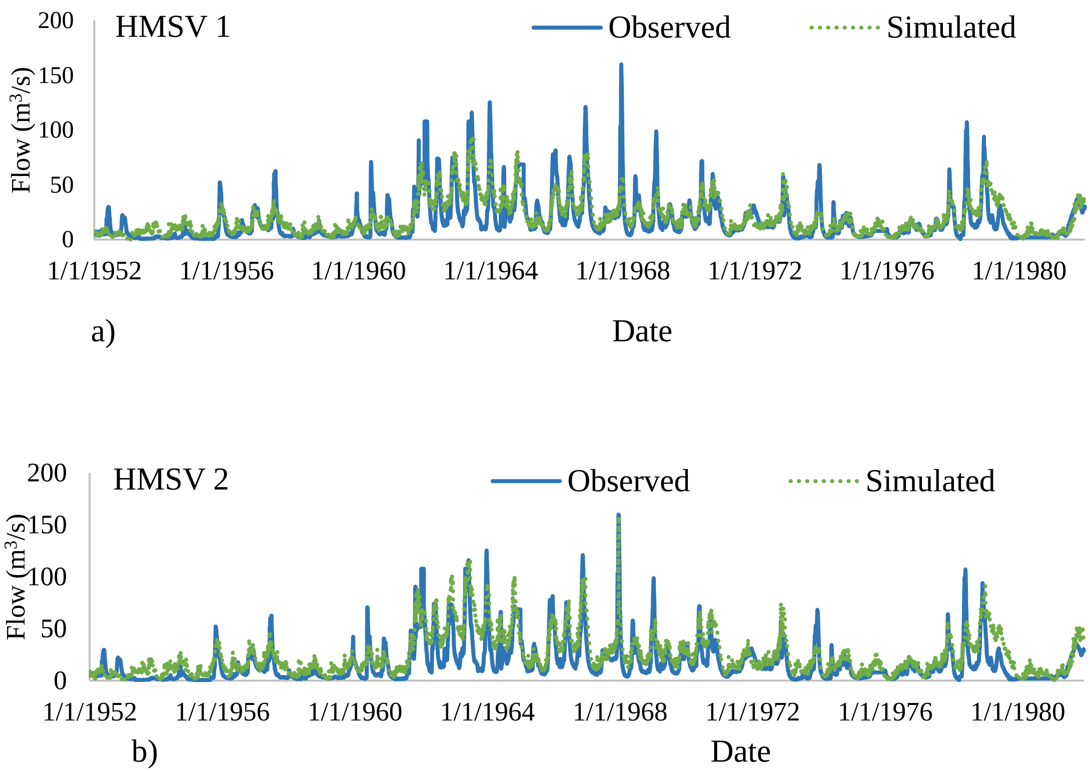


Figure 4. 4 Observed versus HMSV (1) - a and HMSV (2) -b – based simulated flows

Table 4. 3 Optimal parameters for HMSV

Parameter	Definition	HMSV(1)	HMSV (2)
S_0	Initial soil moisture storage (mm)	70.48	71.64
S_{max}	Maximum soil moisture storage def (mm)	83.77	84.53
a_1	Baseflow parameter	8.65	8.50
t_a	Baseflow recession constant (day)	17.00	18.00
a_2	Interflow recession constant (day)	9.59	9.62
t_b	Overland flow parameter 1	9.00	8.00
a_3	Interflow parameter	8.780	8.80
t_u	Overland flow recession constant1 (day)	4.00	4.00
c_3	Overland flow parameter 2	5.38	5.50
t_v	Overland flow recession constant 2 (day)	2.00	2.50

4.2.4 SIMHYD MODEL

Figure 4.5 shows observed verses simulated flows for both calibration and validation periods. Visual look at the hydrographs shows the model’s inability in depicting the observed flows. The mismatch between the observed and simulated flows is bigger as compared to results from AWBM and HMSV but the NSE value produced was average of 0.56. It was noted that high flows were well captured in most of the model period while low flows were equally well captured in most of the period. The study however acknowledged the inconsistency in capturing the peaks as this may be attributed to the data quality and catchment behavior.

The optimal parameters used to obtain the simulated results of SIMHYD presented in Figure 4.5 can be found in Table 4.4. The calibration results considering the overall water balance places SIMHYB with a NSE values of 0.19 and considering the full time series, the NSE values was 0.56.

Zhang et al., (2013) deployed SIMHYD, SACRAMENTO and GR4J in two contrasting Great Barrier Reef catchments and SACRAMENTO out performed SIMHYD and GR4J. SIMHYD was able to produce NSE below 0.5 and the study recommended SCRAMENTO as the best model for such study. According to Clanor et al., (2015), SIMHYD model was deployed in modeling Molawin watershed and the NSE value obtained was 0.80 which represents a good goodness-of-fit measure. It was however not the best performed model since other models like AWBM had NSE greater than 0.8. The ability of the model to perform with such a good NSE in different catchments calls for more comparison in different catchment both with good data quality and limited data catchment.

Zhu et al., (2017) also applied SIMHYD and GR4J in the Hydrological modeling for conjunctive water use in the Murrumbidgee Catchment and both models yielded an average NSE value. SIMHYD was out performed by GR4J with NSE of 0.59 much equivalent to the NSE obtained in this study. The researcher confidently acknowledges the average performance of the model for consideration when estimating groundwater recharge based on the simulated streamflow.

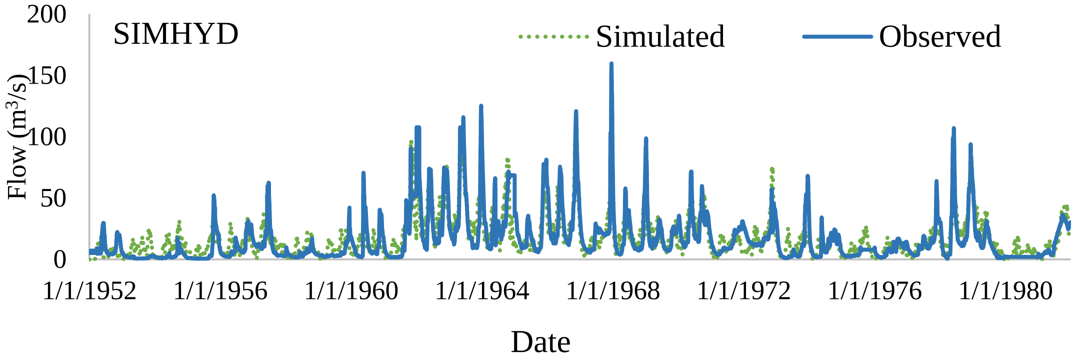


Figure 4. 5 Observed versus SIMHYD – based simulated flows

Table 4. 4 Optimal parameters for SIMHYD

S/No	Parameter Description	Unit	Value
1	Base flow coefficient	(-)	0.03
2	Impervious threshold (mm)	(-)	0.01
3	Infiltration coefficient	(-)	725
4	Infiltration shape	(-)	0.21
5	Interflow coefficient	(-)	0.057
6	Pervious fraction	(-)	1.00
7	Rainfall interception store capacity	(mm)	0.39
8	Recharge coefficient	(-)	0.634
9	Soil moisture store capacity	(mm)	338

4.2.5 SACRAMENTO MODEL

Figure 4.6 shows observed verses calibrated flows for both calibration and validation periods. The model was able to capture most of the high flows with small variation and overestimation of the flows in some period. Low flows were as well captured in most of the model period. According to Yan et al., (2014) in their study of applying different hydrological models along little river catchment in Georgia USA, SACRAMENTO was the best model with the highest NSE and was selected as the optimal model of little River catchment. The best performance is also related to the humid climate and saturated storage based runoff generation. It was also noted that models performed differently in different climatic conditions. For this study conducted on River Kafu catchment, SACRAMENTO yielded a small NSE value and this could be due to the reduced compatibility of the model structure with the poor quality data.

Salmani et al., (2015) in their study of simulation in Arakoose tributary of Goorganroad River, Golestan province in Iran, three models (AWBM, SAC, TANK) were applied and after automatic calibration and evaluation criteria deployed, confirmed Sacramento as the best model with NSE of 0.669 and RMSE of 7.905m^3/s. And with the good results, it was later found that the model was not able to perform well in simulating peak flows.

According to Kunnath et al., (2019), model performance was compared in simulation of runoff in the upper Godavari river in India and upon calibration of the models, SACRAMENTO was found to be less appropriate as compared to the GR4J model. The researchers acknowledged the choice of right model for water resource assessment in a particular region is a big challenge to hydrologists. This therefore calls for modelers to be very vigilant while choosing the model for each catchment.

The inconsistency in the past study and this study could be related to data quality and catchment behavior and thus need for more studies. The optimal parameters used to obtain the simulated results of SACRAMENTO presented in Figure 4.6 can be found in Table 4.5. The calibration results considering the overall water balance places SACRAMENTO with a NSE values of 0.20 and considering the full time series, the NSE values was 0.35.

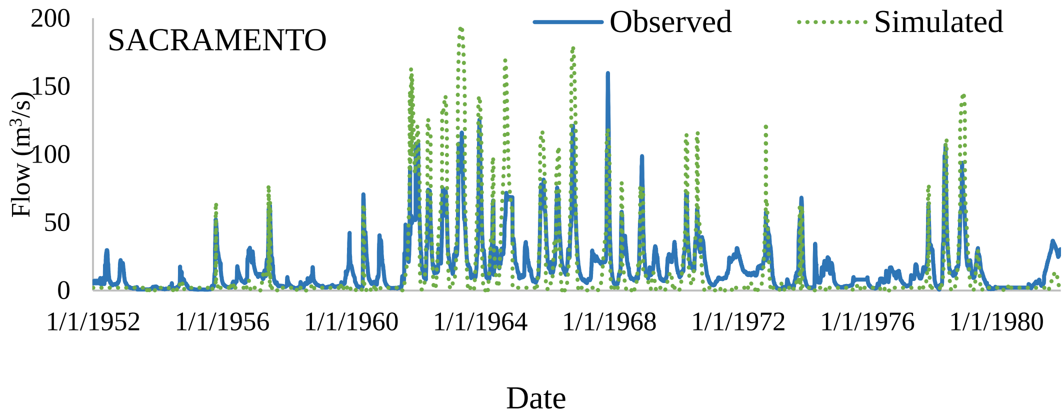


Figure 4. 6 Observed versus SACRAMENTO – based simulated flow

Table 4. 5 Optimal parameters for SACRAMENTO

S/No	Parameter description	Unit	Value
1	Additional fraction of pervious area (Adimp)	(-)	0.012
2	Lower zone free water primary maximum (L_{zfpm})	(mm)	49.00
3	Lower zone free water supplemental maximum (L_{zfsm})	(m)	48.00
4	Ratio of water in LZFPM (L_{zpk})	(mm)	0.02
5	Ratio of water in LZFSM (L_{zsk})	(mm)	0.02
6	Lower zone tension water maximum (L_{ztwm})	(mm)	400
7	Impervious fraction of the basin (P_{ctim})	(-)	0.03
8	Minimum proportion of percolation (P_{free})	(-)	1.00
9	Exponential percolation rate (R_{exp})	(-)	1.12

S/No	Parameter description	Unit	Value
10	Fraction of water unavailable for transpiration (R_{serv})	(-)	1.00
11	Catchment portion that loses water by evaporation (Sarva)	(-)	0.12
12	Fraction of base flow which is groundwater flow (S_{ide})	(-)	1.00
13	Flow volume through porous material (S_{cout})	$m^3/s/km^2$	0.89
14	Upper zone free water maximum (U_{zfwm})	1/day	74.00
15	Ratio of water in UZFWM (U_{zk})	1/day	0.03
16	Upper zone tension water maximum (U_{ztwm})	1/day	1.00
17	Factor applied to PBASE (Z_{perc})	(-)	78.00

4.2.6 SMAR MODEL

Figure 4.7 shows observed verses calibrated flows for both calibration and validation periods. It was noted that the model captured most of the high flows and for some periods, there was overestimation. For the side of low flows, there was overestimation of the observed flows in most of the model period. Basically, the mismatch between the observed and simulated flows is much bigger as compared to AWBM and HMSV

According to Teklu et al., (2008), application of SMAR as a rainfall run off hydrological model along Wami river basin of Tanzania indicated the low performance of SMAR in which they recommended need for more detailed study and understanding of the catchment coupled with quality data. Same model was used by Obada et al., (2016) to reproduce the flow of Kompongou outfall Mekrou basin in Benin and the model was rated as having the lowest performance. They made a conclusion for model comparison to be deployed in same catchment for a better understanding of the catchment. Yang et al., (2019) in their study of dynamic runoff simulation in a changing environment in China applied SMAR and other models in the new application of a data stream which allows capturing the evolving relationship between runoff and its impact factors revealed SMAR as the poorly performed model among SWAT, AWBM, TANK and others.

Previous study on comparing the performance of AWBM, SACRAMENTO, SIMHYD, SMAR and TANK by Khalaj et al., (2016) in simulation of runoff from Nodeh watershed in Golestan province applied pattern search calibration optimizer in calibration of the models and the NSE for SMAR was 0.417 and 0.338 for calibration and validation. AWBM performed best with NSE of 0.71 and 0.63 for calibration and validation, respectively. The researcher also noted that most of the models applied gave an average NSE values which they felt can be used according to the needs in water resource management. There has been consistency in the results from this study and the past studies.

The low performance of SMAR may be taken up for further analysis and comparison with other models, good data quality and limited data. The optimal parameters used to obtain the simulated results of SMAR presented in Figure 4.7 can be found in Table 4.6. The calibration results considering the overall water balance places SMAR with a NSE values of 0.12 and considering the full time series, the NSE values was 0.41.

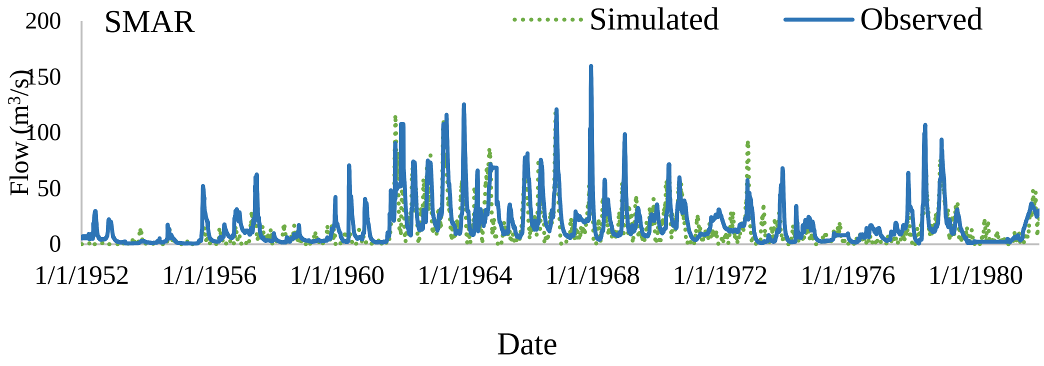


Figure 4. 7 Observed versus SMAR – based simulated flow

Table 4. 6 Optimal parameters for SMAR

S/No	Parameter Description	Unit	Value
1	Ground water evaporation rate (C)	(-)	0.289
2	Groundwater runoff coefficient (G)	(-)	0.554
3	Proportion direct runoff (H)	(-)	0.058
4	Storage loss coefficient (Kg)	(-)	0.256
5	U.H linear routing (N)	(-)	1.40
6	Linear routing component (NK)	(-)	1.00
7	Evaporation conversion parameter (T)	(-)	0.812
8	Infiltration rate (Y)	(mm)	4320
9	Soil moisture total Storage depth (Z)	(mm)	3700

4.3 General discussion on applications of the selected models under moderate conditions

By graphical representation, it was noticed that all the models managed to capture variation in flow with time as indicated in the different hydrographs in the previous discussions. However, the peak high flows were under- or over-estimated in some cases. For instance, most of the peak high flows were overestimated by SACRAMENTO. These results indicate the acceptability of the models in reproducing moderate flows under moderate conditions.

Under statistical analysis, the performance of a hydrological model is indicated by the NSE of one. For this study, it was found that the calibration results after considering the overall water balance indicates the highest NSE values of 0.54 and 0.52 for HMSV (1) and AWBM, respectively. On the other hand, the NSE values of the remaining models were noted to be below 0.5. Upon considering the full time series, the NSE values for AWBM, HMSV (1), SACRAMENTO, SIMHYD, SMAR, TANK, and HMSV (2), were recorded as 0.70, 0.67, 0.35, 0.56, 0.41, 0.14, 0.53, respectively.

Looking at the past studies conducted by other researchers, (Yang et al, 2019; Zhang et al. 2016, Kunnath and Eldho 2019; Onyutha 2019; Yu and Zhu 2015Kumar et al. 2015 and Ankit and Tiwari 2015) the performance of the models from the RRL tool kit (TANK, SAC, AWBM, SMAR and SIMHYD) that was applied under this research performed with some difference. AWBM was also applied o Bina basin in India and yielded a NSE of 0.824 and 0.618 for calibration and validation respectively (Ankit and Tiwari 2015). Application of AWBM on Pyang Lake basin yielded a NSE value of greater than 0.9 using monthly streamflow (Zhang et al. 2016). Kunnath and Poovakka (2019) obtained NSE of about 0.6 using both the SACRAMENTO and AWBM applied to Mula Catchment. However, SACRAMENTO and AWBM applied to model monthly flow of Bhandardara Catchment yielded NSE values around 0.5 (Kunnath and Poovakka 2019) AWBM and SACRAMENTO when applied by Kunnath and Poovakka (2019) to simulate monthly flows of a number of catchments in the upper Godavari river basin yielded NSE values below 0.5 for Adhala, Gargaon, and Kadwa catchments. However, in this study, the hydrological models applied considered daily hydro- meteorological data and the NSE still varies with results from other Catchment upon considerations of daily data. For instance, Kumar et al. (2015); Odisha (India), applied SMAR, TANK, SACRAMENTO, AWBM and SIMHYDE in modeling the daily flow of Kesinga catchment and obtained NSE values greater than 0.5. Also Manual and Automatic calibration was undertaken for the RRL models during the studies by Onyutha (2016) and Kumar et al. (2015). Upon application of SIMHYDE and AWBM by Yu and Zhu (2015) on Fernow in north central West Virginia, USA, the NSE values found were 0.46 and 0.49 respectively. Onyutha (2016) applied SACRAMENTO, AWBM, TANK, SIMHYDE and IHACRES in simulation of hydrological extreme conditions in Blue Nile and the NSE obtained during calibration varied from 0.65 to 0.85. Many reasons do exist why results of hydrological models keeps differing from catchment to catchment. This is because, models are of different structures which leads to different equations, the equations further affect the model compatibility with the available data. Furthermore, it has also been realized that catchments are not spatially similar with respect to size, soil, topography, Geology and hydrological conditions (Onyutha 2016) as well as space time variability of the PET and rainfall. Climate variability and human factors also varies from catchment to catchment which impact differently on the hydrological conditions and this ca result into different response by different models upon deploying them under the hydro-meteorological inputs from various catchments (Rutkowska et al. 2017; Pirnia et al. 2019)

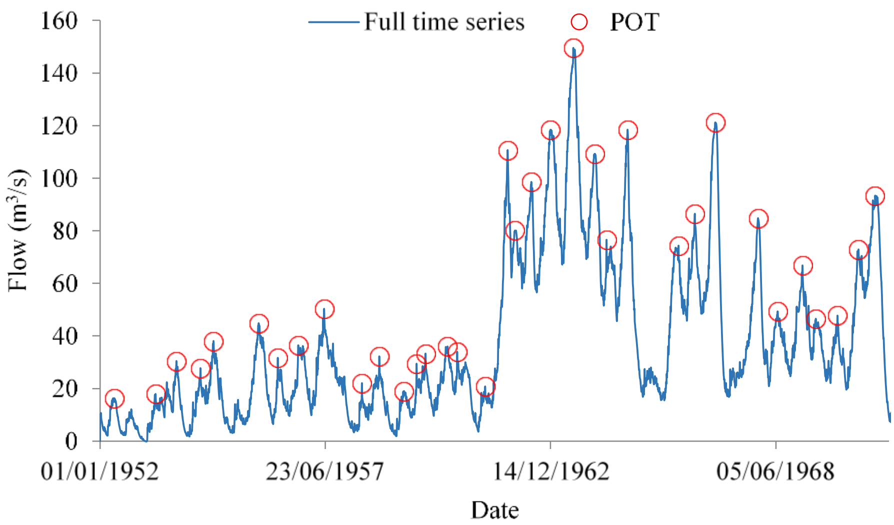
The NSE of calibration normally tends to be higher than that of Validation during hydrological modeling. This is because its normally very difficult to transfer model performance with respect to variation in the catchment hydro-climatic conditions over time. However, for this study, the NSE values for validation were higher than those for calibration (see Figure 4.8). To explain this result, it is good to first note that around 1961, there was a step jump in the flow mean (Figure 4.1 to Figure 4.7), the flows were higher during that period before 1961 as compared to years after that. This can be related to equation 2 in chapter three, by using the squares of the difference between the simulated flows and the observed variable at each step, the errors tends to be larger for high flows as compared to low flows. This makes errors minimization during calibration premised NSE as an objective function enhance the performance of the models during periods where the flows values were higher. And this is the reason to the higher NSE during validation than those obtained during calibration.

Figure 4. 8 Statistical measure (NSE) of the mismatch between observed and simulated flow

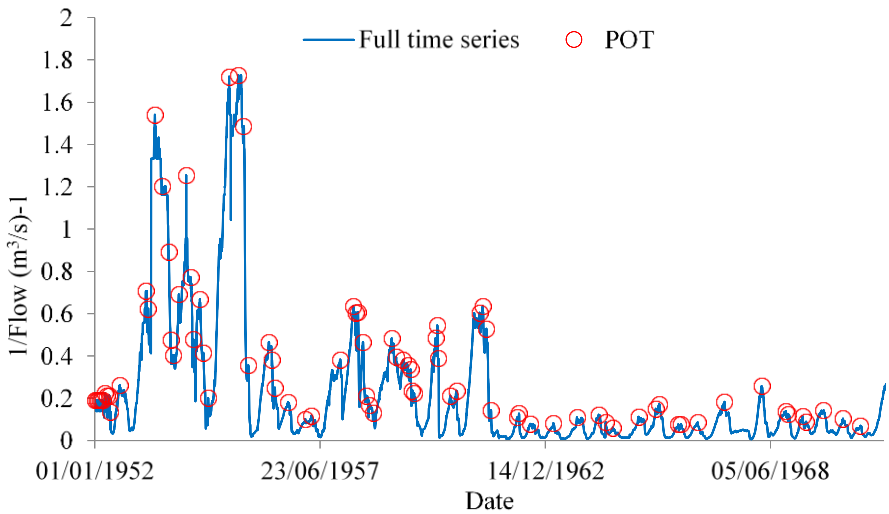
4.4 Assessment of performance of hydrological models under extreme conditions

Figure 4.9 shows an example of extracted POT events verses full time series for both high flows (a) and low flows (b) based on criteria of nearly independent events (threshold ratio, inter-event time and independency ratio). In high flows, the threshold ratio considered was $10m^3/s$ and all the flows above that were selected as flows with characteristic of high flows and those are independent flows. While for low flows, the threshold ratio considered was 1.5m3/s and inverted plots only considered independent peaks below that. This was done for all the models for both the observed flows and the simulated flows.

Note that for proper visualization of the graph, the period shown is from 1952 to 1968



a) Full time series and extracted high flow



b) Full time series and extracetd low flow

Figure 4. 9 Untransformed and inverted POT- (a is for High flows and b is for Low flows

Figure 4.10 shows graphical performance of the different models undertaken in the study in reproducing nearly independent hydrological extreme events while considering the thirty years of the study. Looking at the high flows in Figure 4.10 a, it is noticeable that within the first 3 years, most of the models exhibited god performance in estimating the high flows quantiles (except for SACRAENTO where showed systematic over estimation for all the high flows events throughout the study period). On the other hand of the low flows (Figure 4.10 b), the low quantiles were under estimated by most of the models throughout the study period. The log-transformed return periods is expected to be linear for a normal tailed flow upon considering the relationship between the extreme flow events and the reduced variate according to this study. For that reason, a model is expected to be presented by a slope of such a line characterizing the variations in the extreme flow conditions and this is what all the models should have adequately reproduced. For this study, SACARAMENTO, SMAR and SIMHYD has been noticed with scatter points which almost appeared like horizontal lines. In other words, HMSV (1) and AWBM presented the slope or return period curves with fair captions. However, HMSV (2) turned out to be the best performed model through visual judgement.

On further analysis, the linear relationship between the observed quantiles and the return periods were seen to have been reproduced much better by high flows quantile as compared to the low flows quantiles. This is all linked to the design of most of the hydrological models which are structurally fit for capturing high flows than low flows (Onyutha 2016; Staudinger et al. 2011). In contrast, more weights are given to high flows than low flows while calibration of the overall water balance using the objective functions (Onyutha 2016). This therefore calls for the hydrological models to have structures which are flexible in capturing both high flows and low flows just like the newly introduced HMSV.

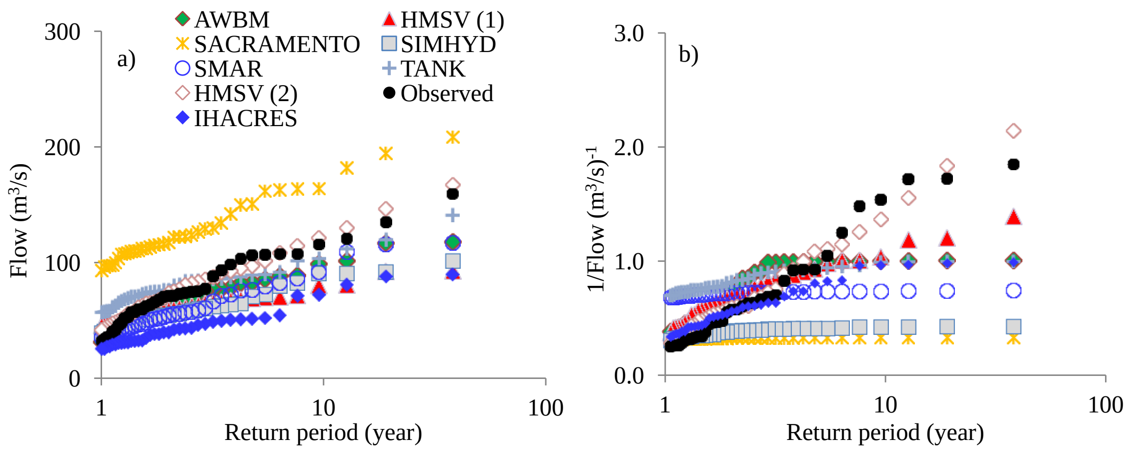


Figure 4. 10 Frequency of observed and simulated POT (a) high flows, and (b) low flow quantiles. The legend entries of chart (a) are as those for (b). SAC stands for SACRAMENTO.

Figure 4.11 and Figure 4.12 shows the statistical performance of the models in reproducing events under high flows and low flows while considering the 30 years return periods under the study. Better models are considered with the smallest values of the MAB and RMSE in any considerations and this means that the smaller the values, the better the model. Taking a look at both figure 4.11 and Figure 4.12 for both for high flows and low flows respectively, the largest mismatch between the observed and the simulated flows was exhibited by SACRAMENTO and this is seen through the largest values of MAB and RMSE reproduced. Taking a look at figure 4.10 previously discussed, it was visualized that SACRMENTO was denoted with the largest mismatch between the observed and simulated quantiles for both the extreme conditions. HMSV (1) and AWBM yielded a much more comparative performance, while HMSV (2) performed better with the lowest values for both the MAB and RMES under high and low flows. As earlier on discussed under methodology section, the good performance of the HMSV (2) is linked to the calibration strategy which is tailored towards capturing such independent extreme hydrological events. Graphical representation shown in Figure 4.10 clearly displayed the good performance of HMSV (2) among other models. Because of the uniqueness demonstrated by HMSV (2), a suggestion is made for all the traditional models to be improved in their structures so that they can have a calibration strategy based on specialized frameworks that can focus on capturing both high flows and low flows (Onyutha 2019). Also exploration of an objective function which give same weights to both high and low flows could be adopted instead of only applying the NSE. This is because, during calibration of models, NSE makes traditional models to perform far better for high flows than for low flows.

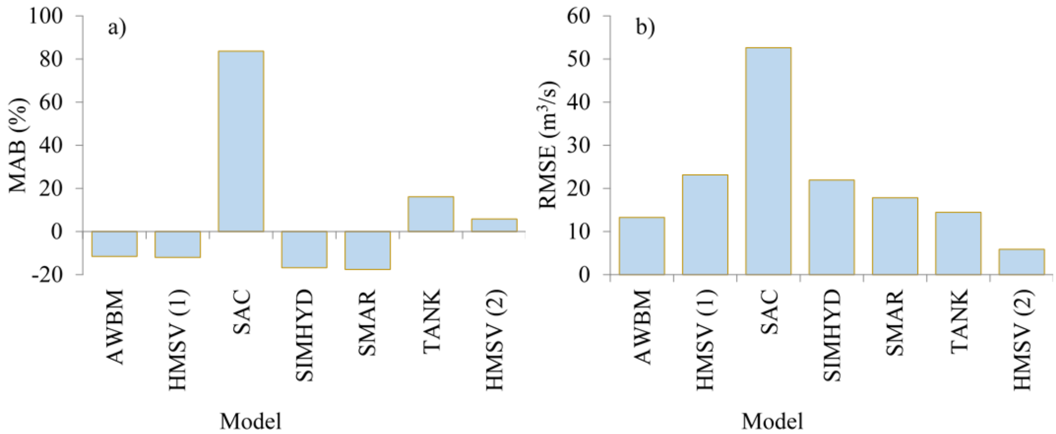


Figure 4. 11 Statistical measure (a, b) MAB and RMSE for high flows. In the label of the horizontal axis, SAC stands for SACRAMENTO.

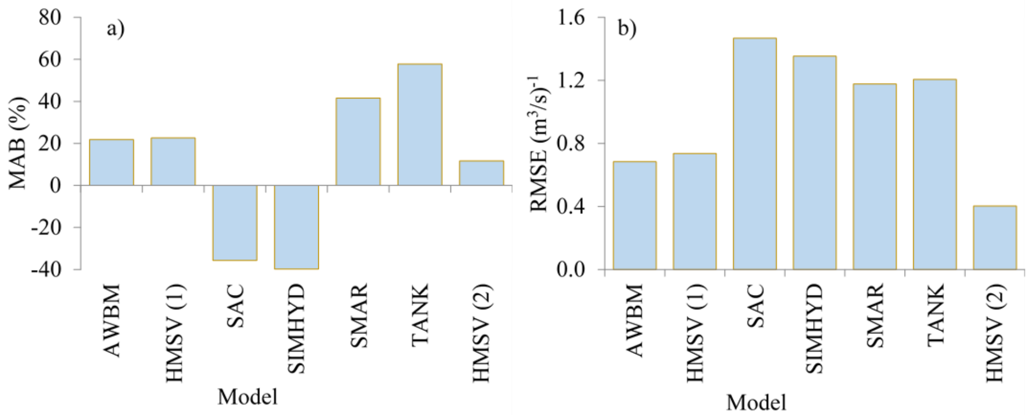


Figure 4. 12 Statistical measure (a, b) MAB and RMSE for low flows. In the label of the horizontal axis, SAC stands for SACRAMENTO.

4.5 Selection of the best model that can be used as a tool to support River Kafu catchment risk-based management plan

Table 4.7 shows model ranking for moderate condition basing on the NSE values obtained during calibration and validation. extremes under high flow condition. The best performance of a hydrological model would be indicated by the NSE of 1. The closer the NSE to 1, the better the model. AWBM emerged with the highest NSE of 0.70 followed by HMSV (1) with 0.67. Tank on the other side had the lowest NSE of 0.14. Under extreme condition, both graphical and statistical comparison was undertaken. For the graphical presentation, figure 4.10 was able to place the models in their preferred degree of ranking. However, while considering statistical comparison, decision matrix ranking was considered and both MAB and RMSE were give the same weight during normalization of the values. The two statistical measures had same weights because they were all meant to serve the same purpose during the study. HMSV (I) it its new calibration strategy performed better in both extreme conditions and followed by AWBM (See Table 4.8 and Table 4.9). SACRAMENTO and TANK had the worst performance under high flows and low flows respectively.

In conclusion, it was noted that the overall best model under extreme condition is HMSV (1) which was attributed as a result of its new calibration framework focusing specifically on extreme hydrological conditions during analysis. This same model recently introduced by Onyutha (2019) also proved to be the best model in capturing extreme flows when deployed along Blue Nile basin study. This indicates the need to adopt a calibration strategy which can allow models to capture both high flows and low flows in a single calibration.

Table 4. 7 Moderate Conditions- Metrics (NSE)

Models	**NSE**	**Ranking**
AWBM	0.7	1
HMSV I	0.67	2
SACRAMENTO	0.35	6
SIMHYD	0.56	3
SMAR	0.41	5
TANK	0.14	7
HMSV II	0.53	4

Table 4. 8 High Flows- Metrics (MAB, RMSE)

Models	**MAB (%)**	**Mag of MAB**	**X**	**X*50%**	**RMSE (m^3/s)**	**Mag of RMSE**	**Y**	**(Y*50%)**	**(X*50%)+(Y*50%)**	**Ranking**
AWBM	-11.52	11.52	0.51	0.25	13.28	13.28	0.02	0.01	0.26	2
HMSV I	-12.03	12.03	0.48	0.24	23.15	23.15	0.01	0.01	0.25	3
SACRAMENTO	83.65	83.65	0.07	0.03	52.66	52.66	0.00	0.00	0.04	7
SIMHYD	-16.75	16.75	0.35	0.17	21.95	21.95	0.01	0.01	0.18	5
SMAR	-17.52	17.52	0.33	0.17	17.85	17.85	0.01	0.01	0.17	6
TANK	16.19	16.19	0.36	0.18	14.47	14.47	0.02	0.01	0.19	4
HMSV II	5.82	5.82	1.00	0.50	0.25	0.25	1.00	0.50	1.00	1

Table 4. 9 Low Flows - Metrics (MAB, RMSE)

Models	MAB (%)	Mag of MAB	X	X*50%	RMSE (m^3/s)	Mag of RMSE	Y	(Y*50%)	(X*50%)+(Y*50%)	Ranking
AWBM	21.80	21.80	0.53	0.27	0.68	0.68	0.59	0.29	0.56	2
HMSV I	22.58	22.58	0.52	0.26	0.74	0.74	0.54	0.27	0.53	3
SACRA MENTO	-35.71	35.71	0.33	0.16	1.47	1.47	0.27	0.14	0.30	6
SIMHYD	-27.80	27.80	0.42	0.21	1.03	1.03	0.39	0.19	0.40	4
SMAR	41.52	41.52	0.28	0.14	1.18	1.18	0.34	0.17	0.31	5
TANK	57.78	57.78	0.20	0.10	1.21	1.21	0.33	0.17	0.27	7
HMSV II	11.65	11.65	1.00	0.50	0.40	0.40	1.00	0.50	1.00	1

4.6 General discussion for the overall objectives

Following the above discussions of results, the study has clearly shown that all the six models deployed for the simulation of River Kafu catchment were able to replicate the hydrological behaviour of the catchment but with different degree of accuracy. Most of the models demonstrated goodness-of-best fit in simulation of general condition as compared to extreme events. This was because during the calibration of the models, emphasis was put on obtaining the best value of NSE which may not focus much on the goodness of fit between the observed and the simulated flows.

The simulation of extreme events was proven to be very difficult for the five models (AWBM, SIMHYD, SAC, SMAR and TANK) given the fact that their structure can only allow simulation to be generated once for all extreme condition with ease. In contrary, the newly introduced HMSV model proved to be the best model to be applied in Kafu catchment for both extreme condition. The good performance of HMSV model is linked to its structure which is designed to separate flows in different sub flows (base flows, interflows and overland flows) which makes it easier for the modeller to streamline his/her attention in simulation of the flows according to the intention of the study such as extreme conditions.

The HMSV calibration framework designed to cater for the extreme condition yielded better hydrological extreme results with consistency in results as compared to its conventional calibration method. Best models are selected based on their performance in regards to the intended purpose and objectives. This study examined the six models discussed in chapter three and for the purpose of the study in having them compared comes with a condition for ranking depending on their performance under all conditions. The selection focused on the objective functions (MAB, RMSE, NSE values) and the smaller the variation from observed and the simulated flow, the better the model. Also bearing in mind that the allowable limits for NSE range from ($-\infty$ - +1), MAB and RMSE having 0 has the perfect model. Any deviation from the range places the model at their preferred levels of comparison.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS:

5.1 Conclusions

The study appreciated the performance of all the six models deployed in the study but with the following key conclusions.

i. It was realized that all the models deployed managed to reproduce flow variability but with different magnitude. This was evidenced by the hydrographs produced by the different models and the statistical measures deployed.
ii. Under moderate condition, few models had their NSE above 0.5 and they performed better in reproducing moderate condition than extreme
iii. Under mean hydrological condition, AWBM Exhibited the best performance. Under extreme conditions, the best model was HMSV (2) and this was based on its uniqueness in calibration strategy which is tailored to capture the extreme conditions.
iv. Due to the buildup of most models, only few performed well under extreme conditions. This therefore calls for other models to be structured in a way that they can be used for capturing extreme condition just like the recently introduced HMSV

5.2 Recommendations

i. The different ministry (Ministry of water and environment, Ministry of Agriculture, Animal industry and Fishery and National Environment Management Authority) should undertake this study conducted as a benchmark to improve on the catchment management plan and strategy. This will help in further combating the bad practices that is currently overwhelming the catchment.

ii. Model structure is specific for a given condition- In future, applications of models should be in respect of the study. For example, study related to extremes can be conducted while considering the HMSV models.

iii. Need to deploy model comparison concept while dealing in a data scarce region bearing in mind that the choice of a model to be deployed for a given task is on case by case basis which are tailored by the objectives.

iv. Future study can be taken up on the same catchment focusing on the physical-based modeling with intention of finding out how land use is affecting the catchment.

v. For the government and Authorities, the study noted the bulk missing of data for some periods that needs to be undertaken to have full updated data and this can only be made possible through investment in data collection and management.

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