ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

HYDROLOGICAL MODELS COMPARISON FOR ESTIMATION OF FLOODS IN THE ABAYA-CHAMO SUB-BASIN

By: - **Abyot Ayka**

Advisor: **Dr. Yilma Sileshi**

A thesis presented to the school of Graduate studies of the Addis Ababa University in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering, Major Hydraulic Engineering

July, 2008

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Approved by examining board

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Declaration

I hereby declare that I am the sole author of this thesis and it has not been presented for any degree in any university and all the resources of material used for the thesis have been duly acknowledged.

Name! ABYOT AYKA

Signature -------------------

Acknowledgements

My study in the Addis Ababa University came true through the involvement of many entities and persons that I would like to mention.

First of all I would like express my gratitude to the **Mirab Abaya Wereda Agriculture & Rural Development Office** for granting me with this scholarship which allows me to continue with my studies.

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Last but not least, my everlasting gratitude goes to my loving family who always encourages me and wishes my success.

Dedicated to my parents with love

Abstract

Nowadays the major environmental disasters in Ethiopia are recurrent droughts and floods. Their socio-economic and ecological impacts are devastating to the entire country, because most of them do not have real time forecasting technology or resource for post disaster rehabilitation.

The Abaya-Chamo river basin is located in the southern part of Ethiopia. The extensive and attractable areas of this region, apart from being densely populated and extensively used for agriculture are also considered as a flood prone. Since most of the rivers in the basin are ungauged, it is essential to now the flow characteristics of the rivers in order to mitigate flooding effects in the basin.

The aim of this study is to test the three conceptual hydrological models and propose suitable model for the estimation of floods in the ungauged catchments of the basin. Two catchments; Kulfo catchment from medium sized and Bilate catchment from large sized catchments, are selected for the analysis.

Model approaches selected are: Soil Moisture Accounting (SMA) model which is embedded in the HEC-HMS software suite. SMA is a lumped, event, conceptual approach that allows continuous stream flow simulation and a number of model parameters are estimated.

The other two models RRL SMAR & RRL TANK models are conceptual continuous daily time series models. Default values of all the parameters are used and then calibration has been made manually and automatically.

Using various models performance evaluation criteria; Nash-Sutcliffe efficiency, NSE (Coefficient of efficiency), Index of agreement d, Coefficient of determination R^2, index of volumetric fit IVF and The relative error of the peak, the output of each models was evaluated.

HEC-HMS SMA model performed well compared to the other models especially with the objective of capturing the peak flow and volumetric fit IVF in the two catchments.

Thus, the HEC-HMS SMA model can be used for the estimation of peak floods in the two catchments and in the ungauged catchments with or without regionalization.

Model uncertainties due to various sources such as improper data input, incorrect model parameterization are also highlighted in the end of this study.

Keywords: Ungauged catchment, floods, HEC-HMS SMA, RRL SMAR, RRL TANK, Abaya-Chamo river basin.

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ABBREVIATIONS

API	Antecedent precipitation Index
ARIMA	Autoregressive Integrated Moving Average
CLS	Constrained Linear Systems
DSS	Data Storage System
EM	Engineers' Manual
EMA	Ethiopian Mapping Agency
FAO	Food and Agricultural Organization
GIS	Geographical Information System
GUI	Graphical User Interface
HEC-HMS	Hydraulic Engineering Center Hydrologic Modeling
NMSE	National Meteorological Service of Ethiopia
PET	Potential Evapotranspiration
RRL SMAR	Rainfall Runoff Library Soil Moisture Accounting and Routing
SCS	Soil Conservation Service
SNNPRS	Southern Nations Nationality & People Regional State System
UH	Unit Hydrograph
USACE	US Army Corps of Engineers

1 INTRODUCTION

1.1 General

Floods are the most common of all environmental hazards. Every year, floods claim over 20,000 lives and adversely affect around 75 million of people worldwide. The reason lies in the widespread geographical distribution of river floodplains and low-lying coasts, together with their long-standing attractions for human settlement (smith, 2001). Floods are recurring phenomena, which form a necessary and enduring feature of all river basin and lowland coastal system. Major floods are the largest cause of economic losses from natural disasters mainly in more developed countries, and they are also a major cause of disaster-related deaths, mainly in the less developed countries.

Despite recent advances in the understanding of the relevant climatologically, fluvial and marine mechanisms, and a greater investment in flood reduction measures, floods take a larger number of lives and damage more properties each year, mainly because of unwise land management practices and growing human vulnerability (Smith and Ward, 1998).

According to UNEP (2002) major environmental disasters in Africa are recurrent droughts and floods. Their economic and ecological impacts are devastating to African countries, because most of them do not have real time forecasting technology, or resource for post-disaster rehabilitation (Manuela, 2004).

In Ethiopia it is very common to see flood-caused environmental hazards in the entire country. The main reason can be explained by the increase of human activities within the river system leading to change in watershed characteristics and river morphology.

Within the southern Ethiopia region, Abaya-Chamo river basin, with one third of the area have experienced a lot of floods since long times. In the last 10 years there has been an increase in flood events in the Rivers causing serious flood problems to the lowlanders at every peak flow time.

1.2 Relevance of the Study

According to the report of one of the flood victim woredas in the region Mirab Abaya and Arbaminch woredas Disaster Prevention and Preparedness Desk in the SNNPRS (2004/2005), 30% of the people of the area were evacuated from their habitation and further 50% of the cultivated land has also become out-of use due to the complete direction change of the Basso river in to the residences of the people and the farm lands. Thus, aggravating and making worse the household level food security situations of the lowland kebeles of the woredas. And also the main asphalt road connecting the zonal capital Arbaminch to the regional capital and Addis Ababa, capital of the country, is under frequent flood damages and usually blocked for land transportation.

Having known the fact that the flood has been part of the region's life since years back and that this natural phenomenon may not be fully controlled, it is important to focus and improve knowledge about the prevention.

The proper prevention and mitigation measures to be recommended depend upon the availability of data on the river flow characteristics. To know the flow characteristics of rivers there has to be optimum river gauges in the river catchments. However, regarding hydrologic data of most of the rivers in the basin there is no any gauging stations along the entire lengths of the rivers, so that the catchments for those rivers considered as ungauged catchments.

In river flow simulation and forecasting at a specific gauging site, particularly in small budget, scarce data or prediction in ungauged basin, the Rainfall-runoff models are appropriate operational tools (Genene, 2006). For this application model testing and evaluation is an essential before using or applying any models to any catchments or river basins.

For these reasons, in this study, an attempt is made to test some known hydrologic models and select a better model which can quantify the peak flood and volume of water from the ungauged catchments. Developing a rainfall – runoff model for the catchments is the first step to be carried out. The model will serve for simulation of catchment runoff into the Lake Abaya in general and will be used as flooding prediction tool at ungauged catchments in particular with regionalization.

1.3 Objective

The general objective of this thesis is to test the performance of three well known **daily** rainfall-runoff models:

1. HEC-HMS SMA Model

2. RRL TANK Model and

3. RRL SMAR Model on two catchments (Kulfo and Bilate) in the Abaya-Chamo sub-basin located in the Rift Valley basin.

2 DESCRIPTION OF THE STUDY AREA

2.1 General

The selected study areas, Kulfo and Bilate catchments are found in Abaya-Chamo sub-basin, the sub-basin of the Rift valley lakes (central lakes) basin. Many perennial and intermittent rivers joining the lakes Abaya and Chamo contribute major amount of runoff to the lakes yield. Among those, two rivers: Bilate from the rivers with large sized catchment and Kulfo from the rivers with midsized catchments in Abaya-Chamo River system are selected for this study for the data availability. See map of the two catchments in Figure 2.1.

According to Ethiopian climate classification the Abaya-Chamo sub-basin is characterized with hot semi-arid warm temperature, tropical climate (Lemma, 1996). The average annual rainfall ranges from 665mm at Bilate to 1240 at Chencha with average maximum temperature of 31.2 C° at Arbaminch and minimum average temperature of 13.9 C° at Chencha.

2.2 Kulfo Catchment

The catchment is located between 5°55'N and 6°15' latitude and 37°18' and 37°36' longitude in the Abaya-Chamo watershed. Its area varies in altitude between 3400m above mean sea level at the highest point and 1180m above mean sea level at the out let of the Kulfo River into Lake Chamo. It is almost flat in the lower part.

The catchment area of the Kulfo River comprises about 492 km^2 including the outlet at Lake Chamo. But it is about 364 km2 at the gauging site. According to the Ethiopian Mapping Authority the Kulfo River is formed from the junction of the Gulando and Titika Rivers. The tributaries Baba, Gulando and Yeremo drain the Upper part of the basin, where as the tributaries Wombale and Majale drain the middle part of the watershed. The tributaries Korzha, Ambule, Titika and kulfo make up the lower part of the catchment area. The mean Annual flow at upper gauging station is 6.21m^3/s.

2.3 Bilate Catchment

The catchment is located between 7^0 28ʿ N and 38^0 02ʿ E in with elevation range of 2200m above sea level at Hosana and 1750m above sea level at Alaba Kulito.

Bilate River is formed after Boyo swampy lake which has two main sources Guracha and Weira Rivers and it drains at Abaya Lake. The Bilate river basin which is located at upper part of the Abaya Chamo Basin drains a catchment area of 5756 km^2. This study considers only the upper part of the basin above the gauging station Alaba Kulito with drainage area of 1980 km^2. The average annual rainfall in the basin is from 1056 mm to 710mm with monthly average maximum and minimum temperature of 25C^o and 12 C^o respectively. Bilate River has average annual flow of 11.3m^3/s at Near Alaba Kulito station.

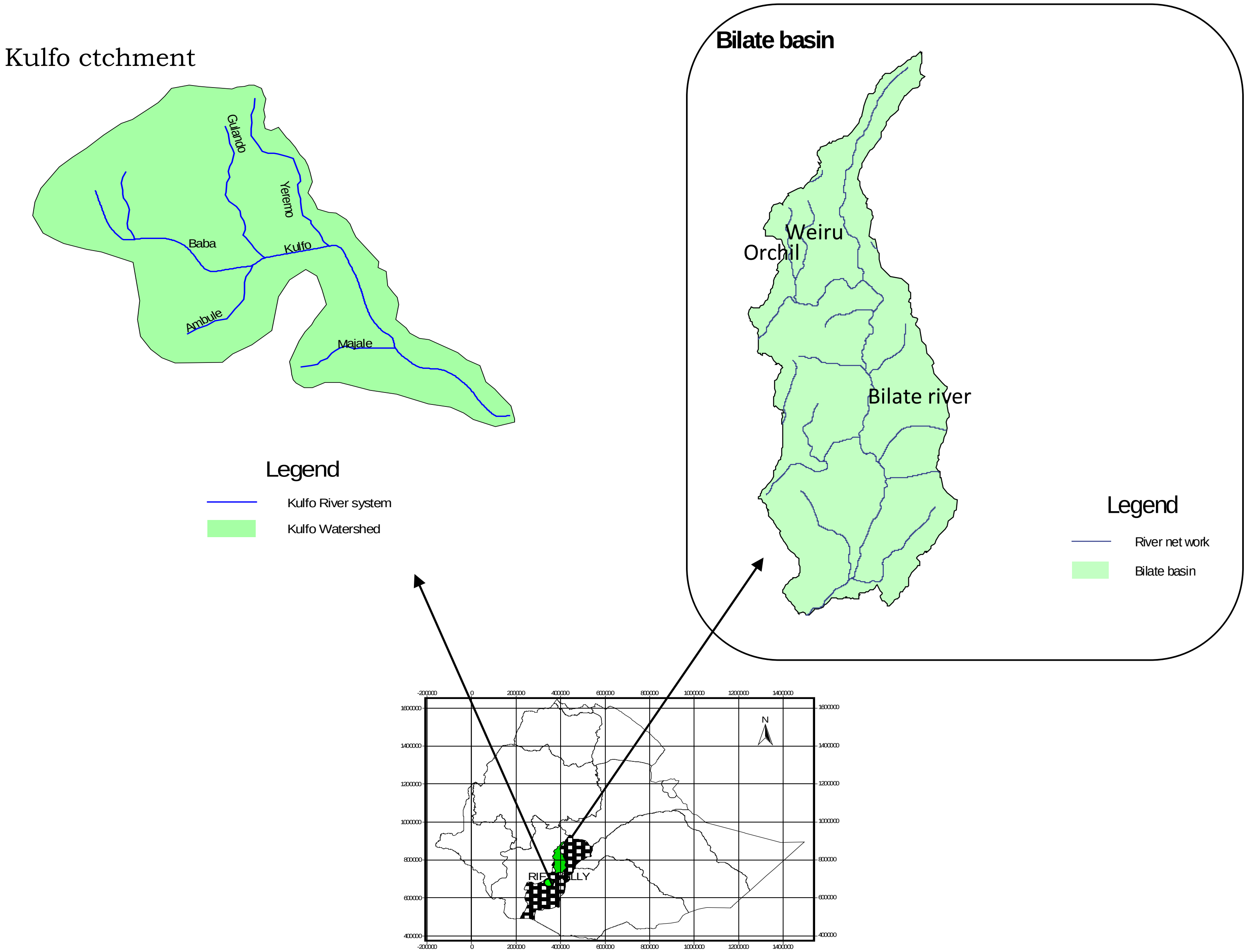

Figure 2.1 Location Maps of Kulfo & Bilate Catchments

3 LITERATURE REVIEW

3.1 The Catchment Hydrologic Cycle

Catchment modelling requires a clear understanding the hydrologic cycle at catchment scale. The catchment hydrologic cycle involves many processes. Many hydrologists investigated this cycle by a number of studies. A summary of the cycle is given by Chow et al (1988) or detail description of some processes can be found in the book of Kirby (1978).

The hydrologic cycle may be treated as a system whose components are precipitation, evaporation, snowmelt, infiltration, runoff and other processes in the hydrologic cycle. The different components can each be grouped together into subsystem or broken down into new sub-processes, depending on the level of detail in the analysis and the purpose of the analysis. To summary the processes, a brief description is presented and is illustrated in Figure 3.1.

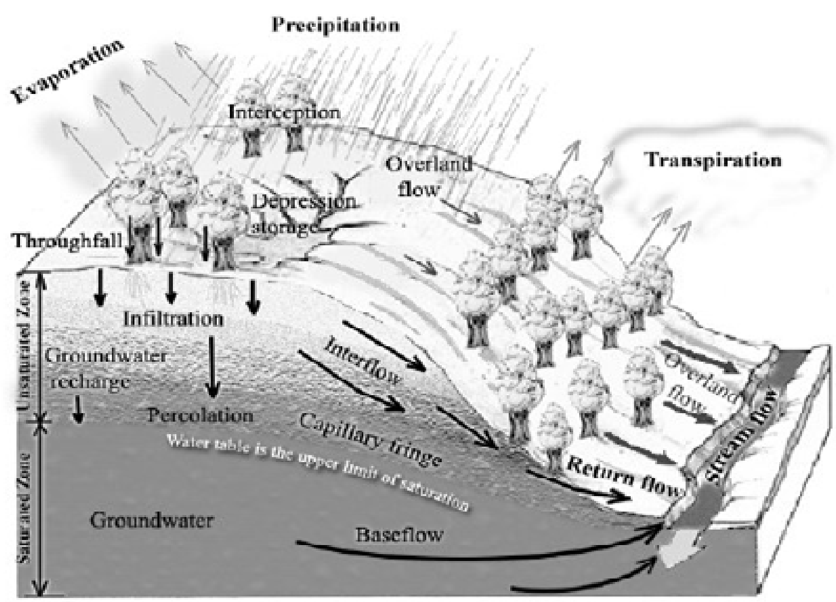

Figure 3.1 Physical processes involved in Runoff Generation (Tarboton, 2003)

Precipitation is the most essential process for the generation of runoff at a catchment scale. The distribution of precipitation varies spatially and temporally by nature. Precipitation can be in the form of snow, hail, dew, rain and rime. In this study precipitation is considered in the form of rain only. Rainfall travels in a catchment in different directions. Due to vegetation, part of rainfall is intercepted by vegetation canopy. Interception is known as a loss function to catchment runoff depending on vegetation type, vegetation density. The rest of rainfall moves down the vegetation as stem flow, drip off the leaves, or directly falls to the ground as through fall.

Rainfall remains at the land surface as depression storage and either evaporates, infiltrates or is discharged as overland flow.

By infiltration of rainwater, the water moves primarily in downward direction by unsaturated subsurface flow and recharges the saturated zone. This process is termed percolation or natural recharge and fills the aquifers of groundwater system. In some cases at the shallow subsurface layer where the lateral hydraulic conductivity is higher than the vertical one, the direct infiltration partly goes toward the channel through interflow or throughflow.

The groundwater pattern is influenced by the catchment characteristics, especially the topographic factors of the catchment, before being discharged to the channel network system. Aquifers of the groundwater system also can discharge groundwater across the catchment boundary.

In Figure 3.2 the global hydrologic cycle is represented in a system. The dashed lines divide it into three subsystems:

- The atmospheric water system containing the processes of precipitation, evaporation, interception and transpiration.

- The surface water system containing the process of snow accumulation and melt, overland flow, surface runoff, subsurface and groundwater outflow and runoff to streams and the ocean.
- The subsurface water system containing the process of infiltration, groundwater recharge, subsurface flow and groundwater flow.

For most practical applications, only a few processes of the hydrologic cycle are considered at a time, and only for a small part of the earth's surface, usually in a catchment. (Killingtveit, 1995)

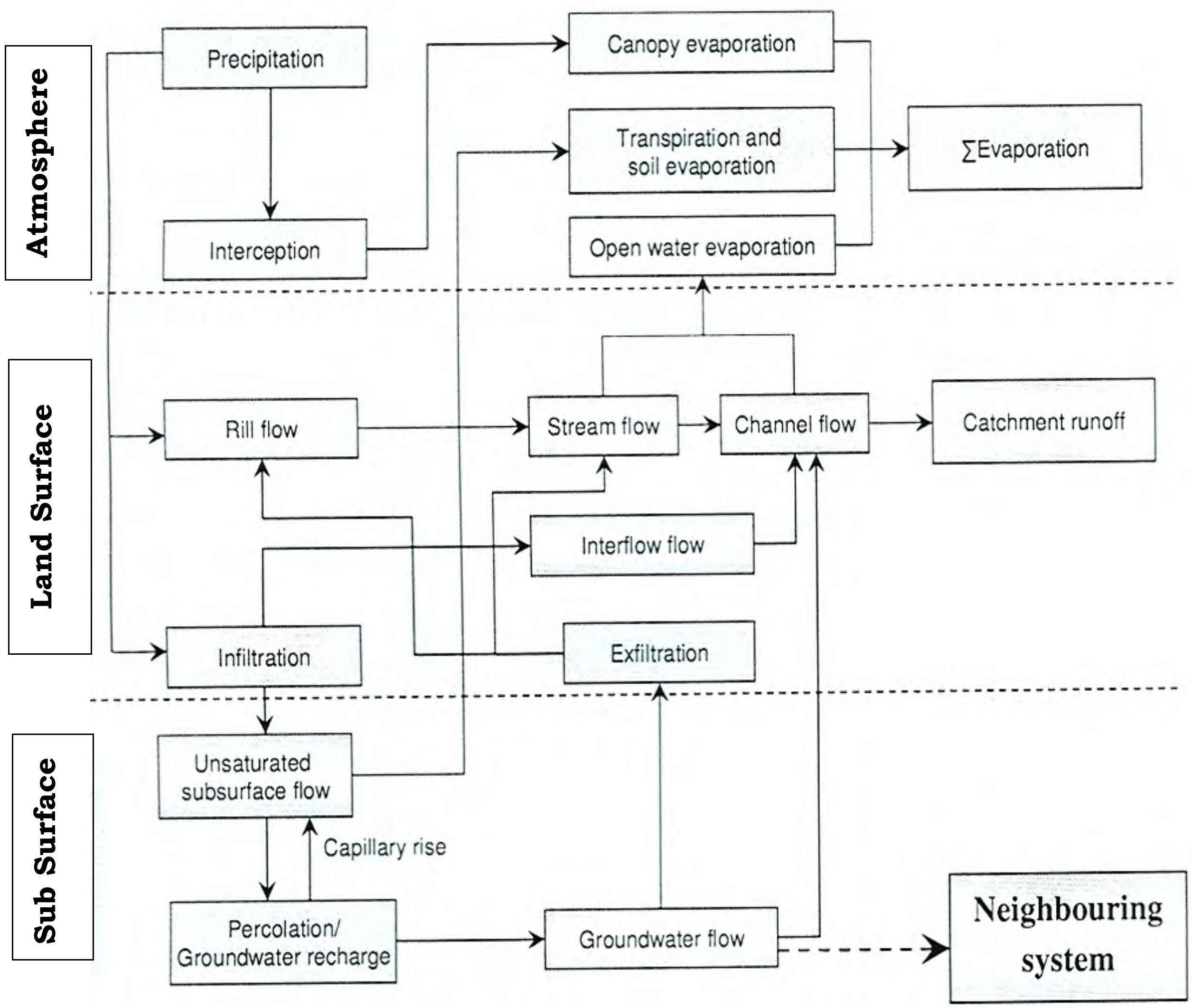

Figure 3.2 Global hydrologic cycle

3.2 Catchment Runoff Generation

Going to a bit detail of the catchment hydrology with respect to the aim of this study, the rainfall –runoff modelling, it is useful to look at the runoff generation of a catchment. The topic is discussed by a number of authors, one can refer to, for example, publications given by Dunne (1982), Rientjes (2004, p.24-39). Basically, the runoff generation at a catchment scale in general or hillslope scale in particular includes 2 main components: (1) surface runoff, (2) subsurface runoff. There are a number of flow processes within each main component as illustrated in figure 3.2 and more detail in figure 3.3.

The surface runoff: Flow processes include overland flow, stream flow, and channel flow which is defined as water flow over the land surface based on the differences on slope gradient. The overland flow is known as infiltration excess overland flow (Horton overland flow) or saturation overland flow (Dunne flow). The Horton overland flow is generated when the rainfall intensity exceeds the infiltration capacity of the soil or by a saturation mechanism where the soil becomes saturated by the perennial groundwater rising to the surface or by lateral or vertical percolation above an impeding horizon (Dunne, 1982). The overland flow is observed as sheet flow which then generates the rill flow. A number of the rill flow will contribute or create the stream flow which then converges into channel flow.

Subsurface runoff: Flow processes include unsaturated subsurface flow, perched subsurface flow, macro pore flow and groundwater flow. Subsurface runoff is generated since water discharged from the surface into the subsurface system. The unsaturated subsurface flow mostly is in vertical direction while the perched flow moves in lateral direction. The perched flow is generated where the shallow soil layer has much more higher hydraulic conductivity as compared to the lower one. The macro pore flow occurs where the subsurface system has macro pores such as voids, natural pipes, cracks, etc. the flow rapidly contributes to the groundwater system. Ground water flow is produced in the saturated zone which is fed through percolation of infiltrated water or from neighbouring system. The ground water contributes to the channel system as rapid groundwater flow in the upper part of the initially unsaturated subsurface domain or as delayed groundwater flow in the lower part of the saturated subsurface domain.

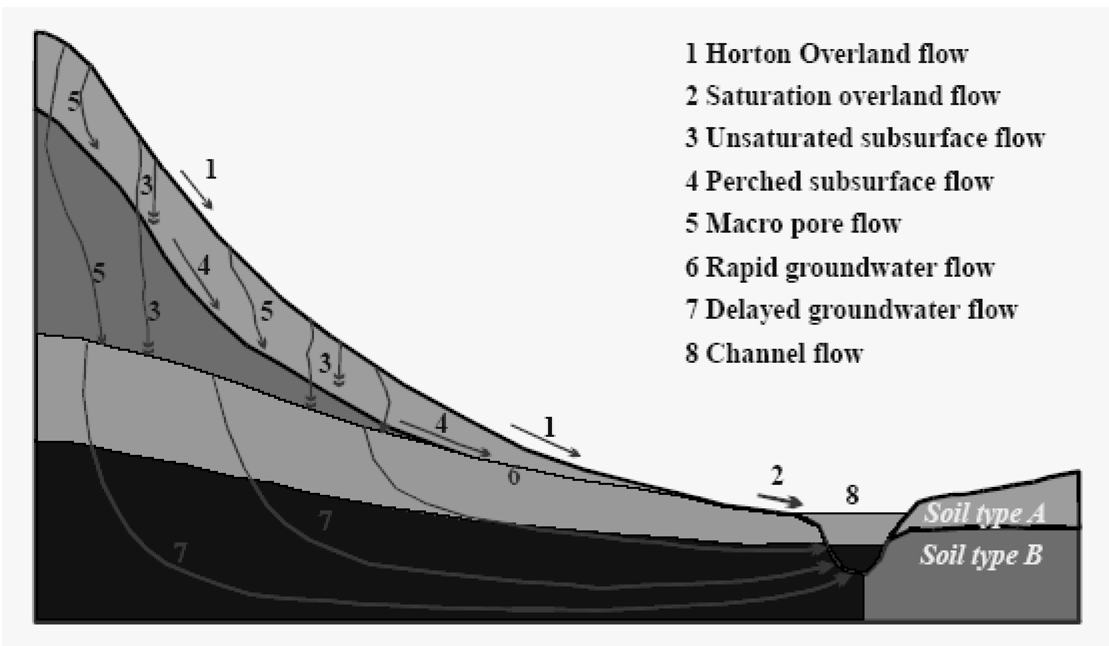

Figure 3.3 Cross-sectional presentation of hillslope flow process (after Rientjes, 2004)

3.3 Rainfall – runoff modelling

The processes described in the previous part are not simple to qualify because most hydrologic systems are extremely complex. Thus we may hope to find an abstraction of the processes instead of understand them in all detail. Rainfall – runoff modelling is a tool for this purpose. In order to simulate the transformation from rainfall to runoff, rainfall – runoff models have been developed already a long time ago and reference is made to the work of Todini (1988) for historical review of rainfall - runoff modelling or Singh and Woolhiser (2002) for review on cachment models. With respect to development over the past decade, Beven (2000, p.ix) wrote "it is now virtually impossible for any one person to be aware of all the models that are reported in the literature " and can be interpreted as that much efforts have been devoted to this issue.

Hydrologists have tried to classify rainfall – runoff models according to their specific approaches as well as their characteristics (Dooge, 1977; Refsgaard, 1996; Rientjes, 2004; Singh, 1988; Wood and O'connel, 1985). Basically, when we consider deterministic rainfall – runoff models and mathematical solutions, we could classify them into 3 main types:

- Physically based (or theoretical, white box) 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. The first two equations are most popularly applied in current models. Examples of this approach are SHE (Abbott et al., 1986), REW (Reggiani and Rientjes, 2005).
- Conceptually based (grey box) models consider physical laws but in a simplified form that is able to explain the hydrologic behaviour by empirical expression. _ Examples of this approach are HEC-HMS SMA, Tank, SMAR (Sugawara, 1995), Sacramento (Burnash, 1995), TOPMODEL (Beven et al., 1995), HBV (Bergstrom, 1995).
- Empirically based (black box) models do not aid in physical understanding. However, they contain parameters that may have

physical characteristics that allow the modelling of input-output patterns based on empiricism. Examples of this approach are unit hydrograph, rational method, etc. which are well described by Singh (1988).

In terms of spatial domains in catchment modelling, models can be classified as lumped, distributed or semi-distributed ones. The lumped model ignores spatial distributed of the catchment characteristics but there are represented by averaged single values. 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.

3.4 Review on the Selected Model Approaches

3.4.1 The HEC-HMS SMA Model

HEC-HMS is comprised of a graphical user interface (GUI), integrated hydrologic analysis components, data storage and management capabilities, and graphics and reporting facilities. The Data Storage System, HEC-DSS, is used for storage and retrieval of time series, paired-function, and gridded data, in a manner largely transparent to the user.

The GUI provides a means for specification of watershed components, inputting data for the components, and viewing the results. The GUI has capability for schematic representation of a network of hydrologic elements (e.g. sub-basins, routing reaches, junctions, etc.). You can configure the schematic by selecting and connecting icons that represent the elements. Once a schematic is developed, pop-up menus can be invoked from the element icons. A menu provides access to an editor for entering or editing data associated with the hydrologic element, and enables display of results of a simulation for that element. The GUI also contains global editors for entering or reviewing data of a given type (e.g., values for Green & Ampt parameters) for all applicable elements

3.4.1.1 Synopsis of Models Included in HEC-HMS Program

HEC-HMS uses a separate model to represent each component of the runoff process that is illustrated in Figure 3-4, including:

- Models that compute runoff volume;
- Models of direct runoff (overland flow and interflow);
- Models of baseflow;
- Models of channel flow.

The HEC-HMS models that compute runoff volume are listed in APPENDIX-I Table 3-1 and refer to it for definitions of the categorizations. These models address questions about the volume of precipitation that falls on the watershed: How much infiltrates on pervious surfaces? How much runs off of pervious surfaces? How much runs off of the impervious surfaces? When does it run off?

The HEC-HMS models of direct runoff are listed in APPENDIX-I Table 3-2. These models describe what happens as water that has not infiltrated or been stored on the watershed moves over or just beneath the watershed surface. APPENDIX-I Table 3-3 lists the HEC-HMS models of baseflow. These simulate the slow subsurface drainage of water from the system into the channels. The choices for modeling channel flow with HEC-HMS are listed in APPENDIX-I Table 3-4. These so-called routing models simulate one-dimensional open channel flow.

3.4.1.2 Runoff volume model

HEC-HMS computes runoff volume by computing the volume of water that is intercepted, infiltrated, stored, evaporated, or transpired and subtracting it from the precipitation. Interception and surface storage are intended to represent the surface storage of water by trees or grass, local depressions in the ground surface, cracks and crevices in parking lots or roofs, or a surface area where water is not free to move as overland flow. Infiltration represents the movement of water to areas beneath the land surface. Interception, infiltration, storage, evaporation, and transpiration collectively are referred to in the HEC-HMS program and documentation as *losses*.

The basic concept of loss methods in the HEC-HMS is arising from considering all land and water in a watershed to be categorized as either:

- Directly-connected impervious surface; or
- Pervious surface.

Directly-connected impervious surface in a watershed is that portion of the watershed for which all contributing precipitation runs off, with no infiltration, evaporation, or other volume losses. Precipitation on the pervious surfaces is subject to losses. Among loss models mentioned on APPENDIX-I Table 3.1 Soil moisture accounting (SMA) Loss Model is selected for the model computes runoff discharge on a continuous time base and the model is described below.

3.4.1.2.1 Continuous Soil-moisture Accounting (SMA) Model

SMA, a loss model within the HEC-HMS software suite, was designed to compute runoff discharge on a continuous time base. This model was successfully applied for long term rainfall – runoff modelling and reference is made to the work of Fleming (2002) Fleming and Neary (2004). The model operates as the Precipitation - Runoff Modelling System – PRMS (Leavesley and Stannard, 1995) whose system domains are expressed by the inflow, outflow, and capacities of each of the storages. The model is conceptualized as a series of reservoirs, controlling the volume of water lost or added to each of these storage components.

River flow is produced from three sources in this model. The first source from overland flow when excess precipitation is transformed to stream flow at the basin outlet if the canopy storage zone is filled; or when the available infiltration rate is exceeded, and the surface storage zone is filled. A number of methods can be used to transform excess precipitation into surface runoff (i.e. SCS Unit Hydrograph, Clark Unit Hydrograph). Later, two others sources, groundwater storage in 2 zones are routed in to a set of linear reservoirs and then used to calculate base flow contributions (Feldman (ed.), 2000).

The model simulates the movement of water through and storage of water on vegetation, on the soil surface, in the soil profile, and in groundwater layers which is illustrated in Figure 3.4. Five zones of a catchment are simulated including canopy interception storage, surface depression storages, soil profile storage, groundwater layer-1 storage, and layer-2 storage.

To run this model, several parameters should be known or estimated that is presented in section 4.4.

3.4.1.2.2 Estimating Model Parameters

SMA model parameters must be determined by calibration with observed data. In this iterative process, candidate parameter values are proposed, the model is exercised with these parameters and precipitation and evapotranspiration inputs. The resulting computed hydrograph is compared with an observed hydrograph for the same period. If the match is not satisfactory, the parameters are adjusted, and the search continues. Bennett (1998) and EM 1110-2-1417 offer guidance for this calibration.

3.4.1.3 Direct runoff models

Direct runoff models are the models that simulate the process of direct runoff of excess precipitation on a watershed. HEC-HMS refers to this process as "transformation" of precipitation excess into point runoff. With HEC-HMS, there are two options for these transform methods: Empirical models (also referred to as system theoretic models). These are the traditional unit hydrograph (UH) models. And the other is conceptual model, that included in HEC-HMS is a kinematic-wave model of overland flow. It represents, to the extent possible, all physical mechanisms that govern the movement of the excess precipitation over the watershed land surface and in small collector channels in the watershed. The SCS UH transform model is used in this thesis.

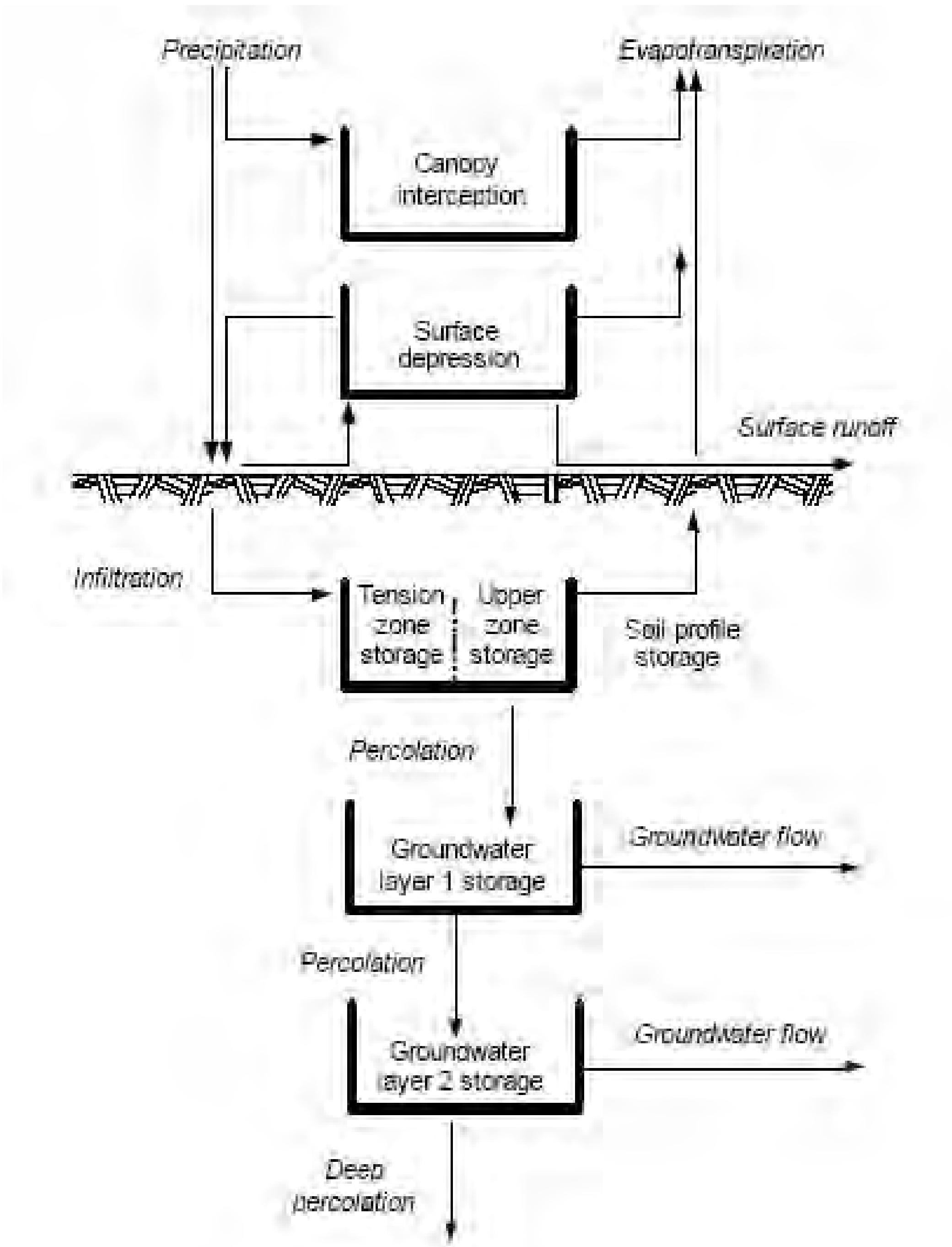

Figure 3.4 Conceptual schematic of the continuous soil moisture accounting algorithm (Bennett, 1998)

3.4.1.3.1 SCS UH Model

This model is based upon averages of UH derived from gauged rainfall and runoff for a large number of small agricultural watersheds throughout the US. SCS UH model is a dimensionless, single-peaked UH. This dimensionless UH, which is shown in APPENDIX III Figure 3-7, expresses the UH discharge, U_t, as a ratio to the UH peak discharge, U_p, for any time t, a fraction of T_p, the time to UH peak.

Research by the SCS suggests that the UH peak and time of UH peak are related by:

$$U_P = C\frac{A}{T_P} \tag{3-1}$$

in which A = watershed area; and C = conversion constant (2.08 in SI and 484 in foot-pound system). The time of peak (also known as the time of rise) is related to the duration of the unit of excess precipitation as:

$$T_P = \frac{\Delta t}{2} + t_{lag} \tag{3-2}$$

in which Δt = the excess precipitation duration (which is also the computational interval in HEC-HMS); and t_{lag} = the basin lag, defined as the time difference between the center of mass of rainfall excess and the peak of the UH. [Note that for adequate definition of the ordinates on the rising limb of the SCS UH, a computational interval, Δt, that is less than 29% of t_{lag} must be used (USACE, 1998).]

When the lag time is specified, HEC-HMS solves Equation 3-2 to find the time of UH peak, and Equation 3-1 to find the UH peak. With U_p and T_p known, the UH can be found from the dimensionless form, which is included in HEC-HMS, by multiplication.

3.4.1.4 Base flow models

Two distinguishable components of a streamflow hydrograph are (1) direct, quick runoff of precipitation, and (2) baseflow. Baseflow is the sustained or “fairweather” runoff of prior precipitation that was stored temporarily in the watershed, plus the delayed subsurface runoff from the current storm. Some conceptual models of watershed processes accounts explicitly for this storage and for the subsurface movement. However, this accounting is not necessary to provide the information for activities described in APPENDIX-I Table 3-3. In this thesis Linear Reservoir Baseflow Model is found to be viable to be applied.

3.4.1.4.1 Linear Reservoir Model

The linear-reservoir baseflow model is used in conjunction with the continuous soil-moisture accounting (SMA) model. This baseflow model simulates the storage and movement of subsurface flow as storage and movement of water through reservoirs. The reservoirs are linear: the outflow at each time step of the simulation is a linear function of the average storage during the time step. Mathematically, this is identical to the manner in which Clark's UH model represents watershed runoff.

The outflow from groundwater layer 1 of the SMA is inflow to one linear reservoir, and the outflow from groundwater layer 2 of the SMA is inflow to another. The outflow from the two linear reservoirs is combined to compute the total baseflow for the watershed.

3.4.2 RRL TANK Model

The TANK model is a very simple model, composed of four tanks laid vertically in series as shown in Figure 3.5. 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 analyze 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.

3.4.2.1 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

$$q = \sum_{x=1}^{4} \sum_{y=1}^{nx} \left(C_x - H_{xy}\right) a_{xy} \qquad (3.3)$$

Where q is the runoff depth in mm, C_x the water level of tank x, H_{xy} 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.

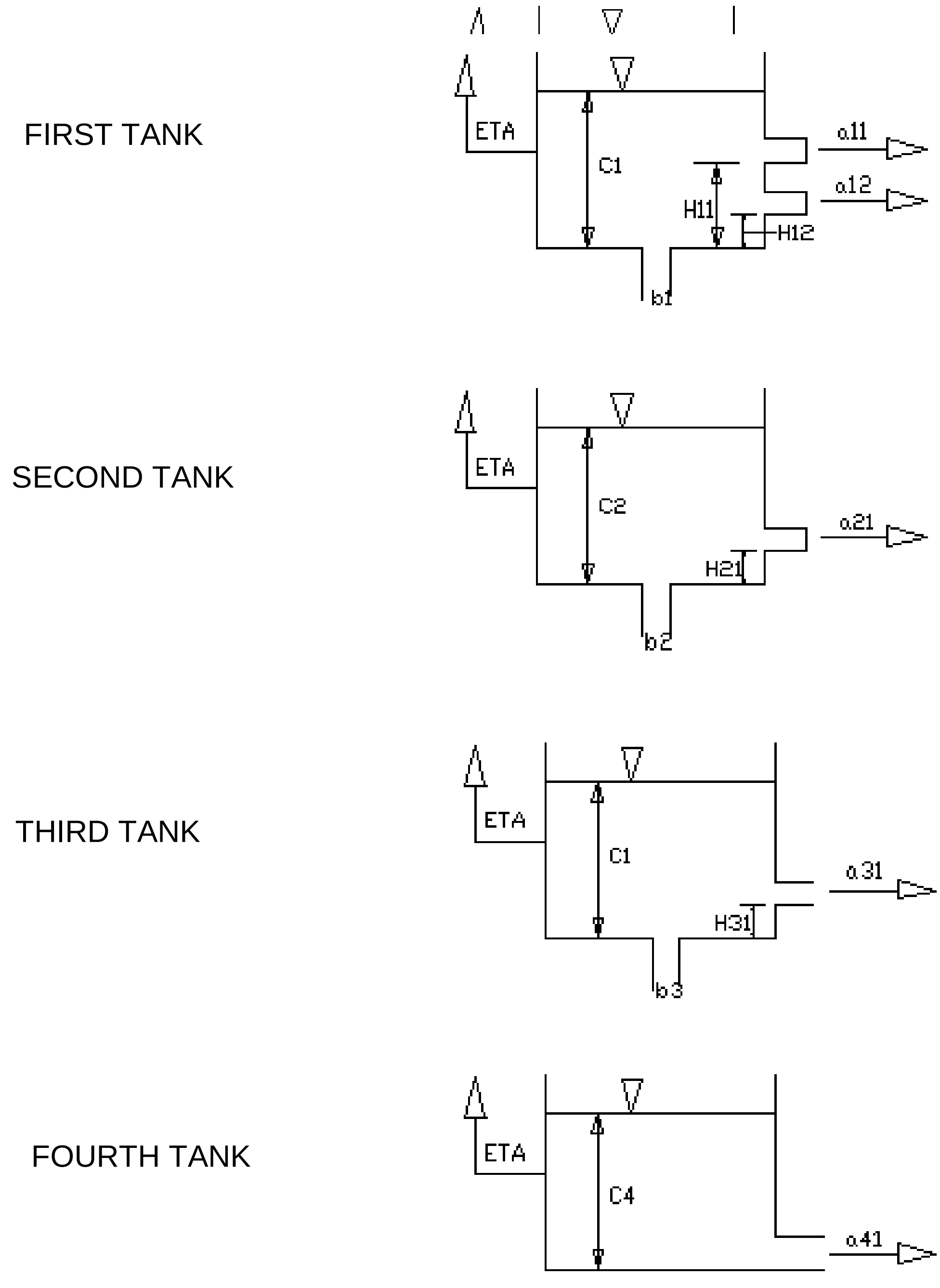

Figure 3.5 Structure of the TANK rainfall runoff model

3.4.2.2 Evapotranspiration

The evapotranspiration is calculated using Beken's (1979) equation

$$ETA = ETP^{*}\left(1 - exp\left(-\alpha\sum_{x=1}^{4} C_x\right)\right) \quad (3.4)$$

Where ETA is the evapotranspiration in mm, α the evapotranspiration coefficient (0.1) and C_x the water level of tank.

3.4.2.3 Infiltration

The infiltration in each tank is calculated using:

$$I_x = C_x B_x \quad (3.5)$$

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

3.4.2.4 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.

3.4.3 RRL SMAR

The soil moisture accounting and routing model (SMAR) is a lumped conceptual rainfall run-off water balance model with soil moisture as a central theme (O'Connell *et al.*, 1970; Kachroo, 1992; Tuteja and Cunnane, 1999). The model provides daily estimates of surface run-off, groundwater discharge, evapotranspiration and leakage from the soil profile for the catchment as a whole. The surface run-off component comprises overland flow, saturation excess run-off and saturated through-flow from perched groundwater conditions with a quick response time.

The SMAR model consists of two components in sequence, a water balance component and a routing component. A schematic diagram of the SMAR model is shown in Figure 3.6. The model utilizes time series of rainfall and pan evaporation data to simulate stream flow at the catchment outlet. The model is calibrated against observed daily stream flow.

The water balance component divides the soil column into horizontal layers, which contain a prescribed amount of water (usually 25 mm) at their field capacities. Evaporation from soil layers is treated in a way that reduces the soil moisture storage in an exponential manner from a given potential evapotranspiration demand. The routing component transforms the surface run-off generated from the water balance component to the catchment outlet by a gamma function model form (Nash, 1960), a parametric solution of the differential routing equation in a single input single output system.

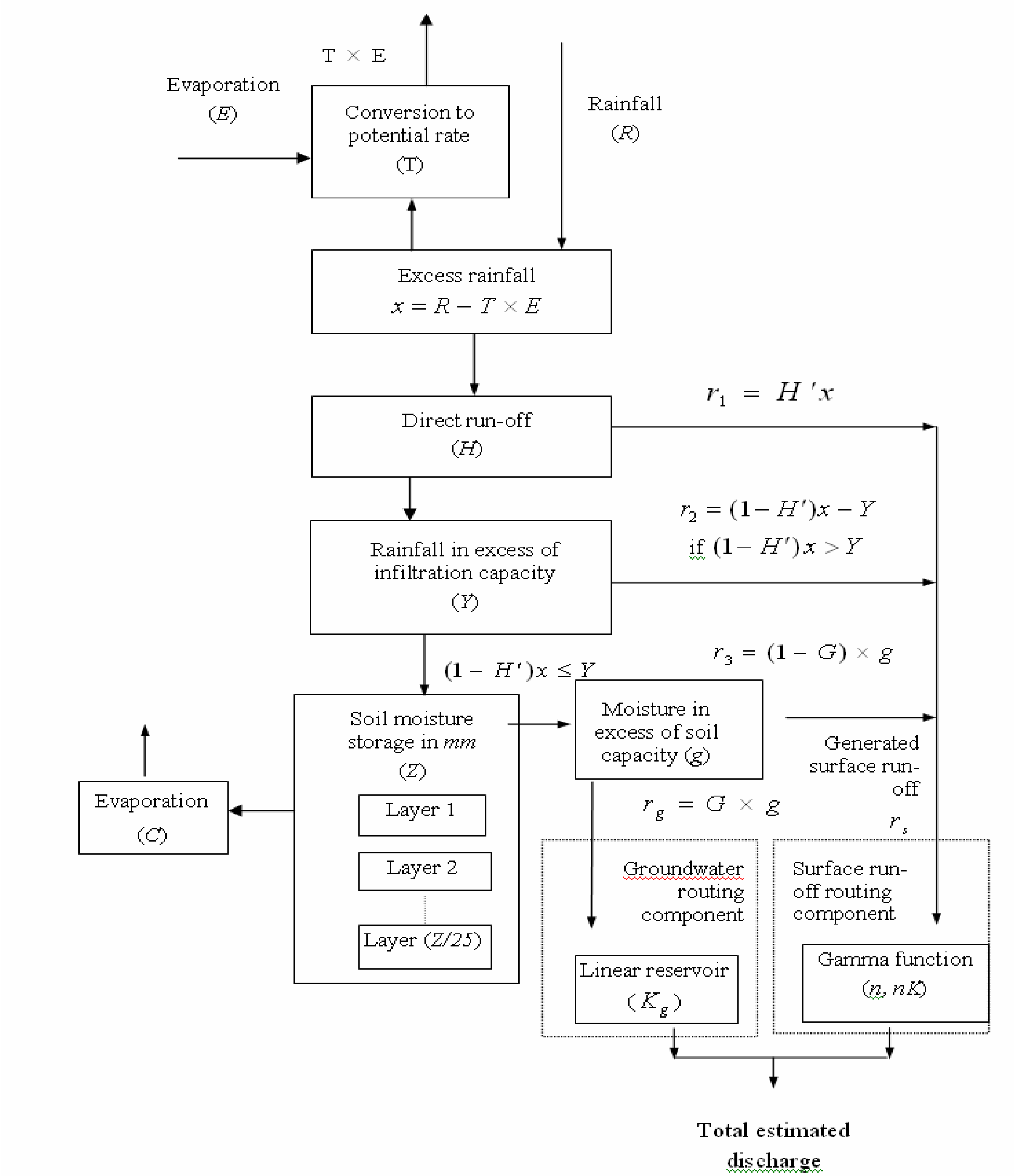

Figure 3.6 Structure of the SMAR rainfall-runoff model

The generated groundwater run-off is routed through a single linear reservoir and provides the groundwater contribution to the stream at the catchment outlet. The SMAR model contains five water balance parameters and four routing parameters.

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.

- The dimensionless parameter C regulates evaporation from the soil layers.
- 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.
- 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.
- 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).
- The dimensionless parameter T is used to calculate the potential evaporation from pan evaporation (E).

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 runoff 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. The detail calculation part is presented in APPENDIX-II.

3.4.4 Model Evaluation

In the field of rainfall – runoff model comparison, several authors investigated models' behaviours usually within their specific approaches. For example, Al-Wagdany and Rao (1998) compared velocity parameters of three GIUH models. Gan et al (1997) distinguished 4 conceptual models including PITMAN, SACRAMENTO, XINANJIANG, SMAR to find out which model performs best by looking at their structures, objective functions, etc. Perrin et al (2001) did an intensive comparative performance assessment of the structure of 19 lumped models carried out 429 catchments. The World Meteorological Organization (WMO), held a project of doing an intercomparison of hydrological models to be applied in real-time forecasting, most of them are conceptual models (Askew, 1989; Reed et al., 2004). Rientjes (2004) gave a comparison of model structure concept, data requirement, model performance etc. of 4 physically-based models including MIKE-SHE, IHDM, THALES, DBSIM. Refsgaard and Knudsen (1996) reviewed on model comparison of 3 conceptual and physically based models including NAM, MIKE SHE, WATBAL based on validation schemes . A number of criteria used in this study to perform models' comparison will be listed in section 4.5 to recommend which model is suitable for application in the area.

3.5 Previous Studies in the Area

Much information was not obtained on models developed for the sub-basin for forecasting flood magnitudes and on model comparison. Most of the available works conducted so far are project-based merely developed to predict flood magnitudes using empirical methods and frequency analysis techniques.

No any models comparison done in the sub-basin except the work of Genene (2006). He has conducted his research in the sub-basin with the objective of testing different hydrological rainfall runoff models. Two linear models (Simple Linear Model SLM and Linear Perturbation Model LPM) and two conceptual models (Soil Moisture accounting & Routing SMAR Model and HBV Models) are used for the test. Based on some performance criteria he has got that the SMAR model performs better in the two catchments. The objective function Nash-Sutcliff Efficiency NSE in the Kulfo and Bilate catchments was 0.4 and 0.63 respectively.

However, using the optimized parameters' value of SMAR model of his result, the model was run and the objective function NSE value was coming -1.404 and -0.486 for Kulfo and Bilate catchments respectively. Thus, in this thesis an attempt has been made to test this SMAR model and other two conceptual rainfall-runoff models.

4 RESEARCH METHOD AND DATA ANALYSIS

4.1 Conceptual framework

A conceptual framework serves to describe the overall research steps. Firstly, three main data types required as input includes rainfall evapotranspiration and observed discharge. After having data, the three models, HEC-HMS SMA, RRL TANK and RRL SMAR models are developed through model parameterization, and then these models are operated on two of Rift valley Rivers draining to the lakes Abaya and Chamo. The main output from these models is simulated discharge at the outlet of the catchment. The output is compared with real discharge data (collected from Ministry of Water Resources) to calibrate the model. Model output is compared based on a number of criteria to see which model yields better result so that the best performing model is proposed to simulate the flow of ungauged neighboring catchments.

4.2 Applications of GIS

The typical application reported in this section is Theissen polygon preparation to find Arial rainfall of the catchment. Several methods are available and routinely used to calculate basin average rainfall from an assumption of areal (i.e., spatial) distribution using point rainfall from a gauge network. The most common, useful method is the Theissen Polygon. The Theissen method weighs each gauge in direct proportion to the area it represents of the total basin without consideration of topography or other basin physical characteristics. The area represented by each gauge is assumed to be that which is closer to it than to any other gauge. Using the meteorological stations presented in Table 4.1

below. The Theissen polygon weights are generated in the GIS environment and the output is summarized below. Table 4.2a- 4.2b present the station names and Theissen coefficients to each catchments.

Table 4.1: Statistical description of selected Meteorological stations

<table>
<tr><th rowspan="2">River Basin</th><th rowspan="2">Meteorological Station</th><th rowspan="2">Station Type</th><th rowspan="2">Type of data</th><th colspan="2">Record year</th><th rowspan="2">NO. of years</th></tr>
<tr><th>From</th><th>To</th></tr>
<tr><td rowspan="18">Bilate</td><td rowspan="6">Hosana
Long. 37.87
Lat. 7.55
Elev.2200</td><td rowspan="6">Principal</td><td>Daily rainfall</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td>Daily min.Temp.</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td>Daily max.Temp.</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td>Monthly Sunshine</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td>Monthly Humidity</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td>Monthly Wind speed</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td rowspan="4">Alaba Kulito
Long. 38.06
Lat. 7.19
Elev. 1790m</td><td rowspan="4">Ordinary</td><td>Daily discharge</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td>Daily rainfall</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td>Daily min.Temp.</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td>Daily max.Temp.</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td rowspan="3">Wulbareg
Long. 38.08
Lat. 7.45
Elev. 1800m</td><td rowspan="3">Ordinary</td><td>Daily rainfall</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td>Daily min.Temp.</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td>Daily max.Temp.</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td rowspan="3">Tora
Long. 38.25
Lat. 7.52
Elev. 1600</td><td rowspan="3">Ordinary</td><td>Daily rainfall</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td>Daily min.Temp.</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td>Daily max.Temp.</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td rowspan="9">Kulfo</td><td rowspan="7">Arbaminch
Long. 37.38
Lat. 6.05
Elev. 1190m</td><td rowspan="7">Principal</td><td>Daily discharge</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td>Daily rainfall</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td>Daily min.Temp.</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td>Daily max.Temp.</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td>Monthly Sunshine</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td>Monthly Humidity</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td>Monthly Wind speed</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td rowspan="2">Chencha
Long. 37.34
Lat. 6.15
Elva. 2680m</td><td rowspan="2">Ordinary</td><td>Daily rainfall</td><td>1995</td><td>2003</td><td>9</td></tr>
<tr><td>Monthly temp.</td><td>1972</td><td>1981</td><td>9</td></tr>
</table>

Table 4.2a: Theissen coefficients of Kulfo River Catchment (A=364 km^2)

No	Station	Avg Annual Rainfall (mm)	Theisson polygon	Area of polygon (km^2)	Weighting factor	Data range
1	Arbaminch	919	3	61.88	0.17	1996-2000
2	Chencha	1287	1	98.28	0.27	1997-2000
3	Baba	1115	2	203.84	0.56	1997-2000

Table 4.2b: Theissen coefficients of Bilate River Catchment (A=1980 km^2)

No	Station	Avg Annual Rainfall (mm)	Theisson polygon	Area of polygon (km^2)	Weighting factor	Data range
1	Tora	1194	3	144.54	0.073	1995-2003
2	Wulbareg	991	1	332.64	0.168	1995-2003
3	Hosana	799	2	617.76	0.312	1995-2003
4	Alaba Kulito	1238	4	885.06	0.447	1995-2003

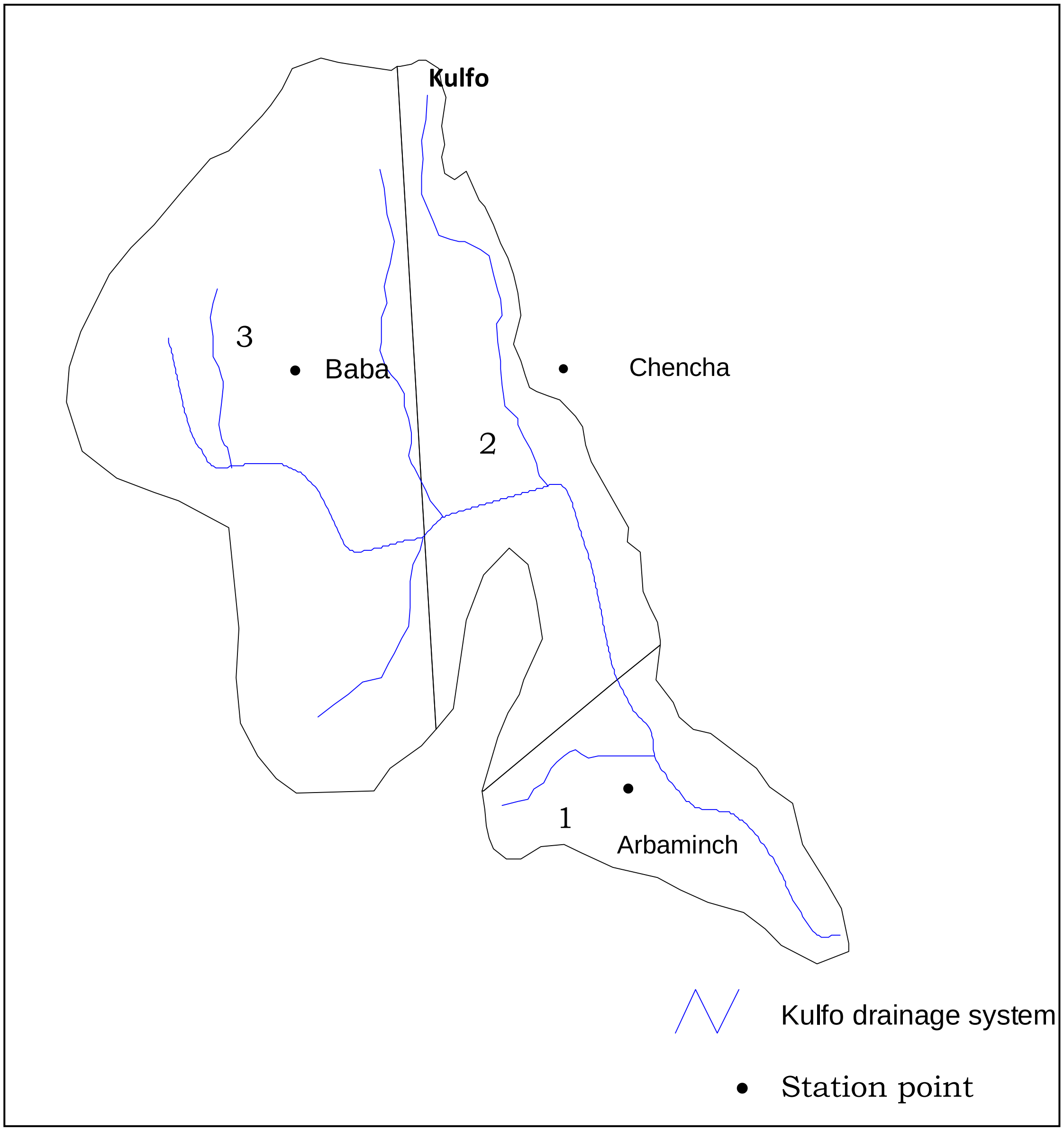

Figure 4.1 Theissen polygons for Kulfo catchment

THIESSEN POLYGONS FOR SELECTED **STATIONS**

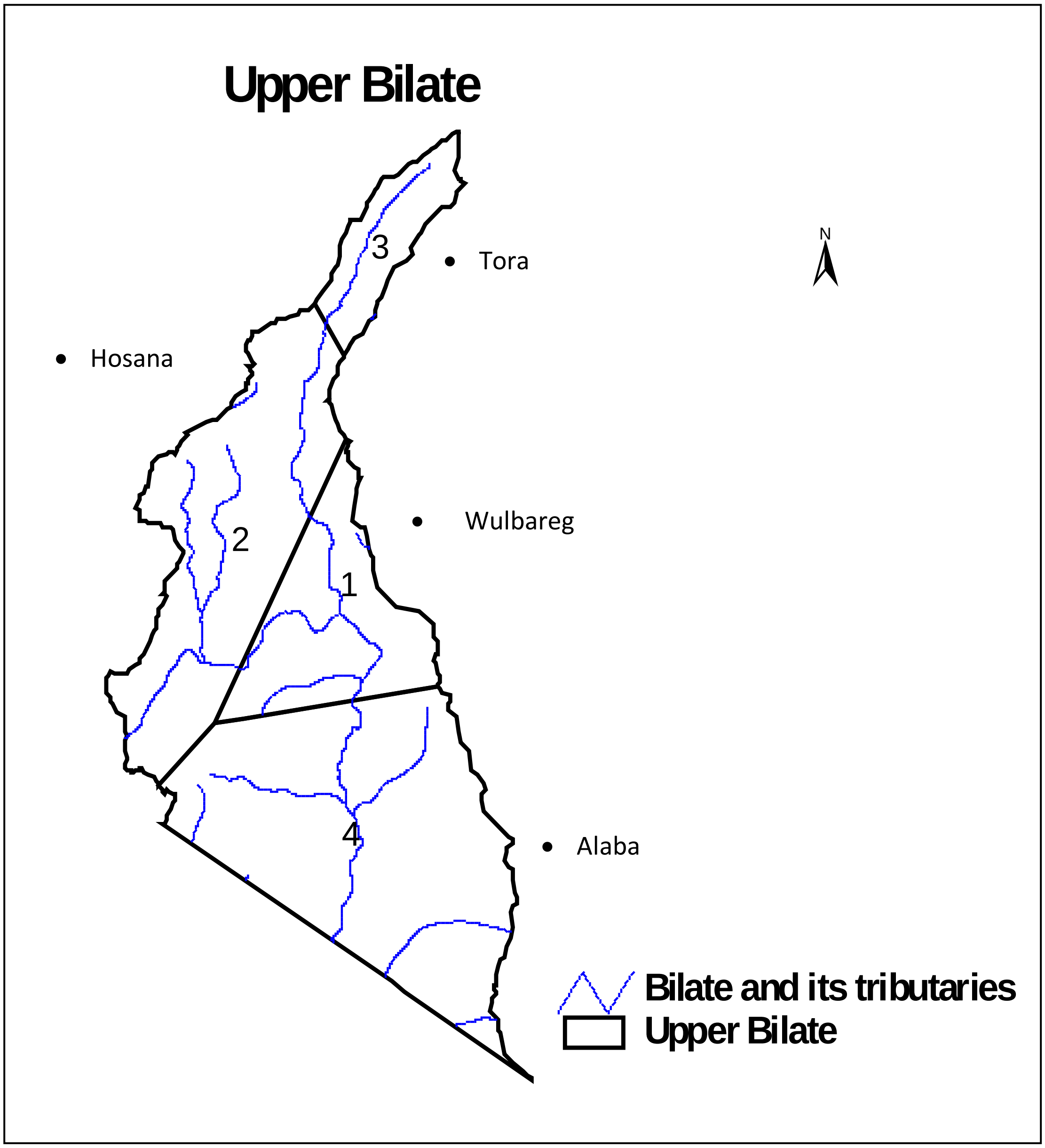

Figure 4.2 Theissen polygons for Upper Bilate catchment

4.3 Data Preparation

4.3.1 Climate and Meteorological Data

Selected nine years climate and stream flow data such as daily rainfall, daily temperature, relative humidity, sunshine hour etc for all stations and daily discharge of Bilate river at Alaba Kulito and Kulfo river at Arbaminch were collected from Ethiopian Meteorological Agency and Ministry of Water Resources accordingly. There was no missing rainfall and flow record in the two catchments at all stations for the time interval selected for the analysis.

The rainfall and corresponding stream flow data is summed up on the basis of average annual rainfall for selected meteorological stations. As a result, higher flow records than rainfall depth has been seen on Kulfo River at Arbaminch gauging station from year 2001-2006. Since there is no lateral flow in the catchment it can be concluded that there might be error in recording the flow at the gauging station of Arbaminch. Therefore the data from year 2001 to 2006 is not taken for Kulfo catchment.

4.3.2 Estimating Potential Evapotranspiration of the Watersheds

Potential evapotranspiration (PET) can be computed from meteorological data. The Penman-Monteith method is recommended as the sole standard method for the definition and computation of the reference evapotranspiration. (FAO Irrigation and drainage paper 56)

The available climatic data for the two catchments was not sufficient to determine PET of the catchments by FAO Penman-Monteith method; hence the Hargreaves method is selected to estimate potential evapotrnaspiration of catchments. Daily extraterrestrial radiation (R_a) for different latitudes for the 15th day of the month for selected stations was taken from FAO Irrigation and drainage paper 56.

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

The original Hargreaves formula calculates reference ET from solar radiation and temperature.

$$ETo = 0.0135\frac{Rs}{\lambda}(T + 17.8) \qquad (4.1)$$

Where

ET_o =Reference evaporation mm/day

λ =Latent heat of vaporization MJ/K = (2.45MJ/kg)

Rs =Solar radiation MJ/m^2d^{-1}

T = Mean air temperature, C^o

Often, solar radiation data are not available. Therefore, an alternate approach is available that requires only measurements of maximum and minimum temperature, with extraterrestrial radiation Ra. Ra is determined from the latitude and the day of the year.

The working Hargreaves equation for an interior region is given by

$$ET_O = 0.0023(T + 17.8)(T\max - T\min)^{0.5} Ra \qquad 4.2$$

Where,

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

T_{min}= Mean monthly minimum temperature, C°

Radiation (mm/Day) =0.408 Radiation [MJ/m2 day]

The average mean monthly PET of the Kulfo and Bilate catchments are presented in Table 4.3 below.

Table 4.3: Potential Evapotranspiration for Kulfo and Bilate catchments

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kulfo PET (mm/month)	133	132	164	141	130	114	109	118	120	130	123	124
Bilate PET (mm/month)	132	134	148	138	138	123	121	123	130	134	129	130

4.3.3 Estimating Areal Temperature of the catchments

Ten years maximum and minimum temperature data was collected from NMSA and the average mean temperature was taken at each stations. For stations which have no maximum and minimum temperature data the average mean temperature was predicted from the neighboring stations with help of Loclim software and Summarized values of mean monthly minimum and maximum temperature for each catchments is presented in APPENDIX-I Table 4.4 & Table 4.5.

4.4 Estimation of Initial Models Parameters

4.4.1 SMA Loss Model Parameter Estimates

To run SMA model, more than 12 parameters are needed, of which some are measurable parameters and some cannot be measured by indirect/direct means. Fleming and Neary (2004) introduced several techniques to acquire these parameters using GIS, stream flow analysis and model calibration when there is sufficient soil map and stream flow data. However, due to lack of data, in this thesis the initial values of all parameters are referred from literatures and default values are used. The initial and calibrated values of all the parameters are presented in Table 5.3.

4.4.2 SUH Transform Model Parameter Estimates

While a sub-basin element conceptually represents infiltration, surface runoff, and subsurface processes interacting together, the actual surface runoff calculations are performed by a transform method contained within the sub-basin. The transform model selected, the SCS unit hydrograph model, was originally developed from observed data collected in small, agricultural watersheds. The data were generalized as dimensionless hydrographs and a best-approximate hydrograph was developed for general application (Figure 3.7). The general hydrograph is scaled by the time lag to produce the unit hydrograph for use. It is interesting to note that 37.5% of the runoff volume occurs before the peak flow and the time base of the hydrograph is five time the lag. The standard lag (t_{lag}) is defined as the length of time between the centroid of precipitation mass and the peak flow of the resulting hydrograph. Studies by the SCS found that in general the lag time can be approximated by taking 60% of the time of concentration (t_c).

The value obtained from this calculation is used as initial value and then the model is calibrated.

$$t_{lag} = 0.6t_c \tag{4-3}$$

Here t_c is determined using Kirpich formula

$$t_c = 3.97L^{0.77}S^{-0.385} \tag{4-4}$$

Where L = the longest flow path from the divide to the outlet (km)

S = the average river slope (m/m)

4.4.3 RRL TANK & SMAR Models Parameters Estimate

There are eighteen parameters in TANK model and nine in SMAR model of which all are determined via calibration. The default initial and the calibrated values of the models are presented in Tables 5.4 and 5.5 respectively.

4.5 Model Evaluation Criteria

Model performance is the most important aspect to evaluate the model approaches. Selected criteria used to evaluate the goodness-of-fit of each model approach are shown in Table 4.6.

Table 4.4 Model Evaluation criteria

ID	Criteria	Equation
1	Nash_Sutcliffe efficiency, NSE (Coefficient of efficiency	$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$
2	Index of agreement, d	$d = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(\lvert O_i - S_i\rvert + \lvert O_i - \bar{O}\rvert)^2}$
3	Coefficient of determination, R^2 (The square of the Pearson's product-moment correlation coefficient)	$R^2 = \left\{\frac{\sum_{i=1}^{n}(O_i - \bar{O})(S_i - \bar{S})}{\left[\sum_{i=1}^{n}(O_i - \bar{O})^2\right]^{0.5}\left[\sum_{i=1}^{n}(S_i - \bar{S})^2\right]^{0.5}}\right\}^2$
4	The index of volumetric fit, IVF	$IVF = \frac{\sum_{i}^{n}(Q_S)_i}{\sum_{i}^{n}(Q_O)_i}$
5	The relative error of the peak	$RE = \left(\sum_{i=1}^{n}\frac{\lvert (Q_P)_{Si} - (Q_P)_{Oi}\rvert}{(Q_P)_{Oi}}\right)/n$

Where: O_i: Observed, S_i: Simulated, $\bar{O}$: average of the observed value, $\bar{S}$: average of the Simulated value, Q_p: peak flows, Qs: simulated discharge, Qo: discharge observed

5 RESULT AND DISCUSSION

5.1 Rainfall Analysis

As discussed in Chapter 4, the data from the national meteorological service is used as the base data. The rainfall and discharge data from the ministry of water resources is plotted in order to analyze which events can be selected for the two catchments. In other words, the relation between rainfall and discharge measurement is first analyzed visually. Several "*abnormal*" events are easily found from Figure 5.1, for example the storms on 19 February 1998 or 10 May 1998 of Kulfo catchment. For these events, there is no clear relation between the areal rainfall recorded at the catchment and discharge recorded at the catchment outlet (very small rainfall produces high discharge, or vice versa).

5.2 Calibration and Validation Analysis Methodology

The nine and five years of available daily data are divided into two parts used as calibration and verification periods for the two catchments as shown in Table 5.1 for the three models: HEC-HMS SMA, RRL TANK & RRL SMAR applied to both catchments.

Manual and automatic calibration was made for two models for each catchment. Initial parameter values and ranges in which the parameters are optimized have been summarized in the tables below. The parameter set that gave the best objective function value over the calibration period was used for validation and taken as suitable model parameter.

Table 5.1 calibration and verification periods

No	Catchments	Full years	No. of data points	Starting date	Calibration period	Verification period
1	Kulfo	5	1827	1/1/96	1996-1998	1999-2000
2	Bilate	9	3287	1/1/95	1995-2000	2001-2003

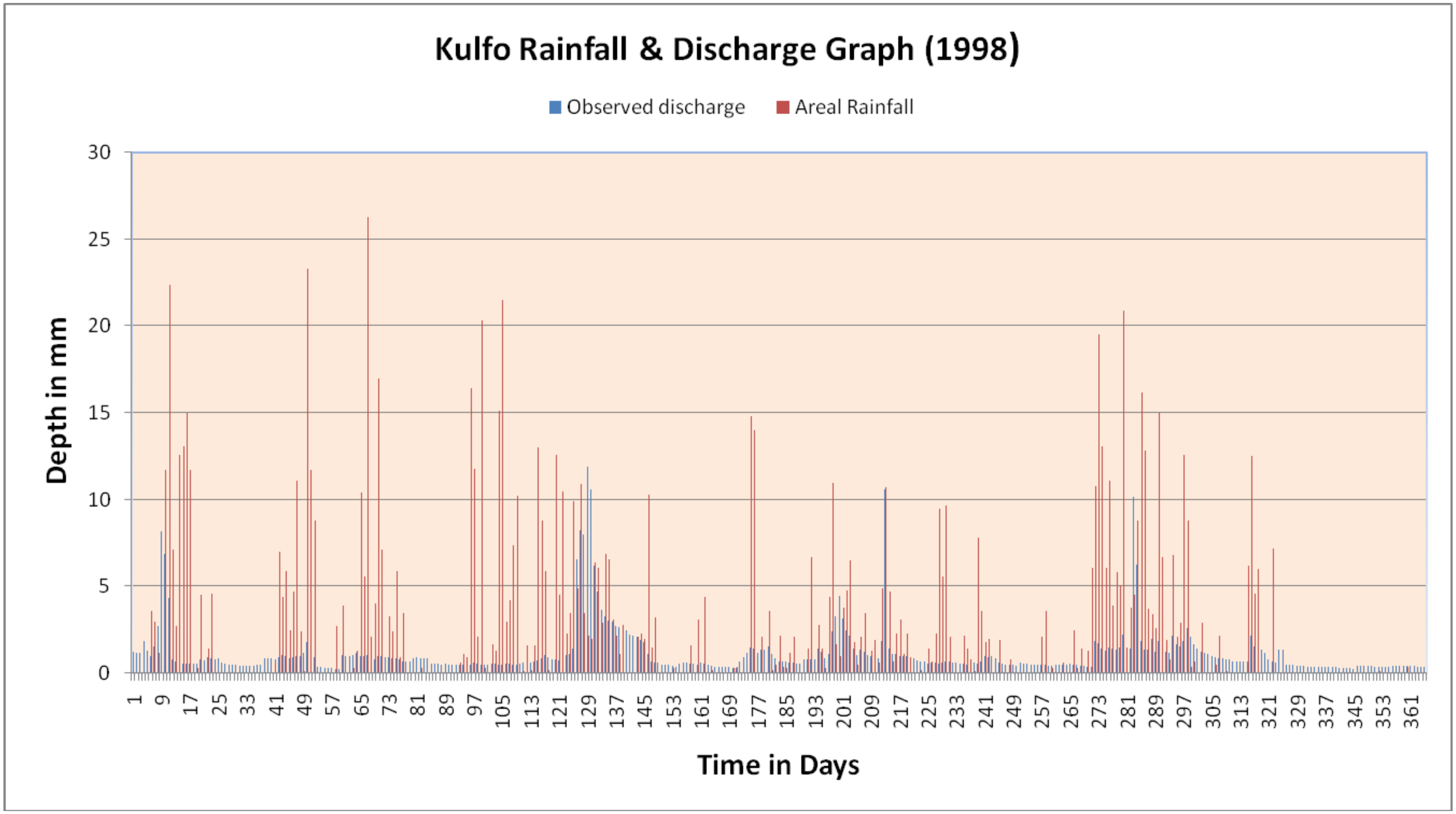

Figure 5.1 Rainfall and discharge graph of Kulfo catchment of year 1998

5.3 Result and Discussion of HEC-HMS SMA

5.3.1 Model parameters and initial output

Table 5.2 Initial parameters values of SMA model for Kulfo and Bilate catchments

	Parameters	Kulfo	Bilate
canopy	%	0	0
surface	%	0	0
soil	%	70	70
Groundwater 1	%	85	85
Groundwater 2	%	90	90
Canopy interception storage	Storage capacity (mm)*	5.07	1.5
Storage Surface depression	storages capacity (mm)*	3	3.5
	Soil infiltration max. rate (mm/hr)*	78	11
Soil profile storage	Storage capacity (mm)*	180	500
	Tension zone capacity (mm)	60	380
	Percolation max. rate (mm/hr)*	0.11	2
Groundwater layer-1 storage	Storage capacity (mm)	19	18
	Percolation max. rate (mm/hr)*	3	2
	Storage coefficient (hr)	30	50
Groundwater layer-2 storage	Storage capacity (mm)	50	48
	Percolation max. rate (mm/hr)*	0.115	0.5
	Storage coefficient (hr);	600	2000

(*) Relatively more sensitive parameters

After being parameterized, the loss model SMA is incorporated with a method for runoff transform (SCS) and base flow model (linear reservoir) in order to run the HEC-HMS. The parameters of SCS module and base flow model are:

- SCS lag : 5000 minutes for Kulfo and 6000 minutes for Bilate catchments;
- Base flow: the storage coefficient is 30 hours and 600 hour for the groundwater storage 1 and groundwater storage 2 respectively for Kulfo catchment and 100 hours and 2000 hour for the groundwater storage 1 and groundwater storage 2 respectively for Bilate catchment.

The first results are shown in Figure 5.4 & 5.5 obviously, the model is not able to simulate the entire hydrograph compared with the observed ones. Especially, almost the simulated peak flows overestimate the observed ones and model calibration and sensitivity analysis is required for both catchments.

5.3.2 Sensitivity Analysis and Model Calibration

5.3.2.1 Sensitivity Analysis

Because one of the objectives of this study is to test the performance of HEC-HMS with respect to the continuous SMA loss model, other parameters relating to runoff transform, base flow estimation were fixed after the initial result. From the analysis for these specific study areas, it has been seen that the soil maximum infiltration rate, the maximum soil depth and the tension zone depth are the most sensitive parameters for both catchments. However, beside the three parameters, surface parameter like surface capacity, canopy capacity, soil percolation rate and ground water 1 & 2 storage coefficients also were taken into account.

The above parameters are analyzed within +30% to -30%. Each of the parameter was changed individually. Figure 5.2 & figure 5.3 shows the effect of these parameters based on the changes of the total depth of water in the Kulfo and Bilte catchments respectively. As it can be seen in the Figure 5.2 that the most sensitive parameter for Kulfo catchment is Ground water layer 2 percolation rate, and then tension zone storage, ground water layer 1 storage, soil percolation rate etc. *the* least sensitive parameter was soil storage capacity.

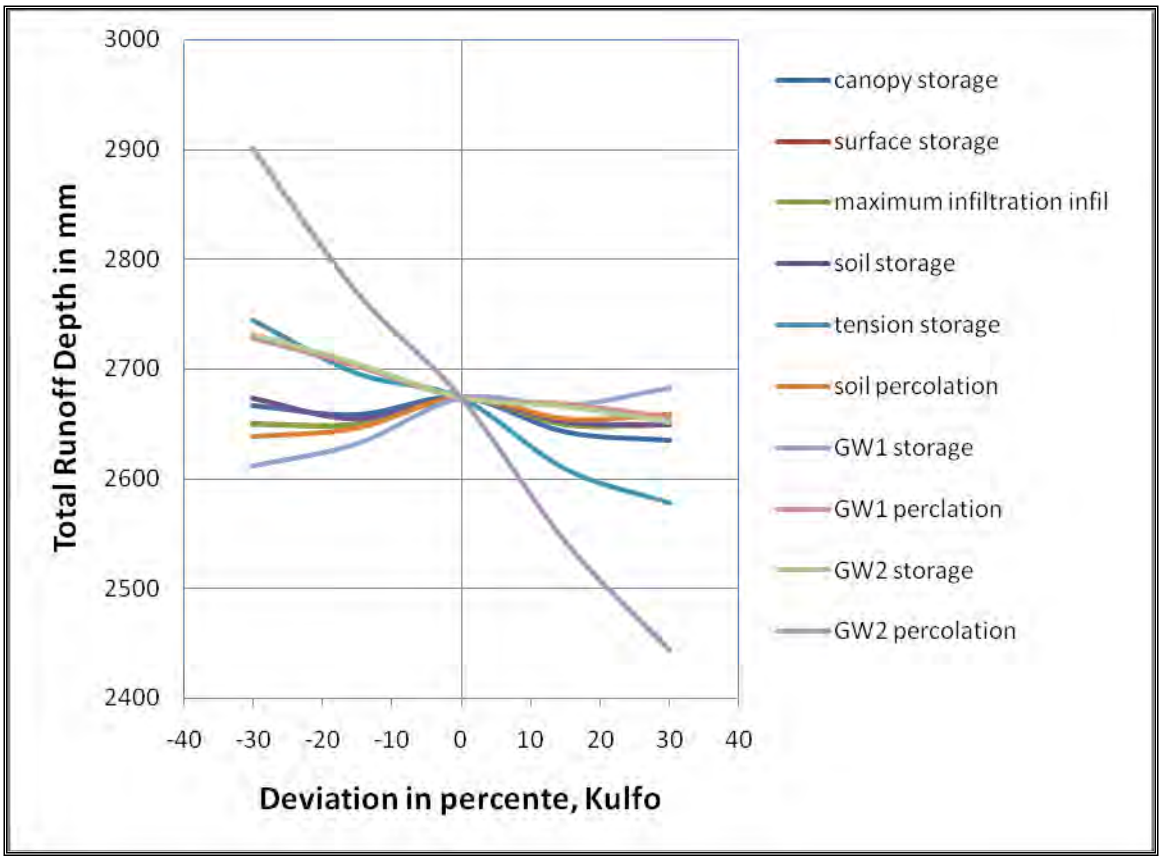

Figure 5.2 Total runoff depth results generated from sensitivity scenarios of the changes of parameters in HEC-HMS SMA for Kulfo catchment

In the same manner, Figure 5.3 can also be referred that the most sensitive parameter for Bilate catchment is soil storage capacity and then tension storage, ground water layer 1 storage, soil percolation rate, ground water layer 2 etc. the least sensitive parameter is surface storage.

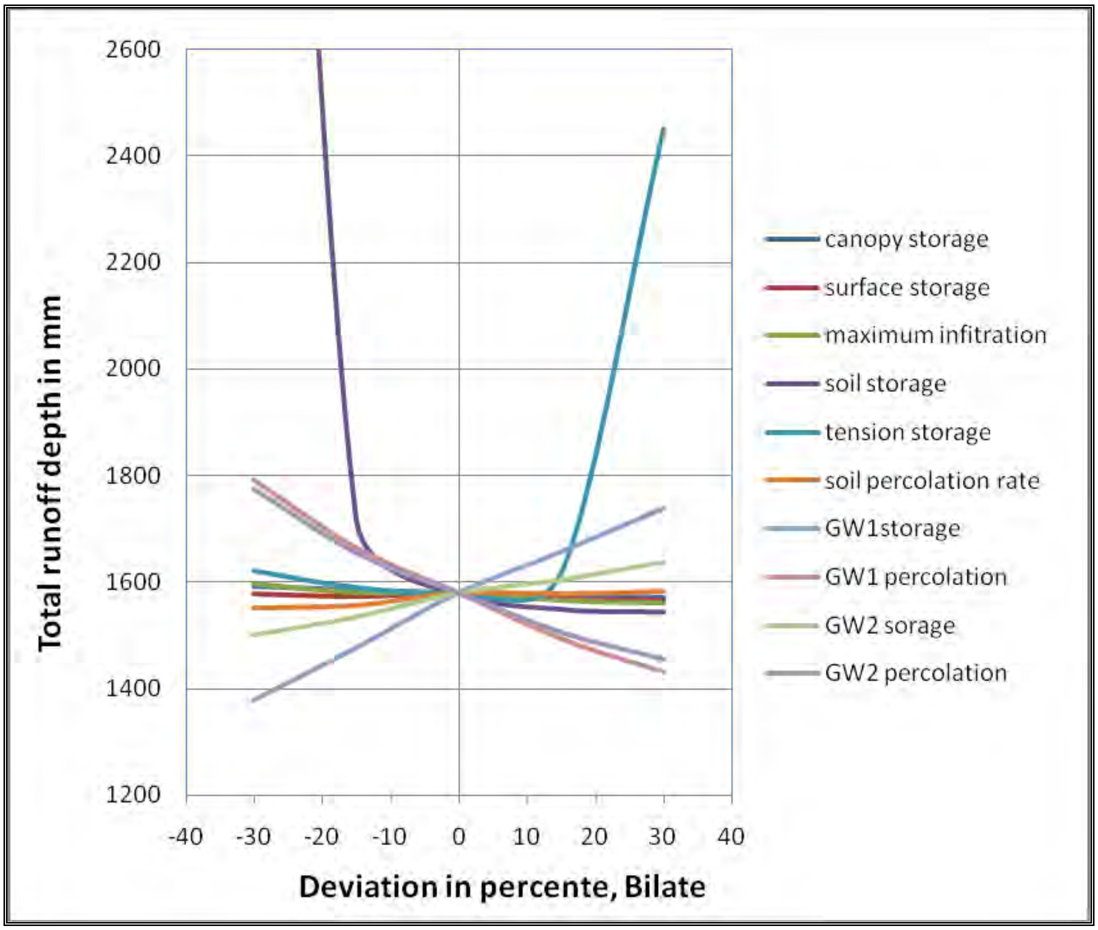

Figure 5.3 Total runoff depth results generated from sensitivity scenarios of the changes of parameters in HEC-HMS SMA for Bilate catchment

Table 5.3: Initial and calibrated parameters for the SMA loss model in the two catchments.

Storages	Parameters	Kulfo		Bilate	
		Initial	Calibrated	Initial	Calibrated
Canopy interception storage	Storage capacity (mm)*	1.5	2.0472	1.5	2.6637
Storage Surface depression	Storages capacity (mm)*	3	4.6146	3.5	9
	Soil infiltration max. rate (mm/hr)*	50	115.2	11	5.0232
Soil profile storage	Storage capacity (mm)*	120	150.73	500	501.49
	Tension zone capacity (mm)	60	90	380	372.4
	Percolation max. rate (mm/hr)*	0.11	0.73727	2	0.39173
Groundwater layer-1 storage	Storage capacity (mm)	19	20.135	18	13.531
	Percolation max. rate (mm/hr)*	3	9.9586	2	1.0047
	Storage coefficient (hr)	30	29.978	100	100.48
Groundwater layer-2 storage	Storage capacity (mm)	50	50.091	100	66.667
	Percolation max. rate (mm/hr)*	0.115	0.0897417	0.5	0.45
	Storage coefficient (hr);	600	600.07	2000	2009.6

5.3.2.2 Model calibration

Manual and automatic calibrations were used in this model. Manual calibration is used to limit the range of parameters where the output is acceptable. The automatic calibration is used to search for optimized parameters. Calibration for each parameter was according to their sensitivity. The least sensitive parameters were calibrated first and then the more sensitive parameters were calibrated subsequently. These 10 parameters were adjusted; Table 5.3 shows the initial parameters and adjusted ones, also followed up by Figures 5.2 & 5.3 with the observed and initial/calibrated simulation flows. It is also noted that the specific stream flow in the catchment is the very sudden/sharp response (high peak flow). Thus, the aim during calibration period is to try to simulate the peak flow so that this model can serve as flood forecasting model in this area.

5.3.3 Conclusions on HEC- HMS SMA

As per the initial simulation results model calibration is needed to improve the performance of the model in both catchments. After calibration the following conclusions have been drawn.

- The high peak flow was well simulated. Model calibration with the aim to simulate the peak proves to be efficient in both catchments. Before calibration, the model mostly overestimates observed peak flows for Kulfo catchment, but after increase the storage capacity of soil zone and surface capacity and infiltration rate the results improved. However, the time of peaks of the observed and simulated flow is not the same and there are still some mismatches between the observed and predicted flow but it can be explained by the improperly observed rainfall varied in time and space or poor quality of the hydro-meteorological data collected.

- For Bilate catchment the model underestimates the observed peak flow before calibration, but like for Kulfo catchment, after increase of the storage capacity of soil zone, surface capacity and groundwater storages the result improved. The low flows were well predicted in case of Bilate than Kulfo catchment.
- Except some few points the base flow and the pattern of the observed flow is well captured in the model for the two catchments.

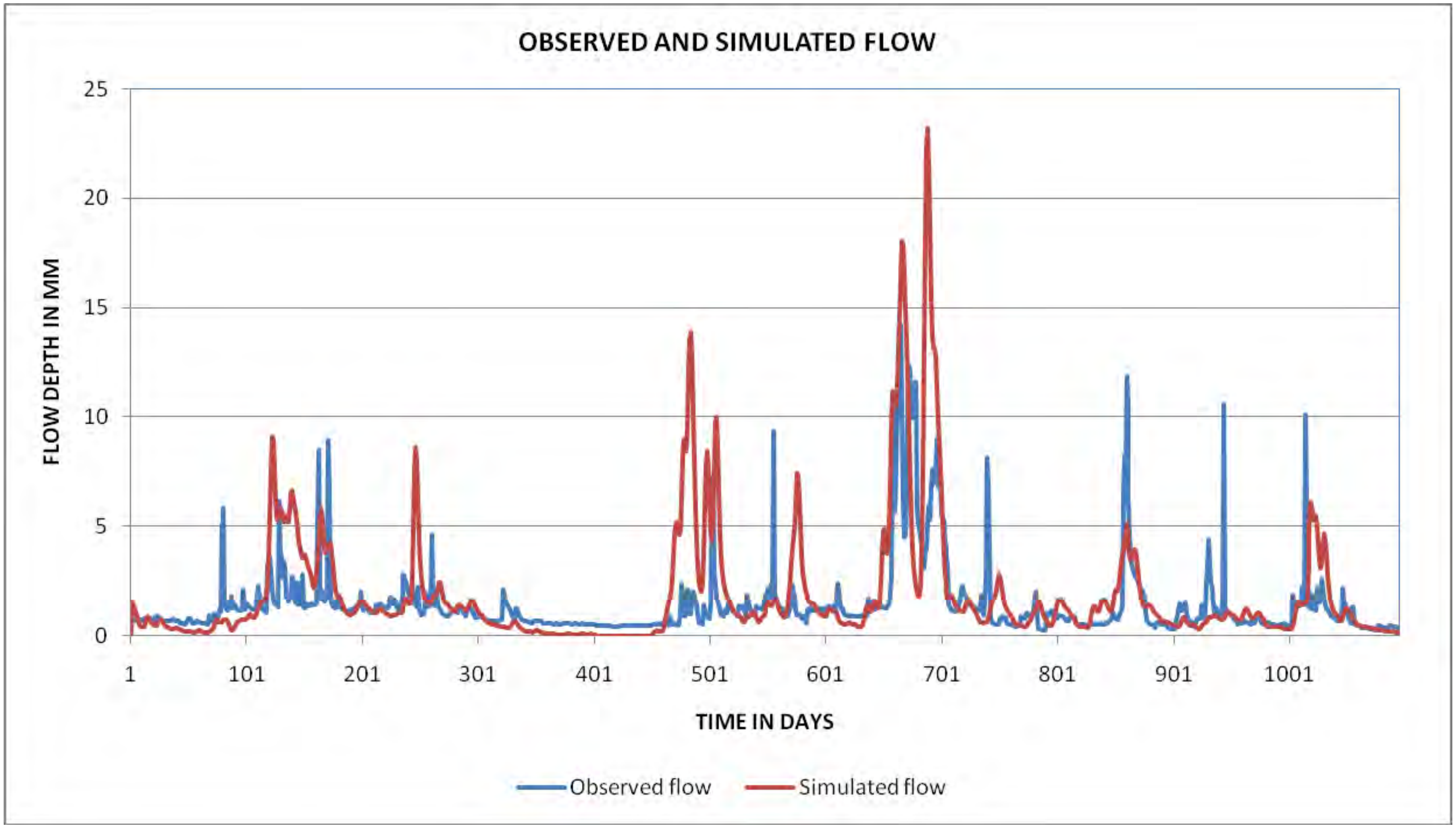

Figure 5.4(a) Initial output of HEC-HMS SMA before calibration for Kulfo catchment

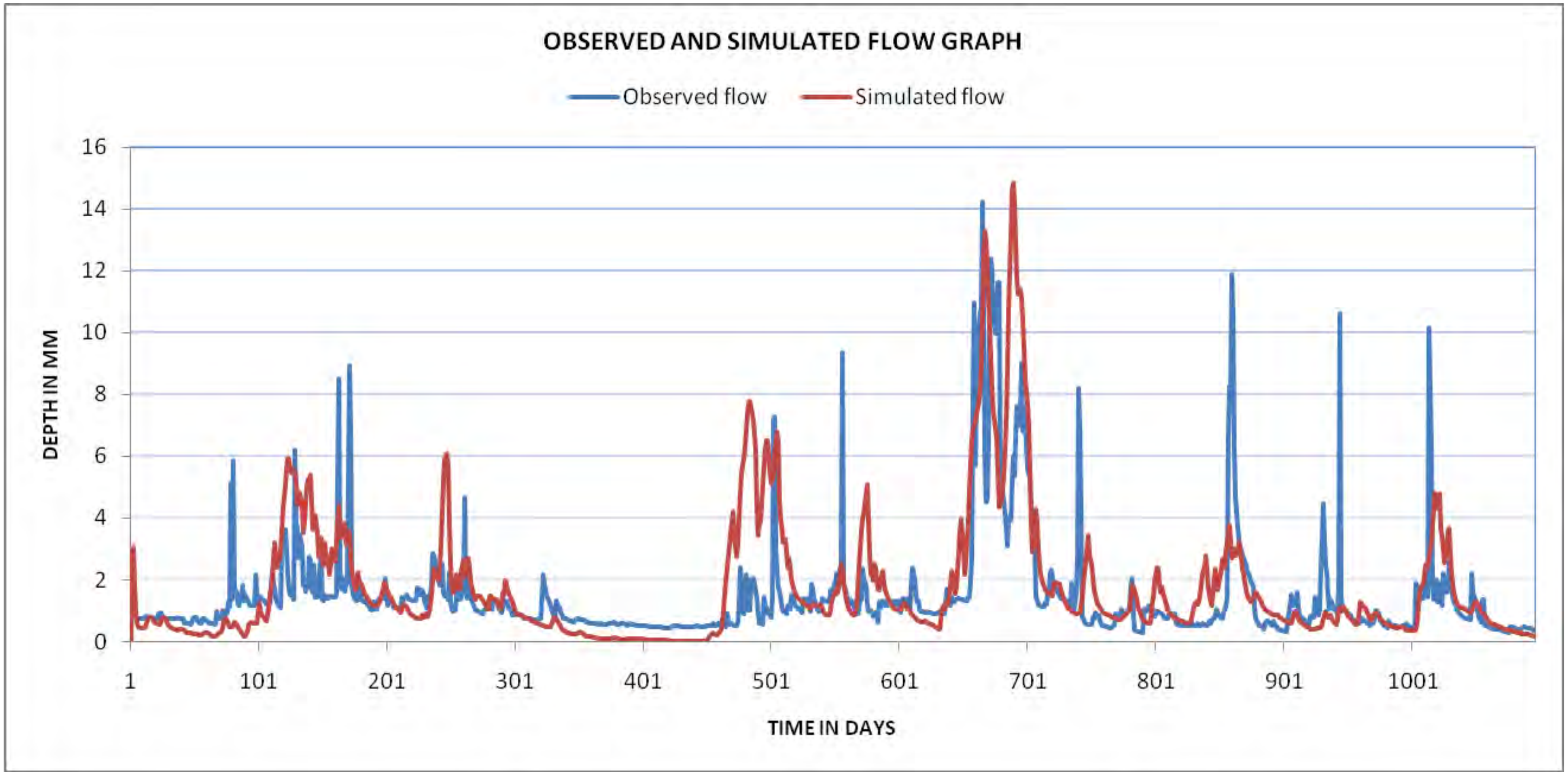

Figure 5.4(b) The output of HEC-HMS SMA for Kulfo catchment after calibration

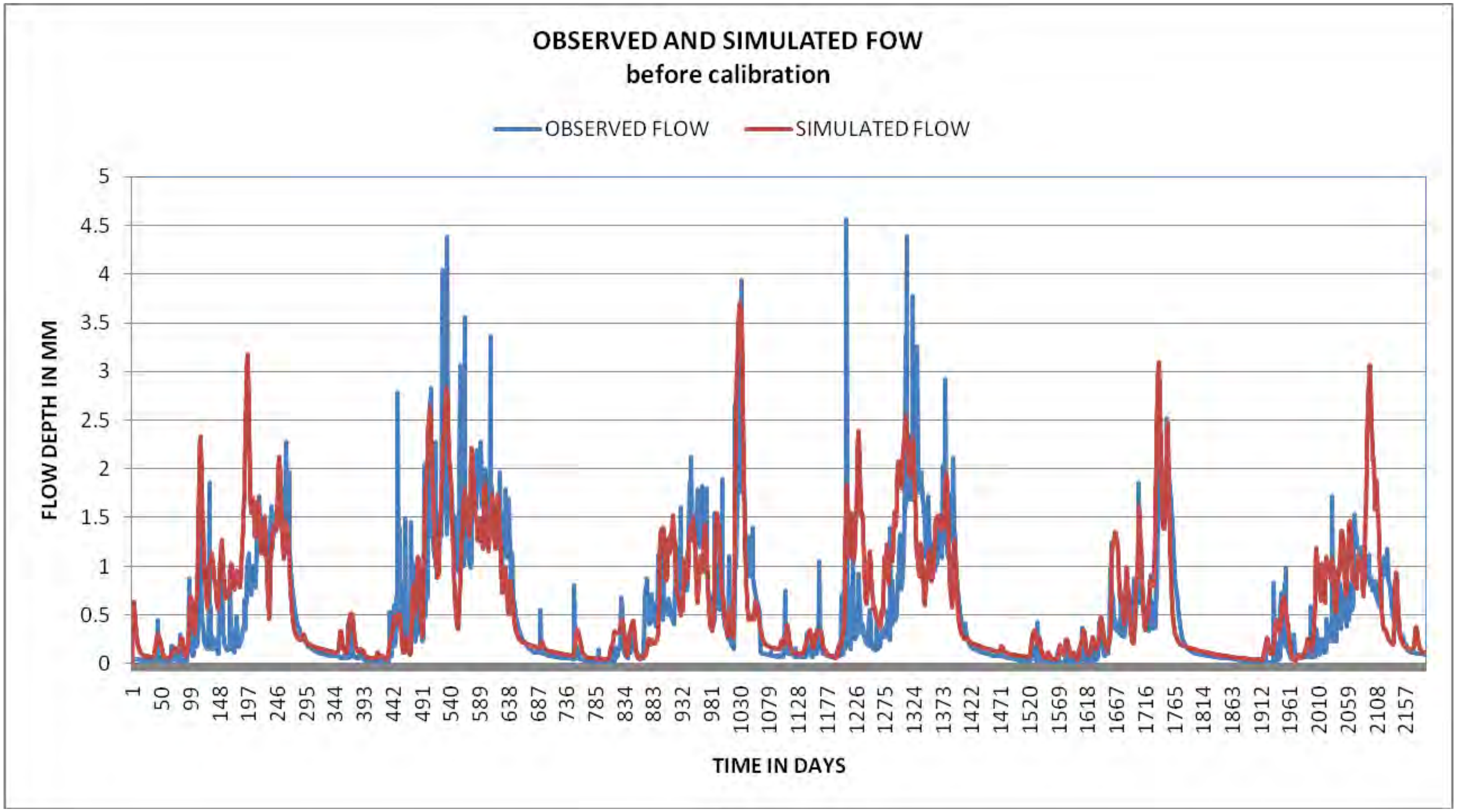

Figure 5.5(a) Initial output of HEC-HMS SMA before calibration for Bilate catchment

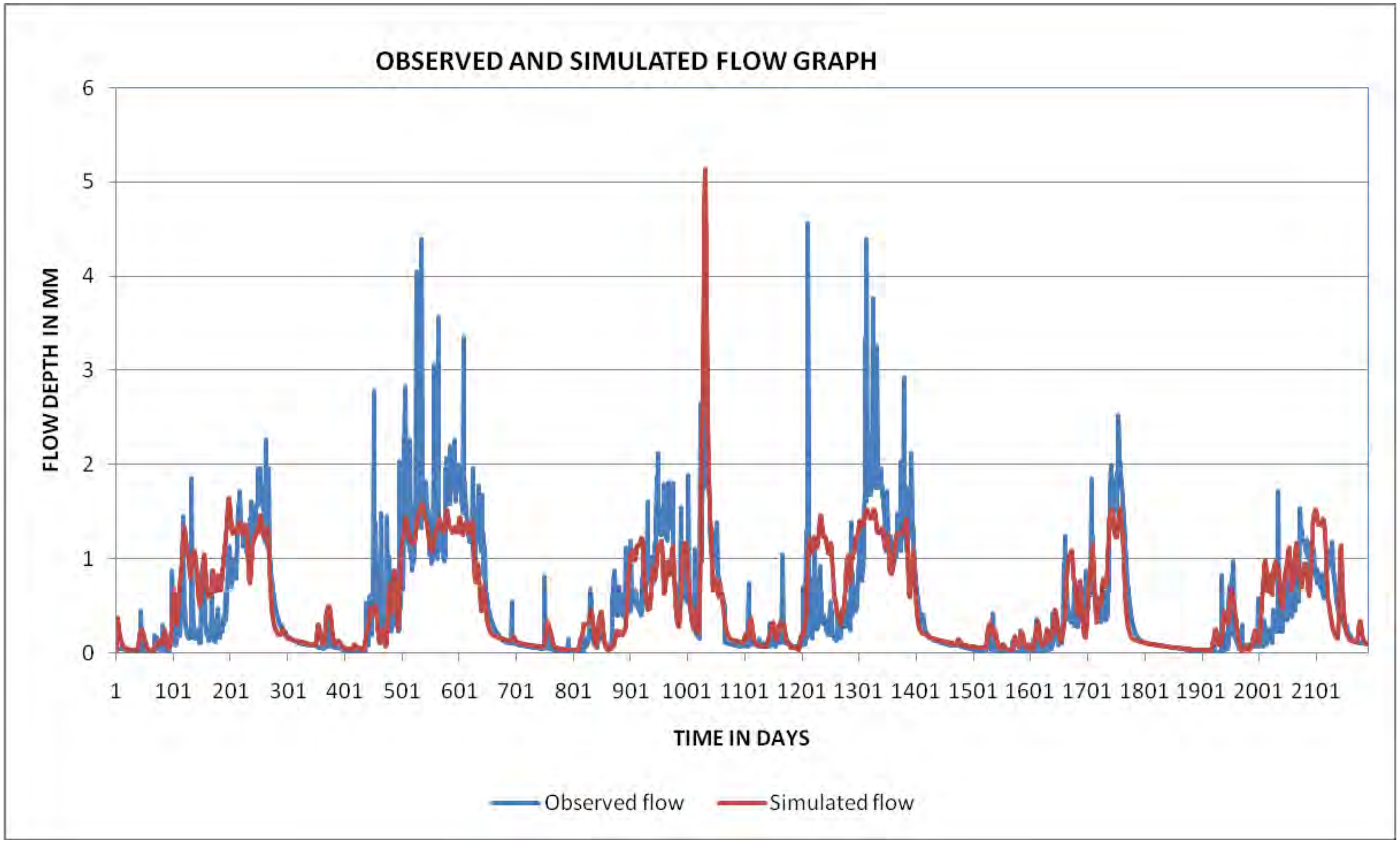

Figure 5.5(b) The output of HEC-HMS SMA for Bilate catchment after calibration

5.4 Results and Discussion of RRL TANK Model

5.4.1 Model parameters and initial output

For this model the same calibration and verification periods were taken as the previous model. The first three years for calibration and the remaining two years for verification for Kulfo catchment and the first six years for calibration and the remaining three years for verification in case of Bilate catchment.

The initial output of the model is processed using the default values for all the parameters. As Figures 5.6a and 5.7a IN APPENDIX-III can be referred, the model highly overestimated the observed flow for both catchments. Thus, sensitivity analysis and calibration is required.

5.4.2 Sensitivity analysis and Calibration

The RRL TANK model is very user-friendly model especially for the sensitivity analysis of parameters. Once the initial default values of the parameters have been set, the model was run for run off generation. Then, very sensitive, half sensitive and non-sensitive parameters were distinguished from the graphical presentation (APPENDIX-IV).

During analysis the very sensitive parameters for Kulfo catchment are the runoff coefficients for the 3rd and 4th tank outlet (a31 & a41), the infiltration coefficients of tank 1, 2 and 3 (b1,b2,b3) and the outlet height of tank 3 (H31). As it is mentioned on Table 5.4 the parameter values with double asterisks are the very sensitive parameters and with one asterisk are the parameters for which the objective function is sensitive up to the optimized value and beyond that values the objective function remains constant.

For Bilate catchment the very sensitive parameters are a12, a21, b1, b2, b3 and H21 and semi-sensitive parameters are alpha, H11, and H31.

Having all sensitive and non-sensitive parameters been selected, manual calibration with the objective function Nash-Sutcliffe criterion was taken and all the calibrated values for the two catchments are summarized on Table 5.4.

Table 5.4: TANK model Test results of the calibration period of Kulfo and Bilate catchments

Parameters	Kulfo		Bilate	
	Initial	Calibrated	Initial	Calibrated
a11	0.2	0.133	0.2	0.63
a12	0.2	0.345	0.2	0**
a21	0.2	0.9686	0.2	0.4049**
a31	0.2	0.12**	0.2	0.082
a41	0.2	0.02**	0.2	0.85
alpha	0.1	1.471*	0.1	1*
b1	0.2	0.143**	0.2	0.051**
b2	0.2	0.949**	0.2	0.452**
b3	0.2	0.115**	0.2	0.02**
C1	20	20	20	20
C2	20	20	20	20
C3	20	20	20	20
C4	20	20	20	20
H11	0	110*	0	160*
H12	0	102*	0	100
H21	0	57*	0	2.5**
H31	0	10**	0	51.98*
H41	0	71.37	0	95

(**) very sensitive parameters, (*) semi-sensitive parameters, the rest non-sensitive

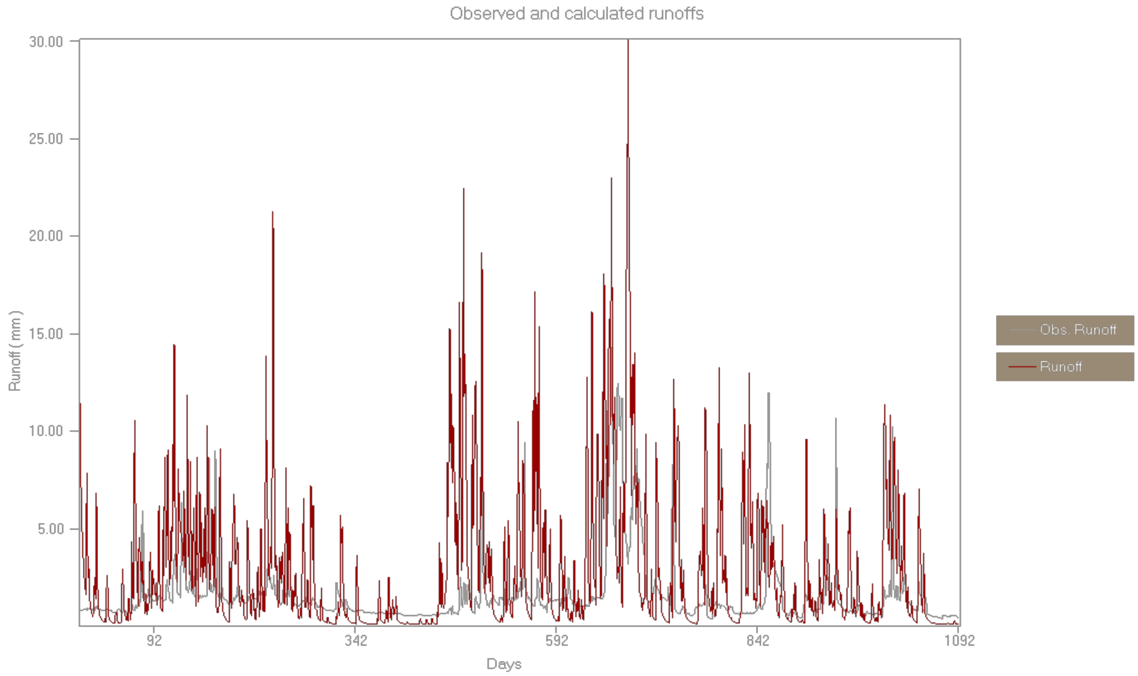

Figure 5.6(a) The initial output of RRL TANK for Kulfo catchment before calibration (observed & simulated runoff) (1996-1998)

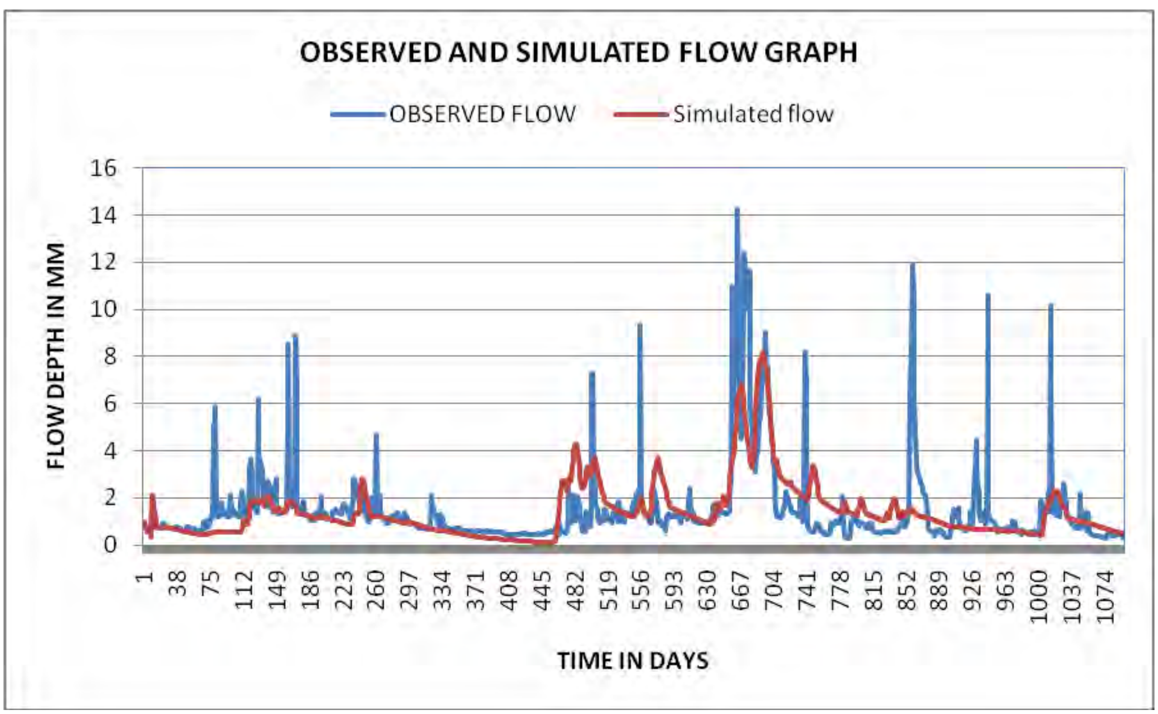

Figure 5.6(b) The output of RRL TANK for Kulfo catchment after calibration (observed & simulated runoff) (1996-1998)

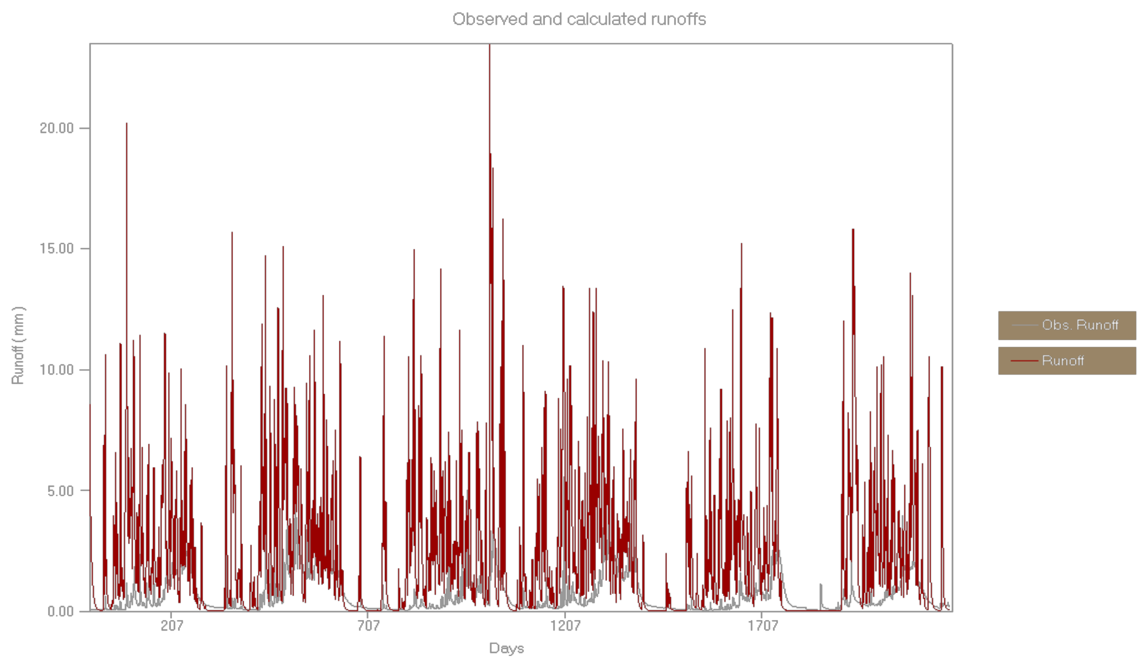

Figure 5.7(a) The initial output of RRL TANK for BILATE catchment before calibration (observed & simulated runoff) (1995-2000)

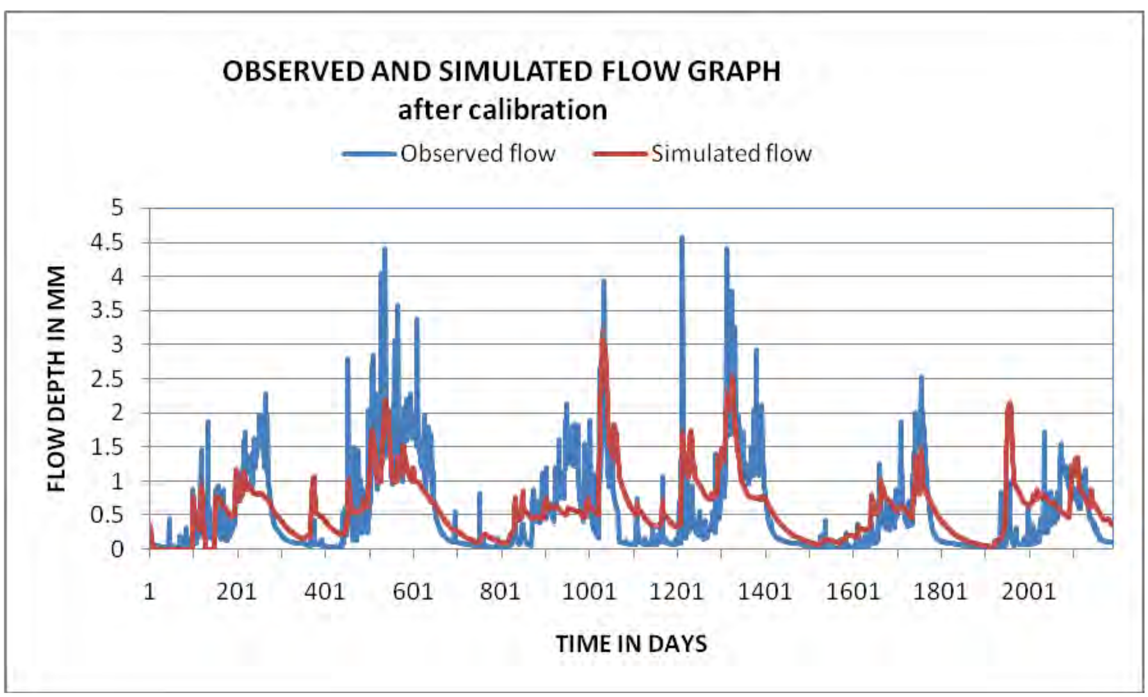

Figure 5.7(b) The output of RRL TANK for BILATE catchment after calibration (observed & simulated runoff) (1995-2000)

5.4.3 Conclusion on RRL TANK Model

It is clear that the TANK model was sensitive with the forcing data (rainfall) as can be seen by a number of peak flows. By calibrating the model, the result improved significantly.

There are a few reasons that may explain the results as following:

- For the Kulfo catchment, before calibration, the model overestimated the peak flow and underestimated the base flow. But by increasing the infiltration coefficient of the second tank (b2) and decreasing the runoff coefficient of the third tank (a31), the objective function is maximized.
- Moreover, the base flow was better predicted. The pattern of the observed flow was well captured in the model. However, the peak flow is under-predicted. The reasons may be explained as the model is predicting low flows well and underestimating high flows. However, for the objective of this study is estimation of the flood, the peak flow can be captured by increasing the infiltration coefficient of the second tank, meaning by enhancing the intermediate runoff even though the objective function is getting lower.
- As per the sensitivity analysis, the Kulfo catchment is not sensitive to the change of runoff coefficient and initial storages in all tanks; that means the contribution of surface flow for the stream flow is very less.
- For Bilate catchment initially the base flow was well predicted, but the peak flow was overestimated. After decreasing the runoff coefficient for the first tank and increasing for the second tank the result is improved. In addition, by increasing the infiltration

coefficient for the second tank and decreasing for the first and third tanks, the result is smoothed and the objective function is maximized as well.

- Unlike for Kulfo catchment, the Bilate catchment is sensitive for the runoff coefficient of the first tank. When the runoff coefficient of the first tank increases the contribution of surface runoff for the stream flow increases.
- Like Kulfo catchment, the initial storage capacity of all tanks in the Bilate catchment is not sensitive at all.

5.5 Results and Discussion of RRL SMAR Model

5.5.1 Model parameters and initial output

For this model also the same calibration and verification periods were taken as the previous models. The initial output of the model is processed using the default values for all the parameters. As Figure 5.8a and 5.9a can be referred, like the previous model, the SMAR model highly overestimated the observed flow for both catchments. Thus, sensitivity analysis and calibration is required.

5.5.2 Sensitivity analysis and Calibration

The effect of parameters on the objective functions and on the ratio of the observed and the estimated mean discharge is shown in Appendix-IV for Kulfo and Bilate catchments respectively.

For Kulfo catchment the ground water evaporation rate C is non sensitive. That means the actual evaporation rate be taken place from the top layer at the potential rate and no evaporation occurs from the second and lower layers. Other water balance parameters G & H are very sensitive parameters in the model. The objective function increases when G & H increases up to their optimum values and beyond those values it decreases. The parameters T, Y & Z are less sensitive parameters relatively. The objective function increases up to their optimum value and beyond those values it keeps constant. All the routing parameters except the storage lose coefficient are non sensitive.

For Bilate catchment except the routing parameter U.H linear routing component N,K all the parameters seem sensitive. However, parameters C, G, H & T are more sensitive than the others. With very small changes of these parameters the objective function changes very significantly.

After the sensitivity analysis has been completed the model was calibrated manually and automatically until the objective function is maximized. The test results are summarized in Table 5.5 below for the two catchments.

Table 5.5: SMAR model Test results of the calibration period of Kulfo and Bilate catchments

No.	Parameters	Initial values	Kulfo	Bilate
			Optimized	Optimized value
1	C	0	0	0.84
2	G	0	1.55	1
3	H	0	0.35	0.05
4	kg	0	0.045	0.02
5	N	1	1	1
6	NK	1	0.51	5.9
7	T	0	1.478	0.421
8	Y	0	50	30
9	Z	200	10	70

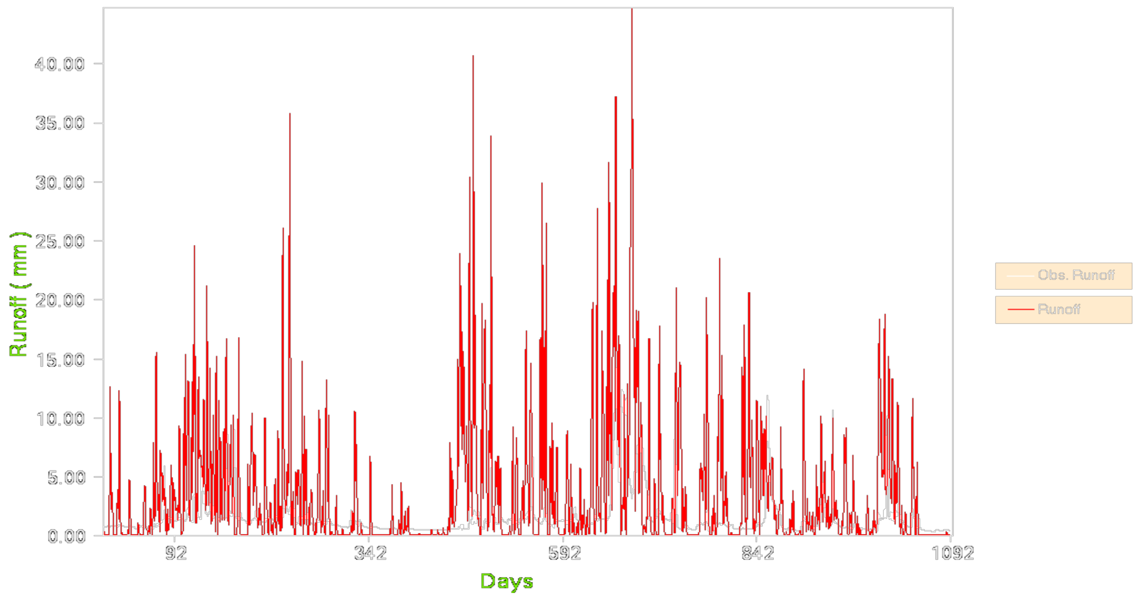

Figure 5.8(a) The initial output of RRL SMAR for Kulfo catchment before calibration (observed & simulated runoff) (1996-1998)

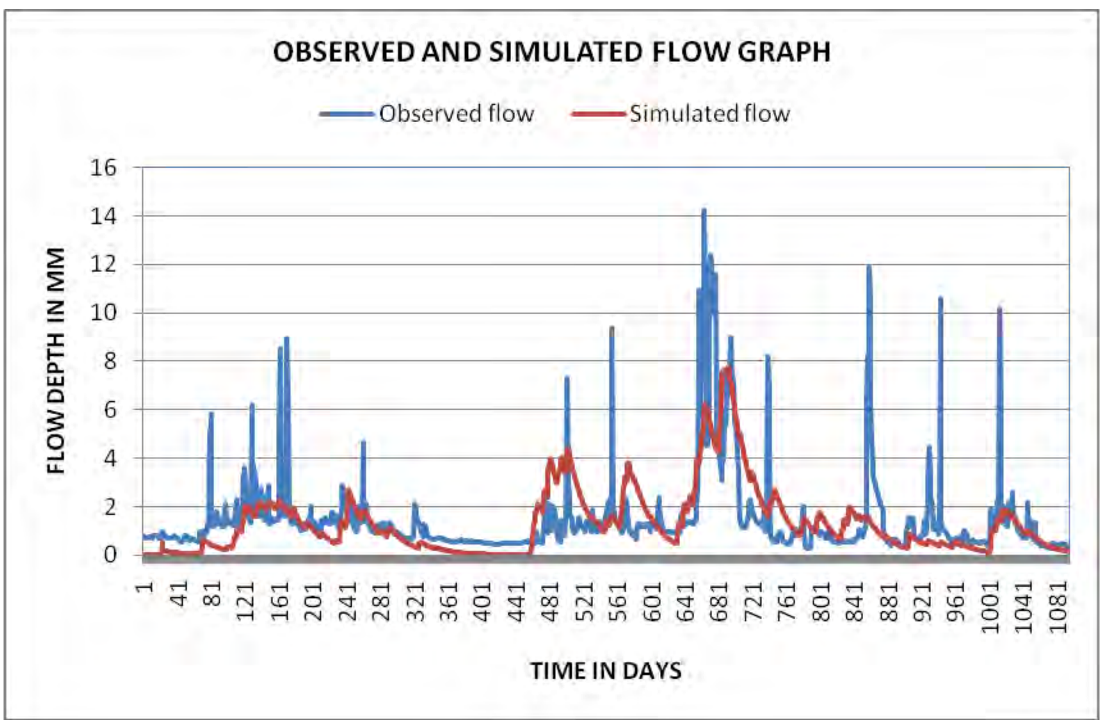

Figure 5.8(b) The output of RRL SMAR for Kulfo catchment after calibration (observed & simulated runoff) (1996-1998)

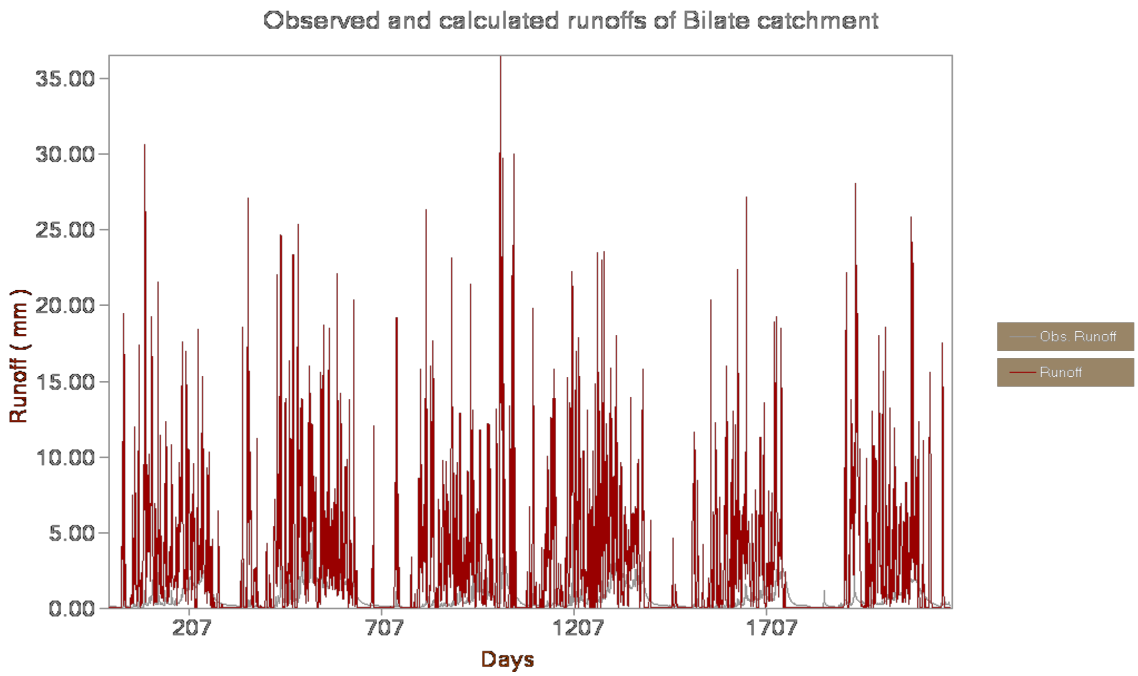

Figure 5.9(a) The initial output of RRL SMAR for BILATE catchment before calibration (observed & simulated runoff) (1995-2000)

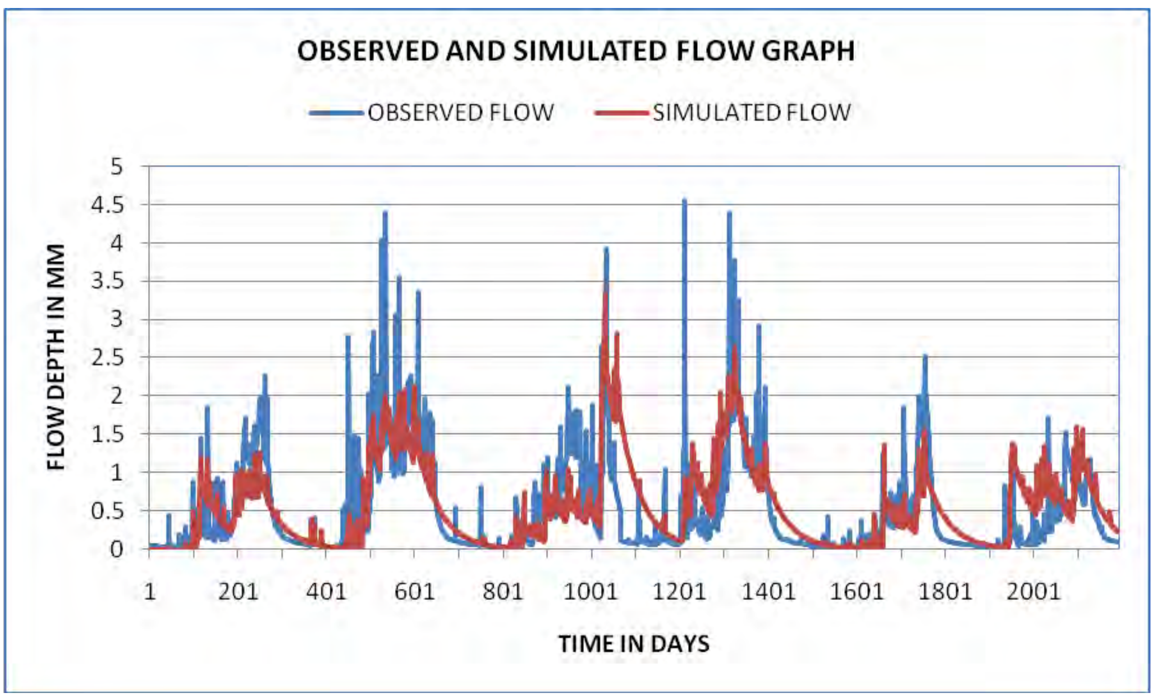

Figure 5.9(b) The output of RRL SMAR for BILATE catchment after calibration (observed & simulated runoff) (1995-2000)

5.5.3 Conclusion on RRL SMAR Model

Like TANK model the SMAR model also overestimated the observed flow in both catchments before calibration. But after calibration the simulated flow pattern could take the flow pattern of the observed flow. However, the peak flows could not be captured at all in both catchments.

5.6 General model results and discussion

5.6.1 Model performance and Comparison

With the respect of performance criteria mentioned in section 4.5 the models were evaluated and presented in Table 5.6 below.

The HEC-HMS SMA model performed well in Kulfo and Bilate catchments, especially the peak was not difficult to capture after calibration with the aim of matching the high peak flows. However, the time to peak is not on the day of time to peak of observed flow. The main explanation could be the location of the outlet which was not at the end of the highest order stream or there might be unrecorded) peak flow (flow escaped unmeasured. Nevertheless, with respect to the performance criteria, the result of the HEC-HMS SMA is promising. The Nash-Sutcliffe efficiency was calculated and is 0.58 for Bilate and 0.28 for Kulfo, and the R^2 is 0.77 and d is 0.83 for the Bilate, and R^2 was 0.64 and d was 0.76 for the Kulfo catchments, respectively (Figure 5.4, 5.5).

Like HEC-HMS SMA model the TANK & SMAR models are also performing better in Bilate catchment than Kulfo. Moreover, the high flow is underestimated highly for both catchments. However, except The

Nash-Sutcliffe efficiency, others performance criteria are showing promising result. NSE, R2, d, IVF and RE are summarized in Table 5.6 below for all the models in calibration and verification for both catchments

Table 5.6: Models performance evaluation result

Calibration										
Models	KULFO (A = 364 KM^2)					BILATE (A = 1980 KM^2)				
	NSE	**d**	**R^2**	**IVF**	**RE**	**NSE**	**d**	**R^2**	**IVF**	**RE**
HEC-HMS SMA	0.31	0.76	0.64	0.91	0.468	0.59	0.83	0.77	0.999	0.292
RRL TANK	0.374	0.79	0.62	0.94	0.522	0.458	0.798	0.697	1.19	0.392
RRL SMAR	0.38	0.79	0.64	0.90	0.514	0.49	0.8	0.72	1.07	0.329
Verification										
HEC-HMS SMA	0.44	0.79	0.725	0.63	0.399	0.53	0.82	0.77	1.04	0.371
RRL TANK	0.29	0.78	0.685	0.627	0.632	0.34	0.791	0.63	0.78	0.634
RRL SMAR	0.29	0.78	0.67	0.59	0.654	0.34	0.78	0.71	0.5	0.607

Model comparison is one of the main objectives of this study. The three models are different with respect to each other. In this study an inter comparison among these models is made based on several criteria.

As summarized in Table 5.6, a discussion on each characteristic is as following:

- The model structure or designed model concept is the most important aspect of any model approaches. The structure of the HEC-HMS SMA, and RRL TANK and RRL SMAR vary from simple to more complexes. They differ not only from model algorithms but also from their ability to capture certain aspects of the catchment hydrology.
- The HEC-HMS SMA model describes the system as a number of interconnected storage layers. Five zones of a profile seem adequately to present the behavior of the real world. The simplification of systems based on reservoir mechanisms in this model is a typical characteristic of a conceptual model, by which the model algorithms require relatively low computation time due to uncomplicated interactions.

- The tank model is a very simple model, composed of four tanks laid vertically in series. 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.

- Like HEC-HMS SMA the RRL SMAR model describes the system in five storage layers except the routing component that transforms the surface run-off generated from the water balance component to the catchment outlet is by a gamma function model form (Nash,

1960) and the generated groundwater run-off is routed through a single linear reservoir.

The HEC-HMS SMA was successfully applied in continuous simulation with very good agreement between predicted and observed flow (section 5.3) in both calibration and validation scheme for the Bilate catchment. Even though, the NSE in calibration for Kulfo is low, the other performance criteria are very good.

The RRL TANK & SMAR model used in continuous simulation produces less prediction for the two catchments in calibration and validation.

5.6.2 Recommended Model

Resulting from the previous sections, this tries to recommend which model approach is appropriate to introduce in the study area. According to the performance criteria, it can be concluded that the HEC-HMS SMA is preferable. This model responds to all the given criteria except NSE. Moreover, since the main objective function of the models is to estimate the peak floods of the rivers, the IVF & RE are very good for the HEC-HMS SMA in calibration and verification. Therefore, to predict the peak discharge and the time series flow of the catchments in the basin in continuous mode, the HEC-HMS SMA is recommended.

With this condition TANK & SMAR model is preferable for the determination of flow contribution to the lakes for water balance calculation from the catchments, since the IVF is higher for TANK model than HEC-HMS SMA in the two catchments.

5.7 Model Uncertainties

Model uncertainty is a very important topic for every hydrologic modeller. Various steps involved during modelling processes lead to a number of uncertainties that need to be quantified. As described by Melching (1995) the uncertainties sources include: (1) natural randomness, (2) data, (3) model parameters, (4) model structure.

5.7.1 Uncertainties in input data

In chapter 4, two main input data sets which were processed in detail is rainfall. In this part, the uncertainty from these two sources is discussed.

Several input data are required for each model approach. They vary from one to another model as already listed in section 3. However, obviously, rainfall data is the most important data source to be considered. However, rainfall variation is so dynamic in time and space that quite a few hydrologists devoted in finding the "proper" rainfall. Review on this issue can be found in the work of Melching (1995), Singh and Woolhiser (2002) and Gupta et al (2005).

For example, Singh (1997) reported that the shape, timing and peak flow of a stream flow hydrograph is significantly influenced by spatial and temporal variability in rainfall and watershed characteristics. Dunne and Leopold (1978) reported that errors for rainfall point measurements can range from several percentage points to 30 percent. The results from rainfall analysis in section 5.1 indicate that, one cannot deny the uncertainty in the rainfall input data. The uncertainties could come from different sources, for example: The assumption of the uniformly distribution of rainfall made is not valid for several days and unreliability of the rain gauge itself due to human interaction. Although there are still many issues related to uncertainties in rainfall input data, they seem out of the scope of this thesis. To conclude this part, it is highly recommended that before trying to operate the model, the modeller must analyze the reliability of the available rainfall data.

5.7.2 Uncertainty in Discharge Measurement

With respects to the discharge measurement, two possible sources should be considered: (1) Reliability of the stage-discharge curve and (2) mistakes in recording data. The first may be overcome by obtaining more than required stage-discharge pair points. However, some problems had been faced during the development of stage-discharge curve using the software "Highdata" due to the unfamiliarity of the experts in the Ministry of Water Resource to the software. Consequently, different data were being developed for a single discharge measuring point for the same year.

The later can be explained as follows:
The discharge was measured at the outlet of the catchment. Due to the location of the chosen outlet, the water from different tributaries was coming very fast after every event. This resulted in an aggressive flow. Flow raised and receded very quickly, usually within a day. Therefore, it is very important to measure the discharge continuously. The discharge data used in this study was recorded only two times a day and then averaged. Here it is obvious to observe how wider the interval is and as a result so many flow events might have remained unmeasured. In addition, a small mistake in reading out the numbers at the staff gauge

or missing recording data for a few hours could cause significant errors (for example, reading 91 cm instead of 191cm the discharge already change significantly. Thus, the discharge data collected in this way may include uncertainties.

5.7.3 Uncertainties in Model Parameterizations

Parameter uncertainties cannot be neglected in any model development. The reason is because it is still very difficult to determine the "representative model parameters". Numerous authors have contributed to solve the problem of the uncertainty in model parameters. For example in the GLUE method (Beven, 2000), which rejects the idea of an optimum parameter set and produce a wider range of final output based on wider parameter sets. By doing this, people will be aware of using the results for other applications such as water abstraction, flood forecasting etc. Thus, quantifying the uncertainty in model parameterization is a very important task. However, to do this work in the scope of this thesis is impossible. In this study, three main points were mentioned where the uncertainty could come from during model parameterization;

(1) Estimating initial parameters;
(2) Setting up initial and boundary condition;
(3) Reliability of the calibrated model parameters.

To estimate the initial parameters, referring from literature is the most convenient way for an ungauged catchment. For a particular model approach, additional information such as field knowledge and GIS data based on aggregation technique is also very helpful.

6 CONCLUSION AND RECOMMENDATION

6.1 Conclusions

The main objective of this study is to test the performance of the three hydrologic models. The study is conducted by with respect to this objective raised in section 1.3.

Data, an essential aspect of rainfall – runoff modeling, is the first focal point in this study. Various sources were explored in order to obtain the real world data. Although efforts are made in data collection, the "real world data" might not be adequately defined yet in this study, specially the discharge data.

Three different selected model approaches were tested in this study. A number of issues on these model approaches have been reviewed. Literature background on these models was presented in chapter 3, model development in chapter 4 and result, discussion and model performance, model structure, model uncertainties, etc. in chapter 5. Hereunder, a few comments on each model based on the results from this study are followed:

There is no any rainfall station in the Kulfo catchment really representing the rainfall distribution over the catchment. The rainfall stations considered in this study are: one is Arbaminch station which is located around the outlet of the catchment and the other is Chencha station which is out of the catchment. Therefore, the distribution of the rainfall stations in the catchment is very minimal and the overall result of the models is definitely affected due to this factor.

Also in the case of Bilate, the catchment selected for the model performance, the distribution of rainfall stations is very scarce. The result could have been improved if the distribution was fairer than the present.

As it was stated in section 5.5.2 about the discharge uncertainty, it can be concluded that the observed discharge data of Kulfo is not representing the flow at the outlet.

In spite of poor quality of the input data used in this thesis, it is evident that the models performance increases with the increase of input data and the catchment size for these particular catchments.

Based on model performances and the criteria introduced in chapter 5, the HEC-HMS SMA model is found to be suitable model to capture the peak of the observed flow and to simulate the volume of the flow. Thus, the model can be used in the ungauged catchments with or without regionalization and the results will essentially serve for water resources planning in the area (eg. Flood forecasting, flood problems mitigation measures).

A complete rainfall – runoff modeling for the ungauged catchments has not been done in this study. Model parameterization, model development for different model approaches and model calibration carried out in this study are not satisfactory. Although the results did not meet all expectations, this exercise has brought to the author a number of interests in the field of hydrology in general and rainfall – runoff modelling in particular.

6.2 Recommendations

Regarding the research methods and the ability to improve model results, further research can be considered as follows:

- Improve rainfall retrieval either by increasing rainfall stations in the area or if it is possible by integrating satellite images and rain-gauge observation relation.
- The uncertainty in discharge measurement should be minimized by improving data recording system. This would be a reason why some parts of the hydrograph were over predicted or under predicted.
- For all the models, the whole catchments were simulated in a lumped manner. Thus, the variation of the catchment characteristics was not explicitly taken into account. Therefore, simulating the catchment at a finer lumped manner by partitioning the catchment into smaller sub-catchment is recommended when data pertaining to the study for sub-catchments is available.
- With all the drawbacks raised in the result & discussion part, the selected model will serve for other ungauged catchments in the region which have similar hydrologic behavior as those of the Kulfo and Bilate catchments with or without regionalization.

For a complete rainfall – runoff modeling for the ungauged catchments Various important steps including data acquisition either from satellite images or field measurements for rainfall & discharge with finer time step (hourly, quarter-hourly), other physical characteristics of the specific catchment and model parameterization is highly recommended.

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APPENDIX-I HYDROMETEOROLOGICAL DATA

Table 4.4: Mean monthly minimum & maximum temperature of selected meteorological stations in Kulfo catchment

Months			Jan	Feb	March	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Stations	Arbamich	Min	15.6	16	17.9	18	17.8	17.6	17.6	17.9	17.6	17.2	15.5	15
		Max	35.5	37	36.2	33.9	31.9	31.4	30.8	31.9	33.7	32.8	33.6	34.4
	Chencha	Min	8.3	9.6	9.9	8.8	9	8.9	8.4	8.2	8.8	9	8.8	8.3
		Max	23.1	22.8	22.2	20.5	20.2	18.9	17.7	17.5	19.5	20.4	21.8	23
	Baba	Min	12.13	13.38	14.24	13.33	13.29	14.43	12.88	12.91	13.23	13.15	12.44	12.13
		Max	26.65	26.95	26.54	25.17	24.12	23.29	22.27	22.45	23.98	24.55	25.53	26.59

Table 4.5 Mean monthly minimum & maximum temperature of selected meteorological stations in Bilate catchment

Months			Jan	Feb	March	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Stations	Hosana	Min	9.8	10.7	11.8	12	11.6	10.8	11	11.3	10.4	10.8	9.9	9.2
		Max	23.7	25.2	24.6	23.5	23.1	20.9	19.4	19.6	21.4	22.3	23.5	23.8
	Alaba	Min	13.2	13.6	14.4	14.6	14.4	14.1	14.2	14.3	13.5	12.8	11.6	12.1
		Max	29	30.6	29.6	28.5	28	25.9	24.3	24.4	26.4	27.2	28.6	29.4
	Bodity	Min	12.9	13.7	14.3	14.3	14.1	13.5	12.9	13.1	13.3	13.1	12.5	12.3
		Max	26.7	28	26.7	25.6	24.6	22.7	21.4	21.7	23.7	24.4	26	26.4
	Wulbareg	Min	9.2	9.7	10.1	10.7	10.4	10	9.9	9.8	9.5	9.2	9.8	9.6
		Max	25.7	26	26.4	26.1	26	25.7	25.5	25.2	25.4	25.6	25.6	25.5
	Angecha	Min	13.7	14.2	13.8	13.7	14	13	13.4	13.1	13.1	13.3	14	13.6
		Max	24	24	24	23.7	23.9	23.5	23.6	23.4	23.3	23.6	24.3	24.2

Table 4.7 Extraterrestrial Radiation (Ra) values on 15th day of the month averaged over the month in mm/day (FAO paper 56) for Kulfo catchment stations

Months		Jan	Feb	mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
Stations	chencha	13.72	14.59	15.25	15.35	14.95	14.58	14.67	15.06	15.22	14.71	13.89	13.40
	a.minch	13.74	14.60	15.26	15.34	14.94	14.57	14.65	15.06	15.22	14.72	13.90	13.41
	baba	13.72	14.59	15.25	15.34	14.95	14.58	14.67	15.06	15.22	14.71	13.89	13.40

Table 4.8 Extraterrestrial Radiation (Ra) values on 15th day of the month averaged over the month in mm/day (FAO paper 56) for Bilate catchment stations

Months		Jan	Feb	mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
Stations	Hosana	13.51	14.45	15.21	15.4	15.07	14.73	14.82	15.14	15.2	14.6	13.7	13.18
	Alaba	13.54	14.47	15.22	15.4	15.06	14.72	14.8	15.13	15.2	14.61	13.72	13.21
	Angecha	13.53	14.46	15.22	15.4	15.06	14.72	14.8	15.14	15.2	14.61	13.72	13.21
	Tora	13.65	14.54	15.24	15.37	15	14.64	14.72	15.1	15.21	14.68	13.83	13.32
	Wulbareg	13.49	14.43	15.21	15.41	15.09	14.75	14.83	15.15	15.19	14.59	13.68	13.16

Table 3-1: Runoff-volume models

Model	Categorization
Initial and constant-rate	event, lumped, empirical, fitted parameter
SCS curve number (CN)	event, lumped, empirical, fitted parameter
Gridded SCS CN	event, distributed, empirical, fitted parameter
Green and Ampt	event, distributed, empirical, fitted parameter
Deficit and constant rate	continuous, lumped, empirical, fitted parameter
Soil moisture accounting (SMA)	continuous, lumped, empirical, fitted parameter
Gridded SMA	continuous, distributed, empirical, fitted parameter

Table 3-2: Direct-runoff models

Model	**Categorization**
User-specified unit hydrograph (UH)	event, lumped, empirical, fitted parameter
Clark's UH	event, lumped, empirical, fitted parameter
Snyder's UH	event, lumped, empirical, fitted parameter
SCS UH	event, lumped, empirical, fitted parameter
ModClark	event, distributed, empirical, fitted parameter
Kinematic wave	event, lumped, conceptual, measured parameter

Table 3-3. Baseflow models

Model	Categorization
Constant monthly	event, lumped, empirical, fitted parameter
Exponential recession	event, lumped, empirical, fitted parameter
Linear reservoir	event, lumped, empirical, fitted parameter

Table 3-4. Routing models

Model	Categorization
Kinematic wave	event, lumped, conceptual, measured parameter
Lag	event, lumped, empirical, fitted parameter
Modified Puls	event, lumped, empirical, fitted parameter
Muskingum	event, lumped, empirical, fitted parameter
Muskingum-Cunge Standard Section	event, lumped, quasi-conceptual, measured parameter
Muskingum-Cunge 8-point Section	event, lumped, quasi-conceptual, measured parameter
Confluence	continuous, conceptual, measured parameter
Bifurcation	continuous, conceptual, measured parameter

APPENDIX-II MODELS DETAIL

1 HEC-HMS SMA Model Details

This appendix includes additional description of features of the HEC-HMS soil moisture accounting (SMA) model.

Time Interval Selection

HEC-HMS models rely on the solution of differential equations to estimate watershed runoff. To solve the equations, the models use a finite-difference approximation, as described in Chapter 6. A discrete time interval (Δt) is selected for the approximation, and for this time interval, HEC-HMS commonly uses the value defined by the user in the *control specifications*. So, for example, if the control specification calls for a 10-minute time interval, the curve number loss model is applied to compute infiltration for successive 10-minute intervals, and the unit hydrograph equations are solved to compute runoff hydrograph ordinates at 10-minute intervals. For these cases, the time interval is user-specified and is constant.

To ensure accuracy of solution of SMA model equations, HEC-HMS determines and uses internally a *computational* time interval. This interval may be the userspecified interval, or it may be a fraction of that value. In either case, HEC-HMS reports hydrograph ordinates at the user-specified interval. HEC-HMS selects the computational time interval as follows:

1. HEC-HMS finds a *minimum time interval* for each storage volume with potential to outflow, using procedures shown in Table C-1.

2. HEC-HMS selects the minimum interval from Step 1. If the user-specified value is less, it is used instead.
3. If the time interval calculated in Step 2 is larger than one-quarter of the time required to fill the combined available canopy, surface and soil profile storage, the interval is reduced to that value.
4. If the interval from Step 3 is greater than the precipitation data interval, the computational interval is set equal the precipitation interval.
5. If the interval from Step 4 is greater than 12 hours, the computational interval is reduced to 12 hours. If the interval is less than 1 minute, the interval is increased to 1 minute.
6. If the interval from Step 5 is greater than the remaining time in the user specified interval, the computational interval is set equal the remaining time.
7. If the interval from Step 6 is less than the remaining time in the user specified interval, the computational interval is adjusted so it is an even divisor of the remaining time.
8. If the remaining time less the interval found in Step 7 is less than one minute, the computational interval is set equal the time remaining in the user specified interval.

The time required to fill or drain storages varies throughout the simulation period, so HEC-HMS varies the computational time interval throughout the simulation. To do so, it repeats these steps for each user-specified interval. So, for example, during periods in which water is moving rapidly into and out of the storages in the SMA, HEC-HMS may select and use ten 1-minute computational intervals to account for soil moisture fluxes during a 10-minute user-specified interval. However, as the movement slows, HEC-HMS may select a longer computational interval—perhaps using two 5-minute computational intervals during the 10-minute user-specified interval.

Table 1 Minimum time steps for storages

Storage	**Minimum time step**
Canopy interception storage	$TimeStep = \frac{1}{4}\frac{CurCanStore}{PotEvapTrans}$ Calculated only if evapotranspiration losses can occur and when the current canopy interception storage at the beginning of the time step exceeds the nominal storage volume
Surface interception storage	$TimeStep = \frac{1}{4}\frac{CurCanStore}{PotSoilInfl + PotEvapTrans}$ Calculated when potential evapotranspiration or infiltration losses > 0, and *CurSurfStore* > 0.
Soil profile storage	$TimeStep = \frac{1}{4}\frac{CurCanStore}{PotSoilPerc + PotEvapTrans}$ Calculated when percolation or evapotranspiration can occur from the soil profile, and *CurSoilStore* > 0.0001 inches.
Groundwater storage	$TimeStep = \frac{1}{4}\frac{CurGw1Store}{PotGw1Perc}$ Calculated when percolation (loss) can occur from a groundwater layer, and the current volume in a groundwater layer > 0 $TimeStep = \frac{1}{16} RoutGw1Store$ Calculated when the groundwater storage volume divided by the linear reservoir routing coefficient > 0
Precipitation intensity	$TimeStep = \frac{1}{4}\frac{MaxCanStore + MaxSurfStore + MaxSoilStore}{PrecipTimeStep}$ Calculated when *PrecipTimeStep* > 0

TimeStep = time step for storage; *CurCanStore* = current canopy interception storage; *CurSurfStore* = current surface interception storage; *CurSoilStore* = current soil profile storage; *MaxCanStore* = maximum canopy interception storage; *MaxSurfStore* = maximum surface interception storage; *MaxSoilStore* = maximum soil profile storage; *CurGw1Store* = current groundwater storage; *PotEvapTrans* = potential ET; *PotSoilInf* = potential infiltration; *PotSoilPerc* = potential percolation from soil profile; *PotGw1Perc* = potential percolation from groundwater layer; *RoutGw1Store* = coefficient for groundwater linear reservoir model; *PrecipTimeStep* = time step for specification of precipitation data.

2 RRL SMAR

The surface run-off generated from the landscape is routed (attenuation and lag) to the catchment outlet using the linear cascade model of Nash (1960). The model was obtained as a general solution relating a given input of unit volume to a given output as in equation 1.

$$h(t) = \frac{1}{t}\int_{t=1}^{t} \frac{1}{K\Gamma(n)} exp\left(\frac{-\tau}{K}\right)\left(\frac{\tau}{K}\right)^{n-1} d\tau \qquad 1$$

where, t = simulation time step (d), τ = time (s), K1 = K2 = …… = Kn = K are the storage coefficients of n linear reservoirs in cascade, $h(t)$ = ordinates of the pulse response function (d^{-1}) and and $\Gamma(n) = exp\int_0^\infty (-\tau)\, \tau^{n-1}\, d\tau$ is the in complete Gamma function (dimensionless).

It was shown by Nash (1960), that under constraints of conservation, stability, high damping and the absence of feedback, this two-parameter equation with n an integer and K positive, is almost as general a model as the differential equation of unlimited order. With additional flexibility obtained by allowing n to take fractional values, the impulse response of this equation has the ability to represent, adequately, almost all shapes commonly encountered in the hydrological context.

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 (r_s mm·d^{-1})) and the routed run-off (Q_T^r mm·d^{-1}) can be time-averaged, as in equations (2) and (3), to represent the daily values.

$$r_s(t) = \frac{1}{t}\int_{\tau-t}^{t} r_s\,(\tau)d\,\tau \qquad 2$$

$$Q_T^r(t) = \frac{1}{t}\int_{\tau-t}^{t} Q_T^r\,(\tau)d\,\tau \qquad 3$$

The linear model described by equation 4 is the simplest representation of a causal, timeinvariant, 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.

$$Q_T^r(t) = \sum_{j=1}^{m} h(j) r_s(t-j+1) \qquad 4$$

where, m = memory of the pulse response function (d).

The parameter pair n and nK are chosen for optimisation, rather than n and K separately, because n is a 'shape' 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 groundwater system can be written as in equation 5.

$$Q_T^{rech}(\tau) - Q_T^{g}(\tau) = \frac{dS(\tau)}{dt} = DS(\tau) \qquad 5$$

where, Q_T^{rech} = recharge to the groundwater system ($mm.\ S^{-1}$), Q_T^{g} = discharge from the groundwater system ($mm.\ S^{-1}$), τ = time (s), $S(\tau)$ = storage of the groundwater system (mm), and $D = d\ /\ d\tau$ is the differential operator (S^{-1}).

There are three basic components of discharge from the groundwater system:

- Discharge to the stream until a maximum threshold, after which discharge to land occurs following shallow watertable development.
- Discharge to the land surface that is locked in the landscape and is eventually lost to the atmosphere.
- Inter-basin transport, from the local groundwater system to the regional groundwater system.

Two assumptions are made in treating the groundwater-routing components as a single linear reservoir:

- Discharge to the land that does not eventually reach the river is negligible.
- Inter-basin transport from the local flow system to a regional groundwater system is substantially less than the discharge to the stream (Bear, 1979)

Therefore, $Q_T^g(\tau)$ is comprised mainly of the groundwater discharge to the stream and to the land surface that eventually reaches the stream. The lag times between natural replenishment and groundwater discharge are substantial, and the groundwater system behaves like a highly damped system. This mechanism can be visualised as one of displacement whereby water from episodic drainage events is continually added at the bottom of the root zone and is removed from the groundwater system at a very slow rate. This process can be expressed by a single linear reservoir with a large storage coefficient Kg. The pulse-response function for the groundwater component can be obtained in a manner analogous to equation 1 as in equation 6.

$$h^g(t) = \frac{1}{t}\int_{t=1}^{t} \frac{1}{K_g} exp\left(\frac{-\tau}{K_g}\right) d\tau \qquad 6$$

The recharge $Q_T^{rech}(t)$ and the discharge $Q_T^g(t)$ can be time averaged to mm·d^{-1} in an analogous manner, as in equations 2 and 3.

APPENDIX-III FIGURES

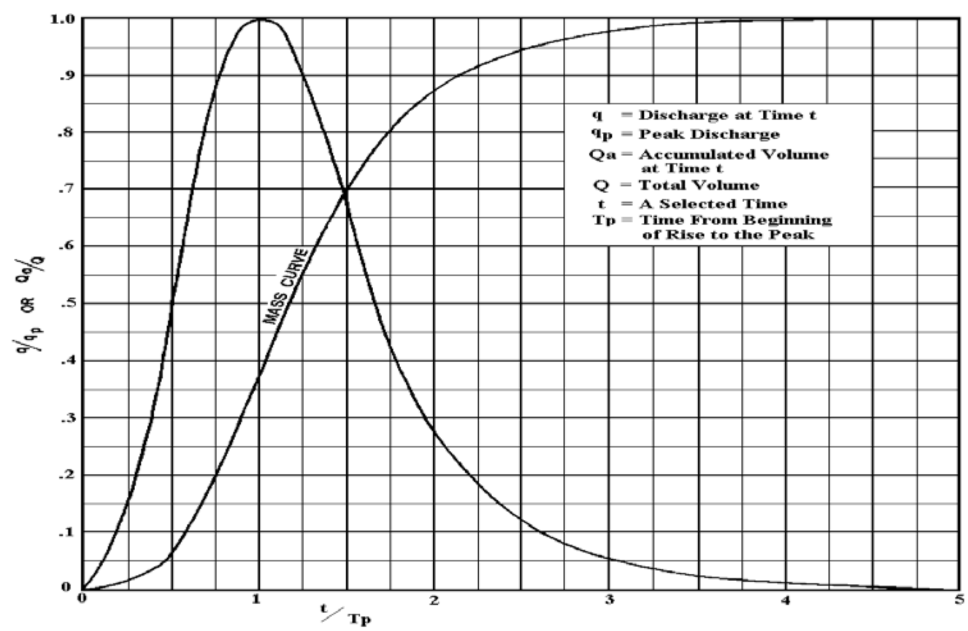


Figure 3-7 SCS unit hydrograph

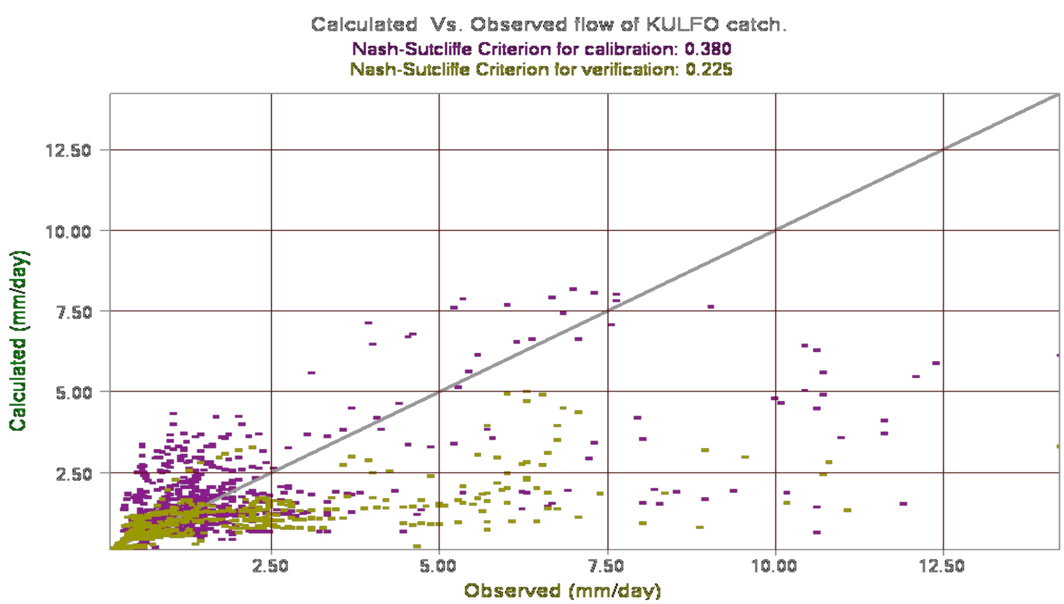


Figure 5.6c Scatter plot of Observed Vs Simulated flow of Kulfo after calibration (TANK model)

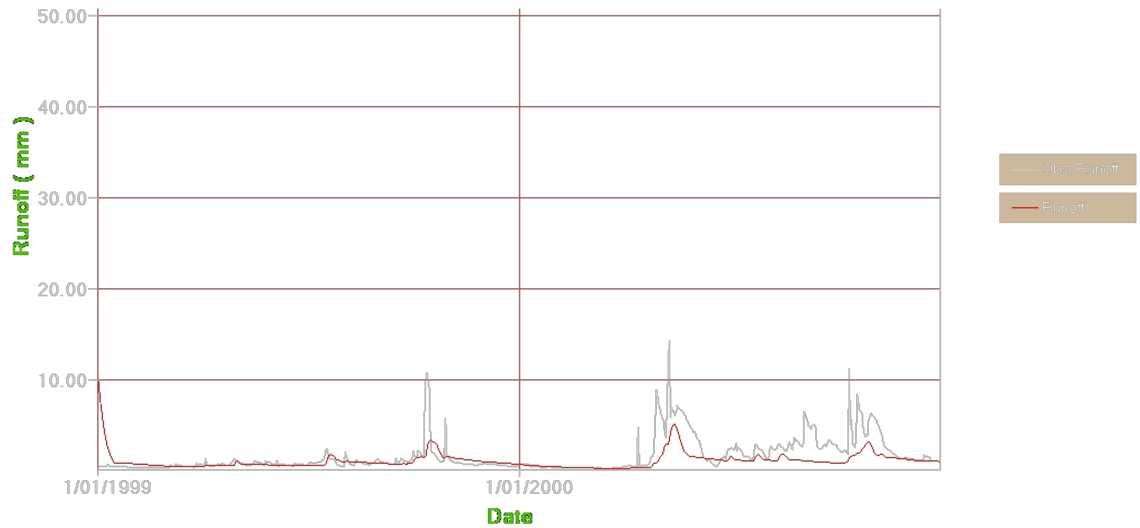


Figure 5.6d Observed and run off output of TANK for Kulfo catchment (verification)

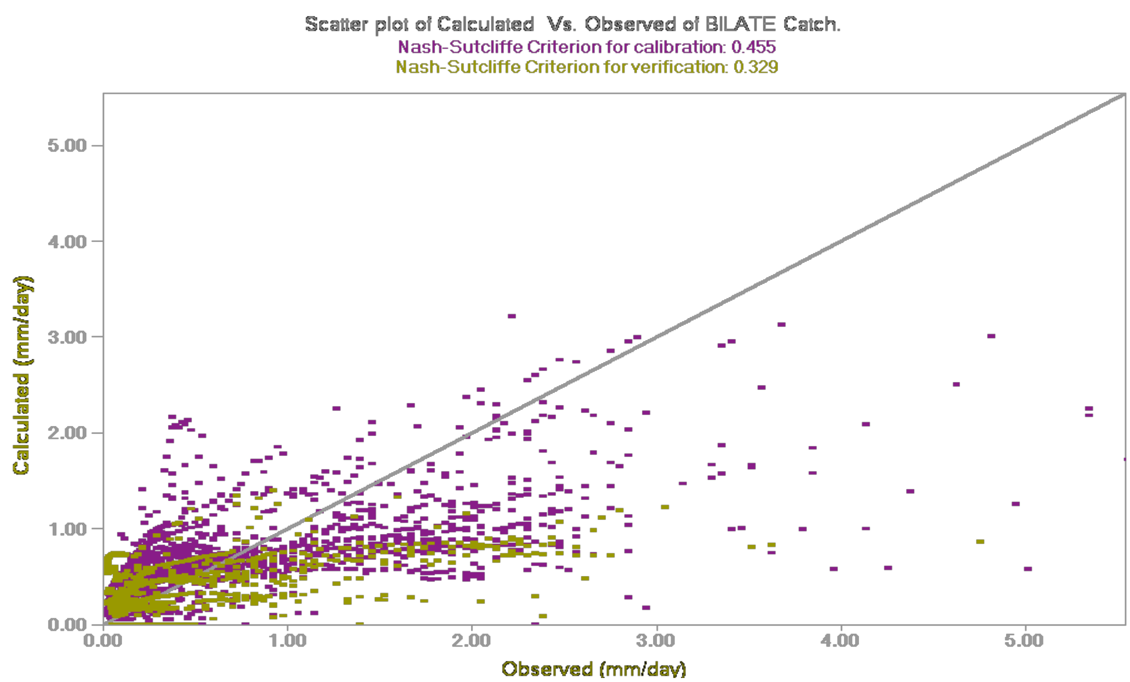


Figure 5.7c Scatter plot of Observed Vs Simulated flow of Bilate after calibration (TANK model)

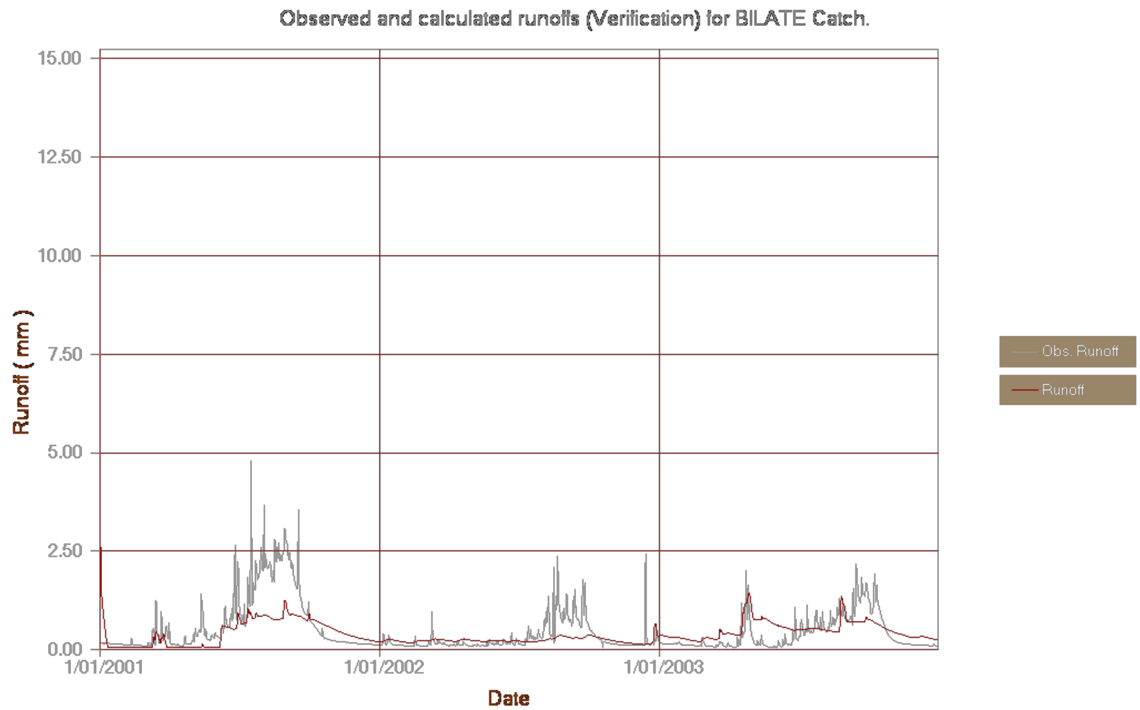


Figure 5.7d Observed and run off output of TANK for Bilate catchment (verification)

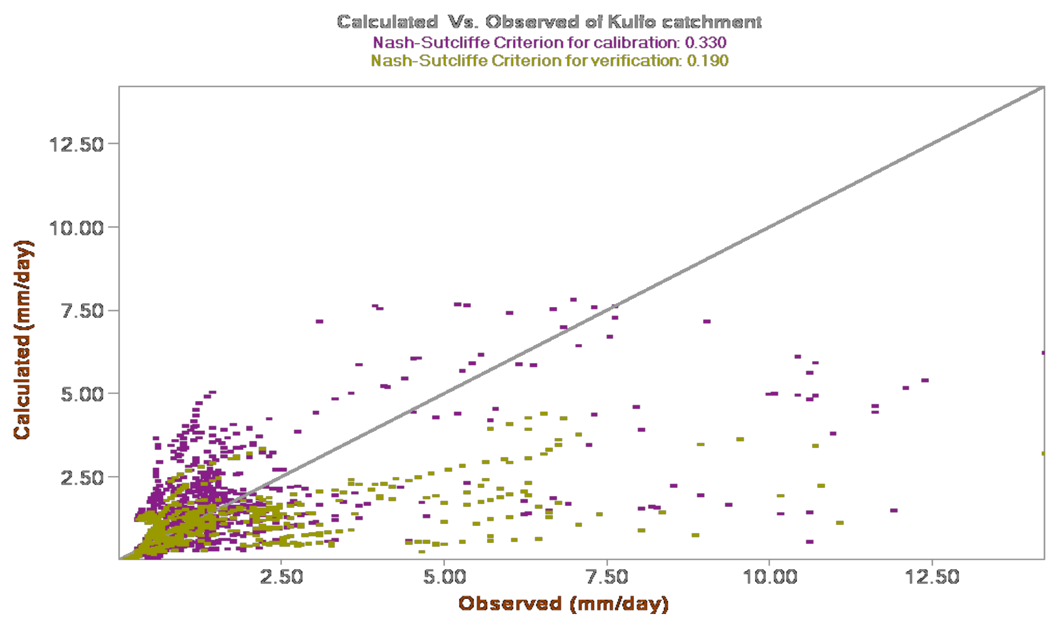


Figure 5.8c Scatter plot of the output of SMAR for Kulfo catchment after calibration

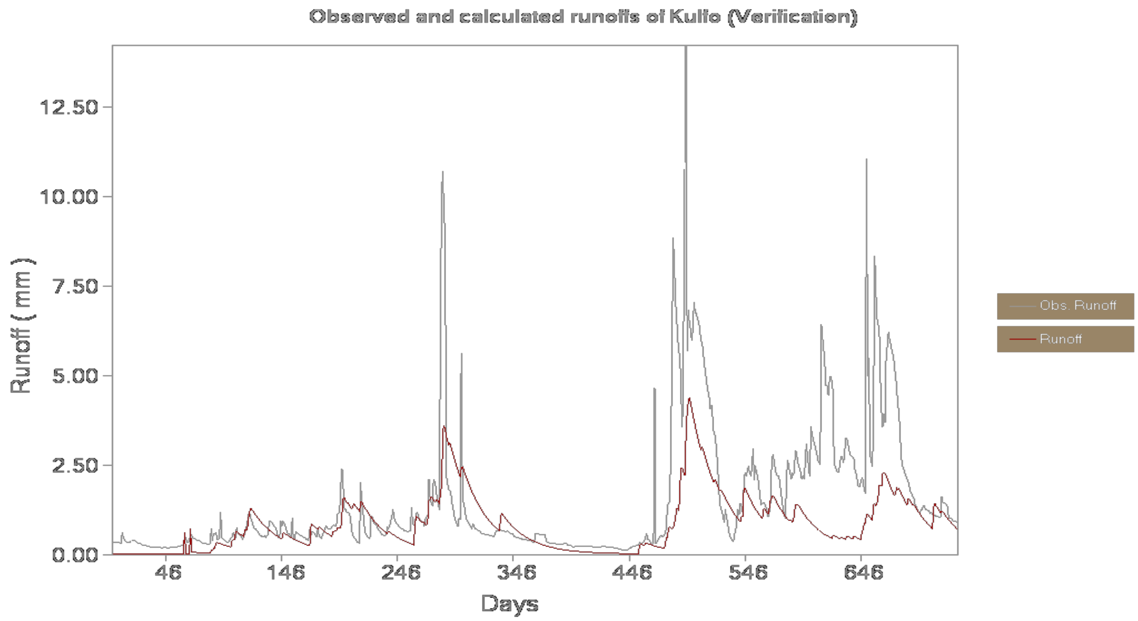


Figure 5.8d Observed and run off output of SMAR for Kulfo catchment (verification)

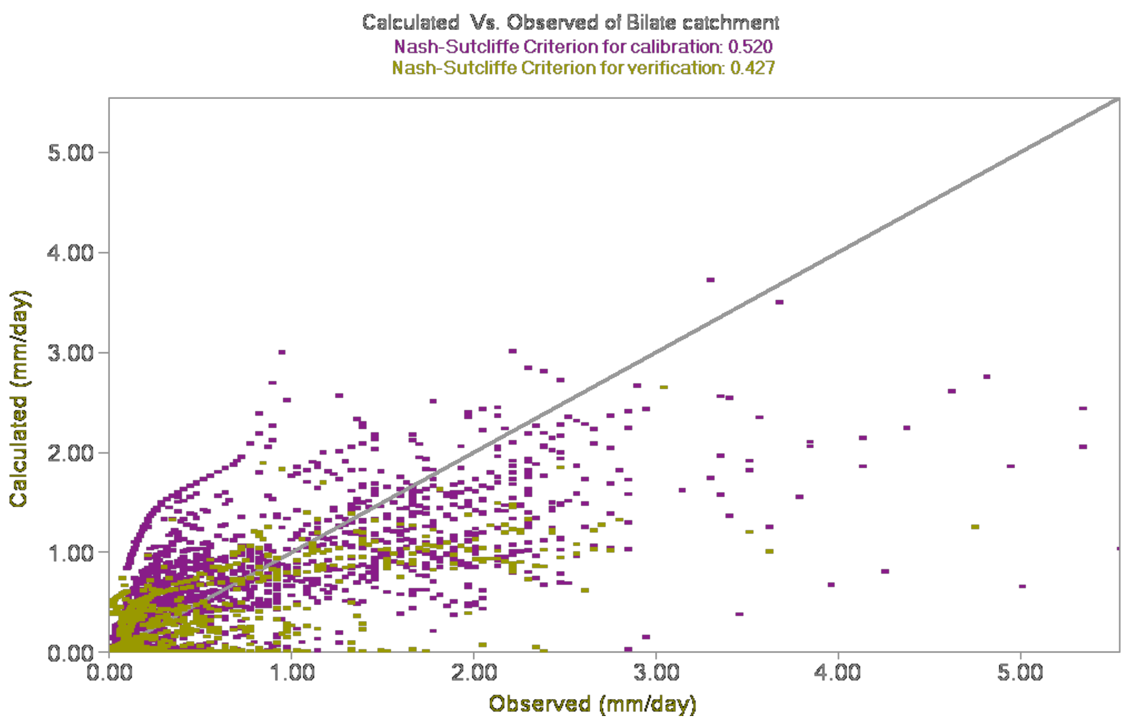
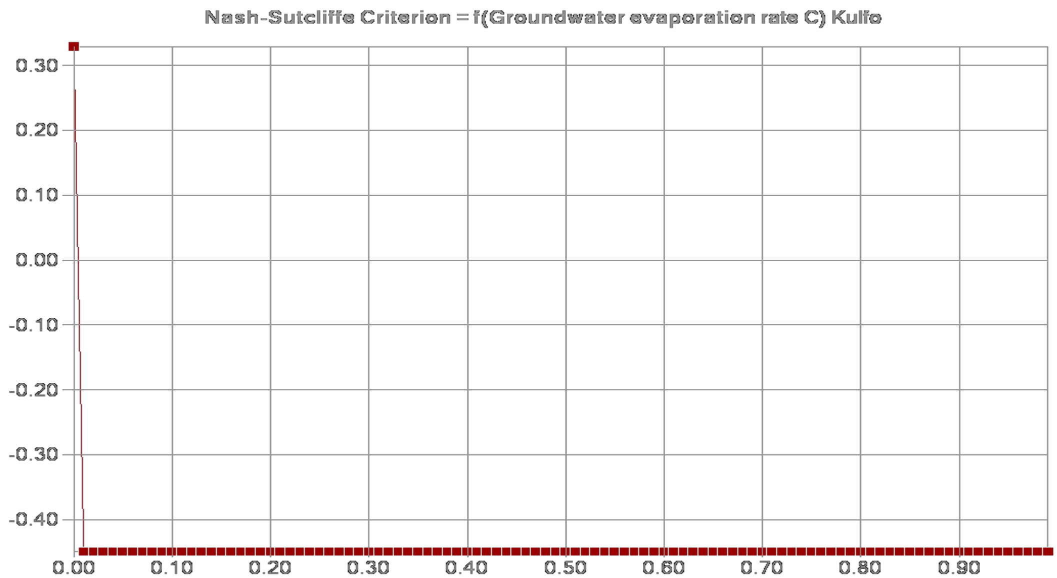
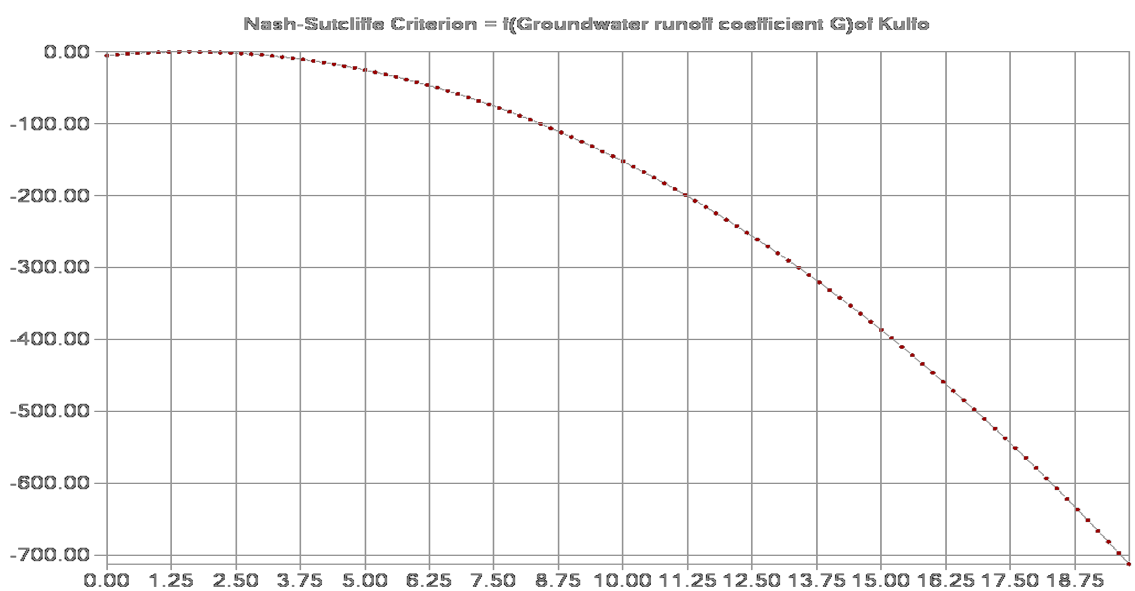


Figure 5.9c Scatter plot of observed Vs simulated for Bilate catchment after calibration (SMAR model)

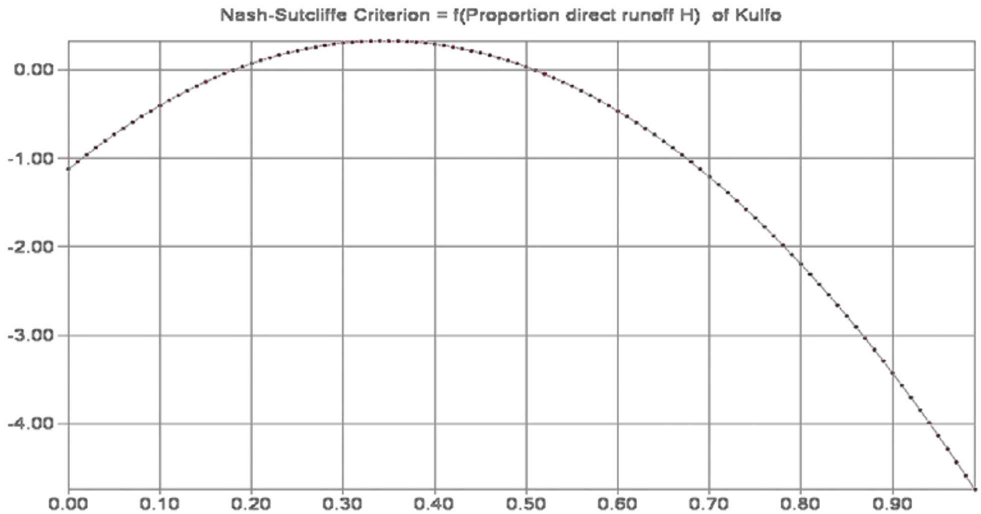
APPENDIX-IV Sensitivity Analysis of Parameters of RRL TANK and SMAR models



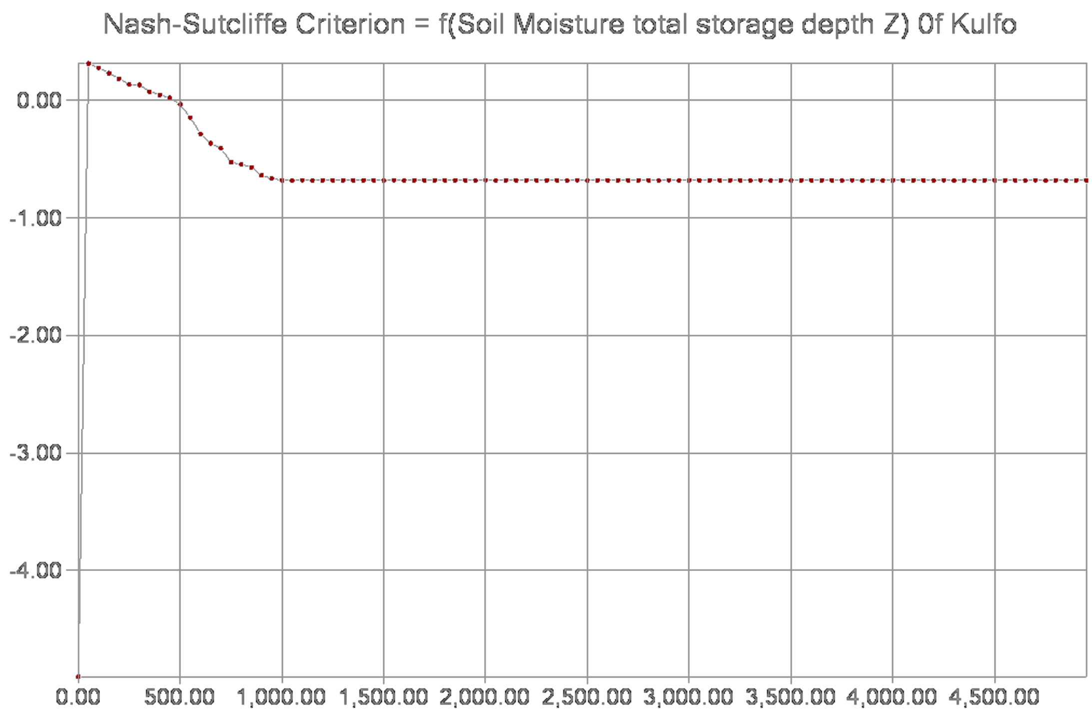
a) SMAR Sensitivity analysis of ground water evaporation, C



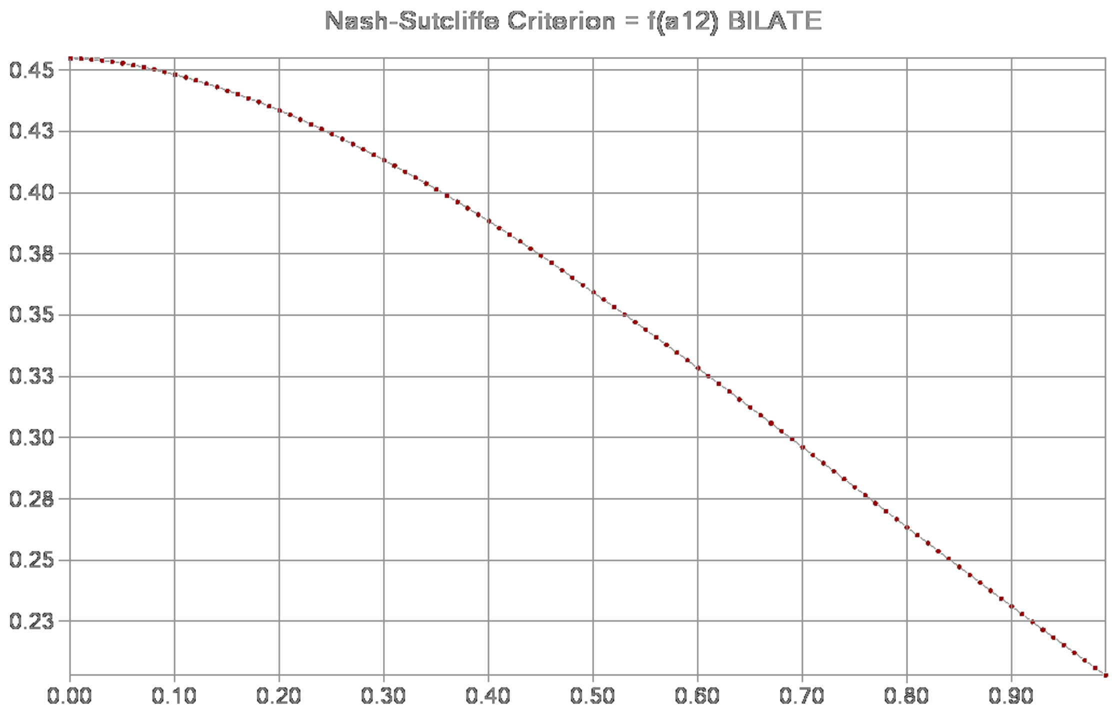
b) SMAR Sensitivity analysis of ground water runoff coefficient, G



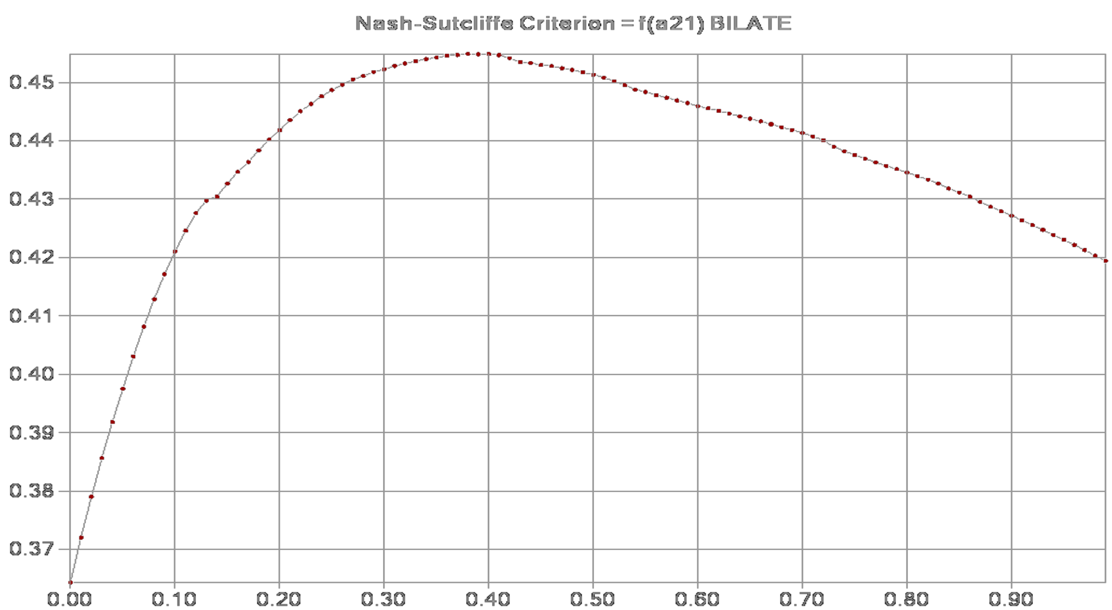
C) SMAR Sensitivity analysis of proportion runoff, H.



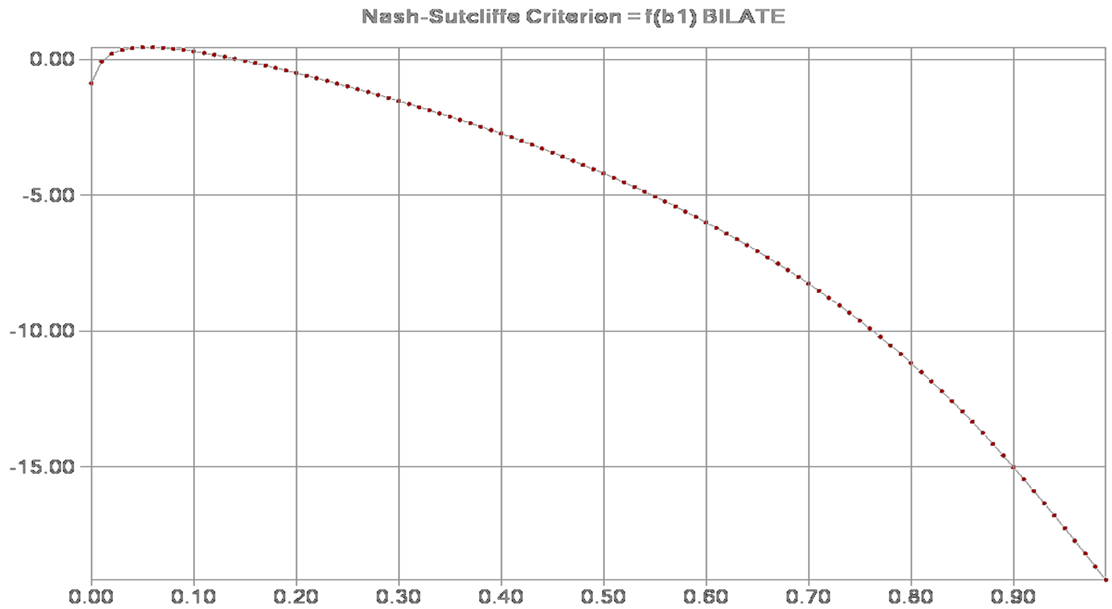
D) SMAR Sensitivity analysis of proportion runoff, H



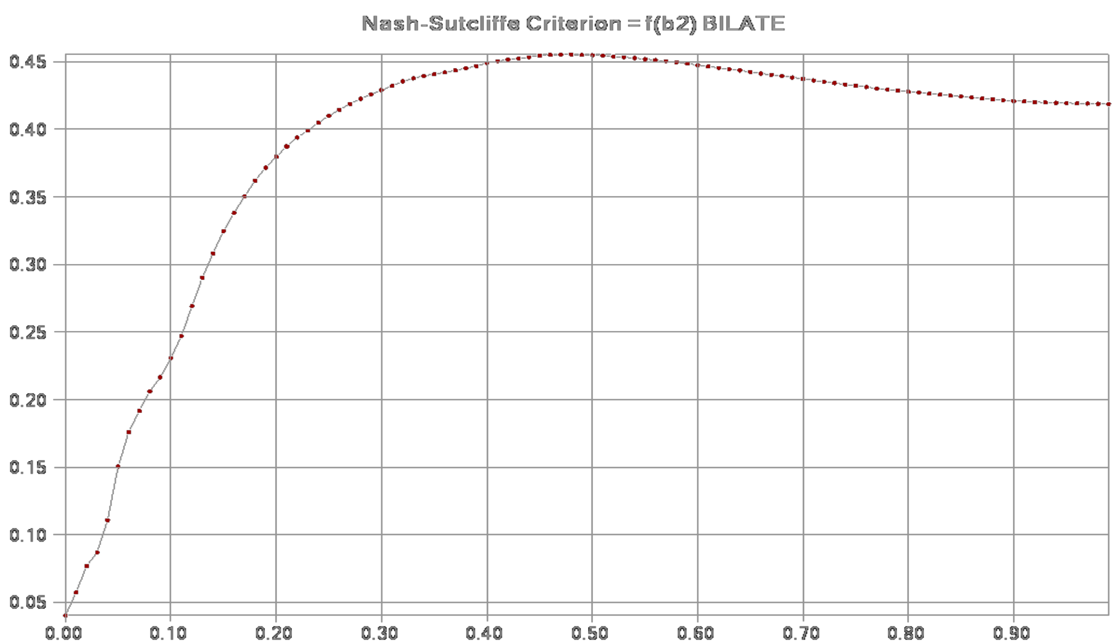
E) TANK Sensitivity analysis of runoff coefficient of 1st Tank 2nd outlet



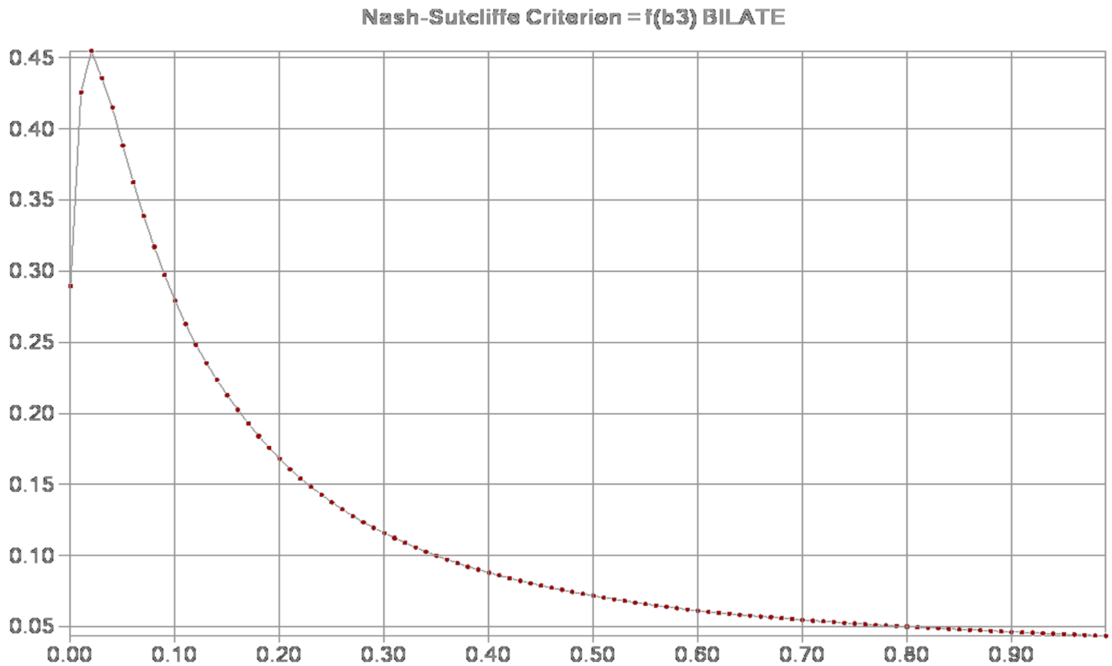
F) TANK Sensitivity analysis of runoff coefficient of 2nd Tank outlet, a21



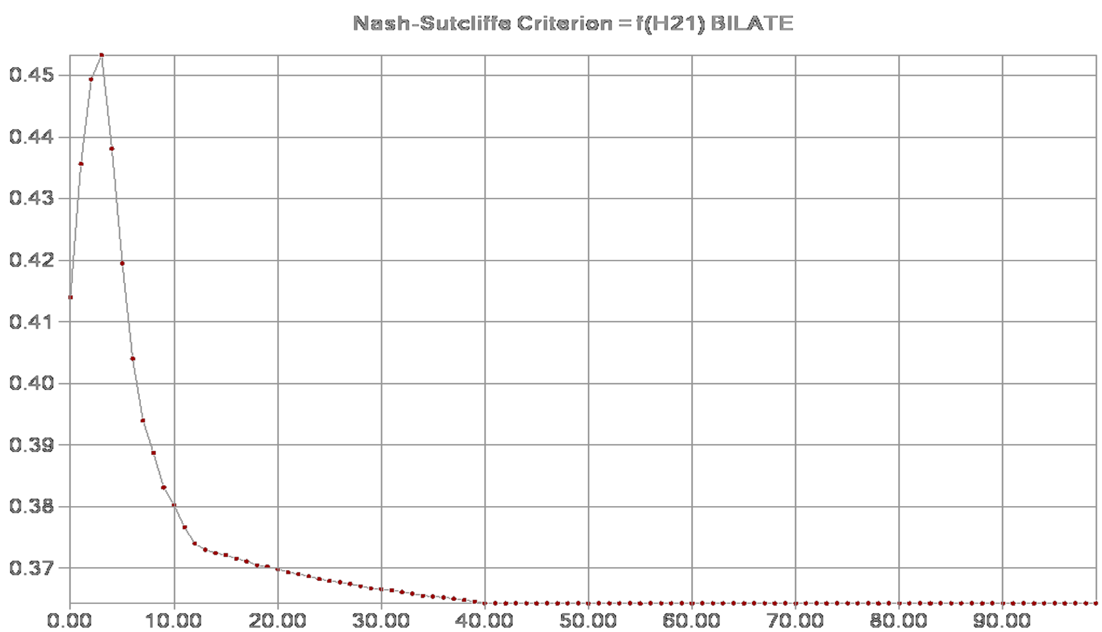
G) TANK Sensitivity analysis of infiltration coefficient of 1st Tank, b1



H) TANK Sensitivity analysis of infiltration coefficient of 2nd Tank, b2



I) TANK Sensitivity analysis of infiltration coefficient of 3rd Tank, b3



J) TANK Sensitivity analysis of outlet height of 2nd Tank, H21