ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
DEPARTMENT OF CIVIL ENGINEERING

DAILY RAINFALL-RUNOFF MODELING FOR THE BELES RIVER CATCHMENT

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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

May 2009

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APPROVAL BY BOARD OF EXAMINERS

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ACKNOWLEDGEMENTS

For the purpose of this research work in particular and its masters program study in general, I have interacted, exchanged ideas and also got advice from various people. I have also got cooperation from various organizations. I am very grateful to all of them.

From organizations, my special thanks is given to the Ministry of Water Resources for giving me the opportunity to join this Masters program and also for allowing me to use the Hydrological and GIS data used in this research. I also wish to pass my gratitude to the National Meteorological Agency for providing me with the meteorological data used in this research.

From individuals, my special gratitude goes to my Advisor Dr. Yilma Seleshi and Co-Advisor Ato Deksyos Tarekegn, for giving me proper instruction, guidance and advice throughout this research work. My special thanks also go to Wzo Semunesh Gola of the Hydrology Department of the Ministry of Water Resources, for providing me with ideas important for this research work.

Dedicated to my family, with love

ABSTRACT

For an effective and sustainable water resource planning and management, the need for complete and reliable hydrological and meteorological data is unquestionable. To get such data there is a need to develop and maintain hydrometric stations in proper networks.

Presently in Ethiopia most of the available gauging stations are located nearby access roads. Because of this situation, most of the rivers which are inaccessible to roads are not gauged. Beles River basin, a sub-basin of the Abay basin, is a basin whose vast area is ungauged, as there are only two gauging stations on its upper part and all its lower parts are ungauged.

In this research hydrological models are used to solve the above indicated problem on the Beles sub-basin. Three Rainfall- Runoff Models are tested on the upper Beles catchment, namely the RRL SMAR, RRL Sacramento and RRL Tank models. For all these models calibration and validation are done using the required input data. Evaluation and selection of suitable model for the catchment is carried out following the objective criteria: Nash-satcliffe efficiency (Reff); Efficiency using ln(Q) (logReff); and Coefficient of determination (R^2).

The RRL Sacramento Model scored the best result among the three Models for all objective functions, and therefore it is selected. Since upper and lower Beles are hydrologically homogenous, the calibrated RRL Sacramento model for the upper Beles are used to the ungauged catchment of Lower Beles without changing its parameter.

However, the Sacramento Model result by itself is not found satisfactory, since there is no meteorological station on the Beles catchment and the data used for this study is by transferring data from nearby station, considering the distance between the station and the catchments area. This kind of transferred data can not be the same as the real station data, creating low performance the model.

Keywords: unguaged, Beles, model, gauged, RRL SMAR, RRL TANK, RRL Sacramento, catchment, Calibration, Validation.

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i. Abbreviations

AMSL	Above Mean Sea Level
ITCZ	Inter-Tropical Convergence Zone
NBI	Nile Basin Initiative
SMAR	Soil Moisture Accounting and Routing Model
RRL	Rainfall Runoff Library
MOWR	Ministry of water resource
GIS	Geographic information system

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1. Introduction

1.1. General

Water is the most complex natural resource correlating its availability from the atmosphere to lithosphere through hydrosphere. The availability of water is highly uneven in space and time.

One of the basic things to be considered while planning and designing of hydraulics structures is evaluation of the hydrologic potential at the project site being considered. Improper assessment of water resources is potentially disastrous. For instance, under estimation of flood can lead to overtopping of dam and consequent failure of its structure. On the other hand, for projects where water potential is overestimated, the system may not come to a position to fill up to the full reservoir level. For these reasons, collection and analysis of long term hydrological and meteorological data like rainfall, runoff, infiltration characteristics, temperature, humidity, wind-speed and others for the area are essential.

In developing countries, in general, there is lack of financial, human and technical resources for developing and maintaining hydrometric stations in proper networks to provide data for sustainable water resource planning, design, and management. The situation in Ethiopia is problematic, as there are no evenly distributed hydrometric stations, as large areas lack of gauging stations, and only a few years of data are available.

Consequently, there is a need to develop method for predicting flow at ungauged sites. The International Association of Hydrological science [IAHS) recognized this need in 2002, and adopted the prediction of Ungauged Basin. Estimation of flow of ungauged catchments is usually based on transferring or extrapolating information from gauged to ungauged site, a process called ‘Regionalization’. Several regionalization approaches have been used. One of the most common approaches that have been used for estimating flow of ungauged catchments is the use of rainfall-runoff models whose parameters have been regionalized, as catchments with similar characteristics show similar hydrological behavior. Thus, it is possible to regionalize model parameters on the basis of catchment characteristics, i.e., to provide a regional parameter set where parameter values vary with measurable catchment characteristics [Seibert, 1999]. This regionalization can be made using relationships between the parameters of the model and the catchments characteristics.

1.2. Relevance of the Study

The result of this study can be used as an input for planning and design of various water development projects (Irrigation, Hydropower, etc.) within the basin.Lower Beles catchment has irrigation potential and there is a need for irrigation based agriculture in the area (Studio pietrangeli (1990). For such important development activity to be realized there is a need to have adequate hydrological data in the catchments. The result of this study can be applied for this and similar cases in the area.

1.3. Objective of the study

The main objectives of this study are finding the suitable rainfall-runoff model for the catchment under study, and estimating daily runoff for the ungauged catchments.

The Specific Objectives of this study are:

- Calibrating and validating three models for the gauged catchment of Beles River,
- Choosing the best rainfall-runoff model,
- Identifying the parameters of selected Rainfall-runoff Models on the basis of the catchment characteristics, and
- Estimating the daily runoff for the ungauged catchment.

2. Description of the Study Area

Beles basin is one of the major sub-basins of the upper Blue Nile. The main stem of the Beles River originates on the face of the escarpment across the divide to the west of the south-western portion of Lake Tana. It then flows on in a westerly direction and enters into the Blue Nile just before it crosses the uEthiopia-Sudan border. It is the only major right bank tributary of the Blue Nile. The Beles basin covers an area of about 14,000 km^2 and geographically it extends from 10^o 56' to 12^o N latitude and 35^{o}12' to 37^0 E longitude. The basin has two gauged sub-catchments: Main Beles and Giligile Beles that have a size of 3212.3 km^2 and 675 km^2 respectively (source: BCEOM (1999).

Figure 2.1 shows the location of Beles basin, and Fig 2.2 shows Beles River Catchments.

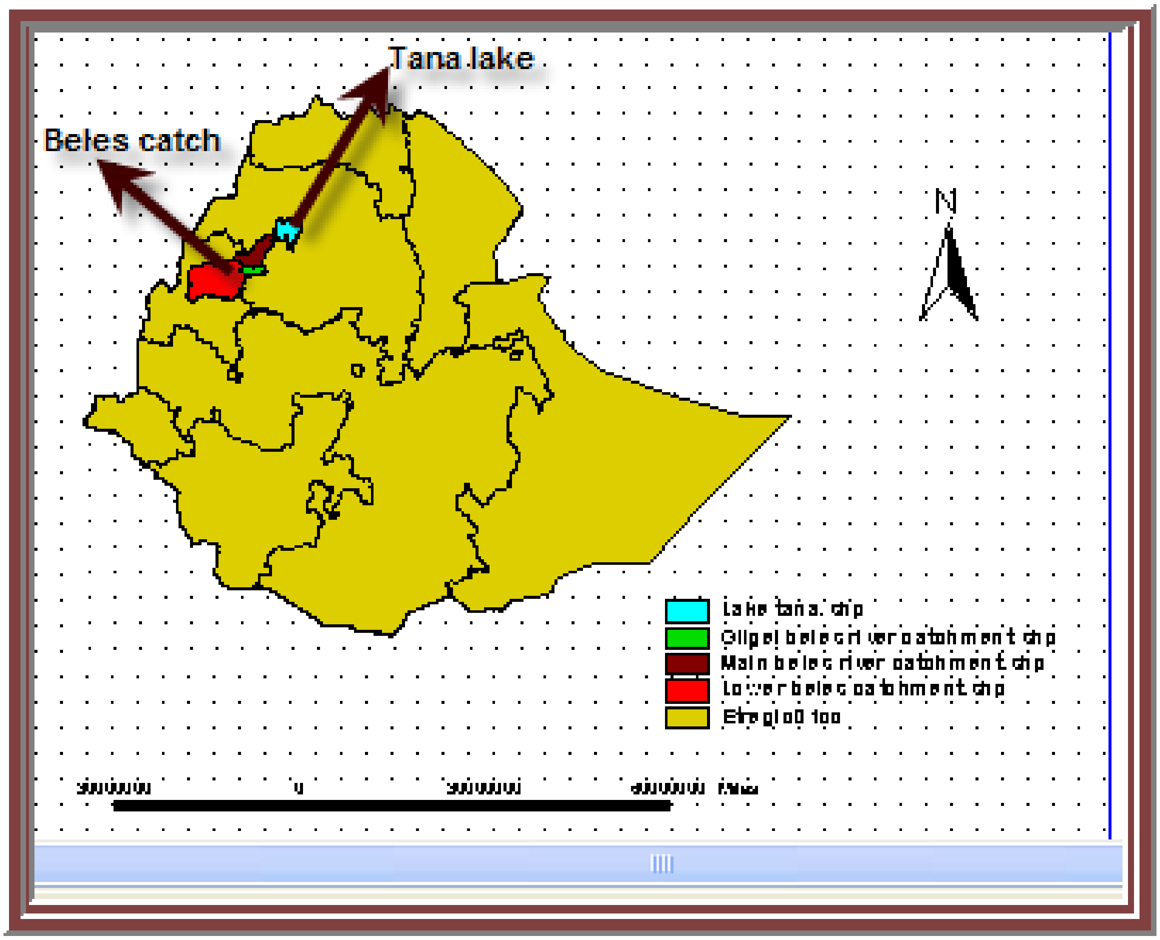

Figure 2.1: The Beles River catchments location (source:(MOWR))

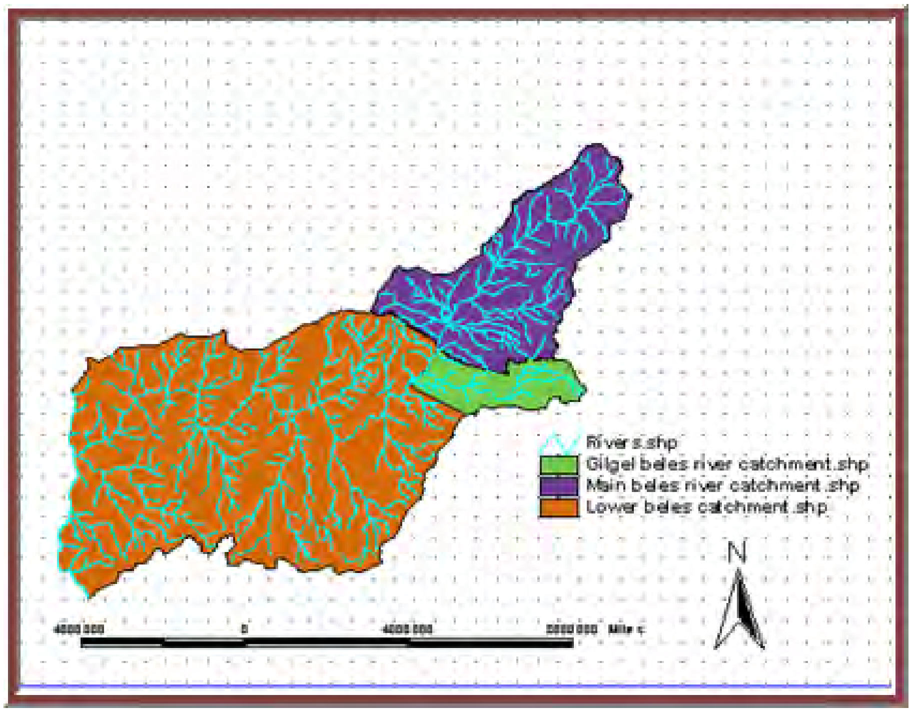

Figure 2.2 The Beles River Catchments

2.1. Topography

The Upper Beles sub basin is bounded on the east and south east by steep escarpment and on the north and west by rolling to hilly terrain which separates it from the Dindir River drainage basin. The highest point in the Basin is 2,725 AMSL at the water divide between the Tana and Beles basins and the mean elevation is about 1870 AMSL. The central part of this watershed encloses the wide, gently undulating to flat plains of the Pawe area.

2.2. Climate

The climate of Ethiopia is very much the reflection of its diversified topography and its location in the tropics. Climate seasons of the country are mainly controlled by the annual migration of the Inter-Tropical Convergence Zone (ITCZ) and the associated atmospheric circulation, which are modulated by the complex topography on the region (Geathun, 2007).

Three main seasons characterize Ethiopia (NMSA, 2001). These are:

(1) ITCZ that drives the summer monsoon in the wet season from June to September, locally called Kiremt;
(2) Saharan anticyclone that generates dry, warm and cool northeasterly winds in the dry season from October to January or February, called Bega, and
(3) Arabian high that produces thermal lows in the mid season from February or March to May called Belg.

The climate in the study area is warm and subtropical. The annual mean yearly minimum and maximum temperature is ranging between 16.5ºC - 32.5 ºC (Pawe metro. station). Precipitation is moderately abundant in the upper Beles (about 1000 mm/year), even in years when other adjacent areas are very severely affected by drought (Ebrahim G.Y(2008)). Rainfall increases with elevation in the study area. Annual potential evapotranspiration is about 1500 mm.

2.3. Land cover

The land use of the study area can be categorized mainly as agricultural, forest, bamboo, bushes and savanna. The upper Blue Nile Master plan study (USBR, 1964) indicates that the north-western portion of the area is dominated by open grass savannah whereas the southern half of the basin is characterized by wood-land savannah composed of various species of acacia, figs, and associated small trees. As it can be seen in Figures 2.3 the Upper Main Beles sub-basin is dominated by open grassland.

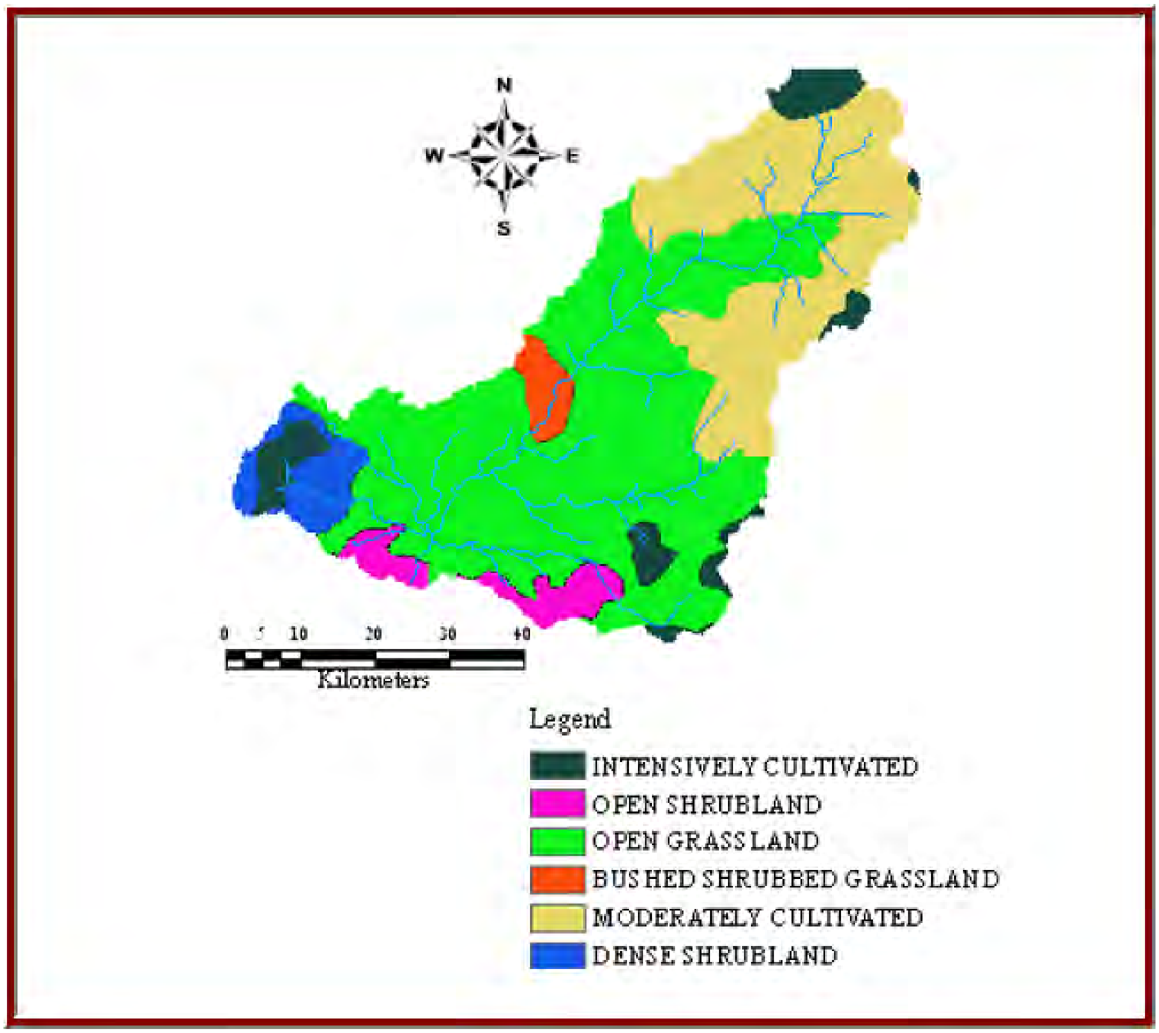

Fig 2.3 Beles River catchments land use map (source:(MOWR))

2.4. Soil

Black clay soils are predominant in the Beles River Basin and particularly in the north-western area where topographic conditions are best suited for irrigation. Upper Beles sub-basin near Pawe plateau is more dominated by Chiromic Vertisols and Chiromic Luvisols which are more dominant at the upper part of the sub-basin. See Figure 2.4.

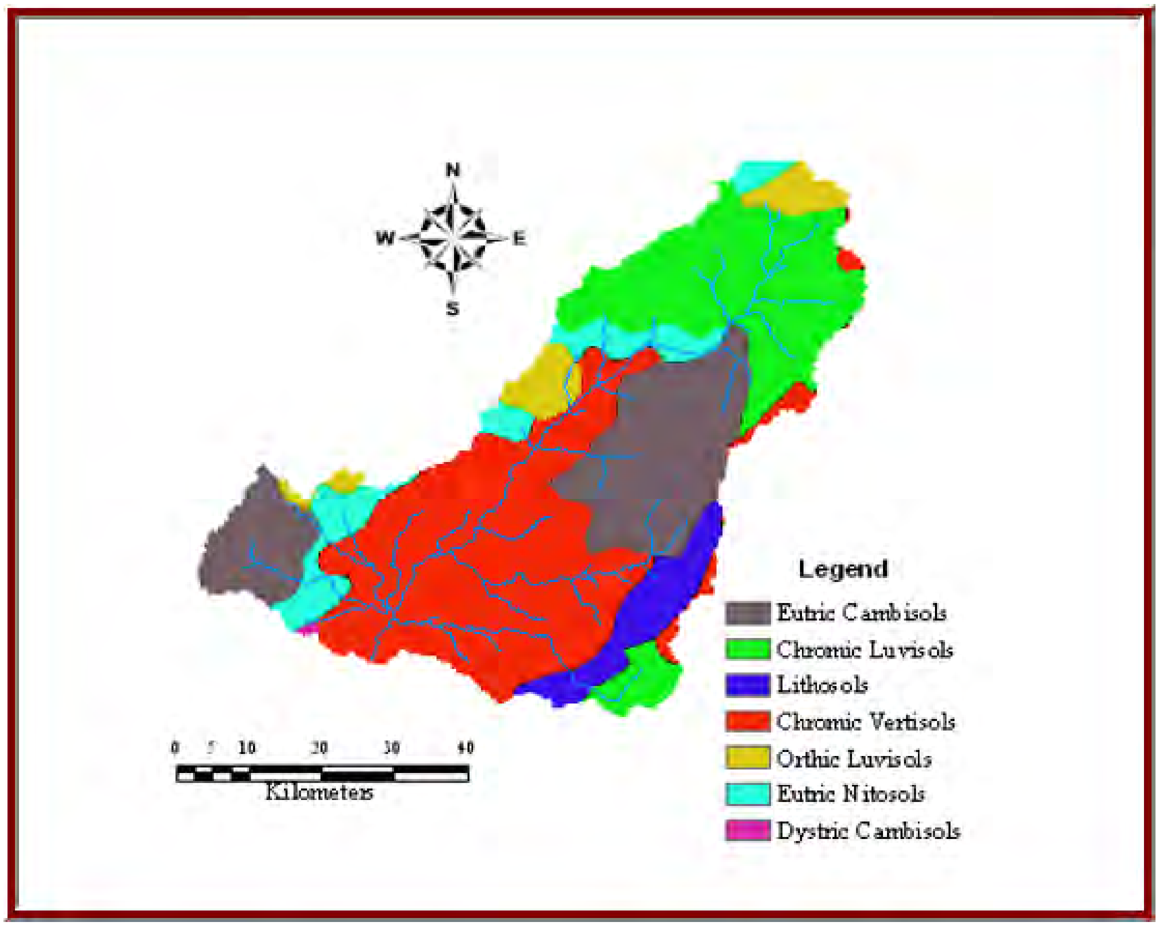

Fig 2.4 - The Beles River catchments soil map (Source :(MOWR))

2.5. Drainage Networks

The Upper Beles sub-basin is comprised of two main rivers namely Main and Gilgel Beles. The head water of Beles River starts from the area close to the western periphery of Lake Tana. Along its way it collects many major and minor tributaries. Gezhig, Burzhi and Chankur, Bula (keteb) and Giligile Beles are the major tributaries. The drainage networks can be viewed in Figure 2.5

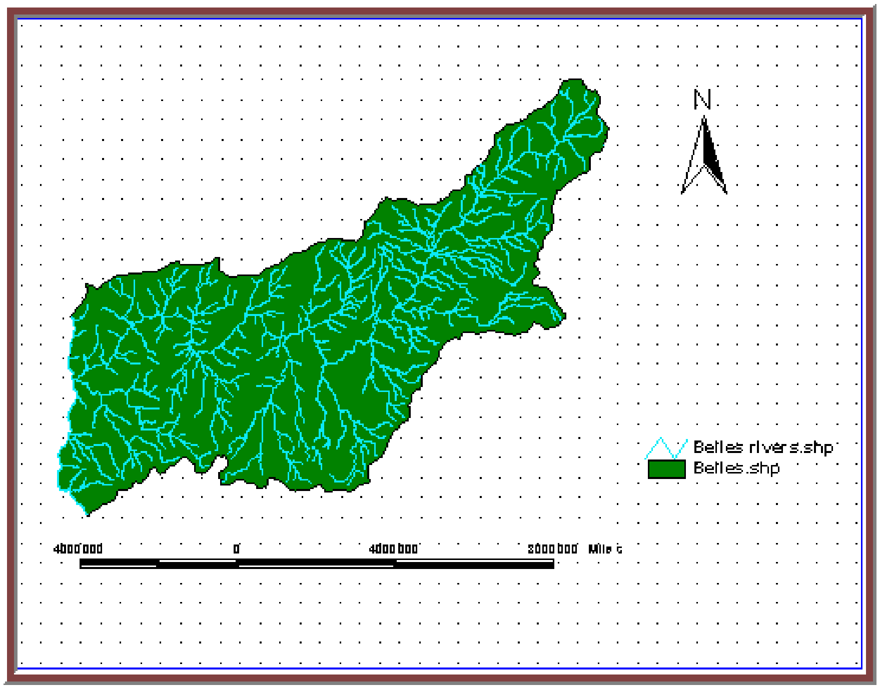

Figure 2.5 Beles River catchments drainage network(source:(MOWR))

3. Literature Review

3.1. Water resource issues in the Blue Nile

Back from the times of earliest civilizations water has been used for agricultural production, water supply, transportation, recreation and energy production. In the history of human-kind, water resource management concerns have passed through different phases that led to the current state of dealing with equally important and exclusively priority water demand and environmental aspects. The increasing population growth, economic development and climate change have proved to be causes of the rising water demand, necessity of improving flood protection systems, and drought (water scarcity). Being one of the rivers which started to be developed in the ancient period, the Nile River is also subject to economic and environmental challenges emanating from the need to balance availability of water with the demand for water (Conway and Hulme, 1996).

The Nile Basin is shared by ten riparian countries: Burundi, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, Sudan, Tanzania, Uganda and Democratic republic of Congo. Present water demand in the basin stems from the increased food and agricultural need generated by the rapidly growing population in the riparian states. In the past, steps taken to make equitable and reasonable use of water resource of the Nile by harmonizing development needs of riparian countries was the major reason for the establishment of the Nile Basin Initiative (NBI). NBI is a process established by the governments of the Nile River riparian countries aimed at meeting the shared vision “to achieve sustainable socio-economic development through the equitable utilization of, and benefit from, the common Nile Basin water resources”.

The Nile basin can be divided into eight major sub-basins identified by taking into account: catchments drainage divides, sub-basin characteristics, and location of river gauging sites. Among the sub-basins, the blue Nile contributes more than 80% flow of the Nile during the wet season and 64% of the water that reaches Aswan in Egypt (El-Khodan, 2003). Flow of the Blue Nile River is regulated by Lake Tana (Dupuis, 1936) which occupies a wide depression at the head of the Blue Nile on the plateau of Ethiopian highlands. From Lake Tana, the river stretches over a length of around 900km to the Sudan border and 1700km to Khartoum.

Through the emerging cooperation of Nile Basin riparian countries various development projects are planned in the Blue Nile Basin. Implementation of those projects needs understanding the catchments hydrology. In this respect, absence of sufficient data and published literature together with the size and complexity of the sub-basins (Conway, 2000) demands putting a lot of effort to come across appropriate methodologies and tools to make optimal use of the water resource development alternatives, where the contribution of this research is relevant.

3.2. Hydrological models in water resource management

Spatial and temporal variability and complexity of hydrological processes and limited availability of spatially and temporally distributed hydrologic, climatologic, geologic, and land use/land cover data challenge the ability to forecast hydrological data. Hydrological models are useful tools to solve such practical problems of forecasting hydrological data. From operational water resources management point of view hydrological models are developed to guide the formulation of water resource management strategies by understanding spatial and temporal distribution of water resources (Dingman, 2002; Lidén and Harlin, 2000).

In terms of spatial domains in catchment modeling, models can be classified as lumped, distributed and semi-distributed ones. The lumped model ignores spatial distribution of the catchment characteristics, represented by an average single value. In contrast, distributed model approaches capture the system by partitioning the catchment into a number of smaller units. Semi-distributed model is something in between the first two that means the catchment is partitioned but in a coarser unit as compared with distributed model.

In another classification, based on deterministic rainfall–runoff models and mathematical solutions, models are classified into physical, conceptual, and empirical models.

- Physically based models are based on physical laws that include a set of conservation equations of mass, momentum, energy and specific case entropy to describe the real world physics that governs nature (Dingman, 2002).

- Conceptually based models consider physical laws but in a simplified form that is able to explain the hydrologic behavior by empirical expression. Examples of this approach are HEC-HMS SMA, Tank, SMAR, Sacramento, TOPMODEL, HBV;x

- Empirically based models do not aid in physical understanding. However, they contain parameters that may have physical characteristics that allow the modeling of input-output patterns based on empiricism. Examples of this approach are unit hydrograph, rational method, etc.

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

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

3.3. Previous studies in the Area.

Previous study on the area entitled HYDROLOGICAL STUDY OF THE TANA-BELES SUB-BASINS - SURFACE WATER INVESTIGATION (by SMEC international pty Ltd., January 2008), is conducted under the coordination of Ministry of water resources.

In this study document comparison of Rainfall-Runoff models are done on the Beles catchment. Three rainfall-runoff models are selected for the comparison: Watbal, Rainrun, and NAM. All the three models are conceptual lumped parameter models. Model calibration was carried out for selected periods for which complete data sets were available on runoff and rainfall. To compare the models two evaluation criterion were used: the correlation coefficient between observed and simulated monthly flows and the goodness of fit based on the deviation between observed and simulated average annual flow volume.

In Table 3.1 the results are shown for two calibration periods: April 1983 – February 1991, and April 1991 – September 2003.

Table 3.1 Comparison rainfall-runoff models for the Beles River

Model	Apr’ 83 – Feb’91		Apr’91 –Sep’03		Average	
	r^2	Fit	r^2	Fit	r^2	Fit
Rainrun	79.8	96.2	87.9	95.6	83.9	95.9
Watbal	88.2	96.5	81.3	87.5	84.8	92.0
NAM	80.8	81.0	86.4	97.0	83.6	88.5

For the Beles catchment the Rainrun model scores best on the average annual runoff and average on the monthly correlation coefficient. The NAM model performs rather poor on the annual runoff volume. The simulated annual runoff seems largely over-estimated for the years 1989 and 1996. However, also here the results seem to be affected by inaccurate rainfall estimates. For example when the rainfall and observed runoff in the years 1988 and 1989 is compared it appears that the runoff in 1988 is almost twice the runoff in 1989, whereas rainfall is of similar magnitude in both years.

4. Materials and Methods

4.1. Data collection

4.1.1. Hydrological Data

There are two gauging station in the Beles sub- basin. The gauged part of the basin is about 30% of the total basin area which is 3212.3km2 (See Figure 4.1). Flow data for Main Beles at bridge and Gilgel Beles flow near Mandura since 2000 G.C. were collected from the Department of Hydrology of the Ministry of Water Resources.

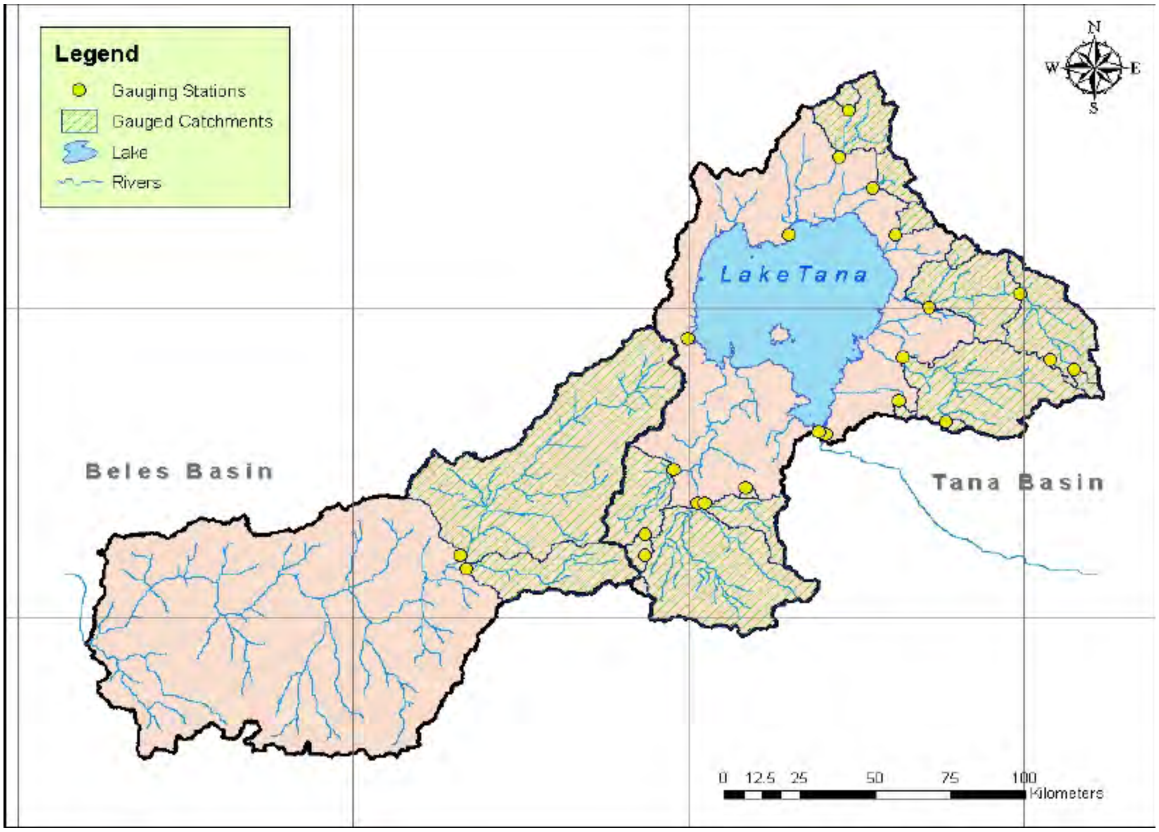

Figure 4.1 Hydrological gauging stations in the Tana and Beles Basins (source SMEC)

4.1.2. Meteorological Data

All meteorological stations are found out of the upper Beles catchment. Name of stations used for this research are pawe, Dangla, Mandura, Chagni, Enjibara, Zege and Bahirdar.From which pawe, mandura and Dangla stations are found on the lower Beles catchment and the others are out of the catchment. The meteorological data measured from such stations are Rainfall, Maximum and Minimum temperature, Relative humidity, Wind speed and Sunshine hour. All meteorological data are found from the Ethiopian Meteorological Agency. Table 4.1 presents Statistical summation of rainfall data. Figure 4.2 shows meteorological stations around the Beles catchment.

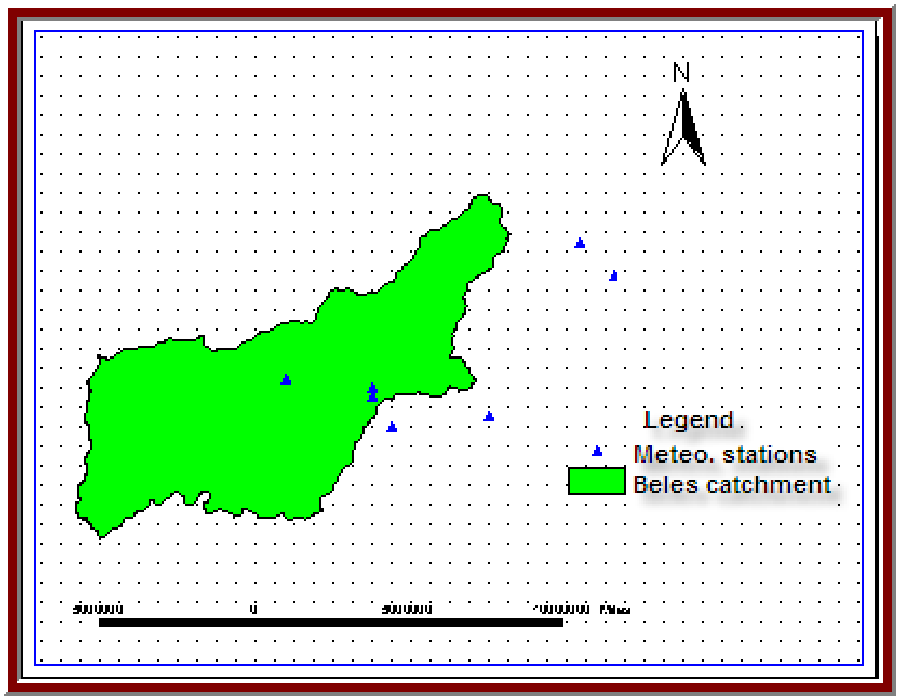

Figure 4.2 Meteorological stations around the Beles catchments

No	Station	Record period	Record length	% missing	Mean annual rainfall
1	Bahirdar	2002 - 2007	6	2.3	1520
2	Zege	2002 - 2007	6	3.3	1657
3	Pawe	2002 - 2007	6	8	1465
4	Chagni	2002 - 2007	6	4.2	1795
5	Mandura	2002 - 2007	6	12.5	1000
6	Dangla	2002 - 2007	6	1.9	1552
7	Engibara	2002 - 2007	6	20.8	2000

Table 4.1 Statistical summation of rainfall data

4.2. Description of used Model

4.2.1. RRL SMAR Model

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 on Figure 4.3 (next page). 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, a parametric solution of the differential routing equation in a single input single output system.

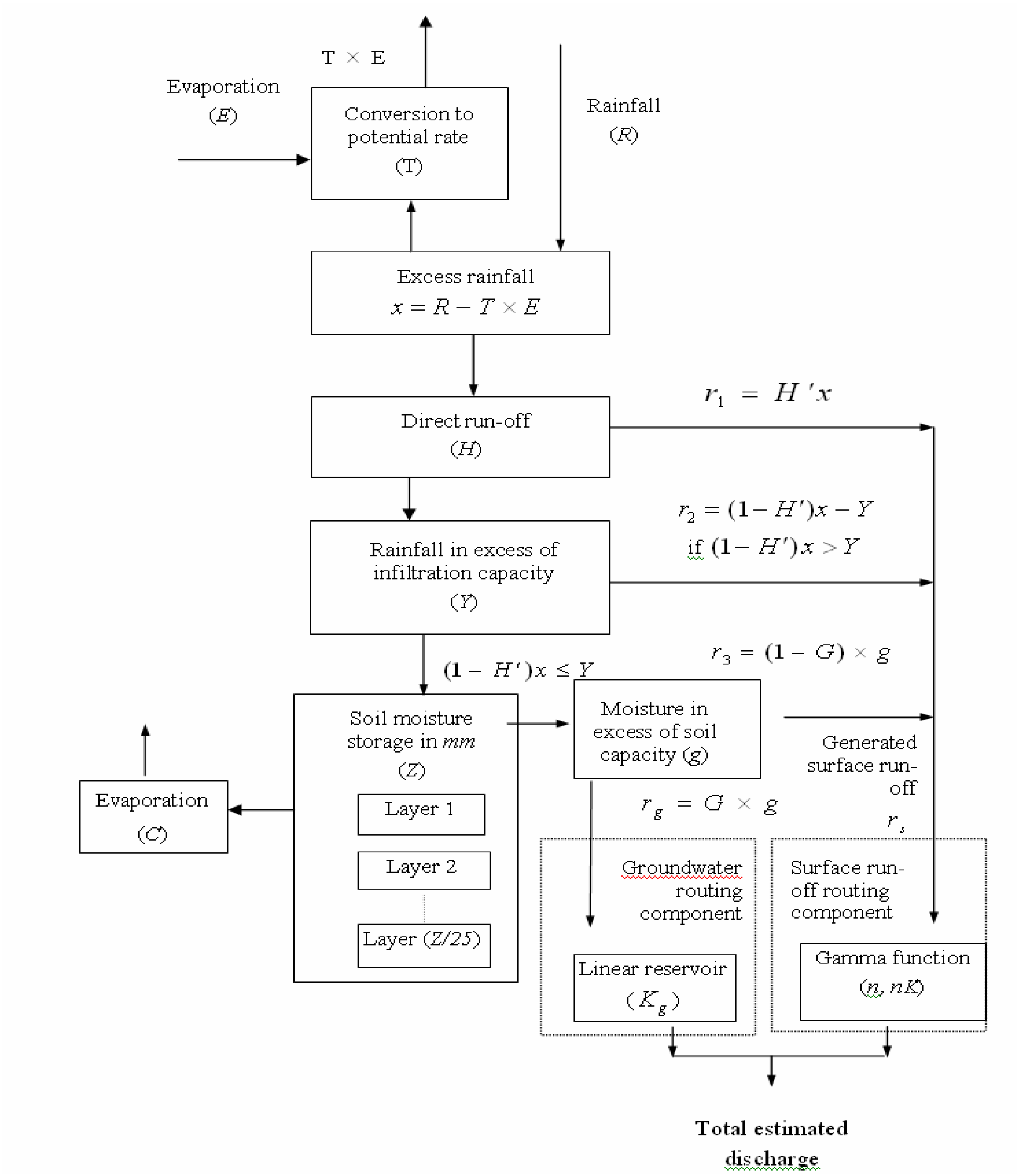

Figure 4.3 Structure of the SMAR rainfall-runoff model (Source: (RRL user guide)

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.

4.2.2. RRL Tank Model

The Tank model is a model composed of four Tanks laid vertically in series as shown in Figure 4.4. 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, output from the third Tank as sub-base runoff and output from the fourth Tank as base flow.

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.

The total runoff is calculated as the sum of the runoffs from each of the Tanks. The runoff from each Tank is calculated as:

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

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.

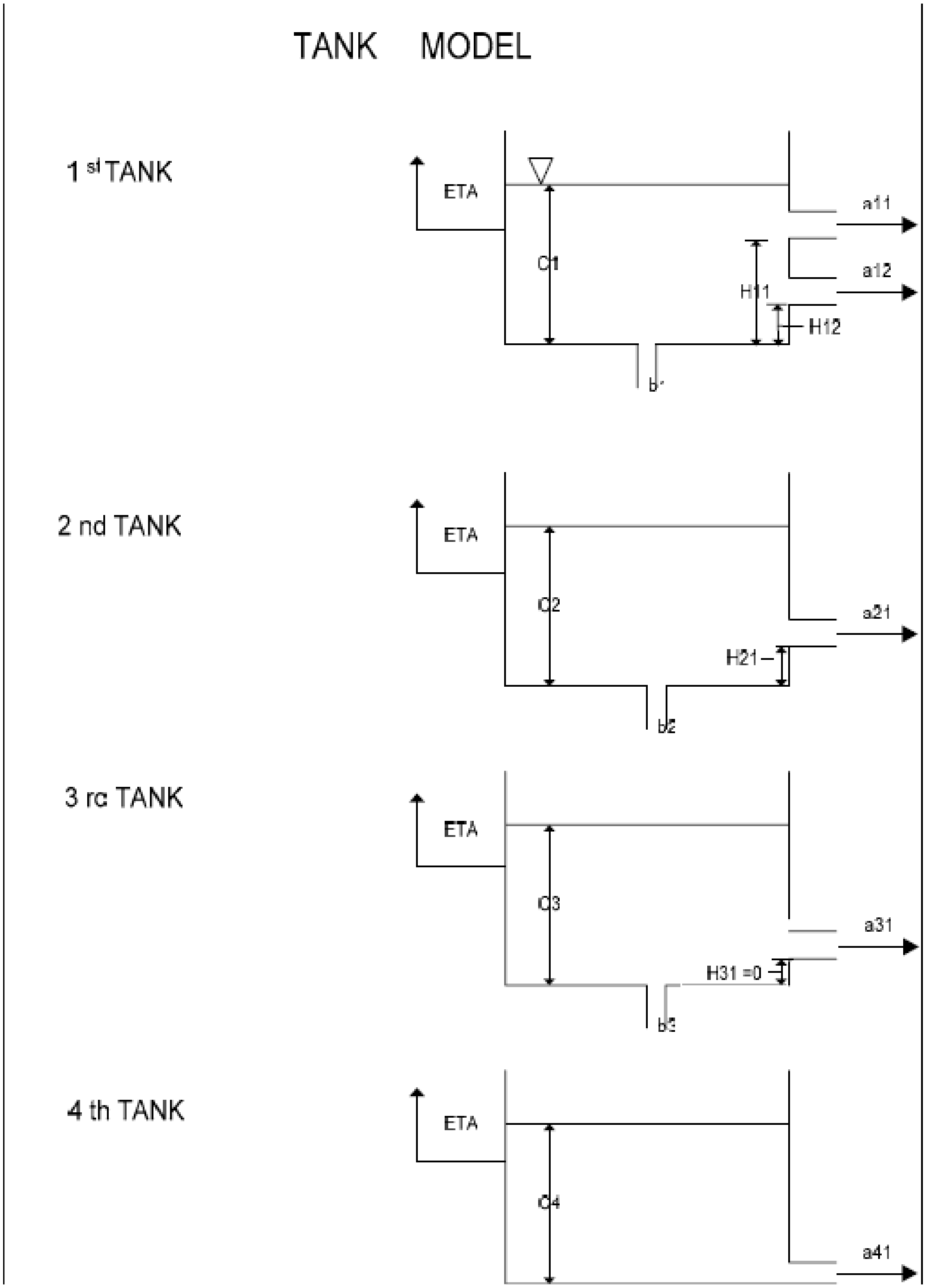

Figure 4.4 Structure of the RRL Tank rainfall-runoff model

4.2.3. RRL Sacramento Model

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

The Sacramento model uses a total of 16 parameters to simulate the water balance. Of these:

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

These parameters are listed and described in Table 4.1.

UZTWM	Mm	Upper Zone Tension Water Maximum. The maximum volume of water held by the upper zone between field capacity and the wilting point which can be lost by direct evaporation and evapotranspiration from soil surface. This storage is filled before any water in the upper zone is transferred to other storages.
UZFWM	Mm	Upper Zone Free Water Maximum, this storage is the source of water for interflow and the driving force for transferring water to deeper depths.
LZTWM	Mm	Lower Zone Tension Water Maximum, the maximum capacity of lower zone tension water. Water from this store can only be removed through evapotranspiration.
LZFSM	M	Lower Zone Free Water Supplemental maximum, the maximum volume from which supplemental baseflow can be drawn.
LZFPM	Mm	Lower Zone Free Water Primary Maximum, the maximum capacity from which primary base flow can be drawn.
UZK	1/day	The ratio of water in UZFWM, which drains as interflow each day.
LZSK	1/day	The ratio of water in LZFSM which drains as baseflow each day.
LZPK	1/day	The ratio of water in LZFPM, which drains as baseflow each day.
PFREE	-	The minimum proportion of percolation from the upper zone to the lower zone directly available for recharging the lower zone free water stores.
REXP	-	An exponent determining the rate of change of the percolation rate with changing lower zone water storage.
ZPERC	-	The factor applied to PBASE to define maximum percolation rate.
SIDE	-	The decimal fraction of observed base flow, which leaves

		the basin, as groundwater flow.
SSOUT	m3/s/km2	The volume of the flow which can be conveyed by porous material in the bed of stream.
PCTIM	-	The impervious fraction of the basin, and contributes to direct runoff.
ADIMP	-	The additional fraction of pervious area, which develops impervious characteristics under soil saturation, conditions.
SARVA	-	A decimal fraction representing that portion of the basin normally covered by streams, lakes and vegetation that can deplete streamflow by evapotranspiration.

Table 4.1 RRL Sacramento Model parameters

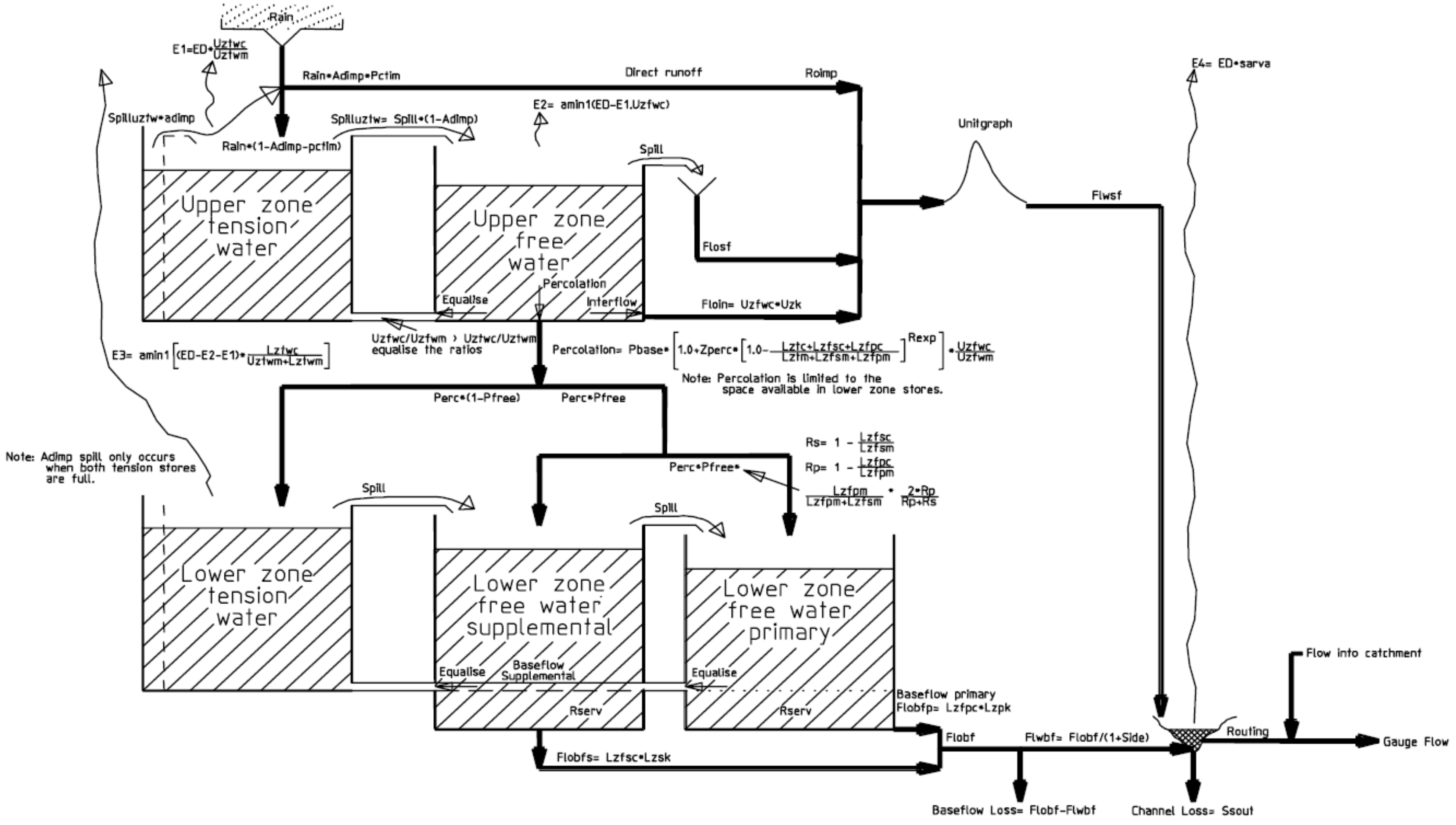

Fig 4.5 Structure of the Sacramento Rainfall runoff Model

4.3. Model data Input

Data requirement of the above three Models are the same .The major inputs to the RRL Models are as follows:

4.3.1. Rainfall data

Rainfall data in mm/day entered using the Models data storage format.

4.3.2. Observed flow

Observed flow found is in m^3/s then changed in mm/day and entered the Model data storage.

4.3.3. Evapotranspiration

Evapotranspiration is calculated using FAO Penman-Monteith equation (eq. 4.1). This equation is derived from the original Penman-Monteith equation and the equations of the aerodynamic and surface resistance.

$$ETo = \frac{0.408\Delta\left(R_n - G\right) + \gamma \frac{900}{T + 273} U_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34U_2\right)} \quad \text{… Eq (4.1)}$$

Where

ET_o	evapotranspiration [mm day^{-1}]
R_n	net radiation at the crop surface [MJ m^{-2} day^{-1}]
G	soil heat flux density [MJ m^{-2} day^{-1}]
T	mean daily air temperature at 2 m height [°C]
u_2	wind speed at 2 m height [m s^{-1}]
e_s	saturation vapour pressure [kPa]
e_a	actual vapour pressure [kPa]
$e_s - e_a$	saturation vapour pressure deficit [kPa]
Δ	slope vapour pressure curve [kPa $°C^{-1}$]
γ	psychrometric constant [kPa $°C^{-1}$]

The equation uses standard climatological records of solar radiation (sunshine), air temperature, humidity and wind speed. To ensure the integrity of computations, the weather measurements should be made at 2 m (or converted to that height) above an extensive surface of green grass, shading the ground and not short of water.

4.3.4 Catchment area (km^2)

The catchment area of gauged part of Beles (Upper Beles) is used for the Model.

4.4. Calibration

Calibration is a major aspect of hydrological modeling and is aimed at fitting simulated versus measured discharge best. Calibration of each model was done separately for the Beles catchment. Four years data was taken for calibration from the period 2002 up to 2005. Manual and Automatic calibration is used because it can be used to investigate how the different parameters change the shape of the simulated hydrograph and refine an optimized calibration. During calibration of the models a simple sensitivity analysis was done to identify the most sensitive model parameters. This was followed by a manual trial and error procedure until the result of the calibrated model was considered acceptable.

4.5. Validation

The degree of accuracy of parameter estimates was assessed by applying the model to different data set that was not used for calibration. Henriksen et al. (2003) defines validation as a process of demonstrating capability of a given site-specific model to make predictions satisfactorily accurate at other site and/or outside the calibration period.

4.6. Models evaluation criteria

In this research the models are evaluated using their performance. The performance of a model must be evaluated on the extent of its accuracy, consistency and adaptability (Goswami et al., 2005). Assessing performance of a hydrologic model (Krause et al., 2005) requires subjective and/or objective estimates of the closeness of the simulated behavior of the model to observations.

Performance of RRL models was evaluated in a subjective way by following the basic approach of assessing model efficiency by visual inspection. This enabled examining systematic behavior, over- or under prediction, and dynamic behavior, timing, rising limb, and recession curve, of the simulated and observed hydrographs visually during calibration and validation of the model. Objective assessment of the model was done by mathematical estimation of the error; it was used as the main criteria for accepting the parameter estimates while calibrating the model manually and also while testing transferability of parameter set values. The error between simulated and observed runoff was quantified using the following efficiency criteria given in Table 4.2.

Objective function	Definition	Value for Perfect fit
Nash-satcliffe efficiency (Reff)	$1-\frac{\sum\left(Q_{obs}-Q_{sim}\right)^2}{\sum\left(Q_{obs}-\overline{Q_{obs}}\right)^2}$	1
Efficiency using ln(Q) (logReff)	$1-\frac{\sum(\ln Q_{obs}-\ln Q_{sim})^2}{\sum(\ln Q_{obs}-\overline{\ln Q_{obs}})^2}$	1
Coefficient of determination (R^2)	$\frac{(\sum(Q_{obs}-\overline{Q_{obs}})(Q_{sim}-\overline{Q_{sim}}))^2}{\sum(Q_{obs}-\overline{Q_{obs}})^2\sum(Q_{sim}-\overline{Q_{sim}})^2}$	1

Table 4.2: Efficiency criteria for evaluating model performance

4.7. Model Parameters transfer to the ungauged catchments

Transfer of model parameters to ungauged catchments generally needs a different study approach on the catchments. Knowledge of the catchments behavior is important to know the hydrology of the catchment. If the catchments are Hydrologically homogeneous, the model parameters of a gauged catchment can be used to the ungauged catchment as it is. Likewise, in order to observe hydrological homogeneity of two gauged and ungauged catchments of Beles River, their catchment similarity should be known. Therefore, in this study, the correlation of the land cover and soil type between gauged and ungauged catchments of Beles River is checked.

5. Hydro meteorological and Hydrological data analysis

5.1. General:

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

5.2. Data screening

5.2.1. Rainfall data

Rough rainfall data screening of seven meteorological stations in the study area was first done by visual inspection of daily rainfall data. To simply visualize the data, charts are done for the stations of Pawe, Dangla, Mandura, Enjibara, Chagni, Bahirdar and Zege for the record period of Jan. 1, 2002 to Dec. 31, 2005. Here, two strange high rainfall values were found on the data of October 16, 2002 and April 27, 2003 at Pawe and Mandura stations respectively And such data considered as a missing data. (The charts are attached as Annex …1).

Time series plotting of monthly rainfall data show that the seven stations have similar periodic pattern of records (See Fig.5.1 below).

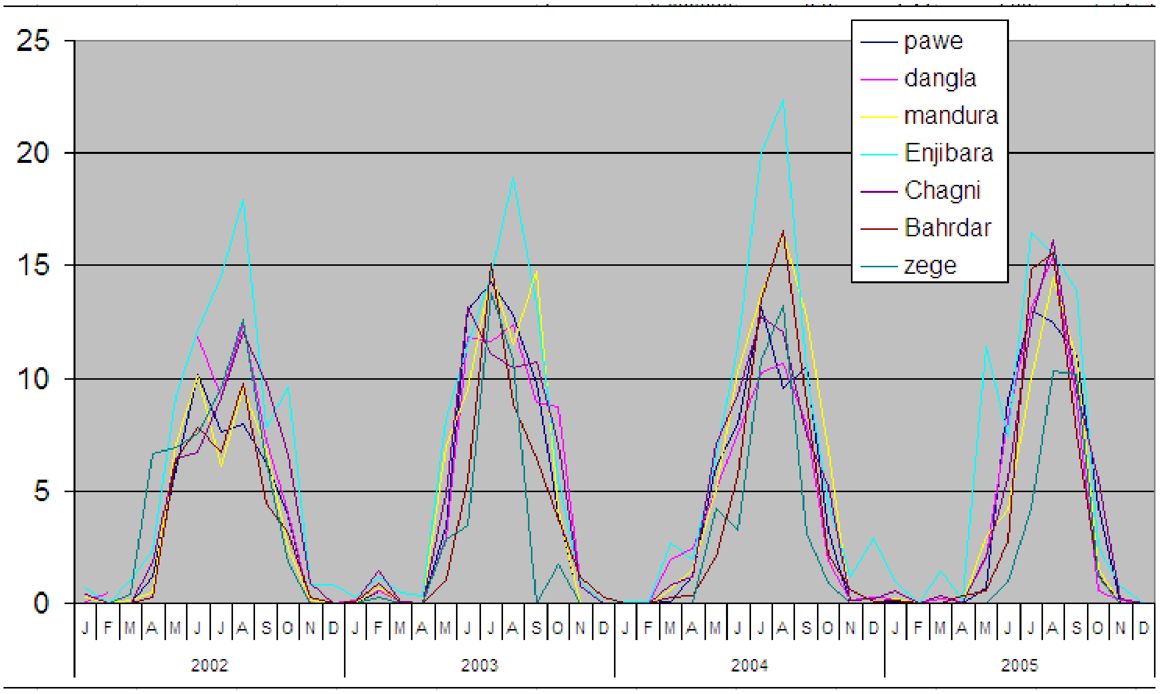

Fig 5.1 Time series of monthly rainfall data

Beside the visual and graphical data comparison, assessment of spatial homogeneity of the daily rainfall data indicated good correlation between records of the seven meteorological stations. Despite the noticeable rainfall amount variation pattern in the area, computation of correlation coefficient on the daily records between April 2002 and March 2007 showed values between 0.3 and 0.5 which is not bad for daily rainfall data series (See Table 5.1 below). For the same period, mentioned above, the correlation between the monthly records of the stations was very good with a coefficient value between 0.8 and 0.9 (See Table 5.2 below).

	Pawe	Dangla	Mandura	Bahirdar	Zege	Enjibara	Chagni
Pawe	1.0	0.4	0.4	0.4	0.3	0.4	0.4
Dangla	0.4	1.0	0.4	0.4	0.4	0.5	0.3
Mandura	0.4	0.4	1.0	0.3	0.3	0.3	0.4
Bahirdar	0.4	0.4	0.3	1.0	0.3	0.4	0.3
Zege	0.3	0.4	0.3	0.3	1.0	0.4	0.3
Enjibara	0.4	0.5	0.3	0.4	0.4	1.0	0.4
Chagni	0.4	0.3	0.4	0.3	0.3	0.4	1.0

Table 5.1 Correlation coefficient matrix of the seven meteorological stations for the period (2002-2007) based on daily data

	Pawe	Dangla	Mandura	Bahirdar	Zege	Enjibara	Chagni
Pawe	1.0	0.9	0.9	0.9	0.8	0.9	0.9
Dangla	0.9	1.0	0.9	0.9	0.8	0.9	0.9
Mandura	0.9	0.9	1.0	0.9	0.8	0.9	0.9
Bahirdar	0.9	0.9	0.9	1.0	0.8	0.9	0.9
Zege	0.8	0.8	0.8	0.8	1.0	0.8	0.8
Enjibara	0.9	0.9	0.9	0.9	0.8	1.0	0.9
Chagni	0.9	0.9	0.9	0.9	0.8	0.9	1.0

Table 5.2 Correlation coefficient matrix of the seven meteorological stations for the period (2002-2007) based on monthly data

5.2.2. River Discharge

Using flow data time series, visual screening of measured flow data for main Beles and Gilgel Beles rivers for the period 2002 - 2005 is conducted. This helped to quick scan the data so as to detect gross errors such as erroneous peak flow, long period of missing records, short term missing records and flows of constant rate. Plotting of time series of the river discharge for main Beles and Gilgel Beles is shown in Figure 5.2 below.

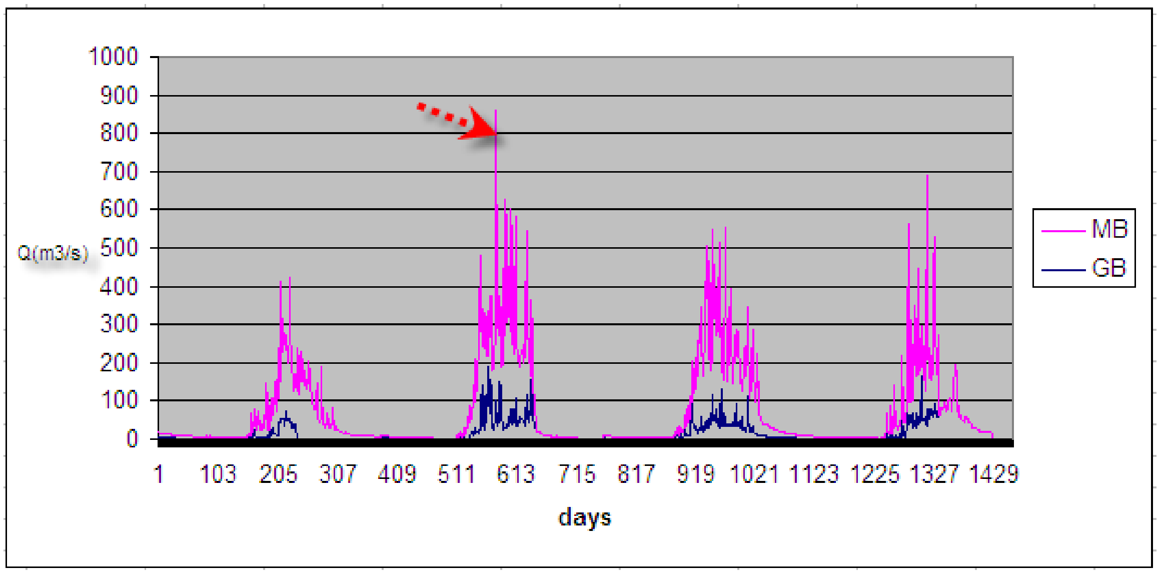

Fig 5.2 Time series of gauged flow for main and Gilgel Beles rivers

5.3. Missing data completion

Missing data is a common problem in hydrology. To perform hydrological analysis and simulation using data of long time series, filling in missing data is very important. The missing data can be completed by using meteorological and hydrological stations located in the nearby stations, provided that the stations are located in a hydrologically homogenous region.

5.3.1. Filling in missing rainfall data

Application of regression analysis made possible completing short and long period breaks in data series for given meteorological station. Because the collected daily rainfall data for most of the stations starts in 2002, missing daily rainfall data from 2002 to 2007 were filled-in for all stations using relations derived for each station. The equations derived are attached as (Annex 2)

5.3.2. Filling in missing air temperature

Missing air temperature data of the meteorological stations were completed by following the same steps and procedures followed to fill-in missing rainfall data. The equations are attached as (Annex 2)

5.3.3. Filling in missing Runoff Data

Runoff records of main Beles and Gilgel Beles rivers were completed by correlating their long term flow rate records. Two equations - Eq. (1) and Eq. (2) - were derived by regression analysis using excel sheet to fill missing data of main Beles river for the months from December to May (when the flow rate is low), and for the months from June to November (when the flow is high).

$$MB \text{ (for low flow)} = 0.54*GB+0.97 \qquad \dots \text{Eq. (1)}$$

$$MB \text{ (for high flow)} = 1.78*GB+43.75 \qquad \dots \text{Eq. (2)}$$

where: MB is Main Beles
GB is Gilgel Beles

5.4. Evapotranspiration

Evapotranspiration of upper beles catchment is estimated using the method mentioned on the section 4.3.1. The data used to estimate evapotranspiration of this catchement is minimum and maximum temperature, relative humidity, wind speed and sunshine hour. Such data are found from the stations of Pawe, Dangla and Bahirdar. Then Daily evapotranspiration of such stations are calculated and changed in to the areal evapotranspiration of the upper Beles catchment. Table (5.3) shows monthly evapotranspiration of the upper Beles catchment.

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	Dec
2002	116.38	125.25	143.27	131.6	109.75	107.35	90.51	92.41	93.58	97.31	99.62	99.83
2003	110.27	123.76	141.41	142.4	128.3	96.91	75.92	88.15	89.17	102.36	108.48	104.93
2004	113.13	112.82	130.17	142.1	122.2	109.79	98.71	99.46	98.65	101.84	107.23	97.96
2005	107.47	116.99	132.27	140.2	135.86	112.76	92.63	96.25	93.03	113.58	110.24	108.24
2006	104.46	114.26	132.85	122.6	139.91	103.76	100.51	94.23	102	105.27	96.11	91.18
2007	88.27	118.21	128.87	135.8	124.63	99.39	82.91	86.52	91.36	91.36	91.35	87.75

Table 5.3 monthly evapotranspiration of the upper Beles catchment

5.5. Meteorological data transfer

There are no any meteorological stations on the upper Beles catchment. Therefore, for calculating areal rainfall of the upper Beles catchment in this study, three stations are created in the catchment and designated as B1, B2, and B3.Then data is transferred from the nearby stations using Inverse Distance method (Equation 3). The rainfall data are transferred to station B1 from the meteorological stations of Pawe, Dangla and Mandura , to station B2 from the stations of Enjibara and Chagni, and to station B3 from the stations of Bahirdar and Chagni. Then changed in to the areal rainfall for the cachment.

$$B = \frac{\sum_{i=1}^{N}\left(\frac{p_i}{d_i^{\,2}}\right)}{\sum_{i=1}^{N}\left(\frac{1}{d_i^{\,2}}\right)} \qquad \text{…Eq.(3)}$$

Where

B = Precipitation at the ungauged point

P = Precipitation at the gauged point

D = Distance from unguaged point to measured point

5.6. Areal Rainfall

Daily areal rainfall of upper Beles catchment is calculated from the daily point transferred data of stations B1, B2, and B3. by using the Thiessen polygon method (Equation 4). Figure 5.3 shows Thiessen polygon for the main Beles river catchment.

$$R_{areal} = \left(B_1 * 32.3\% + B_2 * 30.6\% + B_3 * 38.1\%\right) \qquad \text{… Equ. (4)}$$

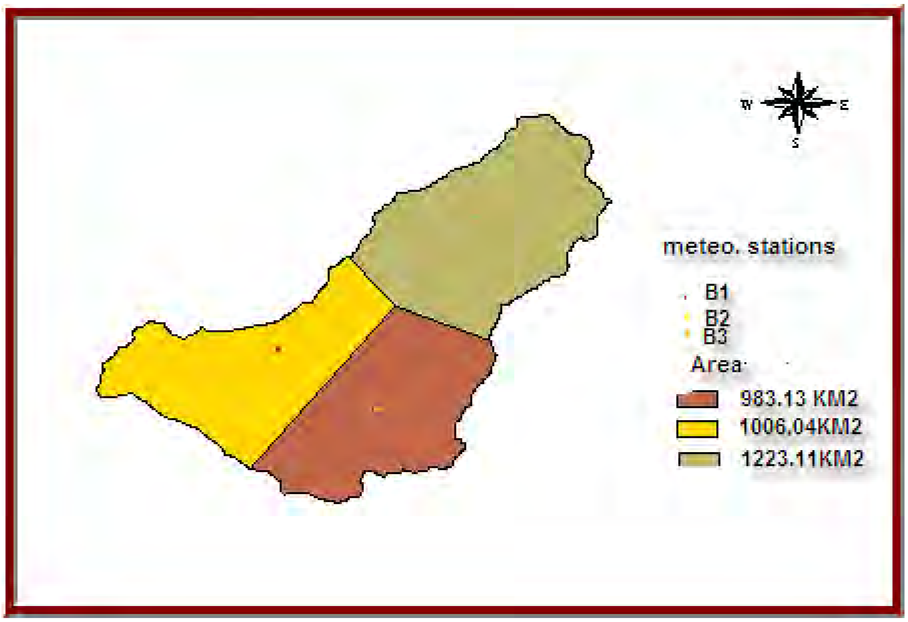

Fig 5.3 Thiessen polygon for main Beles river catchment

6. Hydrological Modeling

6.1. Model analysis for RRL SMAR Model

6.1.1. Calibration

The period taken for calibration and verification was between January 1, 2002 and December 31, 2007. From this period, the first four years are taken for calibration and the last two years for verification. Manual and automatic adjustment of the calibration parameters (listed in Table 6.1) resulted in a set of parameters that minimized the difference between observed and simulated discharge for the gauged catchment of main Beles. For visual evaluation, goodness of fit between the observed and simulated flows before and after calibration is shown on Figure 6.1 and Figure 6.2 respectively. As observed on Figure 6.2 the simulated run-off could not catch the pick run-off of the observed run-off since the model underestimates the pick run-off. This is because of the absence of the meteorological stations on the upper Beles catchment and therefore the data used for calibration is by transferring data from the near by stations. Figure 6.3 shows the scatter plot of Nash-sutcliffe efficiency criterion for calibration and validation.

No	Parameters	Optimized	Initial value
1	Groundwater evaporation rate C	0.51	0.00
2	Groundwater runoff coefficient G	0.50	0.00
3	Proportion direct runoff H	0.745	0.00
4	Storage loss coef. Kg	0.60	0.00
5	U.H linear routing N	5.94	1.00
6	U.H linear routing component NK=N*K	2.00	1.00
7	Evap. Conversion param.T	1.020	0.00
8	Infiltration rate Y	25	0.00
9	Soil moisture total storage depth Z	225	200

Table 6.1 Optimal model calibration parameters of RRL SMAR model for the main Beles river catchment.

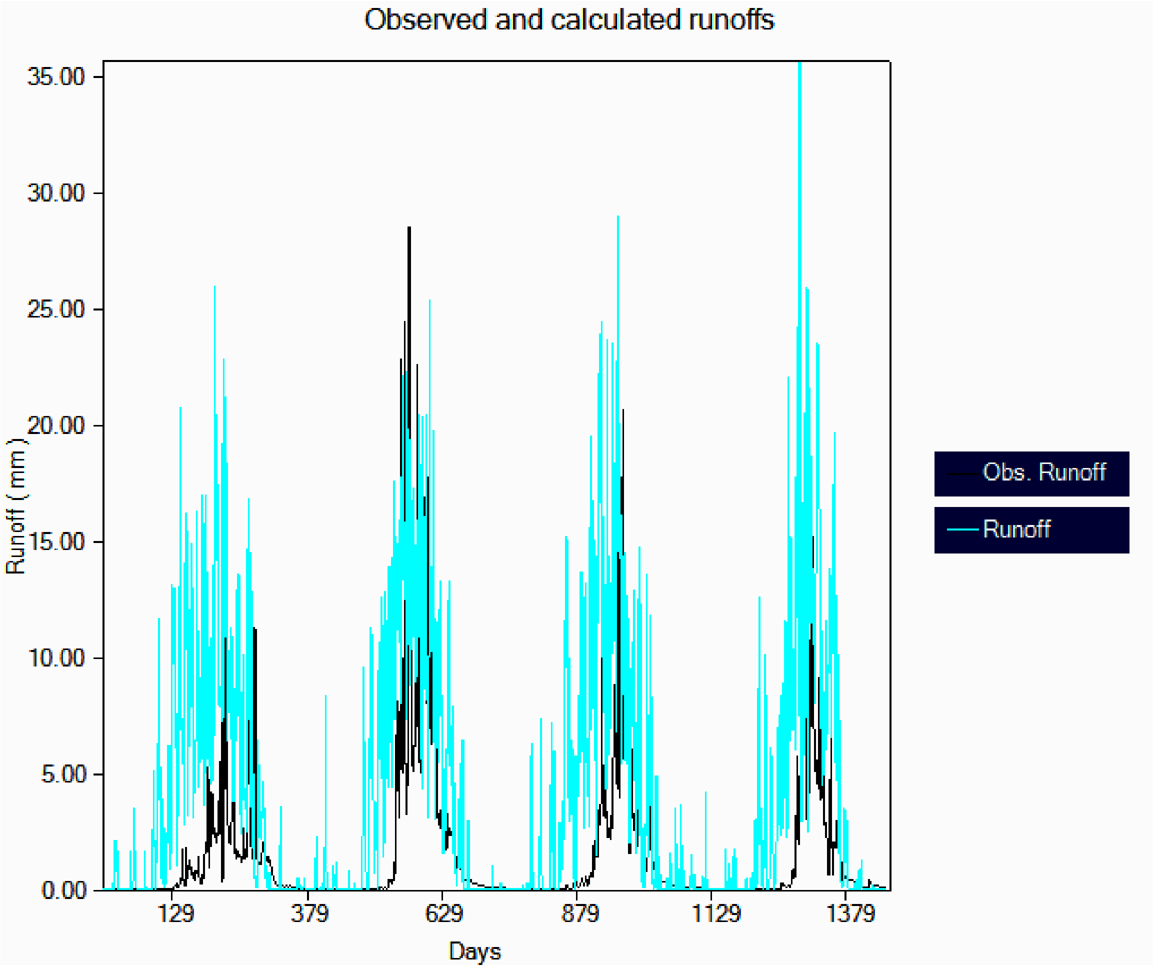

Figure 6.1 The SMAR Model before calibration for Beles River at main Beles

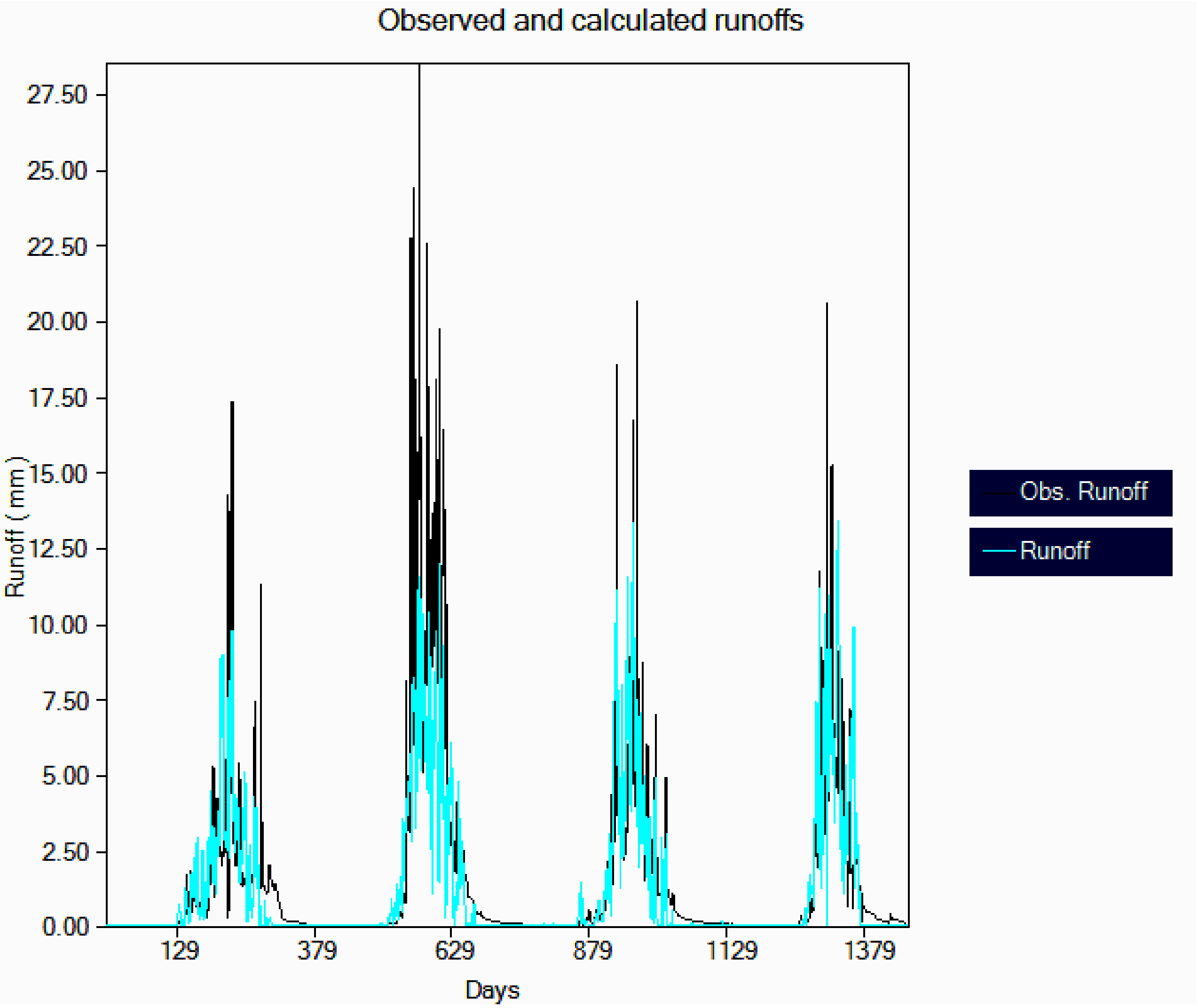

Figure 6.2 The SMAR Model after calibration for Beles River at main Beles

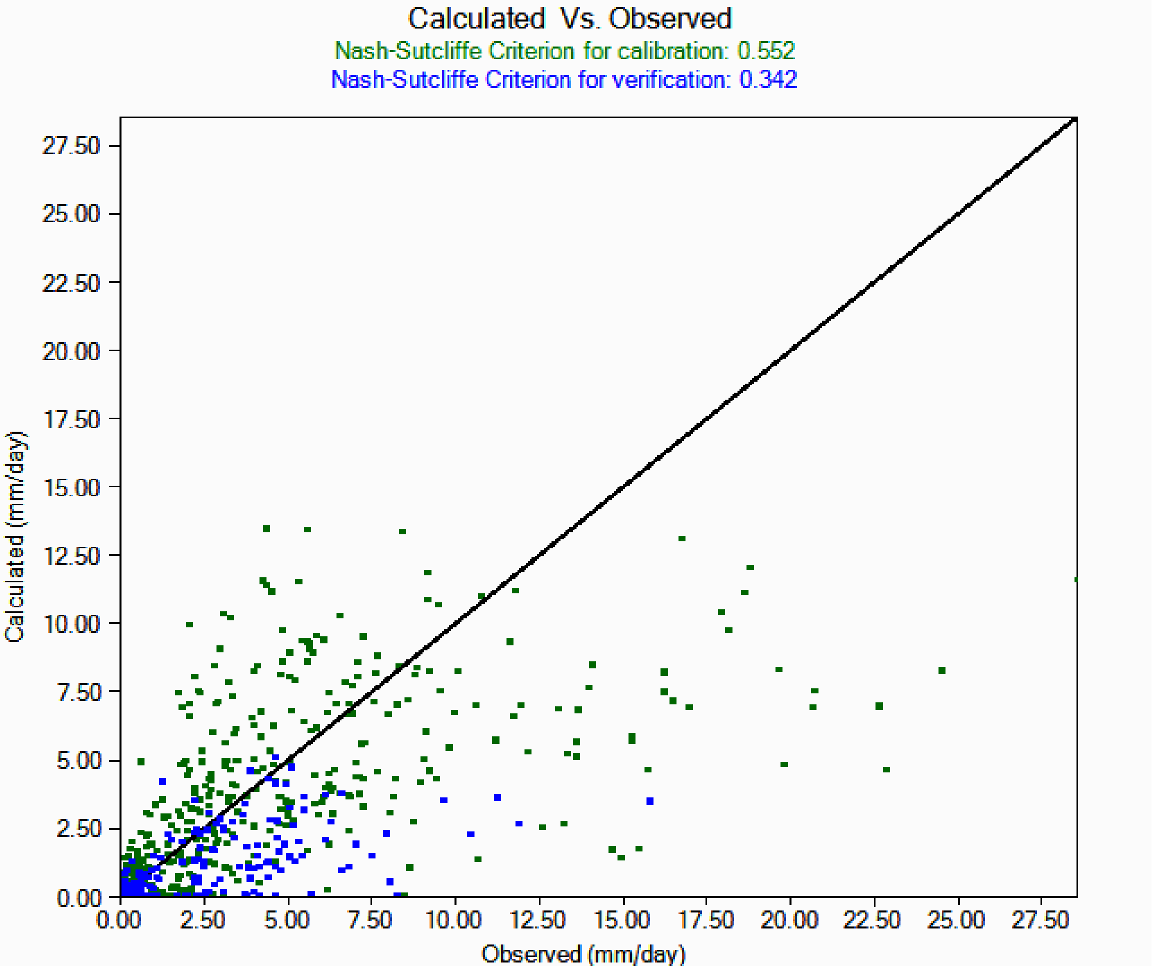

Figure 6.3 The SMAR Model scatter plot of calibration and verification result for Beles River at main Beles

6.1.2. Sensitivity:

Sensitivity analysis for SMAR Model are conducted and some parameters are found highly sensitive, some low sensitive and the rests are found non-sensitive - meaning model efficiency will be constant whether the parameter value has increased or decreased.

Highly sensitive parameters are proportion direct runoff H, U.H linear routing N, U.H linear routing component NK = N*K and Evap. Conversion param.T. Low sensitive parameter is Groundwater evaporation rate C. And non sensitive parameters are Ground water runoff coefficient (G), Storage loss coef. Kg, Infiltration rate Y, and Soil moisture total storage depth Z.

Sensitivity graphs are attached as (Annex 3)

6.1.3. Verification:

The RRL SMAR model used data for verification from the period January 1, 2006 up to December 31, 2007 (i.e., two years data).The model performance for validation using Nash-sutcliffe criterion was not good as the result is Reff = 0.342, which is less than 50 percent. The validation result is shown on the graph in Figure 6.4 below.

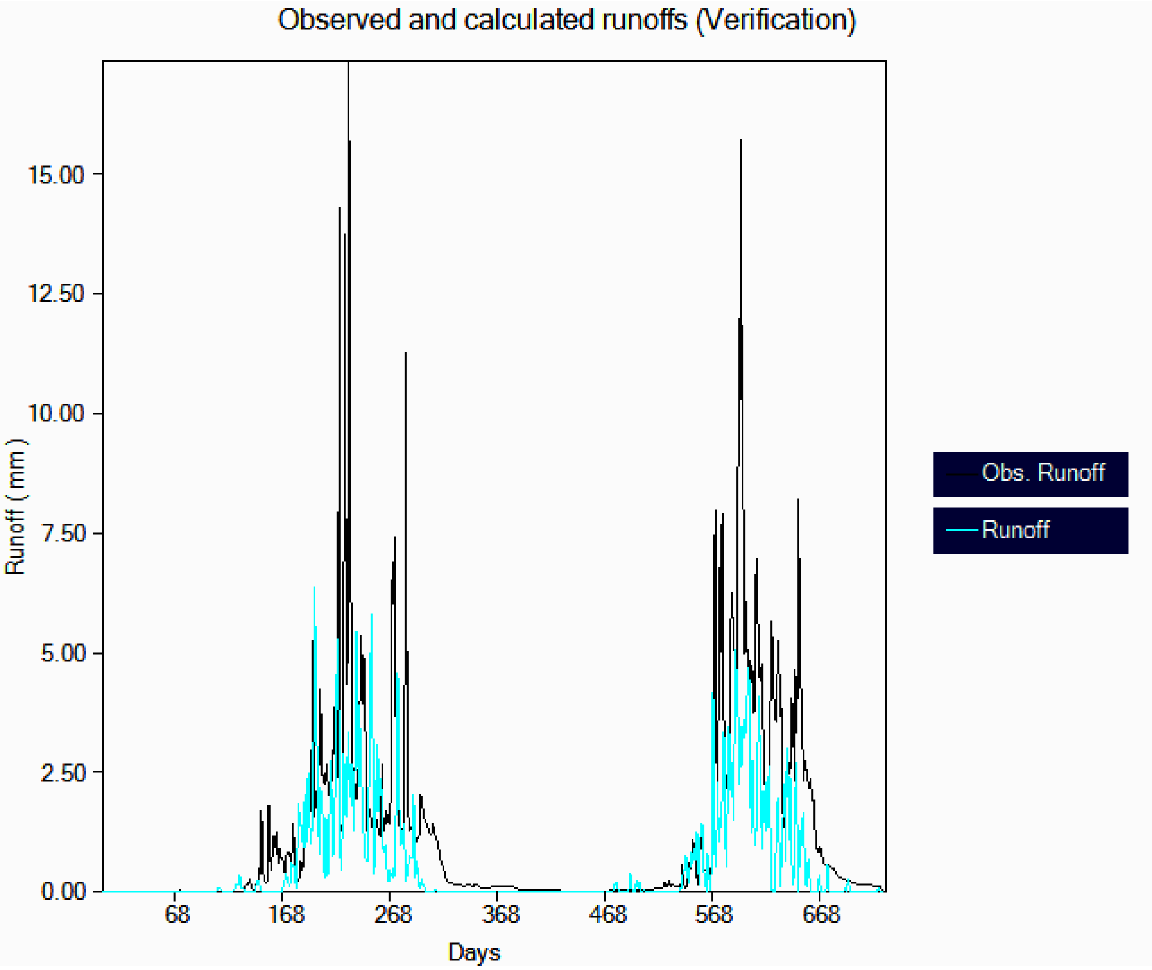

Figure 6.4 The SMAR Model Verification result for Beles River at main Beles

6.2. Model analysis for RRL Tank model

6.2.1. Calibration

For the RRL Tank model, the calibration and verification period was taken the same as RRL SMAR model. Similarly, four years data for calibration and two years data for verification are used. Manual and automatic adjustment of model parameters is carried out. After calibration the model underestimates the pick runoff that is because of the absence of the meteorological stations on the upper Beles catchment and the data used for calibration is by transferring data from the near by stations. The result of the optimized model parameters are shown in Table 6.2. The graphs of observed and simulated flow before calibration and after calibration are shown on Figure 6.5 and 6.6, respectively. In order to assess the efficiency of this model using Nash-Sutcliffe criterion the scatter plot is shown on Figure 6.7.

No	Parameters	Optimized Value	Initial value
1	a_{11}	0.00	0.2
2	a_{12}	0.2	0.2
3	a_{21}	0.350	0.2
4	a_{31}	0.459	0.2
5	a_{41}	0.000	0.2
6	alpha	5.000	0
7	b_1	0.039	0.2
8	b_2	0.114	0.2
9	b_3	0.275	0.2
10	C_1	40	20
11	C_2	28	20
12	C_3	0.00	20
13	C_4	0	20
14	H_{11}	431	0
15	H_{12}	145	0
16	H_{21}	15	0
17	H_{31}	9	0
18	H_{41}	0	0

Table 6.2 Optimal model calibration parameters of RRL TANK model for the Beles river catchment

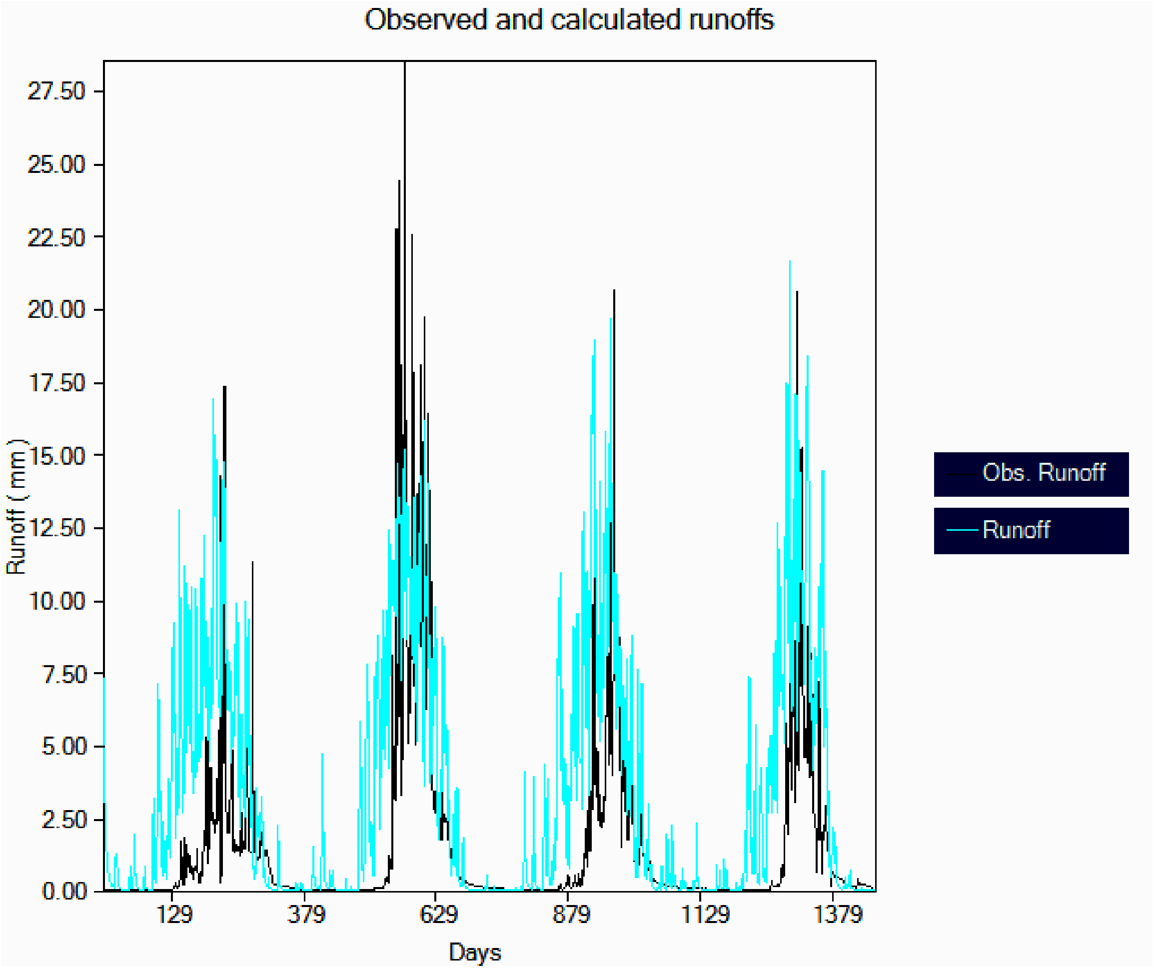

Fig.6.5 RRL Tank Model before calibration for Beles River at main Beles

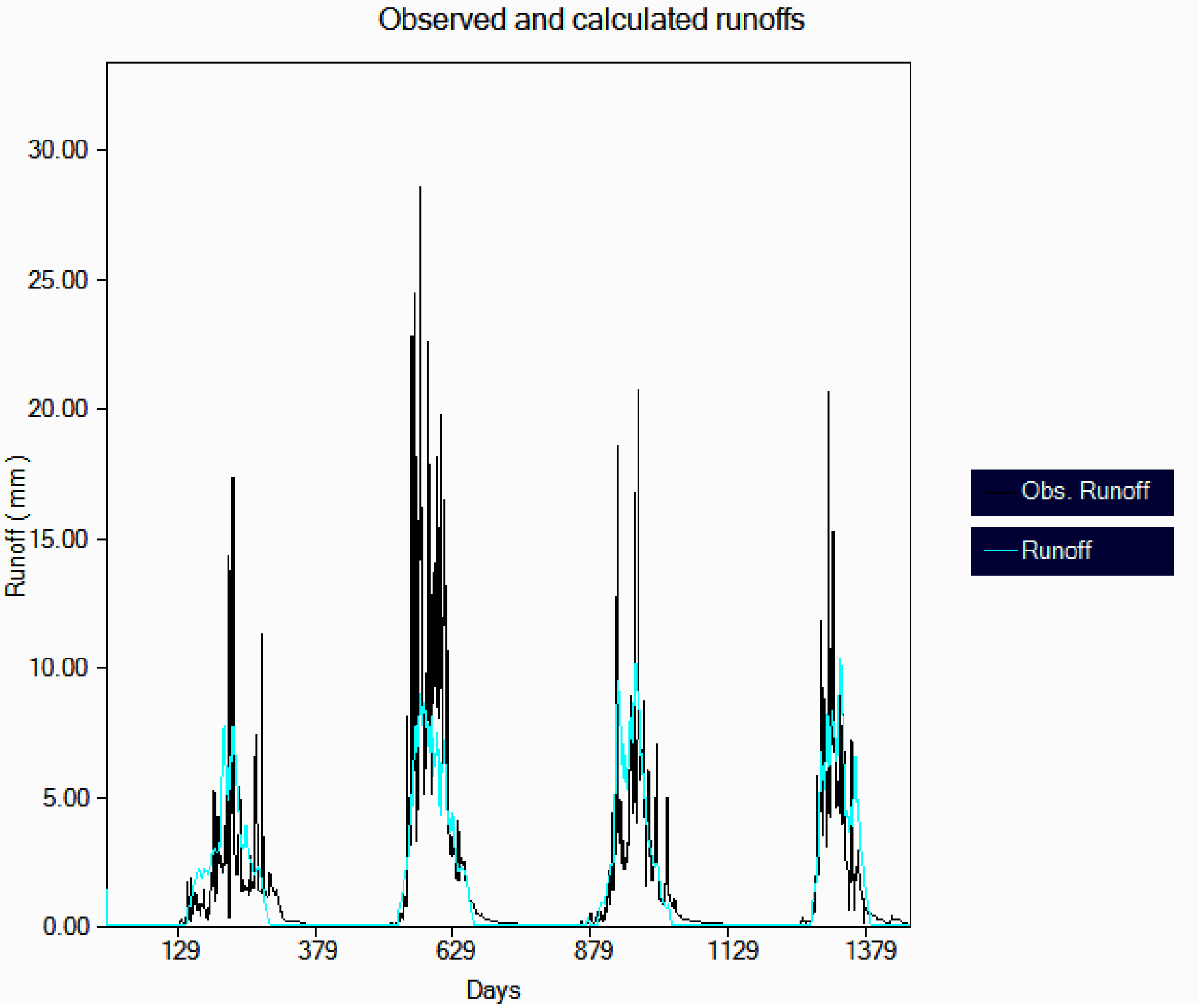

Fig.6.6 RRL Tank Model after calibration for Beles River at main Beles

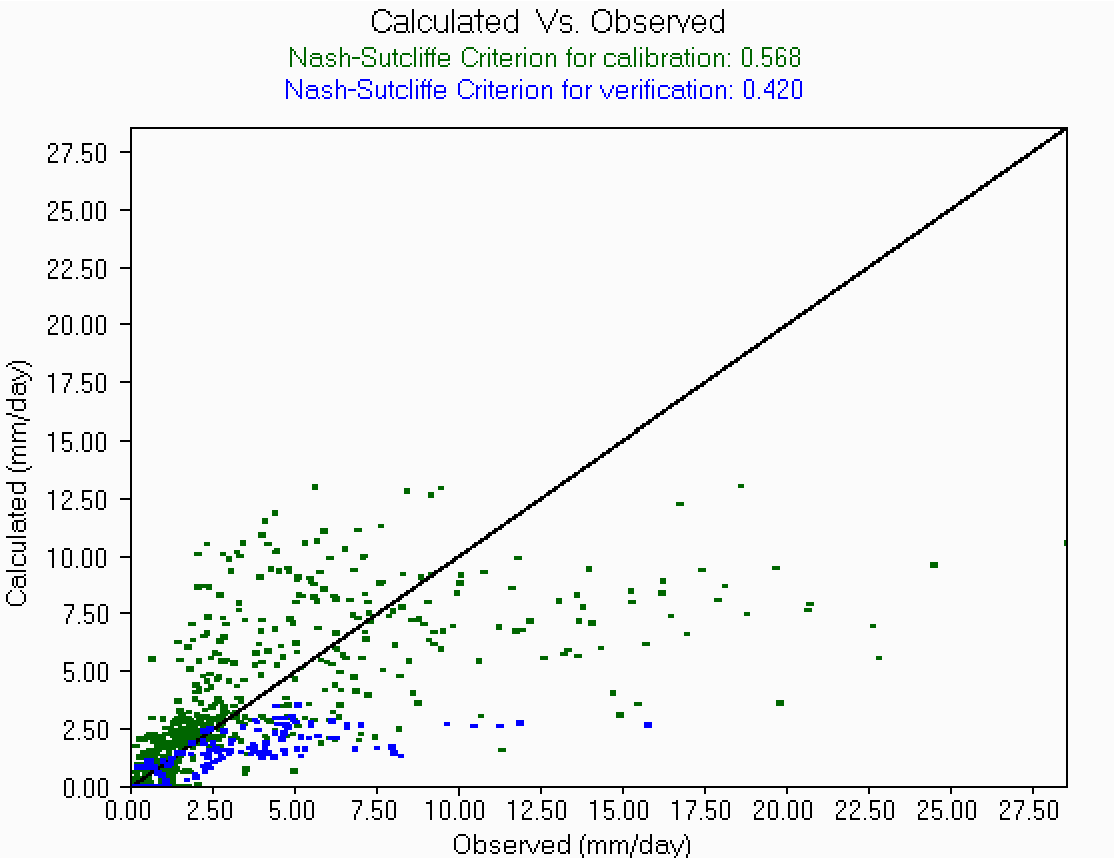

Figure 6.7 - RRL Tank Model scatter plot of calibration and verification result for Beles River at main Beles

6.2.2. Sensitivity:

Sensitivity analysis for RRL Tank model is done and the result indicated that from sixteen parameters five highly sensitive, five low sensitive and the rest six parameters are non sensitive.

- High sensitive parameters are a12, a31, b1, H12, H21
- Low sensitive parameters are a21, a41, b2, b3, H31
- Non sensitive parameters are H11, a11, alpha, C3, C4, H41

The graph is attached as (Annex 4)

6.2.3. Verification:

The verification is carried out for two years data from the period of January 1, 2006 up to December 31, 2007. The Verification result for Nash-Sutcliffe criterion is (Reff= 0.42) which is not good because it is less than 50 percent. The observed and calculated runoff for verification is shown on the graph in Figure 6.8.

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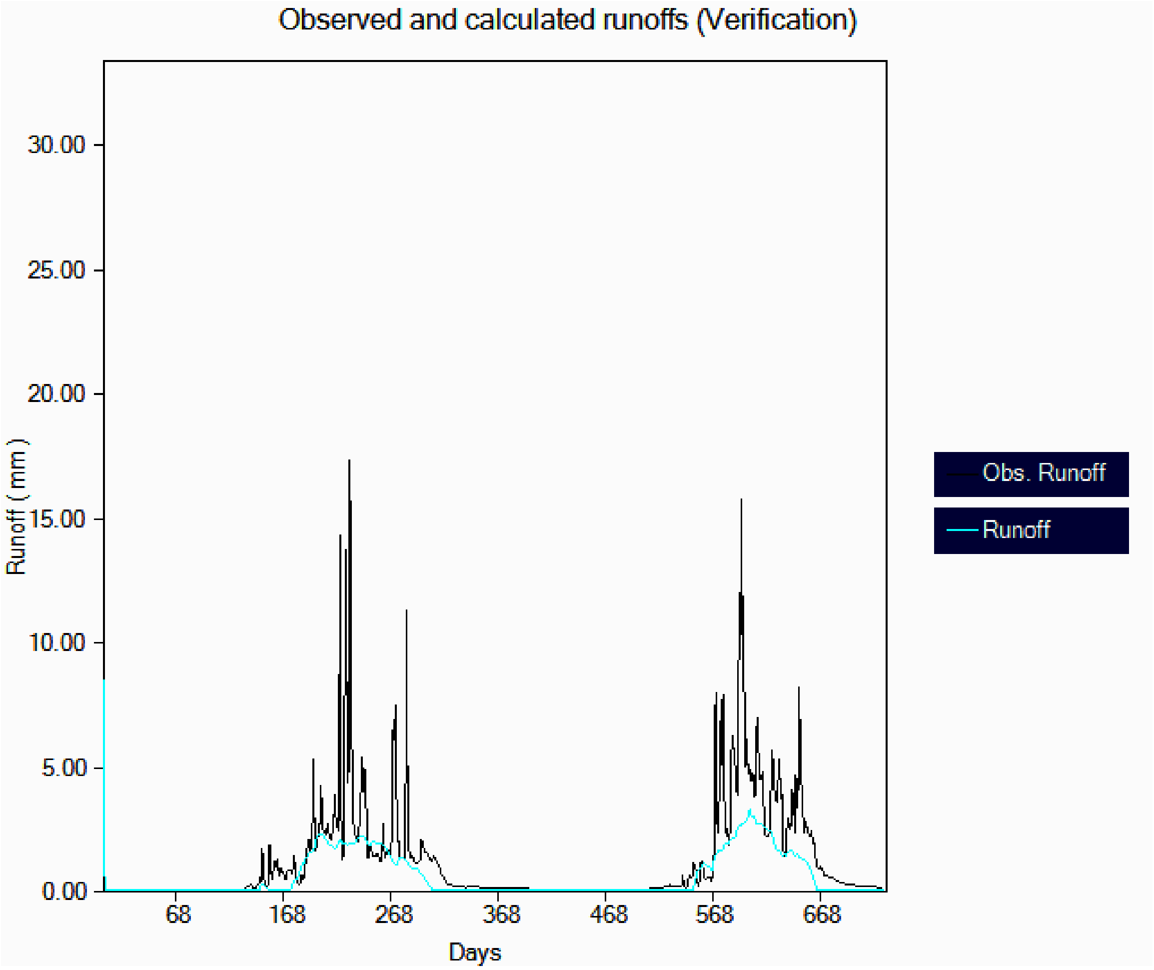

Figure 6.8: RRL Tank Model Verification result for Beles River at main Beles

6.3. Model analysis for RRL Sacramento Model

6.3.1. Calibration

The RRL Sacramento Model calibration and verification period was taken the same as RRL SMAR model and RRL Tank Model. Four years data for calibration and two years data for verification is used. The pick runoff condition of Sacramento model is the same as SMAR and Tank model. The Sacramento model also underestimates the pick run-off due to the same reason as the other two models. Manual and automatic adjustment of model parameters are carried out and the result of optimized model parameters are shown in Table 6.3. The graphs of observed and simulated flow before calibration and after calibration are shown on Figure 6.9 and 6.10 respectively. In order to evaluate the efficiency of this model using Nash-Sutcliffe criterion the scatter plot is shown on Figure 6.11.

No	parameters	optimized	Initial value
1	Adimp	0.06	0.01
2	LZfpm	31	40
3	Lzfsm	35	23
4	Lzpk	0.11	0.01
5	Lzsk	0.00	0.04
6	Lztwm	367	130
7	Pctim	0.00	0.01
8	Pfree	0.49	0.06
9	Rexp	2.75	1
10	Rserv	0.23	0.3
11	Sarva	0.19	0.01
12	Side	0.00	0.00
13	Ssout	0.02	0.00
14	Uzfwm	74	40
15	Uzk	0.13	0.25
16	Uztwm	99	50
17	Zperc	58	40

Table 6.3 - Optimal model calibration parameters of RRL Sacramento model for the Beles River catchment

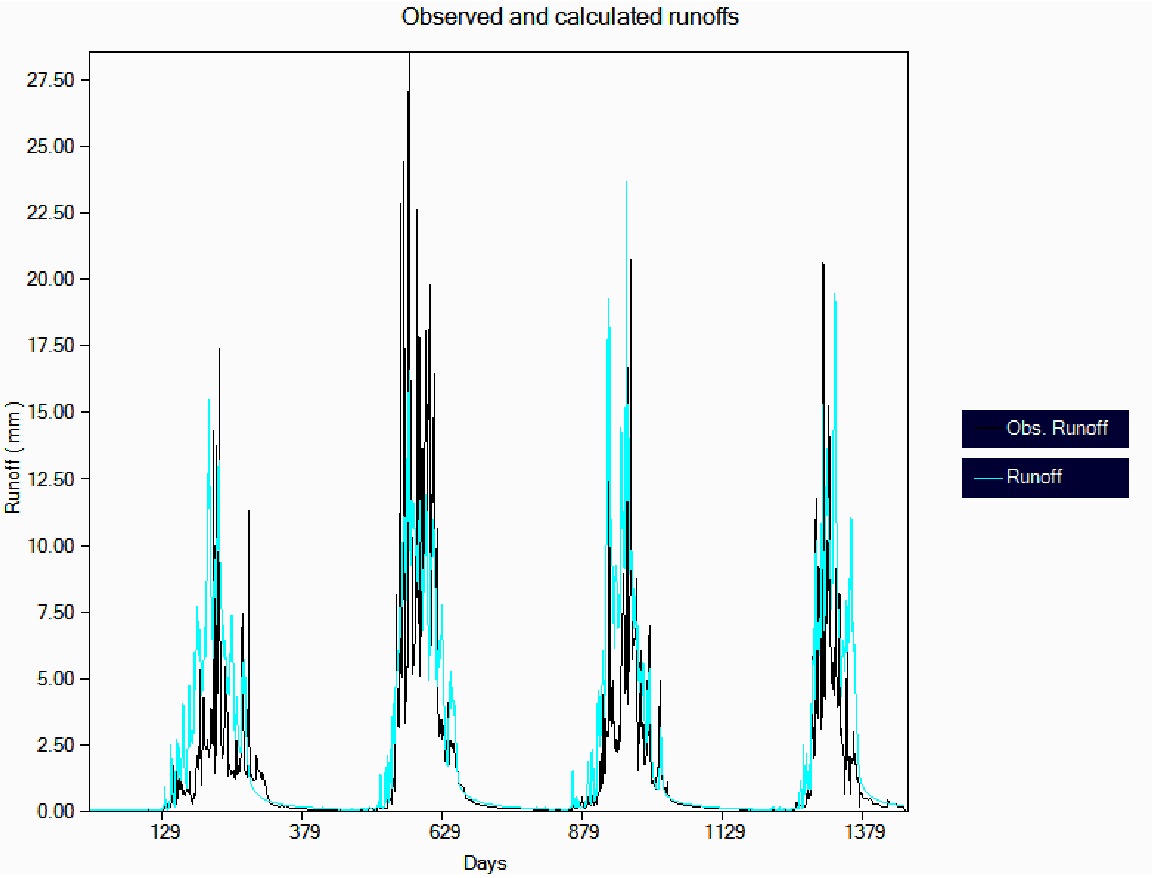

Fig.6.9 RRL Sacramento Model before calibration for Beles River at main Beles

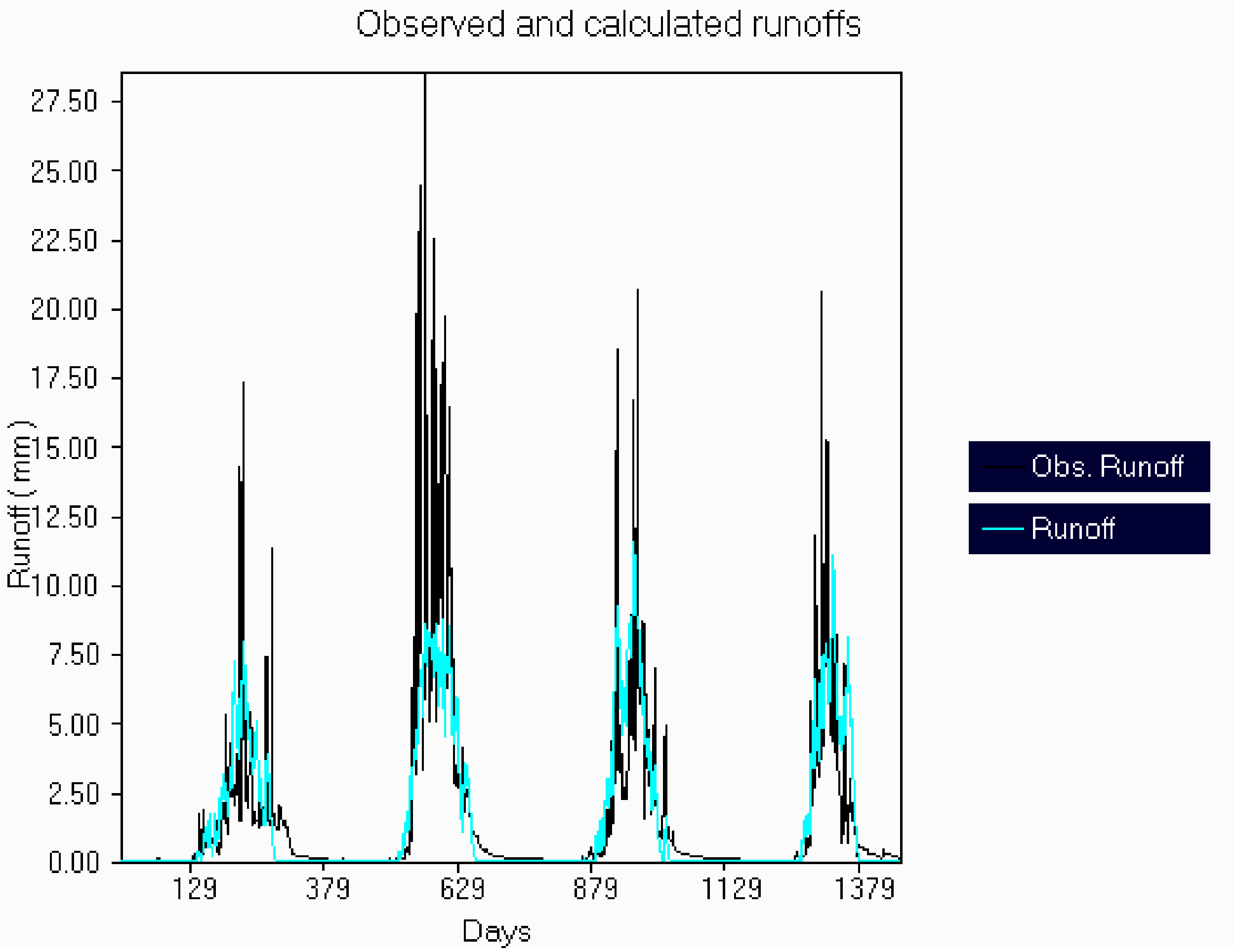

Fig.6.10 RRL Sacramento Model after calibration for Beles River at main Beles

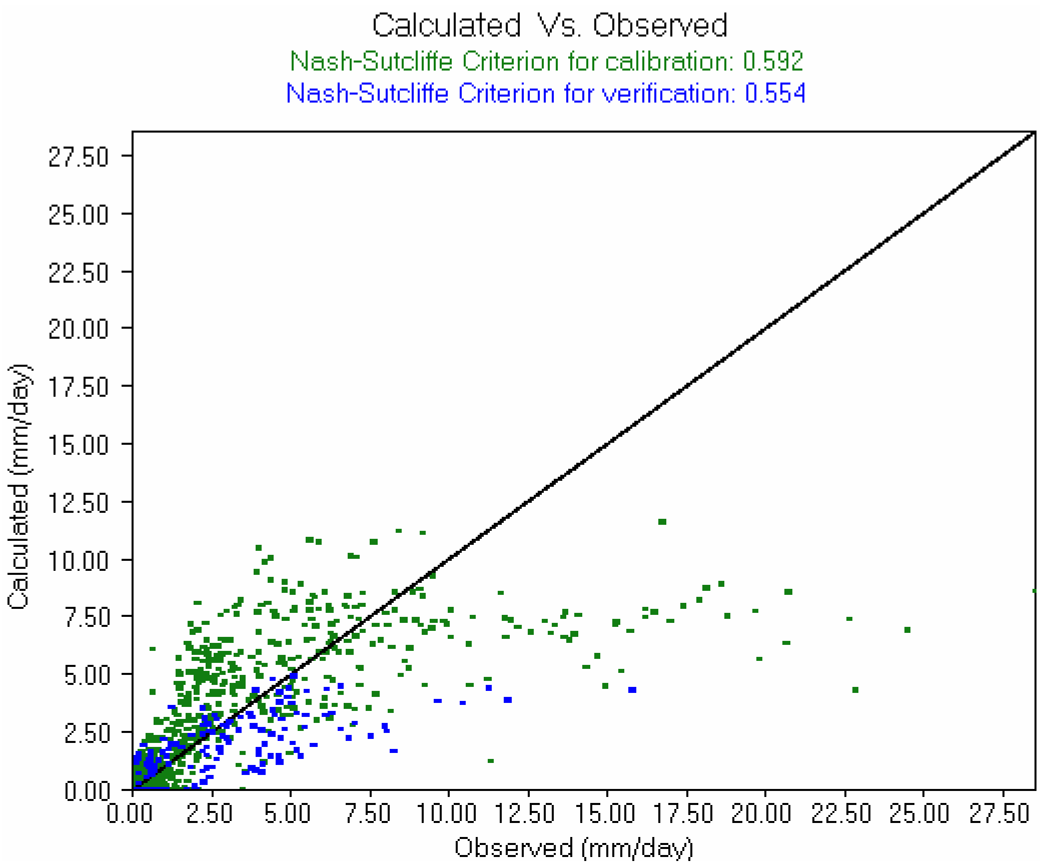

Fig.6.11 Sacramento Model scatter plot of calibration and verification result for Beles River at main Beles

6.3.2. Sensitivity

Sensitivity analysis is conducted. There is no any non sensitive parameter, ten parameters are highly sensitive and seven parameters are low sensitive parameters. Highly sensitive parameters are Adimp, Lzfsm, Lzsk, Pctim, pfree, Rexp, Sarva, Side, Ssout, Uzk, while low sensitive parameters are Lzpk, Lztwm, Rserv, Uzfwm, Uztwm, Zpenc, Lzfpm.

The graphs of highly sensitive parameters are attached as (Annex 5)

6.3.3. Verification

Verification is carried out for RRL Sacramento Model for the two years data from the period jan1, 2006 up to dec31, 2007.The verification result for Nash-Sutcliffe Criterion was good (Reff= 0.554) which is greater than half percent. Regarding to that Sacramento model is the best of all two RRL SMAR and RRL Tank Model. The verification result of observed and calculated runoff is shown on the graph below (Fig 6.12).

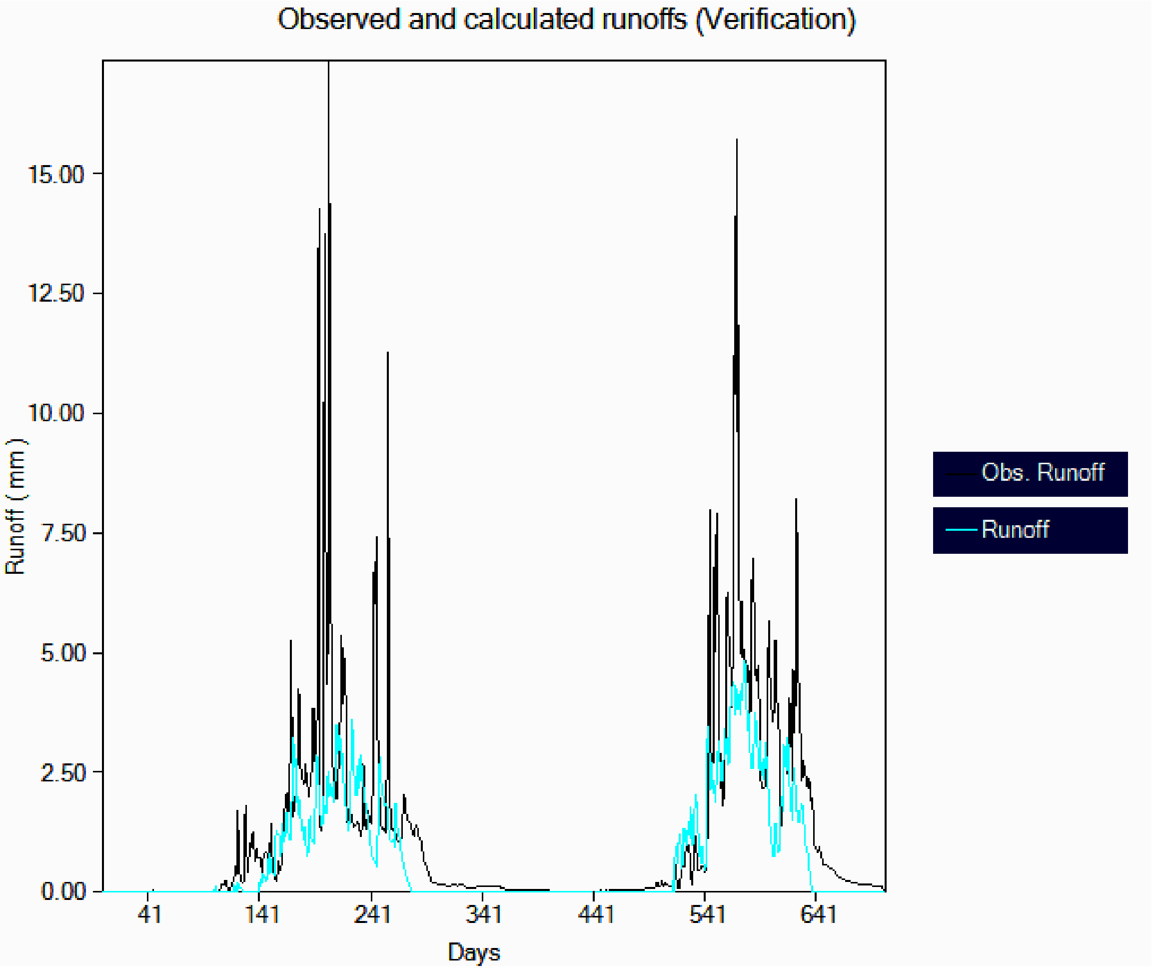

Figure 6.12 RRL Sacramento Model Verification result for Beles River at main Beles

7. Model Evaluation and selection of suitable Model

The model evaluation is done using the criteria mentioned in section 4.6. The result of Model efficiency for the different criteria is shown on Table 7.1 below.

The calibration results of all Models (RRL Sacramento, SMAR and Tank Models) are good for the objective function of Nash-Sutcliffe efficiency, Efficiency Using ln(Q), and Coefficient of determination. Since the calibration results statistics value is greater than 50 percent it can be accepted as good result. But When compared to each other the RRL Sacramento Model scored the best result among the three Models for all objective functions.

In case of verification the RRL Sacramento Model has the best result compared to the others. However, its efficiency is only good for the Nash-Sutcliffe criteria and not good for the other objective functions.

In general because of the best calibration and verification results, Sacramento Model is selected among the three Models.

	Objective function	**RRL Sacramento**	**RRL SMAR**	**RRL Tank**
Calibration	Nash-Sutcliffe efficiency	0.592	0.552	0.568
	Efficiency using ln(Q) (logReff)	0.597	0.546	0.53
	Coefficient of determination (R2)	0.531	0.527	0.516
Verification	Nash-Sutcliffe efficiency	0.554	0.342	0.42
	Efficiency using ln(Q) (logReff)	0.484	0.343	0.247
	Coefficient of determination (R2)	0.254	0.173	0.229

Table 7.1: Models performance evaluation result

8. Transfer of the selected Model parameters to the ungauged catchment

As it is mentioned on the section 4.7 catchments similarity has been observed by correlating the catchment land cover and soil type. The percentage land cover and soil type of upper and lower Beles catchments are shown on the table 8.1 and 8.2 respectively.

The correlation result of land cover of upper and lower Beles catchment is 95% which indicates that the two catchments are similar with their land cover. Similarly, the soil types of two catchments are 98% correlated each other. Therefore, the correlation result shows that the two catchments have similar soil type.

In general, upper and lower Beles catchments have similar catchment behavior, and therefore are hydrologically homogeneous. In the case of hydrologically homogeneous catchments the Model parameters of gauged catchments can be used to the ungauged catchments, as it is. Hence, the calibrated RRL Sacramento Model can be used to the ungauged catchment of Lower Beles without changing its parameter.

No	Land cover	Upper Beles catch.	Lower Beles catch.(ungauged)
1	Intensively cultivated	6%	5%
2	Open shrub land	5.5%	8%
3	Open grass land	60%	50%
4	Bushed shrubbed grass land	2.5%	16%
5	Moderatly cultivated	22%	15%
6	Dense shrub land	4%	6%

Table 8.1: Percentage land cover of upper and lower Beles catchments

No	Soil type	Upper Beles catch.	Lower Beles catch. (ungauged)
1	Eutric cambisols	20%	16%
2	Chromic Luvisols	20%	17%
3	Lithosols	6%	8%
4	Chromic vertisols	40%	42%
5	Orthic Luvisols	4%	5%
6	Eutric Nitosols	9%	10%
7	Dystric cambisols	1%	2%

Table 8.2: Percentage soil types of upper and lower Beles catchments

9. Run-off estimation on the ungauged catchment

Runoff estimation on the ungauged catchment (lower beles) of Beles River is conducted using the calibrated Sacramento model without changing its parameters. The input data for the model are Rainfall and evapotranspiration. Evapotranspiration is calculated using the climate data obtained from the pawe station and the rainfall data is obtained by distributing the daily rainfall of Pawe station using the Isohyets map (source:SMEC) done on the catchment. Three years data are used from the period Jan 1, 2005 up to Dec 31, 2007. The Simulation result is shown on the figure 9.1.

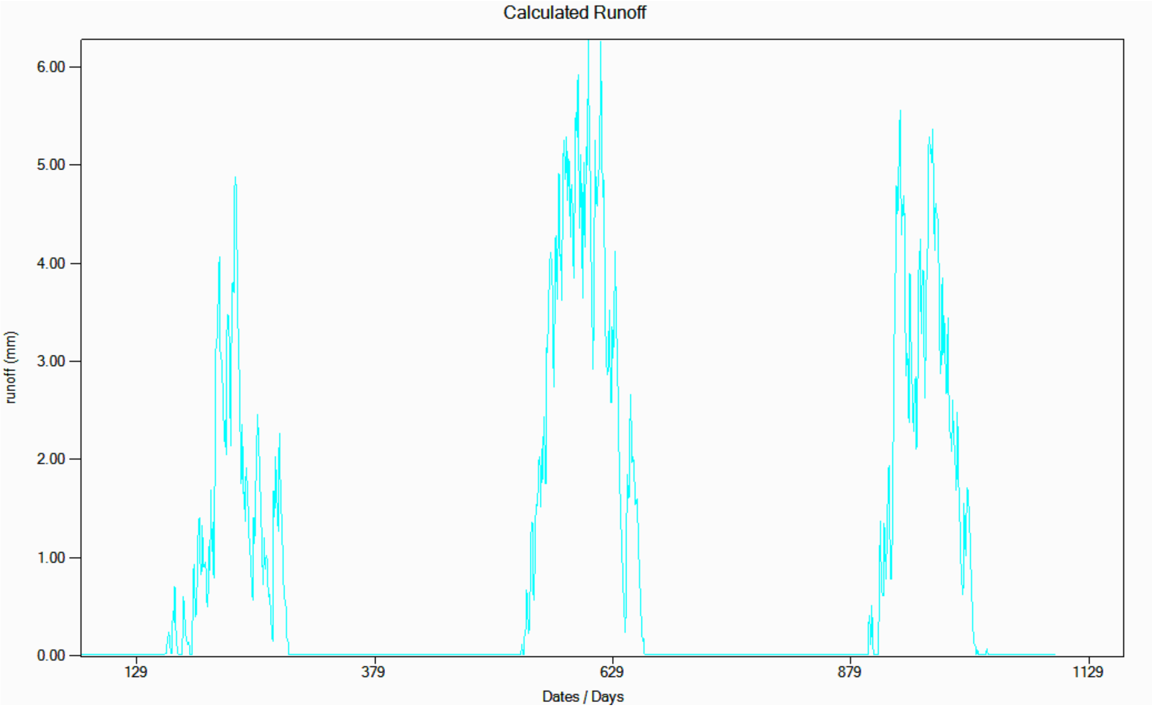

Figure 9.1 The simulated runoff for ungauged catchment of Beles River

10. Conclusion and Recommendation

10.1. Conclusion

To carry out the selection of suitable rainfall-runoff model for the gauged catchment of upper Beles, three conceptual rainfall-runoff models are tested, namely RRL SMAR Model, RRL Tank Model and RRL Sacramento Model. In all the three Models the same input data for the same period of time are used for model calibration and verification purpose.

Model evaluation and selection of suitable model is done using the criteria set under section 4.6, based on which the RRL Sacramento Model is selected because of its better performance among the other models.

Even though the Sacramento Model is the best among the other two models, its result by itself is not satisfactory. That is because on the Beles catchment there is no meteorological station and the data used for this study is by transferring information from the nearby station, considering the distance between the station and the catchment area. Such kind of transferred data can not be the same as the real station data and this is the main reason for the less performance of the Model. Here it can be observed on the calibrated Sacramento Model graph that the model can not catch the peak runoff.

As discussed in chapter 7, transformation of Model parameter to the ungauged catchment of Beles River can be done without changing the parameters of RRL Sacramento Model. This is because of the similarity of upper (gauged) and the lower (ungauged) Beles catchments in their land cover and soil type.

10.2. Recommendations

The hydrological finding of this study is calibrating a suitable model for the gauged catchment of Beles River and applying the same model for its ungauged catchment, so as to get runoff for the ungauged catchments of Beles River. The importance of the study is in that the output data from the Model can be used in planning of water resource for the lower Beles catchment (especially for its irrigation potential).

However, as indicated in this study, the selected Sacramento Model doesn’t catch the peak run-off, because of the lack of reliable data. This shows that the above indicated benefit may not be obtained if there is no reliable data.

Therefore this research recommends the following:

- Further research should be carried out on the study area by improving the rainfall pattern using other technique like satellite data,
- Additional meteorological stations should established on the study area following the proper grid pattern,
- The uncertainty in discharge measurement should be minimized by improving data recording system, as this would be a reason why some parts of the hydrograph were over predicted or under predicted.
- The RRL Sacramento Model can be used for small scale purpose for the ungauged catchment of the Beles River, with its drawback mentioned.

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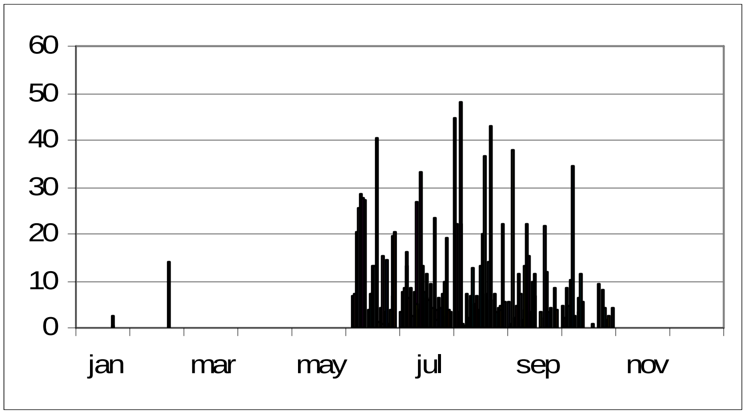
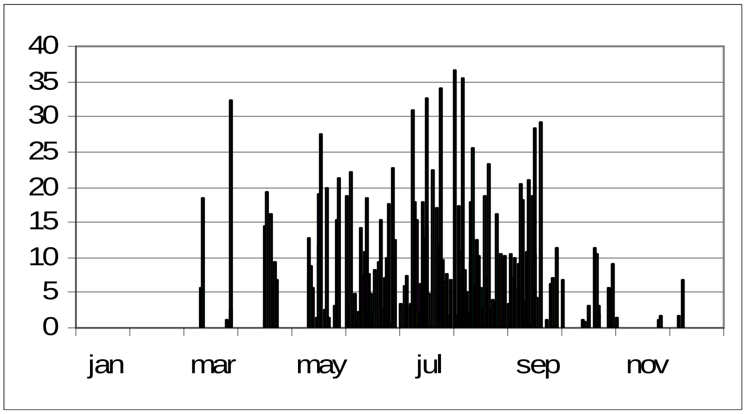
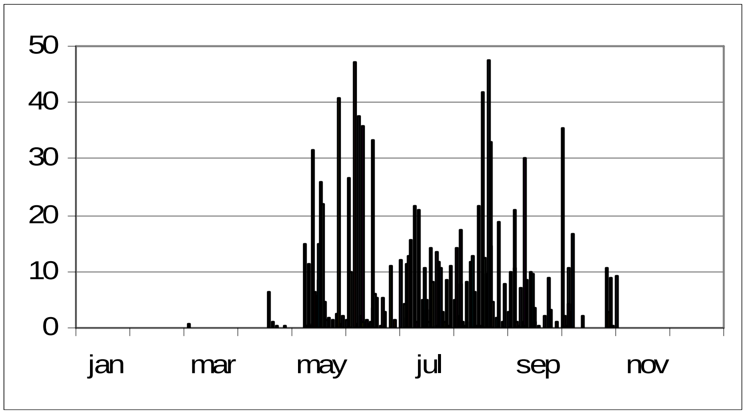
Annex 1- Charts of Rainfall Data

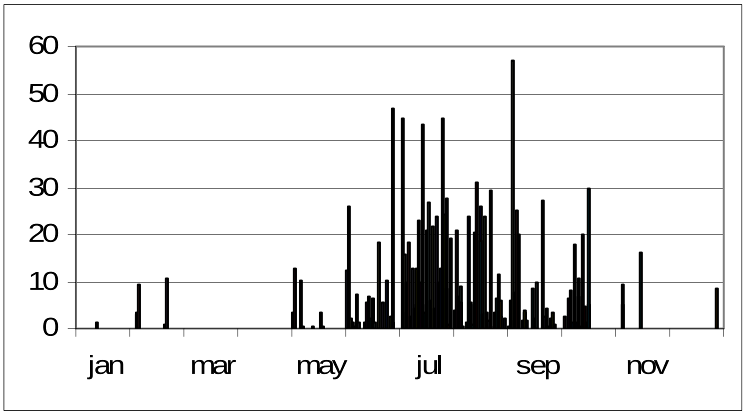
1) Dangla: (Jan 1, 2002 – Dec 31, 2003)



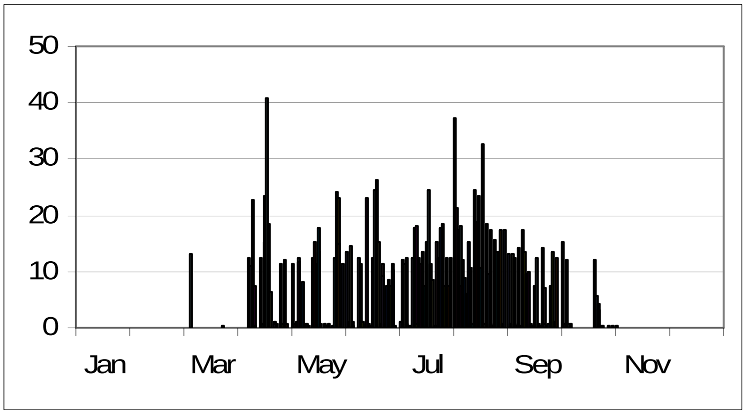


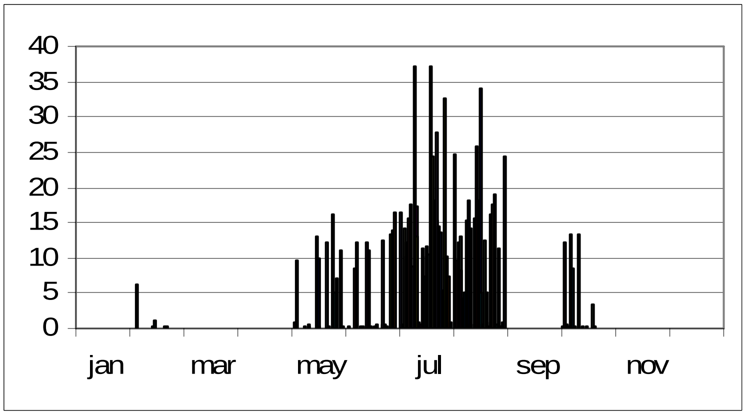
2) Bahirdar: (Jan 1, 2003 – Dec,31 2004)



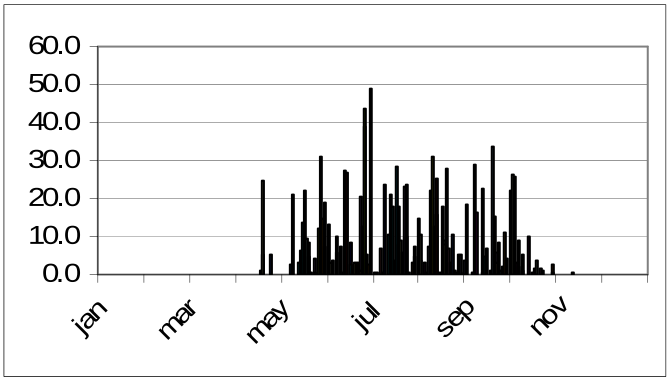


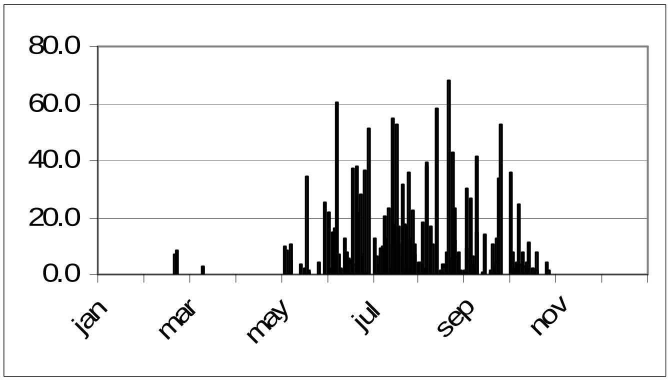
3) Zege:(jan,1 2003 – Dec, 31 2004)

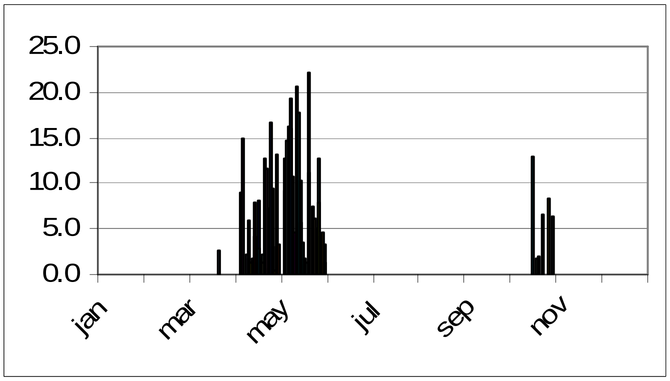


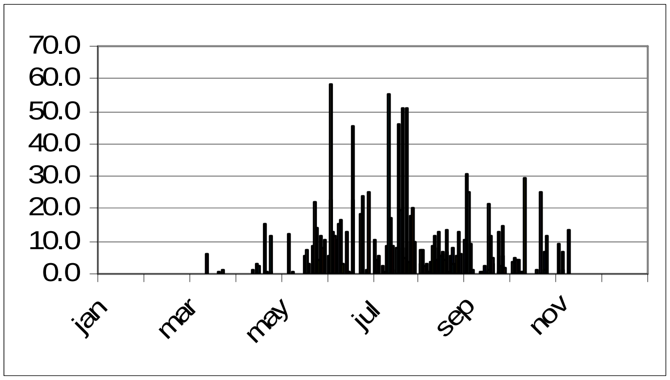


4) Pawe: (Jan 1, 2002 – Dec 31,2005)









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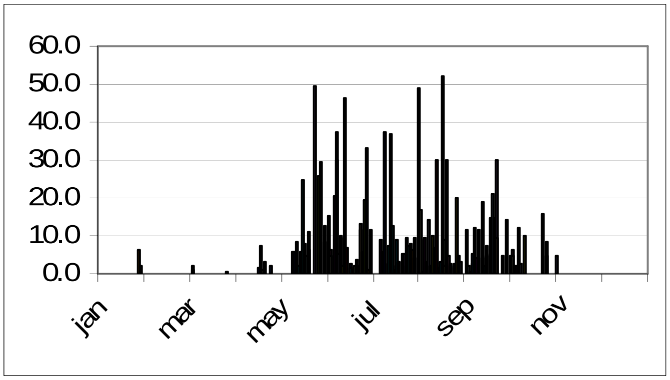

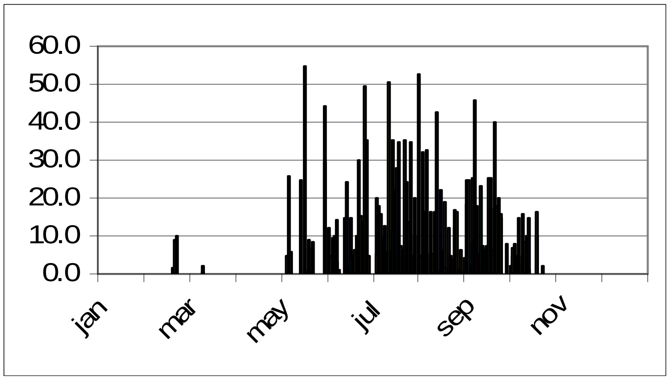

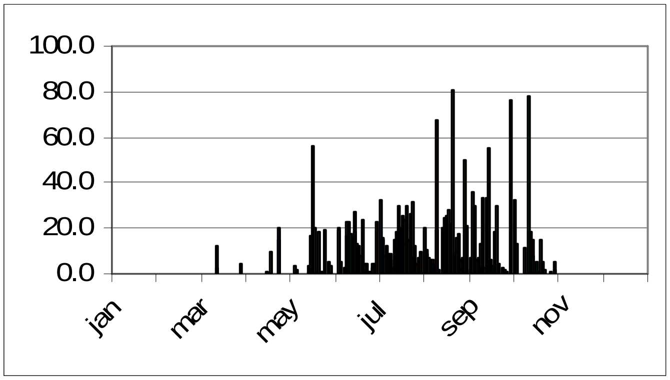

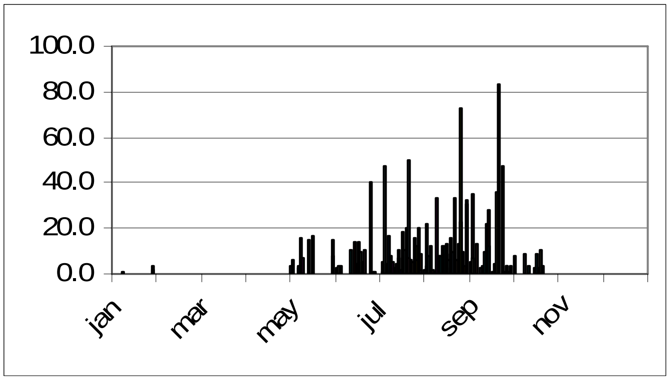
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60.0
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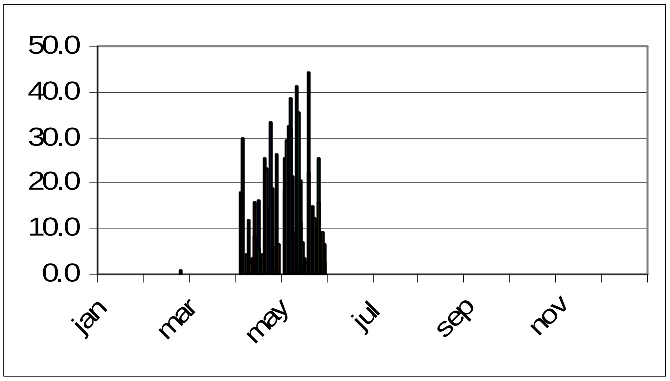
0.0
jan
mar
may
jul
sep
nov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40.0
30.0
20.0
10.0
0.0
jan
mar
may
jul
sep
nov

Annex 2 - Regression Equations

Daily Rainfall Regression (station-station) (mm)

Pawe = 0.21 Dangla + 3.6, $R^2=0.85$

Bahirdar = 0.388 Zege + 2.85, $R^2=0.90$

Dangla = 0.5 Wetet abay + 2.39, $R^2=0.73$

Engibara = 0.398 Chagni + 4.58, $R^2=0.95$

Daily Max Temperature Regression

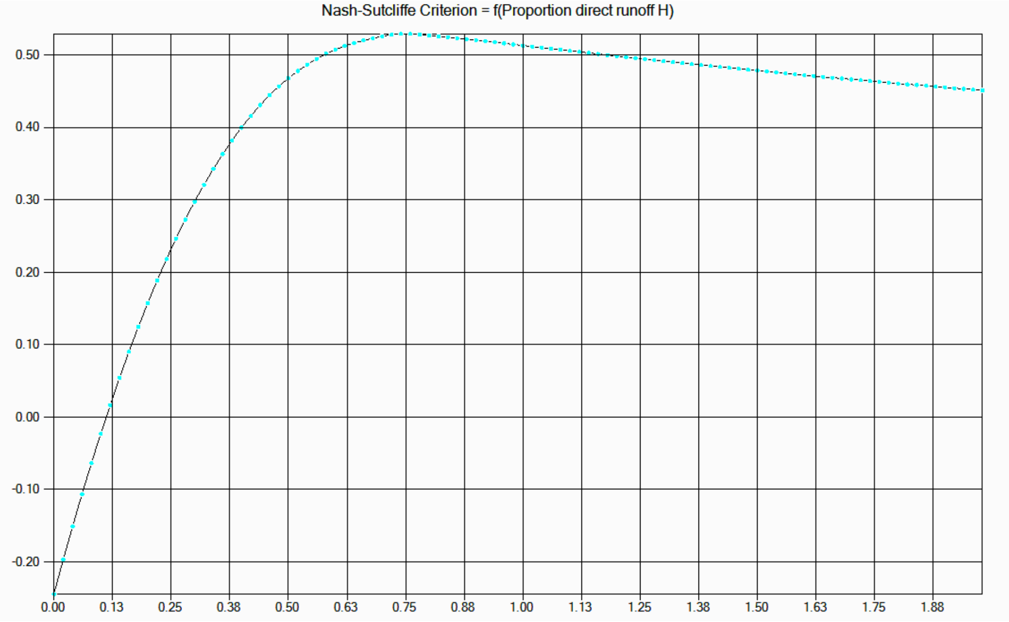
Pawe = 0.85 mandura + 5.58, $R^2=0.88$

Mandura = 0.72 zege + 10.63, $R^2=0.80$

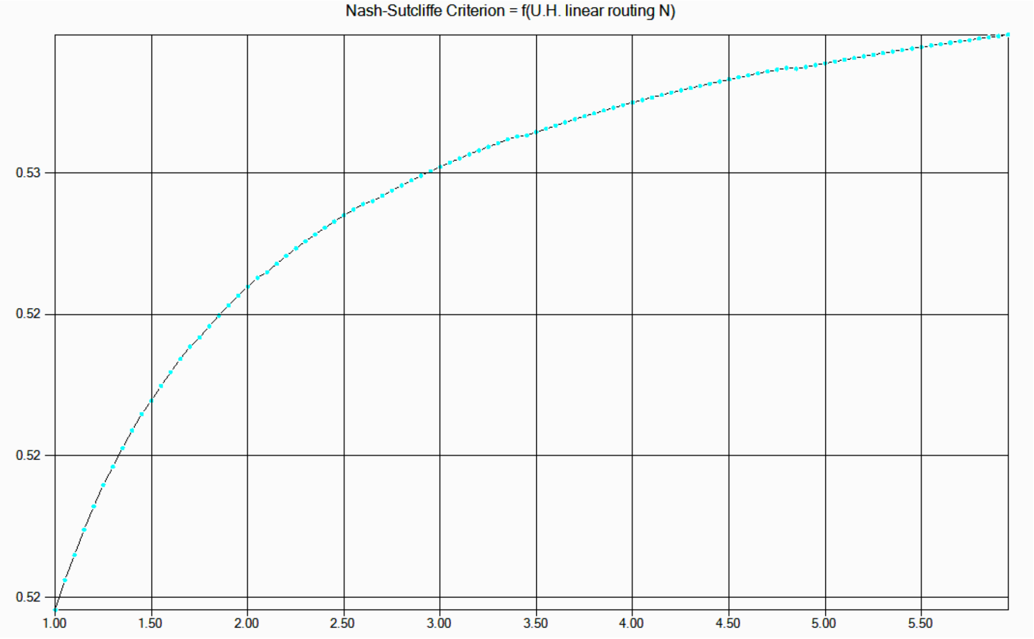
Dangla = 0.59 chagni + 8.68, $R^2=0.98$

Annex 3 - Sensitivity graphs of RRL SMAR Model

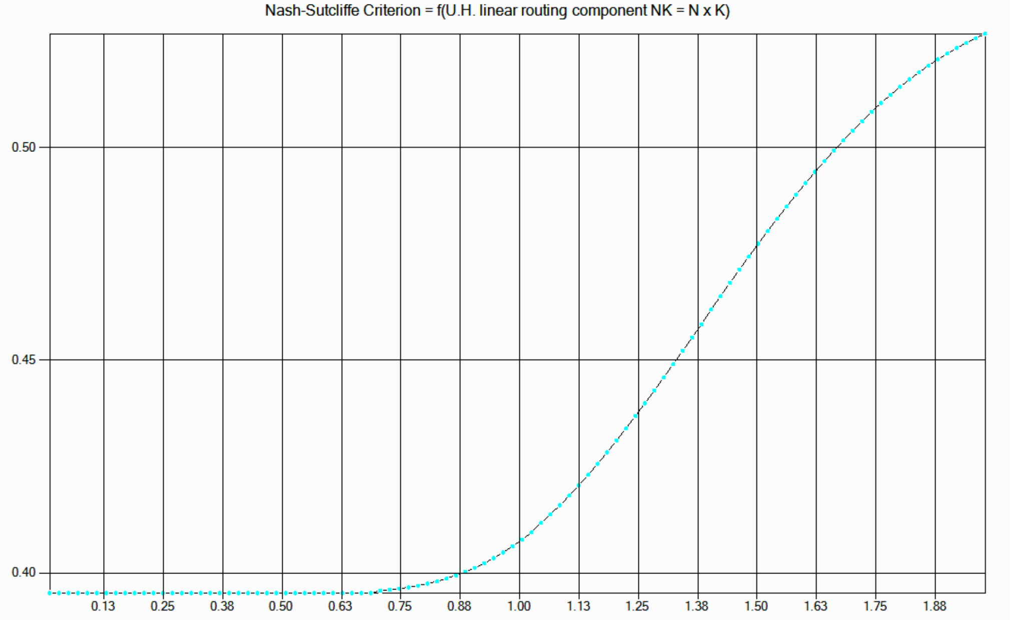
1) Proportion Direct Runoff H



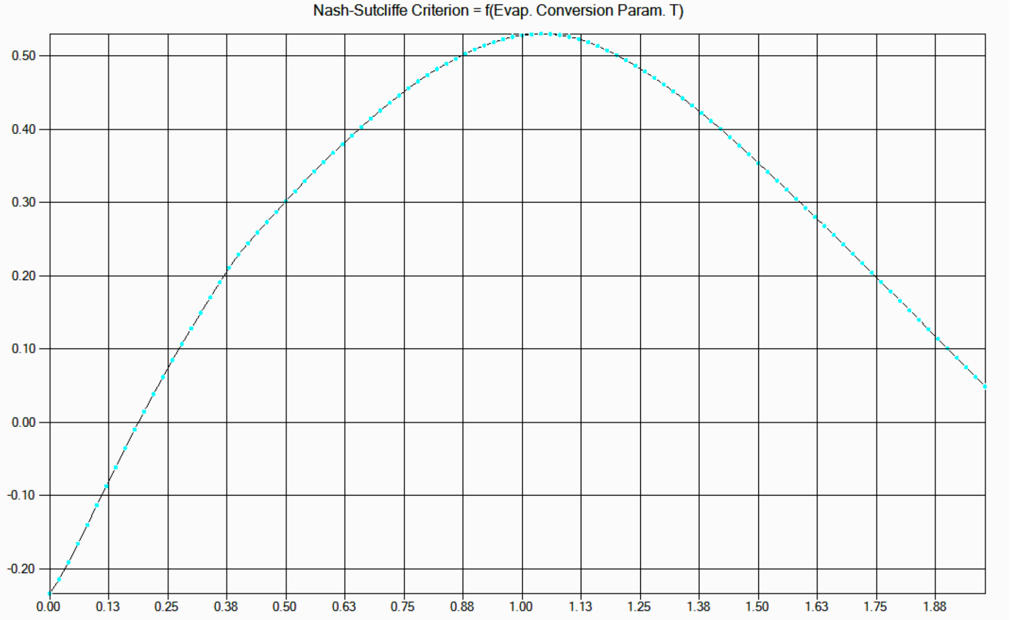
2) U.H Linear routing N



3) U.H Linear routing component NK= N*K

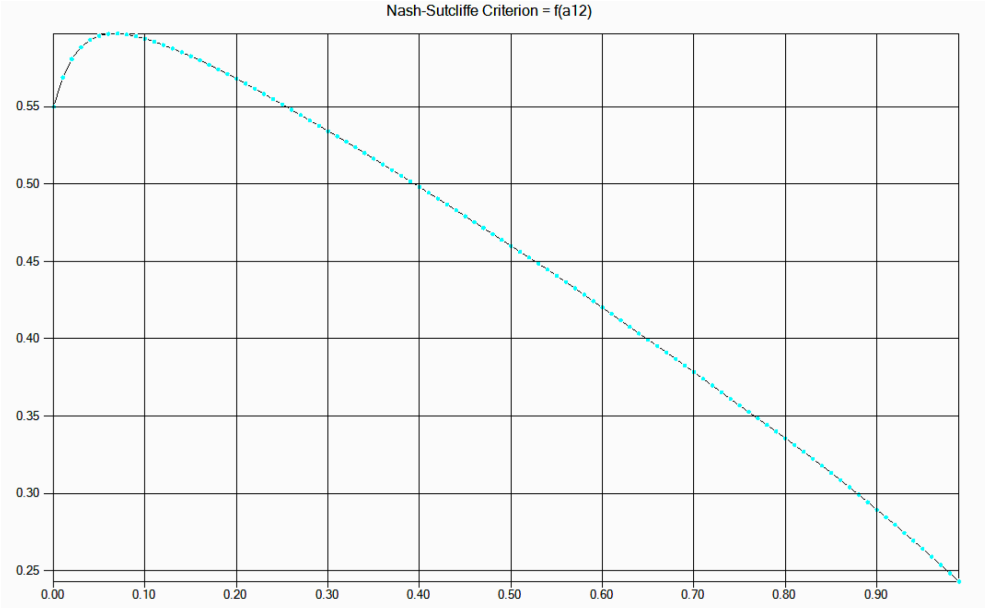


4) Evapo. Convertion param. T

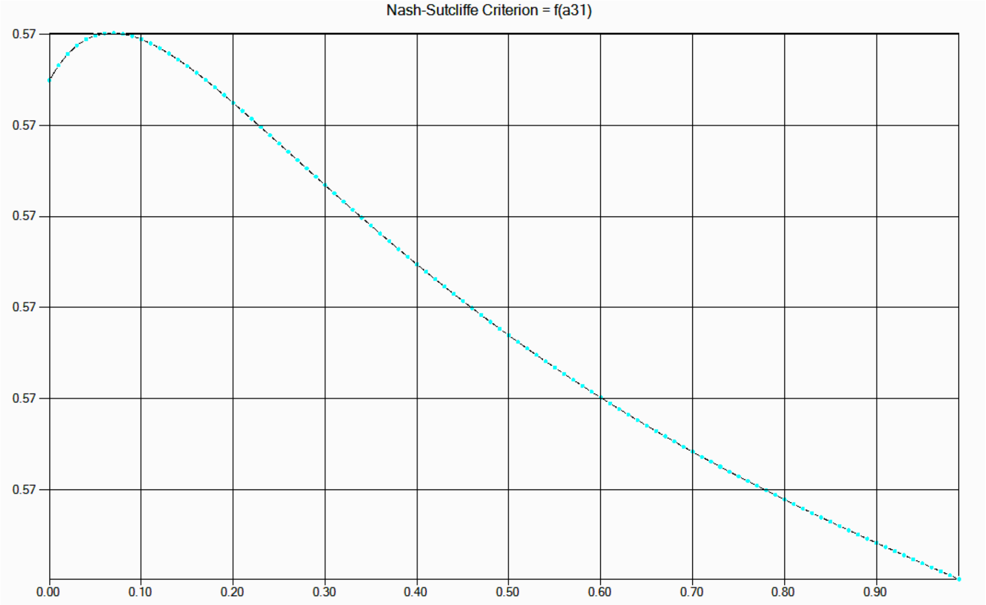


Annex 4 - Sensitivity graphs of RRL Tank Model

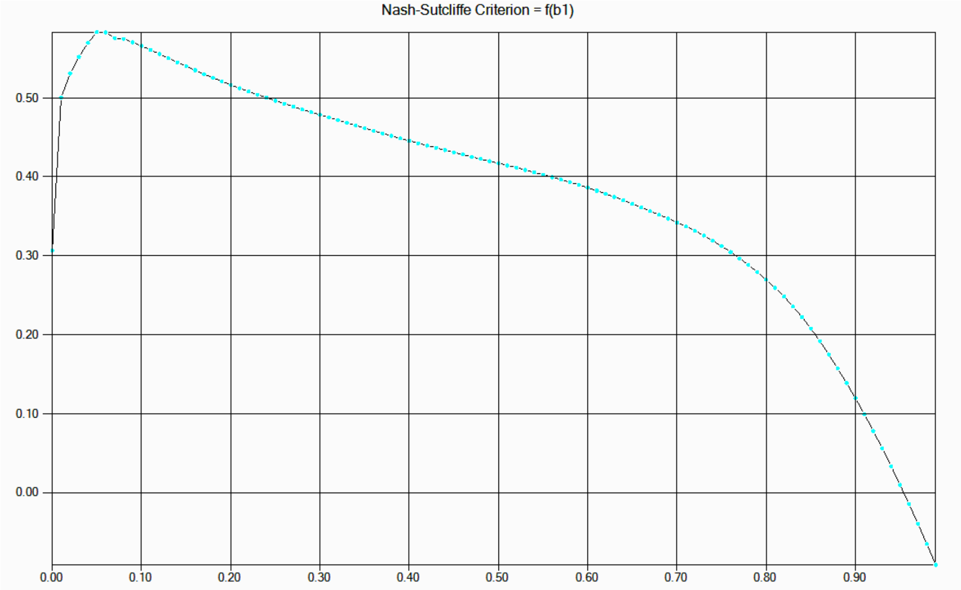
1) A12



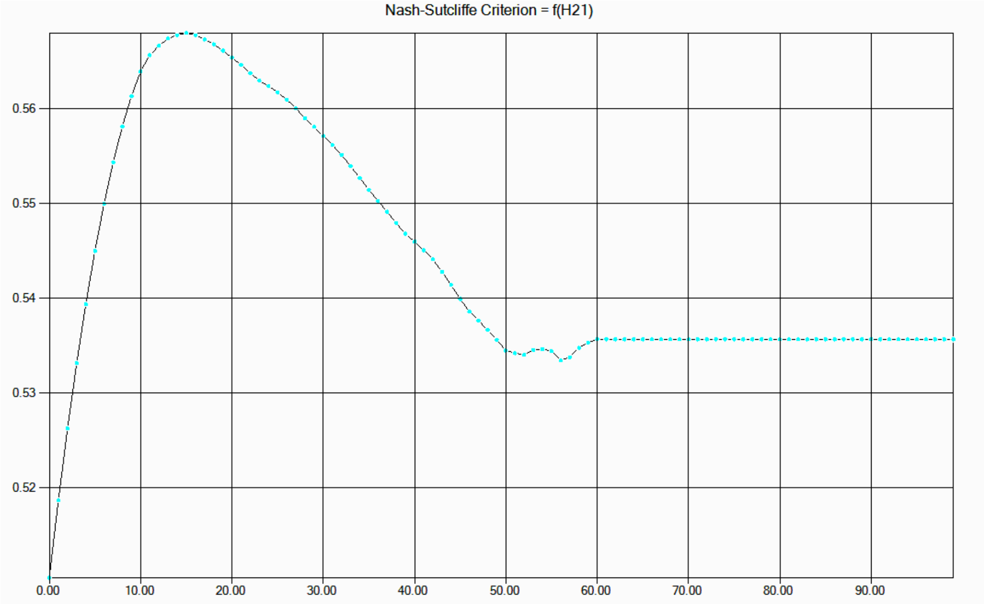
2) A31



3) B1


Nash-Sutcliffe Criterion = f(b1)
0.50
0.40
0.30
0.20
0.10
0.00
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90

4) H21


Nash-Sutcliffe Criterion = f(H21)
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10.00
20.00
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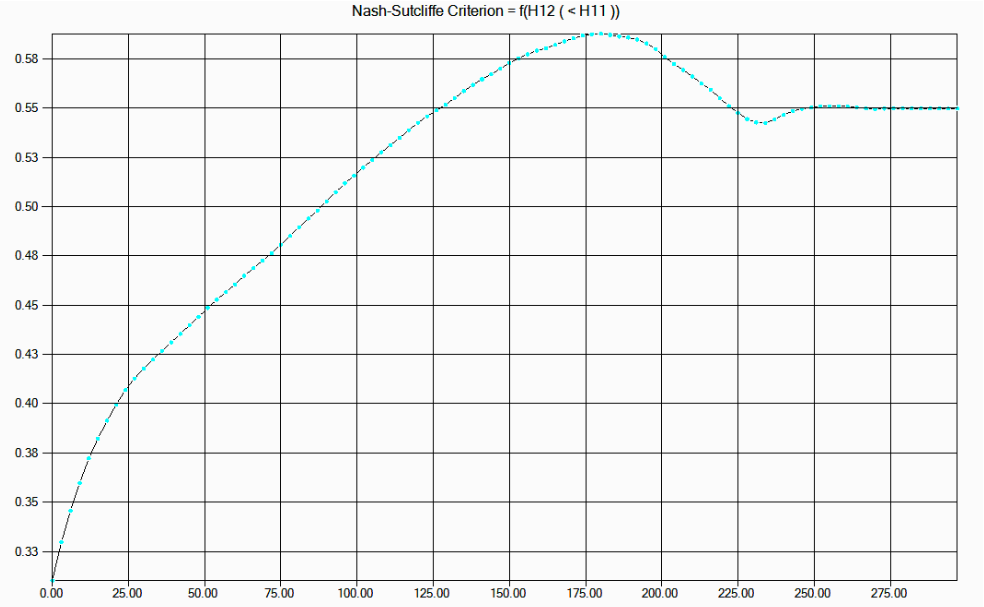
40.00
50.00
60.00
70.00
80.00
90.00

5) H12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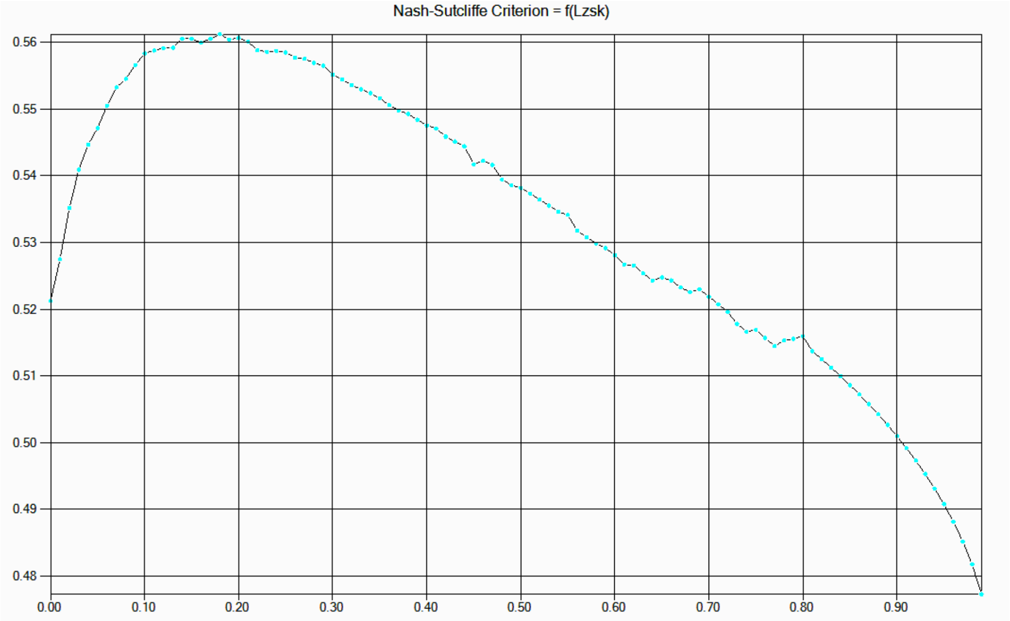
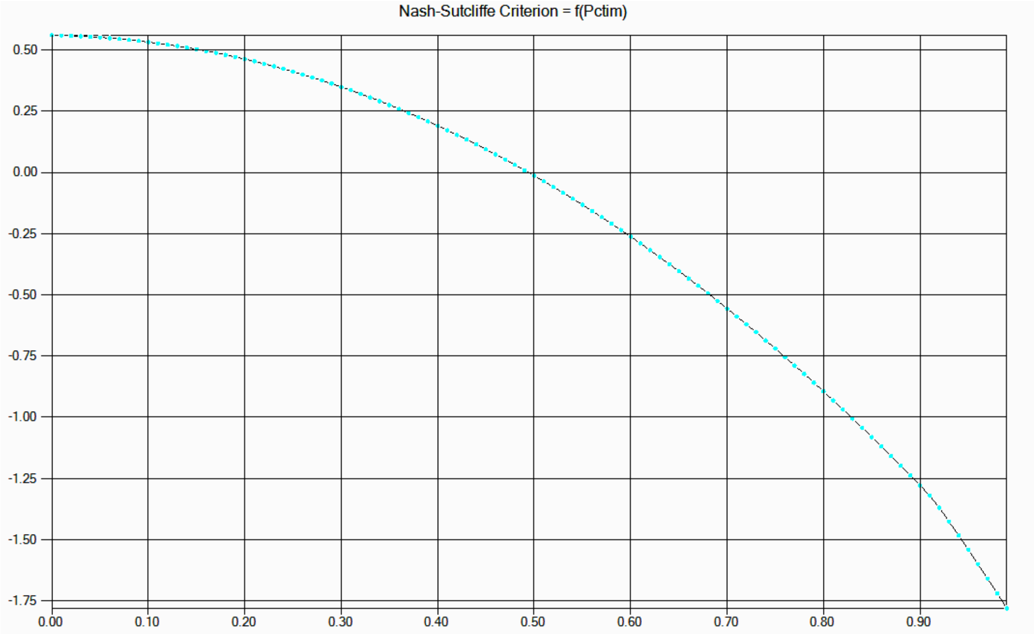
0.48
0.45
0.43
0.40
0.38
0.35
0.33
0.00
25.00
50.00
75.00
100.00
125.00
150.00
175.00
200.00
225.00
250.00
275.00

Annex 5 - Sensitivity graph of RRL Sacramento Model:

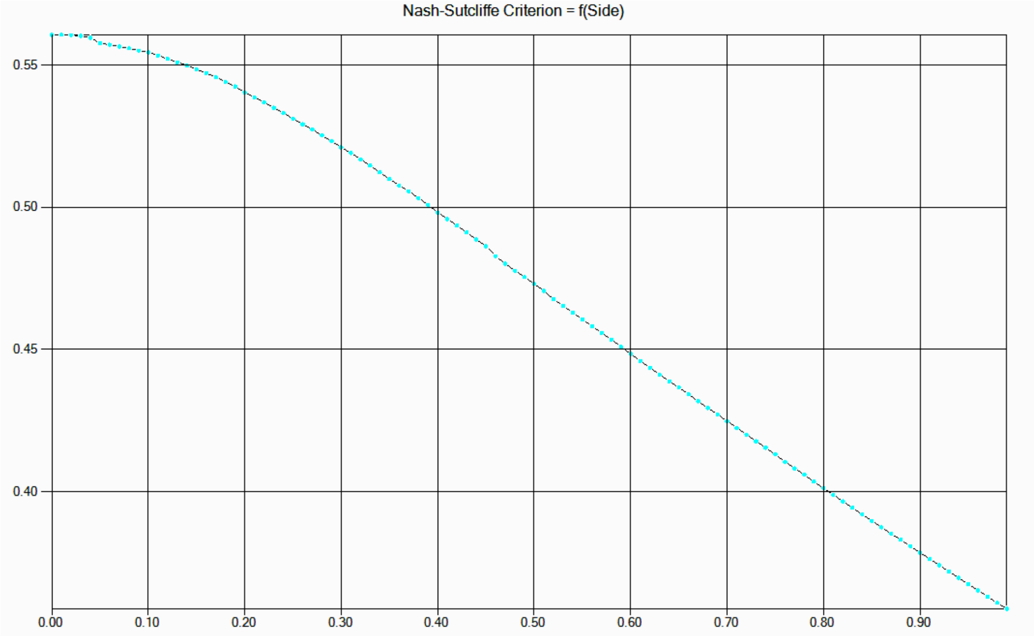
1) Adimp:



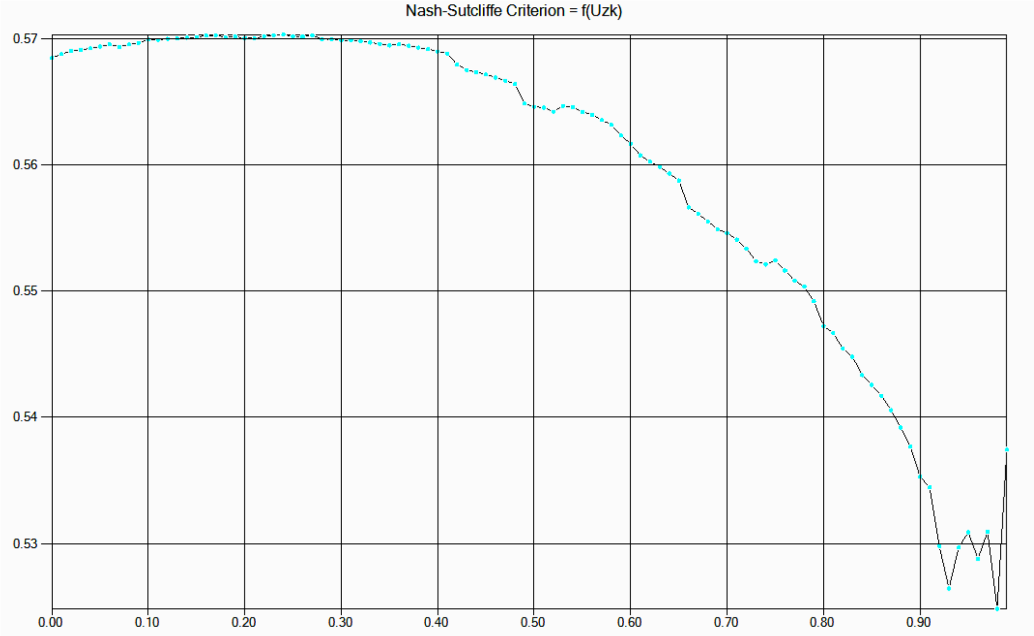
2) Pctim:



3) Side:


Nash-Sutcliffe Criterion = f(Side)
0.55
0.50
0.45
0.40
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90

4) Uzk:


Nash-Sutcliffe Criterion = f(Uzk)
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0.56
0.55
0.54
0.53
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90

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: Woinishet Hailemariam

Signature: -----------------------------