2020-03-17

EVALUATION OF RESPONSE OF RAINFALL RUNOFF MODELS IN THE GILGEL ABAY WATERSHED, UPPER BLUE NILE BASIN, ETHIOPIA

AMARE, YESHIWAS

http://hdl.handle.net/123456789/10525

BAHIR DAR UNIVERSITY
BAHIR DAR INSTITUTE OF TECHNOLOGY
School of Research and Graduate Studies
Faculty of Civil and Water Resources Engineering

HYDROULIC ENGINEERING DEPARTMENT

Evaluation of the Response of Rainfall Runoff Models in the Gilgel Abay Watershed, Upper Blue Nile Basin, Ethiopia

YESHIWAS AMARE WALELEGNE

Bahir Dar, Ethiopia
December 24, 2017

EVALUATION OF RESPONSE OF RAINFALL RUNOFF MODELS IN THE GILGEL ABAY WATERSHED, UPPER BLUE NILE BASIN, ETHIOPIA

YESHIWAS AMARE WALELEGNE

A Thesis Submitted to the School of Research and Graduate Studies of Bahir Dar Institute of Technology, Bdu in Partial Fulfillment of the Requirements for the Degree of Master of Science in Hydraulic Engineering

Advisor Name:- Fasikaw Atanaw (PhD)

Bahir Dar, Ethiopia
December 24, 2017

DECLARATION

I, YESHIWAS AMARE, declare that the content of this thesis comprises my own work. In compliance with internationally accepted practices, I have acknowledged and refereed all materials used in this work. I understand that non-adherence to the principles of academic honesty and integrity, misrepresentation/ fabrication of any idea/data/fact/source will constitute sufficient ground for disciplinary action by the University and can also evoke penal action from the sources which have not been properly cited or acknowledged.

Name of the student : YESHIWAS AMARE

Signature ——————
Date of submission: ————————————————————-
Place: - Bahir Dar
This thesis has been submitted for examination with my approval as a university advisor.
Advisor Name: Fasikaw Atanaw (PhD)

Advisor's Signature: ————————————————————-

Dedication

This thesis is dedicated to my lovely sister, Meseret Derebew who proud a lot of love and a spirit of hard work and encouragement upon me round-the-clock until I feel I was at home. Finally, I lost you, May God rest your soul in peace!

Yeshiwas Amare

Bahir Dar University

Bahir Dar Institute of Technology-

School of Research and Graduate Studies

Faculty of Civil and Water Resources Engineering

THESIS APPROVAL SHEET

Student:

Yeshiwas Amare Walelegne February 26/2018
Name Signature Date

The following graduate faculty members certify that this student has successfully presented the necessary written final thesis and oral presentation for partial fulfillment of the thesis requirements for the Degree of Master of Science in Hydraulic Engineering.

Approved By:

Advisor:

Fasikaw Atanaw (PhD) February 26, 2018.
Name Signature Date

External Examiner

Fiseha Behulu Muluneh (PhD) February 26, 2018.
Name Signature Date

Internal Examiner

Mamaru Moges (PhD) February 26, 2018.
Name Signature Date

Chair Holder

Michael Mehari February 26, 2018.
Name Signature Date

Faculty Dean

Endalamaw Aragie Tefera
Faculty Dean
February 26, 2018.
Name Signature Date

ACKNOWLEDGEMENTS

At first and at most I would like to thank the one almighty God for giving me the courage and wisdom to reach this point in my life. I would like to express my sincere gratitude to my advisor, **Dr Fasikaw Atanaw**, for his unreserved assistance, constructive and timely comments at all stages of my work and also for supplying me relevant materials to carry out the research. I should strongly appreciate his patience full guidance in a lot of discussions we made on various problems I faced during the course of the work.

I am very grateful to Bahir Dar Institute of Technology, Department of hydraulic Engineering for allowing me to take part in the Master Program. Last but not least I would like to thank my dad **Amare Walelegne** and my lovely wife **Birtukan Ewnetu**, who have been always encouraging my academic undertakings with prayer and moral inspiration. I would like to express my warm feeling of appreciation and thank to my brother who helped me in all stages especially to **Dereje Hayilu**, brothers, sister and others, who were spiritually with me, and gave me the strength to finalize my duties successfully. Thanks for your encouragement and true friendship! Your friendship meant a great deal to me.

Finally, I would like to thank my earlier office "**TIS ESAT WWP.L.C**" and i would like to Kindly apologize my current respected office **(AWWCE)** higher officials since, they were giving different support, permission and advice to conduct my research paper.

ABSTRACT

There are a number of Rainfall Runoff models that used to predict the future runoff volume of a given catchment. But the result of each models above and under the observed flow, those evaluation of hydrologic model behavior and performance is commonly made and reported through comparisons of simulated and observed variables. mostly, comparisons are made between simulated and observed stream flow at the catchment outlet. In this study, a daily rainfall- runoff Model modeling is very helpful to evaluate the performance of each models and analysis the sensitive parameter of them for Gilgel Abay catchment by using five lumped conceptual models that are AWBM, Sacramento, SIMHYD, SMAR and TANK are check their performance with Rainfall-Runoff Library. The calibration and validation of the RRL models were performed using SCE-UA and Pattern search optimization methods together with Nash Sutcliffe criteria and runoff difference % as primary and secondary objectives respectively. The quality of fit between the observed and simulated flow is judged by stastical values and visual observation of scatter plots of observed vs simulated flow correlation and hydro-graph. Furthermore, performance of the models were assessed by using Nash Sutcliffe efficiency criteria.all of the models are applied to the catchment, using split record evaluation, involving the calibration and validation periods (about 70% for calibration and 30% for verification). model sensitivity analysis was undertaken to analyze the sensitivity of model parameters of the selected model with regard to its objective function and subsequently the most sensitive parameters for the model were determined. Based on the results all models can represent the observed flow in a very good performance. whereas, in a validation period AWBM and SIMHYD models, have a very good performance to represent the peak and low flow and over predict intermediate flow of the catchment because those models work on saturation and infiltration excess respectively. where as, Sacramento model has a limitation to capture low flow.so except Sacramento model the rest four models can be used to predict a Gilgel Abay river flow conditions for hydraulic design and other research's that uses flow data. Generally, AWBM model predicts the stream flow fairly well using SCE-UA optimization method with overall Nash Sutcliffe Efficiency of 0.86 and 0.81 for calibration and verification periods respectively.Base flow index BFI (base flow index) and KSurf (daily surface flow recession constant) are the most sensitivity parameters of AWBM. Generally, conceptual models have given encouraging results in Gilgel Abay catchment.

Keywords: Conceptual Rainfall Runoff models (CRRM), AWBM, Sacramento (SAC), SIMHYD, SMAR, Tank, calibration, verification, sensitivity, goodness of fit.

LIST OF ABBREVIATIONS

CRR	Conceptual rainfall-runoff
ANRS	Amhara National Regional State
AET	Actual Evapotranspiration
DEMs	Digital Elevation Model
ETo	Potential Evapotranspiration
E	Pan evaporation
Kp	Pan coefficient
Masl	Meter above sea level
RRL	Rainfall Runoff Library Model
AWBM	Australian Water Balance Model
SMAR	Soil Moisture and Accounting model
UBNB	Upper Blue Nile Basin
SIMHYD	Simplified version of HYDROLOG
ME	Mean Error
MAE	Mean Absolute Error
RMS	Root Mean Square Erro
NRMS	Normalized Root Mean Square Error
rSD	Ratio of Standard Deviations
SA	Sensitivity Analysis
Sac	Sacramento model
NSE (E)	Nash-Sutcliffe efficiency (cofficent of Efficency)
mNSE	Modified Nash-Sutcliffe efficiency
rNSE	Relative Nash-Sutcliffe efficiency
rd	Relative Index of Agreement
cp	Coefficient of Persistence
pbias	Percent Bias
KGE	Kling-Gupta efficiency
BFI	Base flow Index
UZTWM	Upper Zone Tension Water Maximum
UZFWM	Upper Zone Free Water Maximum
LZTWM	Lower Zone Tension Water Maximum
LZFSM	Lower Zone Free Water Supplement Maximum
$SCE - UA$	Shuffled Complex Evolution University of Arizona
Reff (LogReff)	Logartmic efficency
RVE	Relative Volume Error
VE	Volume Error
SRTM	Shuttle Radar Topographic Mission
ENMA	Ethiopian National Meteorological Agency

Contents

List of Figures

List of Tables

Chapter 1

INTRODUCTION

1.1 Background

Hydrological models are tools that describe the physical processes controlling the transformation of precipitation to stream flows. There are different hydrological models designed and applied to simulate the rainfall runoff relationship under different temporal and spatial dimensions. Among hydrological modeling tools, conceptual rainfall-runoff models are indispensable tools for flood studies and operational flood forecasting, for integrated catchment planning and flood emergency management (Tan et al. 2005).

Rainfall Runoff models have been developed that are based on conceptual representations of the physical processes of the water flow lumped over the entire catchment area. Examples of this type of lumped conceptual model are the Sacramento model (Burnash 1995) developed to estimate the peak flow of sarisso river and Tank model for of water resource planning purposes (Sugawara 1995).

Conceptual rainfall-runoff models generally have a large number of parameters which, because of their conceptual nature, cannot be measured directly therefore, estimated by calibration processes which involves adjusting the simulated discharge till it fits the corresponding observed discharges as closely as possible. Measurement of the deviation between the two series are mainly represented by the objective function. Therefore, the purpose of calibration is ultimately to find the values of the model parameters which reduce this deviation to a minimum or, in other words, those values which minimize the objective function (Franchini,1997).

The process of model calibration is normally done to estimate the model parameters either manually or automatically by using computer-based procedures. rainfall runoff models are also used for estimating flow of ungauged catchments whose parameters have been regionalized, as catchments with similar characteristics have similar hydrological behavior. Thus, it is possible to regionalize model parameters on the basis of catchment characteristics, i.e., to provide a regional parameter set where parameter values vary with measurable catchment characteristics (Seibert 1999).

Establishing a rainfall-runoff relationship is the central focus of hydrologic modeling from its simple form of unit hydrograph to rather complex models based on fully dynamic flux equations. As the computing capabilities are increasing, the use of these models to simulate a catchment response has become a standard. Models are generally used as utility in various areas of water resources development, in assessing the available resources, in studying the impacts of human interference in an area such as land use change, deforestation and other hydraulics structures such as dams and reservoirs (Moreda, 1999) .Rainfall-runoff models are useful tools where data are scarce and resources are under development. It is possible to generate runoff discharges from rainfall and meteorological data where river flow is not available (Beven, 2002) .

Estimation of runoff is essential in various kinds of water resources planning and studies. rainfall-runoff model are really helpful in calculating runoff from a basin. a rainfall-runoff model is a mathematical model describing the rainfall-runoff relations of a catchment area, drainage basin or watershed. Rainfall runoff models have their own parameters that are used for simulation of the flow. these models permit calculation of the runoff generated by precipitation events by simulating the physical process that affect the movement of water over and through the soil. The accuracy of these calculations depends both on the structure of the model and on how the relevant parameters are defined.

Rainfall-runoff models have been under a continuous state of development. Models used in the earlier days did not integrate the different phases of the hydrological cycle. Instead, they implemented simplified mathematical relationships between precipitation and certain attributes of the final catchment's response. However, estimation of runoff is essential in various kinds of water resources studies. Runoff estimation is normally based on rainfall runoff process. In order to model rainfall-runoff process, a variety of hydrological models have been applied (Hundecha, 2005) .

Now the target of this research is to undertake rainfall runoff modeling by applying rainfall runoff library which is a catchment modeling tool and a cocktail of different conceptual rainfall run off models to establish a relationship between various hydrological components such as precipitation, evapotranspiration, and surface runoff for the selected catchments of Gilgel Abay catchment.

1.2 Significance of the Study

The purpose of this study is to evaluate the performance of five daily conceptual rainfall runoff models on a humid watershed in the Blue Nile basin. The result of this study can be used to identify the best conceptual rainfall-runoff model that best captures the hydrological process of a watershed in a humid region.

1.3 Statement of the problem

Hydrologists and engineers need planning tools for the effective utilization of water resource and predicting the future demand. It is the state of the art to use hydrologic models for the planning process of different kinds of water resource development projects. Currently, a number of rainfall-runoff models exist for generation of flow and establishing a rainfall-runoff relationship at different time steps. However, in areas where data are sparsely and scarcely available the realistic solution to model the flow is to apply conceptually sound lumped rainfall-runoff models with minimum number of parameters.

Models are designed conceptually with a simplification to capture the essential response characteristics of a catchment or capture the dominant hydrological processes. In the same manner, Gilgel Abay river flow was forecast by different models using monthly and short duration input data's. In this study we consider five CRR Australian models with different conceptualization to the hydrological process and test which ones is best capturing the processes in a humid catchment like Gilgel Abay using long duration daily time series data. Therefore, this study is conducted to understand the runoff generation mechanisms at the Gilgel Abay catchment (a major tributary into lake Tana, source of Blue Nile, Ethiopia) and to evaluate which conceptual rainfall-runoff hydrological model mimics the behavior of the watershed.

1.4 Research Question

1. Which model best performs or suits the study area in the calibration and validation periods?
2. Why is that model best performing?

1.5 Objectives of the study

1.5.1 General Objective

The main objective of this study is to conduct daily rainfall-runoff modeling by using daily time series rainfall, evapo-transpiration and flow data to select the best conceptual rainfall-runoff model that captures the hydrological process of the Gilgel Abay catchment.

1.5.2 Specific Objectives

- Evaluate performance of five rainfall-runoff models.
- To identify the sensitive parameters of the selected model.
- Analysis the selected Models on the basis of catchment characteristics.

1.6 Organization of the Thesis

This paper is organized into five sections. The first section states about the introduction or background of study, statement of the problem, objectives of the study . In section two, review of related literatures and rainfall runoff models. Section three describes about methodology, data collection, and description of the study area, description of used models, calibration and validation process, model performance evaluation and sensitivity analysis of best performed model. Section Four describes about the results and discussion of the study. Finally, in the last section, conclusions and recommendations of the study are provided.

Chapter 2

LITERATURE REVIEW

2.1 Rainfall runoff Models

Rainfall Runoff models are currently still in use despite continued expansion in computer capabilities that have far surpassed what is required of the models and that have provided fresh encouragement for proponents of physically based, distributed models (Hornberger,1995) . In spite of this, it is unlikely that the acceptance of conceptual Rainfall Runoff models will decline, for there are many modeling environments for which these models are most suited. Therefore, research on these models needs to continue to address the many shortcomings that still plague application of conceptual Rainfall Runoff models. The growth in the speed and capacity of digital computing equipment from the early 1960's was a significant stimulus to the development of various mathematical models for investigating the rainfall-runoff process. arising from this were models such as: the Stanford Watershed Model IV (Crawford,1966); the Boughton,1966); the APIC model (Sittner et al. 1969); nowadays, the conceptual lumped rainfall-runoff model widely used in hydrology for the propose of flood forecasting (Kumela.T,2011) . Rainfall-Runoff models can also be used for processing the daily rainfall and reference evapo-transpiration at basin scale, reproduces surface and subsurface runoff, soil moisture dynamics and actual evapo-transpiration fluxes. The Sacramento soil moisture accounting model is also used to assess the hydrological catchment property (Viola et al. 2014).

Spatial and temporal variability and complexity of hydrological processes and limited availability of spatially and temporally distributed hydro-logic, climatologic, geologic, and land use/land cover data challenge the ability to forecast hydrological data. hydrological models are useful tools to solve such practical problems of forecasting hydrological data. from operational water resources management point of view hydrological models are developed to guide the formulation of water resource management strategies by understanding spatial and temporal distribution of water resources (Tadele,2012). In terms of spatial domains in catchment modeling, models can be classified as lumped, distributed and semi-distributed ones.

The lumped model ignores spatial distribution of the catchment characteristics, represented by an average single value. In contrast, distributed model approaches capture the system by partitioning the catchment into a number of smaller units. Semi-distributed model is something in between the first two that means the catchment is partitioned but in a coarser unit as compared with distributed model. In another classification, based on deterministic rainfall-runoff models and mathematical solutions, models are classified into physical, conceptual, and empirical models.

1. Physically based models are based on physical laws that include a set of conservation equations of mass, momentum, energy and specific case entropy to describe the real-world physics that governs nature (Dingman, 2015).
2. Conceptually based models consider physical laws but in a simplified form that is able to explain the hydrologic behavior by empirical expression. Examples of this approach are HEC-HMS SMA, AWBM, SIMHYD,Tank, SMAR, Sacramento, TOPMODEL, HBV.
3. Empirically based models do not aid in physical understanding. However, they contain parameters that may have physical characteristics that allow the modeling of input-output patterns based on empiricism. Examples of this approach are unit hydro-graph, rational method, etc.

Physically based hydrological models are theoretically better process based than conceptual models but require extensive data and need less tuning of parameters. With their less data demanding character, the principle on which conceptual rainfall-runoff models is best, it is sufficient to produce reasonably accurate output. Especially in conditions where there is scarcity of data in the study area, which is a common situation in many developing countries (Liden,2000). However, (Bergstrom, 1998) discussed that, nowadays both physically-based and conceptual models are applied by dividing large catchments into sub-catchments.

Catchment modeling can be used to assess its water resource potential and needs choosing the appropriate modeling approach. (Uhlenbrook et al. 2004) indicated that applicability of lumped, physically based and conceptual model approaches is restrained by various factors. Use of lumped type modeling approach is mired in its incapability to extrapolate output for future change in model variables. On the one hand, the need for vast data and the sub-grid variability of model variables make the use of physically based distributed modeling approach difficult for basins of larger sizes than the experimental headwaters. the availability of input data and their simplicity make conceptual rainfall-runoff models handier than the other two approaches.

2.1.1 Previous Studies

Water resource development in Lake Tana basin has been studied at different stages of details by different consultants of various times since the 1900s. The most relevant studies carried out are presented as follows:

The study conducted by the United States department of the interior, bureau of reclamation in 1964 is named as study of land and water resource of the Blue Nile and at this time there was no enough available data recorded. This study was conducted at reconnaissance level mainly done to identify considerable potentials for irrigation and hydro power in both Tana and Beles basins. The USBR studies have also proposed a regulation dam for Lake Tana at charachara with the objective to the upper Beles hydro power plant. USBR,1964).

Melkamu has carried out Rainfall-runoff modeling applied to estimate total water resources potential of Lake Tana sub basin. He carried out the water balance simulation on monthly time step. Evaporation was estimated by a combination of Mass transfer and Energy budget method. (Melkamu, 2005). The hydrological modeling of Ethiopian catchments using limited data shown on Gilgel abay and Gumara catchment are both on temperature are not representative in a physical based model (Mekonnen et al. 2009). There is a methodology present to study impacts of climate change on Gilgel Abay river with a catchment area.

The changes in land cover in the upper Gilgel Abay catchment that changes in stream flow records are a result of changes in land cover and changes in the annual and seasonal distribution of rainfall. In terms of land cover changes, most pronounced is the relatively large decrease of forested area and the large increase of agricultural land (Rientjes et al. 2011) .also, hydrological response to climatic change of the upper Blue Nile River basin: based on IPPC fifth assessment of report (AR5)(Legesse,2015). Understanding spatial and temporal distribution of water resources has an important role for water resource management.(Gragne et al. 2008)

Although the above reviewed literature has been conducted regarding to hydrological response to the change in land use and land cover in a catchment and also assessing the effects of watershed characteristics in a river flow by using some hydrological model. Evaluating the climate anomalies impacts on the Upper Blue Nile Basin (UBNB), Ethiopia, was investigate using Sacramento model by Mohamed Helmy Elsanabary, he wrote a large basin with scarce hydro climatic data, through hydrologic modeling is a challenge. A fully distributed, physically-based model, a modified version of the Interactions Soil, Biosphere Atmosphere model of Motto France (MISBA), and a lumped, conceptual rainfall runoff Sacramento model, SAC-SMA of the US National Weather Service, were used to simulate the stream flow of the basin, the results provide useful information on the effects of global oceanic anomalies on the hydrology of UBNB.

The rainfall runoff process is well described in many literature's. Numerous papers on the subject have been published and many computer simulation models have been developed. All these models, however, require detailed knowledge of a number of factors and initial boundary conditions in a catchment area, which in most cases are not readily available, due to this reason most of the researchers use short duration input data (not more than 10 years). Therefore, some researches have a difficulty of accurately predicting the amount of runoff a study area that is resulting from a rainfall event, (Elsanabary et al,2015) all the above reviewed literature are not consider the influence the rainfall-runoff process and the degree of performance of the model are not evaluated. It also includes popular model-independent and multi-objective parameter optimizers, including the Pattern Search, Shuffled Complex Evolution Uniform random search, Multi start pattern search, Rosenbrock method, Multi start Rosenbrock search and Genetic Algorithm are methods of optimization. To calibrate the model there is a number of primary and secondary calculation objectives. In addition, a custom parameter optimization method for AWBM is provided. The RRL has powerful visualization and data handling features. It is expected that end-users will be more willing to trial a range of models and parameter estimation methods on their particular modeling problem as the 'cost 'of moving from one method to another is relatively minor given the common interface elements.

In this study, the response of Gilgel Abay watershed for five rainfall runoff models are review and the comparison of Rainfall-Runoff models are done on the catchment to evaluate the performance of selected model by using at least 22 years of data. The RRL includes Five rainfall-runoff models those are AWBM, SIMHYD, Sacramento, SMAR and TANK. All the five models are conceptual lumped parameter models. Model calibration was carried out for selected periods for which complete data sets were available on river flow, rainfall and Evaporation.

Chapter 3

METHODOLOGY AND DATA ANALYSIS

3.1 General

Hydrological modeling to a large extent depends on hydro-meteorological data (precipitation, temperature and potential evapotranspiration) and hydrological data (river discharge). Reliability of the collected raw hydro-meteorological and hydrological data significantly affects quality of the model input and the model output. This chapter sequentially presents, data screening of raw hydro meteorological and hydrological data, completion of identified missing data, estimation of areal rainfall and temperature for the study area, and analysis is done to check consistency and homogeneity of the estimated areal data sets.

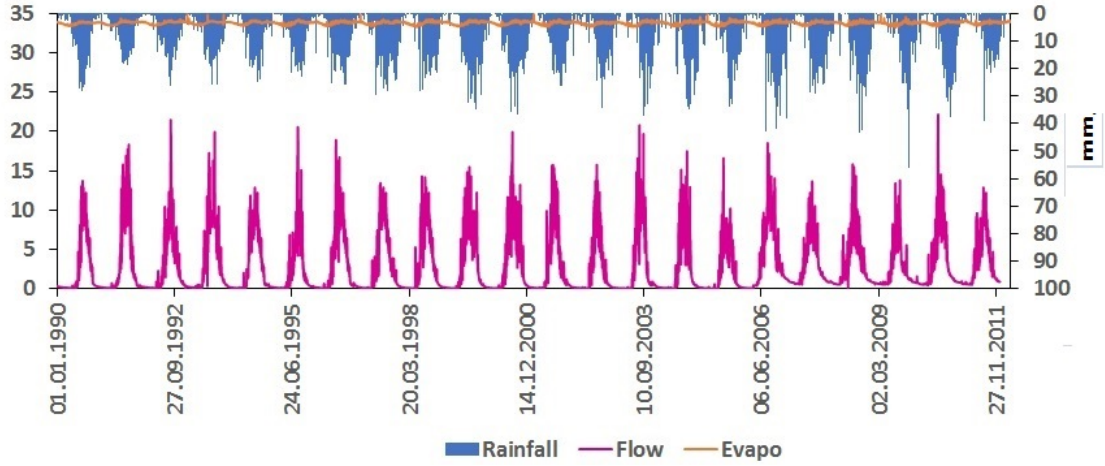


Figure 3.1: Daily Areal rainfall, flow and Evaporation on Gilgel Abay catchment

It is the state of the art to use hydrologic models for the planning process of different kinds of water resource development projects. Currently, a number of rainfall runoff models exist for generation of flow and establishing a rainfall-runoff relationship using different time steps. However, in areas where data are sparsely and scarcely available the pragmatic solution is to apply conceptually sound lumped rainfall-runoff models with fewer parameters such as models included in Rainfall Runoff Model. In this study, a daily rainfall- runoff modeling which is very helpful to further strengthen assessment, planning and management of water resource in the Gilgel Abay watershed using five models namely AWBM, Sacramento, SIMHYD, SMAR and TANK models in Rainfall-Runoff library.

3.2 Methodology

Generally, the study involves the following procedures:

1. Collection of important data for the study such as, meteorological data, hydrological data topographical and digitized map of the Gilgel Abay watershed.
2. Data quality checking and Analysis (checking for gaps, continuity, homogeneity/ consistency.
3. Flow generations from rainfall and evaporation data by using RRL.
4. Calibration and Verification of models.
5. Comparison of generated and simulated flows.
6. Determination of model parameters.
7. Sensitivity Analysis of model parameters.

3.3 Data Collection and Analysis

Hydro- meteorological data that are necessary and important to undertake rainfall runoff modeling were collected from the different sources using official supporting letter written from Bahir Dar university for Regional water resource and development Bureau, Tana basin Authority, Amhara Regional meteorological Agency.

These data were collected from the above governmental offices and my advisor. the collected data includes, daily rainfall data, evaporation data, flow data. In addition, collection of meteorological data such as temperature, wind speed, pan evaporation, humidity which support the modeling work and available at existing meteorological stations-in the nearby and inside the study area were undertaken from them. Model calibration and verification more than anything relies on the quality of data available (RRL 2004). the most important step in rainfall runoff calibration is data preparation and analysis. time spent in ensuring that the best possible data set is used will greatly speed up the calibration process.

Then, data quality analysis such as checking for outliers and gaps has been done using appropriated methods. Next, the necessary data quality checking and analysis were accomplished. The major input data for conceptual rainfall-runoff models are daily rainfall, evapo-transpiration and observed discharge.

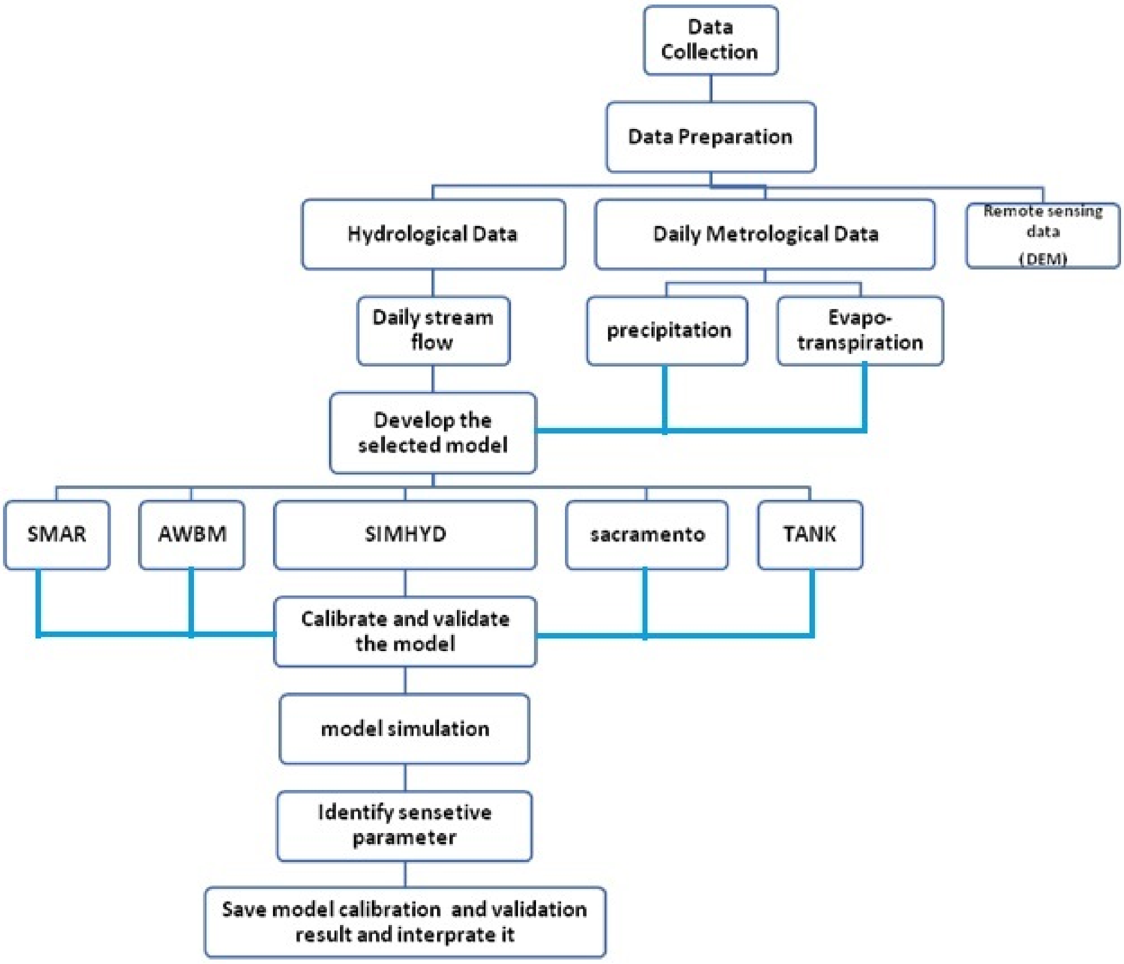


Figure 3.2: Methodology flow chart

3.3.1 Meteorological Data

NMAS Bahir dar branch is the responsible organization for the collection and issuing of meteorological data. There are a number of rainfall ganging stations in the whole Catchment. Some of are not fully recorded and have not daily Evaporation, wind speed and humidity Among the total gauging stations, precipitation data were available in the Catchment to represent the rainfall distribution. However, these all stations are not selected for the modeling. according to assessment made some stations are not functional, only part of them got a good record of data. some of non selected Gauging station has days with out records scattered with in a year and whole months or even whole years without recording can be found in the dataset.
Most of the stations are short time-recording type and few are recording type. only Adet, Dangela, Enjibara, Gundil, Sekela and wotet Abay stations are long time recording type. The calibration and validation periods are shown by the number of days in the ranges of 1 up to 5110, that are 5110 days (from 1990 upto 2003) and 5111 up to 8032 that are 2922 days (from 2004 up to 2011) respectively.

Rainfall

A continuous time series of daily rainfall data that represents the rainfall across the catchment, from (1990-2011) in mm/day is adopted from the National Meteorological Agency. All the data sheets received from Meteorological Agency are manually checked for gaps to roughly assess the quality and reliability of data. In the preparation and data quality checking of rainfall data point-rainfall and catchment or areal-rainfall are considered. The number of stations are very important components when multiple rainfall sites are available. Typically, to fill the missing data Arithmetic Mean method and Theisson weightings are also used to associate a portion of the catchment with each rainfall station.

Filling in Missing Rainfall Data

Gaps in a rainfall records are common for a variety of reasons. A gauge may have been installed after the period of interest or may have been closed down for some period. Moreover, it may not have been functioning properly or may not have been read regularly. In order to fill the missing rainfall data, joint application of the regression analysis and spatial interpolation techniques are used to complete short and long period breaks in data series for a given meteorological station. Measured precipitation data are important to many problems in hydrologic analysis and design. For gauges that require periodic observation, the failure of the observer to make the necessary visit to the gauge may result in missing data. Vandalism of recording gauges is another problem that results in incomplete data records, and instrument failure because of mechanical or electrical malfunctioning can result in missing data. Any such causes of instrument failure reduce the length and information content of the precipitation record. A number of methods have been proposed for estimating missing rainfall data. The station-average method is the simplest method. The normal-ratio and quadrant methods provide a weighted mean, with the former basing the weights on the mean annual rainfall at each gauge and the latter having weights that depend on the distance between the gage where recorded data are available and the point where a value is required. The isohyetal method is the fourth alternative. For this study, normal ratio method is used method, because normal-ratio method is conceptually simple, but it differs from the station-average method in that the average annual catch is used to derive weights for the rainfall depths at the individual stations.

Areal rainfall

Measurements at meteorological stations are considered point rainfalls. In order to change the point rainfall to an average areal rainfall is determined by one of the following three methods: These methods are the Arithmetic mean, the Thiessen polygon and the Isohyetal method etc. However, the thiessen polygon was used for this study its sound theoretical basis and availability of computational tools. But the method is dependent on a good network of representative rain gauges.

To determine the mean areal rainfall, the rainfall amount of each station is multiplied by the area of its polygon and the sum of these products is divided by the total area of the catchment. If P_1, $P_2 \ldots P_n$ are the rainfall magnitudes recorded by the stations 1, 2 and n respectively and A_1, $A_2 \dots A_n$ are areas of Thiessen Polygon, then the average rainfall over the catchment P_w is given by:-

$$P_w = \frac{P_1A_1 + P_2A_2 + P_3A_3 + P_nA_n}{A_1 + A_2 + A_3 + A_n} \tag{3.1}$$

$$P_w = \frac{\sum(P_n * A_n)}{\sum A_T}$$

Stations	**Lat.**	**Long.**	**Area**	**Wt.**
Adet	335176	1246258	7.46	0%
Dangela	265275	1244482	398.05	24%
Enjibara	230809	1318955	0	0%
Gundil	292304	1201149	67.19	4%
Sekela	303324	1215463	775.44	47%
W.Abay	281748	1257642	407.66	25%
Total			1656	100%

Table 3.1: Rainfall stations and their weight-age for the Gilgel Abay catchment

Based on table 3.1 intersecting the Thiessen polygon over the Gilgel Abay catchment and Adet and Enjibara stations have less area coverage, so they are out of the computation.

Evapo-transpiration

A continuous time series of potential evapotranspiration (PET) or actual evapotranspiration data that represents the evapotranspiration across the catchment. the type of evaporation data expected will vary from model to model, and only the appropriate data should be used. we computed the potential evapo-transpiration using Penman Moneth method.

Figure 3.3: Distribution of rainfall and flow gauging stations in Gilgel Abay Catchment.

There are number of methods to estimate potential evapo-transpiration. However, the methods vary based on climatic variables required for calculation. the temperature based method use only temperature and sometimes day length; the radiation based method uses net radiation and air temperature some other formula like Penman requires a combination of the above net radiation, air temperature, wind speed, and relative humidity. The FAO Penman Monteith method is recommended when sunshine,humidity and wind speed data's are only available (Allen et al.., 1998) where as stations which is only temprature data are avilable we use Hargreaves method. In this research we use Hargreaves method to calculate ETo of Gundil, sekela, Enjibara and Wetete Abay stations. where as for Adet and Dangela we use Penman Monteth method. Where,

$$ETo = \frac{0.408(R_n - G)\gamma\frac{900}{T+273}u2(e_a - a_s)}{\gamma + \varDelta(1 + 0.34u_2)} \tag{3.2}$$

ET_0 = reference Evapotranspiration (mm day^{-1})

R_n = net radiation at the crop surface ($MJm^{-2}day^{-1}$)

G = Soil heat flux density ($MJm^{-2}day^{-1}$)

T = air temperature at 2m height (^0C)

U_2 = wind speed at 2m height (ms^{-1})

e_s = saturation vapor pressure (kPa)

e_a = actual vapor pressure (kPa)

$e_s - e_a$ =saturation vapor pressure deficit (kPa)

Δ= slope vapor pressure curve (kPa^0C^{-1})

Potential evapotranspiration for the study area was computed by FAO Penman Monteith method. The long-term potential evapotranspiration was computed for all stations to be used as input for all conceptual hydrological models.

3.3.2 Test for Consistency/Homogeneity

According to Chang and Lee (1974), a time series of hydro-meteorological data is relatively consistent if the periodic data are proportional to an appropriate simultaneous time series (Dahmen,1990) . In other words, relative consistency means mechanism that generated similar or related data at other stations. For Gilgel Abay, TREND software which has 12 statistical tests, based on the WMO/UNESCO Expert Workshop on Trend/Change Detection and on the CRC for Catchment Hydrology publication Hydrological Recipes.

$$Sk = \sum_{i=1}^{k}(Xi - X^{-}) \tag{3.3}$$

where Xi are the records from the series X1, X2, . . . , Xn and X the mean. (where k = 1,........,n) The initial value of Sk=0 and last value Sk=n are equal to zero (Figure 3.1). When plotting the Sk's (also called a residual mass curve) changes in the mean are easily detected. For a record Xi above normal the Sk=i increases, while for a record below normal Sk=i decreases. For a homogeneous record one may expect that the Sk's fluctuate around zero since there is no systematic pattern in the deviations of the Xi's from their average value X To test the homogeneity of the data set, TREND resample the cumulative deviations by dividing the Sk's by the sample standard deviation value. By evaluating the maximum (Q) and the range (R) of the rescaled cumulative deviations from the mean, the homogeneity of the data of a time series can be tested. High values of Q or R are an indication that the data of the time series is not from the same population and that the fluctuations are not purely random. Critical values for the test-statistic which test the significance of the departures from homogeneity are plotted as well

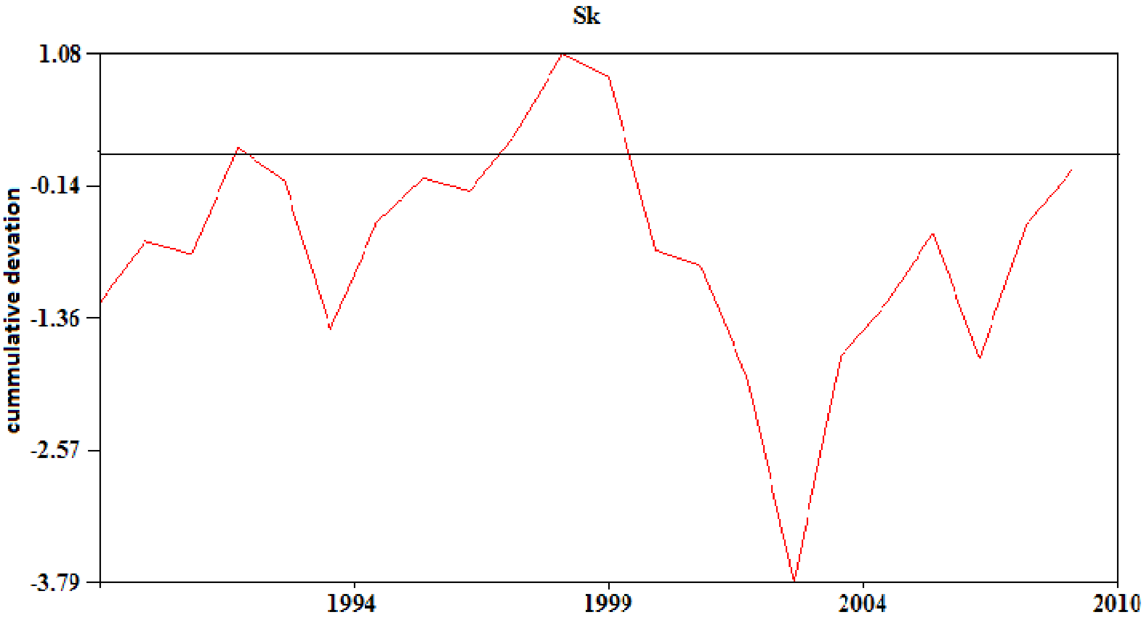


Figure 3.4: TREND 90, 95 and 99% probability lines

3.4 Description of the study area

3.4.1 Location

Gilgel Abay is the largest tributary of the Lake Tana basin, Ethiopia. This watershed is located in West Gojjam and Awi Administrative Zones of the Amhara National Regional State (ANRS) of Ethiopia. The watershed area comprises of 10 Woredas namely: Mecha, South-Achefer, Dangla, Sekela, Fagtalakuma, North-Achefer, Bahir-Dar zuria, Banja, Quarit and Yilmanedensa.

In terms of geographic coordinate system, the watershed lies between 10.95^0 and 11.8^0 North latitudes and 36.7^0 and 37.4^0 East longitudes. Gilgel Abay originates from the Southern side of the Lake Tana watershed and flows in to the North direction and forms part of the Lake Tana basin (Figure 3.5). The total area of the watershed is estimated to be 1656 Km^2.

3.4.2 Topography

The elevation of the upper Gilgel Abay catchment varies from 1934 to 2917 m.a.s.l from analysis of SRTM-DEM (Shuttle Radar Topographic Mission Digital Elevation Model) as shown in figure 3.6 on the south-eastern ridges and northern most parts of the catchments where the highest and the lowest elevations are located respectively. The slope of the catchment was classified to gentle (0.6%), steep (7-14%)and excessive (>14%) slope classes (S Uhlenbrook & Gragne, 2010).About 80% of the catchment area falls in the slope range of (0-7.8%),15% of the area falls in the slope ranges of (9-21%)and the remaining 5% is steeper than (22%). It was also stated that the excessive slope of the catchment area lies in south east and decrease to the north (refer Figure 3.6.

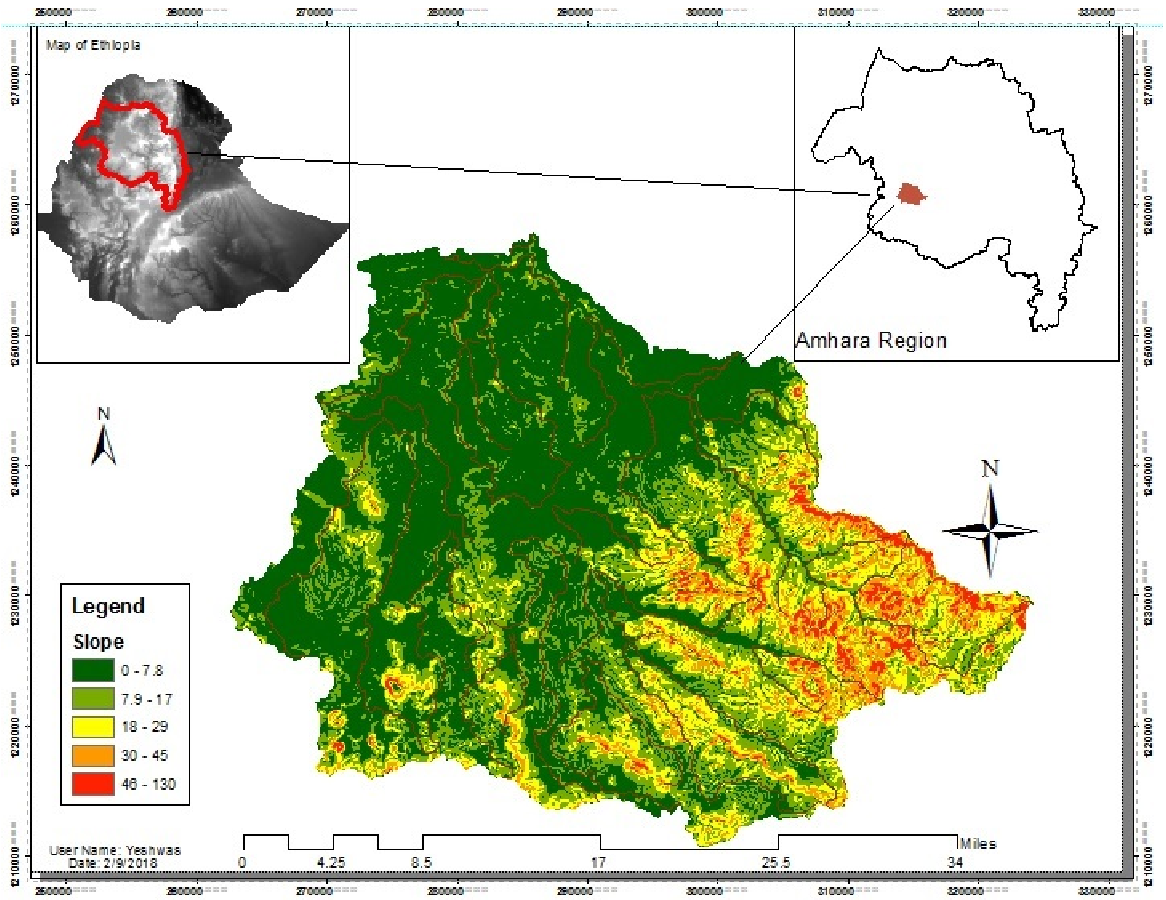


Figure 3.5: Location of Gilgel Abay Catchment.

Generally, the catchment area is mountainous and it is highly dissected terrain with steep slopes in the upstream part, and an undulated topography and gentle slopes in the downstream part.

3.4.3 Climate

The climate of Ethiopia can be classified in different ways according to the Traditional, Koppen's, Throthwaite's, Rainfall regimes and Agro-climatic zone classification systems (deressa, 2008) .

The most common used classification systems are the traditional and the agro-ecological zones. The traditional classification system, mainly relies on altitude and temperature; there are five climatic zones namely: Wurch (cold climate at more than 3000 Mts. altitude), Dega (temperate like climate-highlands with 2500-3000 mts altitude), WoinaDega (warm at 1500-2500 Mts. altitude), Kola (hot and arid type, less than 1500m in altitude), and Berha (hot and hyper-arid type) climate (NMSA, 2001). Therefore Gilgel Abay watershed lies in the WoinaDega zone. There is high spatial and temporal variation of rainfall in the study area. The main rainfall season which accounts around 70-90% of the annual rainfall occurs from June to September, while small rains also occur occurs during December to March.

The monthly rainfall distributions of the study area indicates that July and August are

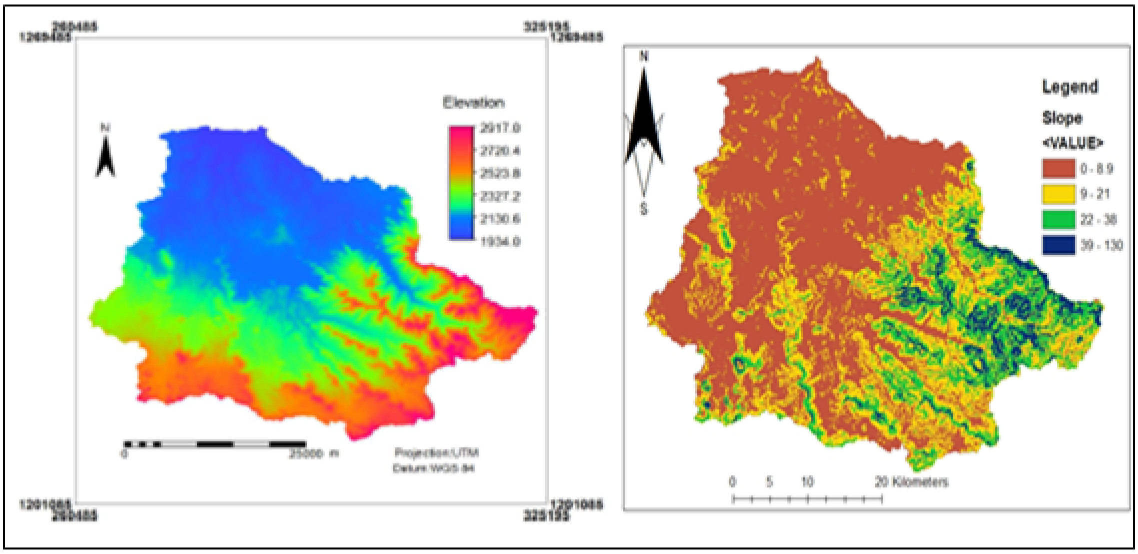


Figure 3.6: Slope and elevation of the Gilgel Abay Catchment.

the wettest months of the year in all the selected stations. Daily runoff values for the gauging station that is to be modeled. These data are used for model calibration and checking. The accepted flow units are mm/day, for this study flow data was collected from Abay basin Authority and ANRS Irrigation and water resource and development Bureau this is used to convert inputs and outputs between flow and depth of runoff. Total catchment area of the catchment is 1656 km^2.

3.5 Description of used models

The conceptual models occupy an intermediate position between the fully physical approach and empirical black box analysis. Such models are formulated on the basis of a relatively small number of components, each of which is a simplified representation of one process element in the system being modeled. The purpose of this break down is primarily to enable the run off from the catchments to be estimated using standard parameters together with actual data. In majority of cases, the watershed characteristics are lumped, many of the processes are lumped, the input is lumped and even some of the boundary conditions are lumped, but some of the processes that are directly related to the output are distributed. Moreover, lumped models do not need as detail input data as distributed models. This makes them more suitable for regions with poor data source.

3.5.1 AWBM Model

Model Description

The AWBM is an acronym for Australian Water Balance Model that can relate rainfall to runoff with daily or hourly data, and calculates losses from rainfall for flood hydrograph modeling. AWBM is run on daily time step. AWBM requires evapotranspiration as an input whereas most models will take PET as input. The model uses 3 surface stores to simulate partial areas of runoff. The water balance of each surface store is calculated independently of the others (figure 3.5). The model calculates the moisture balance of each partial area at either daily time step. At each time step, rainfall is added to each of the 3 surface moisture stores and evapotranspiration is subtracted from each store. The water balance equation is:

$$store_n = store_{ni} + rain - evap \quad \text{when, n=moisture store 1 to 3} \tag{3.4}$$

where:-$store_n$the amount of moisture in sore n, $store_{ni}$ is the previous moisture or avilable moisture in store n. If the value of moisture in the store becomes negative, it is reset to zero, as the evapotranspiration demand is superior to the available moisture. If the value of moisture in the store exceeds the capacity of the store, the moisture in excess of the capacity becomes runoff and the store is reset to the capacity. The three parameters A_1, A_2 and A_3 representing the proportions of the areas of the catchment are constrained; thus, only A_1 and A_2 can be set. The default pattern is A_1 = 0.134, A_2 = 0.433, A_3 = 0. 433 and this pattern is fixed (i.e. calibration tools will not modify it). When A_1 and/or A_2 are changed, A_3 will be adjusted to respect the constraint. If the user increases A_1, and A_3 cannot compensate, then A_1 is reduced to still respect the constraint.

When runoff occurs from any store, part of the runoff becomes recharge of the base flow store if there is base flow in the stream flow. The fraction of the runoff used to recharge the base flow store is BFI*runoff, where BFI is the base flow index, i.e. the ratio of base flow to total flow in the stream flow. The remainder of the runoff, i.e. (1.0 - BFI) * runoff, is surface runoff. The base flow store is depleted at the rate of (1.0 - K) * BS where BS is the current moisture in the base flow store and K is the base flow recession constant of the time step being used (daily or hourly).

The surface runoff can be routed through a store if required to simulate the delay of surface runoff reaching the outlet of a medium to large catchment. The surface store acts in the same way as the base flow store, and is depleted at the rate of (1.0 - KS) * SS, where SS is the current moisture in the surface runoff store and KS is the surface runoff recession constant of the time step being used.

Default values of model parameter

The AWBM is configured with a set of default values for each model parameter. These default values specify the initial parameter value plus the upper and lower bounds for that parameter.

parameter	Default Value	Minimum Value	Maximum value	Remark
A_1	0.134	0	1	Fixed
A_2	0.433	0	0.866	Fixed
BFI	0.35	0	1	
C_1	7	0	50	
C_2	70	0	200	
C_3	150	0	500	
K_{base}	0.95	0	1	
K_{surf}	0.35	0	1	

Table 3.2: Default Values of AWBM parameters

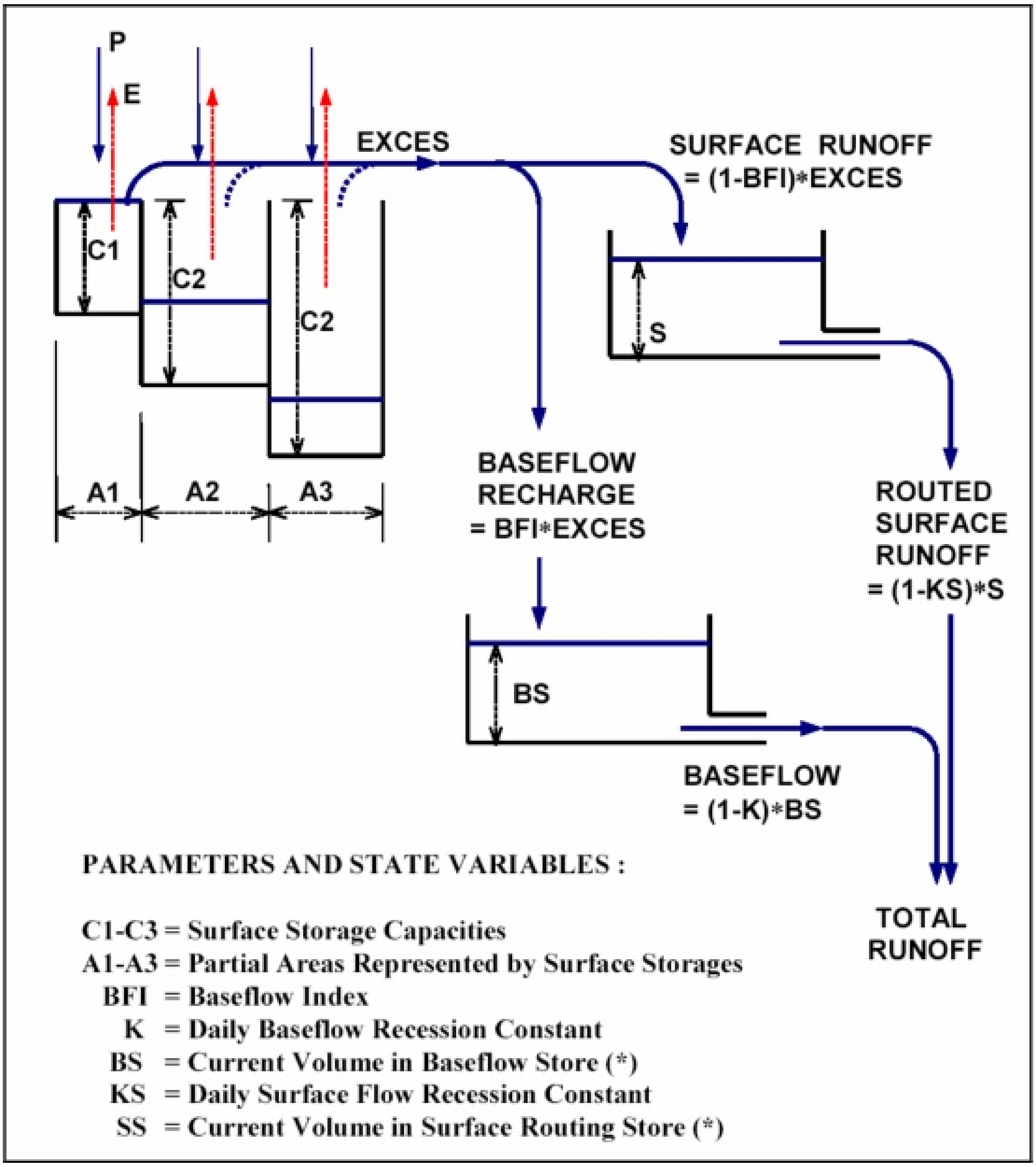


Figure 3.7: Structure of the AWBM model (Source:WWW. toolkit.net.au/rrl)

3.5.2 Sacramento Model

Model Description

Sacramento model is a Spatially-lumped continuous soil moisture accounting model and it is ideal model for the simulation of large-scale (over 1000 km2) basins takes mean precipitation, evaporation and temperature as input.

The model accounts for all water entering, stored in, and leaving a drainage basin. though many parameters are used in this water balance accounting process, precipitation has the main impact on runoff. model calibration by adjusting base flow, tension water capacities and runoff simulation parameters.

Inputs for a model are Point or areal estimates of historical precipitation, temperature, and potential evaporation, Topography, Soil characteristics, Location of important features such as reservoirs and river junctions.

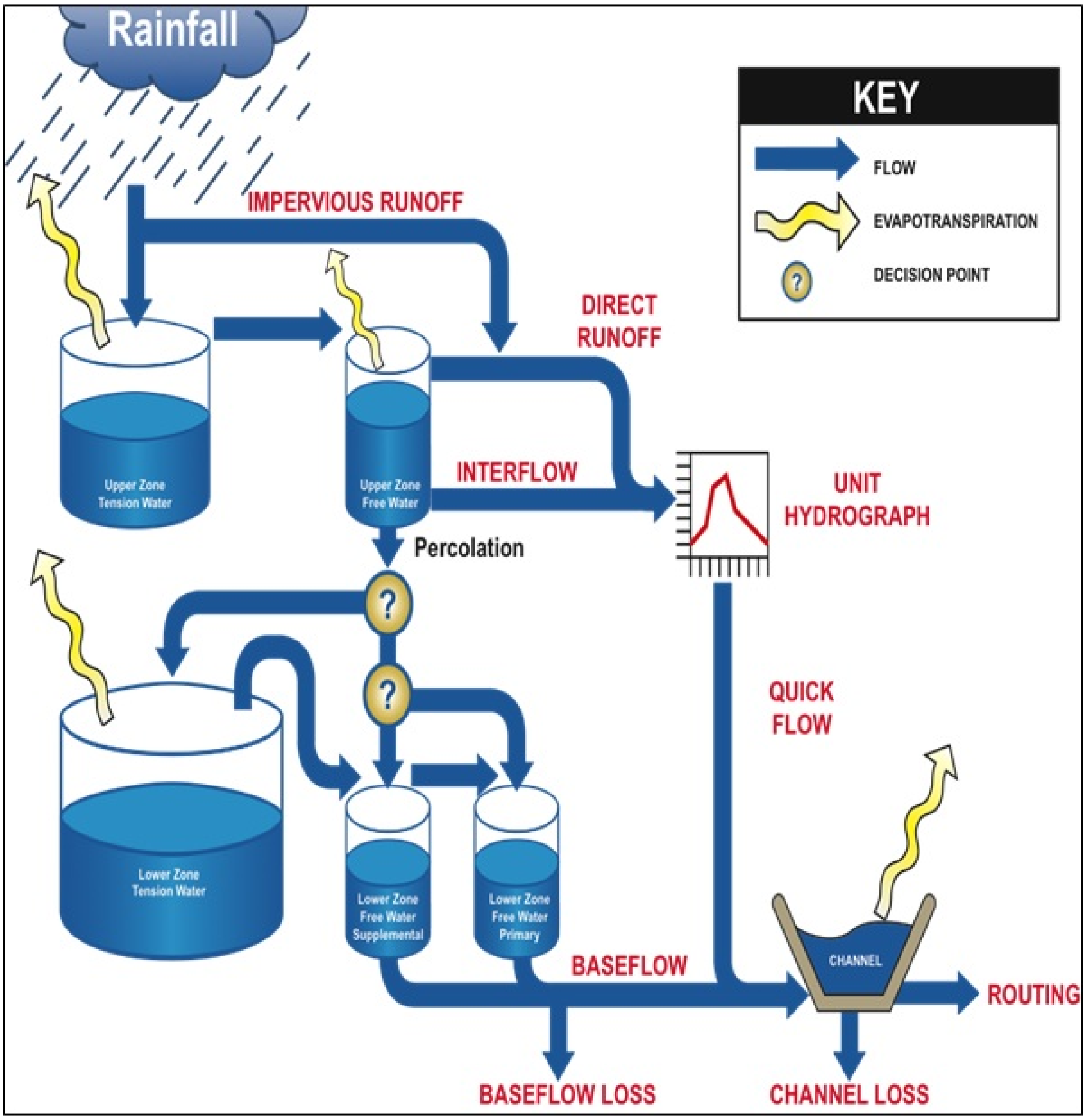


Figure 3.8: Structure of the Sacramento rainfall runoff model

Principle of the Sacramento Model

The Sacramento Model uses soil moisture accounting to simulate the water balance within the catchment. Soil moisture storage is increased by rainfall and reduced by evaporation and by flow of water out of the storage. the size and relative wetness of the storage then determines the depth of rainfall absorbed, actual evapo-transpiration, and the amount of water moving vertically or laterally out of the store. rainfall in excess of that absorbed becomes runoff and is transformed through an empirical unit hydrograph or similar device. lateral water movements from the soil moisture stores are superimposed on this runoff to give stream flow. the Sacramento model uses a total of 16 parameters to simulate the water balance. Of these:

- 5 define the size of soil moisture stores,
- 3 calculate the rate of lateral outflows,
- 3 calculate the percolation water from the upper to the lower soil moisture stores,
- 2 calculate direct runoff
- 3 calculate losses in the system

Default values of model parameter

The RRL is configured with a set of default values for each model parameter. These default values specify the initial parameter value plus the upper and lower bounds for that parameter. Table 3.4 lists the default values for the Sacramento model.

Stores

There are five stores in the Sacramento Model:

1. Upper zone tension water (UZTW)
2. Upper zone free water (UZFW)
3. Lower zone tension water (LZTW)
4. Lower zone primary free water (LSFWP)
5. Lower zone supplementary free water (LZFWS)

The tension water stores represent the volume of water that is held in the soil matrix by surface tension. Water can only be removed from tension stores by evapotranspiration. In the free water stores water can move through the soil vertically to other stores, or laterally as interflow (upper zone) or as base flow (lower zone).
Water movement through the stores is determined by rules, where the UZTW store receives the rain first, and when this is filled water will go to the UZFW store. The UZFW store then supplies water to the lower stores simultaneously, with a user determined split between the free water and tension water stores. When the LZFWS is filled water will go to the tension water stores.

Evapotranspiration

Evapotranspiration can only take place from upper and lower tension water stores and upper free water stores, and directly from the streams. The upper limit of evaporation is the evaporative demand, and is the product of the pan evaporation modified by the (user-specified) pan factor. Evaporation occurs first from the UZTWS, then from the UZFWS, and lastl from the LZTWS. Evaporation can also occur directly from the stream as set by SARVA.

Parameter	**unit**	**Description**
UZTWM	mm	Upper Zone Tension Water Maximum. The maximum volume of water held by the upper zone between field capacity and the wilting point which can be lost by direct and evapotranspiration from soil surface. This storage is filled before any water in the evaporation upper zone is transferred to other storages.
UZFWM	mm	upper Zone Free Water Maximum, this storage is the source of water for interflow and the driving force for transferring water to deeper depths.
LZTWM	mm	Lower Zone Tension Water Maximum, the maximum capacity of lower zone tension water Water from this store can only be removed through evapotranspiration.
LZFSM	m	Lower Zone Free Water Supplemental Maximum, the maximum volume from which supplemental baseflow can be drawn.
LZFPM	1/day	Lower Zone Free Water Primary Maximum, the maximum capacity from which primary base flow can be drawn.
UZK	1/day	The ratio of water in UZFWM, which drains as interflow each day.
LZSK	1/day	The ratio of water in LZFSM which drains as baseflow each day.
LZPK	1/day	The ratio of water in LZFPM, which drains as baseflow each day.
PFREE	1/day	The minimum proportion of percolation from the upper zone to the lower zone directly available for recharging the lower zone free water stores.
REXP	1/day	An exponent determining the rate of change of the percolation rate with changing lower zone water storage.
ZPERC	1/day	The factor applied to PBASE to define maximum percolation rate.
SIDE	1/day	The decimal fraction of observed base flow, which leaves the basin, as groundwater flow.
SSOUT	$m^3/s/km^2$	The volume of the flow which can be conveyed by porous material in the bed of stream.
PCTIM	$m^3/s/km^2$	The impervious fraction of the basin, and contributes to direct runoff.
ADIMP	$m^3/s/km^2$	The additional fraction of pervious area, which develops impervious characteristics under soil saturation, conditions
SARVA	$m^3/s/km^2$	A decimal fraction representing that portion of the basin normally covered by streams, lakes and vegetation that can deplete streamflow by evapotranspiration.

Table 3.3: Sacramento parameters

Parameter	Default Value	Minimum Value	Maximum Value
p	0.01	0	1
Lzfpm	40	0	50
Lzfsm	23	0	50
Lzpk	0.009	0	1
Lzsk	0.043	0	1
Lztwm	130	0	400
Pctim	0.01	0	1
Pfree	0.063	0	1
Rexp	1	0	3
Rserv	0.3	0	1
Sarva	0.01	0	1
Side	0	0	1
Ssout	0.001	0	1
Uzfwm	40	0	80
Uzk	0.245	0	1
Uztwm	50	0	100
Zperc	40	0	80

Table 3.4: Default parameters for the Sacramento model

Percolation

The percolation to the lower stores is a key process of the Sacramento Model. The driving force for percolation is the relative wetness of the UZFWS as moderated by the relative wetness of the lower zone stores. Percolation increases when either the storage in the UZFW store increases or the storage in the lower zone stores decrease. This is equivalent to supply increasing and demand increasing respectively. Conversely, percolation decreases when the lower stores start becoming full. The lower limit of percolation, Pbase, occurs when the lower zones are saturated, and is determined by the rate at which the lower zones drain Equation (3.5). The maximum rate of percolation occurs when the lower zones are dry, and Pbase is factored up using the ZPERC parameter Equation (3.7).

$$P_{base} = LZFM * LZSK + LZFSM * LZPK \tag{3.5}$$

$$PERC_{max} = P_{base}(1 + ZPERC) \tag{3.6}$$

The actual percolation is moderated by the relative saturation of the lower and upper zones, which is the ratio of actual storage to maximum storage in these stores, to give an estimate of percolation Equation (3.7).

$$Perc = P_{base}[1 + Zperc[1 - LZrs]^{Rexp}]UZrs \tag{3.7}$$

Normally, the lower zone tension store would fill before water goes to the lower zone free water store. However, variations in soil types cause deviations from average conditions and therefore in the Sacramento Model a fraction of the percolation (PFREE)

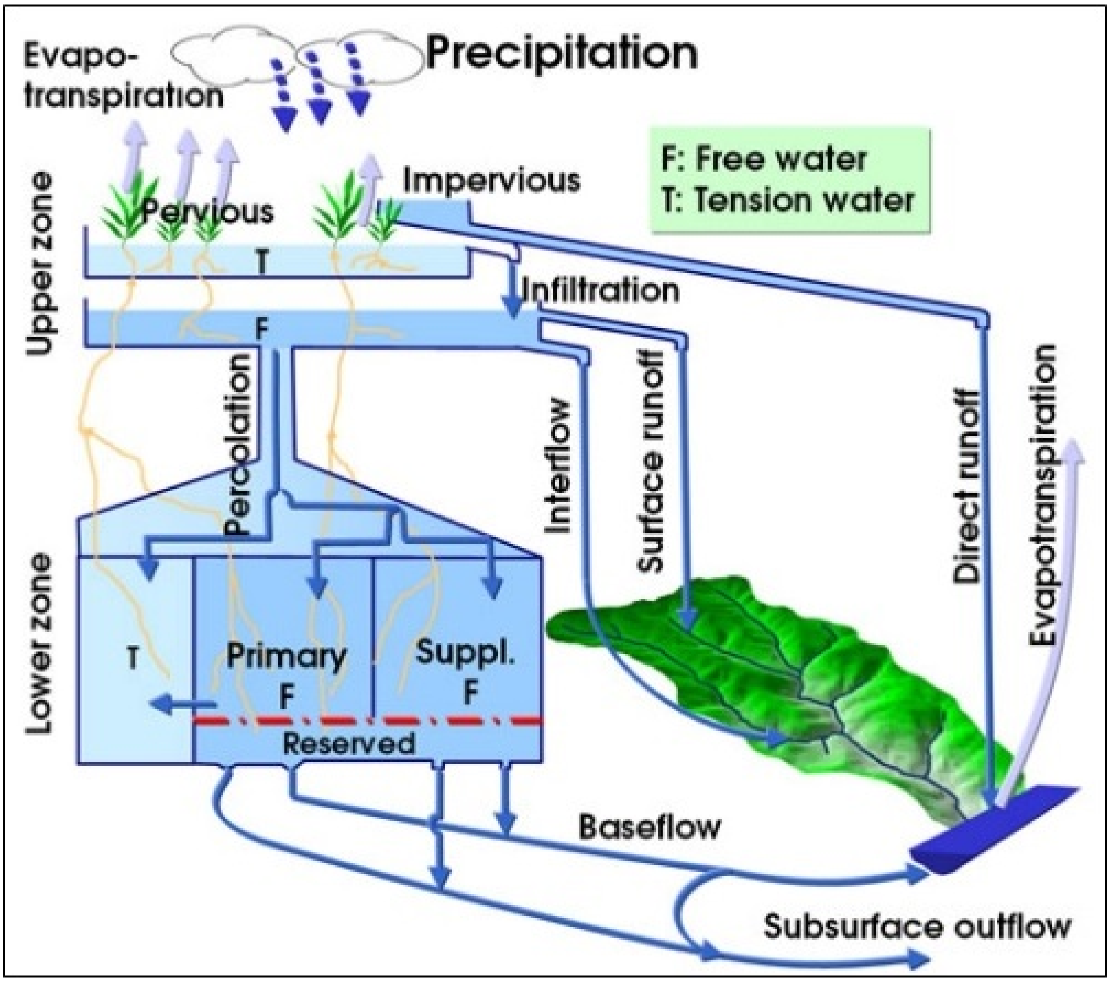


Figure 3.9: stores and zonal classification of Sacramento Model

is made available for lower zone free water stores. The Sacramento Model is a catchment water balance model that relates runoff to rainfall with daily data. The model contains five stores and has sixteen parameters. The Sacramento Model is a continuous rainfall-runoff model used to generate daily stream flow from daily rainfall and potential evapotranspiration data. It uses soil moisture accounting to simulate the water balance within the catchment (i.e. functional unit). The conceptual layout of the model is shown in Figure 3.8. At each model time step the sequence of calculations is:

1. Soil moisture depletion by evapotranspiration and soil moisture redistribution.
2. Soil moisture replenishment by rainfall and percolation, and streamflow generation.

The internal Sacramento Model calculations represent water quantities using units of depth (in millimeters). The model outputs are converted to volumes by multiplying infiltration excess runoff the catchment area. Here of the calibration of the result depends on the amount soil moisture of the catchment, due to this reason the model needs effective measures and analyzers of evapotranspiration and soil moisture distribution of the catchment area.

3.5.3 SIMHYD RRL Model

Model Description

SIMHYD, a simplified version of HYDROLOG (Porter and McMahon 1971), is widely used in modeling catchment runoff in Australia and elsewhere the model was classified as a lumped conceptual model. This study uses the nine-parameter of SIMHYD implemented in the Rainfall Runoff Library (Boughton 2004). The version of SIMHYD described by the Rainfall Runoff Library documentation (Podger 2004) is capable of simulating runoff values for daily or monthly time steps.

When used on a daily time step, SIMHYD uses daily values of catchment potential evapotranspiration for each month and daily catchment rainfall values to calculate daily runoff. The model is calibrated against daily runoff data. The model features three connected storages, the first intercepts rainfall and the other two are each associated with a variable representing the amount of water in the storage and a parameter that defines the storage capacity. Catchment rainfall and water in the storages is distributed between storages and runoff according to deterministic rules which depend on the volumes in the storages, parameter values and inputs. The rules aim to model the dependence of water transport on the history of the climate variables in the catchment.

As a result, the output of SIMHYD is strongly non-linear in the inputs. In summary, the data requirements for the application of the lumped model SIMHYD to a catchment on a daily time step are three daily catchment values; derived rainfall, estimated potential evapotranspiration and measured runoff.

Default values of model parameter

The RRL is configured with a set of default values for each model parameter. These default values specify the initial parameter value plus the upper and lower bounds for that parameter. 3.5 lists the default values for the SimHyd model.

Parameter	Default Value	Minimum Value	Maximum value
Base flow cofficent	0.3	0	1
Impervious Cofficent	1	0	5
Infiltration Coeff.	200	0	400
Infiltration shape	3	0	10
Interflow Coeff.	0.1	0	1
Prev. Fraction	0.9	0	1
RISC	1.5	0	5
Recharge Coefficent	0.2	0	1
SMSC	320	1	500

Table 3.5: Default parameters values for the SimHyd model

In SIMHYD, daily rainfall first fills the interception store, which is emptied each day by evaporation. The excess rainfall is then subjected to an infiltration function that determines the infiltration capacity. The excess rainfall that exceeds the infiltration capacity becomes infiltration excess runoff.

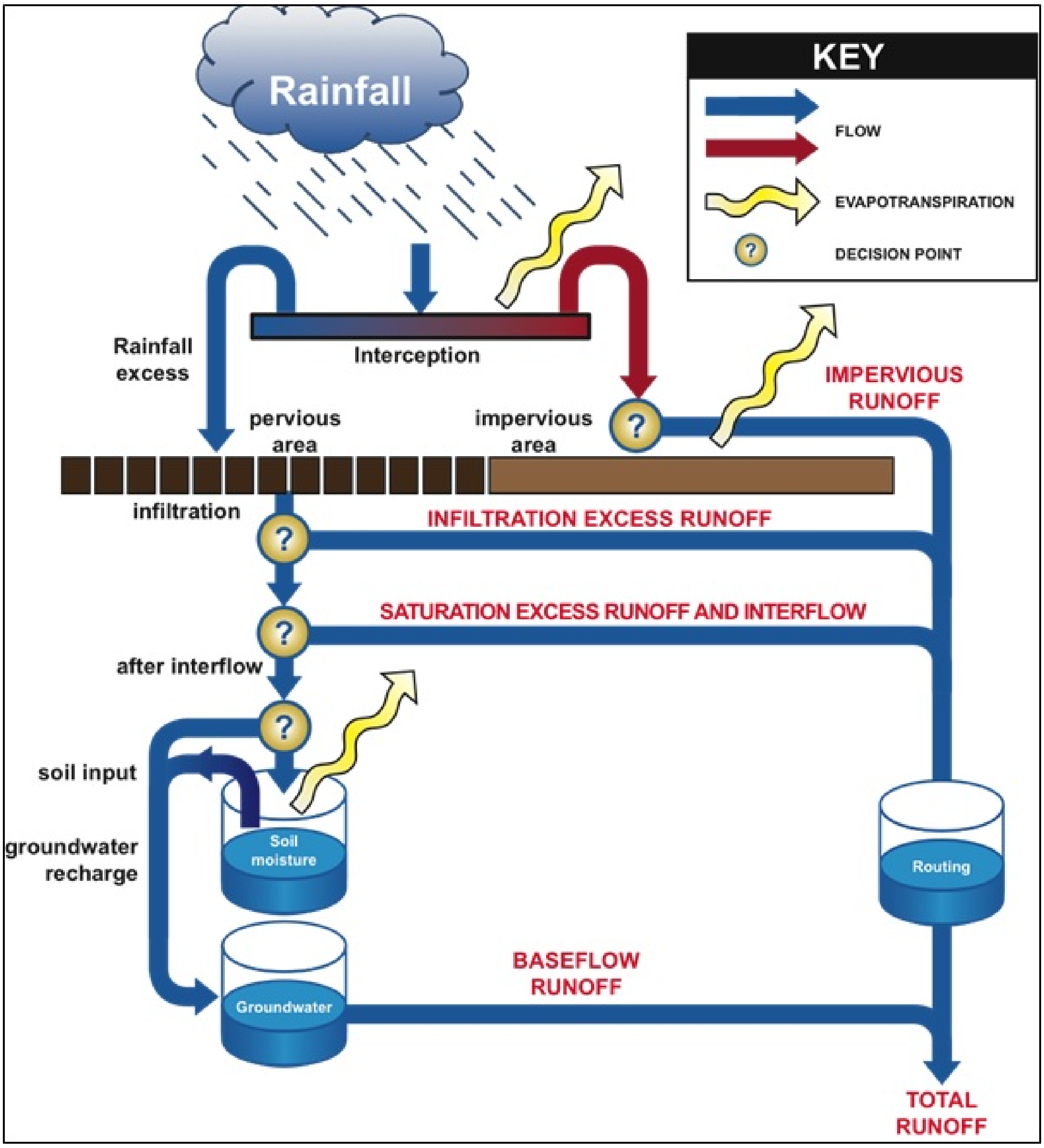


Figure 3.10: Structure of the SIMHYD rainfall-runoff model

Moisture that infiltrates is subjected to a soil moisture function that diverts the water to the stream (inter flow), groundwater store (recharge) and soil moisture store. Inter flow is first estimated as a linear function of the soil wetness (soil moisture level divided by soil moisture capacity). The equation used to simulate inter flow therefore attempts to mimic both the inter flow and saturation excess runoff processes (with the soil wetness used to reflect parts of the catchment that are saturated from which saturation excess runoff can occur).

Groundwater recharge is estimated, also as a linear function of the soil wetness. The remaining moisture flows into the soil moisture store. Evapotranspiration from the soil moisture store is estimated as a linear function of the soil wetness, but cannot exceed the atmospherically controlled rate of areal ETo. The soil moisture store has a finite capacity and overflows into the groundwater store. Base flow from the ground water

store is simulated as a linear recession from the store.
Therefore, the model estimates runoff generation from three sources.these are:

- Infiltration excess runoff,
- Inter flow (and saturation excess runoff) and
- Base flow

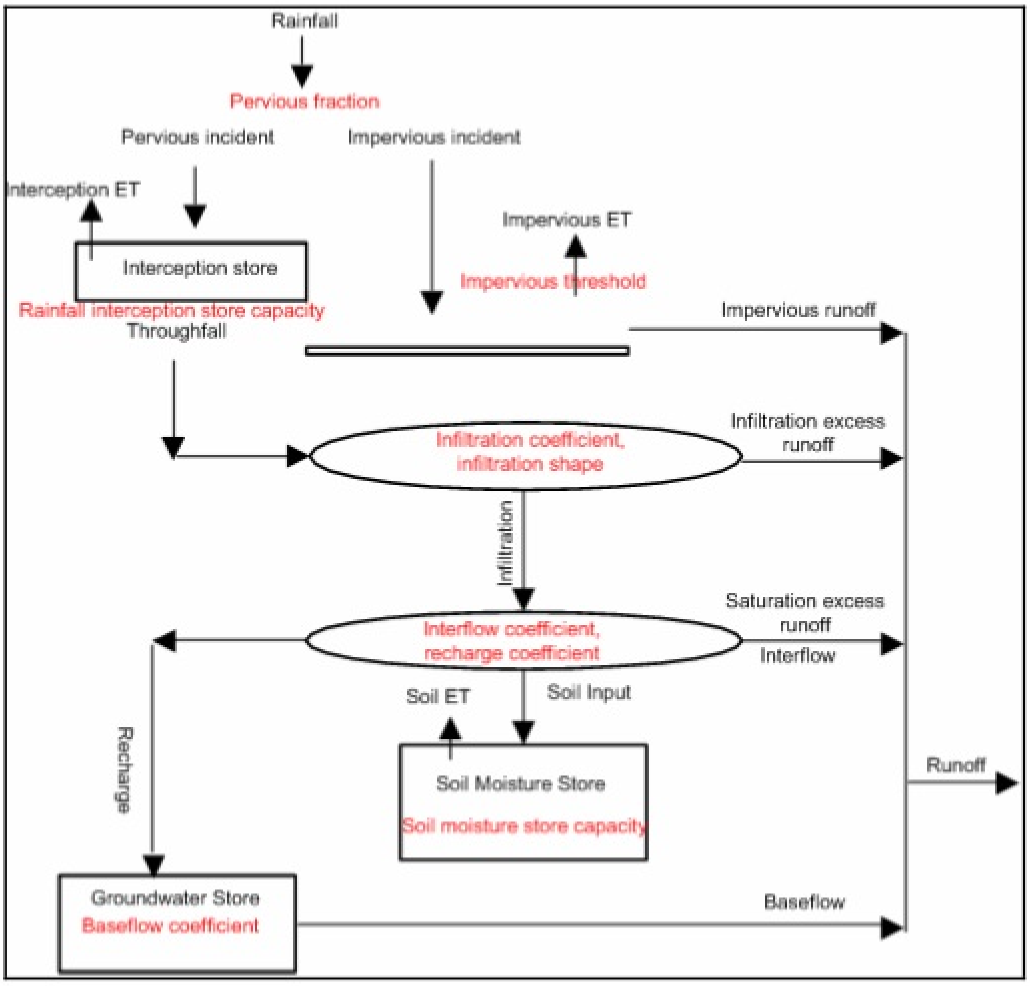


Figure 3.11: Detail Structure of the SIMHYD rainfall-runoff model (from Geoff Podger 2004)

The fundamental equations of the model are:

$$imp(ET) = min(PET, (1-previousFraction)\times previousthreshold, impIncident) \tag{3.8}$$

$$interceptionET = min(perviousIncident, pet, rainfallInterceptionStoreCapacity \tag{3.9}$$

$$InfilCapa = PreviousFraction\times infiltrationCoef\times exp(-infiltrationShape\times Smf) \tag{3.10}$$

$$Infiltration = min(throughfall, infiltrationCapacity) \tag{3.11}$$

$$InterflowRunof = IC \times SMF \times infiltration \tag{3.12}$$

where:-
Smf=soil moisture fraction
IC= Inter flow coefficient

3.5.4 Soil Moisture Accounting and Routing, SMAR

Model description

The SMAR model is a lumped quasi-physical conceptual rainfall-evaporation-runoff model, with quite distinct water-balance and routing components. 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 diffusive effects of the catchment by routing the various generated runoff components, through linear time-variant storage elements. For each time-step, the combined outputs of the two routing elements adopted i.e., the generated surface runoff and groundwater runoff becomes the simulated discharge. the version of SMAR used in this study has nine parameters, five of which control the overall operation of the water-budget component, while the remaining four parameters, including a weighing parameter, which determines the amount of generated groundwater runoff, control the operation of the routing component.
the schematic diagram of the version of SMAR used in the present study incorporates the suggested modification, application of an empirical infiltration equation in the SMAR conceptual model (Tan and O'Connor 1996) is the SMAR model along with the parameters are presented in figure 3.12 and refer appendix P.
Water Balance
The water balance component uses five parameters to describe the movement of water into and out of a generalized soil column under conditions of atmospheric forcing: C, Z, H, Y and T.

1. The dimensionless parameter C regulates evaporation from the soil layers. Evaporation is assumed to vary as an exponential function of the form Ci -1 , where C lies between 0 and 1 and i = 1,2,3 refers to the successive soil layers. That is, for a given potential evaporation the first layer can meet that demand at the potential rate, the second layer at a rate C, the third layer at C 2 etc, resulting in a reduction in the soil moisture store in an approximately exponential manner. The potential evapotranspiration rate from the top layer conceptually represents evapotranspiration from the interception storage and from the topsoil during periods of negligible capillary resistance.

2. the parameter Z (mm) represents the effective moisture storage capacity of the soil contributing to the run-off generation mechanisms. Each layer holds 25 mm at field capacity.

3. The dimensionless parameter H is used to estimate the variable H', the proportion of rainfall excess contributing to the generated run-off as saturation excess run-off or the Dunne run-off. H' is obtained as a product of H, rainfall excess and soil saturation. Soil saturation is defined as the ratio of available soil moisture in mm at time t (days) and 125 mm, representing the maximum soil moisture content of the first five layers.

4. The parameter Y (mm/d^{-1}) represents the infiltration capacity of the soil and is used for estimating the infiltration excess run-off (Hortonian run off).

5. The dimensionless parameter T is used to calculate the potential evaporation from pan evaporation (E).

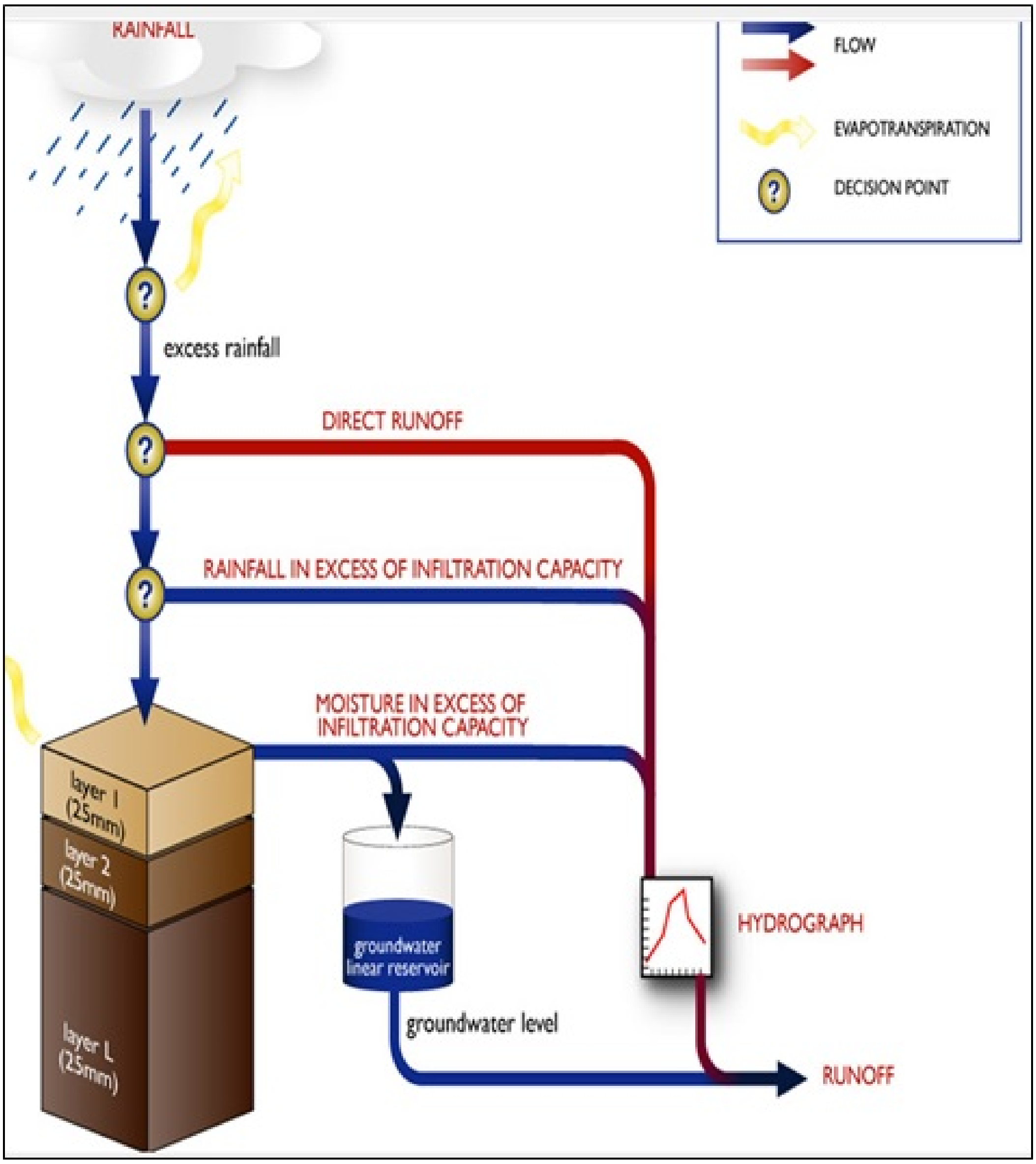


Figure 3.12: Structure of the SMAR rainfall-runoff model

Generated surface run-off is calculated from the excess rainfall (rainfall minus potential evaporation) as saturation excess run-off (shallow sub-surface flow) plus the Hortonian run off and plus a proportion (1-G) of moisture in excess of the effective soil moisture storage capacity (g) (i.e. through flow). The remaining proportion (G) of the latter, i.e. the deep drainage component discharged from the groundwater system to the stream, is routed through a linear reservoir, and the total generated surface run-off is routed using a gamma function model form to obtain the daily total estimated discharge at the catchment outlet.

Routing

Groundwater and surface run-off, generated from the water balance component, are routed to simulate the associated lags between rainfall events and flow out of the catchment. The governing equations used in routing component of the SMAR model are presented as follows (Kachroo and Liang, 1992).

The surface runoff routing component

The generated run-off (rs mm/d) and the routed run-off (Q mm/d) can be time averaged, as in equations (3.13) and (3.14), to represent the daily values.

$$r_{s(t)} = \frac{1}{t}\int r_s(\tau)d\tau \tag{3.13}$$

$$Q_T^{r(t)} = (\frac{1}{t}) * \int Q_T^r(\tau)d\tau \tag{3.14}$$

The linear model described by equation 3.15 is the simplest representation of a causal, time invariant, relationship between an input function of time (generated run-off) and the corresponding output function (routed run-off). It is used in conceptual modelling, as a component, representing the routing or diffusion, effects of the catchment on those components of the rainfall hyetograph contributing to the outflow.

Parameter	Default Value	Minimum Value	Maximum Value
Groundwater evaporation rate C	0	0	1
Groundwater runoff coefficent G	0	0	1
Proportion Directrunoff H	0	0	1
Storage loss coef.Kg	0	0	1
U.H Linear routing N	1	1	6
U.H Linear routing Component NK=N*K	1	0.01	1
Evap.Conversion Param.T	0	0	1
Infiltration Rate Y	0	0	5000
Soil moisture total storage depth Z	200	0	5000

Table 3.6: default parameter values for the SMAR model

$$Q_T^r(t) = \sum_{j=1}^{m} h(j)r_s(t-j+1) \tag{3.15}$$

where, = m memory of the pulse response function (d).the parameter pair n and nK are chosen for optimization, rather than n and K separately, because n is a shape of parameter and nK is the scale parameter. Expressed in this way, the two parameters are likely to be more independent than would be n and K separately, both of which contribute to the scale and to the shape, although in different ways.

Groundwater routing component

The mass balance equation for the ground water system can be written as bellow.

$$QT^{rech}Q_T^{r(t)} = \frac{ds(\tau)}{dt} = Ds(\tau) \tag{3.16}$$

Where QT^{rech}= recharge to the groundwater system (mm.s-1) The RRL is configured with a set of default values for each model parameter.These default values specify the initial parameter value plus the upper and lower bounds for that parameter.Table 3.8 lists the default values for the SMAR model.

The SMAR model is a lumped quasi-physical conceptual rainfall-evaporation-runoff model, with quite distinct water-balance and routing components. 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 diffusive effects of the catchment by routing the various generated runoff components, through linear time-variant storage elements. For each time-step, the combined outputs of the two routing elements adopted i.e., the generated surface runoff and groundwater runoff becomes the simulated discharge.

3.5.5 TANK model

Model description

The tank model is a very simple model, composed of four tanks laid vertically in series as shown in Figure 3.13 Precipitation is put into the top tank, and evaporation is subtracted sequentially from the top tank downwards. as each tank is emptied the evaporation shortfall is taken from the next tank down until all tanks are empty.
The outputs from the side outlets are the calculated runoffs. the output from the top tank is considered as surface runoff, output from the second tank as intermediate runoff, from the third tank as sub-base runoff and output from the fourth tank as base flow. despite this simple conceptualization the behavior of the tank model is not so simple. The behavior of the model is strongly influenced by the content of each of the stores. Under the same rainfall and different storage volumes the runoff generated is significantly different. the tank model is applied to analyses daily discharge from daily precipitation and evaporation inputs. The concept of initial loss of precipitation is not necessary, because its effect is included in the non-linear structure of the tank model.

Default values

The RRL is configured with a set of default values for each model parameter. These default values specify the initial parameter value plus the upper and lower bounds for that parameter. Table 3.7 lists the default values for the Tank model.

Parameter	Default Value	Minimum Value	Maximum Value
a11	0.2	0	1
a12	0.2	0	1
a21	0.2	0	1
a31	0.2	0	1
a41	0.2	0	1
alpha	0.1	0	5
b1	0.2	0	1
b2	0.2	0	1
b3	0.2	0	1
c1	20	0	100
c2	20	0	100
c3	20	0	100
c4	20	0	100
H11	0	0	500
H12(<H11)	0	0	0
H21	0	0	100
H31	0	0	100
H41	0	0	100

Table 3.7: default parameter values for the TANK mode

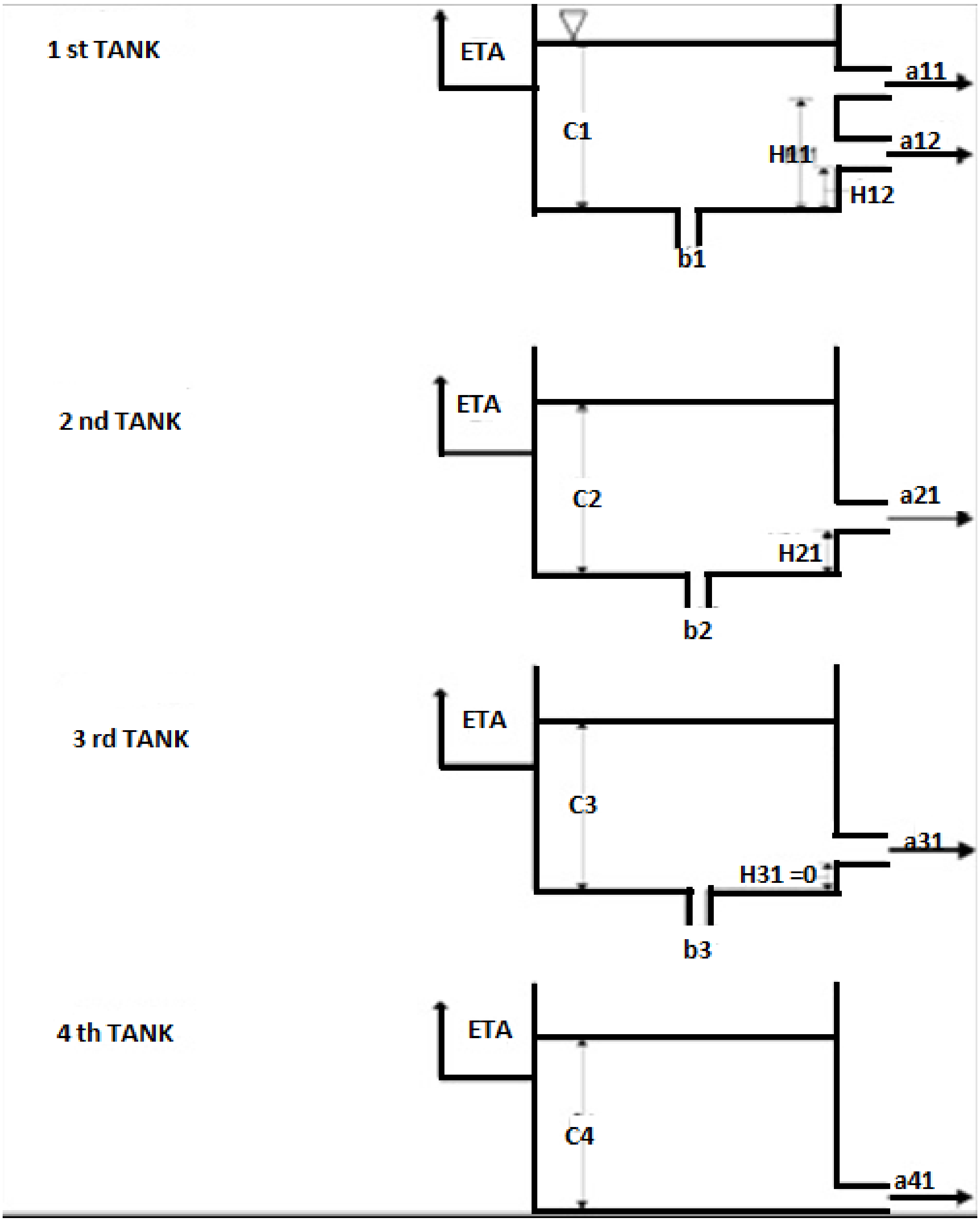


Figure 3.13: Structure of the RRL Tank rainfall-runoff model

Runoff

The total runoff is calculated as the sum of the runoffs from each of the tanks. The runoff from each tank is calculated as

$$q = \sum_{x=1}^{4} \sum_{y=1}^{nx} (C_x - H_{xy}) a_{xy} \tag{3.17}$$

Where q is the runoff depth in mm, Cx the water level of tank x, Hxy the outlet height and a_{xy} is runoff coefficient for the respective tank outlet. Note if the water level is below the outlet no discharge occurs.

Evapo-transpiration:

The evapo-transpiration is calculated using Bekens (1979) equation.

$$ETA = ETP * (1 - exp(-\alpha \sum_{x=1}^{4} C_x)) \tag{3.18}$$

Where ETA or ETo is the evapo-transpiration in mm, (α) the evapo-transpiration coefficient (0.1) and Cx the water level of tank.

Infiltration

The infiltration in each tank is calculated using:

$$I_x = C_x * B_x \tag{3.19}$$

Where I_x is the infiltration in mm, C_x the water level of tank x and B_x the infiltration coefficient tank x.

Note that the C_x parameters are initial store values only, not the store capacities.

Storage

The amount of water in each tank affects the amount of rainfall, infiltration, evaporation and runoff. The storages are calculated from the top to the bottom tank. The evaporation is initially deducted from the first storage up to a maximum of the potential rate. The remaining potential evapotranspiration is taken from each of the lower tanks until the potential rate is reached or all of the tanks have been evaporated. After evaporation has been taken from the tanks rainfall is added to the top tank and based on the revised level runoff and infiltration is estimated. This is subsequently deducted from the storage level. The next tank subsequently receives the infiltration from the tank above. The process continues down through the other tanks. shows the schematic of design Tank Model which has 4 tanks. Consists of Surface Tank (A), Intermediate Tank (B), Sub-Base Tank (C), Base Tank (D). Rainwater that precipitates on the catchment area is the main input after deducting the amount of water that evaporates because of evapo-transpiration process. In the concept of Tank Model, water can fill the reservoir that lies beneath it, and water flows out at horizontal outlet in each reservoir, which is represented as Outflow Discharge (Runoff Flow).

1. Tank A has two horizontal outlets and a vertical outlet. Horizontal outlets consist of Surface Flow (Qa1) and Subsurface Flow (Qa2). Horizontal flows only occur if the water level in the Tank A (Ha) is higher than its outlet (Da1 and Da2). Vertical flow (Ia) is represented as an infiltration. The amount of Qa1, Qa2 and Ia are influenced by the characteristic of each outlet.

2. Tank B has a horizontal outlet and a vertical outlet. Horizontal outlets represent Intermediate Flow (Qb). It only occurs if water level in Tank B (Hb) is higher than its outlet (Db). Vertical flow (Ib) is represented as an infiltration. Qb and Ib are influenced by the characteristic of its outlet.

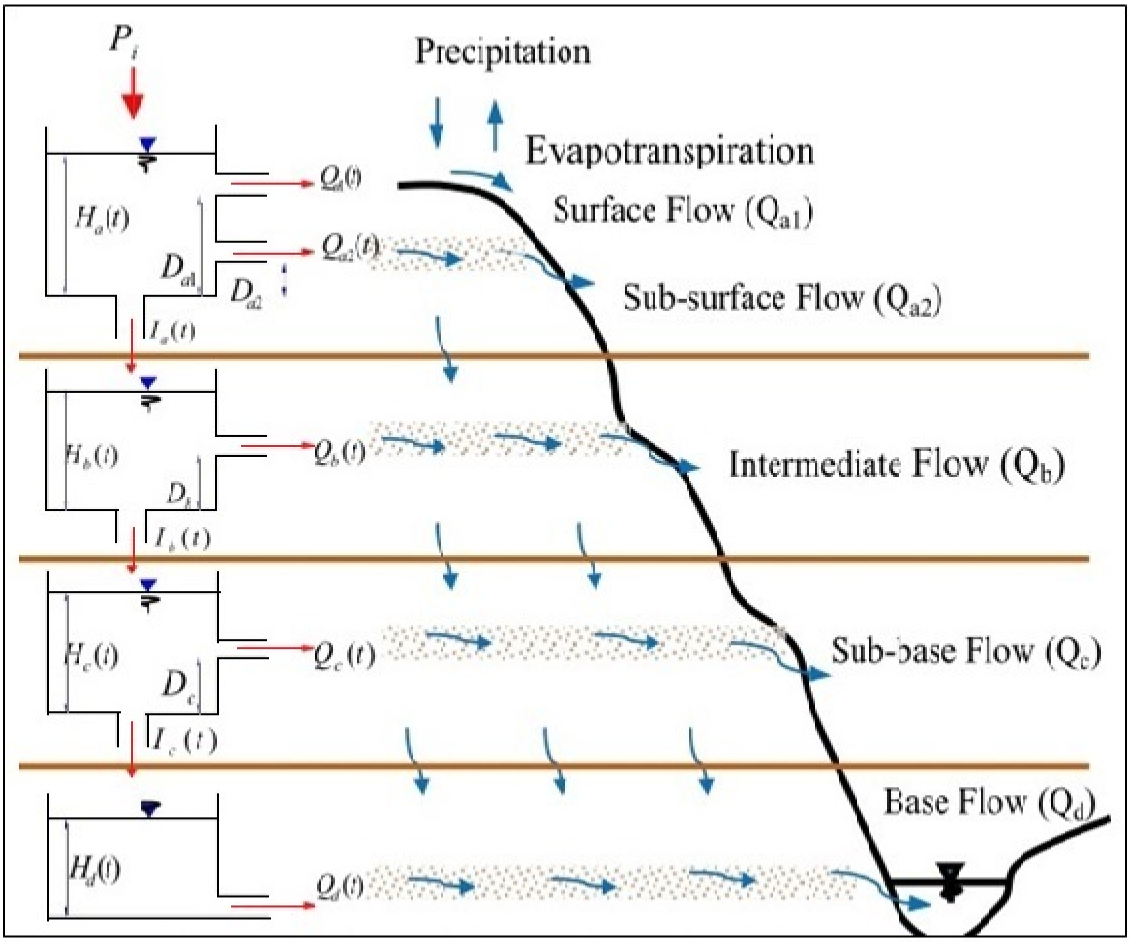


Figure 3.14: Schematic Design Tank Model /source Gunawan Suntoro

3. Tank C has a horizontal outlet and a vertical outlet. Water flows out through horizontal outlet or we can call it Sub-Base Flow (Qc). It only occurs if water level in Tank C (Hc) is higher than it outlet (Dc). Vertical outlet (Ic) is represented as an infiltration. Qc and Ic are influenced by the characteristic of its outlet

4. Tank D (Base Reservoir) only has a horizontal outlet. Water flows only through this outlet and it represented as Base Flow (Qd). It is influenced by the characteristic of the outlet.

3.6 Calibration and Validation

3.6.1 Model calibration

Model calibration is a process of optimizing or systematically adjusting model parameter values to get a set of parameters which provides the best estimate of the observed stream flow. Virtually all rainfall runoff models must be calibrated to produce reliable estimates of stream flow because there has been little evidence identified of strong links between physical characteristics of catchments and the parameters of rainfall runoff models (Beven 1989). Models should always be calibrated to observed data to demonstrate that the model can produce observed flow time series with an acceptable level of accuracy. The acceptable level of accuracy will depend upon the statistics of the flow data to be reproduced, which is determined by the purpose that the model will be applied for.

3.6.2 Model validation

Model validation is a process of using the calibrated model parameters to simulate runoff over an independent period outside the calibration period to determine the suitability of the calibrated model for predicting runoff over any period outside the calibration period. If there is not enough data available, the validation may be performed by testing shorter periods within the full record. Model validation is one of the most important steps in rainfall-runoff modeling as the performance of the calibrated model in the validation period provides us confidence in the modeling results when the calibrated model is used for simulating stream flow outside the measured stream flow period or when the model is used for predicting stream flow under future climate change scenarios.

Validation has often been achieved using a ”split sample” process, whereby a period of observed data (say the first two-thirds of the available record) are used for calibration and the remaining one-third are used for validation. The model that was calibrated using the calibration data set is run for the validation period without changing the model parameters and the goodness of fit statistics are computed for the validation period.

After accomplishing the necessary data quality checking rainfall runoff modeling was conducted using all five models that found in Rainfall Runoff Library (RRL) ewater toolkit. twenty-two years of data (1990 - 2011) is used since a suitably long period of flow record, from 1990 - 2003 is calibration period from this 1990 is used for calibration warm up period. the preferred method for calibrating and verification rainfall runoff models.This method gives a way of assessing the robustness of the model for periods outside of the calibration period. If possible the verification (validation) and calibration periods should be of similar length. However, to include sufficient climatic variability in the calibration period it may be possible to have the validation period only cover one third of the period of record. Therefore, taking the aforementioned facts in to consideration, and from 2004 - 2011 is verification period from this 2004 is also used for verification warmup period is set for all models. Comma delaminated column daily time series format (.cdt) is used to convert rainfall, Evaporation and flow time series data into dragable format that may then be dragged and dropped on to the appropriate time series filed. After dragging and dropping rainfall, flow and evaporation data, optimization method to be used in the modeling, Rainfall Runoff Library has a choice of seven optimization algorithm methods are available. These include:

1. Genetic algorithm
2. Uniform random sampling
3. Pattern search
4. Pattern search multi start

5. Rosenbrock
6. Rosenbrock multi start
7. Shuffled Complex Evolution (SCE)

However, from the above optimization parameters Shuffled Complex Evolution (SCE-UA) and Pattern search are selected. For this study, there are two tabs are available below the optimization parameter, those are primary and secondary Optimization methods objective functions. To calibrate the model based on the above two optimization method, Nash Sutcliffe criteria (coefficient of efficiency)and runoff difference in % as primary and secondary objectives respectively were used to undertake the modeling work.

3.6.3 Pattern Search

The pattern search is the simplest of all the search methods and has the advantage that it is quick but can suffer from finding local optimums rather than global optimums. This is particularly the case when models are strongly non-linear. The problems of reaching local optimums can be overcome by using a multi-start on the search as discussed in the following section.
The search works by the following method:

1. Start with an initial value and search increment for each of the parameters.
2. Evaluate the objective function for an incremental increase and decrease in current value.
3. If the objective function improves in one direction set the parameter to that value.
4. Increment each of the parameters in the optimum direction and evaluate the objective
5. Repeat to step 4 until there is no improvement in any of the parameters
6. Halve the incremental and go to step 2 until the number of specified interval halvings is reached.

Note: if at any stage a parameter reaches a boundary the parameter is limited to the specified boundary value.

3.6.4 Shuffled Complex Evolution Criterion (SCE-UA)

The Shuffled Complex Evolution (SCE-UA) has been used extensively and proved to be a robust and efficient global optimization method for the calibration of conceptual models. This method is based on a synthesis of four concepts:

1. Combination of deterministic and probabilistic approaches,

2. Systematic evolution of a ?complex? of points spanning the parameter space, in the direction of global improvement,
3. Competitive evolution, and
4. Complex shuffling

This enhanced version of SCE-UA is tested, first on a suite of test functions and then on a conceptual rainfall-runoff model using synthetically generated runoff values. It is observed that the strategically located initial population drastically reduces the number of failures and the modified simplex search also leads to a significant reduction in the number of function evaluations to reach the global optimum, when compared to the original SCE-UA. Thus, the two enhancements significantly improve the robustness and efficiency of the SCE-UA model calibrating algorithm.

3.7 Model Performance Evaluation

Model performance was evaluated for both calibration and validation in different ways. Evaluation is compare the simulated outflow with the observed outflow. To give interpretation to the output given by the calibration method's, evaluation methods have to be chosen. Some of the evaluation methods are Nash Sutcliffe efficiency (NSE), relative volume error, peak flow, base flow, index agreement and coefficient of determination (R^2). In addition, the simulated Vs observed hydrograph shows the relation between simulated and observed out flow.
The goodness of fit can be also evaluated by different measures (Lasocki and Weglarczyk 1998) the efficiency of models is checked by its degree of simulation, this degree of simulation was checked by coefficients of Nash and Sutcliffe (1970), it is a dimensionless transformation of the sum of squared errors and has become one of the most widely used goodness-of-fit measures. Moreover, logarithmic efficiency (Reff,), volumetric error and coefficient of determination are used to evaluate model performance in most studies. in this thesis, the log-efficiency and the volume error were also computed. (refer table 3.8 for definitions).

Goodness of fit measure	**Notation**	**Value of perfect fit**
Nash Sutcliffe Efficiency	E	1
Log Efficiency	Leff	1
Relative Volume Error	RVE	0
Coefficient of determination	R^2	1

Table 3.8: Goodness of fit measures

3.7.1 Nash-Sutcliffe Efficiencies (NSE)

The Nash Sutcliffe Efficiency (NSE) also called coefficient of Efficiency (E) (Nash and Sutcliffe, 1970, Grunewald and Fred 1999) is away a measure of fit between the predicted and measured values. The computation of E essential is the sum of deviation of the observation from linear regression line with slope of 1.

$$E = 1 - \left(\frac{\sum(Q_{obs} - Q_{sim})^2}{\sum(Q_{obs} - QM_{obs})^2}\right) \tag{3.20}$$

Where:
Q_{obs}=observed discharge
Q_{sim} = simulated discharge
Q_{Mobs} = mean of observed discharge
Nash Sutcliffe efficiency can range from -∞ to 1.

An efficiency of 1 (E = 1) corresponds to a perfect match of modeled discharge to the observed data. An efficiency of 0 (E = 0) indicates that the model predictions are as accurate as the mean of the observed data. Negative values show that the observed mean is a better predictor than the model or, in other words, when the residual variance (described by the numerator in the expression above), is larger than the data variance (described by the denominator). Essentially, the closer the model efficiency is to 1.According to the classification of Moriasi et al. (2007), performance of models is very good, good, satisfactory, and unsatisfactory if the NSE statistic is larger than 0.75, between 0.65 and 0.75, between 0.5 and 0.65 and less than 0.5, respectively.

3.7.2 Coefficient of determination

The coefficient of determination (R^2) the square of coefficient of correlation, it is the measure of strength of the relationship between two variables and it gives the ratio of explained variance to the total variance. it is subjected to more precise interpretation because it can be presented as a proportion or as a percentage.
estimates how much of the observed dispersion is explained by the prediction. Its value range lies between 0 and 1 and a value of zero means no correlation at all whereas a value of 1 means that the dispersion of the prediction is equal to that of the observation. Similar to Reff, (R^2) is not very sensitive to systematic model over- or under prediction especially during low flow periods. A model which systematically over- or under predicts all the time will still result in good R^2values close to 1.0 even if all predictions were wrong.

$$R^2 = \frac{\sum(Q_{obs} - QM_{obs})^2 \sum(Q_{sim} - QM_{sim})^2}{\sum(Q_{obs} - QM_{obs})^2} \tag{3.21}$$

Where:
Q_{obs}=observed discharge
Q_{sim} = simulated discharge
Q_{Mobs} = mean of observed discharge
Q_{Msim}= mean of simulated discharge

3.7.3 Efficiency using Logarithmic Value (logReff):

Efficiency using Logarithmic Value (logReff): is modification of Reff calculated by taking logarithmic values of the observed and simulated runoff. Logarithmic transformation of the runoff values flattens the peaks and keeps the low flows more or less at the same level. As a result, the influence of the low flow values is increased in comparison to the flood peaks resulting in an increase in sensitivity of logReff to systematic model over- or under-prediction.

$$E = 1 - (\frac{\sum(\ln Q_{obs} - \ln Q_{sim})^2}{\sum(\ln Q_{obs} - \ln QM_{obs})^2}) \tag{3.22}$$

3.7.4 Mean Difference (meandiff)

measures long-term annual difference between the observed and simulated runoff; meandiff values equal to zero were considered perfect. In summary, performance of all models in simulating the observed discharge was assessed during calibration, verification and transferability test of the model.
Inspecting simulated and observed runoff graphs visually assessing accumulated difference between simulated and observed runoff and comparing the Reff, logReff, R^2 and meandiff values (the main objective functions used for deciding goodness of fit during calibration were Reff and mean diff).

3.7.5 Peak Flow

The peak flow evaluation method will evaluate the peak flow of the simulated runoff and compares the simulated flow with the observed runoff (Madsen, 2000). The peak flow is calculated by:

$$Pf = \frac{1}{Mp}\sum[\sum[Qs(i) - Qs(\theta)]^2]^0.5 \tag{3.23}$$

Whereby Mp is the number of peak flow events. the peak flow appears to be a flow above a given threshold discharge Qs(θ). the value of this threshold should be set for calibration and validation period and it is fixed for all models. The value of the threshold is should be set by using indication of Hydrological alteration threshold manual.

3.7.6 Base Flow

The peak flow evaluation method will evaluate the low flow of the simulated runoff and compares the simulated flow with the observed runoff (Madsen, 2000). the low flow is calculated by:

$$Bf = \frac{1}{Ml}\Sigma[[Qs(i) - Qs(\theta)]^2]^1/2 \tag{3.24}$$

Where Ml is the number of low flow events.

3.7.7 Index Agreement

The index of agreement gives the simulated outflow as a fraction of the Mean square error of the simulated outflow and the absolute error of the observed outflow itself. (Biondi et al. 2012) . The index of agreement is calculated by:

$$D = 1 - \frac{\sum(Qs(i) - Qs(\theta))^2}{\sum(/Qs(i) - Qm(o)/ + /Qo(i) - Qm(o)/)^2} \tag{3.25}$$

The value of the index of agreement is between 0 and 1. A value of 1 indicates a perfect match, and 0 indicates no agreement at all (Willmott, 1981)

3.7.8 Relative volume Error

The relative volume error (Biondi, Freni, Iacobellis, Mascaro, & Montanari, 2012) is a method to calculate the percentage of the absolute error between the simulated and observed error. The RVE coefficient is calculated by:

$$RVE = 100 * \frac{\sum(Qs - Q_{obs})}{\sum(Q_{obs})} \tag{3.26}$$

Where Q_s and Q_{obs} is the same as in the NS coefficient. A RVE between -5 and 5 is an acceptable simulation, because het volume of the runoff is 95$\%$ the same (-5 is 5$\%$ volume less simulated than observed, 5 is 5$\%$ volume more simulated than observed). A RVE of 0 is a perfect simulation for the volume of the runoff during a given period because the volume of the simulated and observed period are the same.

3.8 Sensitivity analysis

Sensitivity analysis involves investigating the behavior of the performance of a model in respect of one or more parameters which might be highly sensitive or insensitive to changes in values. It is a fundamental tool in the building, use and understanding of models of all forms. (Massmann and Holzmann 2012) concluded that “SA can get useful information regarding the behavior of the underlying simulated system. This information can range from the identification of calibration variables to model reduction or simplification, better understanding of the model structure for given components of a system, model quality assurance, and model building in general. Sensitivity analysis enables identifying the most important calibration parameters, detect parameter interactions, test model conceptualization, improve the model and provide a basis for an uncertainty analysis of the model (Krause and Base 2006); (Sieber and Uhlenbrook 2005).

Visual comparison of simulated and observed hydrographs provides a quick and often comprehensive means of assessing the accuracy of model output. Some disagreements, for instance in peak flow rates or in total flow volumes, are immediately evident, and a qualitative assessment can soon be made. Visual comparison, however, tends to be subjective, especially when a number of similar, but not identical, model outputs are compared to observed data and the "best" fit is sought. To overcome this difficulty, as well as to highlight certain model particularities, one or more of the statistical goodness-of-fit procedures discussed in the above section. Although the use of certain statistical goodness-of-fit techniques may be essential.

It is important to understand how sensitive a model is to certain parameters. This is useful to understand how the model functions and also what parameters need more attention than others. If the model is significantly affected by a particular parameter then the focus of calibration should be on that parameter. The uncertainty of the model will also be closely related to the uncertainty in estimating the most sensitive parameters. The RRL provides a facility to investigate the sensitivity of all model parameters. In most rainfall runoff models the behavior of many parameter's is related to the values of other parameter's i.e. the models are non-linear (RRL 2004). Consequently, the sensitivity of particular parameters may be different depending upon the values of other parameter's.

Chapter 4

RESULT AND DISCUSSION

4.1 General

Advances in scientific hydrology and practice of engineering hydrology depend on good, reliable and continuous measurements of hydro- Meteorological variables. Model calibration more than anything relies on the quality of data available (RRL 2004). Hydro-Meteorological data must be cleaned from random and systematic error for erroneous data leads to either non-veritable rejection of a model or wrong calibration that affects the usefulness of a model. Thus, the most important step in rainfall runoff calibration is data preparation and analysis. Time spent in ensuring that the best possible data set is used will greatly speed up the calibration process. As it is stated under chapter three of this paper, the rainfall runoff models require four important data sets.

- Catchment characteristics,
- Rainfall,
- Evapotranspiration, and
- Flow.

4.1.1 Catchment characteristics

Generally the only catchment characteristic required by lumped rainfall runoff models is the catchment area. However, in some cases models e.g. SWAT need to know slope, land use, soil profile, soil depth, and hydraulic conductivity. The models operate in mm and to convert the model output from runoff depth to runoff volume catchment area is required. According to the rainfall runoff library manual the catchment area is usually an easy parameter to obtain but should be used with caution. The area is dependent on the scale of maps or DEMs that it was derived from and in flatter areas there can be large uncertainty with regard to where catchment boundaries are. A small error in catchment area can cause a large error in the estimated volume that runs off the catchment.In addition the manual emphasizes that, although slope, land use, soil profile, soil depth and hydraulic conductivity may not be used by a model this information is also worth considering. The type of land use will influence surface runoff characteristics, evpo-transpiration rates and interception losses. Moreover, the soil characteristics will influence the size of soil stores and seepage rates. This sort of information is invaluable for setting realistic bounds on model parameters as well as sanity checking the fluxes out of the model. Taking the stated issues in to consideration, the catchment area obtained from Ministry of Water Resource GIS Department is rechecked and prepared for use in modeling work as it is shown under section 4.3.2.During modeling work the characteristics of soil in Upper Awash were taken in to consideration to set realistic National meteorological Agency bounds on model parameters as well as sanity checking the fluxes out of model

4.1.2 Rainfall Data

There are several things that need to be considered in the preparation and data quality checking of rainfall data:

1. Point rainfall and Catchment average(a real) rainfall
2. Selection of appropriate rainfall sites.
3. Outliers
4. Checking for gaps
5. Homogeneity and consistency test

4.1.3 Test for Consistency/Homogeneity

As described in section 3.3.2, errors can be introduced due to different reasons in point measurement of rainfall. Relocation of a gauge, the growth of trees close to gauge site, or the use of shields may alter gauge catching significantly. After a number of years , it is may be felt that data of that station is not giving consistent rainfall values .In order to detect any such inconsistency , and to detect any such inconsistency , and to correct and adjust the reported rainfall values ,a technique called double mass curve method in which , is generally adopted . In general, time series observational data is relatively consistent and homogeneous if the periodic data are proportional to an appropriate simultaneous period. As mentioned above, this proportionality can be tested by double mass curve analysis in which the cumulative precipitation of doubt full station is plotted against the cumulative of the group average.However, currently there are soft wares such as TREND in table 4.1 and (Appendix Q_1 up to Q_2) refers the homogeneity test and statistical tests respectively.that can be used to test for trend, change and randomness in precipitation, Evapo-transpiration and flow input data for all models computation which was produced by WMO/UNESCO Expert Workshop for analyzing climatological/hydrological data homogeneity test .Thus, for Upper Awash rainfall Stations, TREND was used for checking consistency/or homogeneity of each station data. All analyzed data, were found to be homogeneous at 0.05 alpha level .The results from the homogeneity test are given in table 4.1.

		(Statistical table)		
S/No	Station	a=0.1	a=0.05	a=0.01
1	Adet	Accepted	Accepted	Accepted
2	Dangela	Accepted	Accepted	Accepted
3	Enjibara	Accepted	Accepted	Accepted
4	Gundil	Accepted	Accepted	Accepted
5	Sekela	Accepted	Accepted	Accepted
6	Wetet Abay	Accepted	Accepted	Accepted

Table 4.1: Result from homogeneity test for the selected rainfall stations

4.1.4 Selection of Model Type

The scarcity of data in most of developing countries is so alarming that one gets a single station for a catchment as large as 1000 km^2. In addition there is always question of data quality problem. This forces scholar to use data from neighboring catchments for those sites which have no observation at all. Similar to any developing countries, in Ethiopia majorwater balance variables such as rainfall and evaporation time series are sparsely and scarcely available (Appendix B.1 and B.2). Moreover, different studies reveal the data available are of poor quality (Kiesel 2006). Thus, this study area is where even major water balance variables are sparsely and scarcely available as compared to different countries although it is relatively with better data set in Ethiopia.. For such areas the pragmatic solution is to apply conceptually sound lumped rainfall-runoff models with fewer parameters. AWBM and SMAR of RRL are characterized by few parameters (RRL 2004).However Scarmento and Simhyd contain many parameters which have to be optimized. Reports from different users of RRL reveals that Tank model in most cases give poor results and errors reported. Owning to this, a Toolkit Steering Group recommend that Tank Model not be used until further notice .Therefore, in this thesis paper, AWBM and SMAR Models are selected for modeling work taking the aforementioned reasons and time constraint in to consideration.

4.2 Calibration and Validation

The comparison of observed and simulated flows for calibration and verification periods using five conceptual rainfall runoff models for Gilgel Abay catchment are presented below.

Rainfall Runoff Library has a choice of seven optimization methods that are listed in chapter three. However, for this research we tested the two optimization methods that are pattern search and SCE-UA. But our test of pattern search algorithm showed that though pattern search is the simplest method, it has a problem of reaching a global maximum easily. However, the SCE-UA optimization method is a powerful tool to determine the local and global maximum values of the objective function. It is also a mostly used tool by many scholars to evaluate the CRR models. Therefore, due to the above aforementioned facts and scope of this study, the SCE -UA optimization method is selected with Nash Sutcliffe criteria and runoff difference in% as primary and secondary objectives (50% weight) respectively are used to conduct the modeling.

Models	SCE-UA	Pattern search
AWBM	0.86	0.82
Sacramento	0.82	0.80
SimHyd	0.84	0.81
SMAR	0.85	0.82
TANK	0.84	0.81

Table 4.2: Simulation result for calibration period using SCE-UA and Pattern search optimization methods

Based on Table 4.2, the two-optimization methods in calibration period perform very good. However, the pattern search method scored the lowest NSE and hence SCE-UA optimization method is selected to compare the model Efficiency here after. the calibration and validation results of each models write as follows.

4.2.1 Calibration

The calibration results of each model are reviewed by their Nash Sutcliffe Efficiency and calibration is done from 1990-2003 G.C, but the first year 1990 is a warm period for calibration. The NSE for each model fell in the range of 0.82 up to 0.86 regarding to their behavior. Similarly, the correlation between the observed and modeled flows of all models was lie between 0.92 and 0.93. In this study, the performance evaluation of each model is checked by using daily rainfall, evapotranspiration and stream flow data.

Statistics	AWBM	Sacramento	SIMHYD	SMAR	TANK
ME	-0.11	-0.12	0.08	-0.05	-0.04
MAE	0.79	0.84	0.87	0.84	0.85
MSE	2.15	2.27	2.41	2.31	2.35
RMSE	1.47	1.51	1.55	1.52	1.53
NRMSE %	37.4	38.5	39.6	38.7	39.1
PBIAS%	-4	-4.3	3	-1.8	-1.6
RSR	0.37	0.38	0.4	0.39	0.39
rSD)	0.93	0.94	0.94	0.94	0.95
NSE	0.86	0.82	0.84	0.85	0.84
mNSE	0.75	0.74	0.73	0.74	0.73
D	0.96	0.96	0.96	0.96	0.96
Md	0.88	0.87	0.86	0.87	0.87
Cp	0.28	0.24	0.19	0.23	0.21
R	0.93	0.92	0.92	0.92	0.92
R^2	0.86	0.85	0.84	0.85	0.85
bR2	0.77	0.77	0.78	0.77	0.77
KGE	0.89	0.89	0.9	0.9	0.91
VE	0.72	0.71	0.69	0.71	0.7

Table 4.3: Statistical comparison of each models

The above table results shows that Generally, all models with a SCE-UA optimization method, will successfully simulate runoff in the Gielgel Abay Catchment during calibration and only AWBM reaches an efficiency of about 86% for 1990 to 2003. The result of other statistical values of each models are shown from the above table 4.3 illustrated as follows.

AWBM Rainfall Runoff Model

The AWBM for 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. Soil moisture in third surface store is minimum that accounts up to 5mm in the catchment based on this model soil moisture in first and second surface store is almost have the same amount. Evaporation is subtracted from each of the stores but on a first and a second store did not affect on the amount of two surface stores. The moisture in excess of storage capacity in a second and third store 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. In total, there are generally 8 parameters which control the rainfall-runoff generation. even though, the most sensitive and effective parameter for this model base flow index due to much volume of base flow volume.

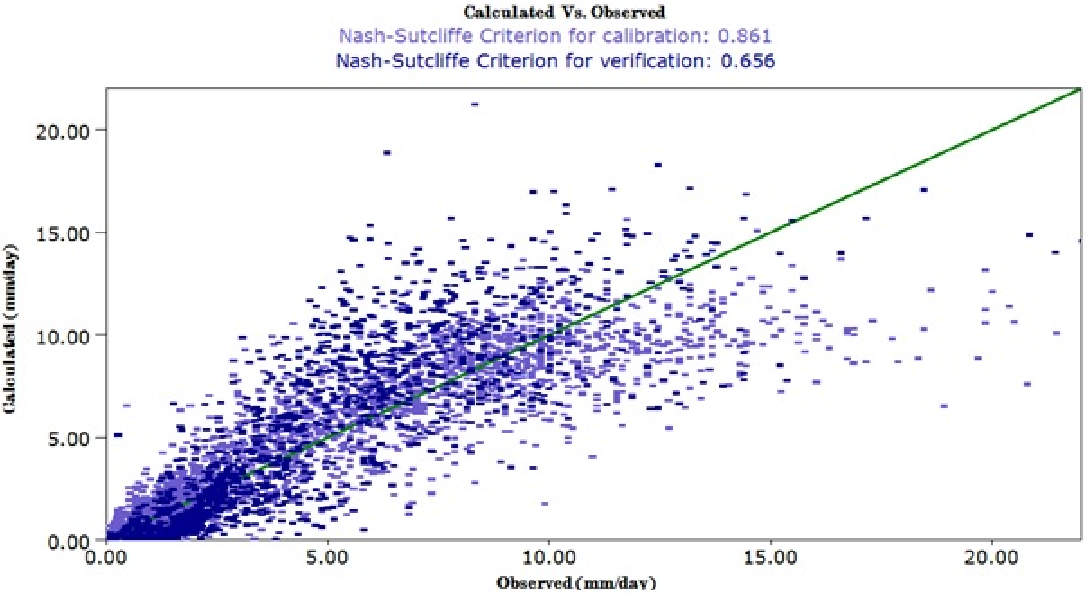


Figure 4.1: Scatter plots of simulated vs observed flow using AWBM model.

As it can be observed from the above scatter plot AWBM predicts the simulated flow with relatively good accuracy as compared as the others with Nash Sutcliffe Efficiency of 0.86 for calibration period.

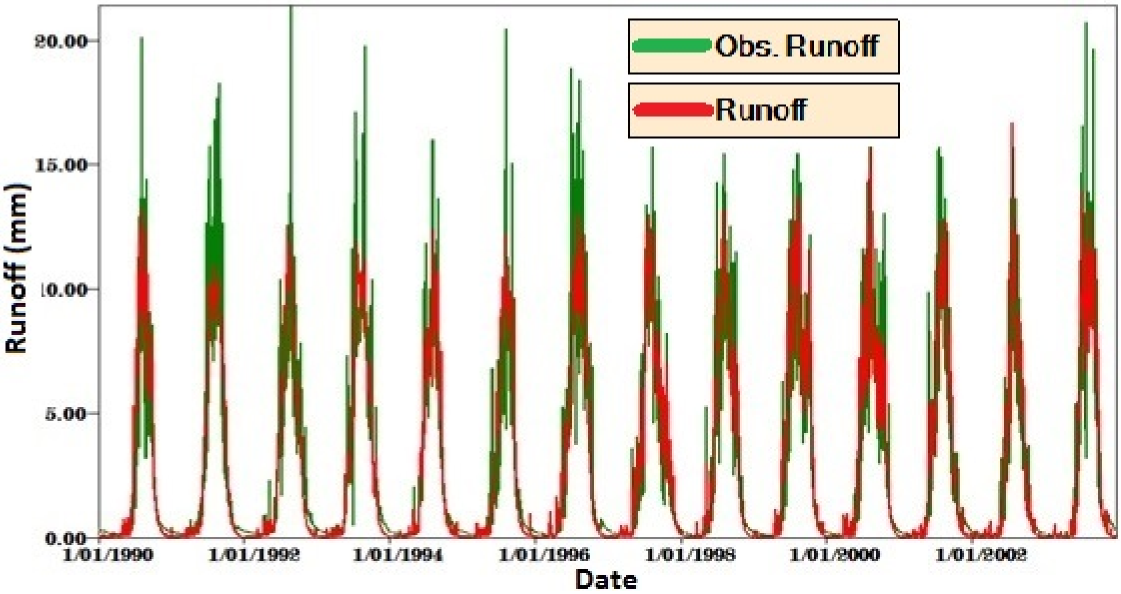


Figure 4.2: Graphical comparison of observed and simulated flow over calibration period for AWBM.

However, Based on figure 4.2 the simulated flow compares with the observed flow AWBM more predicts the flow volume for low and medium flows fairly good, But the model have a limitation to capture the peak flow that is >15mm flow depth and good for median and low flow simulation that is < 15mm runoff flow depth. the observed peak flow exceeded the simulated peak flow for 20% and 80% of the simulated and observed flows are equal in this model refer Appendix D. but based on peak flow simulation the model has a very good performance to represent the peak flow of the catchment As

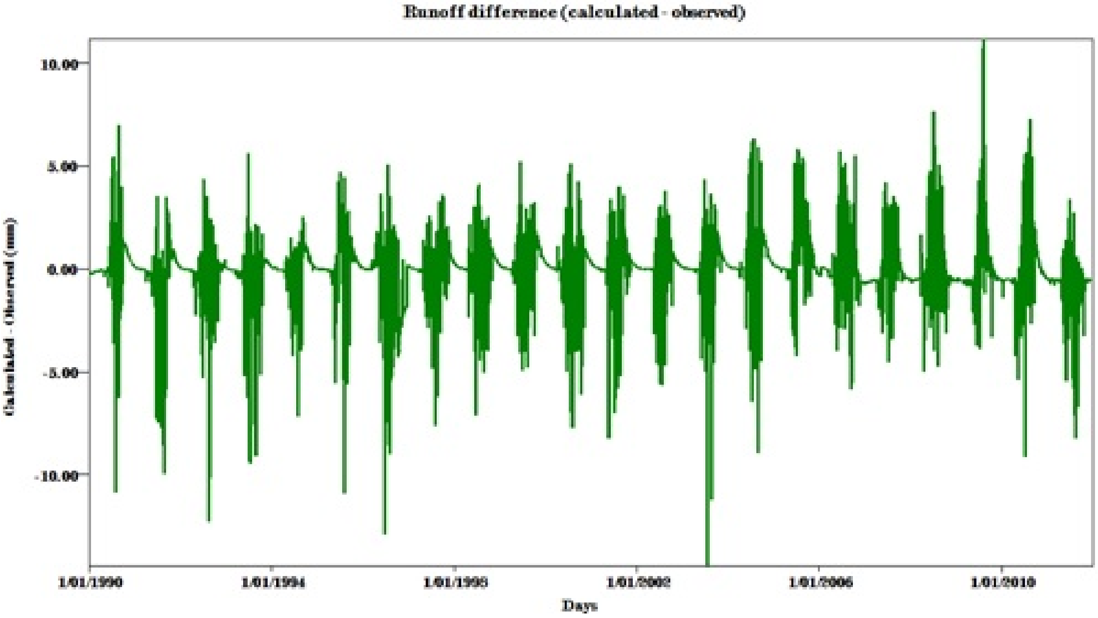


Figure 4.3: Runoff difference of AWBM with SCE-UA optimization method

it can be observed from the above figure: 4.3 AWBM also confirms that its low performance to capture a peak flow because (-ve) value refers the difference amount of observed flow that exceeds the simulated flow and (+ve) value also refers the amount of calculated flow exceeds the observed flow. when compare the two difference the greater value is that observed flow exceeds the simulated flow in a calibration period
Generally, the difference between observed and simulated runoff also can be checked statistically by volumetric efficiency that shows in table 4.3 comparing to others, AWBM have much captured the low and median observed flow rather than the others, that means 86 % of observed flow are captured by the model. from the above point AWBM have a performance to simulate the low, median and and peak flow Gilgel Abay river. so we can use to flow forecasting flows that used for flood forecasting and Irrigation project design.

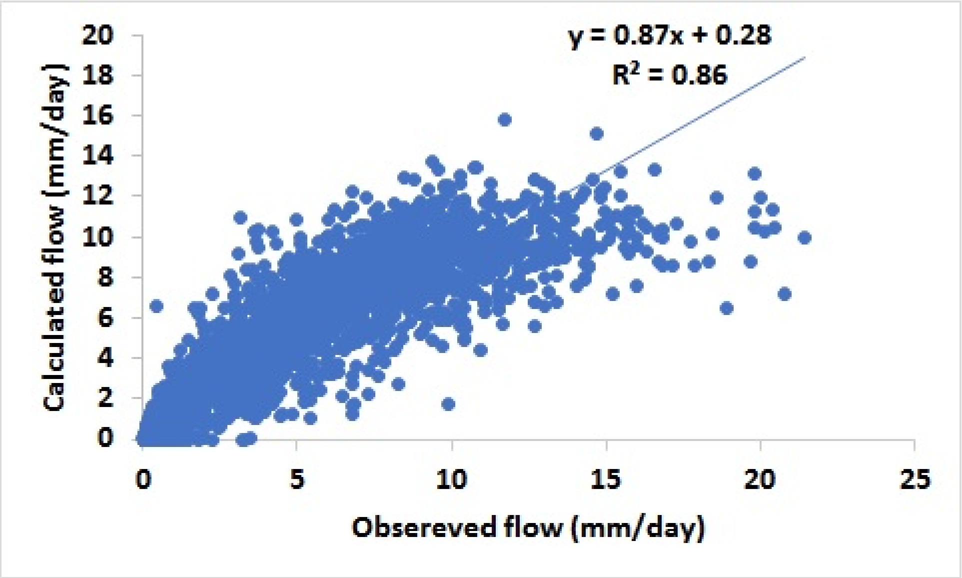


Figure 4.4: Coefficient of determination(R^2) of AWBM for calibration period

The Coefficient of determination value or (R^2) values for the calibration (1990-2003) was found as 0.86. this value shows the relationship between observed and simulated flow for calibration has value of 86%.

Sacramento Rainfall Runoff Model

As it can be shown in figure 4.5 the model has a good performance to the peak flow and median flow. this shows that, this model can be used to estimate for flood forecasting purposes because the model is not account the base flow refer figure Appendix K. The scatter plot of Sacramento model predicts the simulated flow for calibration period with relatively less accuracy as compared as others with Nash Sutcliffe efficiency of 0.82, it shows that there is a deviation between observed and simulated flow value. When we see the statstical comparison of this models in table 4.3 it has low performance to predict each low flow stages.

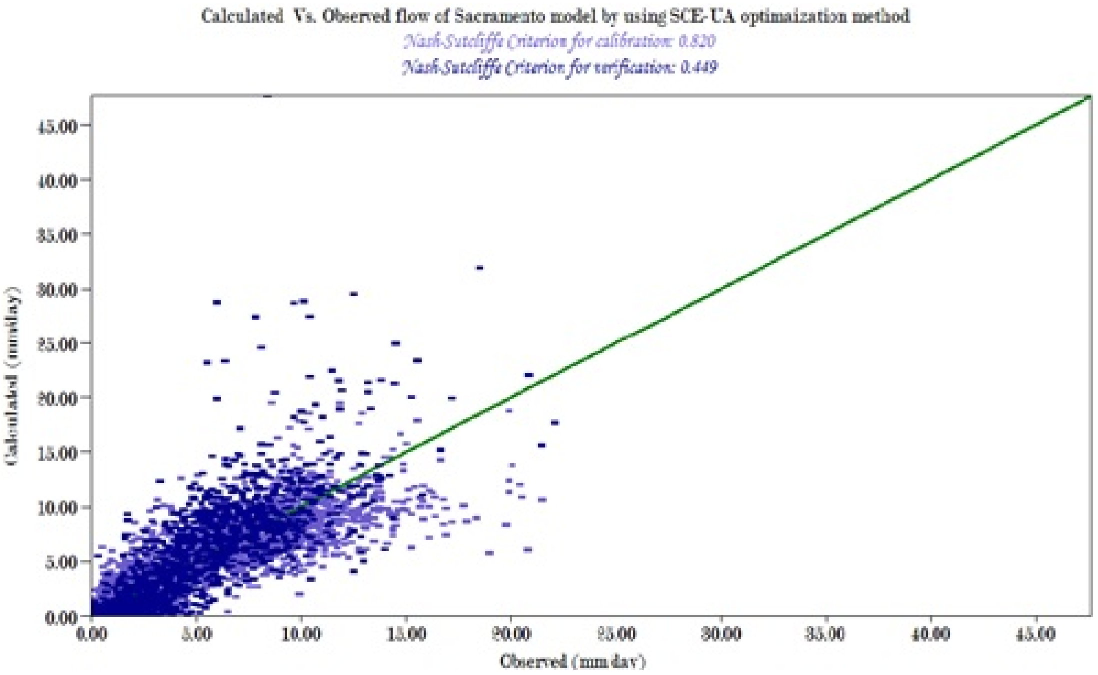


Figure 4.5: Scatter plots of simulated vs observed flow using Sacramento model

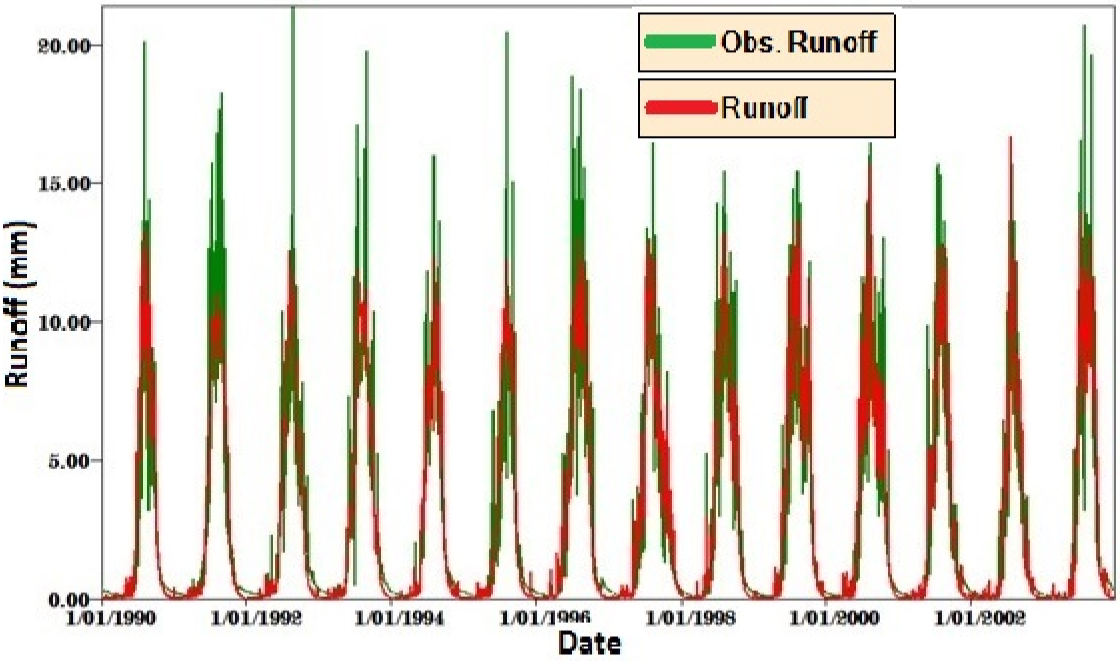


Figure 4.6: Graphical comparison of observed and simulated flow over calibration period for Sacramento model

From the above figure 4.6 we can analysis that sacramento model have 82% performance to represent the catchment flow.based on Appendix D flow duration curve 30% of the peak and median simulated flows are equal with the observed flow the rest 70% of simulated value represents the low flow. Although, the model has a little bit efficiency to predict this flow.

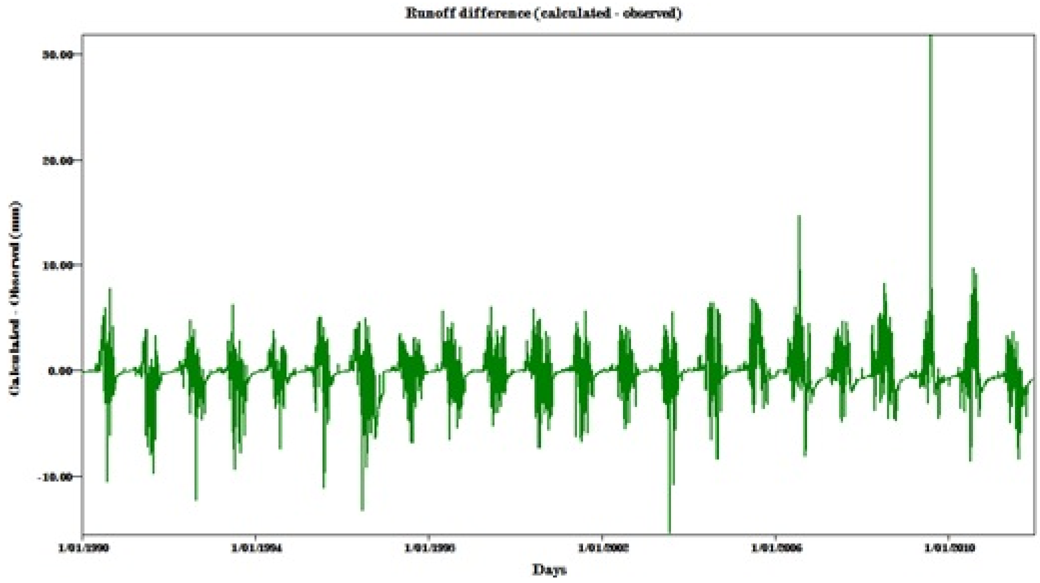


Figure 4.7: Runoff difference of calibration result Sacramento Model with SCE-UA optimization method.

From figure 4.7 and Appendix K we can analysis that the model has a limitation to counter the base flow because most of the soil moisture and surface stores are held by tension force and freely available on the upper zone due to this nature the amount of base flow should be minimum and Sacramento has a low performance to predict base flow. As it can be observed from the above figure 4.8 simulated flow is in acceptable range which is 82.3% of the observed flow predicted by the model, which reflects the under prediction of 17.7% at all-time steps.

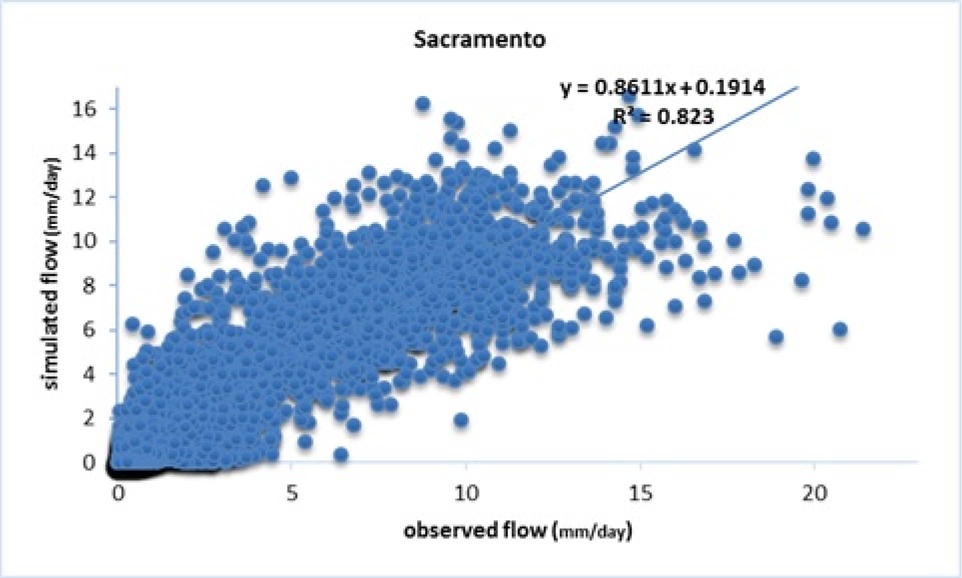


Figure 4.8: coefficient of determination (R^2) of Sacramento for calibration period.

SIMHYD Rainfall Runoff Model

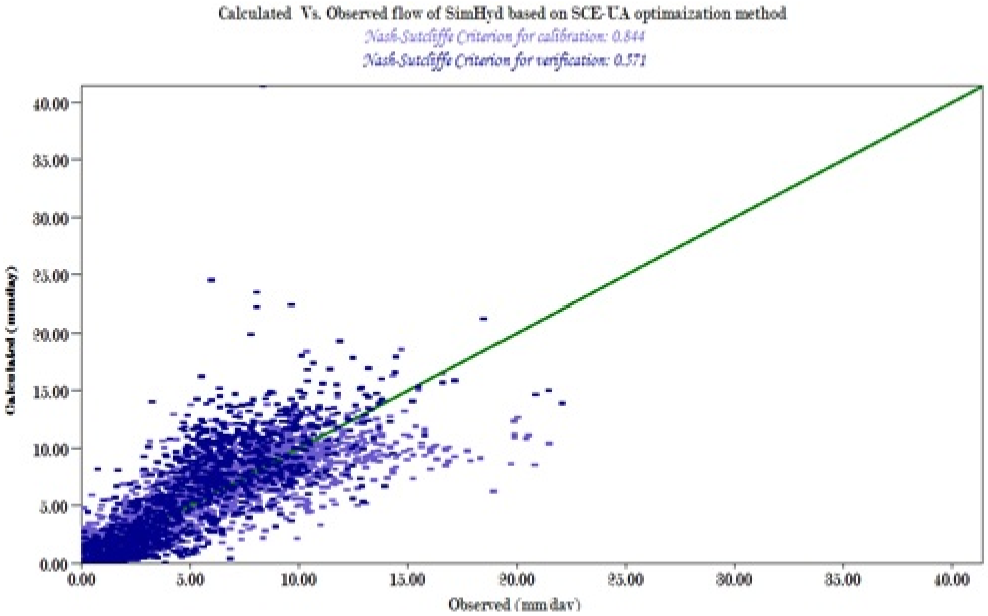


Figure 4.9: Scatter plots of simulated vs observed flow using SimHyd model.

The simulated model predicts the flow with Nash Sutcliffe value of 0.844 and 0.571 for calibration and verification period respectively. The model has the ability to reproduce 84.4% of historical and future watershed behavior. As it can be observed from figure 4.10 the model has the performance to predict the low and medium flow but it has a limitation to predict the peak flow for calibration period. The model has low performance to predict observed flow relatively with others, as it can be observed from statistical analysis Table 4.3 has less volumetric efficiency value.

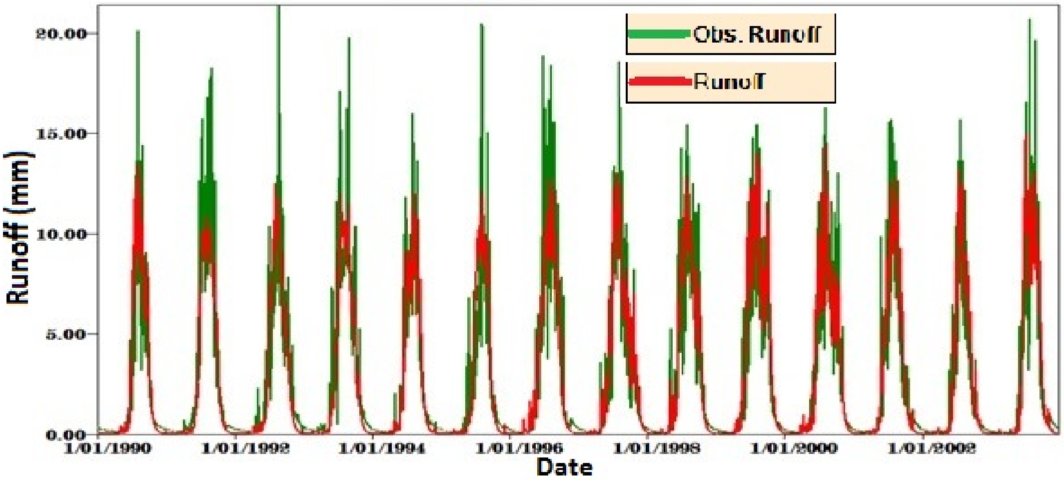


Figure 4.10: Graphical comparison of observed and simulated flow over calibration period for SimHyd model.

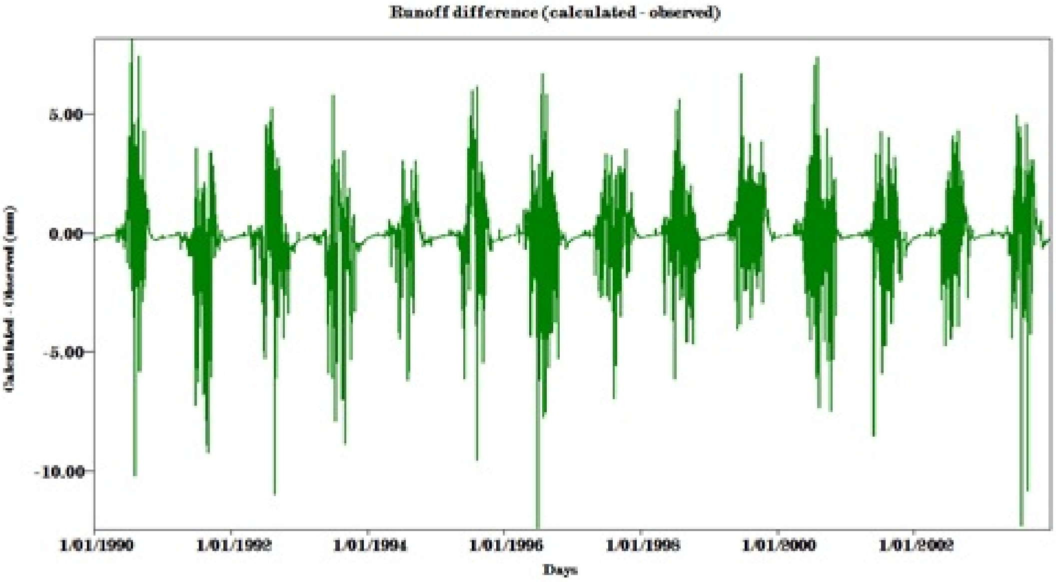


Figure 4.11: Runoff difference of calibration result SimHyd model with SCE-UA optimization method.

For a calibration period, SimHyd model has a performance to predict the low and medium flow but it has a limitation to predict the peak flow. The model has 90% of the observed flow is equal to the simulated medium and low flow refer Appendix D, we can also have from statics table 4.3 has low volumetric efficiency value.

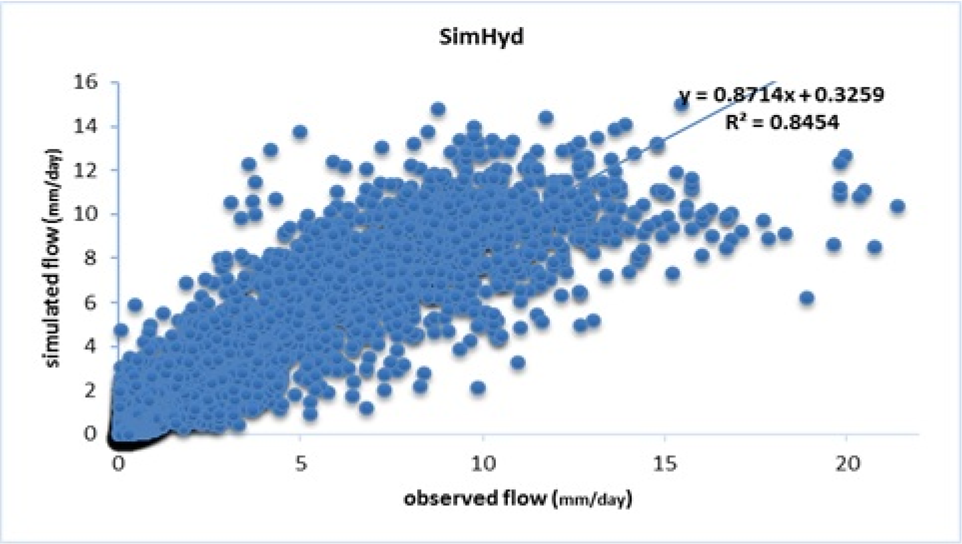


Figure 4.12: coefficient of determination (R^2) of SimHyd for calibration period.

As it can be shown from figure 4.12 simulated flow is in acceptable range which is 84% of the observed flow predicted by the model, which reflects the under prediction of 16% at all-time steps.

SMAR Rainfall Runoff Model

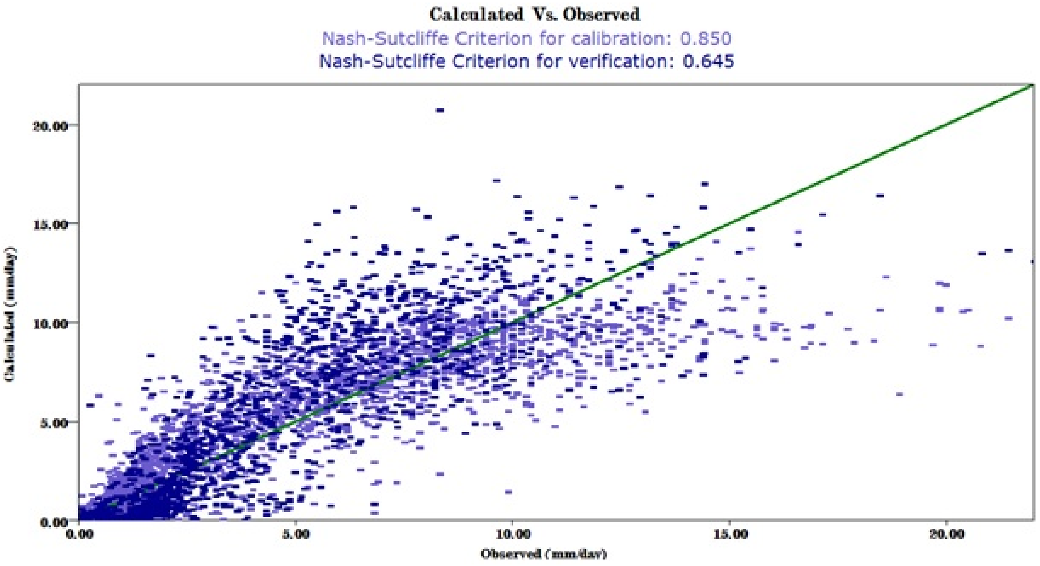


Figure 4.13: Scatter plots of simulated vs observed flow using SMAR model.

As it can be observed from figure 4.13, SMAR model predicts the flow with Nash Sutcliffe value of 0.85 for calibration period. The model has ability to reproduce historical and future watershed behavior.except 15 % of the observed flow other peak and median flow was captured by the model all peak and median flow have 30 % of expedience (Appendix D).

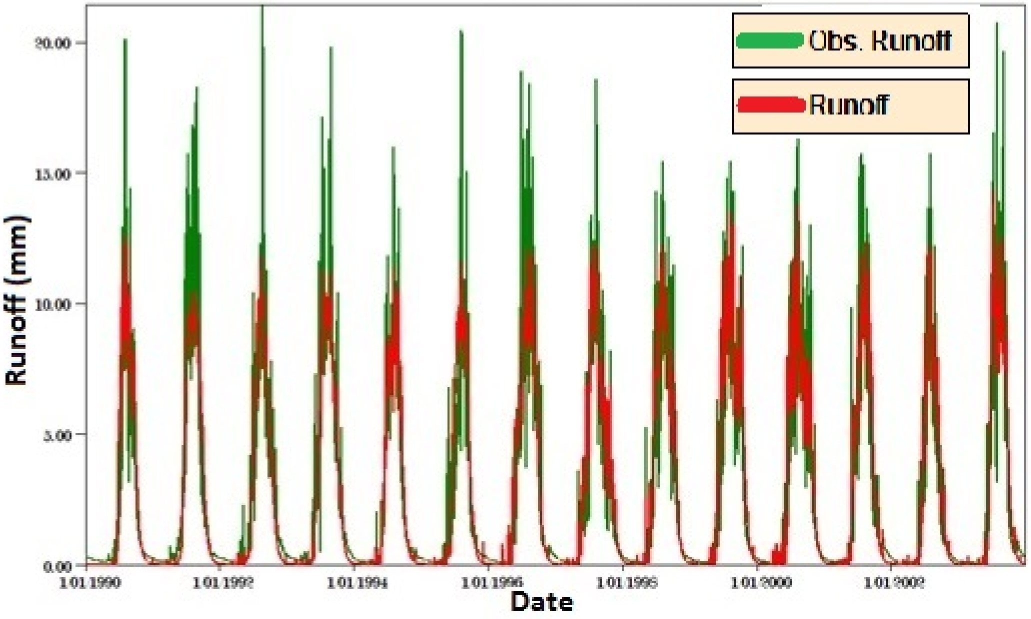


Figure 4.14: Graphical comparison of observed and simulated flow over calibration period for SMAR model

However, the simulated flow compares with the observed flow SMAR more predicts

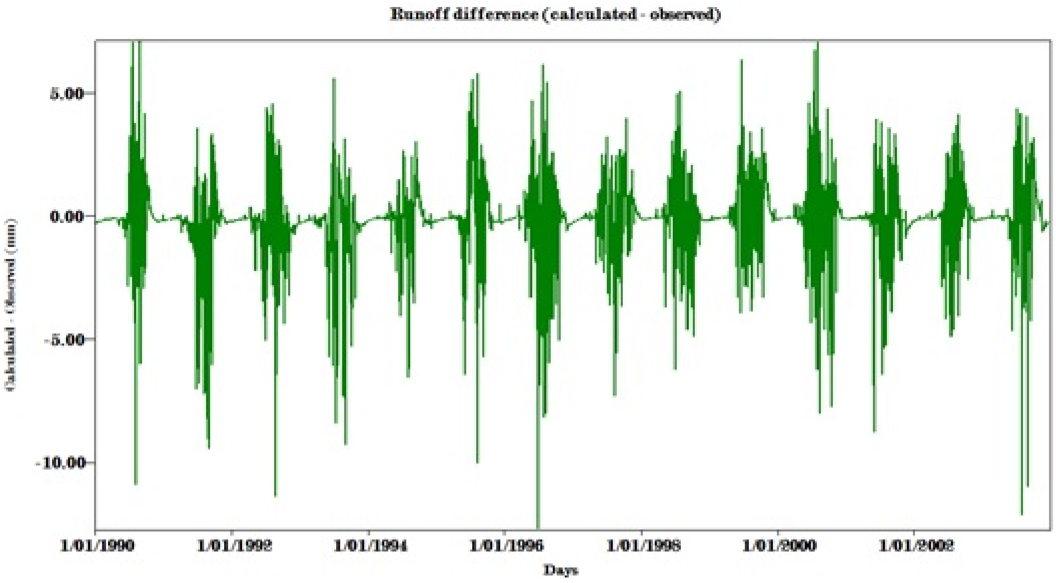


Figure 4.15: Runoff difference of calibration result SMAR model with SCE-UA optimization method.

the flow volume for all flow condition fairly good, But the model have a little bit limitation to capture low flow that is 0.2-2 mm flow depth and very good for median and peak flow simulation refer Appendix D

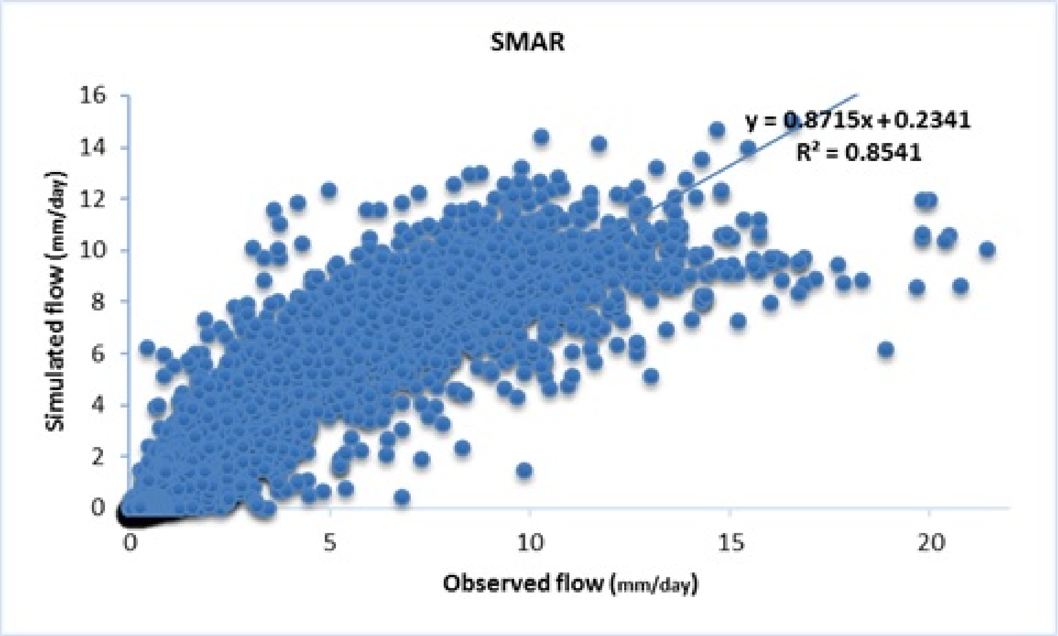


Figure 4.16: Coefficient of determination (R^2) of SMAR for calibration period.

In this study soil moisture accounting routing model have a good performance to simulate the base flow better than the others, where as peak flow simulation it has also a good performance next to Australian water balance model.

TANK Rainfall Runoff Model

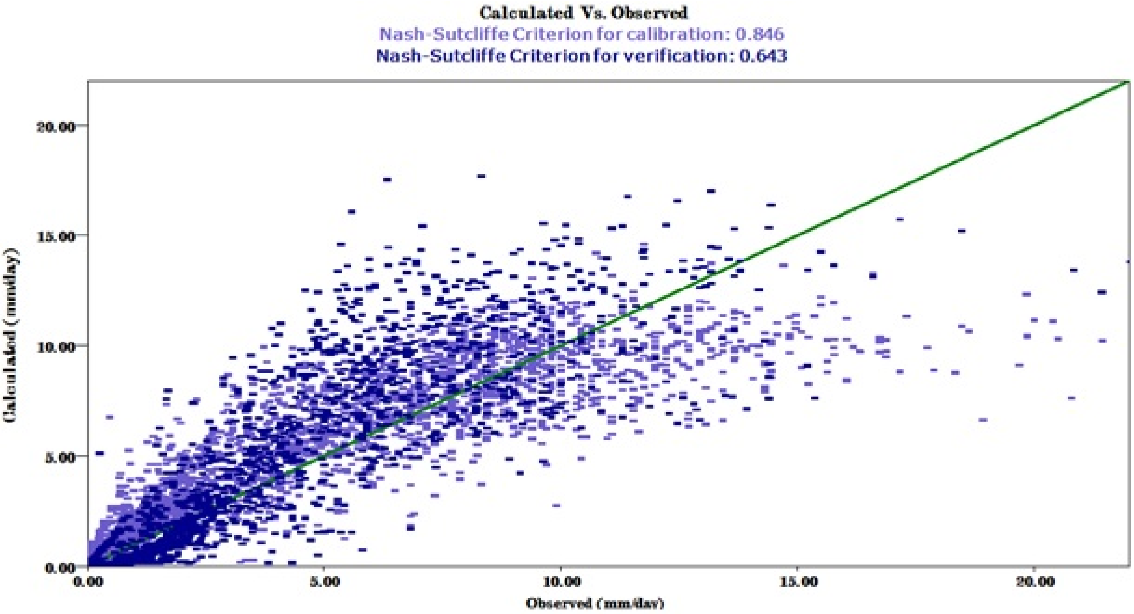


Figure 4.17: Scatter plots of simulated vs observed flow using TANK model.

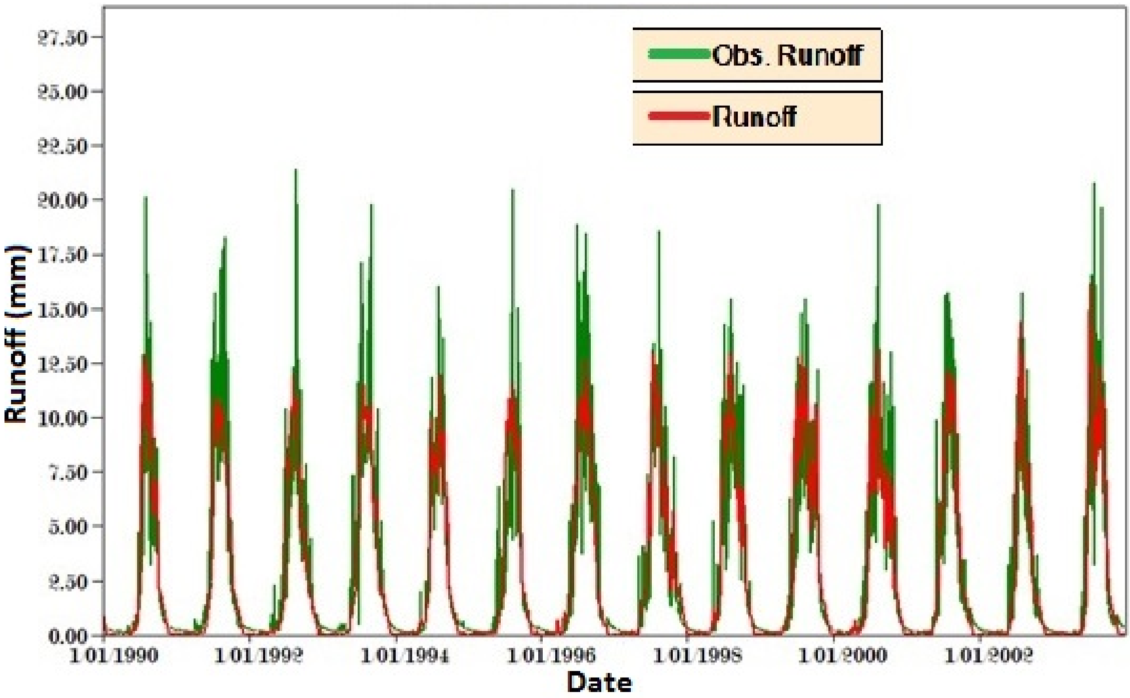


Figure 4.18: Graphical comparison of observed and simulated flow over calibration period for TANK model

The values of above three performance evaluation criteria namely, the coefficient of efficiency (NSE), the runoff difference and the coefficient of determination, are very

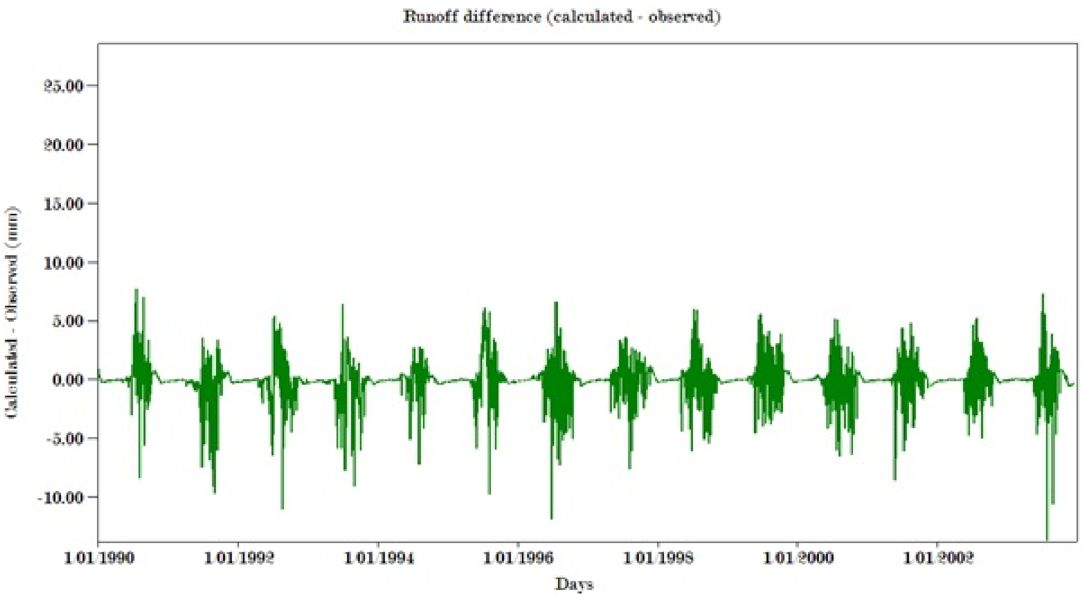


Figure 4.19: Runoff difference of calibration result TANK model with SCE-UA optimization method.

similar and consistent. The volumetric difference between the observed and simulated flow can be clearly show the peak and base flow difference, here of, (-ve) and (+ve) difference almost equal, this implies that the model is fit to to peak and low flows but when it compares with AWBM over all flow simulation it is good next to AWBM. The comparison of simulated and observed flow on calibration period Tank model more

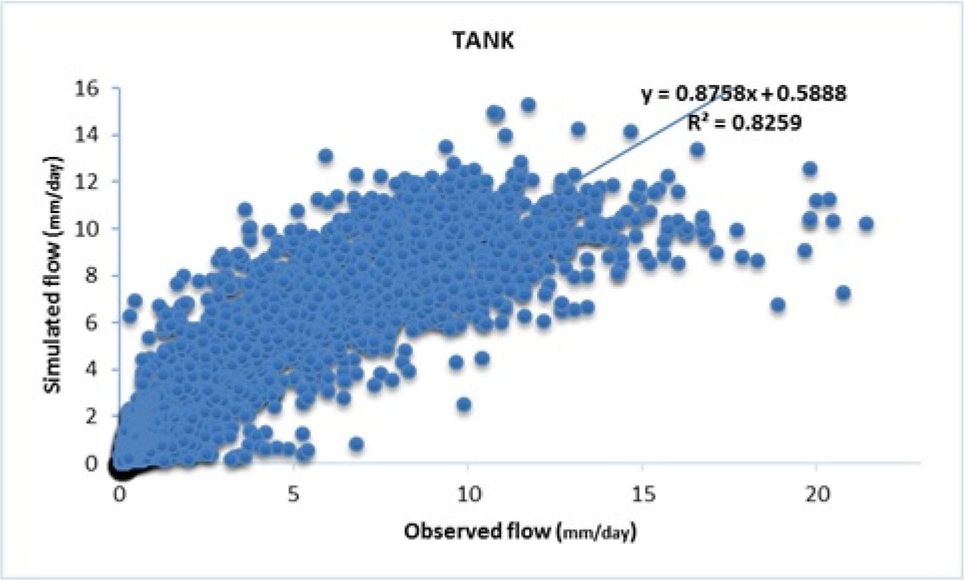


Figure 4.20: coefficient of determination (R^2) of Tank for calibration period

predicts the flow volume for low and medium flows fairly good, But the model have a limitation to capture the peak flow that is >10mm flow depth and good for median and low flow simulation that is < 10mm runoff flow depth. the observed peak flow exceeded

the simulated peak flow for 10% and 90% of the simulated and observed flows are equal in this model refer Appendix D.
while the difference between computed and observed peak flow is lower than 10%. This proves that the calibration parameter set is consistent, predictive and can be used for estimation of flood frequency from rainfall data.

SUMMARY FOR CALIBRATION

To be able to evaluate the rainfall runoff models after calibration, eight evaluation methods have been used. The Nash Sutcliffe coefficient (NSE), the Index of Agreement and the Coefficient of determination evaluate the shape of simulated compared with observed runoff. Nash Sutcliffe coefficient is the basic of proposed evaluation method and uses to evaluates the best shape that fit observed and simulated flow. others evaluation methods compare different elements of the simulated runoff. The RVE evaluate the differences between simulated and observed runoff. the second important element of the evaluation method which should be included comparison of the Peak flow and the Low flow, it depends if they contribute to the evaluation.

parameter	AWBM	Sacramento	SIMHYD	SMAR	TANK
NSE	0.861	0.838	0.853	0.850	0.852
R^2	0.86	0.85	0.84	0.85	0.85
LogEff	0.65	0.00	0.00	0.00	0.00
RVE	-4.01	-4.21	2.97	-1.80	-1.54
Md	0.12	0.16	-0.02	0.15	-0.02
NSE peak.f	0.93	0.48	0.90	0.90	0.90
NSE base.f	0.99	0.90	0.99	0.99	0.99
d	0.96	0.96	0.96	0.96	0.96

Table 4.4: Model comparison and goodness of fit measures for calibration period

Generally, the quality of fit between observed and computed out flows also can be checked by reviewing plots of hydrographs. But the most criteria to select the best fit models for the catchment Nash Sutcliffe value is dominant.
The Nash-Sutcliffe coefficient describes how well the stream flows are simulated by the model. This efficiency criterion is commonly used for model evaluation because it involves standardization of the residual variance and its expected value does not change with the length of the record or the scale of runoff. From 0.82 up to 0.86 NSE value's are obtained for Gilgel Abay catchment for calibration period. As it can be observed from goodness of fit measured value on (Table 4.3), AWBM simulates the flow series fair well compared with others. The comparison of observed and computed flow using flow duration curve and runoff hydrograph reveals that except for the extreme peak flows the medium flows and low flows are generally modeled or captured very well by AWBM, SIMHYD, SMAR and TANK models those models are useful for irrigation structure design and to analyses irrigation capacity determination. Peak flow and medium flow analysis of those models in a calibration period indicates that models have ability to forecast wet season flow

In order to check the performance of models the peak, medium and base flow analysis are very important, so according to the indicator of hydrological iteration first determine the median flow amount of the observed flow and take a threshold to split high and low flow pulse threshold plus or minus 25% of the threshold are taken respectively. 0.53 mm/day is the median for observed flow and 0.40 mm/day and 0.66 mm/day are low and peak flow thresholds for simulated respectively. Hence, depending up on the observed base and peak flow thresholds calculate the Nash Sutcliffe coefficient of simulated base and peak flow of all models are shown in table 4.4. According to the classification of Moriasi et al. (2007), performance of models is very good, good, satisfactory, and unsatisfactory if the NSE statistic is larger than 0.75, between 0.65 and 0.75, between 0.5 and 0.65 and less than 0.5, respectively. so, depending up on the result that shown on table 3.3 all models have a very good performance. Although AWBM has beastly perform relatively with others based on over all NSE value of peak and base flow analysis.

4.2.2 Validation

A model approach may not be accurate. therefore, models are uncertain and cannot be stated reliable when only one field station is simulated. As such, it may occur that under different hydrological stress conditions the model does not accurately represent the real-world system behavior despite the fact that optimal and calibrated model parameter are used. Validation is a process of demonstrating that a given site-specific model is capable of making accurate predictions for periods outside a calibration period (Refsgaard and Knudsen 1996). Simple model structures, calibrated over a certain period, are influenced by the rainfall-runoff sequence specific to that period (Parajka and Bloschl 2008). therefore, in order to prove validity of a model; the model should be tested against a second, independent set of stress conditions. Validation was done for the Gilgel Abay catchment with data from 2004 to 2011.

Performance of the model in the validation period, as measured by SCE-UA optimization method, indicated that better simulation efficiency than in the calibration period. but all models that are AWBM, Sacramento, SimHyd, SMAR and TANK model's can not indicate better simulation efficiency that compared to calibration period. the model under prediction of simulation runoff in a validation period could be express by low flow simulation. Therefore, AWBM has satisfactory efficiency of Nash Sutcliffe value. Even though all models under predict the observed low flow. Table 4.5 and (Figure 4.21) up to (Figure 4.25) runoff hydrographs shows that the comparison of calculated and observed discharge for the validation period confirmed that satisfactory performance of the Validation process. However, the comparison made for the validation data, revealed some problems with low performance simulation but peak flow analysis shows that all models are in a very good performance.Even so, In this research the performance of all models are adjudge by over all NSE value.

Statistics	AWBM	Sacra	SIMHYD	SMAR	TANK
ME	0.02	-0.01	0.22	0.1	0.08
MAE	1.31	1.38	1.35	1.35	1.4
MSE	3.8	4.45	4.07	3.93	4.65
RMSE	1.95	2.11	2.02	1.98	2.16
NRMSE	58.8	63.6	60.9	59.8	65
PBIAS	0.7	-0.3	7.4	3.5	2.6
RSR	0.59	0.64	0.61	0.6	0.65
rSD	1.27	1.32	1.29	1.28	1.32
NSE	0.65	0.44	0.57	0.64	0.64
mNSE	0.5	0.48	0.49	0.49	0.47
rNSE	0.38	0.25	0.22	0.27	0.39
D	0.93	0.92	0.93	0.93	0.92
Md	0.79	0.78	0.78	0.78	0.78
Rd	0.87	0.85	0.84	0.85	0.88
Cp	-0.75	-1.05	-0.87	-0.81	-1.14
R	0.89	0.88	0.89	0.89	0.88
R2	0.8	0.78	0.79	0.79	0.77
bR2	0.74	0.72	0.71	0.73	0.7
KGE	0.71	0.66	0.68	0.7	0.65
VE	0.56	0.54	0.55	0.55	0.53

Table 4.5: statistical comparison of simulated and observed hydrological time series for verification period (2004-2011)

Based on table 4.5 shows that all statical results indicates that, the deviation between the measured and predicted values for verification period of each model is represented by Nash Sutcliffe value not more than 0.65 this shows that all models have satisfactory efficiency and not quietly represent the catchment behavior based on the verification result. where as, flow hydrograph concerned, all models predict the flow volume for medium and peak flow fairly good have low performance to represent the low flow for verification period they under predict the base flow starts from 2007.

Verification Result Analysis by Using Observed and Calculated Runoff Hydrograph

The relation between observed and computed flow of the catchment is can be judged by reviewing plots of the hydrograph.

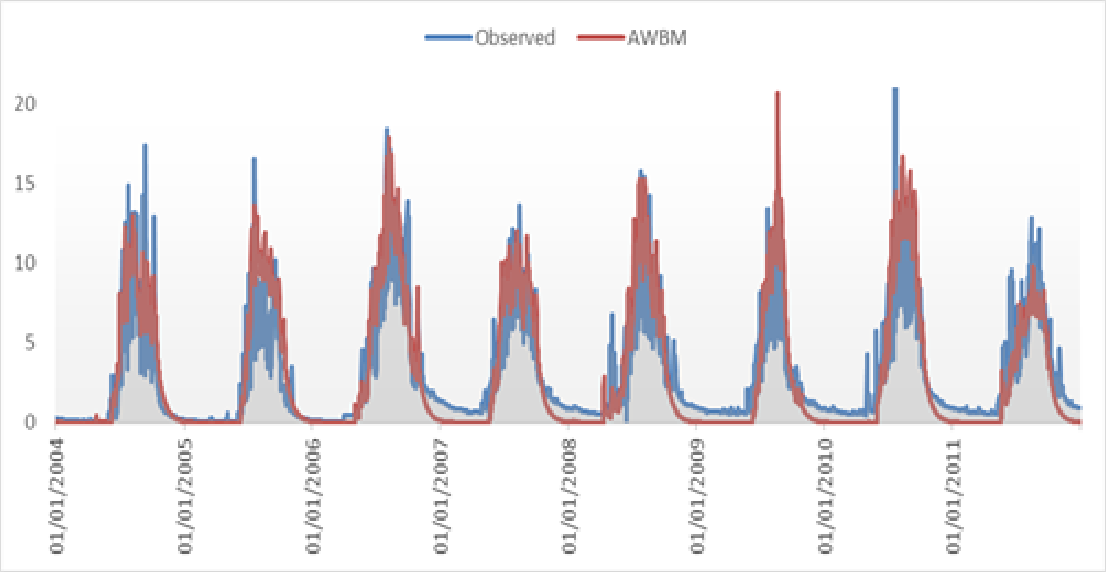


Figure 4.21: Simulated and observed flow by AWBM for verification period (2004-2011)

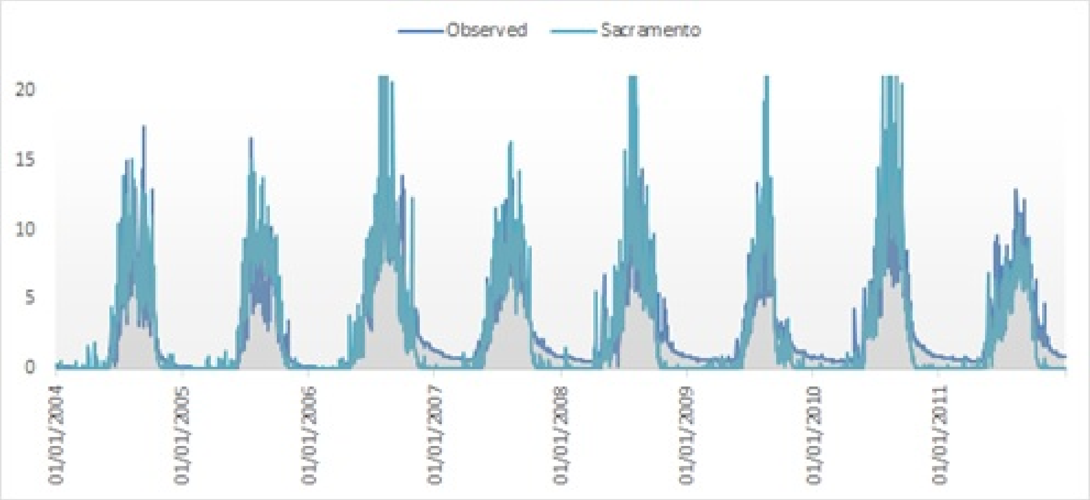


Figure 4.22: Simulated and observed flow by Sacramento for verification period (2004-2011)

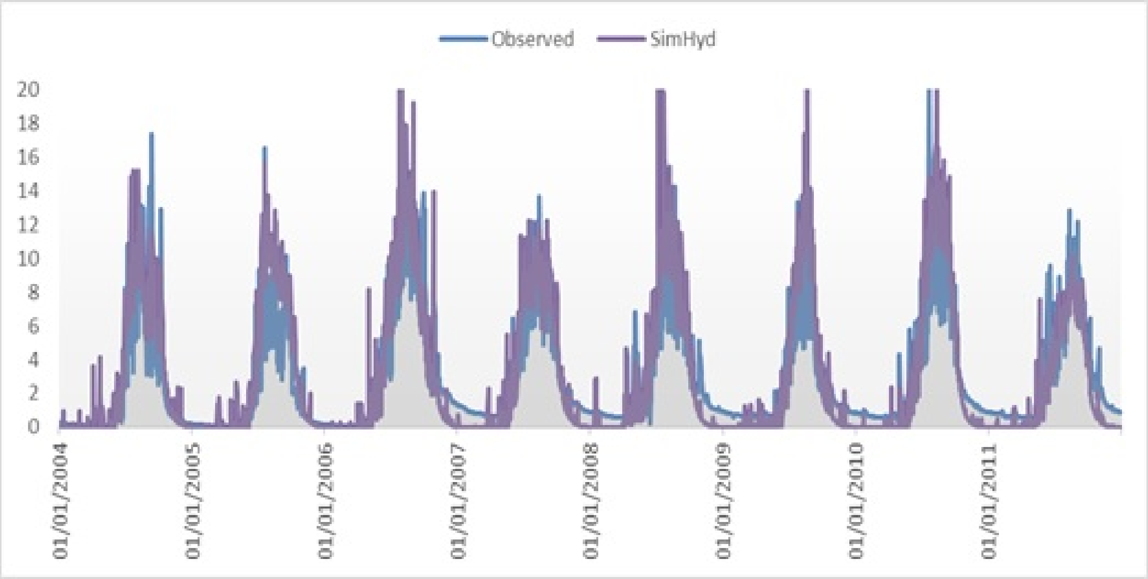


Figure 4.23: Simulated and observed flow by SimHyd model for verification period (2004-2011).

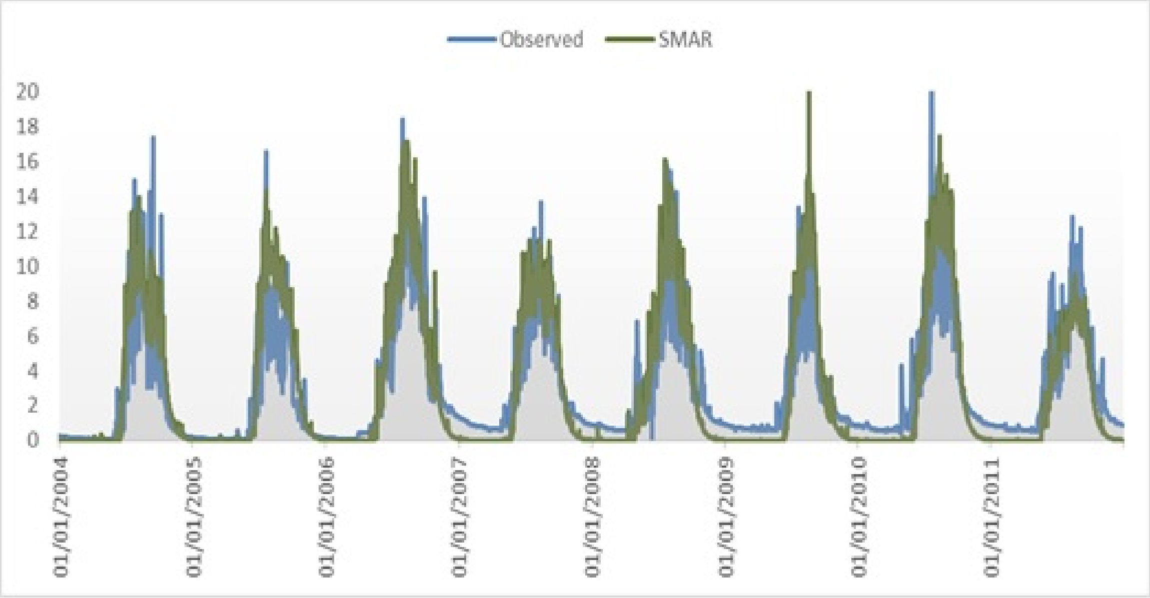


Figure 4.24: Simulated and observed flow by SMAR model for verification period (2004-2011)

All validation hydrographs (figure 4.21 up to 4.25) we can observe that the limitation of all models for under predict the low observed flow since from 2007 up to the ends of validation date. it is noted that modeling the low flow is the weak point due to the available flow data of Gilgel Abay river.
This shows that the base flow amount of observed flow or the recorded data are changed by increasing mean (0.55mm/day) from the previous calibration and validation period. due to this reason the Nash Sutcliffe efficiency is lowered than the calibration period.

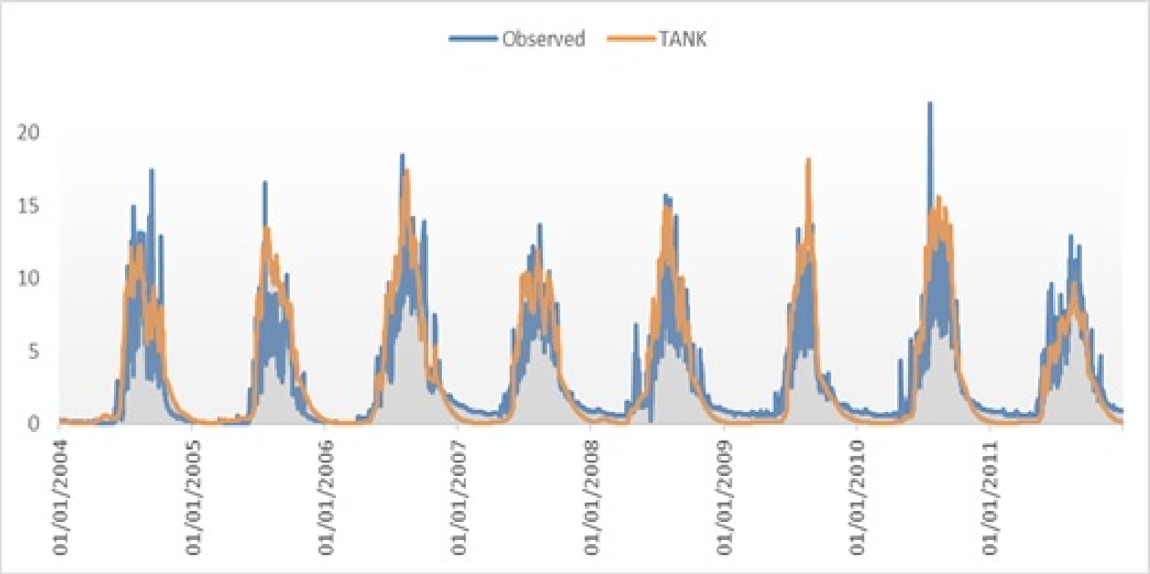


Figure 4.25: Simulated and observed flow by TANK model for verification period (2004-2011)

To analysis the data trend change that uses to detect the time of data trend change, so it was analyzed by using trend/change detection e water toolkit software is called TREND, so in order to detect the change by using cumulative deviation test the variation of the data starting time can be detect.Hence, the change of observed flow clearly seen in runoff hydrograph from 2007 G.C in observed vs simulated hydrograph (figure 4.21 up to figure 4.25).

Verification Result Analysis by Using Flow Duration Curve

The shape of the flow duration curve in high flow region indicates the type of flood regime is likely to have, whereas, the shape of the low- flow region characterizes the ability of the basin to sustain low-flows during dry seasons. A very steep curve (high flow for short periods) shows rain caused floods on watersheds. However, a very flat FDC indicates that moderate flows are sustained throughout the year due to natural or artificial stream flow regulation, or to a large groundwater capacity which sustains the base flow to the stream. From (Figure 4.26) flow duration curves which represent the model is highly perform the peak and the the low flow of the observed discharge of the catchment it is also over estimate the medium flow that ranges from 2mm up to 12 mm runoff depth. it is also illustrated from (Figure 4.3) Runoff difference graph. Hence, the flow duration curves AWBM have 10% ability to represent the peak flows of the catchment and also have underestimation of the low flow.

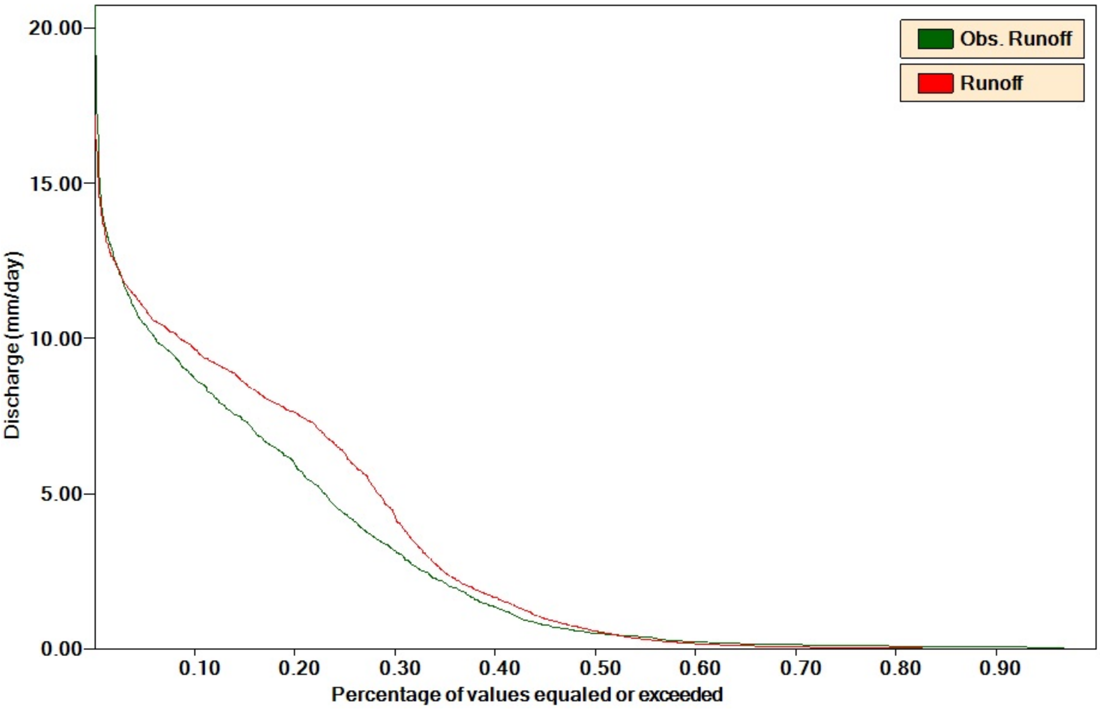


Figure 4.26: Simulated vs observed flow duration curve for verification of AWBM (2001-2006)

The flow duration curve of figure 4.27 shows that Sacramento model have a tendency to overestimate the peak flow and underestimate lower flows and has a limitation to captures the intermediate flows very well (refer figure 4.27). However, in many cases, the model has good efficiency to represent the peak flow based on NSE value of peak flow. so the model was used for irrigation and flood forecasting purpose.

From (Figure 4.28) flow duration curves SIMHYD model has perform a similar performance like AWBM. based on the FDC a model has a good tendency to capture the peak and low flow but it has an overestimation the medium flows because the model assumption impervious runoff that generates from impervious area infiltration excess,

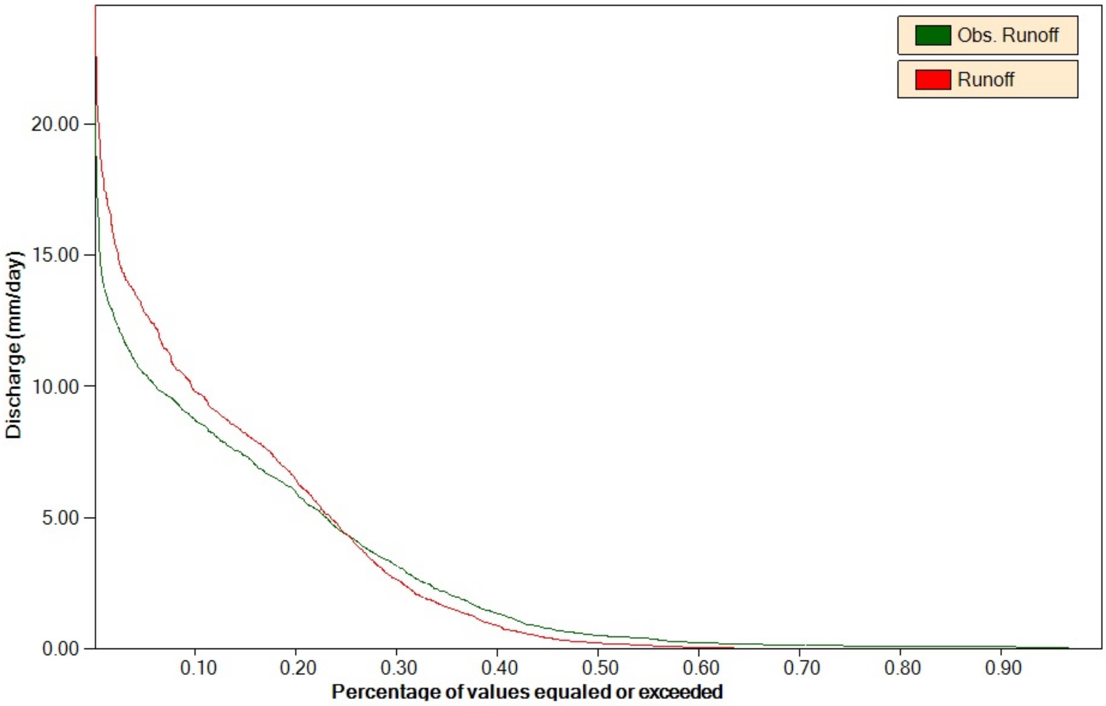


Figure 4.27: Simulated vs observed flow duration curve for verification of Sacramento model (2001-2006)

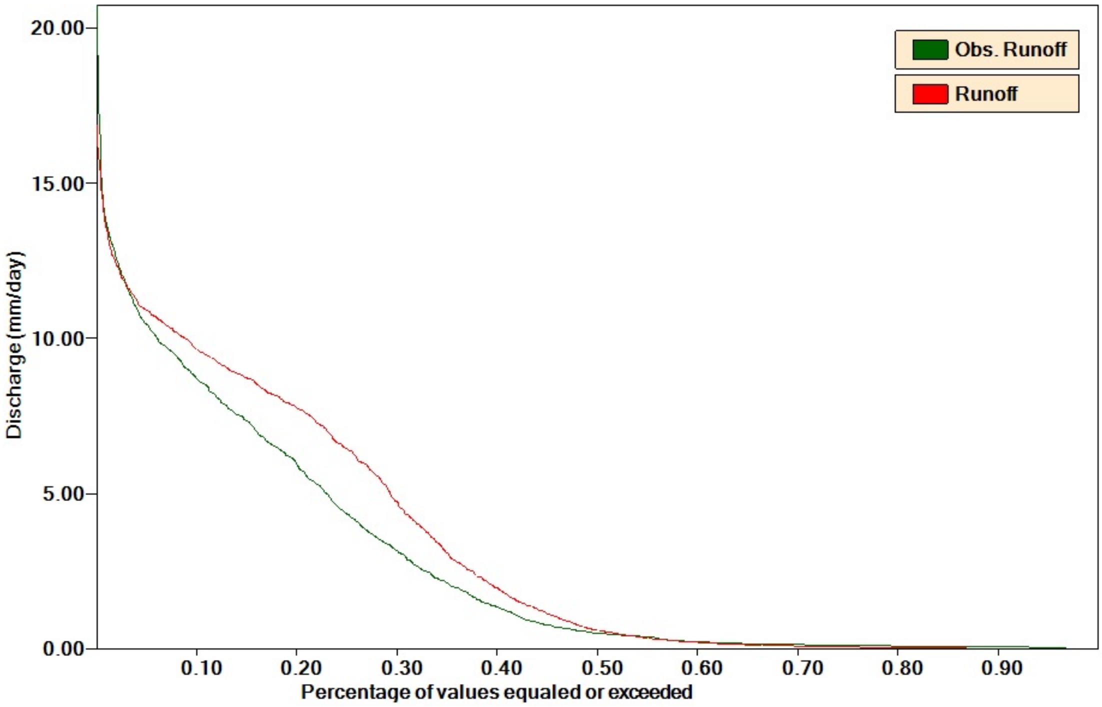


Figure 4.28: Simulated vs observed flow duration curve for verification of SIMHYD model (2001-2006)

saturation excess and base flows are considered as a source for total runoff from the catchment so the amount and length of to show the peak and low flow from the catchment should be for a short period .

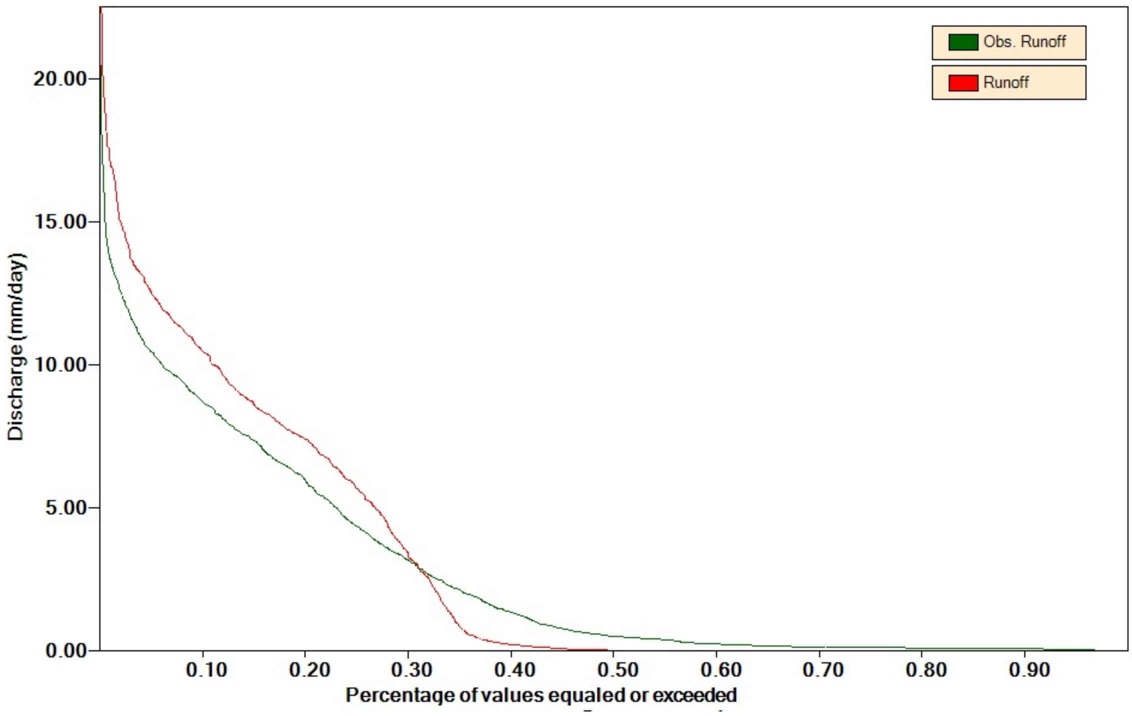


Figure 4.29: Simulated vs observed flow duration curve for verification of SMAR model (2001-2006)

From figure 4.29 SMAR model shows overestimation of the peak and medium flow and underestimate low flow of a Gilgel Abay catchment. As it can be observed from (Figure 4.30) flow duration curve TANK model predicts the peak flow equally and overestimate the medium flow that ranges from 3mm up to 12mm flow, it has also low performance to reproduce low flow that has 50% of exceed.

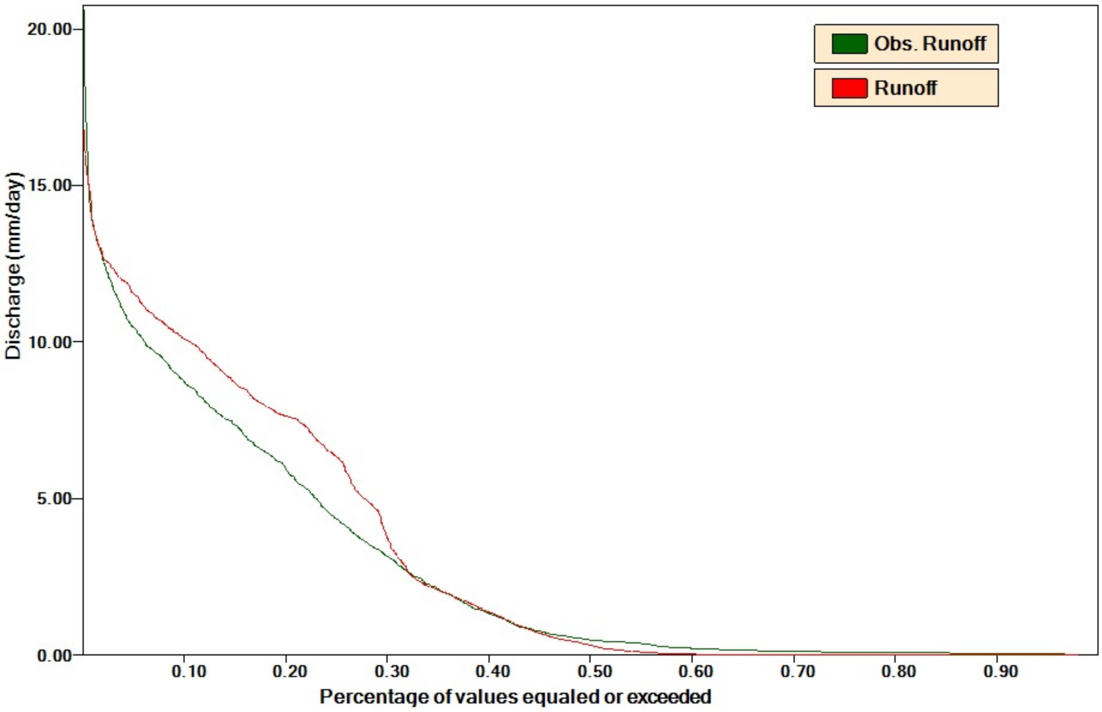


Figure 4.30: Simulated vs observed flow duration curve for verification of TANK model (2001-2006)

SUMMARY FOR VALIDATION

As we shown from runoff hydrograph of simulated and observed flow the scatter is denser around the median and peak flows, starting from 2007G.C all models cannot seizure the low flow regimes.
The comparison of observed and simulated flow duration curves is probably the most effective visual test of model performance. Flow duration curves are useful in providing an indication of the distribution of daily flows, as might be required for licensing abstractions or effluents, and other design applications. However, they cannot show whether a particular flow estimate is simulated on the same day on which it is recorded, as might be required for operational matters such as flow forecasting; for this it is necessary to compare observed and simulated by daily flow hydro-graphs. The flow duration curves which represent the lower, median and upper observed and simulated discharge of the river is also illustrated by the Runoff difference (calculated Vs observed flow) and flow hydrograph. Generally all models have a good efficiency to simulate the median and peak flow of it is clearly shown the above FDC and runoff hydrograph. But all five models have a weakness to capture a low flow.

Value	AWBM	Sacramento	SIMHYD	SMAR	TANK
NSE	0.65	0.44	0.57	0.64	0.64
R2	0.89	0.88	0.89	0.89	0.88
LogEff	0.57	0.00	-1.07	-1.29	-1.34
RVE	0.65	0.00	0.00	0.00	-0.27
Mean Diff	-0.02	0.01	-0.22	-0.10	-0.10
NSE for Peak flow	0.84	0.80	0.82	0.82	0.79
NSE for Base flow	0.32	0.18	0.17	0.14	0.16
Index Aggrement	0.93	0.92	0.93	0.93	0.92

Table 4.6: Model comparison and goodness of fit measured values of each models for validation period(2004-2011)

Finally, from Table 4.6 we can analysis that, based on over all NSE value AWBM has a good performance as compared to others. SimHyd, SMAR and Tank models have satisfactory performance. In the other way Sacramento model unsatisfactory that shows low performance relatively with others. However, all models that shows a very good performance to represent the peak flow but According to low flow simulation all models are not satisfactory at low flow simulation in the first validation period but in the second adjusted period that of from (2001-2006).

4.3 Performance of The Models

The performance of a model must be evaluated on the extent of its accuracy, consistency and adaptability (Goswami et al. 2005) . A forecast efficiency criterion is therefore necessary to judge the performance of the model. Assessing performance of a hydrological model requires subjective and/or objective estimates of the closeness of the simulated behavior of the model to observations (Krause et al. 2005) should be checked and evaluated on the above eight selected criteria on Table 3.3 the most effective and dominant model performance evaluation criteria, that was evaluated for both calibration and validation in Nash-Sutcliffe efficiencies (NSE),other criteria or parameters that uses coefficient of determination criteria, log-efficiency, the relative volume error, by comparing the simulated and observed hydrograph for low and peak flow analysis. however, all models have limitation to under predict the low flow in validation period since starting from 2007 G.C because of the change in observed flow data (increasing the mean flow by 0.55 mm/day from the previous calibration periods) this increment has its own impact on base flow analysis. Nash Sutcliffe efficiency of simulated runoff for validation period under 66%.

This efficiency shows that, there is a problem on observed data. due to this result a validation efficiency more decreases as compared to that of calibration period. It is seen that all models underestimate cumulative low flows in verification period, Therefore, in order to check the performance of all models in a validation period by readjust the period from (1990-2006) and split to that, from 1990 G.C – 2000 G.C and 2001 G.C – 2006 G.C for calibration and validation period respectively. Finally the performance of the model's reviewed by NSE value an the validation result shows that all models performance lay on between a very good and good performance. the result put on Appendix (E,F,G,H and I) for AWBM, Sacramento, SIMHYD, SMAR and TANK model respectively. and yet AWBM has large value and a very good performance relatively with others, that is 0.86 and 0.81 NSE for calibration and verification respectively.

4.3.1 probable reasons for under predictions of validation results of all models

In this Research modeling the low flows was the weak point of the whole used CRR modeling with the time steps considered. This is most probably due to the data recording system and availability of data. For instance, during data analysis period I observe that the observed flow data increases by averagely 0.55 mm/day, so the data trend was changed visually from runoff hydrograph starts from 2007 G.C.but the data pattern change was checked by using trend software that starts from 2005.
To check the reason of changing of this measured flow data of Gilgel Abay river I get three hypothetical reasons. that are:

1. shifting of River gage station location 50m to downstream but without changing the rating curve. (from my informal inquire from my colleagues in ANRS Irrigation and water development Bureau and Abay Basin Authority.)
2. Joining of another tributaries with base flow are checked and not available. However, It may be ground water (spring) inflow in the side of the river within this 50m length.
3. Changing in land use land cover of the watershed (conservation practice and deforestation...)

The above three reasons have their own implication to increase the base flow of the river, the first one may increase the catchment area and adds other tributaries or lowering the river bed and increase the flow depth. the third reason may be related to that changes in land use and land cover have contributed more to increased runoff. Both of them changes have occurred together to have an even greater impact than if each were acting alone. models are usually developed for particular regions using diverse physical and mathematical descriptions to reproduce the watershed in a simplified way with local climate, soil, vegetation, size of watershed and its special localized processes (e.g. for semi-humid, arid, semi-arid regions, rural or urban areas). Similarly, the models used in this study are originally developed for Australian Catchments and thus they may luck incorporation of concepts and parameters that account for the hydrological characteristics of the semi-humid and semiarid conditions of the catchments like those in Ethiopia.Finally it needs detail investigation on flow data change.

4.4 Sensitivity Analysis

In this study sensitivity analysis was carried out to identify the sensitive model parameters and associate them with the catchment runoff generation characteristics and model sensitivity analysis was undertaken to analyze the sensitivity of a particular model parameter with regard to a selected objective function. The model parameter selection drops down list box of rainfall runoff library allows the selection of the model parameter to be analyzed. It displays the result of analysis in graphical form. In the graphical representation, the x-axis is the number of iterations and the y axis is the value of the objective function. The parameters displayed in this list are dependent upon the rainfall runoff model selected.

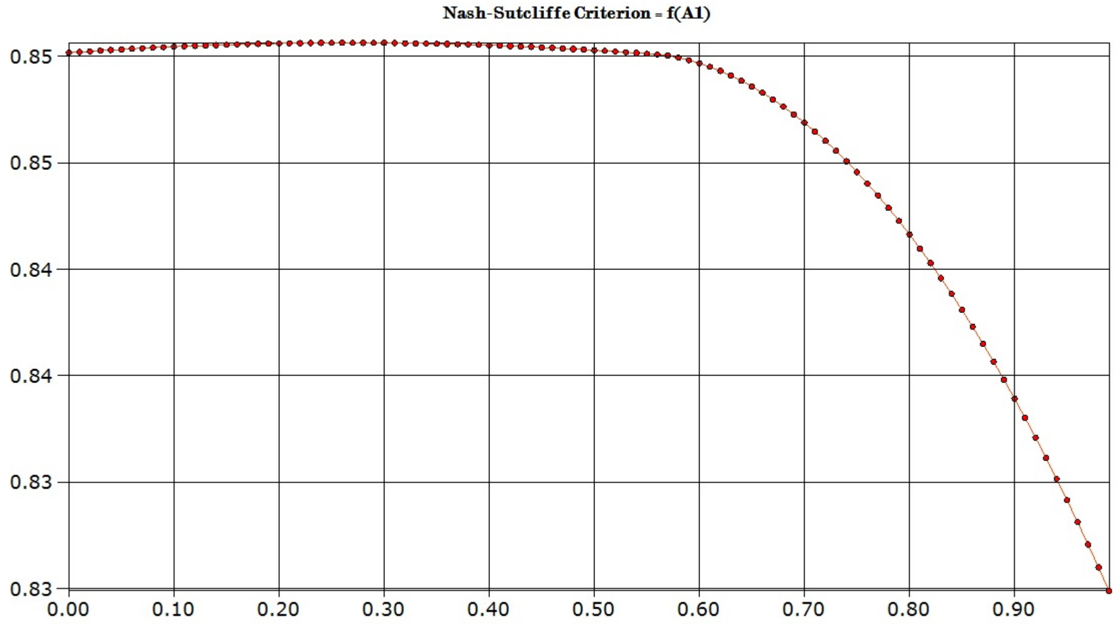


Figure 4.31: Sensitivity analysis for A1 of AWBM.

As it is stated under section 3.6.1, Nash-Sutcliffe criterion (Coefficient of efficiency) is the objective function used in this modeling. Therefore, it is for this objective function that sensitivity analysis of the selected model that is AWBM parameters conducted considering each parameter and recording the outcomes for each in order to identify the most sensitive parameters.

After making the necessary analysis, AWBM is the best representative model based on its Nash Sutcliffe efficiency Therefore, the following observations made for only AWBM model parameters.

For maximum and minimum values of A1, A2 and A3 of AWBM, which represent the proportions of areas, the values of objective function (Nash Sutcliffe value) vary over small range. For instance, in case of A1, the Nash Sutcliffe value is constant for values of A1 up to range of 0.57. However, for values of A1 more than 0.57, the relation with Nash Sutcliffe criteria is linear with small variation in magnitude of the value of Nash Sutcliffe (Figure 4.31). In case A2, Nash Sutcliffe value vary almost linearly up to 0.4 and drops after wards linearly (Figure 4.32).

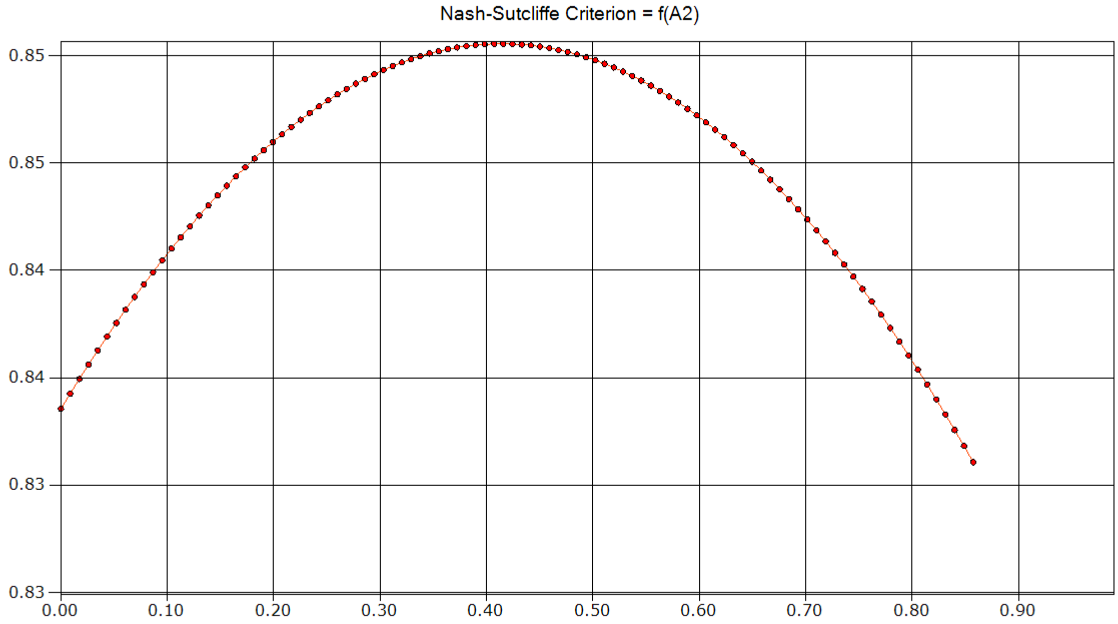


Figure 4.32: Sensitivity analysis for A2 of AWBM

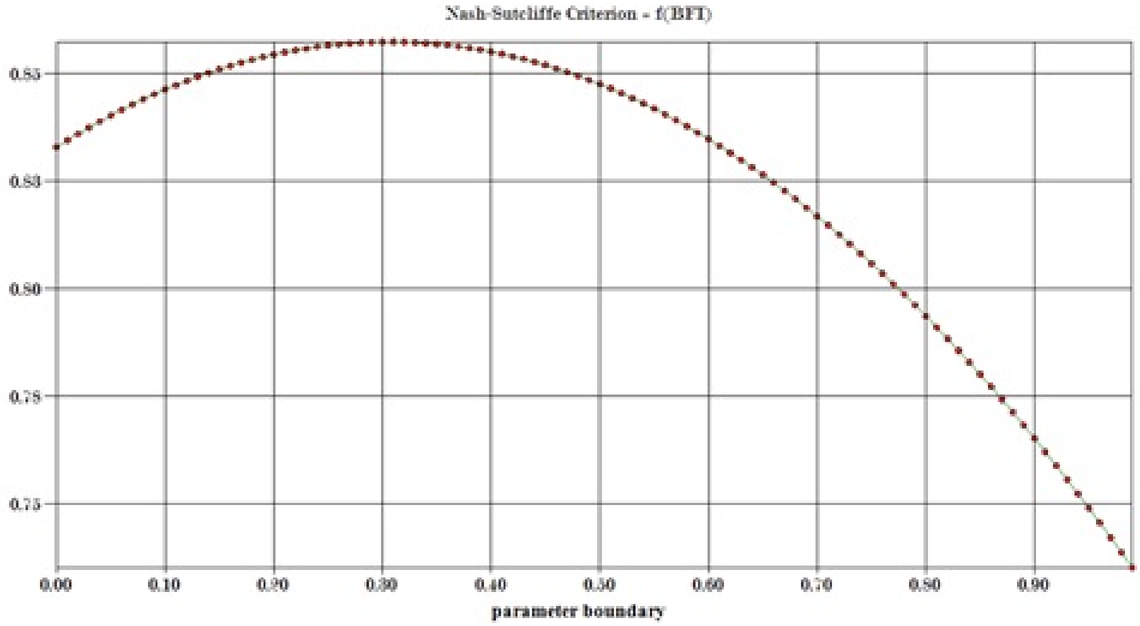


Figure 4.33: Sensitivity analysis for Base Flow Index (BFI) of AWBM.

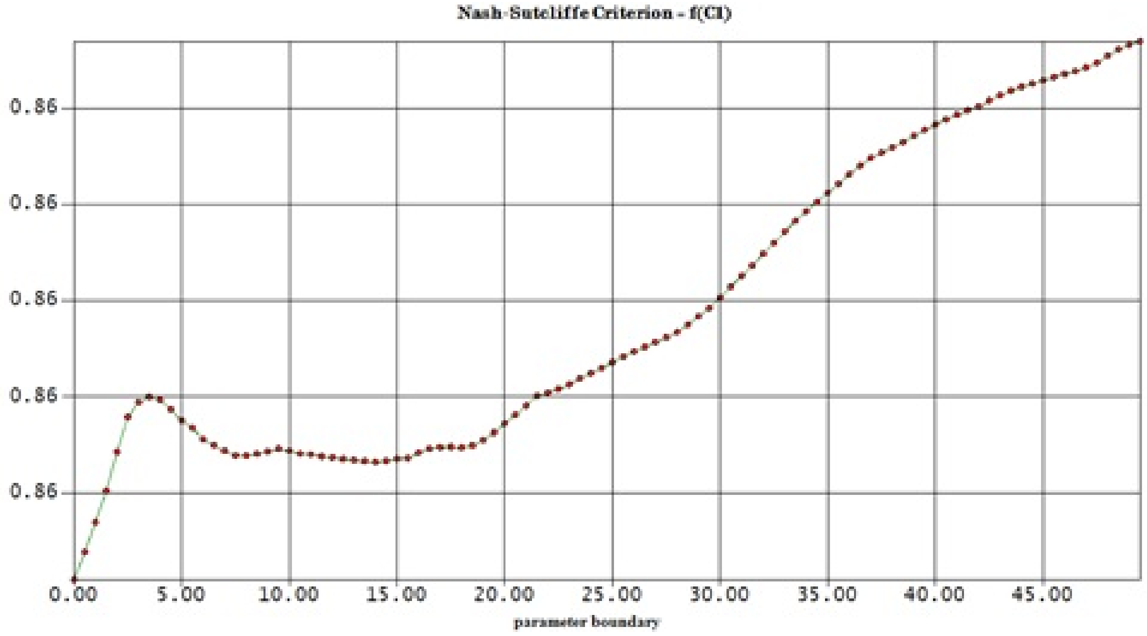


Figure 4.34: Sensitivity analysis for C1 of AWBM.

Moreover, the sensitivity analysis result shows that for the maximum and minimum values of storage capacities (C1, C2, C3), Nash Sutcliffe values varies relatively over the large range as compared to the Nash Sutcliffe Values variation for partial areas (A1, A2, A3) which in urn indicates that storage parameters are more sensitive than partial area parameters (Figure 4.34, figure 4.35 and figure 4.36).

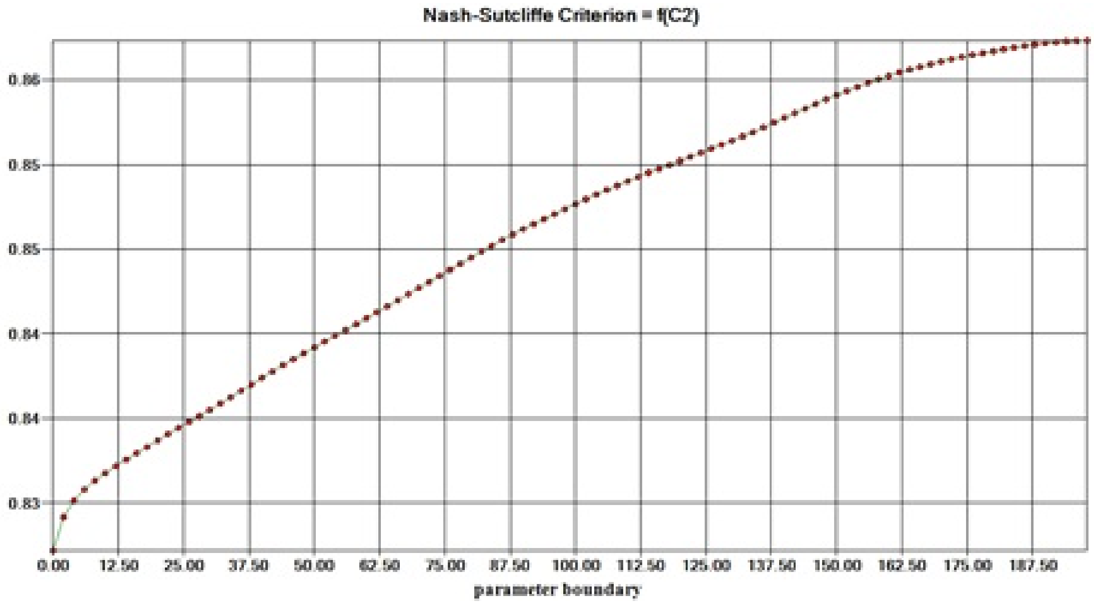


Figure 4.35: Sensitivity analysis for C2 of AWBM.

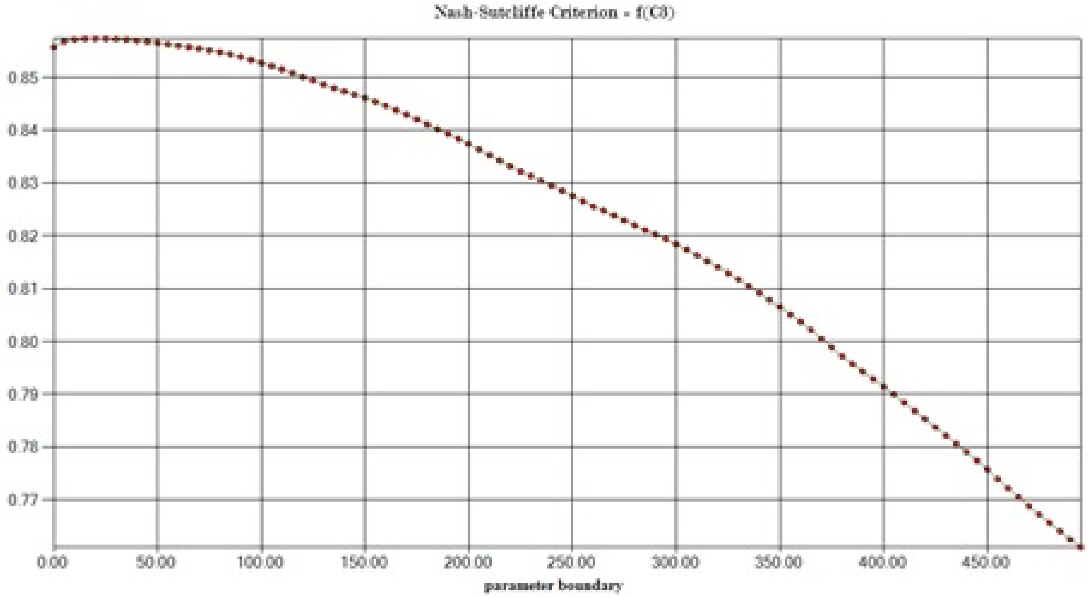


Figure 4.36: Sensitivity analysis for C3 of AWBM.

As it can be observed from (figure 4.33), the other parameters of AWBM such as BFI (base flow index) which is the ratio of base flow to total flow in stream and KSurf (daily surface flow recession constant) varies over the large range which indicates that these parameters are the most sensitive parameter of AWBM with respect to the selected objective function in this modeling.

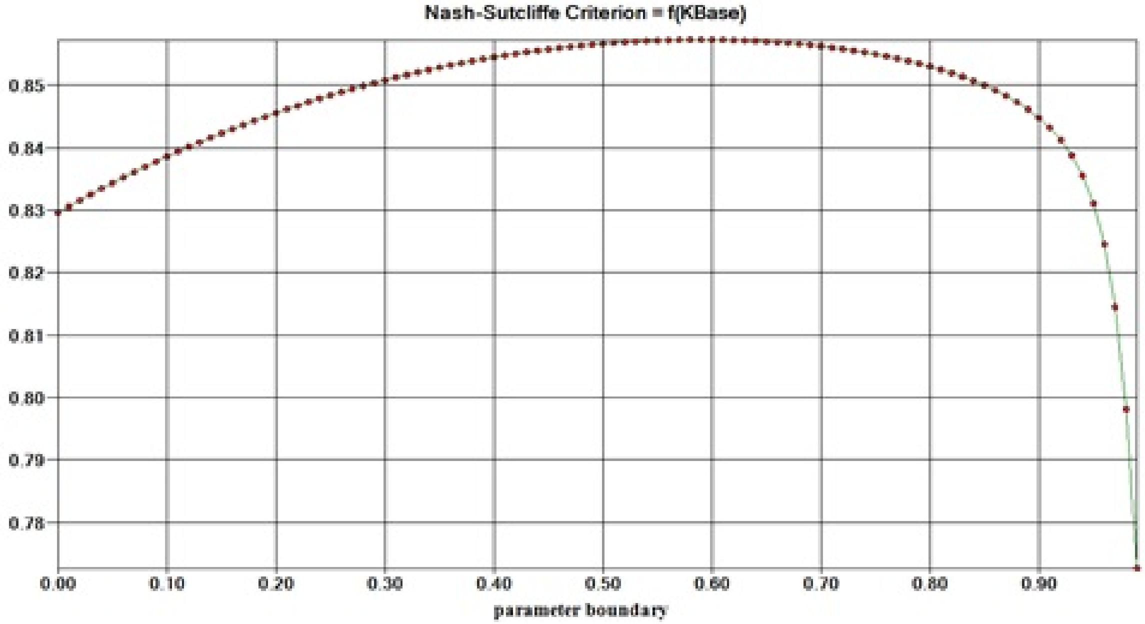


Figure 4.37: Sensitivity analysis for base flow of AWBM.

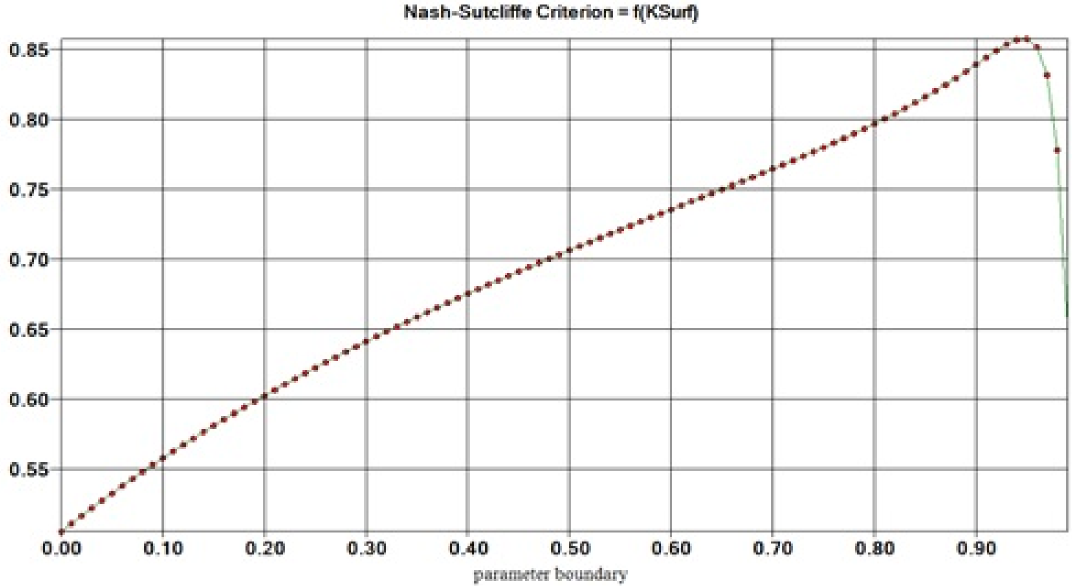


Figure 4.38: Sensitivity analysis for daily surface flow recession constant (KSurf) of AWBM.

Chapter 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this study, we tried to evaluate five well-known conceptual rainfall-runoff models including AWBM, Sacramento (SAC), SIMHYD, SMAR and TANK models for Gilgel Abay catchment based on hydro meteorological data available from Ethiopian National Meteorological Agency (ENMA) Bahir Dar Branch and Abay Basin Authority. Optimal parameters of all the selected models were obtained through automatic calibration using Nash-Sutcliffe Efficiency as an objective function. Each model was tested by evaluating its capacity in capturing moderate and extreme hydrological events and the temporal changes in the flows.

The performance of the models were evaluated using 12 goodness-of-fit measures including Quantitative statistics which are: Mean Error (me), Mean Absolute Error (mae), Root Mean Square Error (rms), Normalized Root Mean Square Error (nrms), Pearson product-moment correlation coefficient (r), Spearman Correlation coefficient (r. Spearman), Coefficient of Determination (R^2), Ratio of Standard Deviations (rSD), Nash-Sutcliffe efficiency (NSE), Modified Nash-Sutcliffe efficiency (mNSE), Relative Nash-Sutcliffe efficiency (rNSE), Index of Agreement (d),Modified Index of Agreement (md), Relative Index of Agreement (rd), Coefficient of Persistence (cp), Percent Bias (pbias), Kling-Gupta efficiency (KGE), the coefficient of determination multiplied by the slope of linear regression between "sim" and "obs" (bR^2), and volumetric efficiency (VE). The model performance was evaluated based on high, low flow analysis, and the overall shape of the hydrograph.

The performance of all the models in simulating the runoff of the study area were found acceptable. Visual observation of the hydrograph of the simulated and observed discharges shows that they very well fit for 1990-2006. However, the best performance in terms of Ratio of Standard Deviations (rSD) and Kling-Gupta Efficiency (KGE) was realized from AWBM.The deficiency of a models in capturing the observed water balance closure evaluated using bias range that are -4% (AWBM), -4.3% (Sacramento), 3% (SIMHYD), -1.8% (SMAR) and -1.6% (TANK) for calibration period. Thus, the best model to reproduce observed cumulative flow based on the above percentage of bias was TANK model, whereas, positive bias value of SIMHYD model indicates that

overestimation of bias Although, other models underestimation of bias.
Coefficients of the correlation between observed and modeled daily flows were above 0.91 for all models. For maximum correlation of 0.93 (AWBM) for daily flow. Therefore, the best performing model to reproduce the observed temporal variability at daily time series was AWBM (for daily low, medium and peak flow) as compared to others.
Generally, for the simulation of flooding and drought conditions, it was found that the use of overall water-balance-based objective function influences the capacity of models to perform better in capturing the changes as well as quantiles of observed high flows compared to low flows. This might not be surprising because low flows are often poorly reproduced by most rainfall-runoff models which are tailored to capture flooding conditions. Whereas, the need to revise concepts on model structures to simultaneously capture both low and high flows acceptable may still remain food for thought, it is recommended that the use of water-balance-based objective function be combined with other criteria for optimization of the numerical performance schemes. Such other criteria may include the overall shape of the hydrograph, peak flow, low flows variability, sub trends in low and high flows. Furthermore, it was generally found that the choice of the criteria for extracting extreme events from the full series for the purpose of intermodal comparison influences the model performance. Thus, caution must be taken to test model performance with respect to extreme events extracted based on criterion's.
In this study, a total of four criteria were considered including the NSE value near to 1, log efficiency value approaches to 1, volume error value to 0 and coefficient of determination value approaches to 1. Considering all the above criteria in a combined way, the overall best model (i.e., with the best "goodness-of-fits") to a very good performance to capture both high and low flow conditions was the AWBM. Because the performance of a particular model may differ from one criterion to another, an attempt to interrelate the performance indicators across all various criteria should be improved by the expert judgment of the modeler.
It can be remarked that prudence must be exercised in the choice of a particular model which can be made on a case by case basis in line with the objectives of the hydrological modeling study. Evaluation of the inter modal differences is vital in the choice of which hydrological models to apply for impact investigations, for example, of climate variability and change on water resources. Importantly, whereas the influence of model selection may be minimal in the simulation of normal flow events, it must be considered carefully for high or low flows to minimize under- and/or overestimation of hydrological extremes. The selection of a particular model for simulating extreme flow events is, in turn, influenced by the choice of the "goodness-of-fit" measures for evaluating the model performance and the criteria for extracting extreme events for the model performance evaluation or intended application. Furthermore, note should be taken that the performance of a hydrological model may be influenced by the quality of the data which can be translated into the ease or difficulty of the model calibration.
In the first validation period, the hydrograph shows that all models could not capture the low flow due to the change in observed discharge data after 2007, However, when the data trend is detected with TREND software it was starts from 2007. Due to this reason the validation performance of each model was low. Therefore the validation period was readjusted from 1990-2006. After the change in the calibration and validation periods the performance of all the models showed a very good performance except sacramento

model. From this study it is confirmed that SIMHYD, Sacramento and SMAR conceptual models underestimate the low flow it does not consider the deep percolation and ground flow. As far as the performance of all models are concerned AWBM gives better results as compared to others in Gilgel Abay catchment.

Lastly, model sensitivity analysis of selected model was undertaken to analyze the sensitivity of a particular selected model parameter with regard to a selected objective function. The model sensitivity analysis conducted tells that daily surface flow recession constant (KSurf) and (BFI) of AWBM are the 1^{st} and the 2^{nd} most sensitive parameters respectively for the selected objective function.

5.2 Recommendation

This study recommends AWBM model which is the best fitting model to the observed data of Gilgel Abay watershed for the low and high discharge values. the other models also predict the flow pretty well in the watershed.

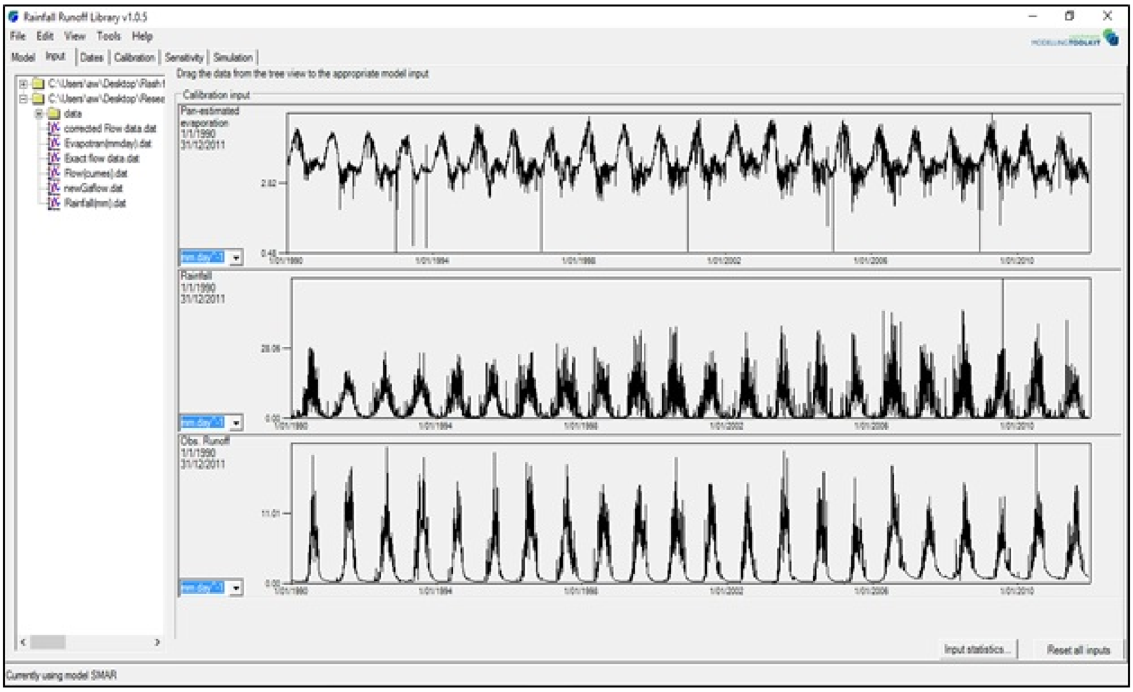
The challenge of having adequate and good quality data may be a faraway dream in the developing countries. In this research it was quite a daunting task to collect data especially from home institutions and when it was made available, the quality was always questionable. A thorough process of quality control is more likely to leave the user with half the data required. As such, other types/ sources of data such as remotely sensed data (e.g. for rainfall) could be explored to provide a wider coverage of rainfall distribution and complement the already existing records.

The hydrological reasons of the change of observed base flow starting from 2005 should be further investigated by other researchers and correct the flow data for other institutional sectors and development works.

Part I

APPENDENCES

Appendix A: model data dialogue



Drag the data from the tree view to the appropriate model input

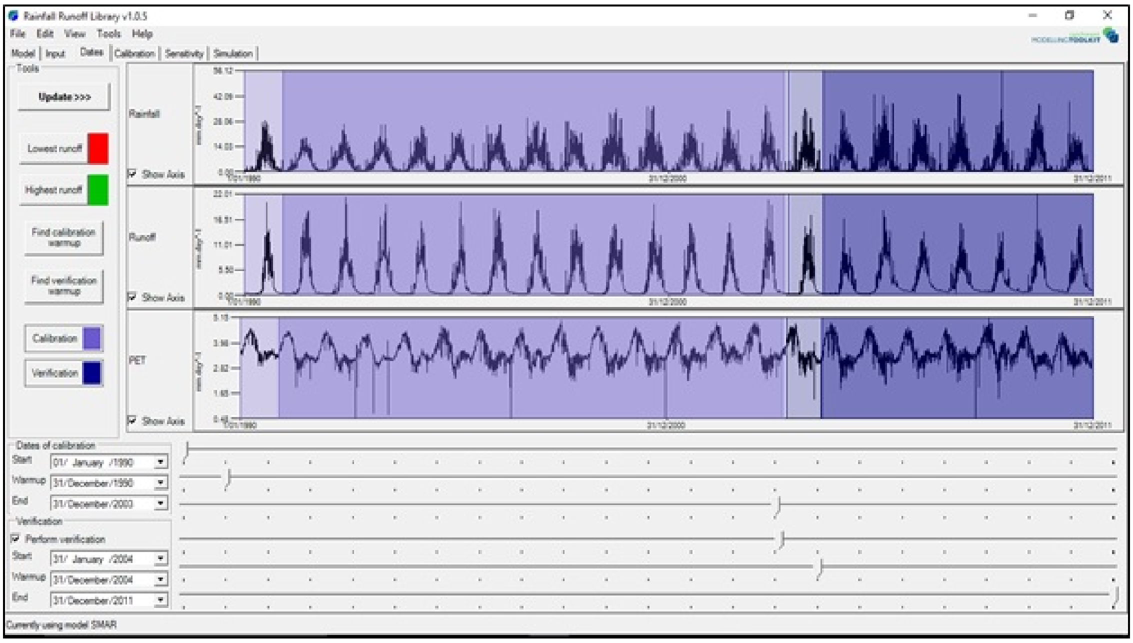
Pan-estimated evaporation 1/1/1990 31/12/2011

Rainfall 1/1/1990 31/12/2011

Obs. Runoff 1/1/1990 31/12/2011

Currently using model SMAR

Appendix B:model calibration and verification date dialogue.



Dates of calibration

Start 01/ January /1990

Warmup 31/December/1990

End 31/December/2003

Verification

☑ Perform verification

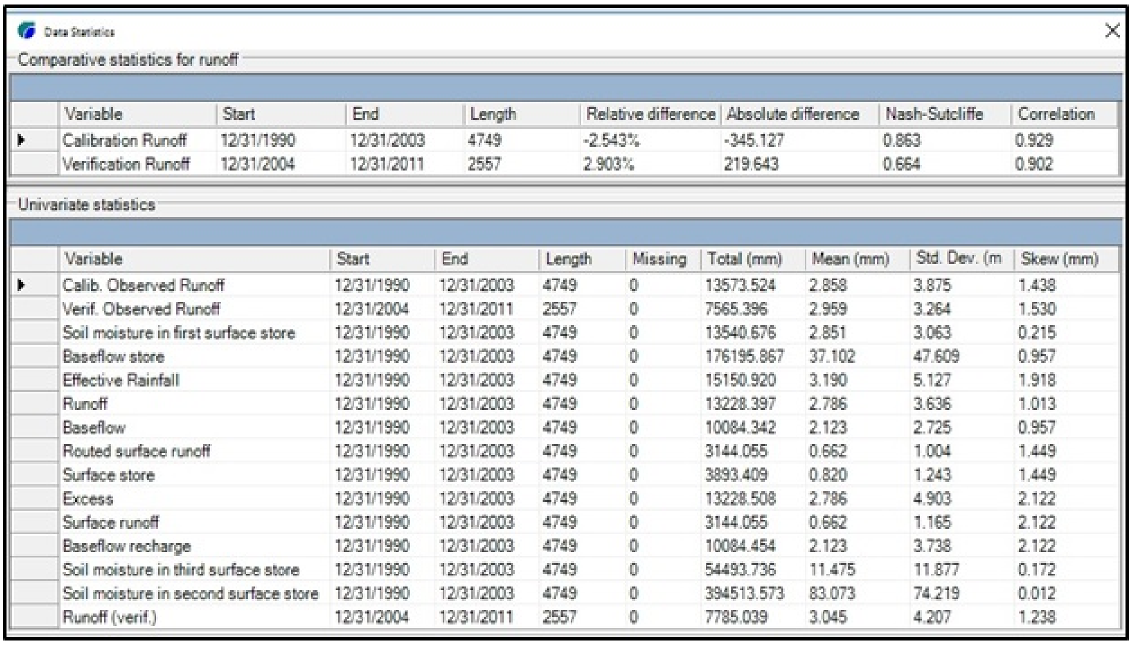
Start 31/ January /2004

Warmup 31/December/2004

End 31/December/2011

Currently using model SMAR

Appendix C1: Comparative data statics for runoff AWBM.



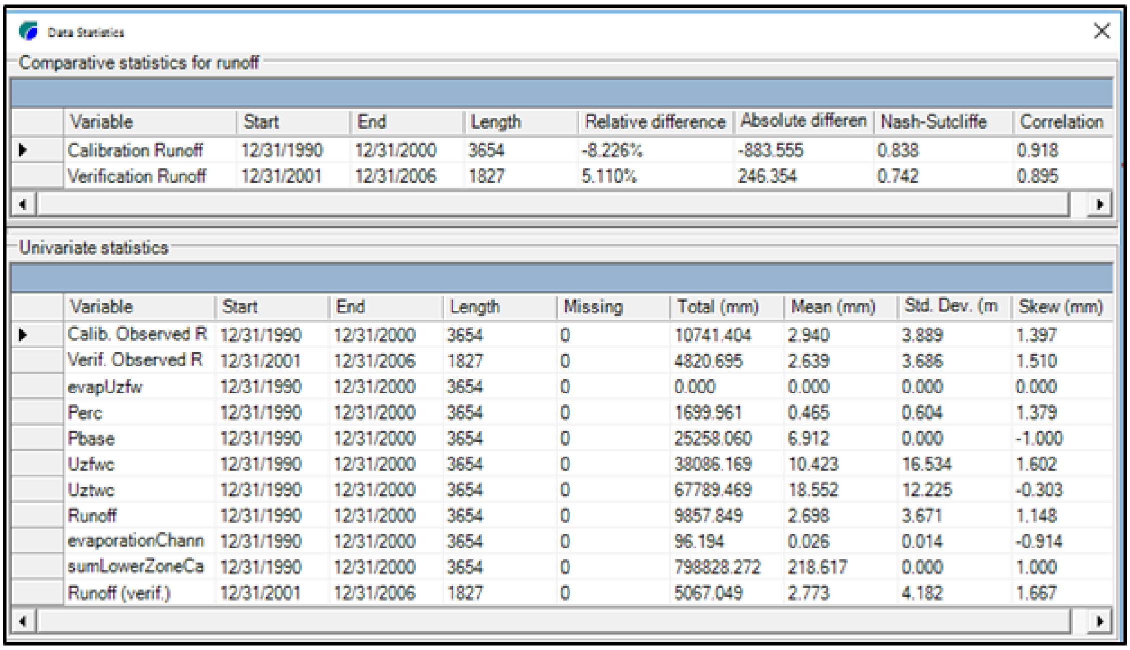
Comparative statistics for runoff

	Variable	Start	End	Length	Relative difference	Absolute difference	Nash-Sutcliffe	Correlation
▶	Calibration Runoff	12/31/1990	12/31/2003	4749	-2.543%	-345.127	0.863	0.929
	Verification Runoff	12/31/2004	12/31/2011	2557	2.903%	219.643	0.664	0.902

Univariate statistics

	Variable	Start	End	Length	Missing	Total (mm)	Mean (mm)	Std. Dev. (m	Skew (mm)
▶	Calib. Observed Runoff	12/31/1990	12/31/2003	4749	0	13573.524	2.858	3.875	1.438
	Verif. Observed Runoff	12/31/2004	12/31/2011	2557	0	7565.396	2.959	3.264	1.530
	Soil moisture in first surface store	12/31/1990	12/31/2003	4749	0	13540.676	2.851	3.063	0.215
	Baseflow store	12/31/1990	12/31/2003	4749	0	176195.867	37.102	47.609	0.957
	Effective Rainfall	12/31/1990	12/31/2003	4749	0	15150.920	3.190	5.127	1.918
	Runoff	12/31/1990	12/31/2003	4749	0	13228.397	2.786	3.636	1.013
	Baseflow	12/31/1990	12/31/2003	4749	0	10084.342	2.123	2.725	0.957
	Routed surface runoff	12/31/1990	12/31/2003	4749	0	3144.055	0.662	1.004	1.449
	Surface store	12/31/1990	12/31/2003	4749	0	3893.409	0.820	1.243	1.449
	Excess	12/31/1990	12/31/2003	4749	0	13228.508	2.786	4.903	2.122
	Surface runoff	12/31/1990	12/31/2003	4749	0	3144.055	0.662	1.165	2.122
	Baseflow recharge	12/31/1990	12/31/2003	4749	0	10084.454	2.123	3.738	2.122
	Soil moisture in third surface store	12/31/1990	12/31/2003	4749	0	54493.736	11.475	11.877	0.172
	Soil moisture in second surface store	12/31/1990	12/31/2003	4749	0	394513.573	83.073	74.219	0.012
	Runoff (verif.)	12/31/2004	12/31/2011	2557	0	7785.039	3.045	4.207	1.238

Appendix C2: Comparative data statics for runoff Sacramento.



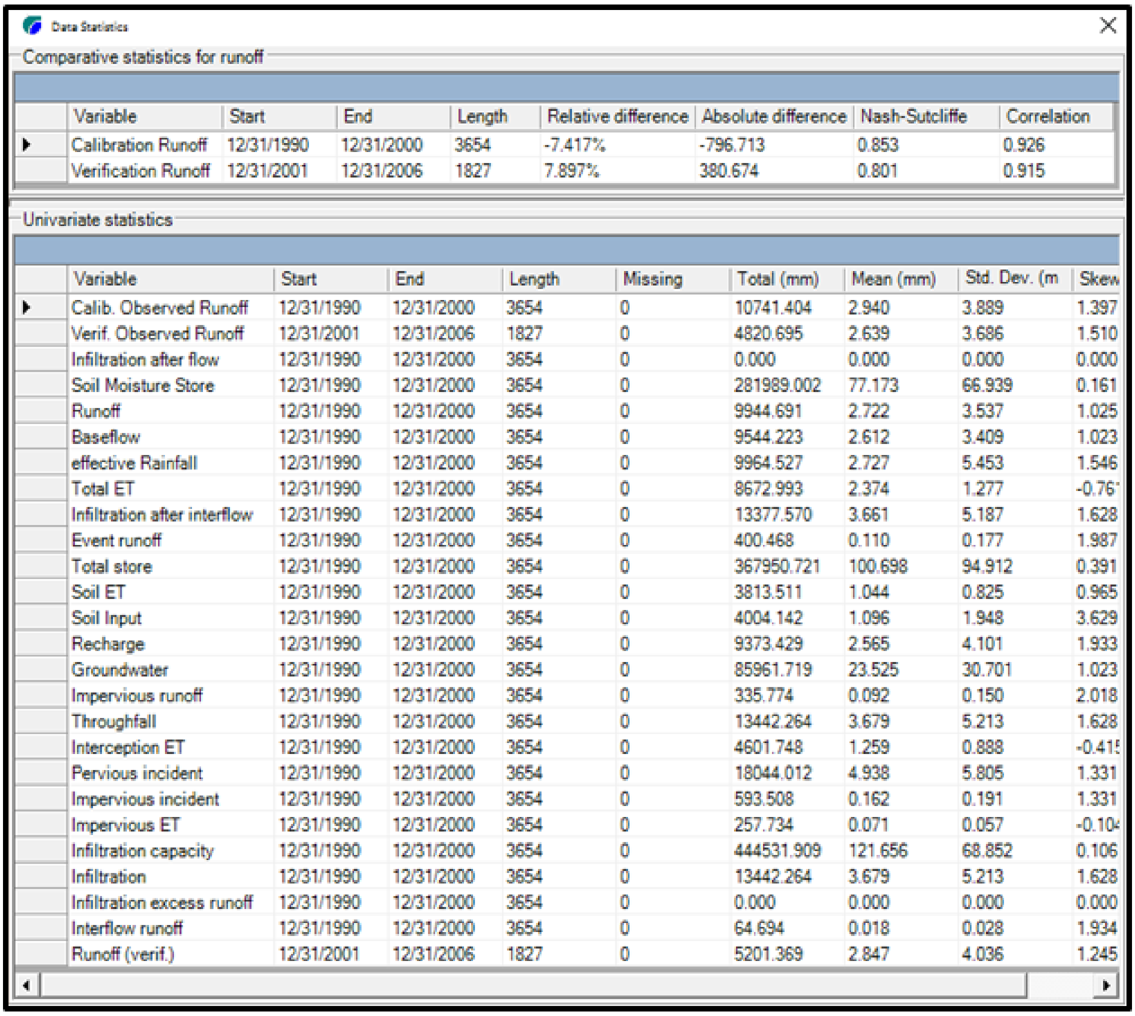
Comparative statistics for runoff

	Variable	Start	End	Length	Relative difference	Absolute differen	Nash-Sutcliffe	Correlation
▶	Calibration Runoff	12/31/1990	12/31/2000	3654	-8.226%	-883.555	0.838	0.918
	Verification Runoff	12/31/2001	12/31/2006	1827	5.110%	246.354	0.742	0.895

Univariate statistics

	Variable	Start	End	Length	Missing	Total (mm)	Mean (mm)	Std. Dev. (m	Skew (mm)
▶	Calib. Observed R	12/31/1990	12/31/2000	3654	0	10741.404	2.940	3.889	1.397
	Verif. Observed R	12/31/2001	12/31/2006	1827	0	4820.695	2.639	3.686	1.510
	evapUzfw	12/31/1990	12/31/2000	3654	0	0.000	0.000	0.000	0.000
	Perc	12/31/1990	12/31/2000	3654	0	1699.961	0.465	0.604	1.379
	Pbase	12/31/1990	12/31/2000	3654	0	25258.060	6.912	0.000	-1.000
	Uzfwc	12/31/1990	12/31/2000	3654	0	38086.169	10.423	16.534	1.602
	Uztwc	12/31/1990	12/31/2000	3654	0	67789.469	18.552	12.225	-0.303
	Runoff	12/31/1990	12/31/2000	3654	0	9857.849	2.698	3.671	1.148
	evaporationChann	12/31/1990	12/31/2000	3654	0	96.194	0.026	0.014	-0.914
	sumLowerZoneCa	12/31/1990	12/31/2000	3654	0	798828.272	218.617	0.000	1.000
	Runoff (verif.)	12/31/2001	12/31/2006	1827	0	5067.049	2.773	4.182	1.667

Appendix C3: Comparative data statics for runoff SIMHYD.



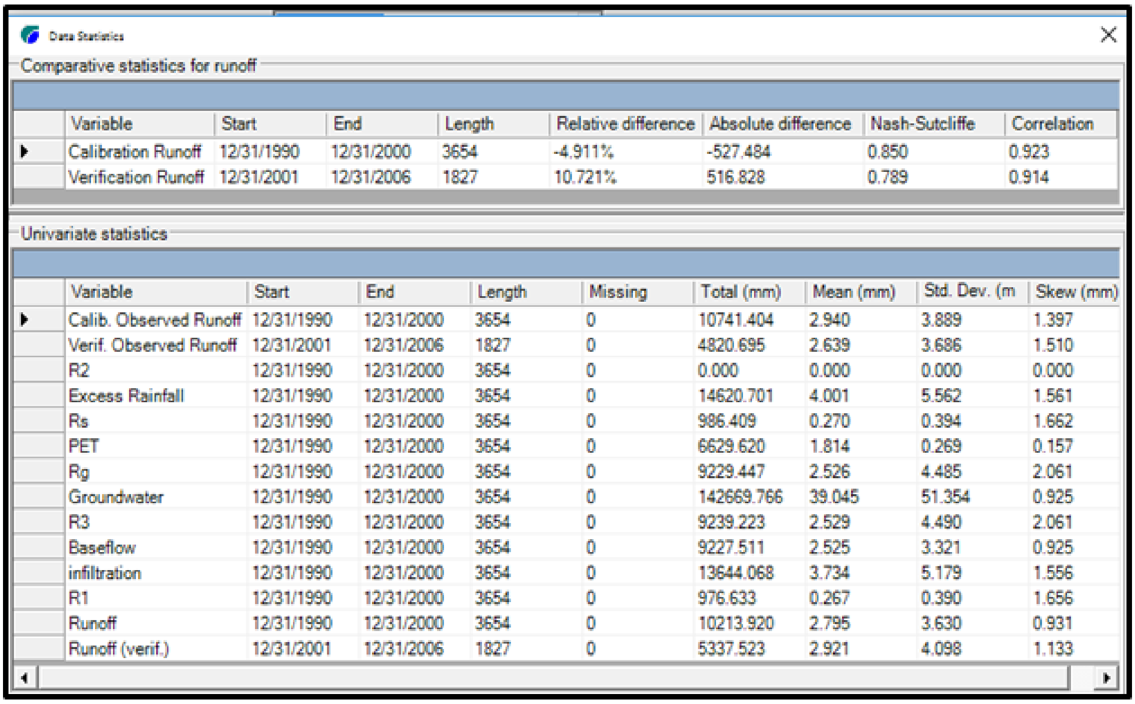
Comparative statistics for runoff

	Variable	Start	End	Length	Relative difference	Absolute difference	Nash-Sutcliffe	Correlation
▶	Calibration Runoff	12/31/1990	12/31/2000	3654	-7.417%	-796.713	0.853	0.926
	Verification Runoff	12/31/2001	12/31/2006	1827	7.897%	380.674	0.801	0.915

Univariate statistics

	Variable	Start	End	Length	Missing	Total (mm)	Mean (mm)	Std. Dev. (m	Skew
▶	Calib. Observed Runoff	12/31/1990	12/31/2000	3654	0	10741.404	2.940	3.889	1.397
	Verif. Observed Runoff	12/31/2001	12/31/2006	1827	0	4820.695	2.639	3.686	1.510
	Infiltration after flow	12/31/1990	12/31/2000	3654	0	0.000	0.000	0.000	0.000
	Soil Moisture Store	12/31/1990	12/31/2000	3654	0	281989.002	77.173	66.939	0.161
	Runoff	12/31/1990	12/31/2000	3654	0	9944.691	2.722	3.537	1.025
	Baseflow	12/31/1990	12/31/2000	3654	0	9544.223	2.612	3.409	1.023
	effective Rainfall	12/31/1990	12/31/2000	3654	0	9964.527	2.727	5.453	1.546
	Total ET	12/31/1990	12/31/2000	3654	0	8672.993	2.374	1.277	-0.76
	Infiltration after interflow	12/31/1990	12/31/2000	3654	0	13377.570	3.661	5.187	1.628
	Event runoff	12/31/1990	12/31/2000	3654	0	400.468	0.110	0.177	1.987
	Total store	12/31/1990	12/31/2000	3654	0	367950.721	100.698	94.912	0.391
	Soil ET	12/31/1990	12/31/2000	3654	0	3813.511	1.044	0.825	0.965
	Soil Input	12/31/1990	12/31/2000	3654	0	4004.142	1.096	1.948	3.629
	Recharge	12/31/1990	12/31/2000	3654	0	9373.429	2.565	4.101	1.933
	Groundwater	12/31/1990	12/31/2000	3654	0	85961.719	23.525	30.701	1.023
	Impervious runoff	12/31/1990	12/31/2000	3654	0	335.774	0.092	0.150	2.018
	Throughfall	12/31/1990	12/31/2000	3654	0	13442.264	3.679	5.213	1.628
	Interception ET	12/31/1990	12/31/2000	3654	0	4601.748	1.259	0.888	-0.41
	Pervious incident	12/31/1990	12/31/2000	3654	0	18044.012	4.938	5.805	1.331
	Impervious incident	12/31/1990	12/31/2000	3654	0	593.508	0.162	0.191	1.331
	Impervious ET	12/31/1990	12/31/2000	3654	0	257.734	0.071	0.057	-0.10
	Infiltration capacity	12/31/1990	12/31/2000	3654	0	444531.909	121.656	68.852	0.106
	Infiltration	12/31/1990	12/31/2000	3654	0	13442.264	3.679	5.213	1.628
	Infiltration excess runoff	12/31/1990	12/31/2000	3654	0	0.000	0.000	0.000	0.000
	Interflow runoff	12/31/1990	12/31/2000	3654	0	64.694	0.018	0.028	1.934
	Runoff (verif.)	12/31/2001	12/31/2006	1827	0	5201.369	2.847	4.036	1.245

Appendix C4: Comparative data statics for runoff SMAR model.



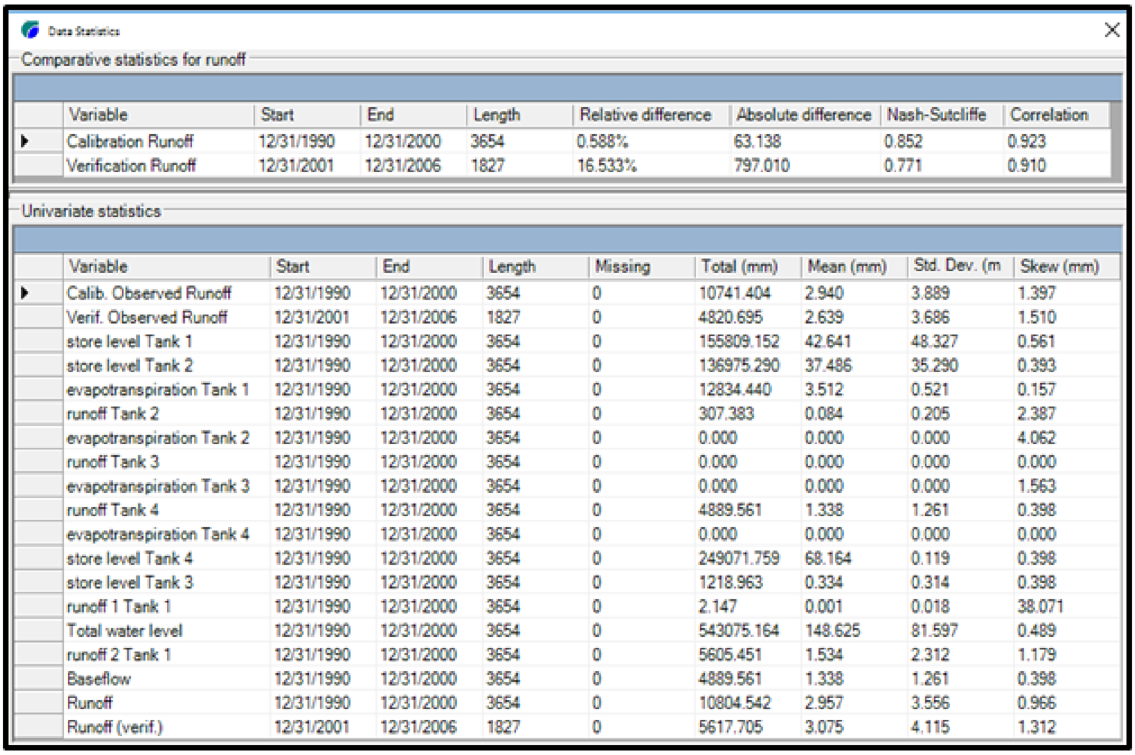
Comparative statistics for runoff

Variable	Start	End	Length	Relative difference	Absolute difference	Nash-Sutcliffe	Correlation
Calibration Runoff	12/31/1990	12/31/2000	3654	-4.911%	-527.484	0.850	0.923
Verification Runoff	12/31/2001	12/31/2006	1827	10.721%	516.828	0.789	0.914

Univariate statistics

Variable	Start	End	Length	Missing	Total (mm)	Mean (mm)	Std. Dev. (m	Skew (mm)
Calib. Observed Runoff	12/31/1990	12/31/2000	3654	0	10741.404	2.940	3.889	1.397
Verif. Observed Runoff	12/31/2001	12/31/2006	1827	0	4820.695	2.639	3.686	1.510
R2	12/31/1990	12/31/2000	3654	0	0.000	0.000	0.000	0.000
Excess Rainfall	12/31/1990	12/31/2000	3654	0	14620.701	4.001	5.562	1.561
Rs	12/31/1990	12/31/2000	3654	0	986.409	0.270	0.394	1.662
PET	12/31/1990	12/31/2000	3654	0	6629.620	1.814	0.269	0.157
Rg	12/31/1990	12/31/2000	3654	0	9229.447	2.526	4.485	2.061
Groundwater	12/31/1990	12/31/2000	3654	0	142669.766	39.045	51.354	0.925
R3	12/31/1990	12/31/2000	3654	0	9239.223	2.529	4.490	2.061
Baseflow	12/31/1990	12/31/2000	3654	0	9227.511	2.525	3.321	0.925
infiltration	12/31/1990	12/31/2000	3654	0	13644.068	3.734	5.179	1.556
R1	12/31/1990	12/31/2000	3654	0	976.633	0.267	0.390	1.656
Runoff	12/31/1990	12/31/2000	3654	0	10213.920	2.795	3.630	0.931
Runoff (verif.)	12/31/2001	12/31/2006	1827	0	5337.523	2.921	4.098	1.133

Appendix C5: Comparative data statics for runoff TANK model.



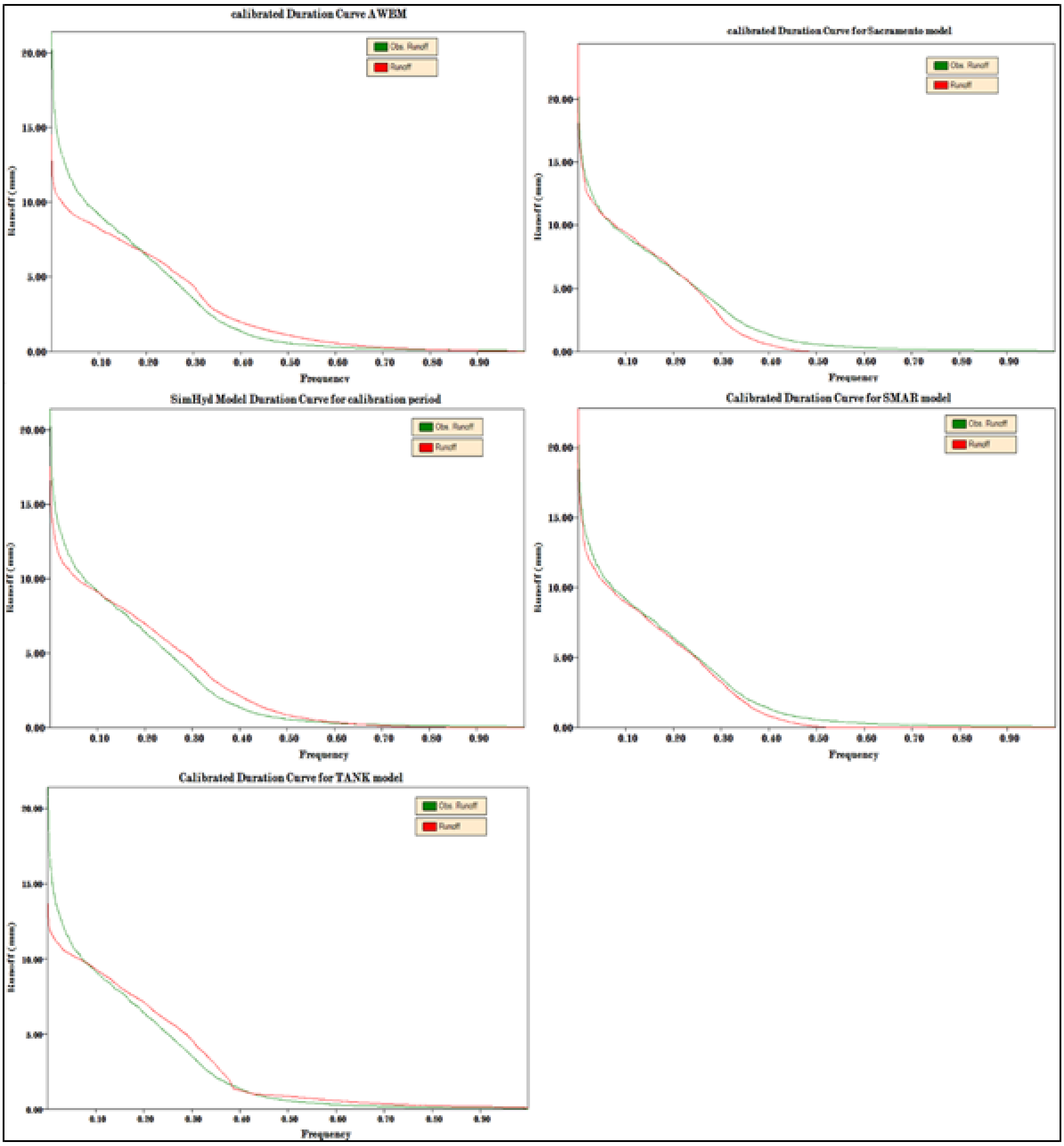
Comparative statistics for runoff

Variable	Start	End	Length	Relative difference	Absolute difference	Nash-Sutcliffe	Correlation
Calibration Runoff	12/31/1990	12/31/2000	3654	0.588%	63.138	0.852	0.923
Verification Runoff	12/31/2001	12/31/2006	1827	16.533%	797.010	0.771	0.910

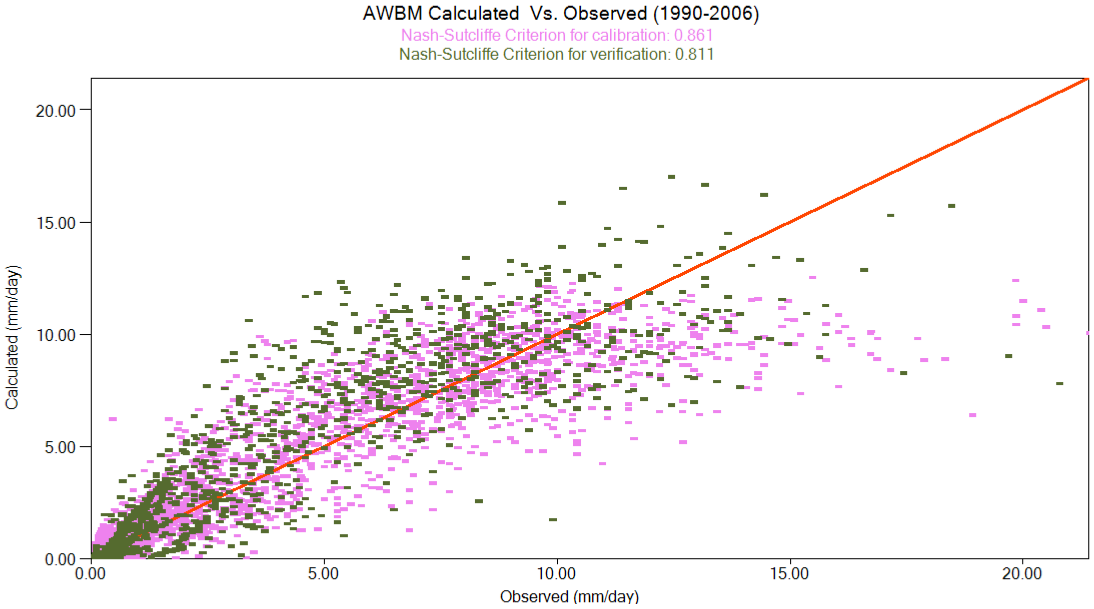
Univariate statistics

Variable	Start	End	Length	Missing	Total (mm)	Mean (mm)	Std. Dev. (m	Skew (mm)
Calib. Observed Runoff	12/31/1990	12/31/2000	3654	0	10741.404	2.940	3.889	1.397
Verif. Observed Runoff	12/31/2001	12/31/2006	1827	0	4820.695	2.639	3.686	1.510
store level Tank 1	12/31/1990	12/31/2000	3654	0	155809.152	42.641	48.327	0.561
store level Tank 2	12/31/1990	12/31/2000	3654	0	136975.290	37.486	35.290	0.393
evapotranspiration Tank 1	12/31/1990	12/31/2000	3654	0	12834.440	3.512	0.521	0.157
runoff Tank 2	12/31/1990	12/31/2000	3654	0	307.383	0.084	0.205	2.387
evapotranspiration Tank 2	12/31/1990	12/31/2000	3654	0	0.000	0.000	0.000	4.062
runoff Tank 3	12/31/1990	12/31/2000	3654	0	0.000	0.000	0.000	0.000
evapotranspiration Tank 3	12/31/1990	12/31/2000	3654	0	0.000	0.000	0.000	1.563
runoff Tank 4	12/31/1990	12/31/2000	3654	0	4889.561	1.338	1.261	0.398
evapotranspiration Tank 4	12/31/1990	12/31/2000	3654	0	0.000	0.000	0.000	0.000
store level Tank 4	12/31/1990	12/31/2000	3654	0	249071.759	68.164	0.119	0.398
store level Tank 3	12/31/1990	12/31/2000	3654	0	1218.963	0.334	0.314	0.398
runoff 1 Tank 1	12/31/1990	12/31/2000	3654	0	2.147	0.001	0.018	38.071
Total water level	12/31/1990	12/31/2000	3654	0	543075.164	148.625	81.597	0.489
runoff 2 Tank 1	12/31/1990	12/31/2000	3654	0	5605.451	1.534	2.312	1.179
Baseflow	12/31/1990	12/31/2000	3654	0	4889.561	1.338	1.261	0.398
Runoff	12/31/1990	12/31/2000	3654	0	10804.542	2.957	3.556	0.966
Runoff (verif.)	12/31/2001	12/31/2006	1827	0	5617.705	3.075	4.115	1.312

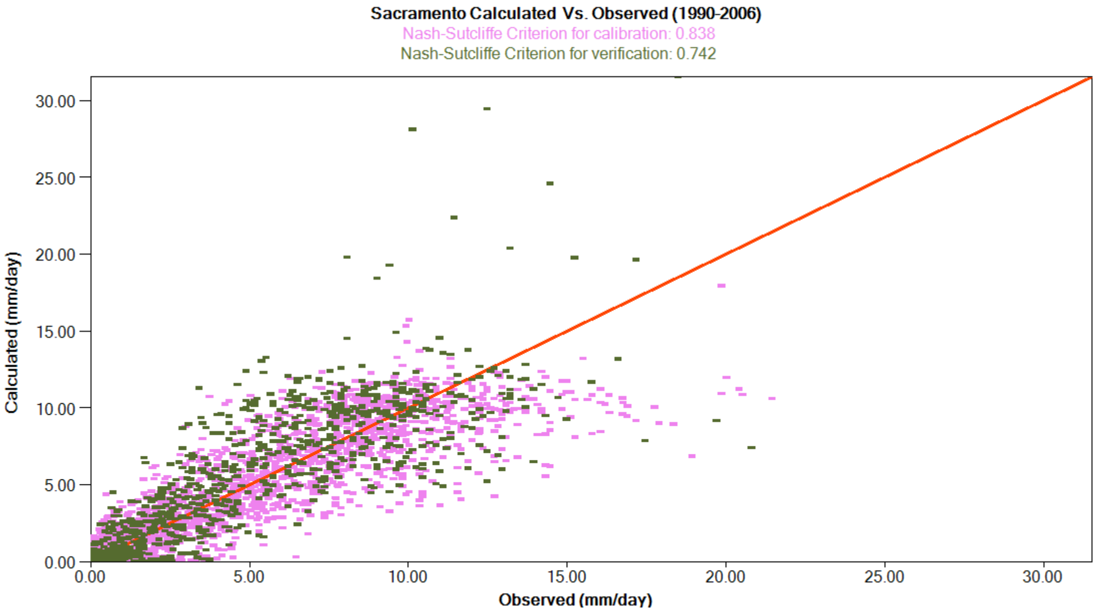
Appendix D: Flow Duration Curve For Calibration Period



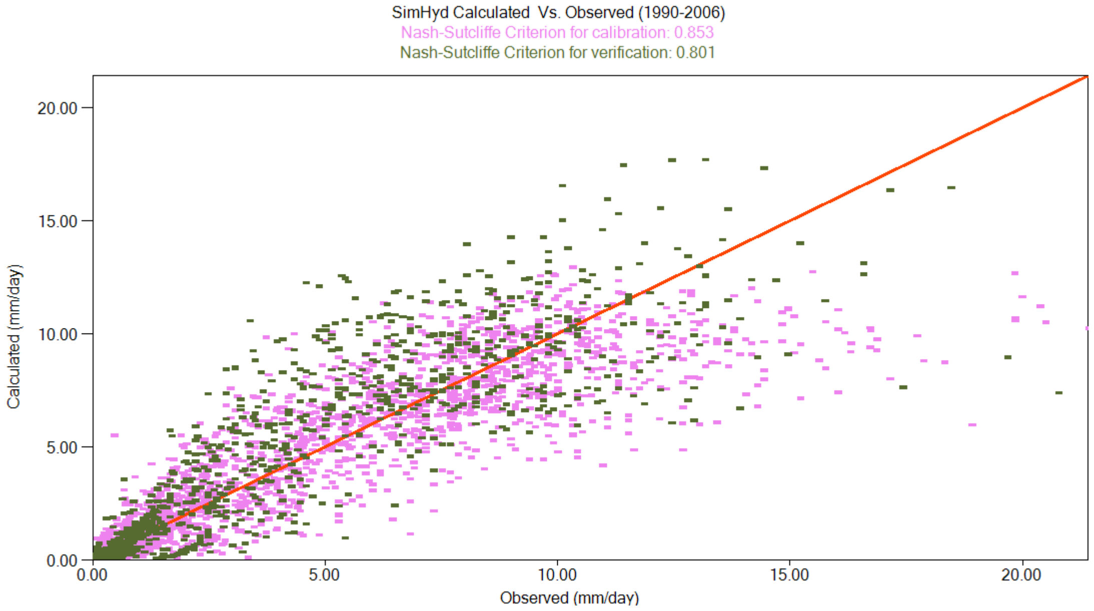
Appendix E: AWBM NSE for calibration and Validation period (1990-2006)



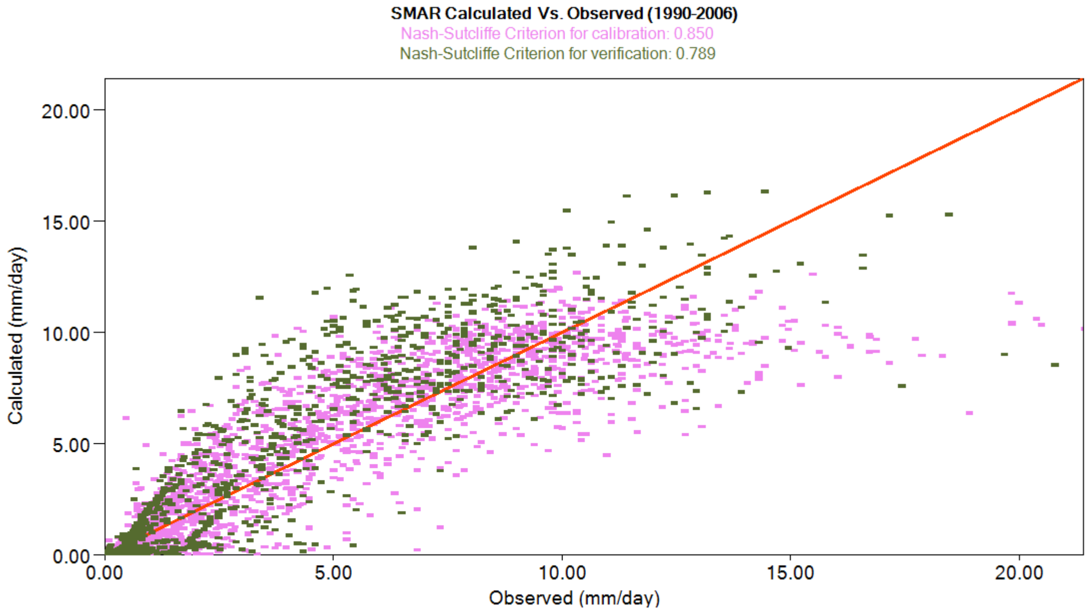
Appendix F: Sacramento Model NSE for calibration and Validation period (1990-2006)



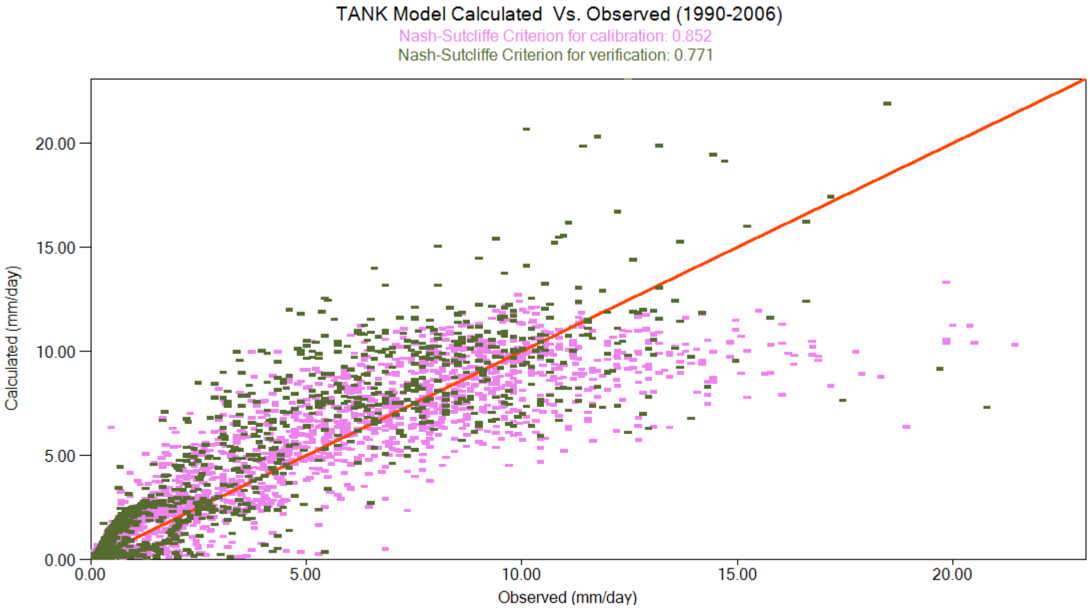
Appendix G: SIMHYD Model NSE for calibration and Validation period (1990-2006)



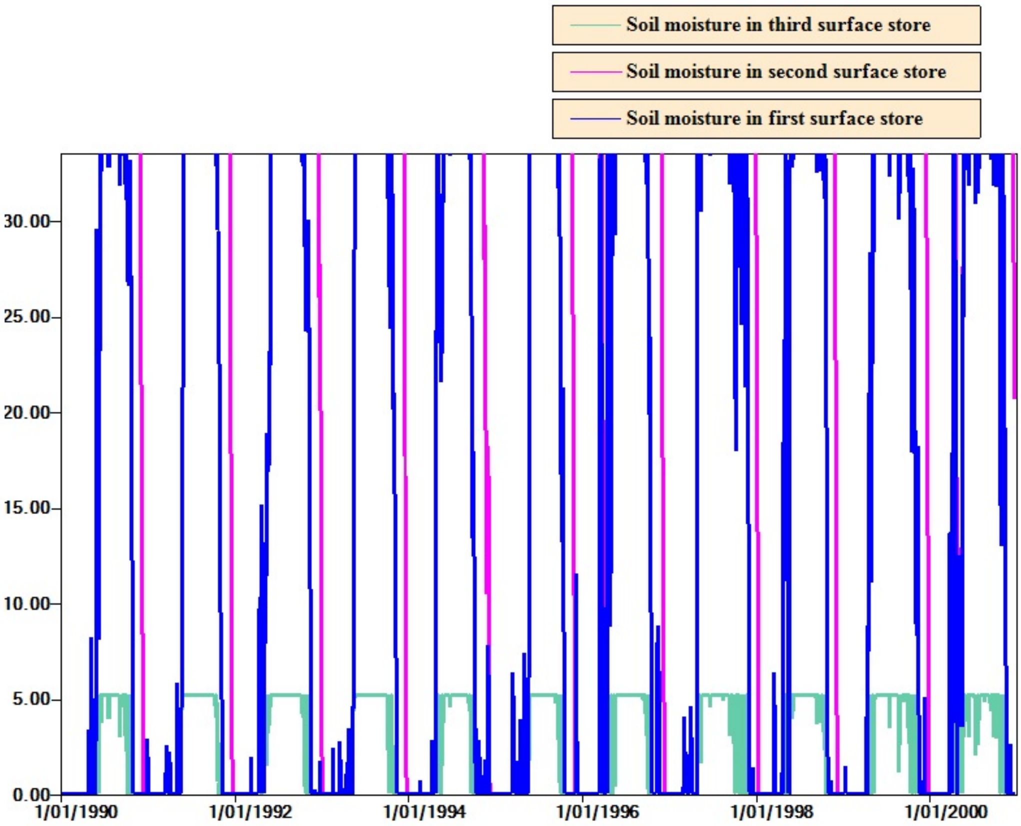
Appendix H: SMAR Model NSE for calibration and Validation period (1990-2006)



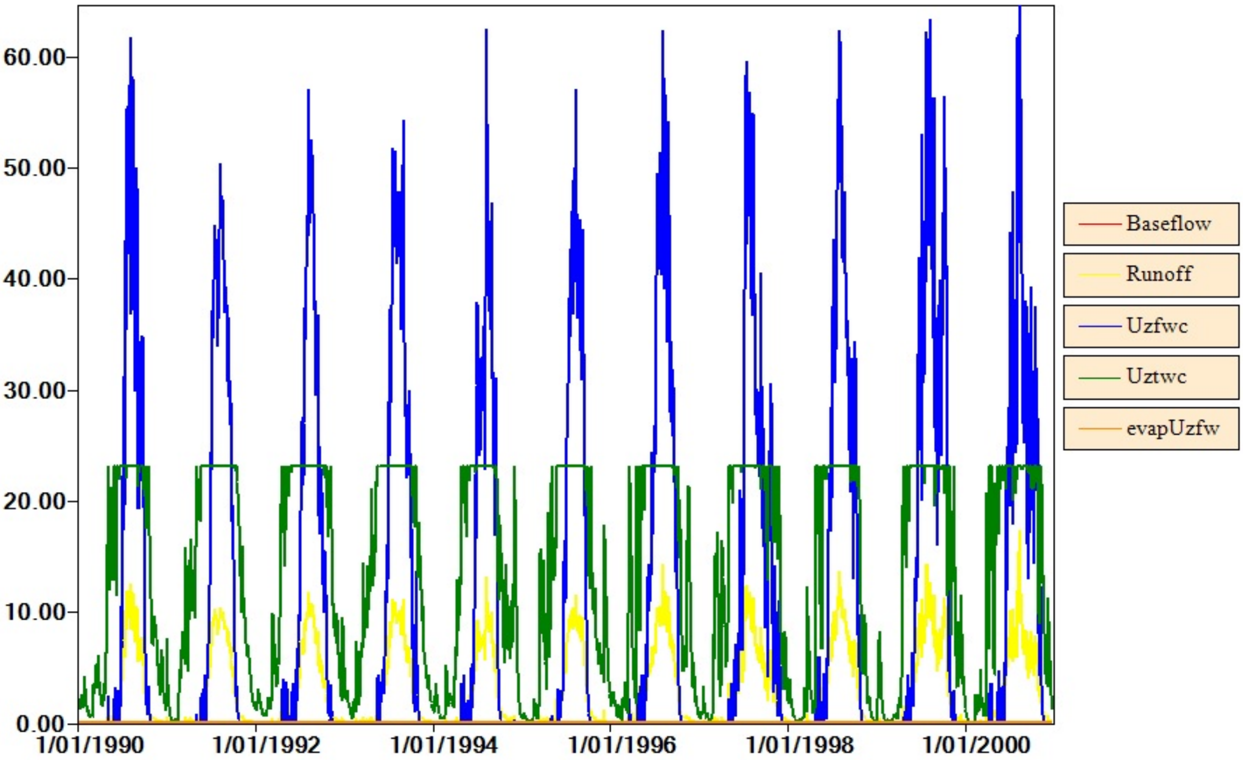
Appendix I: TANK Model NSE for calibration and Validation period (1990-2006)



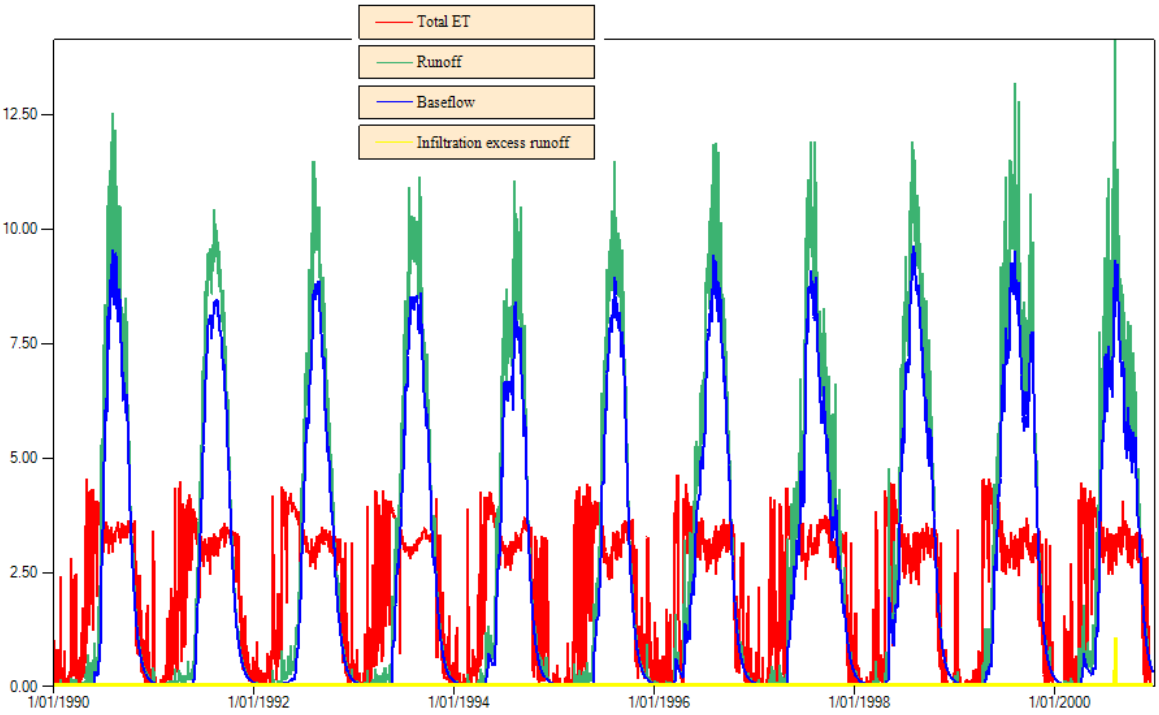
Appendix J: The Three surface soil moisture stores of AWBM



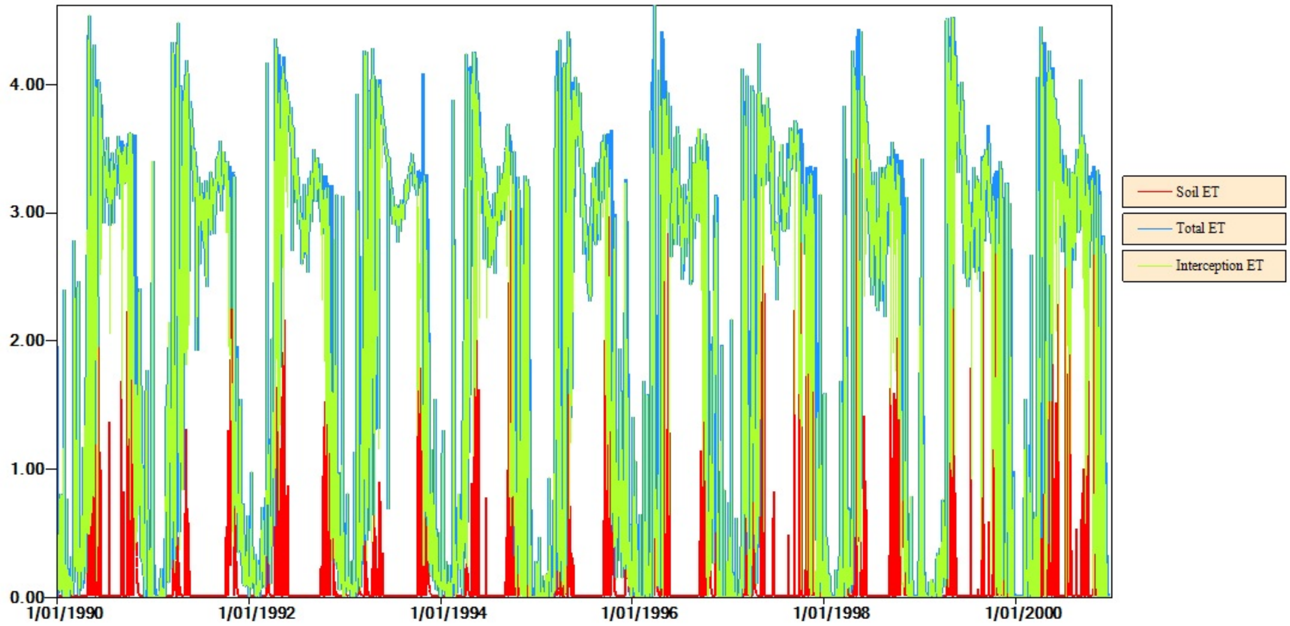
Appendix K: The different Flow conditions for Sacramento model



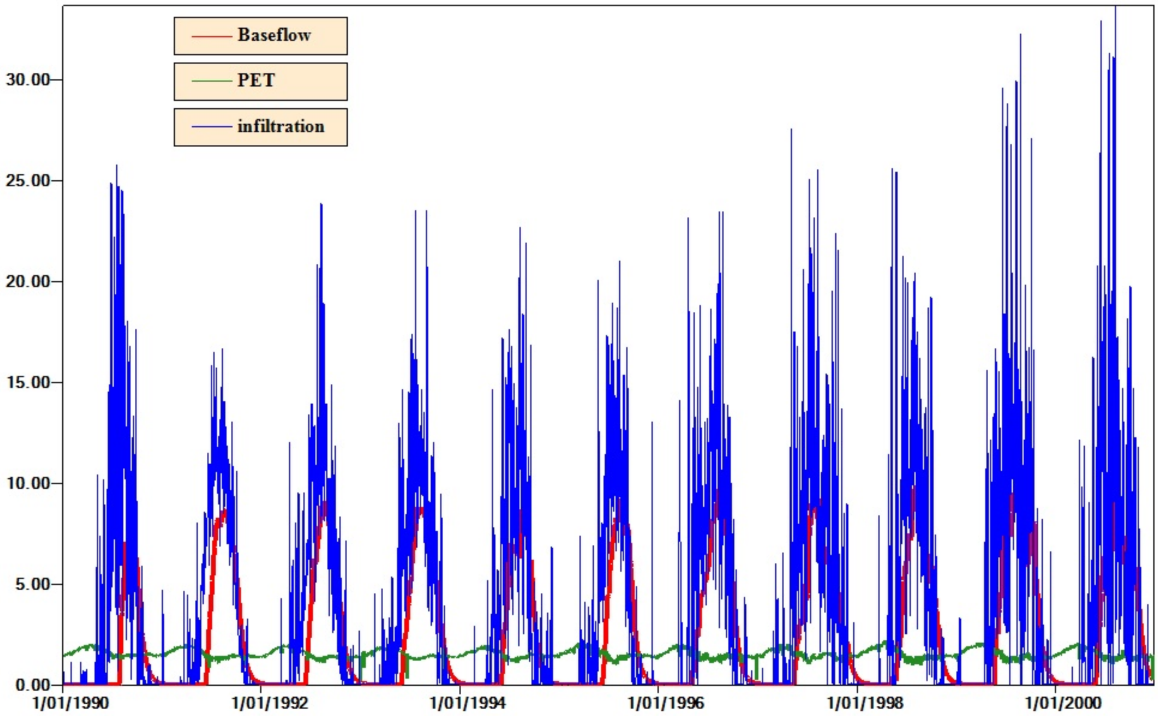
Appendix L1: Excess rainfall,soil moisture and Base flow for SimHyd model



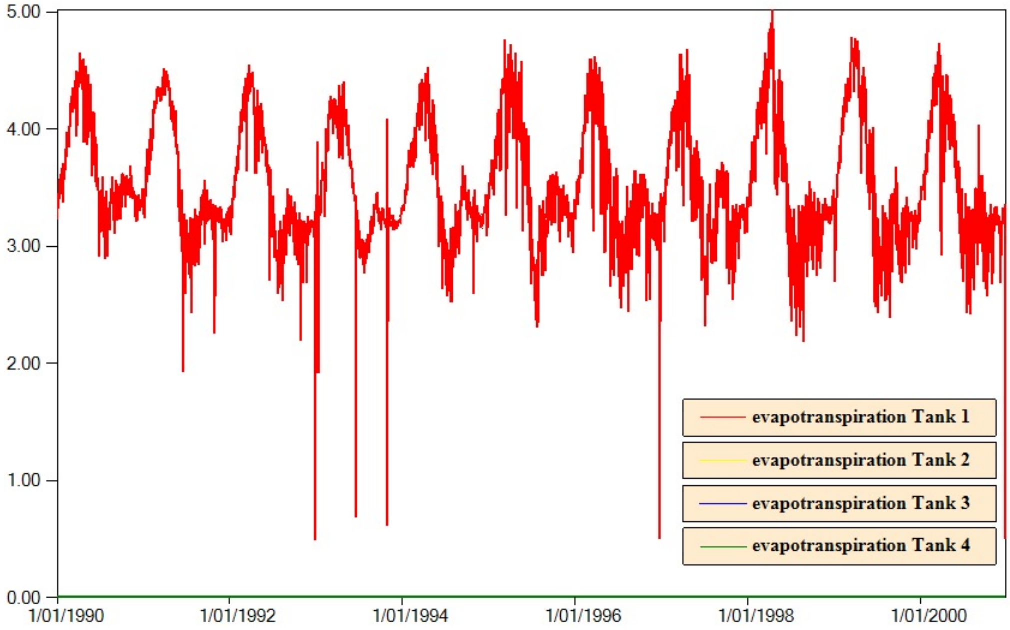
Appendix L2: Different Evapotranspiration of SIMHYD model.



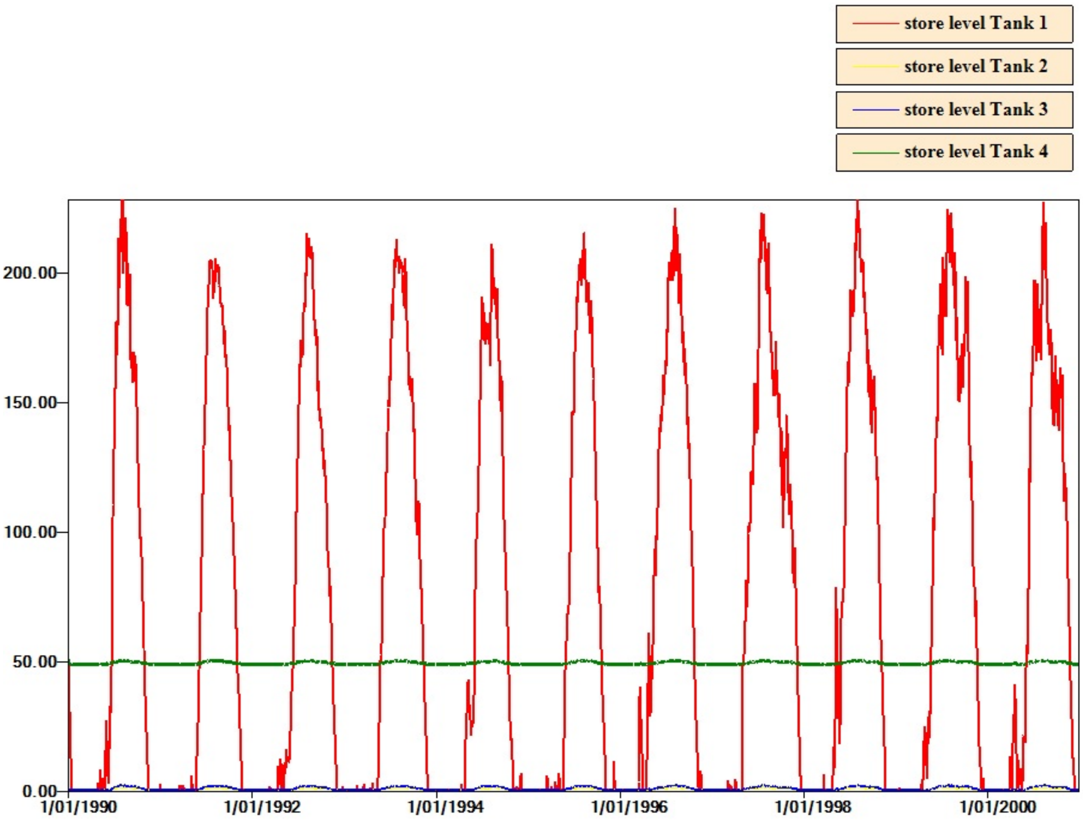
Appendix M: baseflow,PET and infiltration of SMAR model.



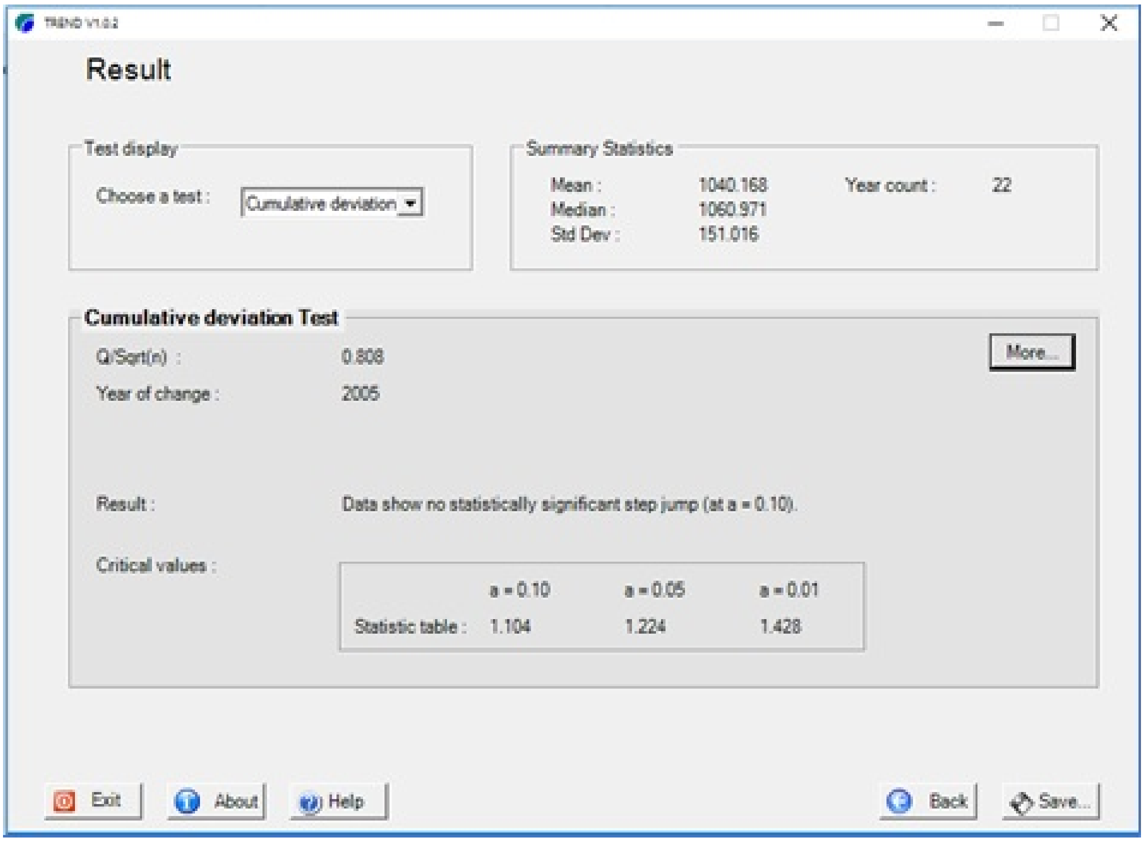
Appendix N1: Evapotranspiration levels of each TANK model.



Appendix N2: Store levels of each surface of TANK model.



Appendix O: cumulative deviation test to check flow data trend (changes starts from 2005).



Result

Test display

Choose a test : Cumulative deviation

Summary Statistics

Mean : 1040.168
Median : 1060.971
Std Dev : 151.016
Year count : 22

Cumulative deviation Test

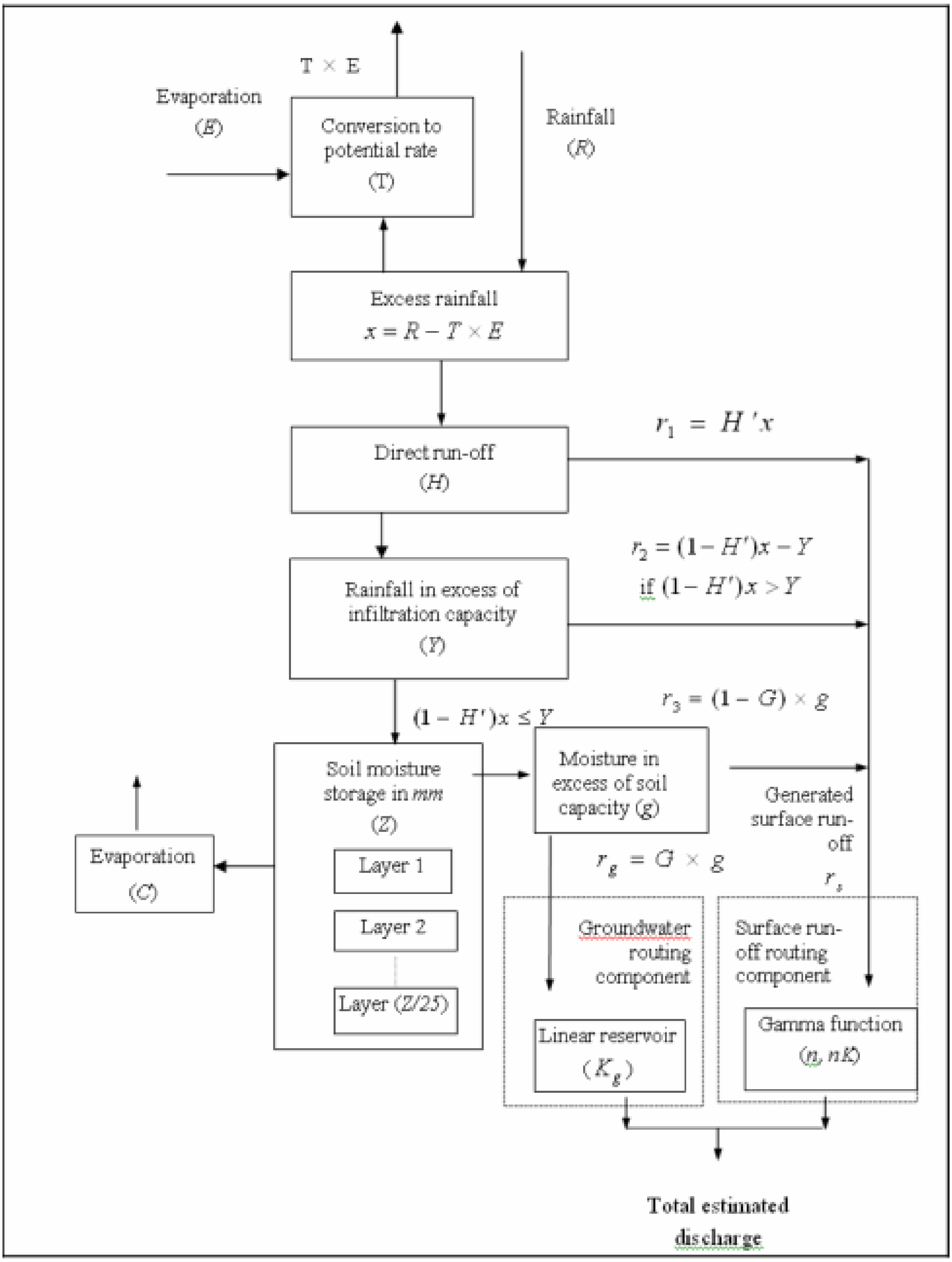
Q/Sqrt(n) : 0.808
Year of change : 2005

Result : Data show no statistically significant step jump (at a = 0.10).

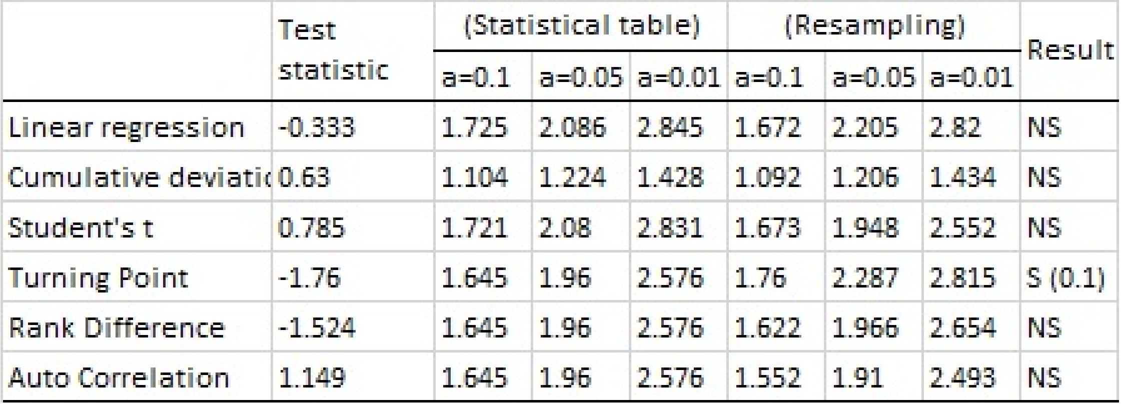
Critical values :

	a = 0.10	a = 0.05	a = 0.01
Statistic table :	1.104	1.224	1.428

Appendix P: Detail Structure of the SMAR rainfall-runoff mode .(source www.ewater toolkit.rrl)

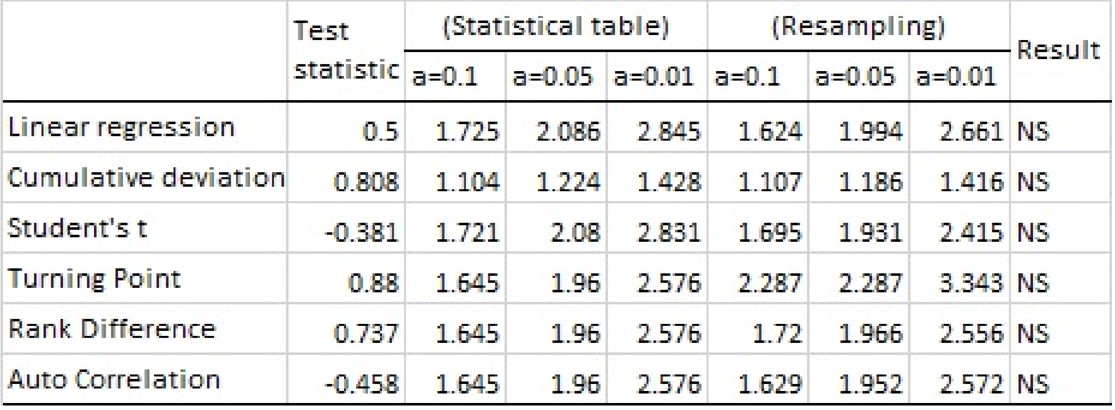


Appendix Q_1: summarizing statistical test for Evapotranspration data)



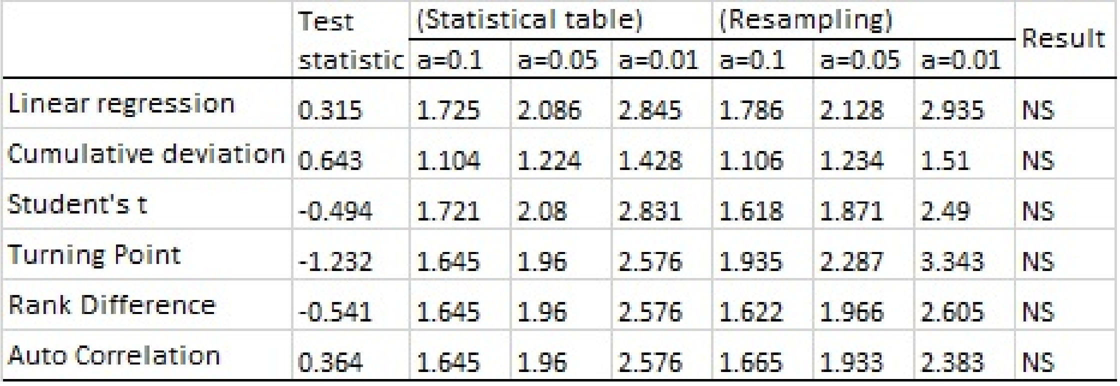
	Test statistic	(Statistical table)			(Resampling)			Result
		a=0.1	a=0.05	a=0.01	a=0.1	a=0.05	a=0.01	
Linear regression	-0.333	1.725	2.086	2.845	1.672	2.205	2.82	NS
Cumulative deviati	0.63	1.104	1.224	1.428	1.092	1.206	1.434	NS
Student's t	0.785	1.721	2.08	2.831	1.673	1.948	2.552	NS
Turning Point	-1.76	1.645	1.96	2.576	1.76	2.287	2.815	S (0.1)
Rank Difference	-1.524	1.645	1.96	2.576	1.622	1.966	2.654	NS
Auto Correlation	1.149	1.645	1.96	2.576	1.552	1.91	2.493	NS

Appendix Q_2: summarizing statistical test for Flow data)



	Test statistic	(Statistical table)			(Resampling)			Result
		a=0.1	a=0.05	a=0.01	a=0.1	a=0.05	a=0.01	
Linear regression	0.5	1.725	2.086	2.845	1.624	1.994	2.661	NS
Cumulative deviation	0.808	1.104	1.224	1.428	1.107	1.186	1.416	NS
Student's t	-0.381	1.721	2.08	2.831	1.695	1.931	2.415	NS
Turning Point	0.88	1.645	1.96	2.576	2.287	2.287	3.343	NS
Rank Difference	0.737	1.645	1.96	2.576	1.72	1.966	2.556	NS
Auto Correlation	-0.458	1.645	1.96	2.576	1.629	1.952	2.572	NS

Appendix Q_3: summarizing statistical test for Precipitation data)



	Test statistic	(Statistical table)			(Resampling)			Result
		a=0.1	a=0.05	a=0.01	a=0.1	a=0.05	a=0.01	
Linear regression	0.315	1.725	2.086	2.845	1.786	2.128	2.935	NS
Cumulative deviation	0.643	1.104	1.224	1.428	1.106	1.234	1.51	NS
Student's t	-0.494	1.721	2.08	2.831	1.618	1.871	2.49	NS
Turning Point	-1.232	1.645	1.96	2.576	1.935	2.287	3.343	NS
Rank Difference	-0.541	1.645	1.96	2.576	1.622	1.966	2.605	NS
Auto Correlation	0.364	1.645	1.96	2.576	1.665	1.933	2.383	NS

The above tables in appendix Q1,Q2 and Q3 referes that statistical testing for trend/change results and Resampling analysis is a robust method for estimating the significance level of a test statistic. It is particularly useful when the test assumptions are violated. In resampling analysis, the original time series (input data) is resampled to provide many replicates of time series data of equal length as the original data. The time series data for each replicate is obtained by randomly selecting data value from any year in the original time series continuously until a time series of equal length as the original data is constructed. In TREND, the data are resampled with replacement (bootstrapping method), i.e., a replicate series may contain more than one of some values in the original series and none of other values. The test statistic value of the original time series data can then be compared with the test statistic values of the generated data (replicates) to estimate the significance level. For example, if the test statistic value of the original data is greater than the 950th highest test statistic value from 1000 replicates, H_0 is rejected at $\alpha = 0.05$ (i.e., a trend/change is detected, with a 5% probability that this trend/change is incorrectly detected). Therefore, the critical test statistic values for significance levels of $\alpha = 0.1$,α= 0.05 and α= 0.01, are the 90th, 95th and 99th percentile values respectively of test statistic values from the generated (re-sampled) time series and the last column gives the test result (NS means not significant at $\alpha = 0.1$; S means statistically significant, with the significance level shown in brackets).

Bibliography

Beven, K. (1989). Changing ideas in hydrology—the case of physically-based models. *Journal of hydrology*, 105(1-2):157–172.

Boughton, W. (1966). A mathematical model for relating runoff to rainfall with daily data. *Civil Engr. Trans. Inst. Engrs.(Aust). CE*, 8:83–87.

Boughton, W. (2004). The australian water balance model. *Environmental Modeling Software*, 19(10):943–956.

Burnash, R. (1995). The nws river forecast system-catchment modeling. *Computer models of watershed hydrology*, 188:311–366.

Crawford, N. H. and Linsley, R. K. (1966). Digital simulation in hydrology'stanford watershed model 4.

Dingman, S. L. (2015). *Physical hydrology*. Waveland press.

Franchini, M. and Galeati, G. (1997). Comparing several genetic algorithm schemes for the calibration of conceptual rainfall-runoff models. *Hydrological Sciences Journal*, 42(3):357–379.

Goswami, M., O'Connor, K., Bhattarai, K., and Shamseldin, A. (2005). Assessing the performance of eight real-time updating models and procedures for the brosna river. *Hydrology and Earth System Sciences Discussions*, 9(4):394–411.

Gragne, A., Uhlenbrook, S., Mohammed, Y., and Kebede, S. (2008). Catchment modeling and model transferability in upper blue nile basin, lake tana, ethiopia. *Hydrology and Earth System Sciences Discussions*, 5(2):811–842.

Hornberger, G. M. and Boyer, E. W. (1995). Recent advances in watershed modelling. *Reviews of Geophysics*, 33(S2):949–957.

Krause, P., Boyle, D., and Bäse, F. (2005). Comparison of different efficiency criteria for hydrological model assessment. *Advances in geosciences*, 5:89–97.

Lasocki, S. and Weglarczyk, S. (1998). Complex and variable magnitude distribution of microtremors induced by mining: An example from a gold mine, south africa. *Abstracts XXVI General Assemb. ESC (Tel Aviv 1998) p*, 37.

Li, Z. Y. and Lam, K. M. (2015). Statistical evaluation of bioretention system for hydrologic performance. *Water Sci Technol*, 71(11):1742–9.

Liden, R. and Harlin, J. (2000). Analysis of conceptual rainfall–runoff modelling performance in different climates. *Journal of hydrology*, 238(3):231–247.

Mekonnen, M. A., Worman, A., Dargahi, B., and Gebeyehu, A. (2009). Hydrological modelling of ethiopian catchments using limited data. *Hydrological processes*, 23(23):3401–3408.

Melkamu, A. (2005). *Reservoir operation and establishment of reservoir rule for Lake Tana*. Thesis.

Podger, G. (2004). Rainfall runoff library user guide. *Cooperative Research Centre for Catchment Hydrology*.

Porter, J. and McMahon, T. (1971). A model for the simulation of streamflow data from climatic records. *Journal of Hydrology*, 13:297–324.

Rientjes, T., Haile, A., Kebede, E., Mannaerts, C., Habib, E., and Steenhuis, T. (2011). Changes in land cover, rainfall and stream flow in upper gilgel abbay catchment, blue nile basin-ethiopia. *Hydrology and Earth System Sciences*, 15(6):1979.

Seibert, J. (1999). Regionalisation of parameters for a conceptual rainfall-runoff model. *Agricultural and forest meteorology*, 98:279–293.

Sittner, W. T., Schauss, C. E., and Monro, J. C. (1969). Continuous hydrograph synthesis with an api-type hydrologic model. *Water Resources Research*, 5(5):1007–1022.

Sugawara, M. (1995). Tank model. *Computer models of watershed hydrology*.

Tadele, D. (2012). Role of performance audit in fighting corruption:(evidences from fdre and oromia national regional state).

Tan, B. and O'Connor, K. (1996). Application of an empirical infiltration equation in the smar conceptual model. *Journal of Hydrology*, 185(1-4):275–295.

Tan, K., Chiew, F., Grayson, R., Scanlon, P., and Siriwardena, L. (2005). Calibration of a daily rainfall-runoff model to estimate high daily flows. In *Congress on Modelling and Simulation (MODSIM 2005), Melbourne*, pages 2960–2966.

Uhlenbrook, S., Roser, S., and Tilch, N. (2004). Hydrological process representation at the meso-scale: the potential of a distributed, conceptual catchment model. *Journal of Hydrology*, 291(3):278–296.

Viola, F., Pumo, D., and Noto, L. (2014). Ehsm: A conceptual ecohydrological model for daily streamflow simulation. *Hydrological processes*, 28(9):3361–3372.