



**ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
INSTITUTE OF TECHNOLOGY
DEPARTMENT OF CIVIL ENGINEERING**

**DAILY RAINFALL-RUNOFF MODELLING OF UPPER
AWASH SUB BASIN USING CONCEPTUAL RAINFALL
RUNOFF MODELS**

Sileshi Gobena

December 2010

Addis Ababa



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BASIN USING CONCEPTUAL RAINFALL RUNOFF MODELS**

A dissertation submitted to the School of Graduate Studies of Addis Ababa University in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering

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CERTIFICATION

The undersigned certify that they have read the dissertation entitled ‘**Daily Rainfall-Runoff Modelling of Upper Awash Sub Basin Using Conceptual Rainfall Runoff Models**’ and here by recommend for acceptance by Addis Ababa University in partial fulfillment of the requirement for the degree of Master of Science in Civil Engineering.

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ABSTRACT

Hydro-meteorological data are very indispensable for the assessment and development of water resource. Upper Awash (UA), part of Awash River Basin, is densely populated and large population growth as well as the expansion of development activities and large farms such as flower farms in the region is expected to put further pressure on the water and associated resources of the area. Moreover, every hydrological process in the upper Awash has effect on the development activities in the downstream of the basin which calls for huge water resource planning and management activities. In this study, a daily rainfall- runoff modeling which is very helpful to further strengthen assessment, planning and management of water resource in the basin was conducted for selected three catchments of Upper Awash Sub Basin using two models namely AWBM and SMAR models among five lumped conceptual models nested in rainfall-Runoff library.

Automatic calibration and verification of the models were performed using Genetic Algorithm optimization method together with Nash Sutcliffe criteria and runoff difference as primary and secondary objectives respectively. In connection with this, flow generation, model parameter determination, a comparison of observed and simulated flow as well as comparison of performance of the two models were conducted. The quality of fit between the observed and simulated flow is judged by reviewing plots of the hydrographs. Comparison of the observed and computed flows reveals that except for the extreme peak flows the medium flow and low flows are generally modeled quite satisfactorily. Further more, performance of the models is assessed by using Nash Sutcliffe criteria and comparing the annual total flow volume and the maximum peak flows. Both AWBM and SMAR models predict the flows fairly well with overall Nash Sutcliffe criteria of 0.6 to 0.85 for both calibration and verification periods except for Mojo catchment. As far as the performance of the two models concerned, AWBM gives better results as compared to SMAR model for selected catchments. In addition, Model sensitivity analysis was undertaken to analyze the sensitivity of a particular model parameter with regard to a selected objective function and subsequently the most sensitive parameters for the two models were determined.

Finally, based on the results obtained the necessary conclusion and Recommendation were drawn. Generally, conceptual models have given encouraging results in this sub basin but further detail work is required verify the performance of the models under strict quality data situation.

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ABBREVIATIONS AND ACRONYMS

AAU	Addis Ababa University
AET	Actual Evapotranspiration
AMC	Antecedent Moisture condition
AWBM	A catchment Water Balance Model
cdt	Comma delaminated column daily time series format
CMS	Catchment Modelling Systems
CN	Curve number
CRC	Cooperative Research Centre
DEMs	Digital Elevation Model
ET_o	Potential Evapotranspiration
E_{pan}	Pan evaporation
FAO	Food and Agricultural Organization
FEWS SFM	Famine Early Warning System Stream Flow Model
GIS	Geographical Information System
ITCZ	Inter-Tropical Convergence Zone
K_p	Pan coefficient
masl	Meter above sea level
MoWR	Ministry of Water Resource
NMA	National meteorological Agency
RRL	Rainfall Runoff Library
SMAR	Soil Moisture and Accounting model
SWAT	Soil and Water Assessment Tool
UA	Upper Awash
USGS	United States Geological Survey
WMO	World meteorological organization

CHAPTER ONE

INTROUDCTION AND GENERAL BACKGROUND

1.1 Introduction

Water resources are vital renewable resources that are the basis for existence and development of a society. Proper utilization of these resources requires assessment and management of the quantity and quality of the water resources both spatially and temporally. Surface water being easy, direct and therefore less expensive to exploit in comparison to other sources like groundwater or sources that need desalinization, makes it the major source of water supply for irrigation, domestic uses, hydropower development and industry. The surface water, in the form of river and lakes discharge (runoff) is predominately obtained from rainfall after being generated by the rainfall - runoff processes. For this purpose, several available empirical, physically based or conceptual models could be used .In order to make decisions for planning, design and control of water resource systems, long runoff data series are required. However, run-off data are not often available with reasonable length. Due to this, the problem of determining runoff from rainfall, evaporation, snowfall and other factors, occupies an important place in hydrology.

Hydrological models are tools that describe the physical processes controlling the transformation of precipitation to stream flows. There are different hydrological models designed and applied to simulate the rainfall runoff relationship under different temporal and spatial dimensions.

The detailed processes that link the rainfall over the catchment to the run off may be studied by applying physical laws that are reasonably well known. But, the complexity of the boundary conditions (i.e. the physical description of the catchment and the initial

conditions and distribution of the variables) makes a solution based on the direct application of the laws of physics impracticable. Moreover, direct application of these laws requires subdividing the catchment into homogenous and isotropic regions.

The sub division depends on catchment characteristics (soil type, land use, slope, vegetation cover, etc.) and these factors may also vary in space and time. For these reasons, instead of exact representation of the processes, effort is directed to the construction of a model by using system concepts relating input and outputs.

In view of this, hydrological modeling which is generally used as utility in various areas of water resource development in assessing the available resources, in studying the impact of human interference in an area such as land use change, deforestation and other hydraulic structure such as dams and reservoirs is very essential.

Among hydrological modeling tools, rainfall-runoff models are becoming an increasingly indispensable tool in flood studies and operational flood forecasting for integrated catchment planning and flood emergency management (Tan, K.S et al.2005).

Awash River Basin is one of the major river basins in Ethiopia with a total catchment area of 112,697 km². Moreover, the River basin is the most developed and exploited of all Ethiopian River Basins and it has massive economic significance for the development of the country. Therefore, proper utilization of this resource requires assessment, integrated catchment planning and management which in turn demands development of run off –rainfall relationship.

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

1.2 PROBLEM STATEMENT

Water resources are essential renewable resources that are the basis for existence and development of a society. In addition, water crises caused by shortages, floods and diminishing water quality, among others, are increasing in all parts of the world. The growth of population demands for increased domestic water supplies and, at the same time, results in a higher consumption of water due to expansion in agriculture and industry. As a result, proper utilization of water resources which requires assessment and management of the quantity and quality of these resources both spatially and temporally is very crucial. Mismanagement and lack of knowledge about existing water resources and the changing climatic conditions have consequences of an imbalance of supply and demand of water. The problem is pronounced in developing countries where the resources are poorly managed.

Hydro-Meteorological data are vital in any water resources development. However, the scarcity of data in most developing countries is so alarming that one gets a single station on average for catchment as large as 1000km². Similar to any developing country, in Ethiopia major water balance variables such as flow, rainfall and evaporation time series are sparsely and scarcely available and also there is question of data quality problem as the available data are most of the time full of gaps . In such circumstances, there is no denying that the need for scientific tools which are helpful to generate flow in ungauged catchments and estimation of missing data.

In the same manner, integrated water resources management in Ethiopia is not at an advanced stage. There is no flood forecasting and warning mechanism in Ethiopia. This is due to absence of long runoff data series, established rainfall-runoff relations and integrated catchment planning and management.

Awash River basin is the most developed and exploited of all Ethiopian River Basins. This implies that it has massive economic significance for the development of the country. Upper Awash (UA), part of Awash River Basin, is densely populated and large population growth as well as the expansion of development activities and large farms such as flower farms in the region is expected to put further pressure on the water and associated resources of the area.

Besides, every hydrological process in the Upper Awash has effect on the development activities in the downstream of the basin.

Although there is an start of integrated water resource management in this basin, it is not at well organized stage due to different reasons. Therefore, to further strengthen assessment, water resource management and planning activities in this river basin the need for establishing rainfall runoff relationship using different rainfall-runoff modeling tools is unquestionable.

Water resource professionals need planning tools for the successful utilization of water resource. It is the state of the art to use hydrologic models for the planning process of different kinds of water resource development projects. Currently, a number of rainfalls-runoff models exist for generation of flow and establishing a rainfall-runoff relationship using different time steps. However, in areas where data are sparsely and scarcely available the pragmatic solution is to apply conceptually sound lumped rainfall-runoff models with fewer parameters such as models included in Rain fall Runoff Library.

Therefore, this study focuses in extending the application of the selected daily conceptual models namely A catchment Water Balance Model (AWBM) and Soil Moisture Accounting) (SMAR) which are nested in Rainfall Runoff Library to Upper Awash Sub River Basin catchments to establish rainfall runoff relationship which is crucial for water resource planning and management and contribute to the current water resource development endeavor in the basin.

1.3 Objectives of the Research

The general objective of the study is to conduct daily rainfall-run off modeling by using daily time series rainfall and evapotranspiration data for catchment of the Upper Awash River Basin (upstream of Koka) . Further, to investigate and study the peculiar hydrological phenomena in the catchments of this sub river basin

The Specific objectives:

- To assess the peculiar hydrological phenomena in the upper Awash river basin
- To generate daily catchment runoff for selected catchments of the basin

- To compare and analyzes the generated run off against observed data for the catchments
- To relate and analyses generated daily runoff with respect to daily rainfall data
- Calibration and Verification of models
- Comparison of performance of the models

1.4 Outline of the Thesis

The thesis is presented in six chapters including conclusion and recommendations. The first chapter provides an introduction regarding the study, general background information concerning location, land features, water resources potentials, and climate and weather conditions of the study area. Problem Statement, the general and specific objectives of the study are also illustrated under this chapter. On the second chapter, literatures such as hydrological cycle, rainfall-runoff relationship, hydrologic models and their classifications, hydrological modeling inadequacy which are relevant and directly helpful during the analysis of main or sub objectives of the work including previous study are reviewed. The methodology and procedures followed in this study are stated under chapter three .

Source and data availability including identification of the available data as well as method of data acquisition for each stated objectives are discussed under chapter four. Chapter five start with the importance of data quality checking in rainfall runoff modeling and deals with data quality checking and data filling .Moreover, identification of data range to be used in modeling , grouping of the data that was used for calibration and verification as well as model selection is presented in this chapter. The results from modeling work undertaken are described in chapter six of the thesis. It includes also interpretation and discussion made. The last chapter (Chapter seven) presents Conclusions and Recommendations of this piece of work.

1.5 Identification and Description of the Study Area

The study area is located in Awash River Basin, which is most developed and exploited and one of major Ethiopian river basins.

1.5.1 Awash River Basin

Ethiopia has twelve river basins (Table1.1). Awash River Basin is one of the twelve major

river basins in Ethiopia. Unlike many Trans-boundary Ethiopian rivers it rises and terminates in the country. Awash rises in the central high plateau of altitude 3000 meter above sea level (m. a. s. l) west of Addis Ababa and flow east wards through the Becho plain and joins several small tributaries before entering Koka reservoir ,built in 1960 for the production of hydropower. The river then descends into the Rift Valley and flows north east wards to the Afar triangle where it terminates in lake Abe at an elevation 250 m.a.s.l (Figure1.1).The Awash Basin is narrow in the upper part and widens towards the north of the catchment. The total length of the main course is 1200 km. The total mean annual water resource of the basin is 4.9 billion meter cube.

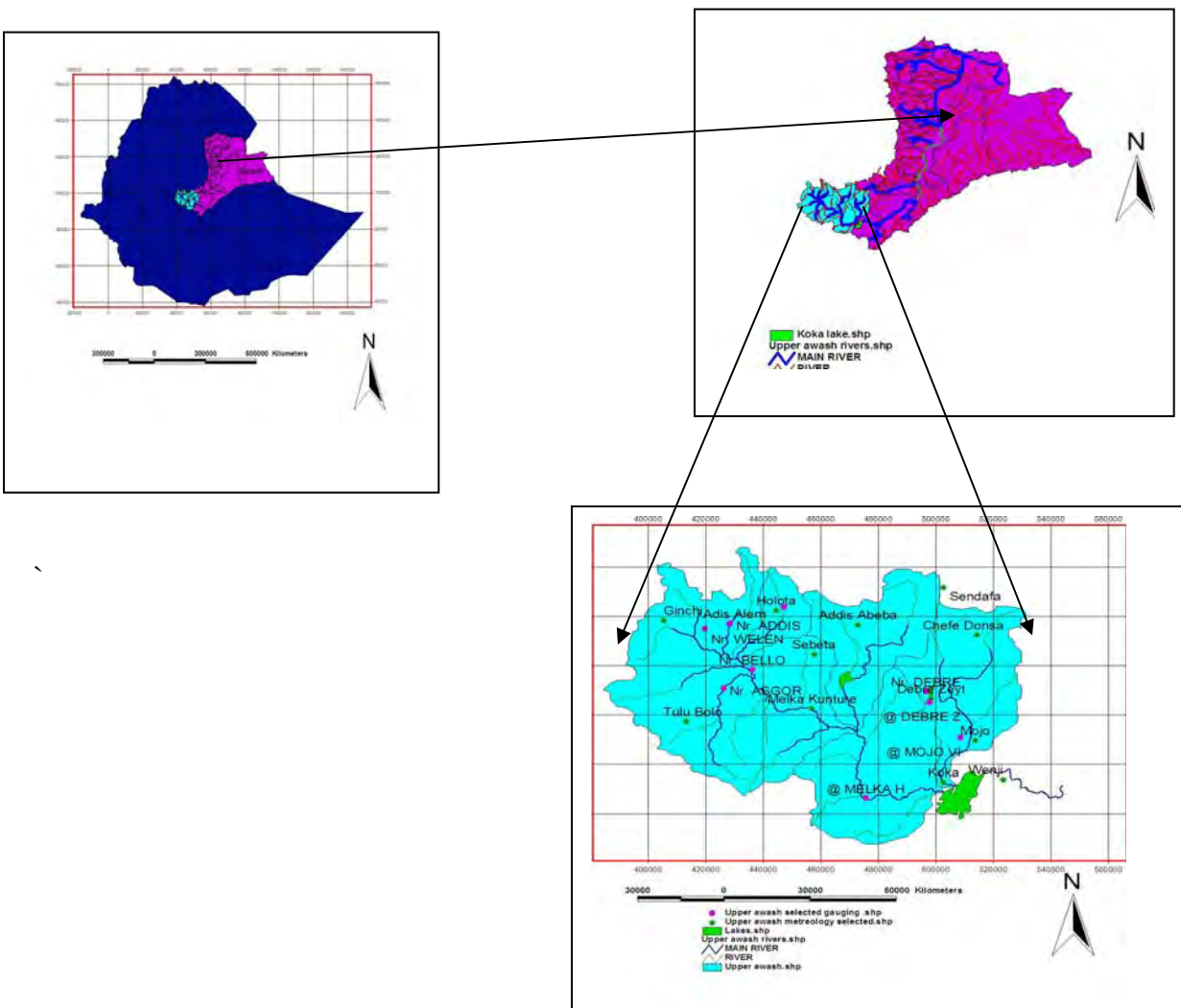


Figure 1.1 Awash River Basin and Upper Awash Sub Basin

S.No	Basin	Location	Area (sq.km)	Coverage (%)
1	Mereb Basin	Extreme North	6065	0.5
2	Tekeze Basin	North	81034	7.2
3	Denakel Basin	North	66489	5.9
4	Blue Nile Basin	North-West	192953	17.1
5	Awash Basin	Central east	113604	10.1
6	Aysha Basin	Extreme East	4717	0.4
7	Ogaden Basin	East	82157	7.3
8	Wabi Shebele Basin	South-East	207497	18.4
9	Genale Dawa Basin	South	172681	15.3
10	Rift Valley Lakes Basin	Central-south	51664	4.6
11	OMo-Gibe Basin	South-West	74912	6.6
12	Baro-Akobo Basin	West	73958	6.5

Table 1.1 Major drainage basins of Ethiopia(Source :MoWR)

The Awash basin is geographically located in between 38° E to 43.50°E longitudes and 8° N to 12.2°N latitudes. Based on the division of governmental administration, wholly or partly contributing regions of the basin are Oromiya, Addis Ababa, Afar, Amhara, Dire Dawa and Somali regional states. Due to the geological conditions, high runoff, and deforestation and over exploitation, high erosion is predominant in the basin.

The Awash Basin is the most utilized in Ethiopia. 70% of the irrigate agriculture and 90% of the nations irrigated cotton production depend on the Awash, mainly down stream of Koka.

There are two major soil types in the catchment; the deep red clay soil, Nitosol, and the dark clay soil, Vertisol (Alem, 1989). The Nitosols are found in the upland areas, whereas the Vertisols are found in lowland areas with slopes ranging from 2 to 8%. Agrarian farmers practicing rain fed agriculture populate the upper part of the catchment (upstream of the Koka

Dam). Farmers practicing pastoral farming and mixed farming sparsely populate the lower part, which is flat lowland. The existing water resources are mainly used for development of hydropower and irrigation schemes with the water being regulated by the two dams, Koka and Tendaho, on the main river.

Various inter-related factors like location, altitude, climate, topography, agricultural development, inhabitants, administrative boundaries etc contribute to the classification of the basin in to zones. Taking climate and altitude as main factors, the basin has been habitually divided into four distinct zones. These are upper basin, upper valley, middle valley and lower plains. (Halcrow, 1989)

Upper basin or uplands:-All lands in the basin above 1500m altitude, generally with a mean annual rainfall in excess of 800mm. The uplands are further sub-divided regionally into eastern and western catchments and upper basin catchment upstream of Koka.

Upper valley: - the area between Koka reservoir and Awash station which lies between 1500m and 1000m altitude.

Middle valley: - the area of the basin between Awash station and the confluence of Mile river lying between 1000m and 500m with mean annual rainfall variation from about 600mm to 200mm.

Lower plains: - are the deltaic alluvial plains in the Tendaho, Asayita, and Dit Bahari areas as well as the terminal lake environs. The area lies between 500m and 250m altitude with a mean annual rainfall of less than 200mm.

1.5.2 Upper Awash Sub Basin

1.5.2.1 General

The Upper Awash Basin lies in the Ethiopian highland plateau in elevation ranging from 1500 to 3000 above sea level. It is located upstream of Koka dam (Figure 1.2).

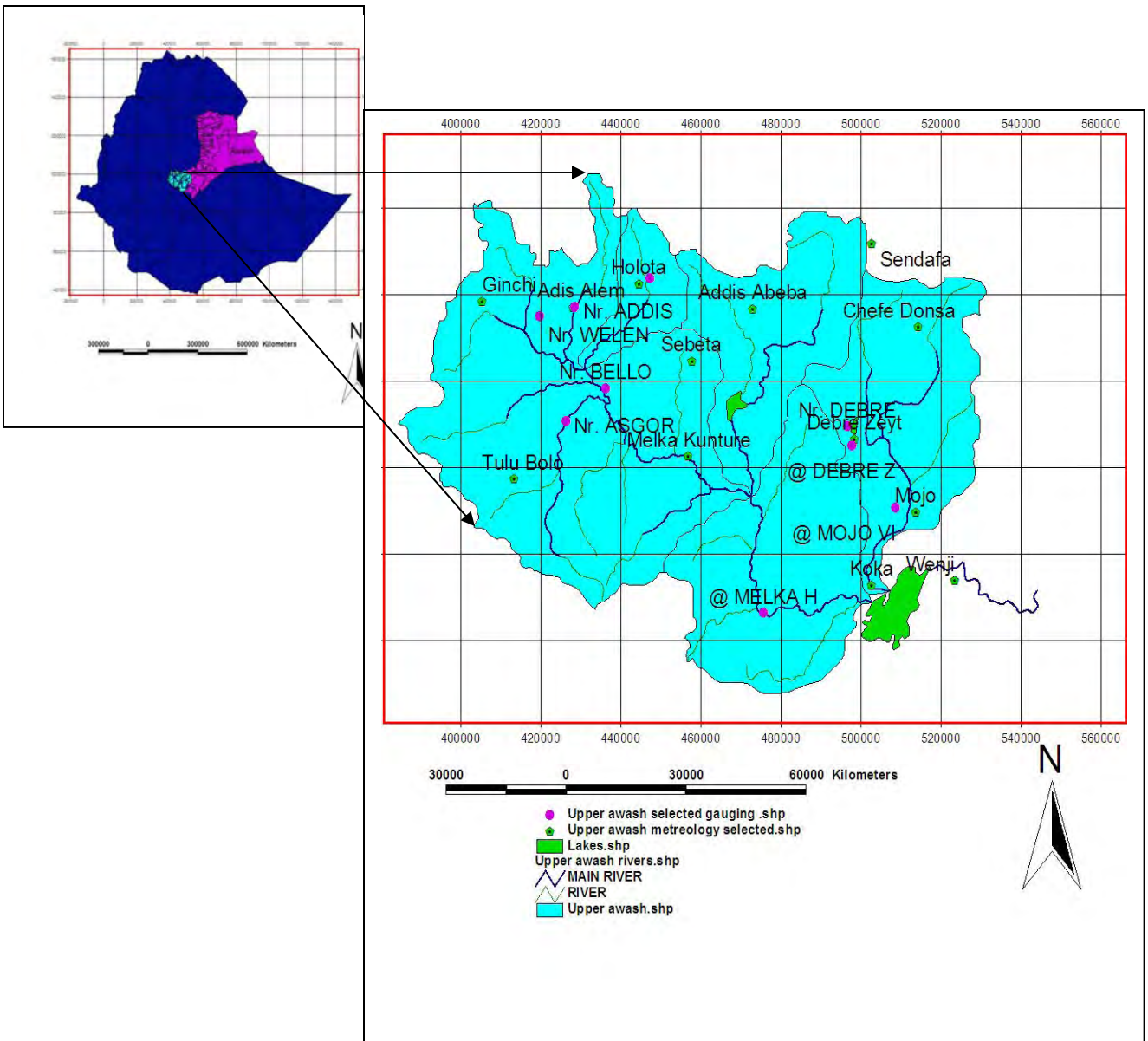


Figure 1.2 Upper Awash Sub Basin

The Upper Awash catchment is found in the highlands of central Ethiopia with all lands above 1500m asl. The land use condition in the Upper Awash catchment includes mainly of cultivated agricultural land, forest land, rural and towns. The Upper Awash River covers the river section from its source up to Koka Reservoir. The Upper Awash River drains a catchment area close to 11,300 km² and the length of the river up to Koka is around 220 km (Halcrow, 1989).

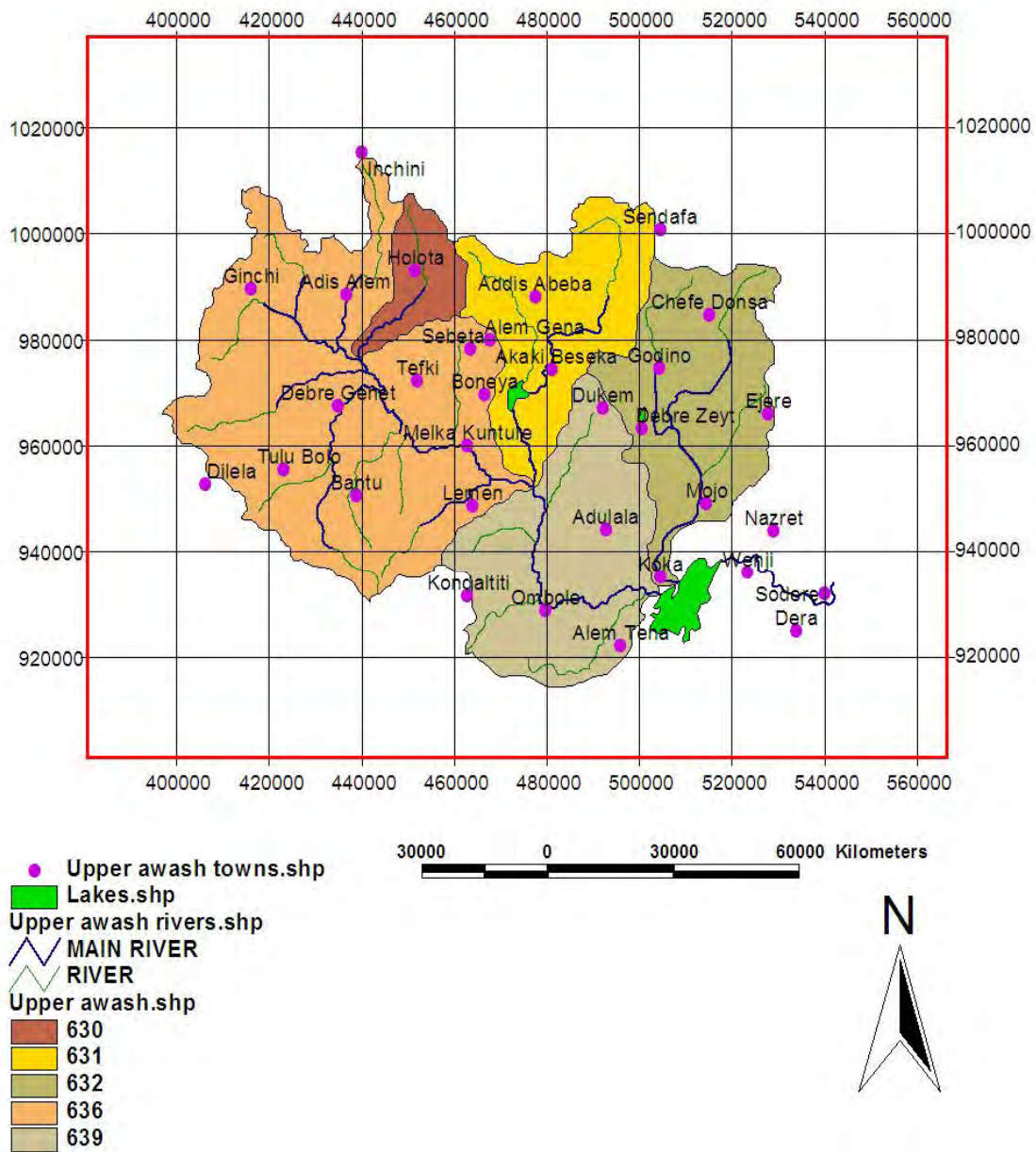


Figure 1.3 Upper Awash Catchments and Rivers

The major tributaries to the upper Awash are Akaki and Mojo rivers. Akaki River starts from the mountainous areas of the northern part of Addis Ababa and join the main Awash River between Melka-Kunture and Melka-Hombole gauging stations. Mojo River, the other main tributary to Awash, originates from the high lands northeast of Addis Ababa. It drains a catchment area close to 1,900 km² and travels a total length of about 105 km before joining Awash (Figure 1.3). According to currently available Ethio-GIS five sub catchments are

located within the Upper Awash River Basin (Figure 1.3,Table 1.2 below and Appendix B.9-B.14) shows river gauging stations and flow data in the sub catchments

S. No	Sub- Catchments	Area (km ²)	Perimeter (km)	River Gauging Stations in the Sub Catchments	Slope of the sub-catchments %
1	Sub-catchments-1	4530.38	412.35	<ul style="list-style-type: none"> ▪ Ginchi ▪ Berga ▪ A.Bello ▪ Teji ▪ M.kunture 	64
2	Sub-catchments-2	474.11	108.85	<ul style="list-style-type: none"> ▪ Holeta 	68
3	Sub-catchments-3	1608.8		<ul style="list-style-type: none"> ▪ Lt.Akaki ▪ Akaki 	83
4	Sub-catchments-4	2176.57	216.99	<ul style="list-style-type: none"> ▪ Hombole 	38
5	Sub-catchments-5	1901.70	235.38	<ul style="list-style-type: none"> ▪ Mojo 	81

Table 1.2 Sub- Catchments in the Upper Awash Sub Basin

S. No	Name of Station	River Length (km)	Catchment Slope (%)	Catchments (km ²)	Latitude (N) in UTM	Long.(E) in UTM
1	Berga Nr. Addis Alem	13.485	17	249	996668	428556
2	Holeta Nr. Holeta	14.97	76	119	1004010	446886
3	Teji @Asgori	24.142	61	663	970876	426678
4	Awash @ Belo	32.383	35	2568	978231	435855
5	Akaki at Akaki Village	44.799	68	884	981872	476159
6	Mojo @ Mojo Village	42.526	96	2175	950545	509170
7	Awash @ Melka Hombole	106.151	33	7656	950551	476159
8	Awash @ Melka Kunture	57.353	30	4456	961622	455998
9	Litle Akaki	21.34	56	131	466795	999047
10	Awash @ Ginchi	58.36	24	76	404697	997173

Table 1.3 River Gauging Stations and Sub Catchments General Characteristics in the Upper Awash Sub- Basin

1.5.2.2 Land Use and Soil Type

The land use condition in the Upper Awash catchments includes mainly of cultivated agricultural land, grassland, and forestland, rural and urban settlements. It is estimated that 67% is intensively cultivated, 25.5% is moderately cultivated, 4.5% is bush land or shrub land or wooded grassland, and 3% is urban area and alpine vegetation. Strictly speaking, even the land use within the upper Awash is diverse.

In the upper most part where there is high rainfall, land use is complete in May with barley and teff. Steeper slopes are heavily wooded with natural acacia and eucalyptus. On the lower most part, however, rainfall is too unreliable and the sparse dry acacia scrub gives way to wide stretches of bare ground with clumps of coarse grass and occasional thickets of acacia. The soil type in the upper Awash sub-basin is diverse. The most common soil types are Clay, Sand, Clay-Loam, Silt-Clay -Loam, Sand-Clay, Silt-Clay (Paulos 1989). Land use and soil type have a direct impact on the flood amount, speed and potential to create damage that the study should give attention for land use and land cover of the sub basin.

1.5.2.3 Climate

According to the definition give by the World Meteorological Organization (WMO),Climate is defined as the synthesis of weather condition in a given area characterized by long-term statistics (mean, variance, probabilities of extremes, etc) of the meteorological elements in an area (NEDECO, 1998). The WMO usually accepts 30 years of statistical data series to define climate.

In January , when the ITCZ is in its most southerly position, most of Ethiopia comes under the influence of North East trade winds , resulting in a pronounced dry season. In March , when the ITCZ crosses the basin from the south , the small spring rain occur. In, June and July the ITCZ reaches its most northerly location. This is associated with relatively humid south west monsoon air, which is responsible for the main rainy season in July and August with heavy rains.The climate of the Upper Awash Basin, in general, comes under the influence of the Inter Tropical Convergence Zone (ITCZ). This zone of low pressure makes the convergence of dry

tropical easterlies and moist equatorial westerly. The explanation of the seasonal rainfall distribution within the basin lies in the annual migration of the ITCZ across the basin. The ITCZ starts its advance across the basin from the south in March, bringing the small or spring rains. In June and July the ITCZ reaches its most northerly location beyond the basin which then experiences the heavy or summer rains throughout. The ITCZ returns southwards during August, September and October, restoring drier, easterly airstreams that prevail until the ITCZ resumes its northward migration in March (Halcrow, 1989).

Apart from this general pattern, there is a high spatial variance within the Upper Awash Basin due to the height dependence of the climatic parameters and the varying topography.

1.5.2.4 Temperature

Temperature varies considerably over the basin and range from a mean annual temperature of 16.7 °C at Addis Ababa to 29 °C at Dubti. The mean annual temperature range in the basin is around 15°C. The temperature at Addis Ababa ranges from a mean monthly maximum of 22.5°C to a mean monthly minimum of 9.6°C (Halcrow, 1989).

1.5.2.5 Wind Speed, Sunshine and Relative Humidity

The wind flow pattern is influenced by the seasonal variation of the ITCZ. The predominant wind direction during June to September is southerly to southwesterly. The wind speed pattern is distinctly bimodal in Addis Ababa region with peaks occurring in March and September and minimum speeds being recorded in July and August. The mean annual wind speed at Addis Ababa is 0.9m/s.

The Awash basin experiences 2700 hours of sunshine annually. The monthly variation closely follows the rainfall pattern as would be expected with more sunshine hours in the dry months than in the wet months. Sunshine hours vary from a daily mean of 9.4 hours in December to 3 hours in July at Addis Ababa. The mean annual relative humidity of the basin is 60.2% measured at Addis Ababa. The monthly variation in relative humidity at Addis Ababa ranges from 50.9% in March to 78.5% in August.

CHAPTER TWO

LITERATURE REVIEW

2.1 Rainfall Runoff Relationship

In order to represent and simplify a catchment in a computer model, one has to have knowledge about the processes in the watershed impacting the local hydrology.

Flood runoff has often been considered to consist of surface runoff produced at the ground surface when the rainfall intensity exceeds the infiltration capacity. While this process, known as Hortonian overland flow, occurs in many situations, two other general storm runoff processes i.e. Saturated overland flow and Through flow are now recognized, as a result of observations on natural basins during storm periods and many detailed studies of instrumented plots and small areas (Maidment 1993). All these processes are discussed in the following paragraphs. Saturated overland flow occurs when one part of the drainage basin the surface horizon of the soil becomes saturated as a result of either the buildup of a saturated zone above a soil horizon of lower hydraulic conductivity or the rise of a shallow water table to the surface (Maidment 1993).

Through flow is water that infiltrates into the soil and percolates rapidly, largely through macro pores such as cracks and root and animal holes, and then moves laterally in a temporarily saturated zone, often above a layer of low hydraulic conductivity. It reaches the stream channel quickly and differs from other subsurface flow by the rapidity of its response and its relatively large magnitude (Maidment 1993). Runoff processes operating at any location vary from time to time. Large variations in hydrologic characteristics, and therefore in runoff processes, also occur over small apparently homogeneous areas to the extent that all three runoff processes discussed above may occur during a single storm runoff event.

The type of runoff process and the location of source areas, whether close to the outlet and adjacent to stream channels or on the ridges remote from the channels, has considerable influence on the resulting hydrographs. However, practical methods for estimating storm losses and runoff have not yet been developed to explicitly account for these differences (Maidment 1993). Uniform or average conditions, at least over sub areas, are generally assumed.

The rainfall runoff process is well described in many literatures. Numerous papers on the subject have been published and many computer simulation models have been developed. All these models, however, require detailed knowledge of a number of factors and initial boundary conditions in a catchment area, which in most cases are not readily available. For a better understanding of the difficulties of accurately predicting the amount of runoff resulting from a rainfall event, the major factors, which influence the rainfall-runoff process, are described below.

2.2 Factors Affecting Runoff

Apart from rainfall characteristics such as intensity, duration and distribution, there are a number of site (or catchment) specific factors, which have a direct bearing on the occurrence, and volume of runoff.

2.2.1 Soil Type

The infiltration capacity is dependent on the porosity of a soil, which determines the water storage capacity and affects the resistance of water to flow into deeper layers. Porosity differs from one soil type to the other. The highest infiltration capacities are observed in loose, sandy soils while heavy clay or loamy soils have considerable smaller infiltration capacities.

The infiltration capacity depends furthermore on the moisture content prevailing in a soil at the onset of a rainstorm. The initial high capacity decreases with time (provided the rain does not stop) until it reaches a constant value as the soil profile becomes saturated.

2.2.2 Vegetation

The amount of rain lost to interception storage on the foliage depends on the kind of vegetation and its growth stage. More significant is the effect the vegetation has on the infiltration capacity of the soil. The root systems as well as organic matter in the soil increase the soil porosity thus allowing more water to infiltrate. Vegetation also retards the surface flow particularly on gentle slopes, giving the water more time to infiltrate and to evaporate. In conclusion, an area densely covered with vegetation, yields less runoff than bare ground.

2.2.3 Slope and Catchment Size

Investigations on experimental runoff plots have shown that steep slope plots yield more runoff than those with gentle slopes. In addition, it was observed that the quantity of runoff decreased with increasing slope length. This is mainly due to lower flow velocities and subsequently a longer time of concentration (defined as the time needed for a drop of water to reach the outlet of a catchment from the most remote location in the catchment) (Ponce 1989). This means that the water is exposed for a longer duration to infiltration and evaporation before it reaches the measuring point. The same applies when catchment areas of different sizes are compared. The runoff efficiency (volume of runoff per unit of area) increases with the decreasing size of the catchment i.e. the larger the size of the catchment the larger the time of concentration

2.3 Establishing Rainfall-Runoff Relationships

Many processes that are interests from a hydrologic point of view are often difficult to observe routinely and unambiguously. Stream flow measurements is one such variable that can only be measured at a gauging stations of a basin with some confidence .However, from a broader perspective , major river basins or catchments , especially in developing countries like Ethiopia have been gauged for determination of hydrological variables , while medium and small size catchments are mostly un gauged. Several major catchments in different parts of the developing country like Ethiopia are still remain ungauged. Thus, there is a need for methods that can be utilized for realistic estimation of such hydrological variables in the un gauged catchments. One of the popular methods is

to make use of the available rainfall-runoff data to develop a relation ship and use the same for extrapolating the rainfall series to generate runoff

2.4 Water Balances

Considering the land phase of the hydrological cycle, any conceptual model predicates its effort on an expansion of the basic water balance or continuity equation .The water balance equation, in general, stipulates that all inflow minus all outflows to an area during a certain time period must be equal to change in storages.

$$I-O=dS/dt$$

where, I is all inflow,O is all outflow, and dS is storage changes that occurred during time period dt. For Specific area and specific period, the water balance equation can be written as :

$$P - Q - E = \Delta S$$

Where ,

P=precipitation

Q=runoff

E=evaporation

ΔS =change in storage

Thus, the main processes encompassed in water balance or continuity equation are precipitation, evapotranspiration, interception, infiltration, subsurface flow and stream flow. It is evident that before any modeling effort can be performed, one has to understand the above physical processes, their extent of effect on the abstraction from or addition of water to a catchment.

2.4.1 Precipitation

Precipitation is the input to the system of catchment, which may have different forms, rainfall, storms, dew or any form of water landing from atmosphere. The amount of

precipitation can be defined as an accumulated total volume for any selected period. Precipitation as a function of time and space is highly variable. Systematic averaging methods such as Thiessen polygon, isohyete and reciprocal distance methods have been developed to account for variations in space to obtain a representation of areal precipitation values from point observation. Singh and Chowdhury, (1986) after comparing the various methods for calculating areal averages, concluded that all methods give comparable results, especially when the time period is long. For short time step records, the conversion of a point observation to an areal rainfall has a large influence.

2.4.2 Evaporation and Transpiration

Evaporation is the general term for describing water release from ground and water surfaces to the atmosphere. This includes evaporation from plants (transpiration) and the direct evaporation from soil and/or water surfaces (evaporation). A summarizing name for both evaporation and transpiration is evapotranspiration.

Catchment evaporation demand is generally defined as that evaporation which would occur if there were no deficiencies in the availability of moisture for evapotranspiration by that area's particular plant regime. The two main factors influencing evaporation from an open water surface are the supply of energy to provide latent heat of vaporization and the ability to transport the vapour away from the evaporative surface: solar radiation and wind. Evapotranspiration from land surface comprises evaporation directly from the soil and vegetation surface and transpiration through plant leaves, in which water is abstracted from the sub soil. The third factor is the supply of moisture at evaporative surface, which brought about the definition of potential and actual evaporation. The amount of water that can theoretically evaporate (water is not a limiting factor, e.g., water can evaporate from free water surface) is called Potential evaporation. The evaporation that takes place when water is a limiting factor, e.g. when soil surface is only partially saturated, is called actual evaporation. Similar nomenclature can be applied to evapotranspiration . Evaporation involves a highly complex set of processes, which themselves are influenced by factors dependent on the local conditions (land use, vegetation cover, and meteorological variables). Mostly the potential evaporation is the

quantity obtained either by using some simple empirical formula such as Thornthwaite, Penman formula and a process-based model of Penman-Monteith.

Since potential evaporation and evaporation from pans are governed by the same meteorological factors they have strong correlation. The relation between them is often give as a simple ratio. Burnash (1995) suggests using seasonal coefficients for converting pan data to potential evaporation rather than a single coefficient. In conceptual rainfall runoff modelling one of the two terms, pan evaporation and potential evapotranspiration are equally used as input, which exerts energy to extract water from open surface or soil moisture storage.

2.4.3 Interception

The portion of rainfall intercepted by the vegetation and roofs before reaching the ground is referred to as interception. The water, which is intercepted by the leaves of vegetation and roofs eventually evaporates into atmosphere. The amount of interception could be significant in densely vegetated areas such as tropical rainforests. Such forests maintain a relatively consistent canopy and do not generally exhibit the seasonal range of interception encountered in areas where deciduous trees are dominant. It is commonly understood that if the density of the vegetation cover is sparse then this loss is insignificant.

2.4.4 Infiltration

The precipitation, which is not intercepted or evaporated from the land, will eventually infiltrate into the soil or flow as overland flow. Infiltration is one of the most difficult hydrological processes to quantify. The difficulty arises due to many physical factors affecting the rate of infiltration such as rainfall intensity, initial moisture content, soil property, etc. Some experimental and empirical formulas such as Horton (1939), Philip (1957), and others are available to compute infiltration rates during a rainfall event. Depending on the soil strata, the infiltrated water gradually percolates to the groundwater or either flows as subsurface flow supplying river or springs within the catchment.

2.4.5 Stream Flow

The rainfall that exceeds the interception requirement and infiltration starts to accumulate on the surface. Initially the excess water collects to fill depressions, until the surface detention requirement is satisfied. There after when water begins to move down slope as a thin film and tiny streams which eventually join to form bigger and bigger channels. This part of the stream flow is termed as surface runoff. The infiltrated part of the rain may sometimes come as subsurface runoff, which combined with the surface runoff, constitutes the direct runoff. Hence the direct runoff is the result of the immediate response of a catchment to the input rainfall. The stream flow consists of the direct runoff (which lasts for hours or days depending upon the catchment size) and the base flow (that emerges from groundwater resources and also delayed subsurface runoff).

2.5 System Approach in Catchment Modelling

The in depth processes that link the rainfall over the catchment to the stream flow may be studied by applying physical laws that are reasonably well known. However hydrological phenomena are extremely complex, and may never be fully understood. The complexity of the boundary conditions (i.e. the physical description of the catchment and the initial conditions and distribution of the variables) makes a solution based on the direct application of the laws of physics impracticable. Moreover, direct application of these laws requires subdividing the catchment into homogenous and isotropic regions. The sub division depends on catchment characteristics (soil type, land use, slope, vegetation cover, etc.) and these factors may also vary in space and time. Thus, representing the hydrological processes in simplified way by means of system concepts is very crucial (Chow 1988). For these reasons, instead of exact representation of the processes effort is directed to the construction of a model by using system concepts relating input and outputs. Hydrologic system analysis is therefore, required to study the system operation and to predict its output. Developing a hydrologic system model, which is an approximation of the actual system, can do this; its input and outputs are measurable hydrologic variables and its structure is a set of equations linking the inputs and out puts.

A hydrologic system is defined as a structure or volume in a space, surrounded by a boundary that accepts water and other inputs, operates on them internally, and produces them as outputs (Chow et al 1988). Schematic representation of the system operation is shown in Figure 2.1 where the symbol Ω represents a transformation between the input and the output.



Figure 2.1 Diagrammatic representation of a hydrological system

The objective of the hydrologic system analysis is to study the system operation and to predict its output. A hydrological system model is an approximation of the actual system. Its input and output are measurable hydrological variables and its structure is the concept of the system transformation.

2.6 Hydrological Modeling Inadequacy

There are many existing computer models which are powerful tools that can be utilized to design and estimate the performance of various development activities. This means that the performance of different development proposals can be assessed and compared using a common measurement system. Essentially, models allow the extrapolation from existing systems and knowledge to analyze potential situations. They are only useful to the extent that they accurately model the real world. Unrealistic models, however internally consistent or persuasive they may be, are misleading and risky.

The study area (Upper Awash) is categorized under semi arid and arid climatological region .In arid regions, an important feature of the water balance is the high proportion of incoming water which is returned to the atmosphere by evaporation from soil surface. In contrast to the humid regions, where evaporation is limited by available energy (e.g. net radiation), in the arid zone water availability is the dominant control over evaporation rates. Because of the sparse density of vegetation, direct evaporation of water from the

soil is of enhanced importance, and frequently as much as half of the annual rainfall can be lost in this manner (Chow 1964). It is noted that the prevailing rainfall and evaporation mechanism in semi-arid and arid catchments, associated with the thin and sparse vegetation cover, alter the runoff generation of these regions in contrast to the humid regions. The runoff generated is mainly controlled by infiltration excess and is frequently localized. The runoff generated on some of the slopes and first order catchments may not always survive to contribute to the flow at the outlet of catchments of sufficient size. Hughes (1995) numerates the possible reasons why deterministic models can fail as tools for water resources estimation purposes, where failure implies the model imperfection. Apart from erroneous data inputs and poor interpretation of model results, the problems associated with the application of rainfall- runoff models to arid and semiarid areas are:

- Inadequate or inappropriate model representation of the prevailing catchment processes
- Inadequate representation of the spatial variability of runoff generation response to runoff. While this problem can be masked by spatial lumping, it may be important if the effects are non-linear and non-stationary
- Inadequate representation of the spatial variability in rainfall input, either through lumping or lack of spatial resolution in the available data.
- Inadequate representation of the temporal variability in rainfall input through the use of a coarse time interval model. This is not always a serious problem as long as the rainfall mechanisms are reasonably consistent and the durations and intensities of the major rainfall events are similar.
- insufficient estimation of parameter values. This problem may relate to the length of the records available for calibration (Görgens, 1983) and the extent to which the rainfall-runoff relationships reflected in the observed data are sufficiently representative to allow a suitable parameter set to be quantified

In general the two interrelated underpinning problems in hydrological modeling in such regions are:

1. The model assumptions and simplifications which are not always justified in modeling in any region but over simplification of the variability in such areas.
2. The limitation of data availability as opposed to the temporal and special variability of the input to any physical or conceptual (distributed or lumped) models.

This implies that any effort in modeling such region should consider and compromise the two underlying problems that on one hand the model has to address the peculiar phenomena and at the same time it should require limited input as only limited data are available.

2.7 Classification of Hydrological Models

Different literatures reveals that depending on the assumptions and concepts formulating the structure of the transformation (Operator) the resulting models may have diverse forms. According to Clarke (1973) mathematical models may be classified in to four main groups.

- 1) Stochastic - Conceptual
- 2) Stochastic - Empirical
- 3) Deterministic - Conceptual
- 4) Deterministic - Empirical

Deterministic stands for using the same in put data for the simulation leads to the same result whereas stochastic stands for usage of random variables can lead to different out put. In other words, If any of the variables is a random variable having a probability distribution, then the model is stochastic. Conversely, if all the variables are free from random variations, then the model is deterministic.

Deterministic models are formulated by following laws of physical and/or chemical processes as described by differential equations. Ideally, a deterministic model should be able to provide the best detail in simulation of physical or chemical processes. In practice, however, the application of deterministic model is often hindered by model's (or

modeler's) inability to resolve the temporal and spatial variability of natural phenomena into sufficient small increments (Ponce 1989).

Any of the four categories indicated above may be classified as linear or non-linear in the system theory sense. Group 1 and 2 may be linear or non-linear in the statistical regression sense. The models in any group may further be classified as lumped, probability distributed or geometrically distributed.

The hydrological models are described as conceptual or empirical according to whether the form of the model equation is, or is not suggested by consideration of the physical processes acting up on the input variable to produce the output variables. This distinction is, however artificial since many physical laws contain empirical constants. Despite the artificiality of the distinction, it is one widely drawn in the literature, the difference between 'conceptual' and 'empirical' corresponding approximately to the O' Connell's (1966) terms 'synthetic' and 'analytic' whilst the term 'black box' used by some writers, corresponds to 'empirical'.

According to some available literatures, conceptual models are simplified representations of the physical processes; usually rely on mathematical descriptions (either in algebraic form or by ordinary differential equations), which simulate complex processes in the mean by relying on a few key conceptual parameters.

Linearity and non-linearity in the system analysis sense is based on the principle of superposition (Clarke 1973). A model is linear in the system analyses sense if the principle of superposition holds. The model is linear in statistical regression sense if it is linear function of the parameters to be estimated.

A lumped model ignores the spatial distribution of the input variables and parameters, which characterizes the physical process. A probability-distributed model describes the spatial variation of the input variables without geometrical references to the point at which the input is measured or estimated. On the other hand a geometrically distributed

model expresses the spatial variability in terms of the orientation of the network points relative to each other and their spacing.

Neither lumped nor distributed models generally perform better results in comparison to each other. The use depends on the data basis (resolution, quality), the available resource (e.g. time , fund and computer power) as well as the desired purpose of the model.

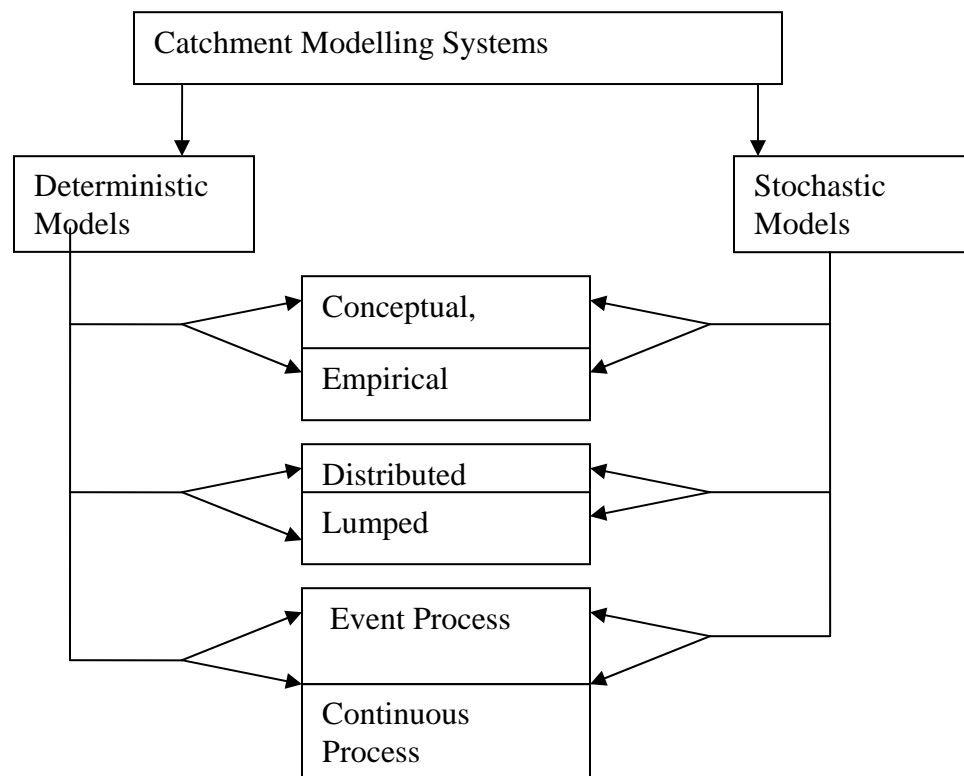


Figure 2.2 Classification of Catchment Modelling System (Kiesel J .2006)

In majority of cases, the watershed characteristics are lumped, many of the processes are lumped , the input is lumped and even some of the boundary conditions are lumped, but some of the processes that are directly related to the output are distributed (Singh 1995).

Moreover, lumped models do not need as detail input data as distributed models. This makes them more suitable for regions with poor data basis.

According to Kiesel J. (2006), one can distinguish models according to figure 2.2, but not all features described there are inescapable differentiation criteria for CMS.

In order to select among the plethora of different mathematical models available today, it is possible to identify models according to a priori knowledge. The latter ranges from total ignorance (pure stochastic models) to the full description of system dynamics based upon differential equations describing the balance of mass and momentum.

Therefore, Todini (1988) classified models based on the level of the priori knowledge on the system under study in terms of both model structure and parameters. Accordingly the recent classification groups the model in the increasing level of a priori knowledge as: 1) purely stochastic, 2) lumped integral, 3) distributed integral and 4) distributed differential. The final choice on which model to use mainly depends on the purpose of application, the accuracy desired, the available data and economics.

2.8 Conceptual Models

The conceptual models occupy an intermediate position between the fully physical approach and empirical black box analysis. Such models are formulated on the basis of a relatively small number of components, each of which is a simplified representation of one process element in the system being modeled. The purpose of this break down is primarily to enable the run off from the catchments to be estimated using standard parameters together with actual data.

In majority of cases, the watershed characteristics are lumped, many of the processes are lumped, the in put is lumped and even some of the boundary conditions are lumped, but some of the processes that are directly related to the output are distributed. Moreover, lumped models do not need as detail input data as distributed models. This makes them more suitable for regions with poor data basis.

Conceptual models consist of two main components: the first represents the soil water balance and the second represents the transfer of water to the closure section of the catchment. The water balance component is the most important aspect that characterizes a model. This component expresses the balance between the moisture content of the soil, generally divided into several zones and the incoming (precipitation) and outgoing (evaporation and runoff) quantities (Franchini and Pacciani 1991).

Conceptual models are widely used in water balance studies and chosen in this study particularly due to:

- their ability in representing the system in terms of parameters.
- their potential to correlate the few parameters with hydro-meteorological and physiographical characteristics.
- their ability to carry out computations on time scales varying from hours to years. The time step chosen depends on the application of the model. Daily and monthly time steps are common in water balance models for basins. Important to note is that the smaller the time step, the more complicated the model becomes and the more stringent are requirements on the data.
- their use of readily available hydro-meteorological data (as mean or totals of daily, weekly or monthly values).

2.9 Rainfall Runoff Library

The Cooperative Research Centre (CRC) for Catchment Hydrology in Australia has produced a series of models in their catchment modeling toolkit. At present there are eight modeling platforms available within the catchment modeling toolkit (Appendix C.1).

Among these models, rain fall run off Library which is used in this thesis work has several models nested in it. The Rainfall Runoff Library is designed to simulate catchment runoff by using daily rainfall and evapotranspiration data. The models may be applied to catchments from 10 km² to 10,000 km² on a daily time step. The models are typically used to fill gaps and extend stream flow records.

The Rainfall Runoff Library (RRL) currently contains five rainfall-runoff models (Appendix I), seven optimization algorithms, a choice of eight primary objective functions, four secondary objective functions and 3 types of data transformation for comparison against observed data(Appendix C.2). There is a graphical user interface that comprises menus, dialogues and graph display tools.

The models provide outputs including standard hydrological analyses (e.g. flow duration curves). Each model has a set of default values given with it.

Each of these models simulates runoff at the catchment (or possibly subcatchment) scale. This information can be linked to other models although the lack of spatial distribution makes it difficult to see how they can be used for investigation issues of cumulative effect within a catchment.

The real advance provided by the RRL is not in the models used but in putting several commonly used models (certainly commonly used in engineering hydrology) into a single framework for use on a desktop PC. By having them all together the practitioner can try different models for the same application and has a very good set of optimisation tool available for use with the different models.

The actual model chosen for use in a particular situation is dependent on the data available to parameterize it and the detail required in the application. The models currently available are all spatially simplistic. They use a simple system of a single unit or can be linked as a series of sub-catchment but cannot be used in a truly distributed fashion. The models include AWBM, Sacramento, Simhyd, SMAR, and Tank. Detail study of these models is not the objective of the study. Thus, only AWBM and SMAR which are selected for this study are described below.

2.9.1 AWBM

AWBM is a lumped conceptual water balance model derived from the work of Boughton. It has many similarities to the water balance model developed at Landcare Research for the SMF funded project on effects of tall vegetation. It relates runoff to rainfall with daily

or hourly data, and calculates losses from rainfall for flood hydrograph modeling (CRC 2004).

However, the RRL is currently geared towards modeling at a daily time step and AWBM is not run on hourly data. One oddity of AWBM is that it requires actual evapotranspiration as input; as opposed to potential evapotranspiration that the other models in the toolkit require (RRL 2004).

2.9.1.1 Simulation Principle

Each catchment is treated as a single unit and the model uses 3 surface stores to simulate partial areas of runoff. The water balance of each surface store is calculated independently of the others (Figure 2.4). The model calculates the moisture balance of each partial area at daily time steps. At each time step, rainfall is added to each of the 3 surface moisture stores and evapotranspiration is subtracted from each store. The water balance equation is:

$$\text{store}_n = \text{store}_n + \text{rain} - \text{evap} \quad (n = 1 \text{ to } 3) \text{-----}(2.1)$$

If the value of moisture in the store becomes negative, it is reset to zero, as the evapotranspiration demand is superior to the available moisture. If the value of moisture in the store exceeds the capacity of the store, the moisture in excess of the capacity becomes runoff and the store is reset to the capacity. The three parameters A1, A2 and A3 representing the proportions of the areas of the catchment are constrained; thus only A1 and A2 can be set.

The default pattern is A1= 0.134, A2= 0.433, A3= 0.433 and this pattern is fixed (i.e. calibration tools will not modify it). When A1 and/or A2 are changed, A3 will be adjusted to respect the constraint. If the user increases A1, and A3 cannot compensate, then A1 is reduced to still respect the constraint (RRL 2004).

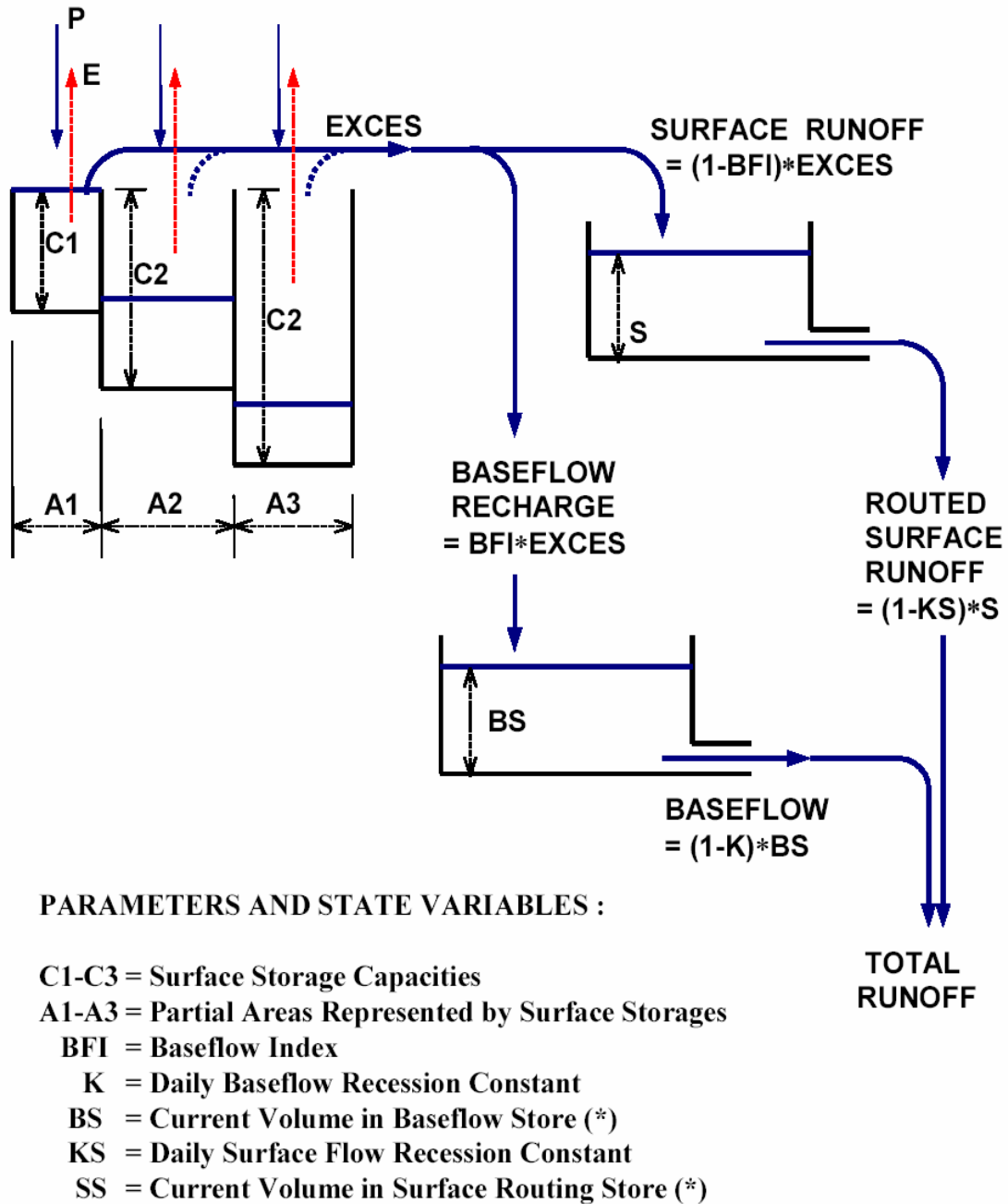


Figure 2.3 A Schematic Representation of the AWBM Model (Source: RRL Manual 2004)

According to rainfall runoff library manual, runoff occurs from any store, part of the runoff becomes recharge of the base flow store if there is base flow in the stream flow. The fraction of the runoff used to recharge the base flow store is $BFI \cdot \text{runoff}$, where BFI

is the base flow index, i.e. the ratio of base flow to total flow in the stream flow. The remainder of the runoff, i.e. $(1.0 - \text{BFI}) \times \text{runoff}$, is surface runoff. The base flow store is depleted at the rate of $(1.0 - K) \times \text{BS}$ where BS is the current moisture in the base flow store and K is the base flow recession constant of the time step being used (daily or hourly). The surface runoff can be routed through a store if required to simulate the delay of surface runoff reaching the outlet of a medium to large catchment. The surface store acts in the same way as the base flow store, and is depleted at the rate of $(1.0 - \text{KS}) \times \text{SS}$, where SS is the current moisture in the surface runoff store and KS is the surface runoff recession constant of the time step being used.

2.9.1.2 Default Values

The RRL is configured with a set of default values for each model parameter. These default values specify the initial parameter value as well as the upper and lower bounds for that parameter. Table 2.1 lists the default values for the AWBM model.

S. No	Parameter	Default Value	Default Minimum	Default Maximum
1	A1	0.134	0.000	1.000
2	A2	0.433	0.000	1.000
3	BFI	0.350	0.000	1.000
4	C1	7	0	50
5	C2	70	0	200
6	C3	150	0	500
7	KBase	0.950	0.000	1000
8	KSurf	0.350	0.000	1000

Table 2.1 Default Parameter of WBM model (Source, Rainfall Runoff Library manual 2004)

2.10.2 SMAR

The soil moisture and accounting 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 2.5. 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.

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 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 2.1.

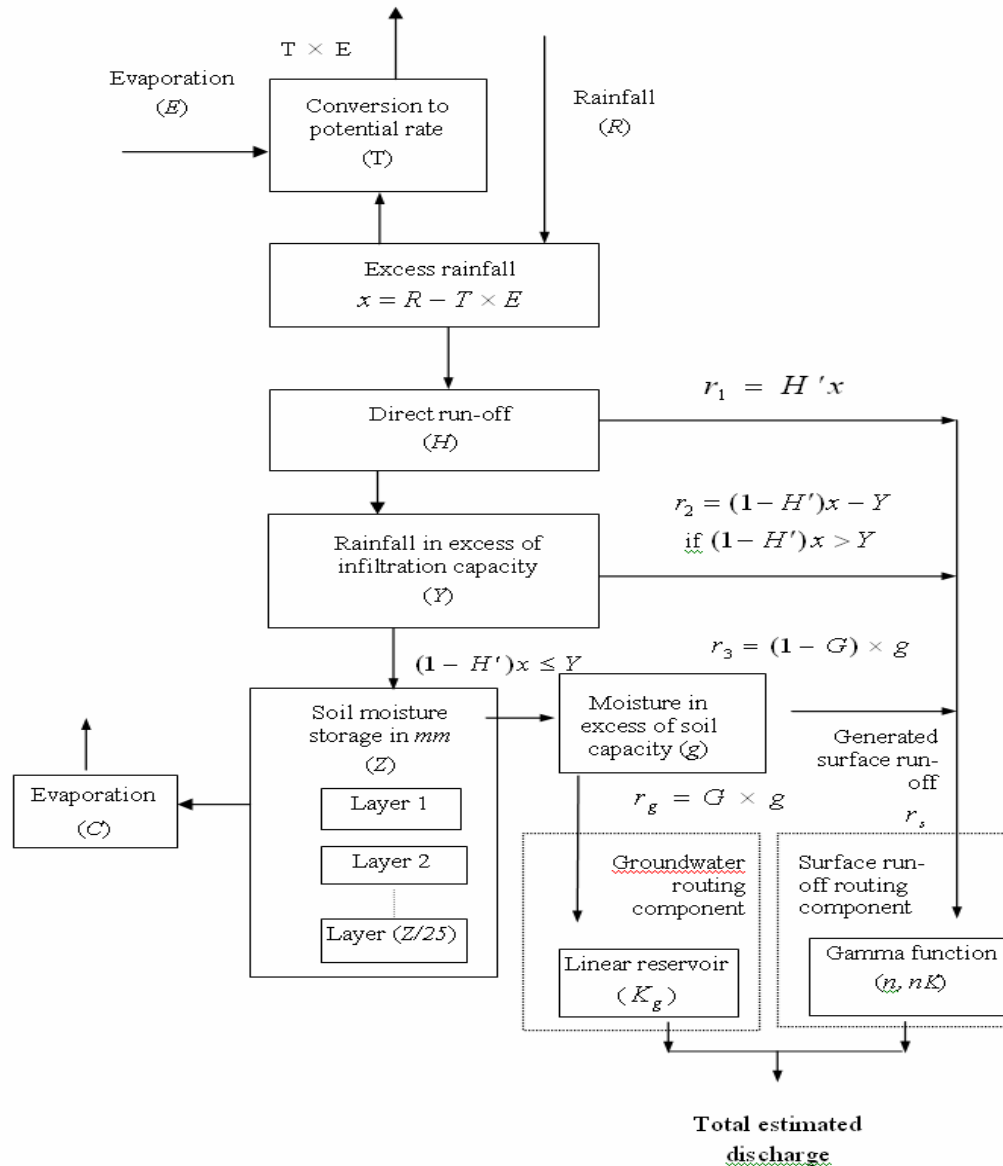


Figure 2.5 A Schematic Representation of the SMAR Model (Source: RRL Manual 2004)

$$h(t) = \frac{1}{t} \int_{t-1}^t \frac{1}{K\Gamma(n)} \exp\left(\frac{-\tau}{K}\right) \left(\frac{\tau}{K}\right)^{n-1} d\tau \text{-----2.1}$$

where, t= simulation time step (d), τ =time(s), $K_1=K_2=\dots=K_n= K$ are the storage coefficients of n linear reservoirs in cascade, h(t)= ordinates of the pulse response

function (d^{-1}) and $\Gamma(n) = \int_0^{\infty} \exp(-\tau) \tau^{n-1} d\tau$ is the incomplete 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.

2.10.2.1 Water balance

The water balance component uses five parameters to describe the movement of water into and out of a generalised soil column under conditions of atmospheric forcing: C , Z , H , Y and T (RRL 2004).

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

- 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

- The parameter Y ($\text{mm}\cdot\text{d}^{-1}$) 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.

2.10.2.2 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 $\text{mm}\cdot\text{d}^{-1}$) and the routed run-off (Q_T^r $\text{mm}\cdot\text{d}^{-1}$) can be time-averaged, as in equation (2.2) and (2.3), to represent the daily values.

$$r_s(t) = \frac{1}{t} \int_{\tau-t}^t r_s(\tau) d\tau \text{ ----- (2.2)}$$

$$Q_T^r(t) = \int_{\tau=t}^t Q_T^r(\tau) d\tau \dots\dots\dots (2.3)$$

The linear model described by equation (2.4) is the simplest representation of a causal, time- invariant, relationship between an input function of time (generated run-off) and the corresponding output function (routed run-off). It is used in conceptual modeling, as a component, representing the routing or diffusion, effects of the catchment on those components of the rainfall hyetograph contributing to the outflow.

$$Q_T^r(t) = \sum_{j=1}^m h(j) r_s(t - j + 1) \dots\dots\dots (2.4)$$

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

The parameter pair n and nK are chosen for optimization, rather than n and K separately, because n is a ‘shape’ 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(RRL 2004).

Ground Water Routing Component

The mass balance equation for the groundwater system can be written as in equation 2.5.

$$Q_T^{rech}(\tau) - Q_T^g(\tau) = \frac{dS(\tau)}{dt} = DS(\tau) \dots\dots\dots (2.5)$$

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 differentials 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 water table 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 visualized 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 K_g . The pulse-response function for the groundwater component can be obtained in a manner analogous to equation 2.1 as in equation 2.6.

$$h^g(t) = \frac{1}{t} \int_{t-1}^t \frac{1}{K_g} \exp\left(\frac{-\tau}{K_g}\right) d\tau \dots\dots\dots (2.6)$$

The recharge $Q_T^{rec}(t)$ and the discharge $Q_T^g(t)$ can be time averaged to $\text{mm}\cdot\text{d}^{-1}$ in an analogous manner, as in equations 2.2 and 2.3.

2.10.2.3 Default Values

The Rainfall Runoff Library (RRL) is configured with a set of default values for each model parameter. These default values specify the initial parameter value plus the upper and lower bounds for that Parameter. Table 2.2 lists the default values for the SMAR model.

S. No	Parameter	Default Value	Default Minimum	Default Maximum
1	C	0	0	1
2	G	0	0	1
3	H	0	0	1
4	Kg	0	0	1
5	N	1	1	6
6	NK	1	0.01	1
7	T	0	0	1
8	Y	0	0	5000
9	Z	200	0	5000

Table 2.2 Default parameter values for the SMAR model (Source: Rainfall Runoff Library Manual 2004)

2.11 Previous Research Work in the study area

Many studies have been done and are currently being done to investigate different hydrological phenomenon in the upper Awash River basin. But rainfall runoff modeling with an adequate and updated data has not fully studied using catchment modeling tools such as conceptual rainfall runoff modeling that comprises commonly used models (certainly commonly used in engineering hydrology) into a single framework for use on a desktop PC. It is important to know what has already been done regarding the hydrological processes. Thus, in this chapter, those works are briefly described and assessed so that this thesis can build on this foundation.

Mengistu (2008) conducted regional flood frequency analysis applying at-site homogeneity test and grouped stations in the Upper Awash Sub Basin in to two regions. According to the study the upper region covers 18.46% of the sub-basin and the lower region covers 81.54% of the Sub Basin.

Another recent study in the Upper Awash Basin indicated that the low quality of flow and sediment load data, a highly varying discharge coefficient as well as a little information on soil parameters make hydrologic modeling of the area difficult (Kiesel 2006).

In this study, keeping the aforementioned problems in mind, the available hydrologic model were assessed and finally two models, the river basin model SWAT that uses the SCS-CN method for rainfall runoff modeling and the TALSIM model, which uses the physical description of the soil moisture, were chosen and applied on an example catchment.

The author observed that, for the chosen Ethiopian catchment, the soil moisture method is more suitable for simulating the run off process than the SCS-CN method. However, both SWAT and TALSIM models showed sever weaknesses in the prediction of the peak flows.

According to this study, the reason for poor model results and difficulties and uncertainties in the model assessment are due to a number of factors including the influence of the catchment size, the daily modeling time step and the daily averaging of the rainfall intensities for the upper Awash Basin.

Paulos (1998) used the soil conservation service curve number (SCS-CN) method to estimate the effective rainfall for the model in order to optimize the water release rules for Koka reservoir.

Although the data basis used for the study was relatively poor, the model gave reasonable results for the intended purpose of predicting the water volume. However, it is rarely showed a good fit with the peak flows. With in the verification process the R^2 value varied form 0.44 to 0.81, with an average of 0.63 for all simulations .Moreover, study on application of the US Soli conservation Service (USSCS) method was conducted for the catchments of Upper Awash (Berhan 2003). In this study, the calculated and observed “summarized monthly flow volume” was compared. The calibration was carried out by varying the antecedent moisture conditions (AMC)- limits and the CN-values manually.

In comparison to the once established AMC- limits for the SCS-method, the newly calibrated values vary significantly (factor of 3 to 10)

Berhan thus concluded that an application of the AMC- limits proposed by the US SCS lead to an inaccurate wrong estimation of runoff in Ethiopia.

Yoseph (2003) was modelled the stream flows in the Upper Awash catchment by applying the Famine Early Warning System Flow Model (FEWS SFM) from the US Geological Survey (USGS) to establish a flood forecasting model. The model used in this study was developed to provide a continuous simulation of stream flow for more than 5000 Basins in Africa and the model was made parsimoniously in order to deal with the scarce data available in most African Countries (Yoseph 2003). It applies the SCS curve number method to estimate excess precipitation. AMC and CN values are estimated and adapted automatically from the digital Arc View data.

According to this study, within validation process a R^2 value of 0.78 was obtained for the stream flow simulation. The model showed weakness in the prediction of fine fluctuations during high and low discharge. Especially, the highest, very sharp peak flow cannot be produced by the model. For most of the years these flows were underestimated by about 50%. However, in other similar study which also applies the FEWS Stream Flow Model on the Upper Awash Basin, improved result with a correlation coefficient of 0.8 in the verification process was obtained (Shimelis 2004).Shemelis investigated a great deal of work and own initiative to obtain a higher quality data basis which result in an improved result.

FEWS generally produced better results for the wet season. Still, peak flows during the heavy rainfall season were usually under estimated which is a major draw back for a flood model.

Shimelis believes it can be inaccurate due to the simplification of the soil classes since the model only distinguishes between three soil textures (clay, sand and loam).

CHAPTETR THREE

METHODOLOGY AND PROCEDURE

3.1 General

Water resource professionals need planning tools for the successful utilization of water resource. It is the state of the art to use hydrologic models for the planning process of different kinds of water resource development projects. Currently, a number of rainfalls-runoff models exist for generation of flow and establishing a rainfall-runoff relationship using different time steps. However, in areas where data are sparsely and scarcely available the pragmatic solution is to apply conceptually sound lumped rainfall-runoff models with fewer parameters such as models included in Rain fall Runoff Library.

In this study, a daily rainfall- runoff modeling which is very helpful to further strengthen assessment, planning and management of water resource in the Upper Awash Sub Basin was conducted for selected three catchments of Upper Awash Sub Basin using two models namely AWBM and SMAR models among five lumped conceptual models nested in rainfall-Runoff library.

Generally, the study involves the following procedure:

- Collection of important data for the study such as, meteorological data, hydrological data topographical and digitized map of the Upper Awash sub-basin.
- Data quality checking and Analysis (checking for gaps, continuity, homogeneity/ consistency.
- Flow generations from rainfall and evaporation data.
- Calibration and Verification of models.
- Comparson of generated and simulated flows.
- Determination of model parameters.

7. Sensitivity Analysis of model parameters

3.2 Data Collection and Quality Checking

Hydro- meteorological data that are necessary and important to undertake rainfall runoff modeling were collected from the different sources using official supporting letter written from Addis Ababa University. These data were collected from the Hydrology Department of the Ministry of Water Resources (MWR) and National Meteorological Agency, Ethiopian Mapping Agency. The data collected includes, daily rainfall data, evaporation data, flow data and different maps as it is stated under chapter four.

In addition, collection of meteorological data such as temperature, wind speed, pan evaporation, humidity which support the modeling work and available at existing meteorological stations-in the near by and inside the study area were undertaken from National Meteorological Agency of Ethiopia.

Model calibration and verification more than anything relies on the quality of data available (RRL 2004). Hydro-Meteorological data must be cleaned from random and systematic error for erroneous data leads to either non-veritable rejection of a model or wrong calibration that affects the usefulness of a model. Thus, the most important step in rainfall runoff calibration is data preparation and analysis. Time spent in ensuring that the best possible data set is used will greatly speed up the calibration process.

Then, data quality analysis such as homogeneity test, checking for outliers and gaps has been done using appropriated methods. Next, the necessary data quality checking and analysis were accomplished.

3.2.1 Missed Data

Gaps in a rainfall record are common for a variety of reasons. A gauge may have been installed after the period of interest or may have been closed down for some period. Moreover, the gauge may not have been functioning properly or may not have been read regularly. All the

data sheets received from National Meteorological Agency are manually checked for gaps to roughly assess the quality and reliability of data as it is stated under section 4.3.1 and 5.3.3.1.

3.2.2 Test for Consistency/Homogeneity

According to Chang and Lee (1974), a time series of hydro-meteorological data is relatively consistent if the periodic data are proportional to an appropriate simultaneous time series (as cited in Dahmen & Hall, 1990). In other words, relative consistency means mechanism that generated similar or related data at other stations. For Upper Awash , Rainbow software package, which was produced at K.U.Leuven University for undertaking analysis of hydrological/Meteorological data frequency analysis i.e. test for homogeneity, was used for checking consistency/homogeneity of each station data as shown under section 4.5.3 .

The restriction of homogeneity assures that the observations are from the same population. One of the tests of homogeneity (Buishand, 1982) is based on the cumulative deviations from the mean:

$$S_k = \sum_{i=1}^k (X_i - \bar{X}) \quad k=1, \dots, n \text{-----}(3.1)$$

where X_i are the records from the series X_1, X_2, \dots, X_n and \bar{X} the mean. The initial value of $S_k=0$ and last value $S_k=n$ are equal to zero (Figure 3.1).

When plotting the S_k 's (also called a residual mass curve) changes in the mean are easily detected. For a record X_i above normal the $S_k=i$ increases, while for a record below normal $S_k=i$ decreases. For a homogenous record one may expect that the S_k 's fluctuate around zero since there is no systematic pattern in the deviations of the X_i 's from their average value \bar{X} .

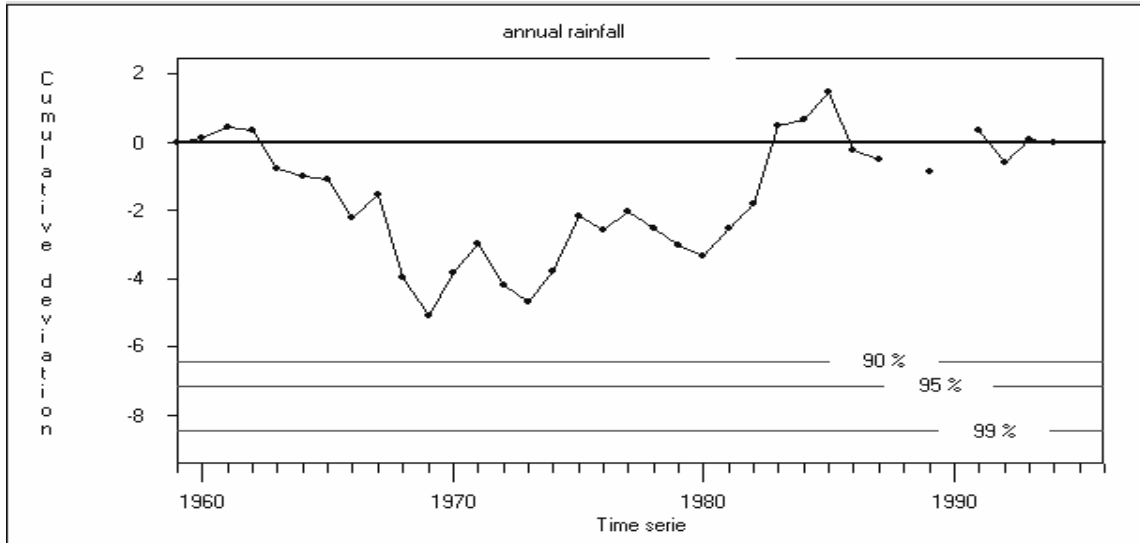


Figure 3.1 Rainbow22 90, 95 and 99% probability lines

The above figure shows Rescaled cumulative deviations from the mean for the total annual rainfall (1960 –1996).When the deviation crosses one of the horizontal lines the homogeneity of the data set is rejected with respectively 90, 95 and 99% probability.

To test the homogeneity of the data set, RAINBOW rescales the cumulative deviations by dividing the Sk 's by the sample standard deviation value. By evaluating the maximum (Q) and the range (R) of the rescaled cumulative deviations from the mean, the homogeneity of the data of a time series can be tested. High values of Q or R are an indication that the data of the time series is not from the same population and that the fluctuations are not purely random. Critical values for the test-statistic which test the significance of the departures from homogeneity are plotted as well (Figure 3.1)

3.3 Calibration and Verification of Models

After accomplishing the necessary data quality checking rainfall runoff modeling was conducted using two models namely AWBM and SMAR among the five models nested in Rainfall Runoff Library (RRL). The two models selected based on the fact stated under section 3.1 since the two aforementioned parameters contain fewer parameters.

Eleven years of data (1994-2004) is used since a suitably long period of flow record is the preferred method for calibrating rainfall runoff models. This method gives a way of assessing the robustness of the model for periods outside of the calibration period. If possible the verification (validation) and calibration periods should be of similar length. However to include sufficient climatic variability in the calibration period it may be possible to have the validation period only cover one third of the period of record. Therefore, taking the aforementioned facts in to consideration, the 11 years data (1994-2004) grouped in to two parts with 6 years (1994-1999) data for calibration and 5 years (2000-2004) data for verification. Comma delaminated column daily time series format (.cdt) is used to convert rainfall , Evaporation and flow time series data into drag able format that may then be dragged and dropped on to the appropriate time series filed. After dragging and dropping rainfall, flow and evaporation data, optimization method to be used in the modeling is selected for each of AWBM and SMAR models Rainfall Runoff Library has a choice of seven optimization methods. These include:

- Genetic algorithm
- Uniform random sampling
- Pattern search
- Pattern serach multi start
- Rosenbrock
- Rosenbrock multi start
- Shuffled Complex Evolution(SCE)

However, the default optimization method is Genetic Algorithm. Moreover, Genetic Algorithm is the most widely used optimization method (RRL 2004). For this study, among three tabs available on the calibration dialogue in RRL (Appendix I),the generic tab which contains drop down menus and buttons to access options for automatic calibration of model parameters is used.Different Optimization methods primary and secondary objective functions, and data transformation can be chosen by clicking the mouse on the optimization method drop down list .However, owing to the facts stated under section 6.1 , combination of Genetic algorithm optimization method , Nash Sutcliffe criteria and runoff difference in % as primary and secondary objectives respectively were used to undertake the modeling work.

3.4 Comparison of Simulated and Observed flow

Comparison of generated flow and observed flow have been made using hydrograph plots, Nash Sutcliffe Criteria, Volume of runoff difference .The quality of fit between the observed and computed hydrographs is judged by reviewing plots of the hydrographs .In case of Nash Sutcliffe Criteria, in general, values should vary from 0 to 1 and the optimum fit represented by 1. Negative values show that the mean of the measured flow is a better fit than the simulated flow. The equation for Nash Sutcliffe criteria is as indicated in equation under section 5.

Based on the aforementioned methods of simulation and observed flow, the calibration results of AWBM and SMAR model were assessed for the three catchments of Upper Awash Sub Basin. Moreover, based on the comparison made the comparison of the performance of the two models were under taken.In line with this, the model parameters were determined for the models calibration carried out.

Sensitivity analysis (SA) is a fundamental tool in the building, use and understanding of models of all forms .This information can range from the identification of calibration variables to model reduction or simplification, better understanding of the model structure for given components of a system, model quality assurance, and model building in general.

It is important to understand how sensitive a model is to certain parameters. This is useful to understand how the model functions and also what parameters need more attention than others. If the model is significantly affected by a particular parameter then the focus of calibration should be on that parameter.

Therefore, after conducting the necessary calibration, sensitivity analysis of AWBM and SMAR model parameters were carried out for the objective function used in the modeling to determine the degree of sensitivity of each model parameter.

Finally, the necessary conclusions and recommendations were made.

CHAPTER FOUR

SOURCE AND AVAILABILITY OF DATA

4.1 General

The scarcity of data in most of developing countries is so alarming that one gets a single station for a catchment as large as 1000 km² and there is always question of data quality problem (RRL 2004). Similar to any developing country, in Ethiopia major water balance variables such as rainfall and evaporation time series are sparsely and scarcely available and also there is question of data quality problem. It is also possible a station from neighboring catchment should be considered for those catchments, which have no observation at all. For such areas the pragmatic solution is to apply conceptually sound lumped rainfall-runoff models with fewer parameters.

4.2 Data Requirement

A range of data sources and information is required to be able to run various models. Similarly, various ranges of data in put is required to conduct rainfall runoff modeling using rainfall runoff library. The major inputs data required for rainfall runoff library are:

- Rainfall - a continuous time series of rainfall data that represents the rainfall across the catchment. Only data in mm/day should be used.
- Evaporation – a continuous time series of potential evapotranspiration (PET) or actual evapotranspiration data that represents the evapotranspiration across the catchment.
- Flow gauging - daily runoff values for the gauging station that is to be modelled. These data are used for model calibration and checking. The accepted flow units are mm/day, ML/day or m³/s. If data are input as ML/day or m³/s then catchment area is required.
- Catchment area – this is used to convert inputs and outputs between flow and depth of runoff.

The type of evaporation data expected will vary from model to model, and only the appropriate data should be used. The evaporation data appropriate for one model may not be appropriate for another. Only data in mm/day should be used.

4.3 Sources and Collection of Data

Using official supporting letter written from Addis Ababa University the necessary data that are important to undertake rainfall runoff modeling are collected from the different sources.

4.3.1 Meteorological Data

National Meteorological Agency is the responsible organization for the collection and issuing of meteorological data. There are 156 rainfall gauging stations in the whole Awash Catchment. Among this total gauging stations, 34 metrological stations were available in the Upper Awash Sub Basin to represent the rainfall distribution (Kiesel 2006).

However, these all stations are not selected for the modeling. According to assessment made and described under chapter four in detail some stations are not functional, only part of them got a good record of data .Almost every gauging station has days without records scattered within a year and whole months or even whole years without recording can be found in the dataset.

Most of the stations are non recording type and few are recording type. In the upper Awash only stations at Akaki, Mojo, and Addis Ababa at Bole and Teklehamanot are recording type. Besides the limitations in the number of the recording type of stations their spatial distribution is not fairly uniform over the basin. They are concentrated in the northeastern part of the basin but fair enough compared to the data availability in the country (Figure 4.1 and Figure 4.2).

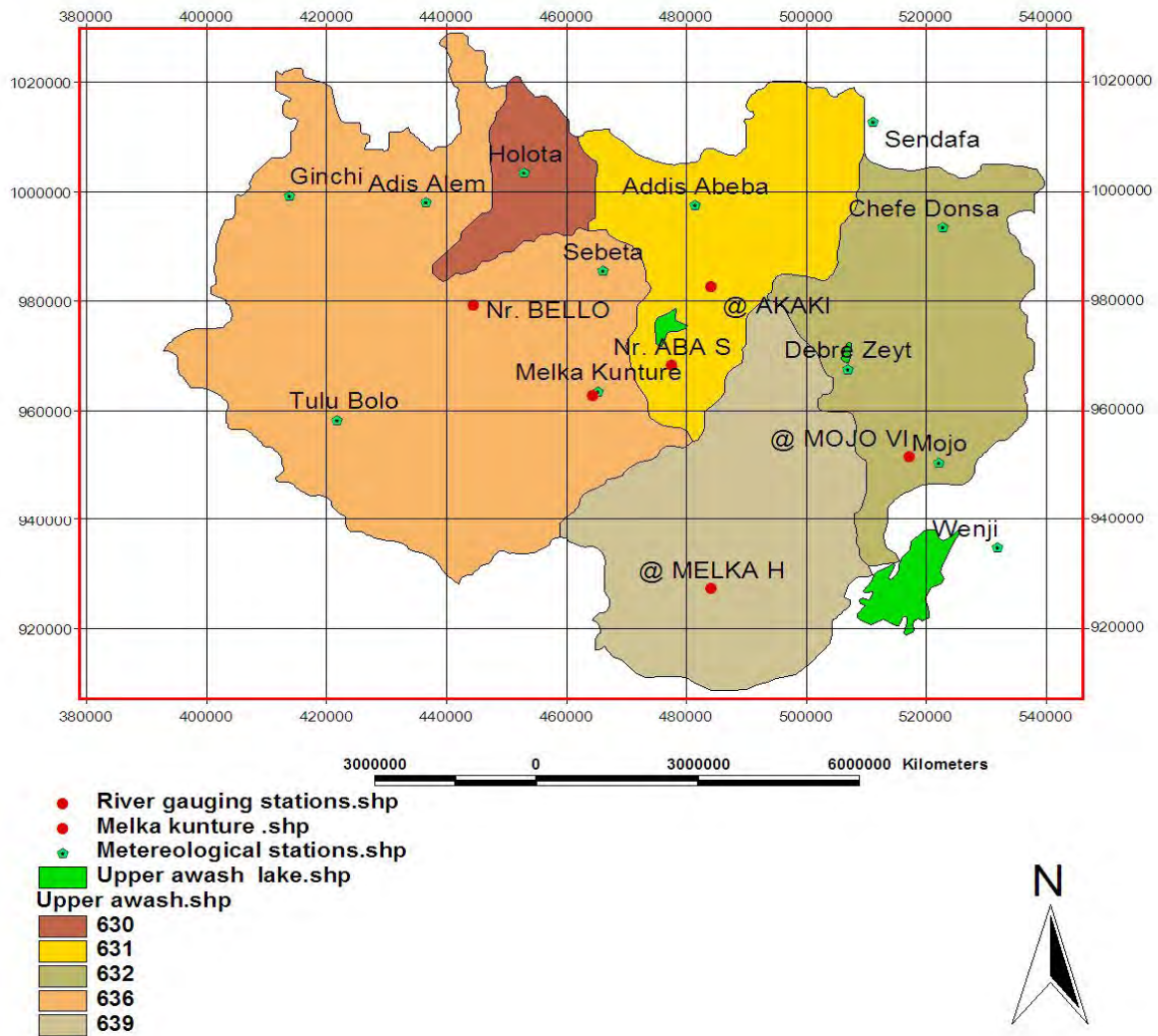


Figure 4.1 Distribution of rainfall and flow gauging stations in Upper Awash Sub Catchments.

The National Metrological Agency was willing to provide data only for limited periods. Accordingly daily rainfall and evaporation data for 11 years were collected. The daily rainfall data were received in soft copy but evaporation data are available in hard copies and then edited in digital form.

The general assessment of the precipitation data was carried out. Recorded data at each rainfall gauging stations are assessed to identify the data setting of each station. All

sheets are checked for gaps and too many gaps result in a “not sufficient “assessment. The assessment results are tabulated as hereunder (Table 4.1).

Rainfall Gauging Station Name	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	Beginning Year	
Addis Ababa Bole	■																									1980	
Addis Alem																											1980
Akaki														■								■	■	■	■	■	1951
Buee									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	1989
Debrezeit							■	■				■	■	■													1951
Bolo Georgis			■												■		■										1962
Ginchi																											1989
Holeta																											1954
Melka Kunture				■		■																					1962
Mojo			■							■																	1963
Welenkomi																											1962
Sebeta																											1954
Sendafa				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	1954
Teji				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	1961
Tullu Bollo																											1992
Wonji																											1951
Zuqala																											1962

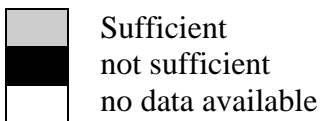


Table 4.1 Rainfall data assessment result for rainfall gauging station in the Upper Awash

After making the necessary assessment, the rainfall stations with sufficient data identified. Then ,the position of rainfall gauging stations with sufficient data were located on the map to further investigate in which particular sub-catchment of the upper Awash Sub Basin the station is found as shown in figure 4.2.

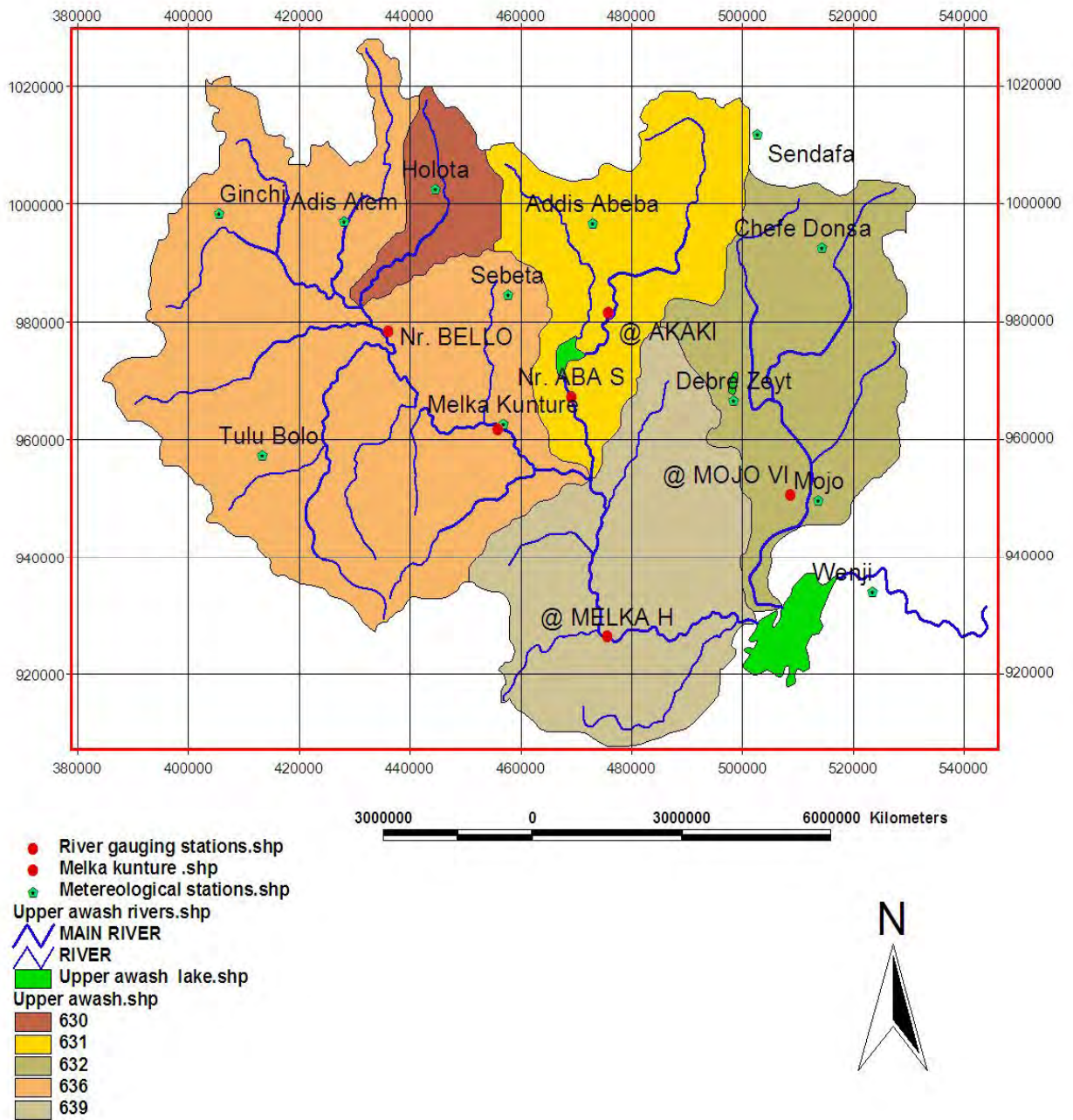


Figure 4.2 Distribution of rainfall and flow gauging stations in Upper Awash Sub Basin with respect to the rivers in the sub basin.

After conducting the necessary assessment, the precipitation stations inside the Upper were selected based on the data adequacy of the stations for further analysis (Table 4.2).

Station	Latitude	Longitude	Elve. a.s.l (m)	Period	Annual Rainfall (mm)
Addis Ababa	09 ⁰ 02'	38 ⁰ 43'	2408	1994 to 2004	1192
Addis Alem	09 ⁰ 03'	38 ⁰ 24'	2340	1994 to 2004	1117
Holeta	09 ⁰ 05'	38 ⁰ 30'	2000	1994 to 2004	1061
Sebeta	08 ⁰ 55'	38 ⁰ 30'	2379	1994 to 2004	2347
Sendafa	09 ⁰ 10'	39 ⁰ 02'	2550	1994 to 2004	890
Debrezeit	08 ⁰ 26'	39 ⁰ 01'	1900	1994 to 2004	781
Modjo	08 ⁰ 37'	39 ⁰ 08'	1870	1994 to 2004	853
Tulu Bolo	09 ⁰ 02'	38 ⁰ 20'	2165	1994 to 2004	1144

Table 4.2 Selected daily rainfall station in upper Awash River Basin

The National Meteorological Agency was not in position to provide meteorological data for Holeta and Sebeta Meteorological Stations. However, incase of Holeta station seven years data were taken from previous study (Kiesel 2006) and the four years data was obtained from Agricultural Research Station Holeta .The recent rainfall data available at Debrezeit and Sendafa are of six years. Therefore, these stations were excluded and only the remaining five stations are considered for the modeling work.

Data on evaporation are only available for the station at Addis Ababa and Debrezeit. Though it is in the form of hard copies and the dataset consists of missing data, relatively well organized daily evaporation data for recent years is available for Addis Ababa (Bole Station) only .The evaporation data set at Debrezeit is with large number of missing data .Since the conceptual rainfall run off models are sensitive to the quality of in put data such as evaporation and rainfall data, it is preferable to use years with continuous data record or with relatively less missing data to obtain reliable results. Thus, data of 11 years record (1994- 2004) at Addis Ababa (Bole Station) shown in figure 4.9 is used to undertake rain fall run of modeling of the selected catchment .

4.3.2 Hydrological Stations

In the Awash basin there are about 76 gauging stations, out of these 21 stations are found in the upper Awash sub- basin particularly in the upstream of Koka Dam (Mengistu 2008). These all stations are not selected for modeling because some have defect, they are under the influence of natural and man made factors. Some of the stations are set at u/s of Koka Reservoir that are directly subjected to the back up effect of the reservoir; others are set d/s of Legedadi Dam which has no natural record due to the influence of the release of the water through spillway and the rest are on the very plate and plain area that may be subjected to the over flow others are highly influenced by land use change such as urbanization which lead to wrong out comes.

The river gauging stations with sound data and natural flow are assessed to identify the data setting of each station (Table 4.3). All sheets are checked for gaps and too many gaps result in a “not sufficient “assessment.

Rainfall Gauging Station Name	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	Beginning Year
Melka Kunture	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	1962
Melka Hombole	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	1962
Mojo	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	1962
Wonji	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	1964
Bello	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	1961
Below Koka Dam	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	1986
Teji	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	1962
Berga	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	1962

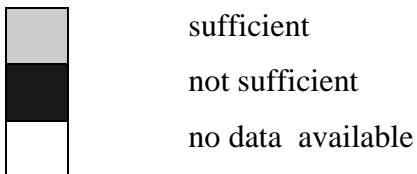


Table 4.3 Flow data assessment result for flow gauging Station in the Upper Awash Sub Basin

The Hydrology Department of the Ministry of Water Resources (MWR) is the responsible department for the collection of hydrological data in Ethiopia. Upon an official request to the Ministry of Water Resource, hydrological data pertinent to the study have been collected for Upper Awash Sub Basin. Thus, depending on the supporting letter written from Addis Ababa University, the Hydrology Department of Ministry of Water Resource provided daily discharge data for eight flow measuring stations in the Upper Awash.

Although the hydrology Department of Water Resource is not willing to provide rating curves equations and data related to them, some rating curve equations for stations which are important for this research are obtained from previous studies to check the daily flow data provided.

Among the stations considered gauging site of Awash Melka Kuntre and Modjo at Modjo are located in a very stable cross-section and hence have unique rating curve for the entire record. In the upper Awash basin, Bello , Melka Kunture, Melka Hombole, Mojo, and Akaki stations have automatic water level recorder. Out of these stations only, Bello, Melka Kunture and Mojo are most important to this study because it is difficult to conduct the calibration work for all flow gauging stations available in the Upper Awash Sub Basin in the scope of this thesis due to time consuming nature of daily data preparation and analysis for rainfall, flow and evaporation data time series.

S.No	Station Name	Area(km2)	Period	Rainfall Station used
1	Awash @Bello	2568	1994-2004	Addis Alem, Holeta
2	Modjo @Modjo	1264	1994-2004	Modjo
3	Awash @Melka Kunture	4456	1994-2004	Addis Ababa, Holeta, Addis Alem and Tullu Bollo

Table 4.4 River flow gauging Stations and the corresponding Rainfall Station used for Modeling

Although Ginchi rainfall station is also located in Bello catchment, the rainfall data is not available for it . Thus ,in case of Belo station ,the daily rainfall data available at Addis Alem Station(Appendix B.3) and Holeta which are located in the catchment is used to under take the modeling .

In case of Mojo catchment the rainfall data recorded at Mojo(Appendix B.4) is used to conduct modeling because the daily rainfall data available at other stations in the catchment and recorded at Chafe Donsa and Debrezeit stations (Appendix B-7and B-8 respectively) are only of few years and contain many missing data.

In case of Melka kunture catchment, areal rainfall derived from Addis Ababa, Holeta ,Tullu Bollo and Addis Alem rainfall stations is used to carry out rainfall runoff modeling for this catchment.

4.3.3 Topographic data

Topographical data are collected from EMA (Ethiopian Map Authority). The map is used to identify the land feature and characteristics of the sub-basin. The digitized map (Ethio-GIS) that was collected from MoWR, GIS department is the most important input to locate metrological and flow gauging stations as well as to identify sub-basin and the catchments in the Upper Awash .

CHAPTER FIVE

DATA ANALYSIS AND MODEL SELECTIONS

5.1 General

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

As it is stated under chapter three of this paper, the rainfall runoff models require four important data sets:

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

5.2 Catchment characteristics

Generally the only catchment characteristic required by lumped rainfall runoff models is the catchment area. However, in some cases models e.g. SWAT need to know slope, land use, soil profile, soil depth, and hydraulic conductivity. The models operate in mm and to convert the model output from runoff depth to runoff volume catchment area is required.

According to the rainfall runoff library manual the catchment area is usually an easy parameter to obtain but should be used with caution. The area is dependent on the scale of maps or DEMs that it was derived from and in flatter areas there can be large uncertainty

with regard to where catchment boundaries are. A small error in catchment area can cause a large error in the estimated volume that runs off the catchment.

In addition the manual emphasizes that, although slope, land use, soil profile, soil depth and hydraulic conductivity may not be used by a model this information is also worth considering. The type of land use will influence surface runoff characteristics, evapotranspiration rates and interception losses. Moreover, the soil characteristics will influence the size of soil stores and seepage rates. This sort of information is invaluable for setting realistic bounds on model parameters as well as sanity checking the fluxes out of the model.

Taking the stated issues in to consideration, the catchment area obtained from Ministry of Water Resource GIS Department is rechecked and prepared for use in modeling work as it is shown under section 4.3.2. During modeling work the characteristics of soil in Upper Awash were taken in to consideration to set realistic National meteorological Agency bounds on model parameters as well as sanity checking the fluxes out of model.

5.3 Rainfall Data

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

- Point rainfall and Catchment average(a real) rainfall
- Selection of appropriate rainfall sites.
- Outliers
- Checking for gaps
- Homogeneity and consistency test

5.3.1 Catchment Average Rainfall

The number of sites is a very important issue when multiple rainfall sites are available. Typically, Arithmetic Mean and Thiessen weightings are used to associate a portion of the catchment with each rainfall station.

An isoheytal map is basically a contour map, of typically, average annual rainfall. Drawing an isoheytal map is a relatively easy process when there are a number of gauges in and surrounding the catchment. The manual of rain fall runoff of library highly emphasizes that care should be taken to ensure all rainfall sites are gap filled and that the period selected is common to all sites. In some countries such as Australia Climate databases such as SILO have splined surfaces that cover Australia. These surfaces take into account location, distance from coast and elevation to derive average annual rainfall across grid squares.

In Ethiopia there are no such data bases and Thessian polygon and Arthematic Mean methods are used to find areal rainfall in this thesis. According to Secretariat of the world Meteorological Organization (1974), when the area of the modeled catchment exceeds about 25km² and only one point measurement describes the precipitation, the measured rainfall height has to be reduced in order to fit the actual average rainfall depth over the whole catchment.

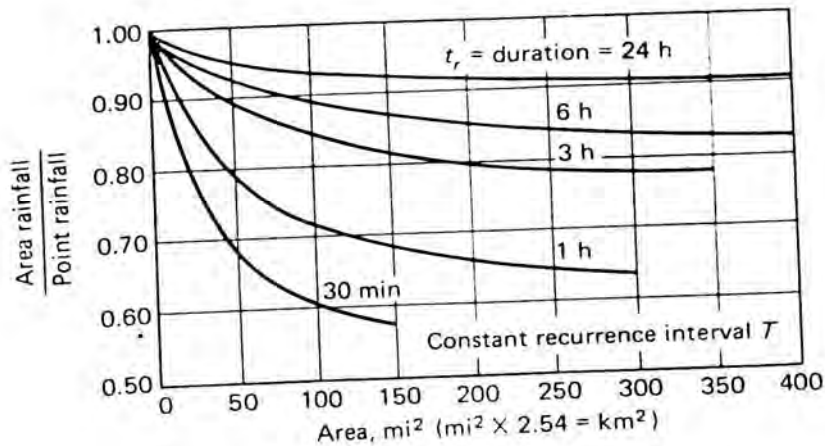


Figure 5.1 Point rainfall and Areal rainfall relation Ship (Secretariat of the world Metreological Organization 1974)

In case of Melka kunture catchment, data of rainfall at Addis Ababa, Tullu Bollo and Addis Alem rainfall stations are used. However, in case of Bello catchment and Mojo the concept

of point rainfall comes to reality since only data of Addis Alem and Mojo are used in conducting rain fall runoff modeling for Bello and Mojo catchments due to absence of other rainfall stations with necessary data set in the catchments . In case of Mojo catchment the rainfall data recorded at Mojo is used to conduct modeling because the daily rainfall data recorded at Chafe Donsa and Debrezeit stations are only of few years and contain many missing data.

Therefore, reduction factor was determined using Figure 5.1 considering the area of Bello and Mojo catchment as well as 24-hour storms .Then, the determined factors used to reduce precipitation height for these catchments.

The RRL has a data scaling dialogue that allows annual or monthly factors to be applied to the rainfall data.

5.3.2 Rainfall Site Selection

There are several things that need to be considered in selecting rainfall sites:

- Difference in average annual rainfall as compared to the catchment average annual rainfall.
- Proximity to the catchment.
- Correlation with flow peaks.
- The number of sites used.

According to RRL manual if the difference in average annual rainfall is great (e.g. more than 20%) then the rainfall process for the catchment and selected site are probably quite different and this is not a good station to use.

Studies have shown that rainfall decorrelation distance is approximately 10km (RRL 2004). Unfortunately there are not many places in Ethiopia where rainfall stations are this much close together. In most cases stations in the catchment should have priority over ones outside the catchment.

5.3.3 Rainfall Data Quality.

The collected data can have accidental and systematic errors, which cause poor quality of the records. For automatic record, failure of field sensors may occur and as a consequence of this false reading will result. Similarly, for manual system of recording, observational errors may occur during reading, encoding of data.

The calibration of a rainfall runoff model is most sensitive to the rainfall data that is provided. Thus, data quality checking is the most important step in modeling and any other rainfall runoff analysis. If the volume of rainfall is incorrect or the rain days are not representative of the peaks in flow then calibration may be difficult with very poor results. Taking these facts in to consideration, the necessary data analysis and checking was conducted for the stations in the area of the study.

5.3.3.1 Missed Data

Gaps in a rainfall record are common for a variety of reasons. A gauge may have been installed after the period of interest or may have been closed down for some period. Moreover, the gauge may not have been functioning properly or may not have been read regularly. All the data sheets received from National Meteorological Agency are manually checked for gaps to roughly assess the quality and reliability of data.

Data for some stations in the Upper Awash such as Sebeta and Holeta are not available and National Metreological Agency is unable to provide the data. However, for Holeta station some data is obtained from previous study and some part of data used is taken from Agricultural Research Station in Holeta. Thus, depending on the availability of data Addis Alem, Holeta Tullu Bollo and Mojo rainfall stations are selected for the modeling work. The selected once by them selves have no fully recorded data; they have missing data in some years of record. Such gaps can be filled by estimating precipitation based on available records. The simplest way of doing this is by regression and correlation analysis of measurements from the station of interest with data from a near by gauging station. The correlation coefficient among the stations on monthly rainfall amount ranges from 0.634 to

0.875 which shows fairly good agreement. In addition, gaps were filled with normal ratio method, which is as indicated by the equation.

$$P_x = \frac{PX}{n} (P_1 / P_1 + p_2 / P_2 + \dots + p_n / P_n) \dots \dots \dots (3.2)$$

Where

P_x = Missing value of precipitation to be computed

PX = Average value of rainfall for the station in question

$P_1 \dots p_n$ = Average values of neighboring stations

$P_1 \dots P_n$ = rainfall of neighboring stations during missing period

n = number of stations used in the computation

5.3.3.2 Test for Consistency/Homogeneity

As described in section 4.2.2, errors can be introduced due to different reasons in point measurement of rainfall. Relocation of a gauge, the growth of trees close to gauge site, or the use of shields may alter gauge catching significantly. After a number of years, it may be felt that data of that station is not giving consistent rainfall values. In order to detect any such inconsistency, and to detect any such inconsistency, and to correct and adjust the reported rainfall values, a technique called double mass curve method in which, is generally adopted. In general, time series observational data is relatively consistent and homogenous if the periodic data are proportional to an appropriate simultaneous period. As mentioned above, this proportionality can be tested by double mass curve analysis in which the cumulative precipitation of doubtful station is plotted against the cumulative of the group average.

However, currently there are soft wares such as Rainbow22 (Appendix E) which was produced by K.U.Leuven University for analyzing climatological/hydrological data homogeneity test. Thus, for Upper Awash rainfall Stations, Rainbow 22 was used for checking consistency/or homogeneity of each station data. All analyzed data, were found to be homogeneous at 0.05 alpha level. The results from the homogeneity test are given in Table 5.1.

S.No.	Station Name	Test statistics for alpha level		
		0.1	.05	.01
1	Addis Ababa	accepted	accepted	accepted
2	Addis Alem	accepted	accepted	accepted
3	Holeta	accepted	accepted	Accepted
3	Tullu Bollo	accepted	accepted	accepted
4	Mojo	accepted	accepted	Accepted

Table 5.1 Result from homogeneity test for the selected rainfall stations

5.3.3.3 Comparison with Neighboring Stations

Further rainfall data analysis and quality check was conducted using graphs by comparing the precipitation of each station with the closest rain gauge station, for instance Addis Alem (2370m asl), Addis Ababa Bole (2430m asl) and Tullu Bolo (2100) are plotted on the same graph to see the rainfall distribution (figure 5.2). Although the stations are located at similar elevations and the distance from Addis Ababa to Addis Alem is 15 km, the rainfall distribution between the two stations vary to certain degree, which can be due to the surrounding topography or uncertainties in the rain gauge readings. Moreover, daily rainfall data variation between the stations can be pronounced due to localized storms.

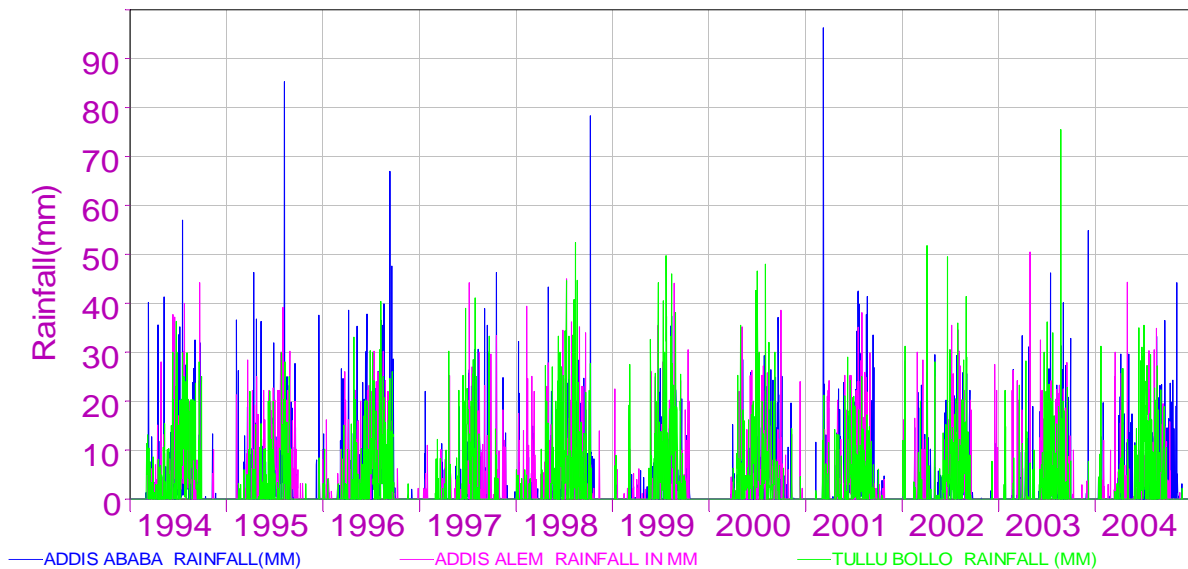


Figure 5.2 Comparisons of Addis Ababa, Addis Alem and Tullu Bollo Rainfalls

However, the comparison of Tullu Bollo and Addis Alem station didn't show any obvious and significant systematic or coincident errors (Figure 5.2).

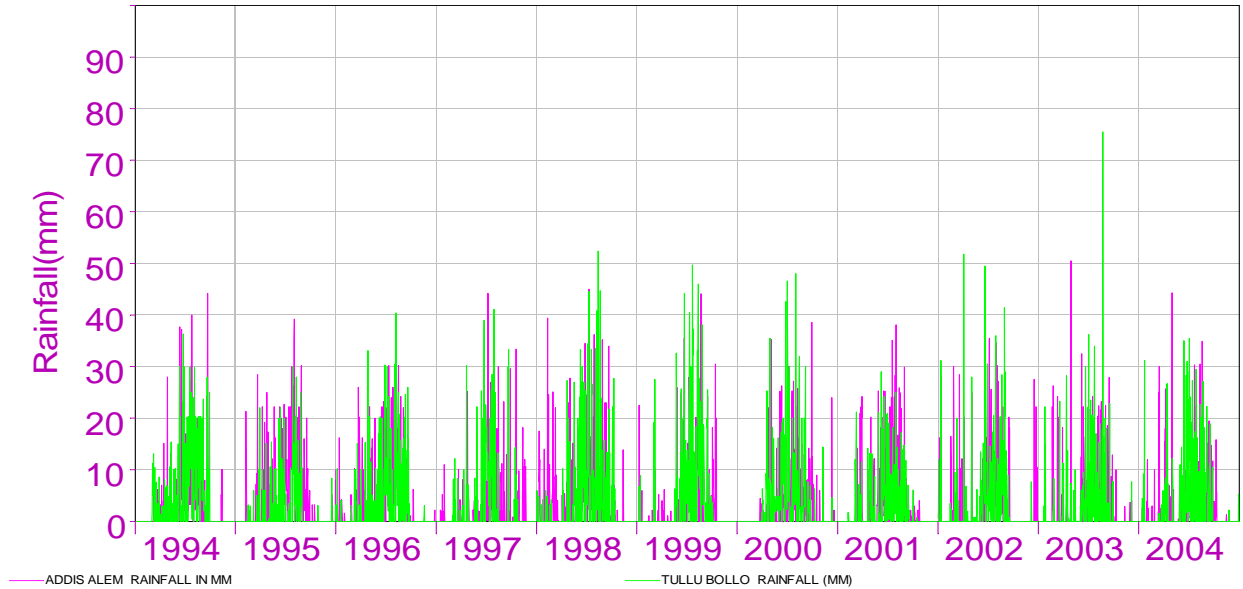


Figure 5.3 Comparisons of Tullu Bollo and Addis Alem Rainfalls

Similar comparison of rainfall data was conducted for Mojo , Chefe Donsa and Debrezeit Rainfall Stations although the data for Chefe Donsa and Debrezeit is not available for the whole period considered in this study (Figure 5.4).

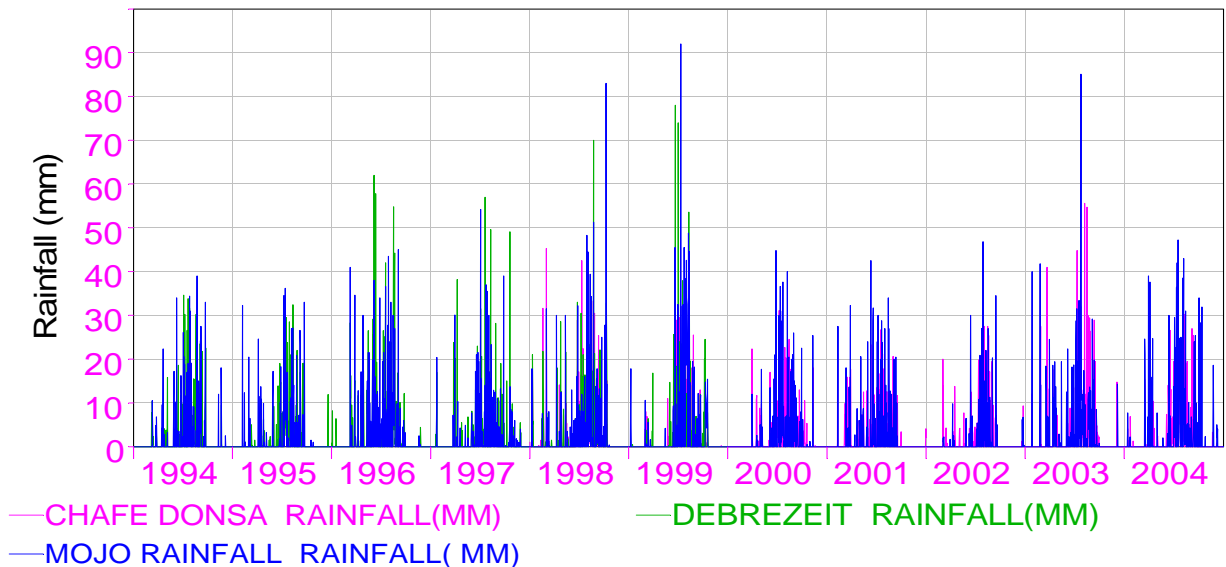


Figure 5.4 Comparison of Mojo ,Chafe Donsa and Debrezeit rainfalls

The general quality of the rainfall data is also checked by inters comparison between the stations. The correlation coefficient among the stations on monthly rainfall amount ranges from 0.634 to 0.875 (Table 5.2). This shows fairly good agreement on the monthly rainfall series. Daily rainfall data variation between the stations is pronounced due to localized storms.

Station	Addis Ababa	Addis Alem	Sendafa	Debrezeit	Mojo	Tullu Bollo
Addis Ababa	1					
Addis Alem	0.875	1				
Sendafa	0.805	0.775	1			
Debrezeit	0.728	0.812	0.753	1		
Mojo	0.715	0.791	0.749	0.814	1	
Tullu Bollo	0.803	0.878	0.634	0.749	0.736	1

Table 5.2 Correlation between monthly rainfall data of stations in the upper Awash Sub Basin

5.3.3.4 Comparison of rainfall and flow data

Another good method for assessing how well a rainfall station represents the flow from the catchment is to plot the rainfall and flow on similar scales (RRL 2004). The rainfall peaks can then be checked against the flow peaks to see if the size of peaks correlates with the amount of rainfall and that the peaks occur at about the same day taking time of concentration into consideration.

In this study HEC- DSSVue which is a strong tool to manipulate different data is used to plot the daily flow and rainfall data on the same graph.

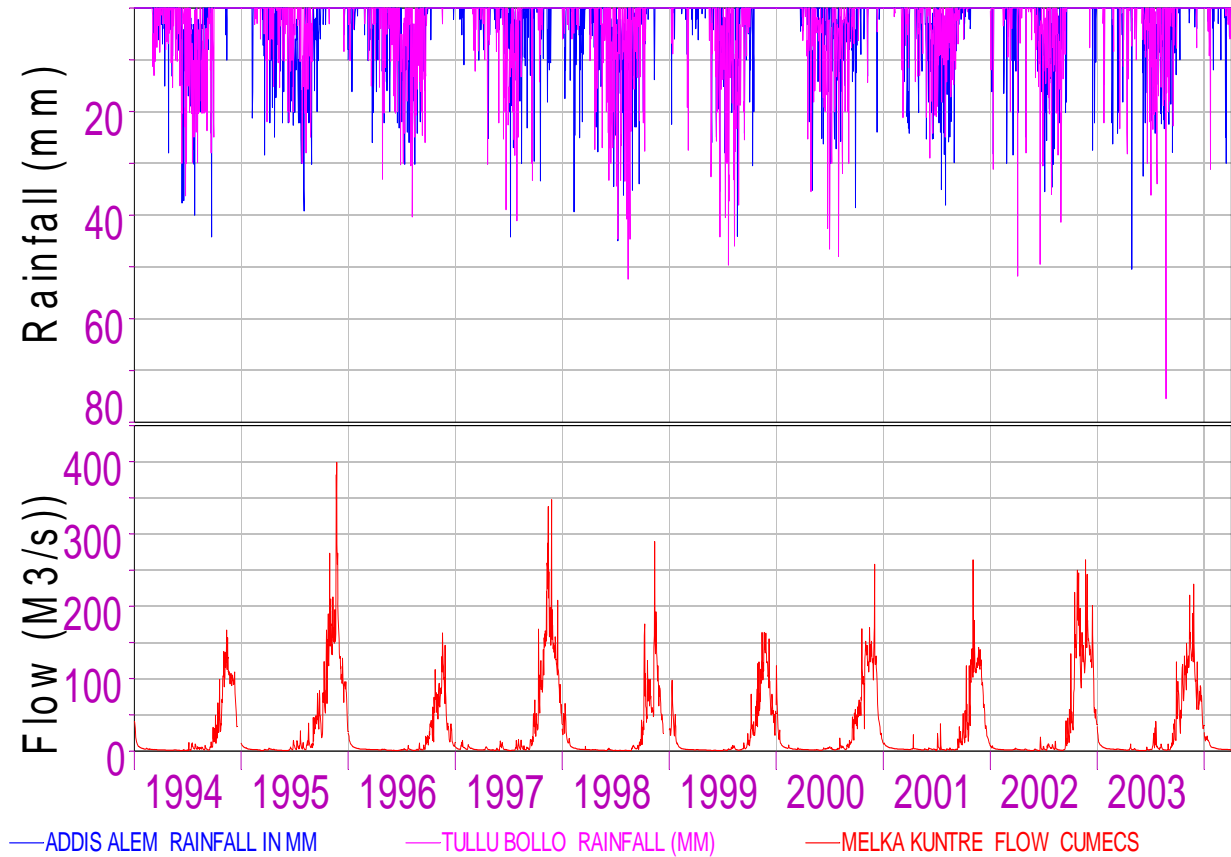


Figure 5.5 Flow records at Melka Kuntre River Gauging Station compared to rainfall data at Tullu Bollo and Addis Alem Rainfall Stations.

Accordingly, daily rainfall and flow data are drawn on the same graph using Hec-DussvUe for selected catchments of Melka Kuntre, Berga, and Mojo (Figure 5.5, 5.7 and 5.8).

As it can be observed from Figure 5.5, the flow values at Melka Kuntre is almost accord with rainfall amounts except during 1996 and 1999 years which can be due to time of concentration.

The flow record at Bello Station agrees well with the rainfall pattern of Addis Alem station (Figure 5.6). In the same manner, it can be observed from figure 5.7 that the flow data recorded at Mojo River Gauging Station agrees with the rainfall recorded at the Mojo Rainfall Gauging Station except for the years of 1997 and 2000.

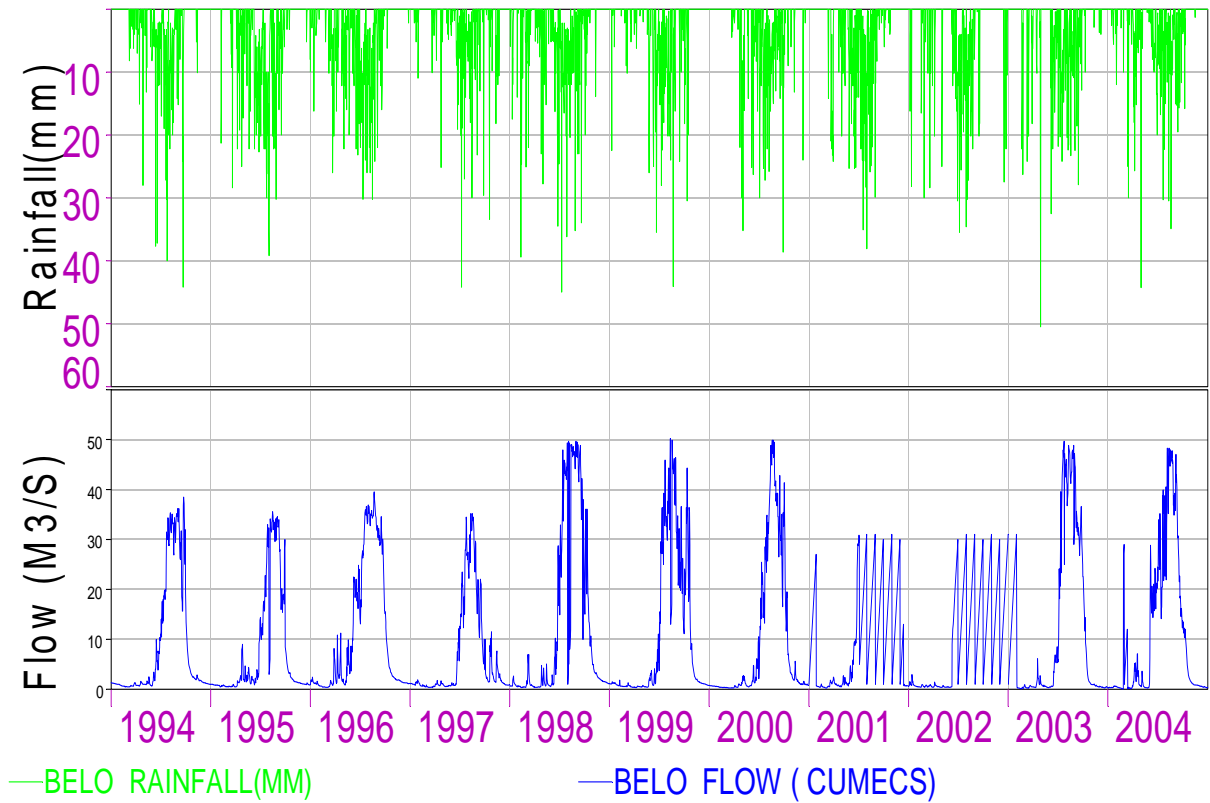


Figure 5.6 Flow records at Bello River Gauging Station compared to rainfall data at Addis Alem Rainfall Station

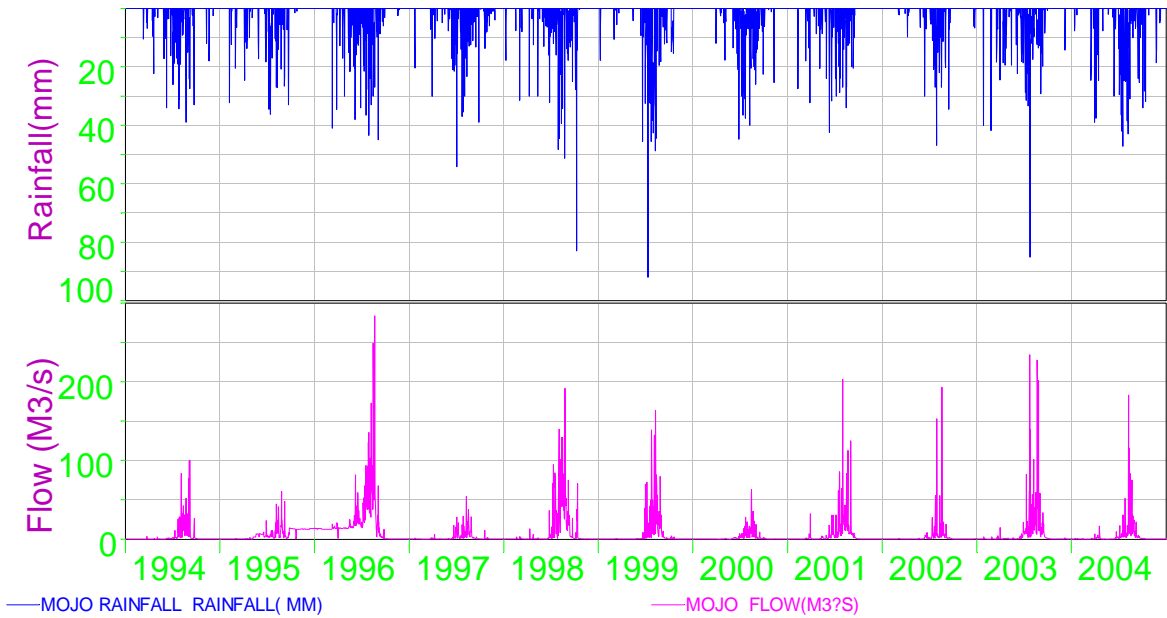


Figure 5.7 Flow records at Mojo River Gauging Station compared to rainfall data at Mojo Rainfall station

5.4 Evapotranspiration data

The Evapotranspiration is an important factor in the water balance equation. Roughly, 62% of all the water falling on the continents is evapotranspired (Neitsch et al).

There are many different methods of estimating evapotranspiration. A few of the common methods are listed below:

- Evaporation pan (Class A, sunken tank, sunken tank with bird gard),
- Lysimeter,
- Priestly Taylor equation,
- Penman equation, and
- Penman Monteith equation
- Atmometers (Pitche evaporate meter),

It is difficult to calculate daily data using some of the methods stated above. Therefore, the evaporation data recorded at Addis Ababa Station (Bole) using Pitche and shown in figure 5.8) is used for modeling work by applying the necessary adjustment coefficient using the data scaling dialogue of RRL (Figure 5.9).

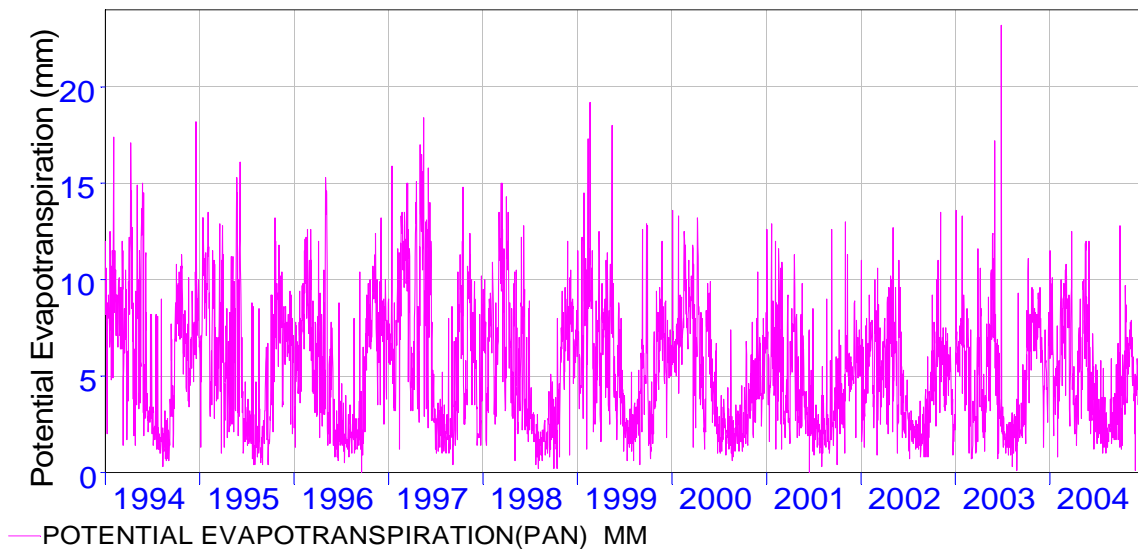


Figure 5.8 Potential Evapotranspiration

The Pan-evaporimeters often overestimate the potential evapo-transpiration. This is because the much smaller water volume in the pan easily heat up to a warmer temperature as compared to the surrounding soil and therefore evaporates more than a larger water body. To overcome this problem, the values of pan-evaporimeters have to be corrected by multiplying with pan correction coefficient. The RRL has a data scaling dialogue that allows annual or monthly factors to be applied to evaporation data (Figure 5.10).

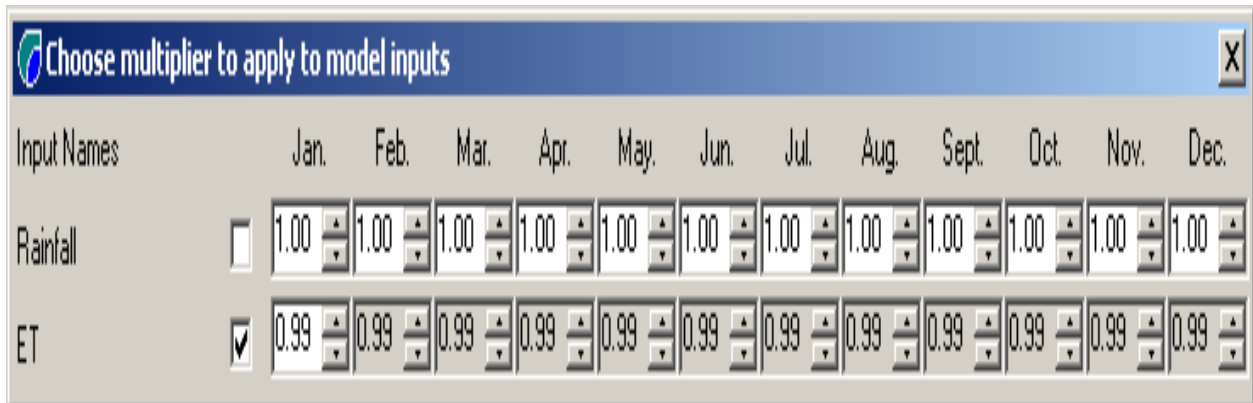


Figure 5.9 Data Scaling Dialogue of RRL

Similar to the rainfall homogeneity test conducted for rainfall time series under section 5.3.3.2, the homogeneity test for evaporation data was conducted using Rainbow 22 which was produced by K.U.Leuven University for analyzing climatological/hydrological data homogeneity test

5.5 Flow data

The flow data is what the rainfall runoff model is calibrated against and in calibrating against the flow data the assumption is made that this data has no errors. This is not the case and consequently care should be taken to ensure that the flow data is of good quality. To roughly assess the quality and reliability of the data, all sheets of data provided are manually checked for gaps and consistency.

5.5.1 Using Graphs to Analyze Flow Data

Further analysis of flow data was conducted and the flow data at a station are validated by simultaneously examining the rainfall time series and the flow of the rivers.

The data for every year and station was plotted using Hec-DussvUe to visualize the flow data (Figure 5.11, 5.12, 5.13). In some cases too many gaps exist. In some cases the data does not match with the general climatic pattern. After assessing the flow data it may be appropriate to remove unrealistic data from the record prior to calibration. It is also important to know what part of the flow range has the least error (RRL 2004). Thus, if the missing data within one year is too long, the data is considered as 'not sufficient' and then rejected.

The data range from 1994 to 2004 is used for modeling work depending on the assessment under taken as stated above and especially to fit the simulation time with availability of rainfall and evaporation data as evaporation data is available in relatively well organized condition only at Addis Ababa Meteorological Station.

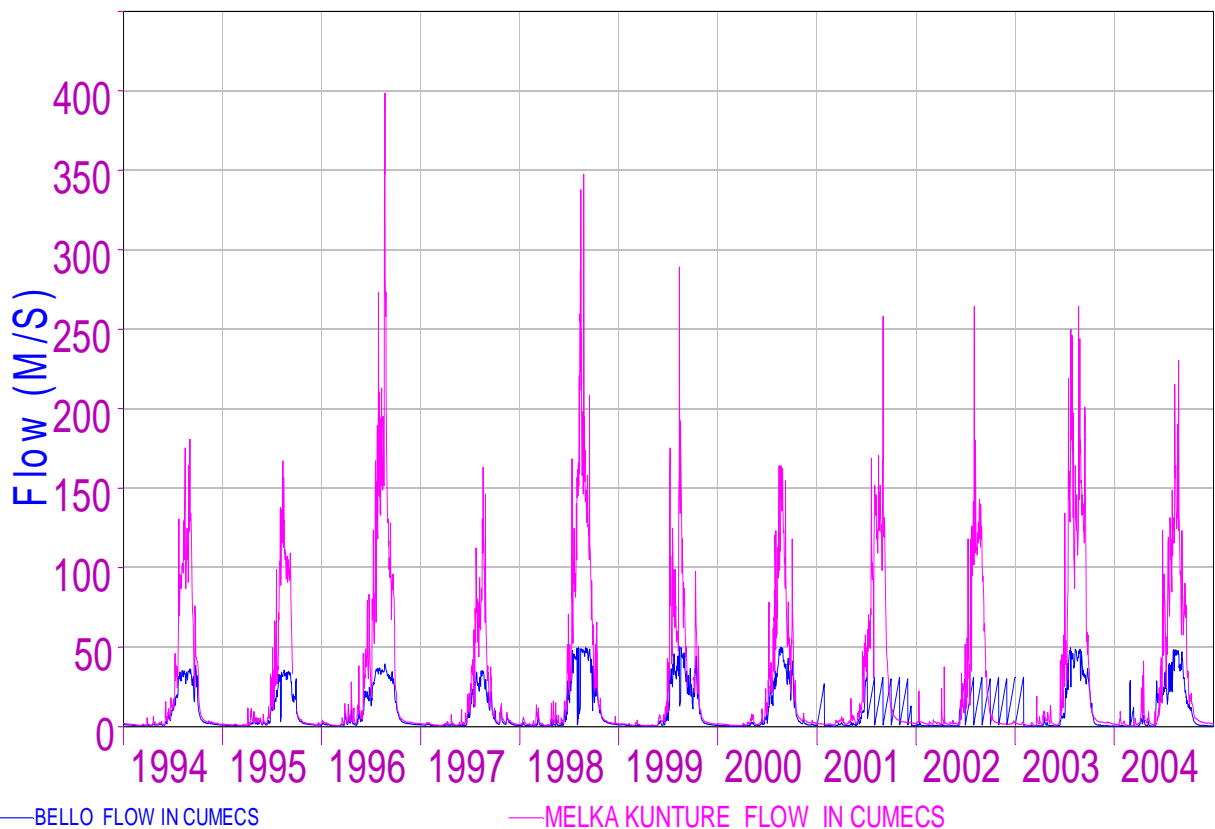


Figure 5.10 Flow Data at Bello and Melka Kunture River Gauging Stations

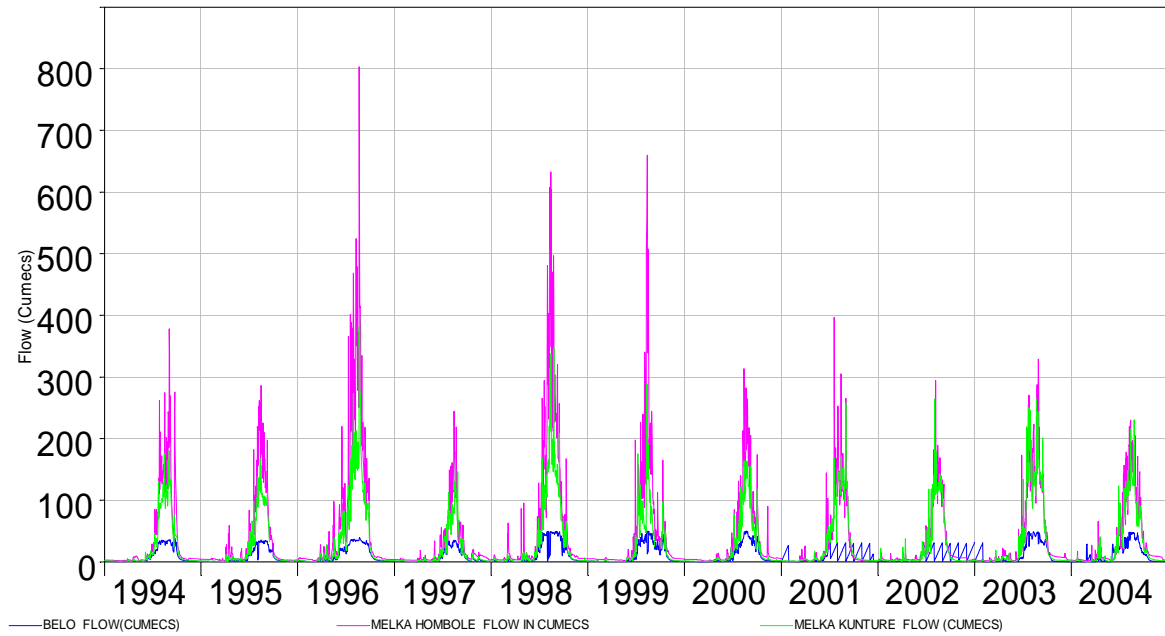


Figure 5.11 Flow Data at Bello, Melka Kunture and Melka Hombole River Gauging Stations

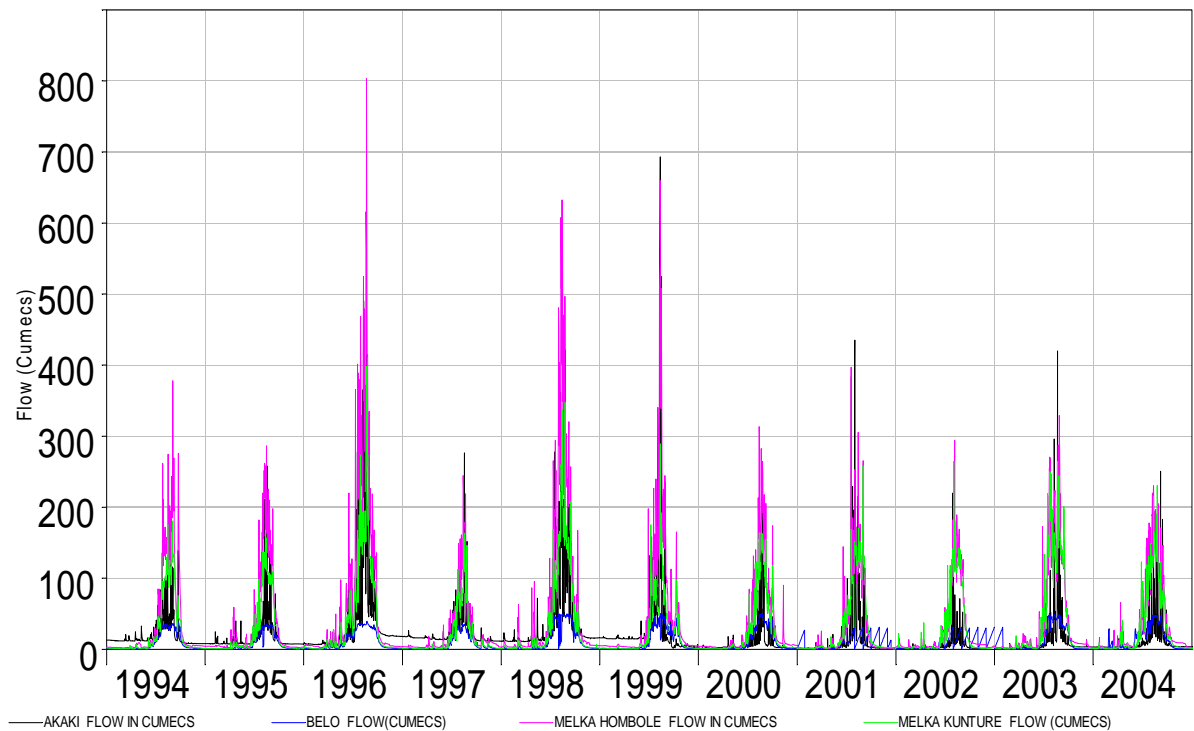


Figure 5.12 Flow Data at Bello , Melka Kunture, Akaki and Melka Hombole River Gauging Stations.

5.5.2 Check for Outliers

Outliers may come due to personal error during recording and inadequacy of measuring device or really due to very extreme condition of natural phenomenon. Therefore, unless the source of the outliers clearly identified, it is difficult to remove outliers completely from analysis.

5.5.3 Test for Consistency/Homogeneity

Rainbow software package, which was produced by K.U.Leuven University for analyzing climatological/hydrological data frequency analysis i.e. test for homogeneity, was used for checking consistency/homogeneity of each station data.

All analyzed data, were found to be homogeneous at 0.05 alpha level .The results from the homogeneity test are given in Table 5.3.

S.No.	Station Name	Test statistics for alpha level		
		0.1	.05	.01
1	Awash@ Bello	accepted	accepted	accepted
2	Awash@ Melka Kunture	accepted	accepted	accepted
3	Mojo	accepte	accepted	accepted

Table 5.3 Result from homogeneity test for the selected river gauging stations

5.6 Selection of Model Type

The scarcity of data in most of developing countries is so alarming that one gets a single station for a catchment as large as 1000 km². In addition there is always question of data quality problem. This forces scholar to use data from neighboring catchments for those sites which have no observation at all. Similar to any developing countries, in Ethiopia major

water balance variables such as rainfall and evaporation time series are sparsely and scarcely available (Appendix B.1 and B.2).

Moreover, different studies reveal the data available are of poor quality (Kiesel 2006). Thus, this study area is where even major water balance variables are sparsely and scarcely available as compared to different countries although it is relatively with better data set in Ethiopia.. For such areas the pragmatic solution is to apply conceptually sound lumped rainfall-runoff models with fewer parameters. AWBM and SMAR of RRL are characterized by few parameters (RRL 2004).

However Scarmento and Simhyd contain many parameters which have to be optimized. Reports from different users of RRL reveals that Tank model in most cases give poor results and errors reported. Owing to this, a Toolkit Steering Group recommend that Tank Model not be used until further notice .Therefore, in this thesis paper, AWBM and SMAR Models are selected for modeling work taking the aforementioned reasons and time constraint in to consideration.

5.7 Calibration and Verification Periods

The process of deriving characteristics equations constants, weighting factors, and other parameters that serve to define the model for a particular watershed is termed'' calibration'' (U.S Army Corps 1994).While verification refers to the testing of calibrated values, generally with data not used for calibration. It enables assessment of the reliability of the calibrated model. Calibration here refers to the process of using observed stream flow, rainfall and evaporation data to develop values for model parameters.

There are two ways of approaching a rainfall runoff model calibration:

- Considering the entire period of record, and
- Considering a proportion of the record for calibration and the other proportion for verification.

The main advantage of doing rainfall runoff models calibration considering the entire period record is that the most optimum calibration for the available data can be achieved. The problems with this is that there is no indication of how the model is likely to perform outside of the calibration period, i.e. how robust is the model. For this reason this is not the recommended approach for calibrating a model. If possible the verification (validation) and calibration periods should be of similar length. However to include sufficient climatic variability in the calibration period it may be possible to have the validation period only cover one third of the period of record.

Therefore, taking the aforementioned facts in to consideration, the 11 years data (1994-2004) grouped in to two parts with 6years data for calibration and 5 years data for verification as shown in Table 5.4.

S. No	Catchment	Calibration (Period1)	Verification (Period2)
1	Bello	1994-1999	2000-2004
2	Melka Kunture	1994-1999	2000-2004
3	Mojo	1994-1999	2000-2004

Table 5.4 Calibration and Verification Periods

CHAPTER SIX

MODEL APPLICATION AND RESULTS

6.1 General

After preparation of necessary data that are important to undertake rainfall runoff modeling for the selected catchments and flow gauging stations, the next step is to perform simulation and subsequently conduct calibration and verification which enable the comparison of observed flow and generated flow of the model as well as to investigate the degree of performance of the model.

To perform flow generation, the file browser of RRL is used to locate a file that may then be dragged and dropped on to the appropriate time series field(Appendix F).The file that is selected must be in valid time series format as stated in RRL manual. These include:

- AWBM daily time series format (.awb)
- Comma delaminated column daily time series (.cdt)
- IQQM daily time series format(.iqqm)
- Rainfall-Runoff library project file (. Jobf)
- QDNR SILO daily time series format (.Silo5)
- Space delaminated column daily series format (.sdt)
- SWAT daily rainfall time stress format (.pcp)
- Tab delimited column daily time series format (.tdt)
- Tarsier daily time series format(.tts)

According to CRC, following a Toolkit Steering Group, the comma separated values file extension is now '.cdt'. The '.csv' extension was too generic and leading some users into thinking that any such file produced by Excel would be readable. Thus, Among these formats, comma delaminated column daily time series format (.cdt) is used to convert

rainfall , Evaporation and flow time series data into drag able format that may then be dragged and dropped on to the appropriate time series filed.

In addition, the units of the data must be compatible with the filed that the data is dropped on. The rainfall and evaporation field are expecting mm/day units while the flow filed is expecting mm/day, m³/s or ML/day units. In this thesis paper among the flow units available for flow, m³/s is used which can be selected by the drop down menu in the flow input field.

After making the necessary adjustments stated above ,the rain fall runoff modeling work was undertaken for eleven years data (1994 – 2004) using rainfall, evaporation and flow data.

In line with this, simulation and calibration processes were undertaken using combination of selected optimization methods and objective function. Finally, the respective optimization parameters of AWBM and SMAR models were identified for the selected sub catchments of the Upper Awash Sub Basin.

Thus, the calibration process and comparison of observed and simulated flows for calibration and verification periods using AWBM and SMAR models for three catchments of Upper Awash Sub Basin namely Awash Belo, Awash Melka Kunture and Mojo are presented hereunder.

Rainfall Runoff Library has a choice of seven optimization methods (AppendixC.2). However, the default optimization method is Genetic Algorithm. Moreover, Genetic Algorithm is the most widely used optimization (RRL 2004).Therefore, due to the aforementioned facts and scope of this study, Genetic Algorithm with Nash Sutcliffe criteria and runoff difference in% as primary and secondary objectives(50% weight) respectively are used to conduct the modeling.

6.2 Calibration and Verification

The process of deriving characteristics equations, constants, weighting factors, and other parameters that serve to define the model for a particular watershed is termed 'calibration' (U.S Army Corps 1994). Calibration here refers to the process of using observed stream flow, rainfall and evaporation data to develop values for model parameters. Verification (Validation) refers to the testing of calibrated values, generally with data not used for calibration. It enables assessment of the reliability of the calibrated model.

In general, it is desirable to use several events (say, four to six) for calibration. It is also desirable to reserve a couple of events for verification. Sometimes the amount of useful data is limited so that there are few events for calibration and no events for verification.

Eleven years of data (1994-2004) is used since a suitably long period of flow record is the preferred method for calibrating rainfall runoff models. This method gives a way of assessing the robustness of the model for periods outside of the calibration period. When using calibration and validation periods it is important that an appropriate calibration period be selected. If possible the validation and calibration periods should be of similar length. However to include sufficient climatic variability in the calibration period it may be possible to have the validation period only cover one third of the total period of record (RRL 2004). The model should be preferably calibrated in a period that has both wet and dry extremes and has an average annual flow similar to the average annual flow for the whole period of record. In this thesis taking the aforementioned facts in to consideration the six years data set from 1994-1999 is used for calibration and five years data set from 2000-2004 is used for verification..

There are three tabs on the calibration tab dialogue in RRL (Appendix I) .The three tabs are:

- 1 Generic
- 2 Custom
- 3 Manual

While the generic tab contains drop down menus and buttons to access options for the automatic calibration of model parameters, the manual tab is provided for manual calibration of the selected rainfall runoff mode. The custom tab is available for rainfall runoff models that have internal calibration algorithms. Currently the only model with this capability is the AWBM model. For this study, the generic tab which contains drop down menus and buttons to access options for automatic calibration of model parameters is used. Different Optimization methods primary and secondary objective functions, and data transformation can be chosen by clicking the mouse on the optimization method drop down list .However, owing to the facts stated under section 6.1 combination of Genetic algorithm optimization method , Nash Sutcliffe criteria and runoff difference in % as primary and secondary objectives respectively is used to undertake the modeling work.

6.2.1 Comparison of observed and computed flow

Generally, the quality of fit between the observed and computed hydrographs is judged by reviewing plots of the hydrographs. Moreover, to conduct the comparison the Nash Sutcliffe criteria was used as the only statistical assessment for this study.

$$R^2 = 1 - \frac{\frac{1}{n} \sum_{t=1}^n (O_t - S_t)^2}{\frac{1}{n} \sum_{t=1}^n (O_t - \bar{O})^2} \text{-----} (6.1)$$

Where

n= Total number of time steps (-)

t= Actual time step

St= Measured flow for each time step (m³/s)

Ot= Simulated flow for each time step(m³/s)

\bar{O} = Mean simulated flow (m³/s)

The Nash and Sutcliffe value is proportional to the square of the difference between measured and simulated flow for one time step. Thus, especially the weak prediction of peak flows will lead to a low Nash and Sutcliffe value. In general, values should vary from 0 to 1, the optimum fit represented by 1. Negative values show that the mean of the measured flow is a better fit than the simulated flow.

The performance of the model is further assessed by comparing the annual total flow volume, the maximum peak flows and the date of the peaks.

6.2.1.1 Belo and Melka Kunture Catchments

Generally, the quality of fit between the observed and computed hydrographs is judged by reviewing plots of the hydrographs (Figure 6.1, 6.2). Nash Sutcliffe value of 0.79 and 0.85 were obtained for Bello and Melka Kunture catchment respectively using AWBM model for calibration period. However, Nash Sutcliffe value of 0.61 and 0.70 were obtained for Bello and Melka Kunture catchments respectively for verification periods (Appendix B.14 and B.15).

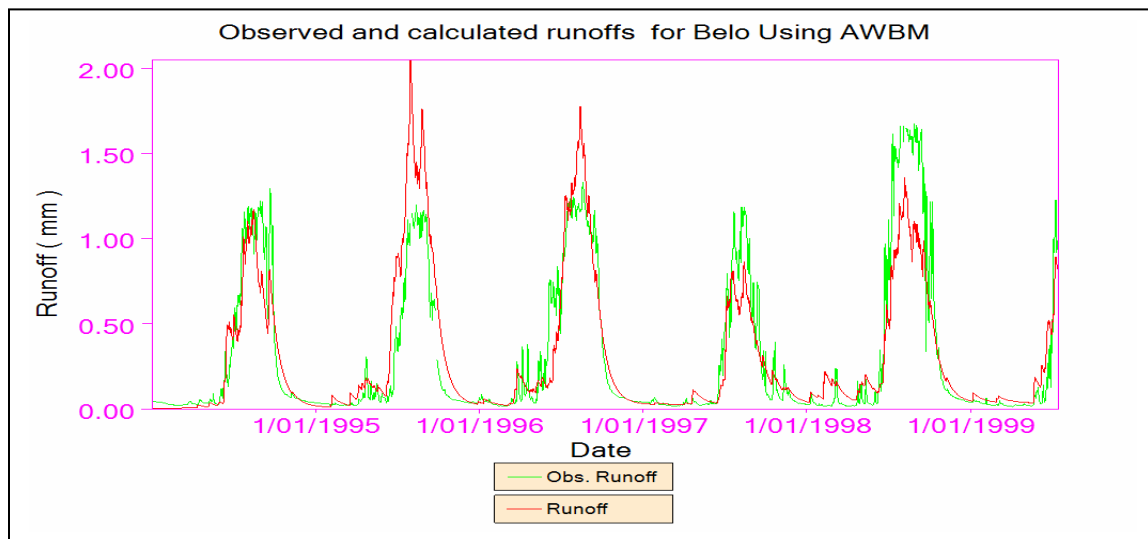


Figure 6.1 Simulated and Observed Runoff using AWBM for Bello Catchment (for Calibration Period)

As it can be observed from the plots of simulated and observed flow the scatter is denser around the low flows for the fact that during large periods of time the flow is in the low flow regimes.

Generally speaking, in both Bello and Melka Kunture catchments AWBM simulate the flow series fairly well. Comparison of the observed and computed flows reveals that except for the extreme peak flows the medium flow and low flows are generally modeled quite satisfactorily (Figure 6.1, 6.2 and Appendix B.16 and B.17).

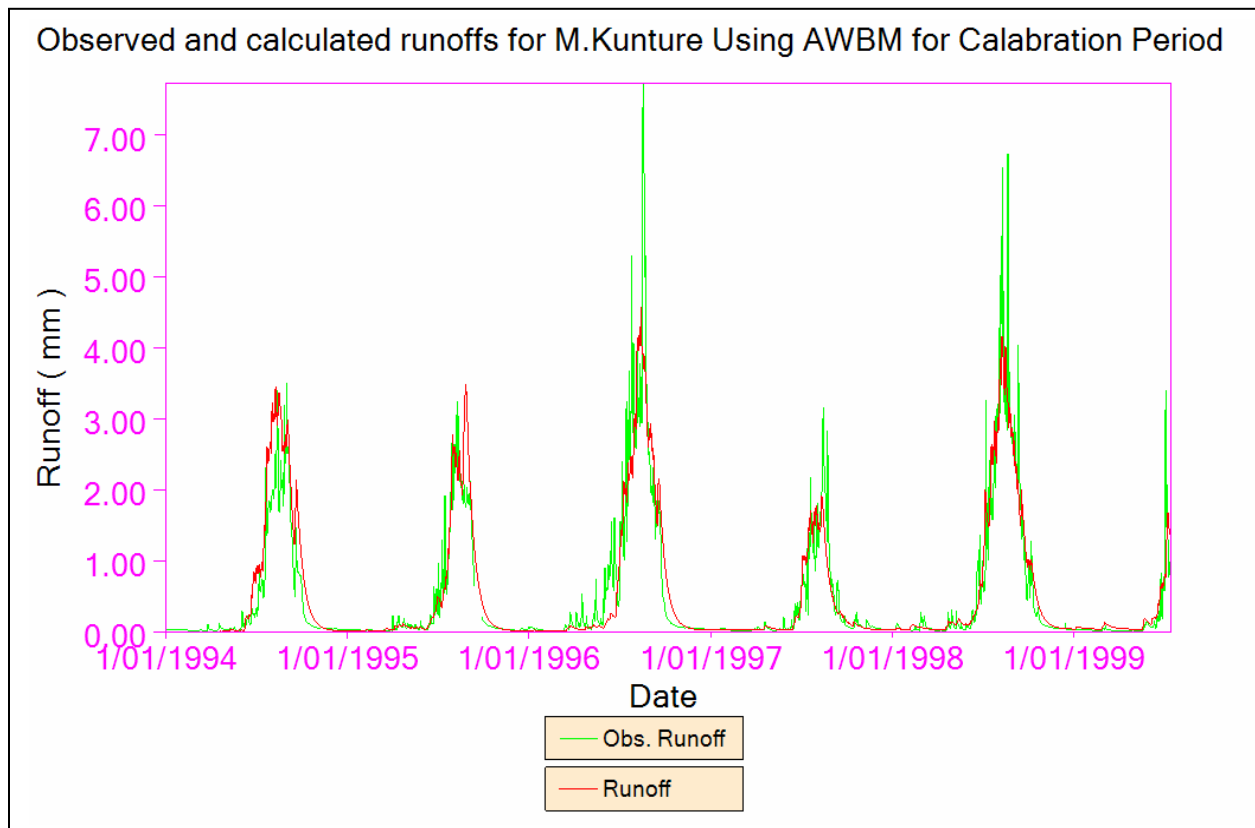


Figure 6.2 Simulated and Observed Runoff using AWBM for Melka Kunture Catchment (Calibration Period)

Relatively good result of simulated flow is obtained for most years in the case of Melka Kunture as it compared to the other catchments of the upper Awash considered in this

study although the results for certain years are not match well with observed flow especially peak flows.

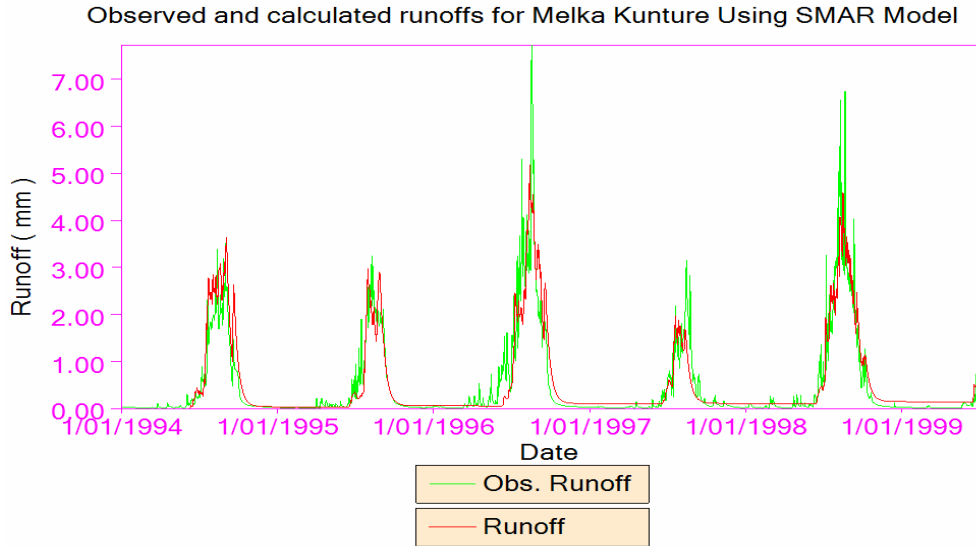


Figure 6.3 Simulated Runoff using SMAR for Melka Kunture Catchment (Calibration Period).

As it can be observed from Appendix B.18 and B.19, the SMAR model predicts the simulated flow with relatively less accuracy as compared to AWBM for Melka Kunture with Nash Sutcliffe value of 0.82 and 0.62 for calibration and Verification Periods respectively.

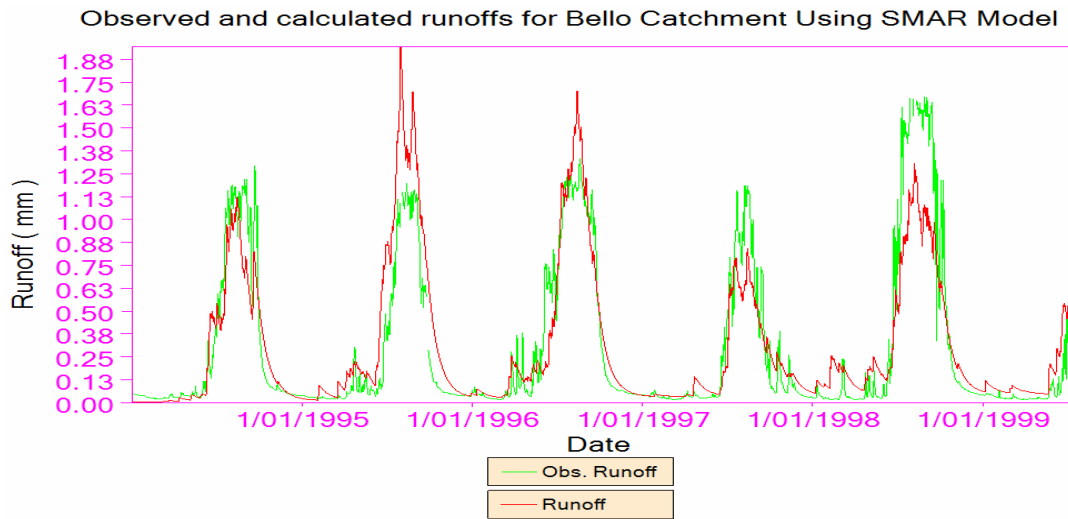


Figure 6.4 Simulated and observed Runoff using AWBM for Bello Catchment (for Calibration Period)

However, in case of Bello catchment SMAR model predicts the flow with Nash Sutcliffe value of 0.79 for calibration and 0.6 for verification period which is almost with equal efficiency as AWBM .As far as the flow hydrograph concerned , SMAR model predicts the flow volume for low and medium flows fairly good for calibration and verification periods similar to AWBM for both Bello and Melka Kunture catchments (Figure 6.3 and 6.4).Generally speaking, in both Bello and Melka Kunture catchments the two models simulate the flow series fairly good except for the extreme peak flows.

Further performance of the models is assessed by comparing the annual total flow volume and the maximum peak flows for both catchments (Table 6.1 and 6.2). In general, percentage flow volume difference varies from year to year as it is shown in the Tables. In most cases under prediction of peaks observed for both AWBM and SMAR Models. However the percentage volume difference is to some extent fair for most years as the Nash Sutcliffe criteria also confirms the same.

S.No	Year	% Volume Difference	
		AWBM	SMAR
1	1994	2.13	2.22
2	1995	-2.21	3.14
3	1996	5.81	6.86
4	1997	6.77	4.23
5	1998	7.21	7.34
6	1999	6.94	7.27
7	2000	6.97	7.64
8	2001	8.78	8.94
9	2002	7.67	7.34
10	2003	22.94	23.11
11	2004	18.66	19.87

Table 6.1 AWBM and SMAR Simulation Assessment for Melka Kunture Catchment

S.No	Year	% Volume Difference	
		AWBM	SMAR
1	1994	4.87	5.63
2	1995	-7.61	-7.82
3	1996	-7.69	-7.47
4	1997	6.23	6.64
5	1998	6.78	6.98
6	1999	7.54	7.65
7	2000	7.69	8.47
8	2001	Observed data missing	Observed data missing
9	2002	Observed data missing	Observed data missing
10	2003	18.76	19.72
11	2004	24.88	22.42

Table 6.2 AWBM and SMAR Simulation Assessment for Bello Catchment

6.2.1.2 Mojo Catchment

The modeling result obtained using both SMAR and AWBM for Mojo catchment is extremely poor. The graphs show no good correlation and the peak flows are mostly under predicted (Figure 6.5 and 6.6).

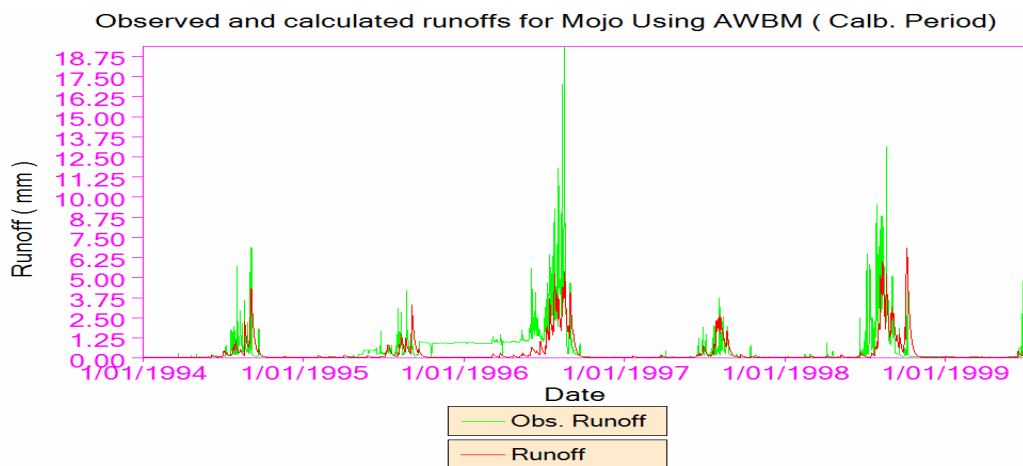


Figure 6.5 Simulated and observed flow for Mojo Catchment using AWBM.

The modeling undertaken using AWBM provides Nash-Sutcliffe criteria of 0.35 and 0.018 for calibration and verification periods respectively (Appendix B.22) Similarly, as it can be observed from Appendix B.24 ,SMAR gives Nash-Sutcliffe value of 0.1 for calibration and -0.11 for verification periods which indicates poor prediction of simulated flows.

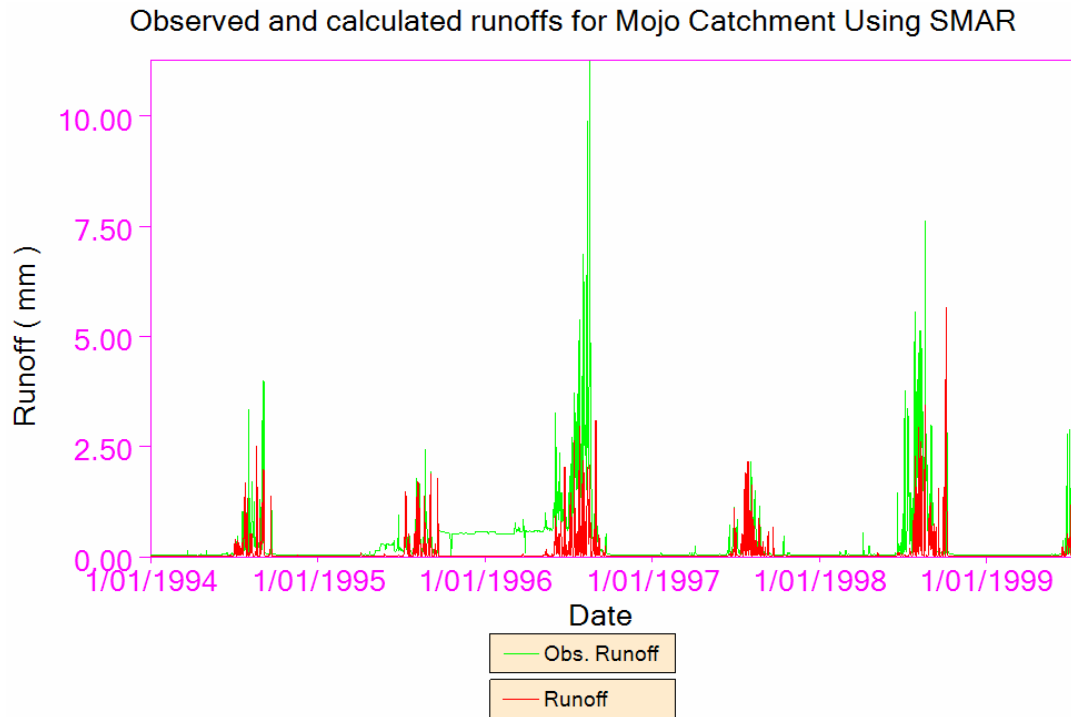


Figure 6.6 Simulated and observed flow for Mojo Catchment using SMAR

6.2.2 Reasons for Under Prediction of Peaks

It is noted that similar to previous studies stated in section 2.11, modeling the peak flows remains the weak point of the whole modeling with the time steps considered. This is most probably due to the data recording system and availability of data. For instance rainfall time duration, the absence of the evaporation data in the catchments which forced us to use Addis Ababa evaporation data which is not so representative as the evaporation data which can be obtained if it would have been recorded in the catchment .Therefore, it clearly shows the attention the data recording trend deserves in the catchments to undertake different water resources planning and management in the basin.

According to Kiesel(2006) models are usually developed for particular regions using diverse physical and mathematical descriptions to reproduce the watershed in a simplified way with local climate, soil, vegetation, size of watershed and its special localized processes (e.g. for semi-humid, arid, semi-arid regions ,rural or urban areas). Similarly, the models used in this study are originally developed for Australian Catchments and thus they may lack incorporation of concepts and parameters that account for the hydrological characteristics of the semi-humid and semiarid conditions of the catchments like those in Ethiopia.

6.3 Calibrated Model Parameter Values

Sorooshian, and Gupta (1995) classify parameters into two groups: physical and process parameters. A physical parameter represents physically measurable properties of the watershed (e.g. areas of the catchment, fraction of impervious area and surface area of water bodies, surface slope etc).Process parameters represents properties of the watershed which are not directly measurable e.g. average or effective depth of surface soil moisture storage, the effective lateral inflow rate, the coefficient of non linearity controlling the rate of percolation to the groundwater and so on. In fact the division between the two groups depends on the spatial distribution and structure of a model. In conceptual rainfall-runoff models, almost all of the parameters are of the second type where the optimum values are obtained by calibrating the model using historical data.As it is stated under 2.10.1.2, the RRL is configured with a set of default parameters values that specify the initial parameter value as well as the upper and lower bounds for that parameter values for each model parameter.

Calibration is the process of modifying model parameters to reduce the error between the simulated stream flow and some portion of the observed flow record. The model parameter determination is undertaken by clicking the mouse on the boundaries and fixed parameter button which displays the calibration parameters dialogue as show in Appendix H. The dialogue displays each of the model parameters, upper and lower bounds to each parameter and check box that can optionally fix the parameter in optimized calibration.Thus, the values of model parameters obtained during calibration are tabulated for both AWBM and SMAR models in the tables below (Table 6.3 and Table 6.4).

S. No	Parameter	Calibrated Parameter Value
1	A1	0.134
2	A2	0.433
3	BFI	0.499
4	C1	11.356
5	C2	172.533
6	C3	203.187
7	KBase	0.834
8	KSurf	1

Table 6.3 Calibrated Model Parameter Values for AWBM

S. No	Parameter	Calibrated Parameter Value
1	C	0.945
2	G	0.345
3	H	0.153
4	Kg	0.490
5	N	1.039
6	NK	0.992
7	T	0.561
8	Y	3333.333
9	Z	1235.294

Table 6.4 Calibrated Model Parameter Values for SMAR model

6.4 Sensitivity Analysis

Sensitivity analysis (SA) is a fundamental tool in the building, use and understanding of models of all forms. Tarantola and Saltelli (2003) concluded that “SA can get useful information regarding the behavior of the underlying simulated system. This information can range from the identification of calibration variables to model reduction or simplification,

better understanding of the model structure for given components of a system, model quality assurance, and model building in general.”

It is important to understand how sensitive a model is to certain parameters. This is useful to understand how the model functions and also what parameters need more attention than others. If the model is significantly affected by a particular parameter then the focus of calibration should be on that parameter. The uncertainty of the model will also be closely related to the uncertainty in estimating the most sensitive parameters ((Tarantola and Saltelli 2003). The RRL provides a facility to investigate the sensitivity of all model parameters. In most rainfall runoff models the behavior of many parameters is related to the values of other parameters i.e. the models are non-linear (RRL 2004). Consequently the sensitivity of particular parameters may be different depending upon the values of other parameters.

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

As it is stated under section 6.1, Nash-Sutcliffe criterion (Coefficient of efficiency) is the objective function used in this modeling. Therefore, it is for this objective function that sensitivity analysis of AWBM and SMAR model parameters conducted considering each parameter and recording the out comes for each in order to identify the most sensitive parameters.

After making the necessary analysis, the following observations made for AWBM and SMAR model parameters.

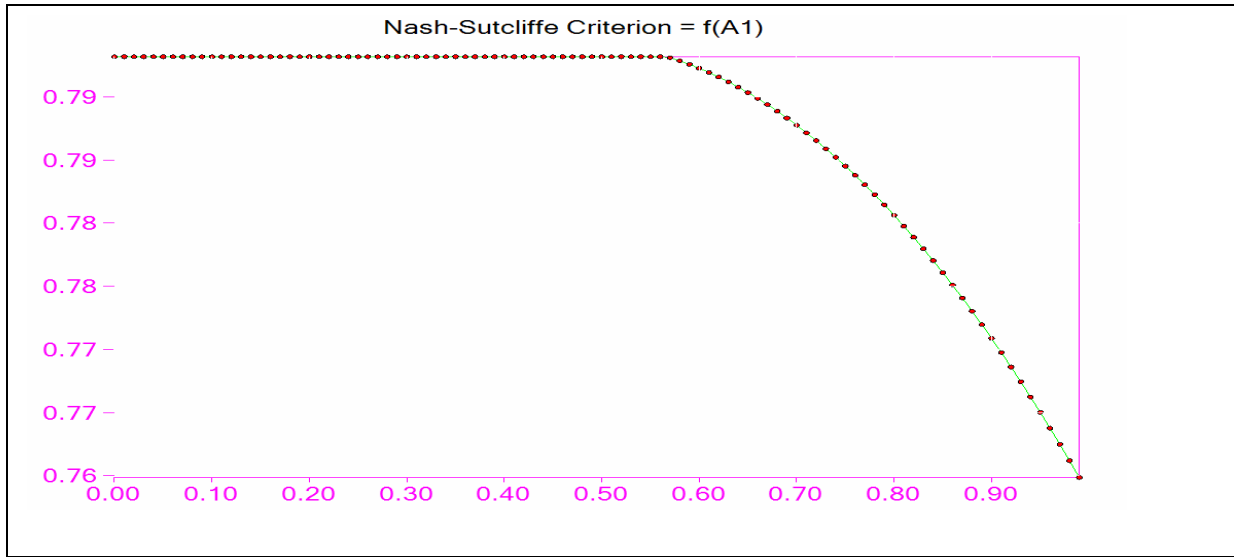


Figure 6.7 Sensitivity Analysis graph for A1 of AWBM

For maximum and minimum values of A1, A2 and A3 of AWBM, which represent the proportions of areas, the values of objective function (Nash Sutcliffe value) vary over small range. For instance, incase of A1, the Nash Sutcliffe value is constant for values of A1 up to range of 0.55. However, for values of A1 more than 0.55, the relation with Nash Sutcliffe criteria is linear with small variation in magnitude of the value of Nash Sutcliffe(Figure 6.7).In case A2 ,Nash Sutcliffe value vary almost linearly up to 0.55 and drops after wards linearly (Figure 6.8).

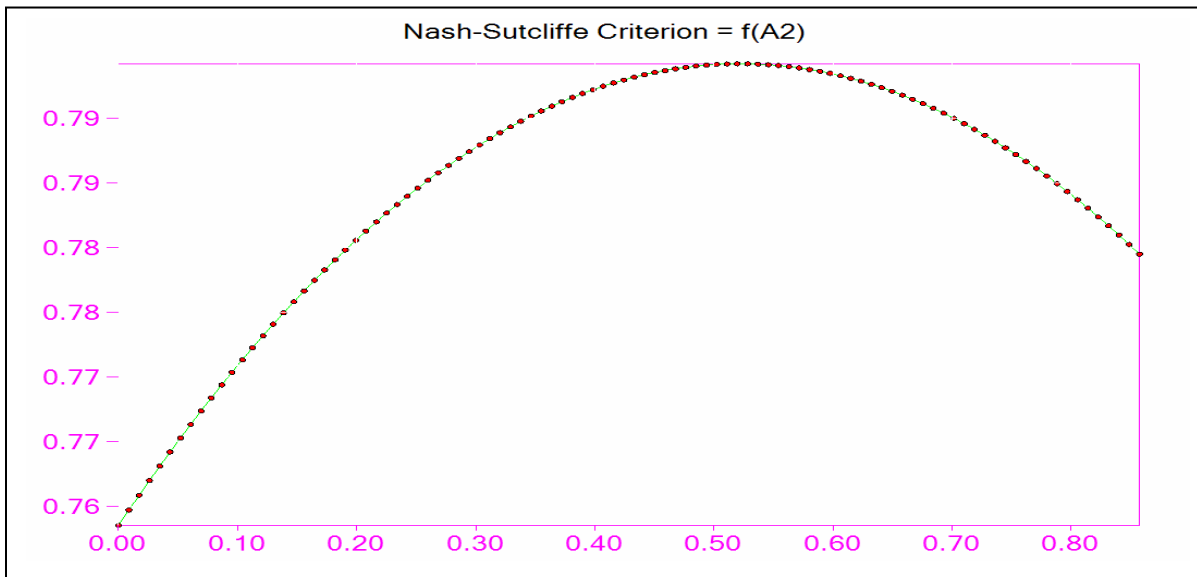


Figure 6.8 Sensitivity Analysis for A2 of AWBM

Further more the sensitivity analysis result indicates that for the maximum and minimum values of storage capacities (C1, C2,C3), Nash Sutcliffe values varies relatively over the large range as compared to the Nash Sutcliffe Values variation for partial areas(A1, A2, A3) which inurn indicates that storage parameters are more sensitive than partial area parameters (Figure 6.9 and 6.10).

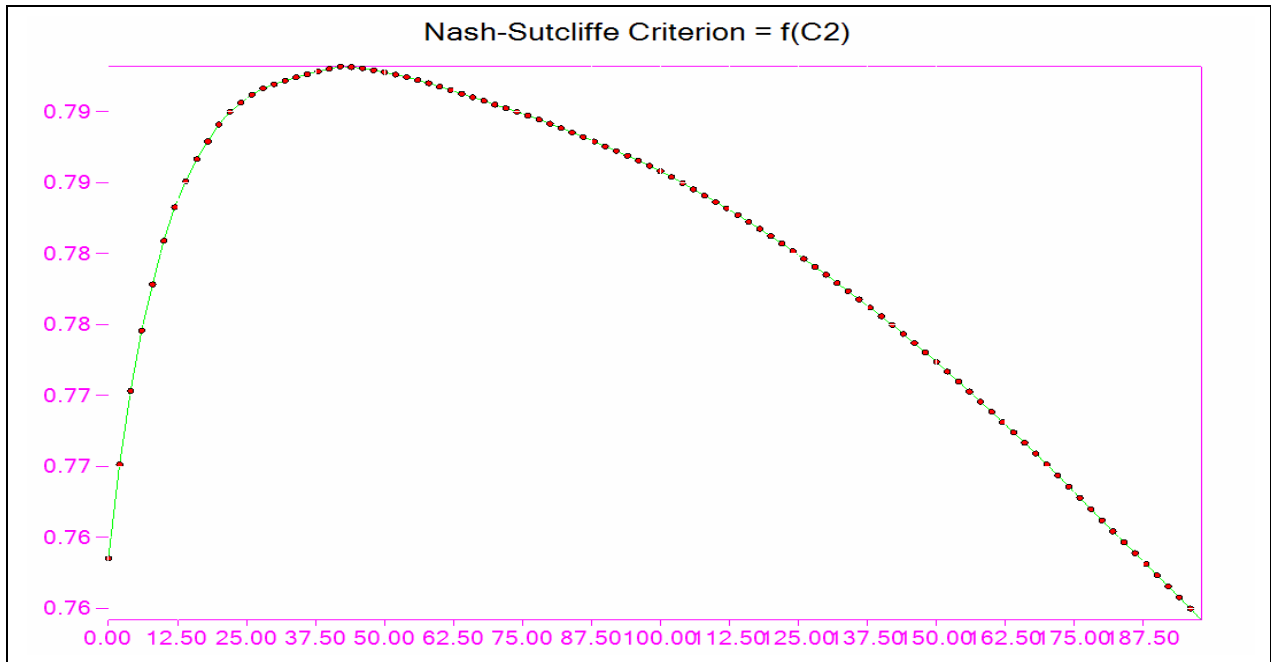


Figure 6.9 Sensitivity Analysis for C2 of AWBM

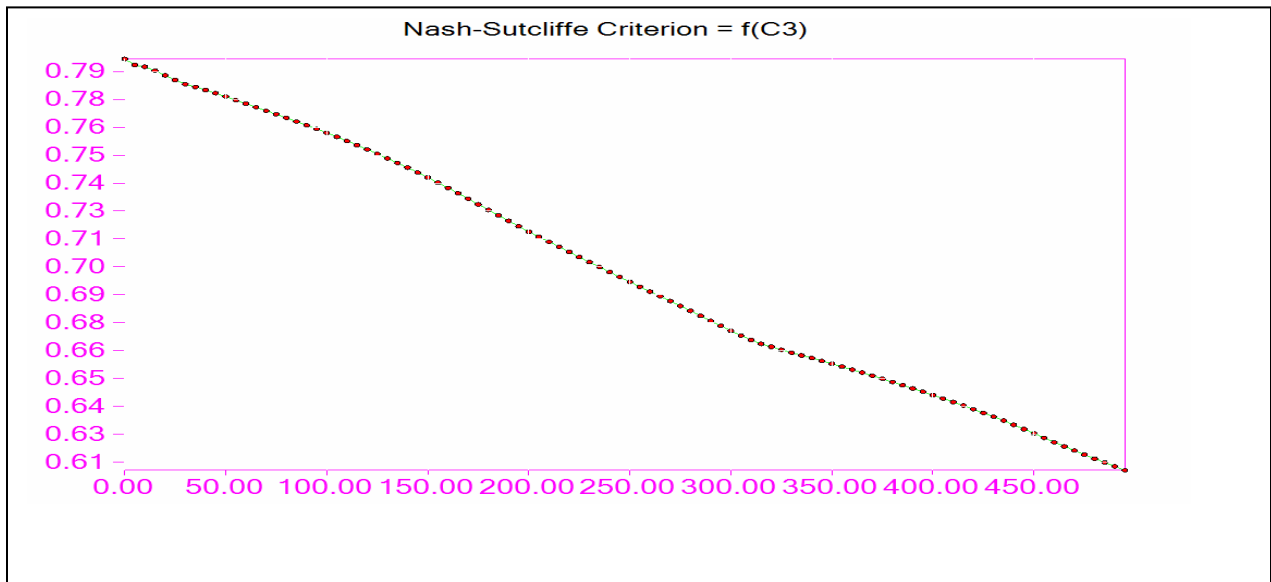


Figure 6.10 Sensitivity Analysis for C3 of AWBM

As it can be observed from figure 6.10, the other parameters of AWBM such as BFI (base flow index) which is the ratio of base flow to total flow in stream and KSurf (daily surface flow recession constant) varies over the large range which indicates that these parameters are the most sensitive parameter of AWBM with respect to the selected objective function in this modeling.

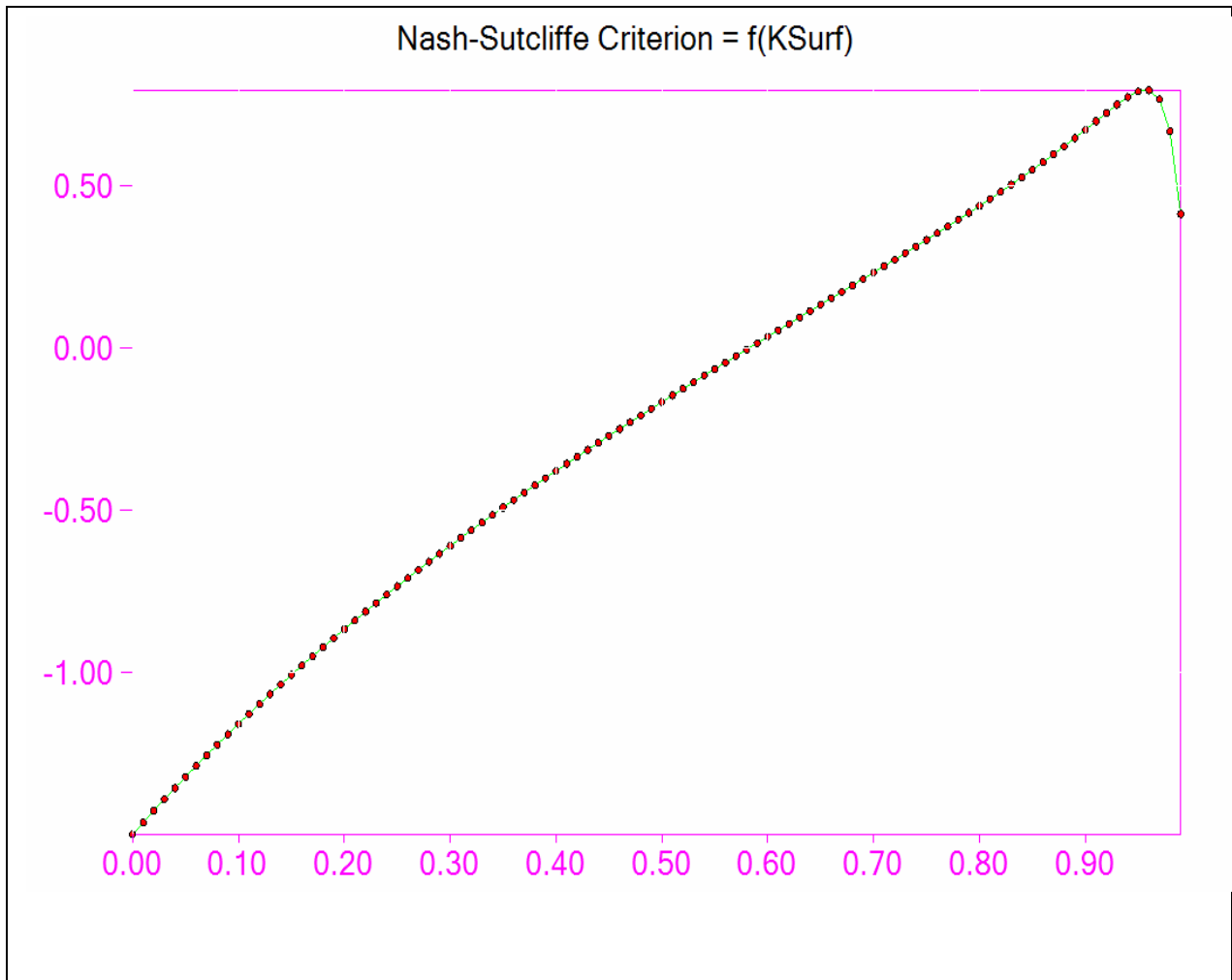


Figure 6.11 Sensitivity analysis for daily surface flow recession constant (KSurf) of AWBM

In case of SMAR models parameters such as the ground water evaporation rate (C), ground water runoff coefficient (G), Storage loss coefficient (Kg) the Nash value is constant for their maximum and minimum values (figure 6.11 and figure 6.12).

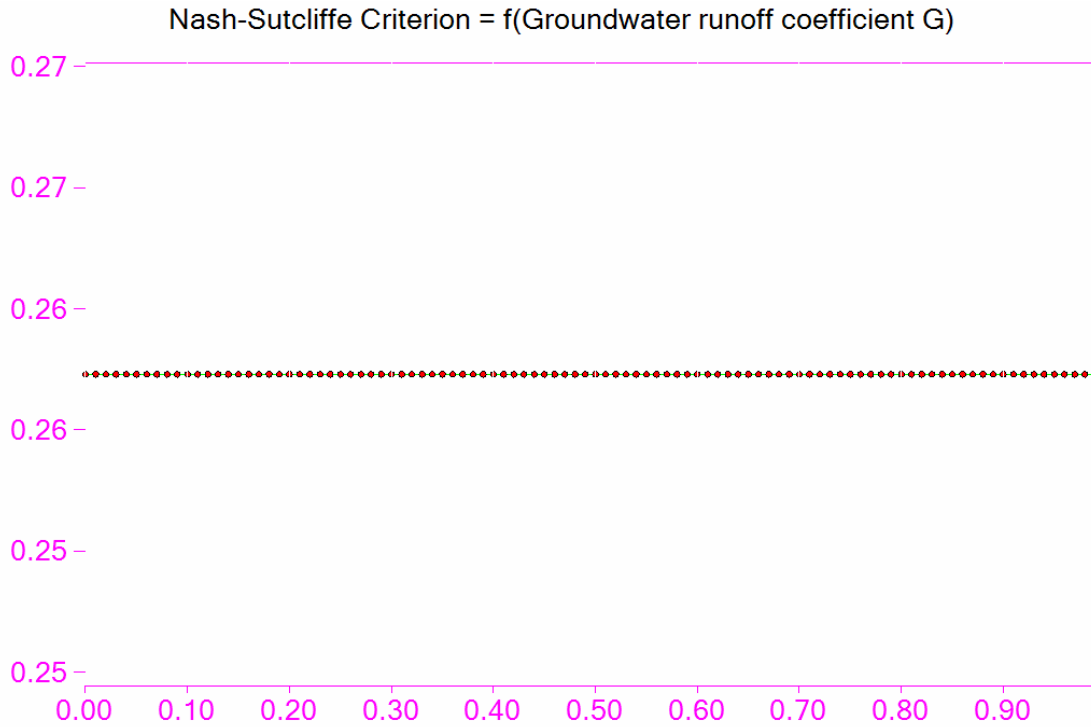


Figure 6.12 Ground Water Coefficient (G) Sensitivity Analysis

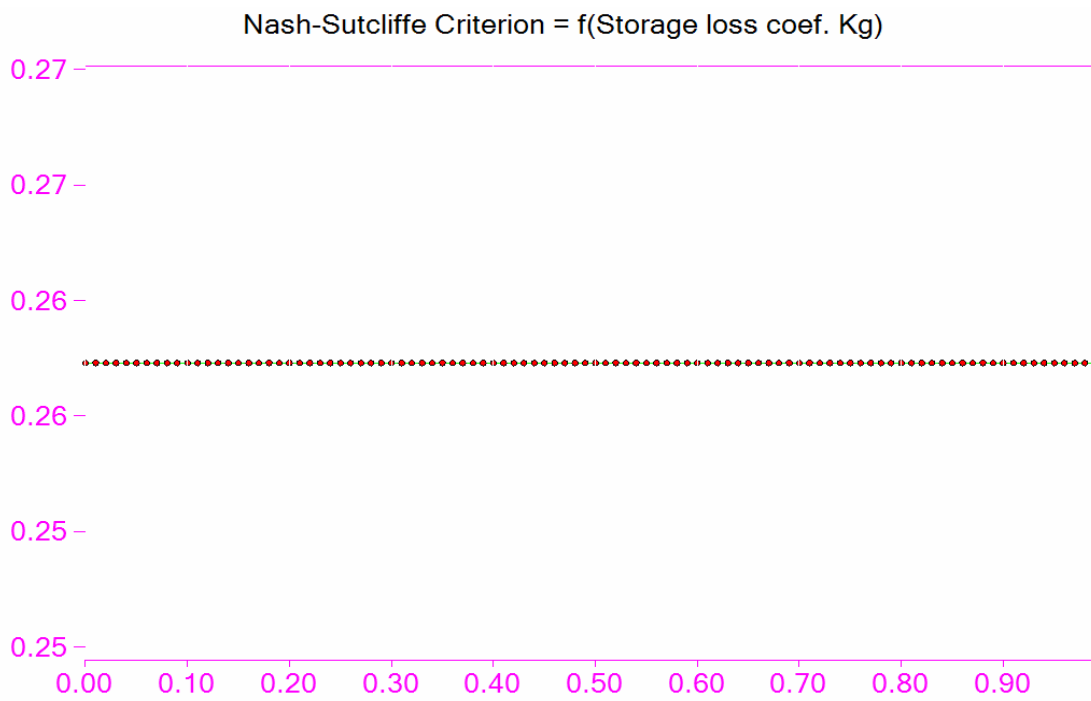


Figure 6.13 Sensitivity Analysis for storage loss coefficient (Kg)

For maximum and minimum value of unit hydrograph linear routing (N) ,unit hydrograph linear routing component(NK),the Nash Sutcliffe value vary rapidly and this two parameters have been found to be most sensitive ones for the selected objective function (Figure 6.13 and 6.14) .

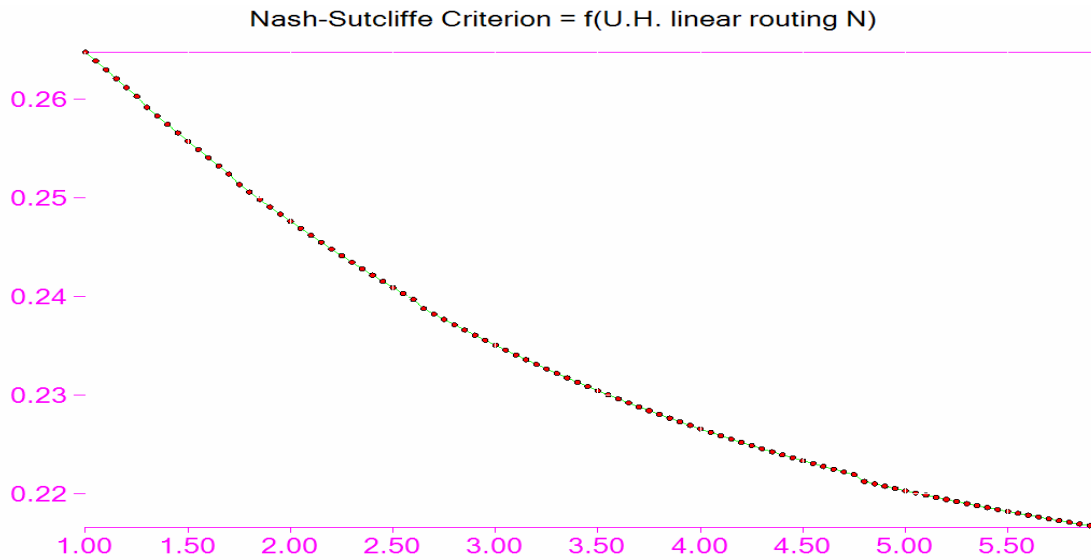


Figure 6.14 Sensitivity analysis for unit hydrograph linear routing parameter (N) of SMAR Model.

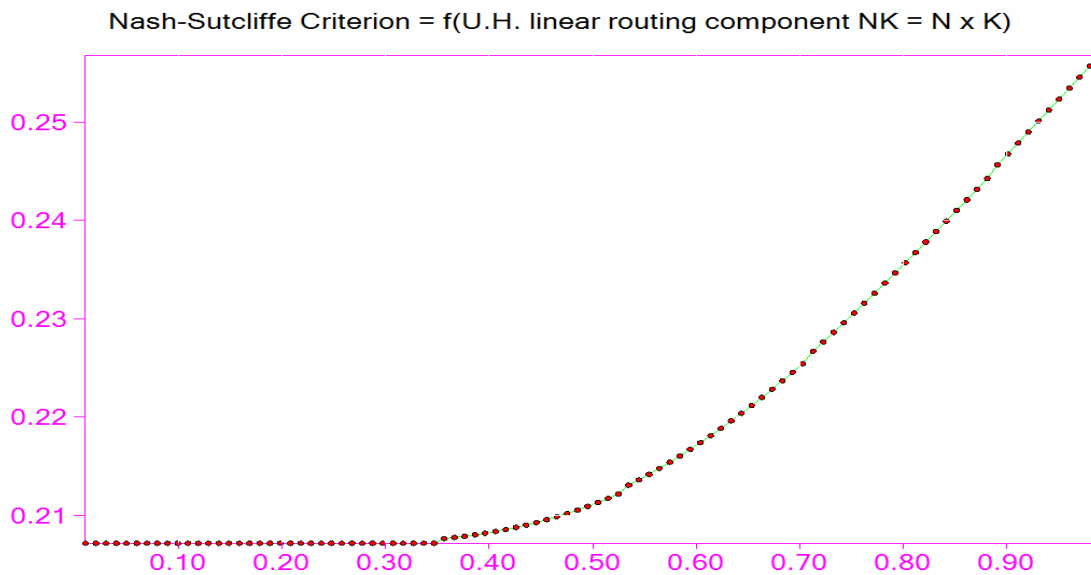


Figure 6.15 Sensitivity analysis for unit hydrograph linear routing component (NK) of SMAR Model

CHAPTER SEVEN

CONCLUSION AND RECOMMENDATIONS

The following conclusions may be specifically drawn from the application of the models and subsequent results obtained:

7.1 Conclusion

In this study, hydrological, meteorological and other related data which are vital to conduct rainfall runoff modeling were collected and subsequent data quality checking was undertaken. Moreover, among the five conceptual models nested in rainfall runoff library, two models namely AWBM and SMAR models were selected based on the parameters of the models and taking the data availability and quality problem in Ethiopia in to consideration. Furthermore, selection of optimization method and objective functions were undertaken based on the general facts and priorities set in rainfall runoff library manual. Accordingly, Genetic Algorithm optimization method and Nash Sutcliffe criteria and runoff difference as primary and secondary objectives respectively were selected to conduct the modeling.

Then, for each AWBM and SMAR models using Genetic Algorithm optimization method coupled with Nash Sutcliffe criteria and runoff difference as primary and secondary objectives respectively, rainfall runoff modeling in three catchments of Upper Awash Sub Basin known as Awash Bello, Awash Melka kulture and Mojo was undertaken using 11 years(1994-2004) daily data of water balance variables such as flow, rainfall, evaporation time series.

Both AWBM and SMAR models predict the low and medium flows fairly well with overall Nash Sutcliffe criteria of 0.6 to 0.85 for both calibration and verification periods except for Mojo catchment. However, the models under predict high peaks in most cases. Thus, similar to previous studies, modeling the peaks flows remains the weak point of the whole modeling with the time step considered.

As far as the performance of the two models concerned AWBM gives better results as compared to SMAR model in both Bello and Melka kunter catchments.

Finally, model sensitivity analysis was undertaken to analyze the sensitivity of a particular model parameter with regard to a selected objective function . The model sensitivity analysis conducted reveals that daily surface flow recession constant (K_{Surf}) and C₃ of AWBM are the 1st and the 2nd most sensitive parameters respectively for the selected objective function. In case of SMAR model, N (unit hydrograph linear routing parameter) is the 1st most sensitive parameter and unit hydrograph linear routing component NK 2nd most Sensitive parameter with respect to Nash Sutcliffe criteria which is the objective function selected for the modeling .

7.2 Recommendations

1. Based on the modeling work undertaken in the selected catchments of Upper Awash, AWBM gives better results. Thus, AWBM is recommended for the catchments of upper Awash .
2. If a further improvement of the simulation should be obtained, sub-daily precipitation measurements will become necessary. One possible way of gaining accurate and consistent data is by installing and maintaining an hourly rain gauge .As a result, hourly data measurement shall be promoted in the Upper Awash Sub catchments.
3. Data collection in Ethiopia is a time consuming process and the data obtained is often of poor quality. However, advances in scientific hydrology and practice of engineering hydrology depend on good, reliable and continuous measurements of hydrological variables. Model calibration more than anything relies on the quality of data available. Therefore, good quality data collection should always be encouraged. No model can be calibrated or even used without a good quality of data. The hydrology community should bridge the gap that is existing in the advancement of model development and the data acquisition. In addition to the traditional ground observation of hydro-meteorological variables derived from satellite images and radar technology can augment the data availability for water resources studies. Of

course even these recent technologies can achieve certain goals if and only if they are well calibrated by ground observations. Thus, advanced hydro-meteorological data acquisition shall be top on the agenda of the concerned bodies.

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3. Old Dominion University , Department of Civil and Environmental Engineering , Civil and Environmental Model Library
<http://www.cce.odu.edu/cce/model>
4. Spatial Hydrology, gateway to GIS ,GPS, hydrological modeling and remote Sensing
<http://www.spatialhydrology.com>
5. Software and Manuals
<http://www.iupware.be>
6. United States Geological Survey (USGS)
<http://www.usgs.gov>
7. Earth Resource Observation &Science (EROS) Africa Land Cover Characterstic Data Base Version 2.0
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<http://www.ess.co.at/WATERWARE/erosion.html>

9 Weather Base , Weather Records for More than 16,439 Cities World Wide,

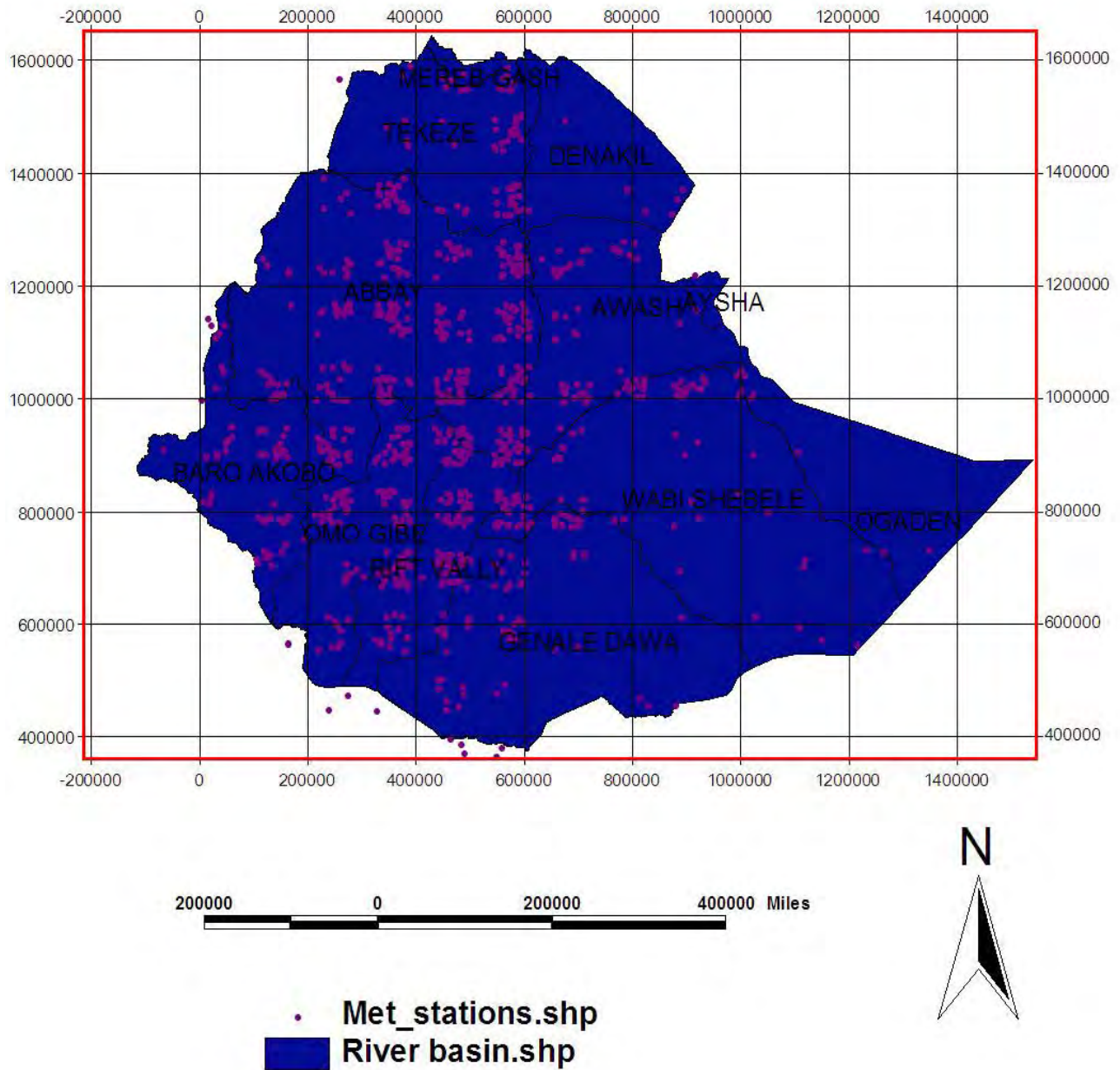
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<http://www.weatherbase.com>

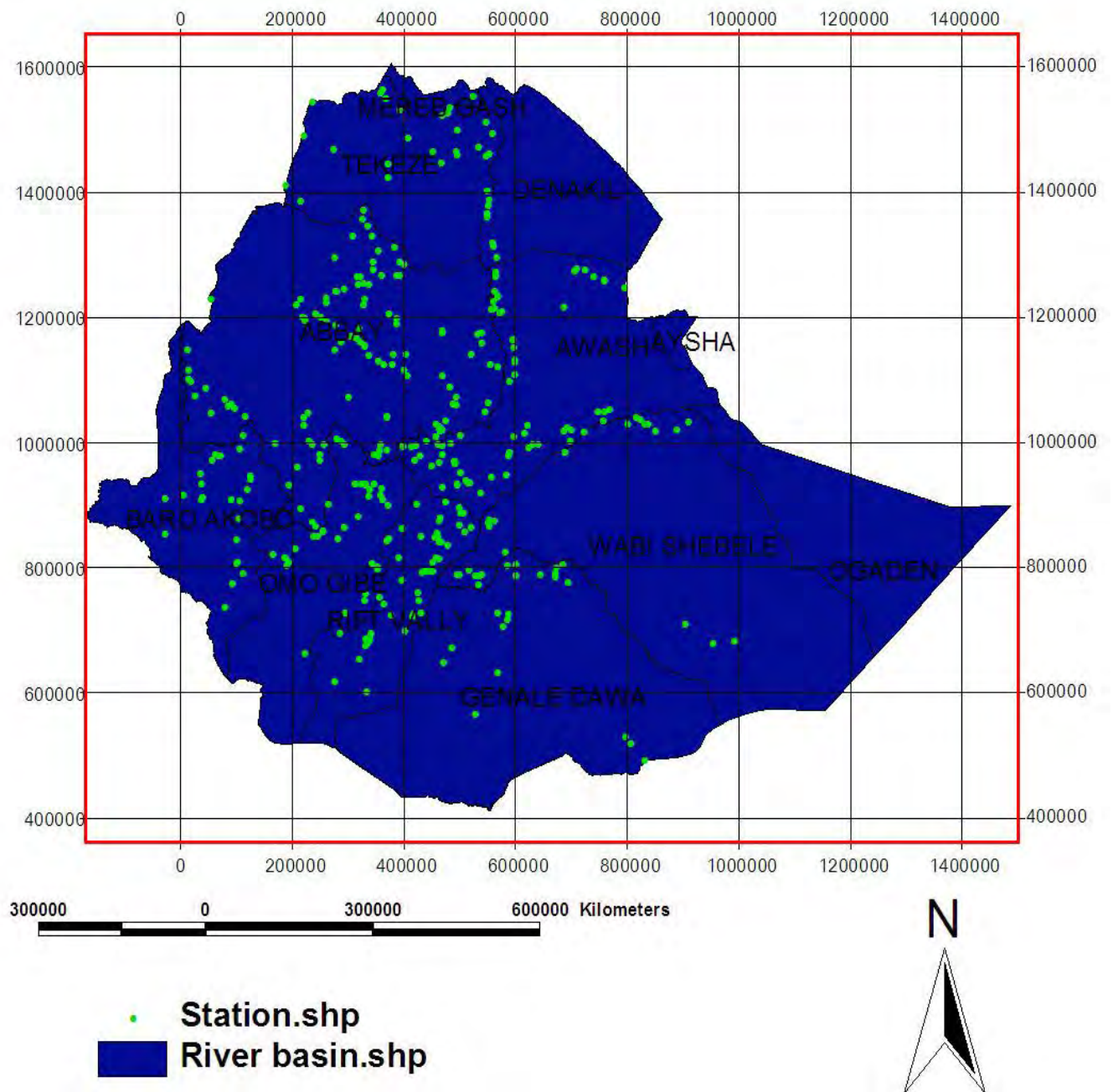
APPENDICES

B. Maps and Figures

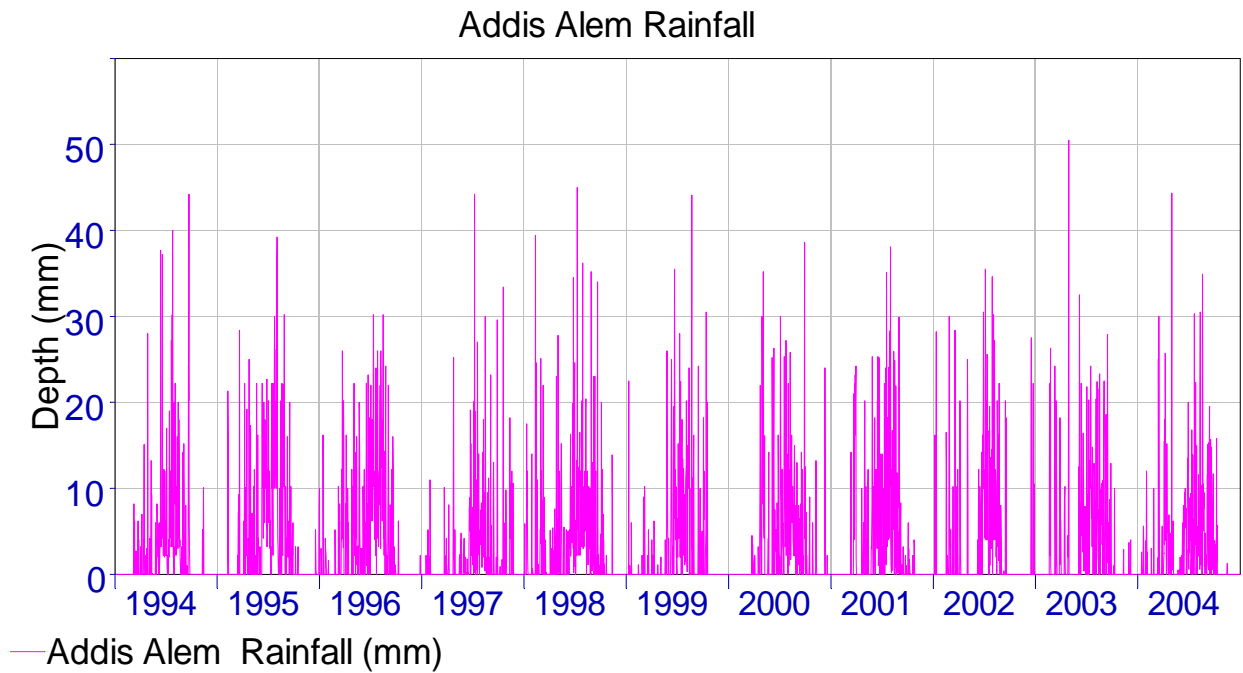
Appendix B.1: Distribution of Meteorological Stations in Ethiopia



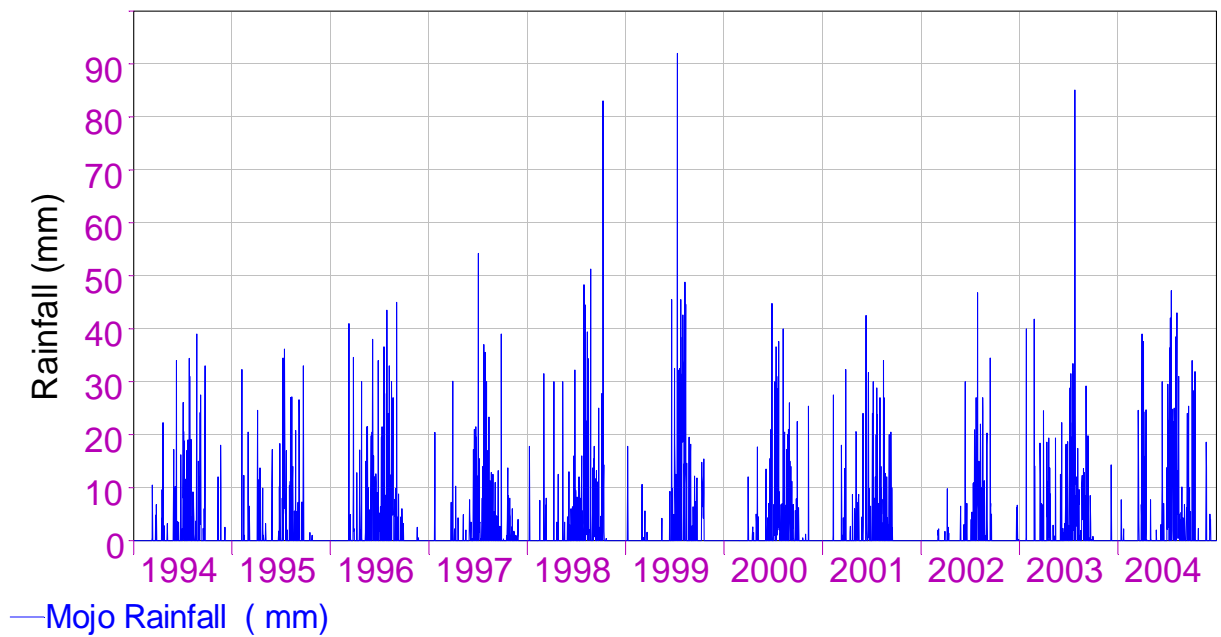
Appendix B.2: River Gauging Stations in Ethiopia



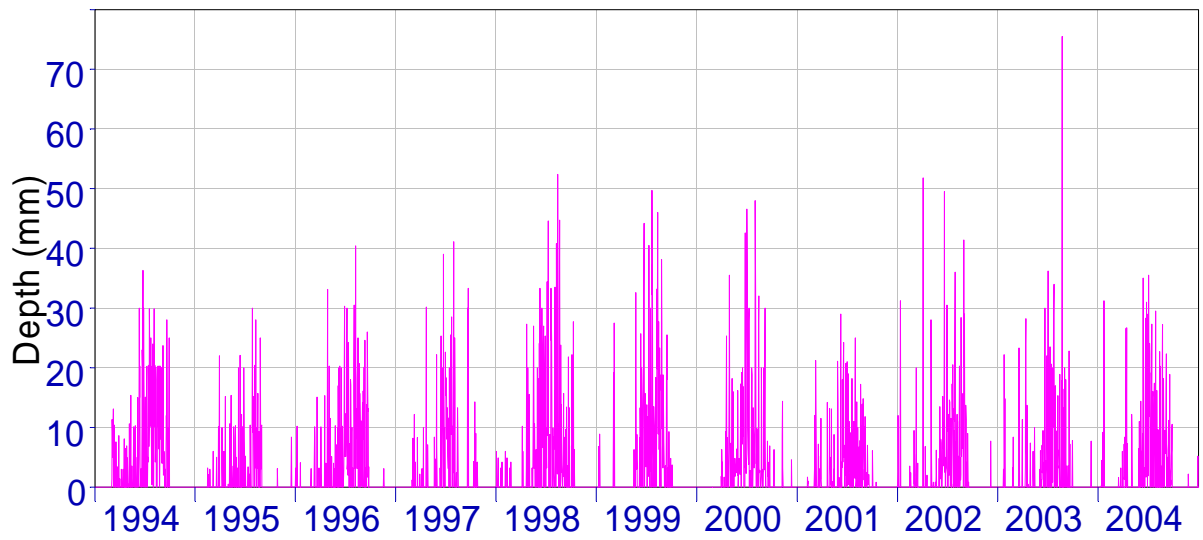
Appendix B.3: Daily Rainfall Recorded at Addis Alem Rainfall Station



Appendix B.4: Daily Rainfall Recorded at Mojo Rainfall Station

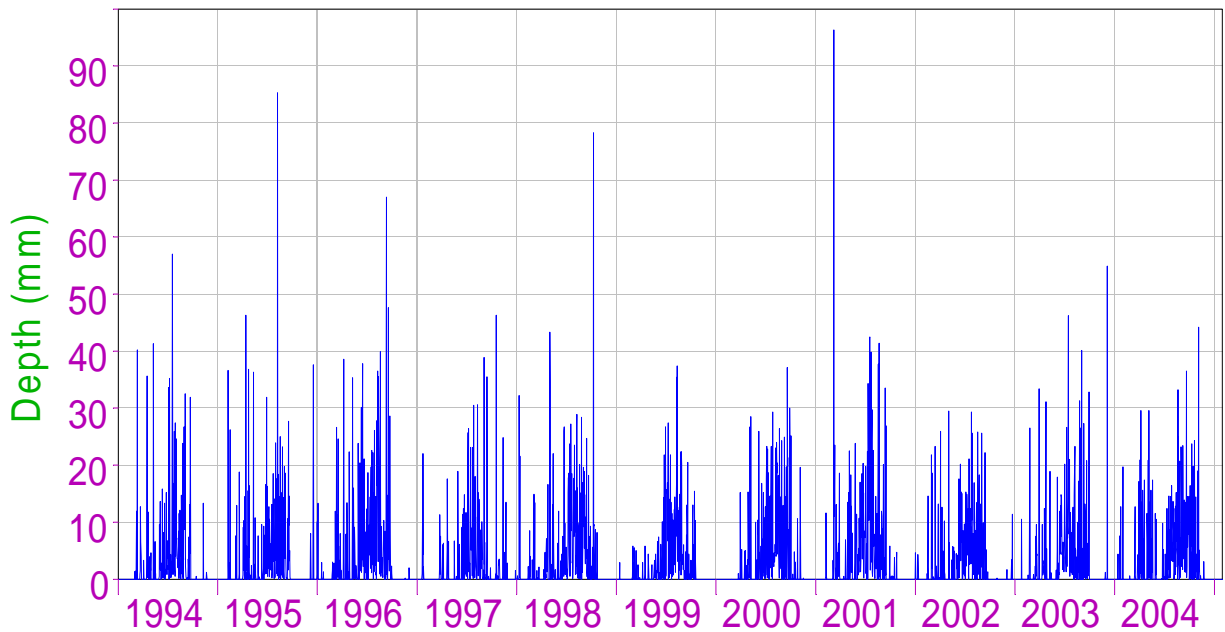


Appendix B.5: Daily Rainfall Recorded at Tullu Bollo Rainfall Station



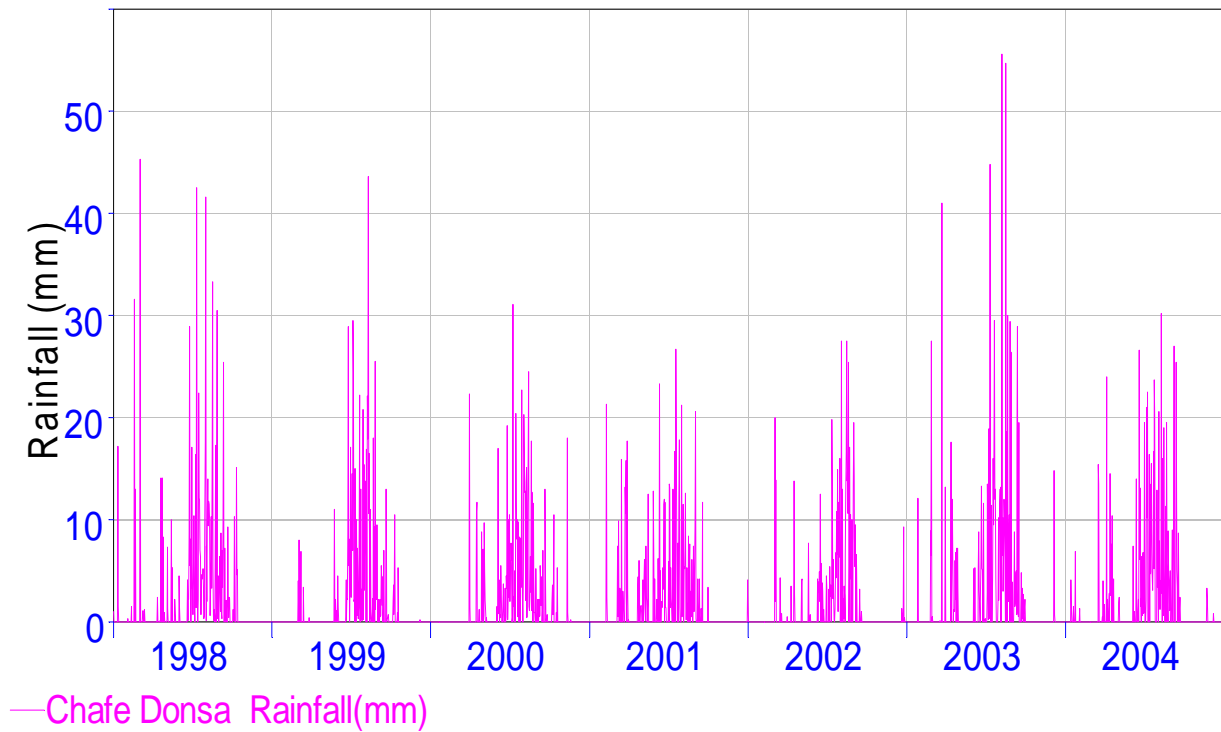
—Tulu Bolo Rainfall(mm)

Appendix B.6: Daily Rainfall Recorded at Addis Ababa Rainfall Station

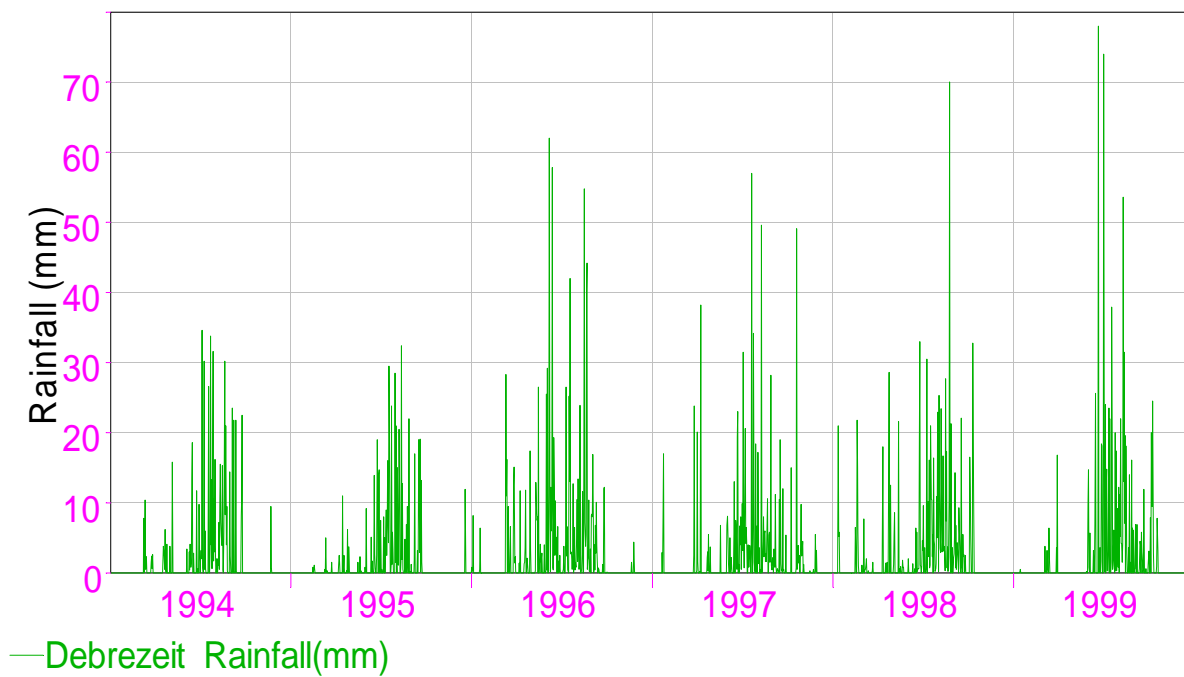


—Addis Ababa Rainfall Rainfall(mm)

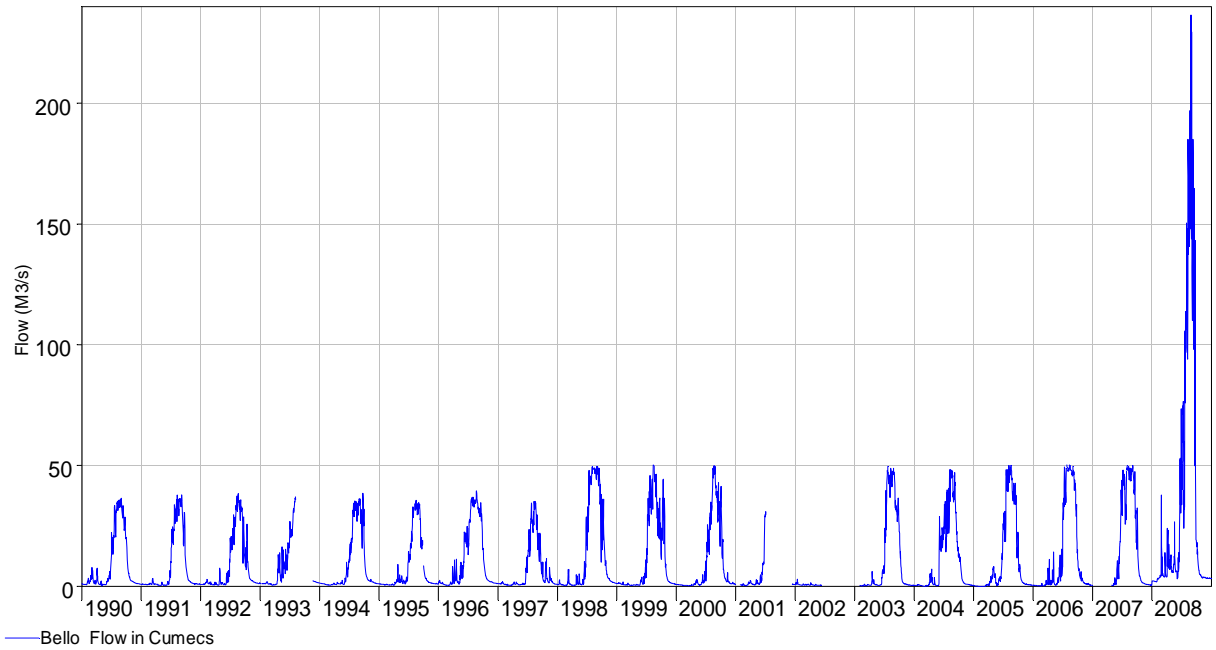
Appendix B.7: Daily Rainfall Recorded at Chafe Donsa Rainfall Station



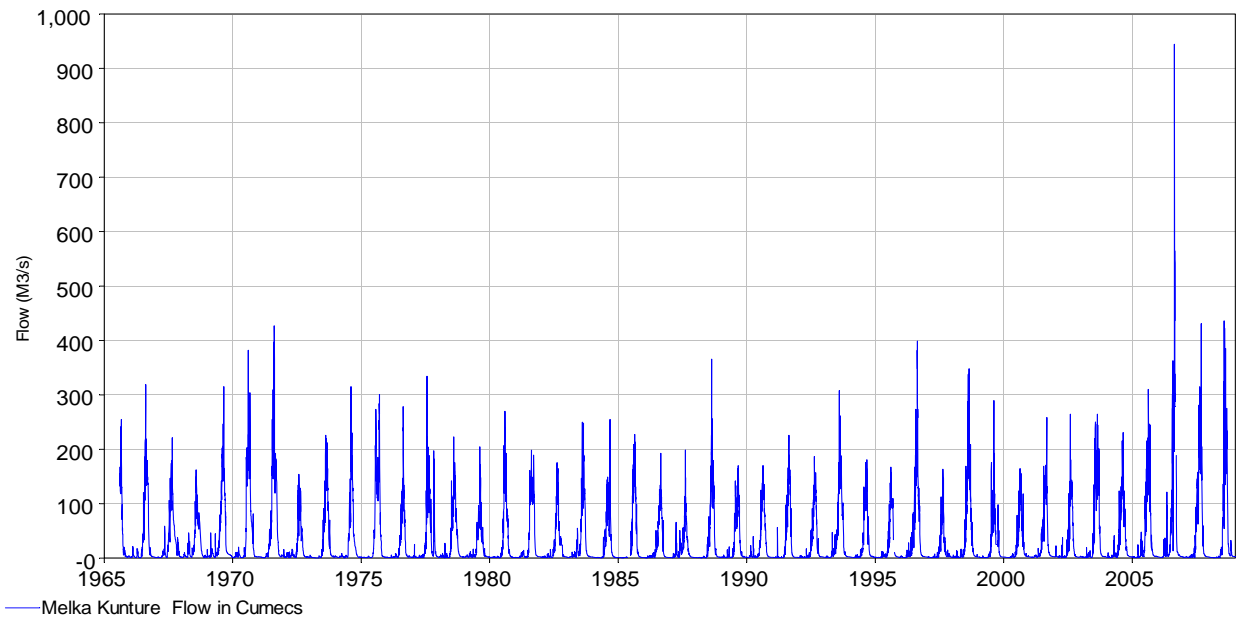
Appendix B. 8: Daily Rainfall recorded at Debrezeit Rainfall Station



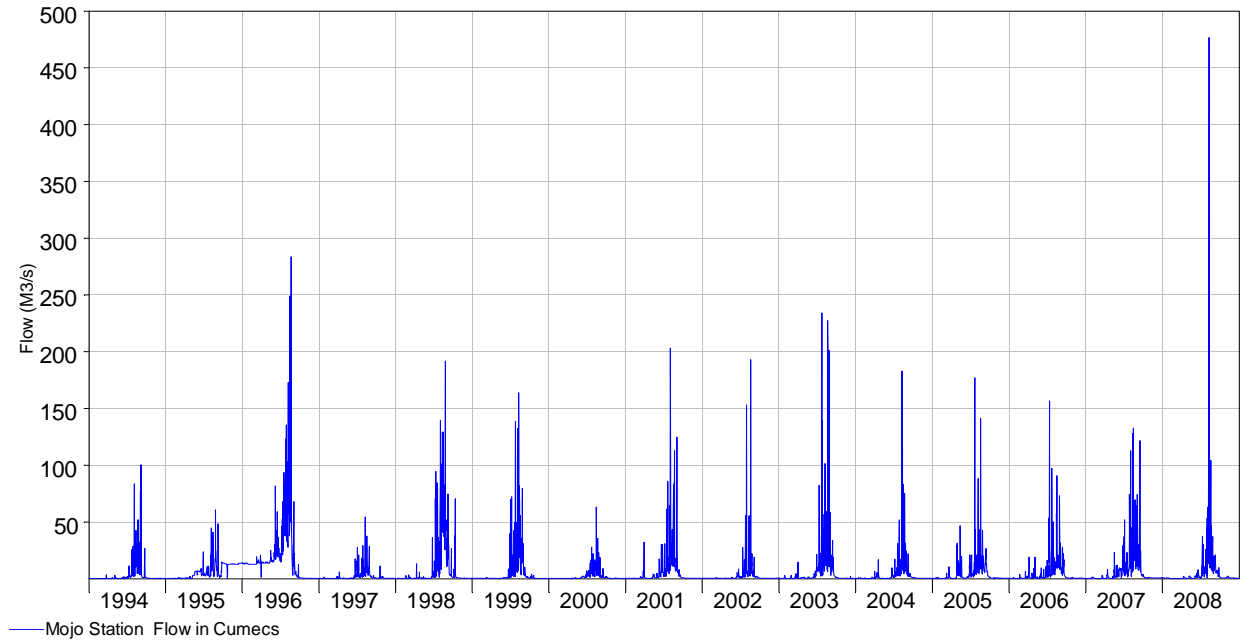
Appendix B. 9 :Daily Flow Data at Bello River Gauging Stations



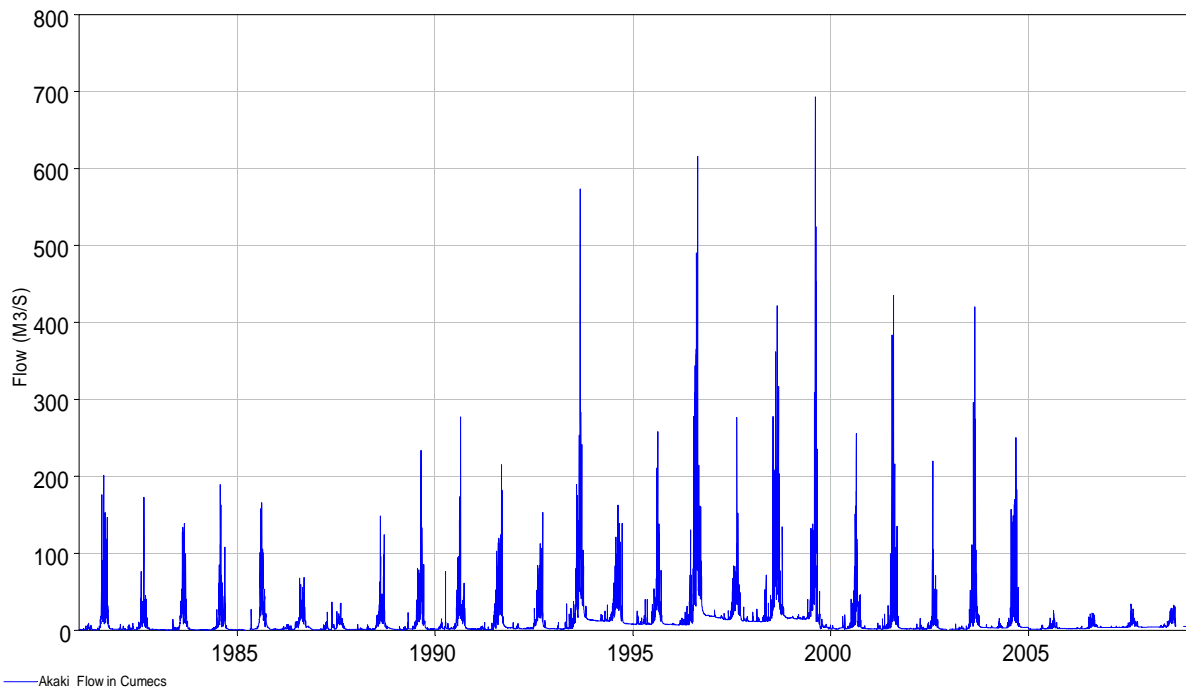
Appendix B.10 :Daily Flow Data at Melka Kunture River Gauging Station



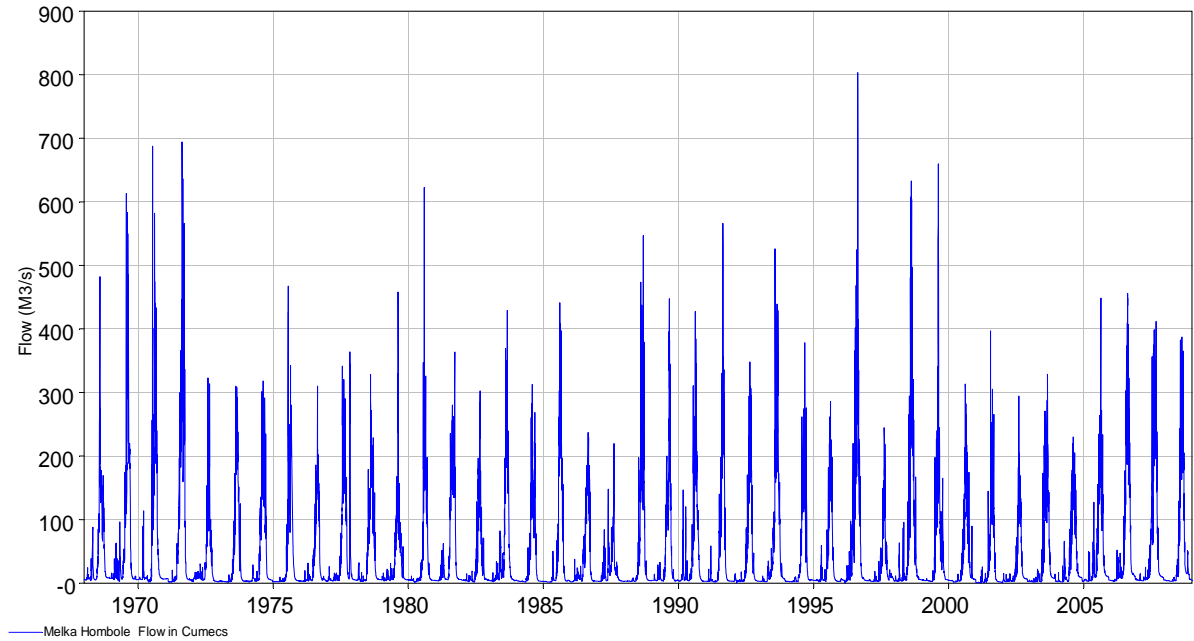
Appendix B.11: Daily Flow Data at Mojo River Gauging Station



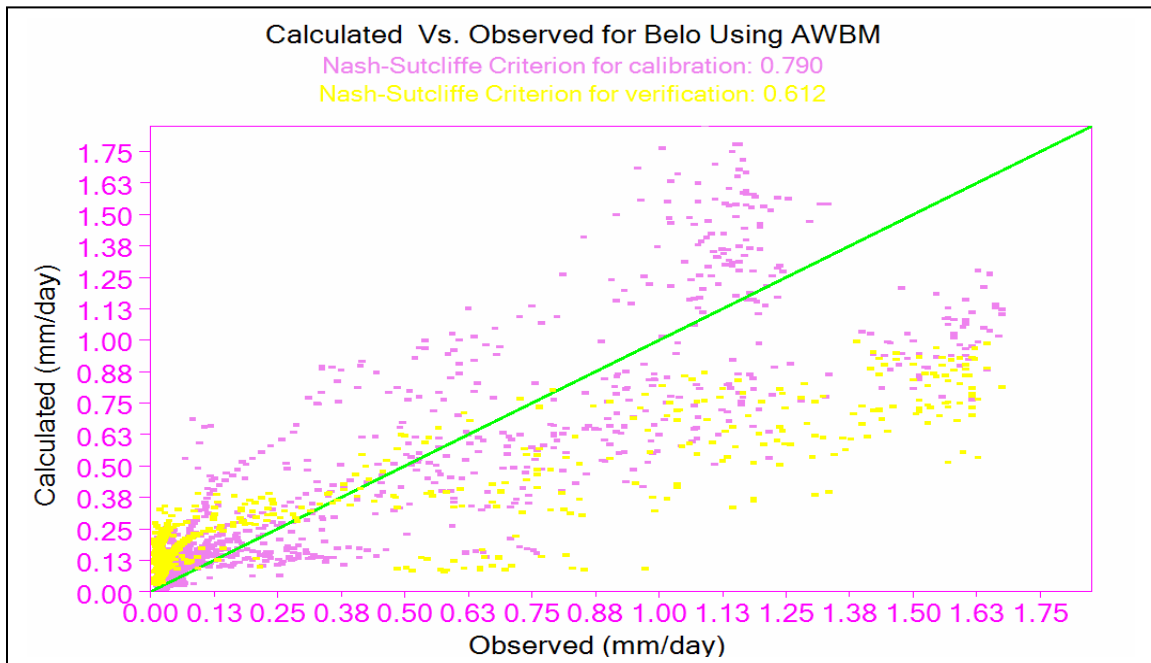
Appendix B.12 Daily Flow Data at Akaki River Gauging Station



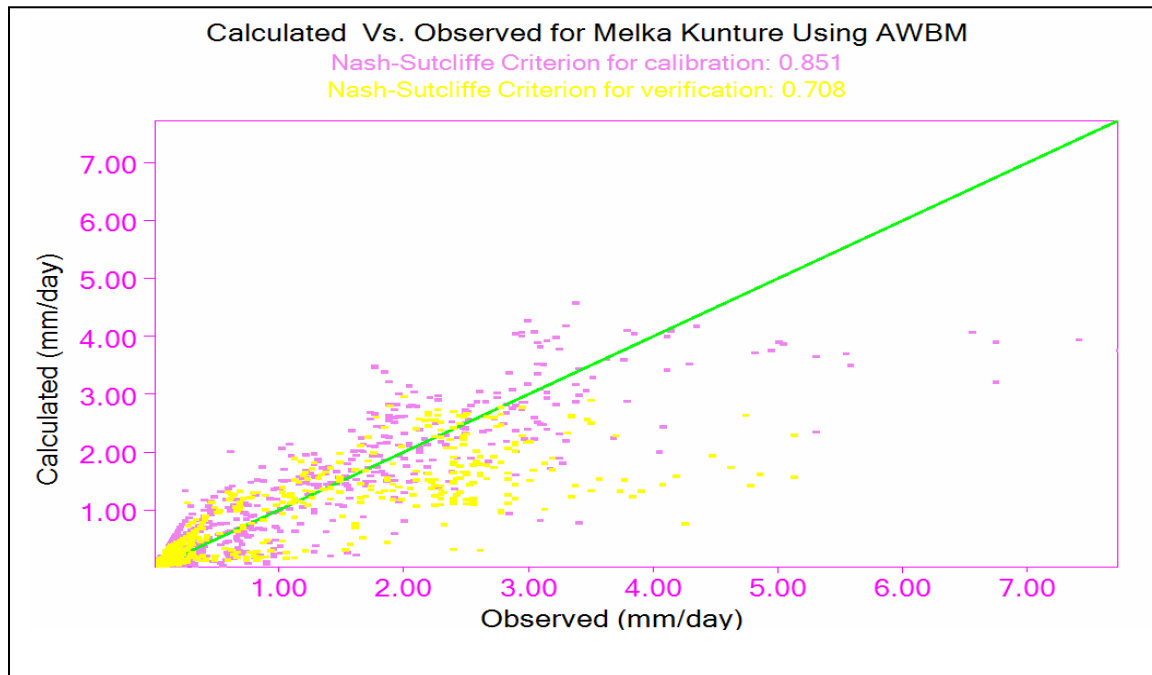
Appendix B.13 Daily Flow Data at Melka Hombole Gauging Station



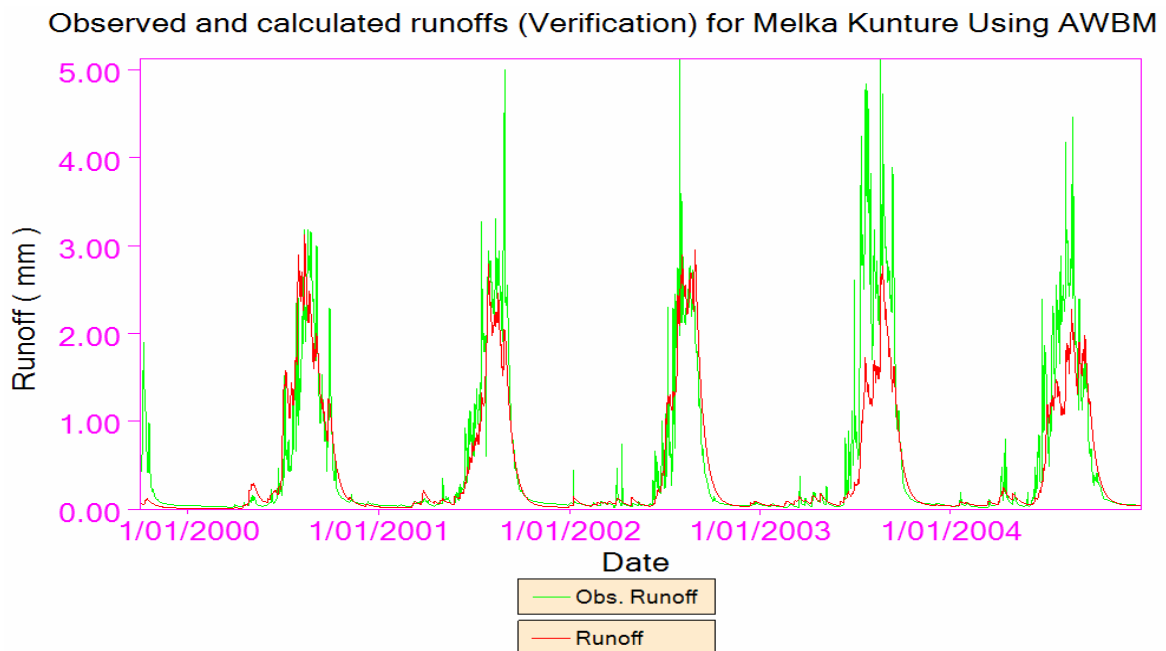
Appendix B.14: Calibration Results for Bello Catchment Using AWBM



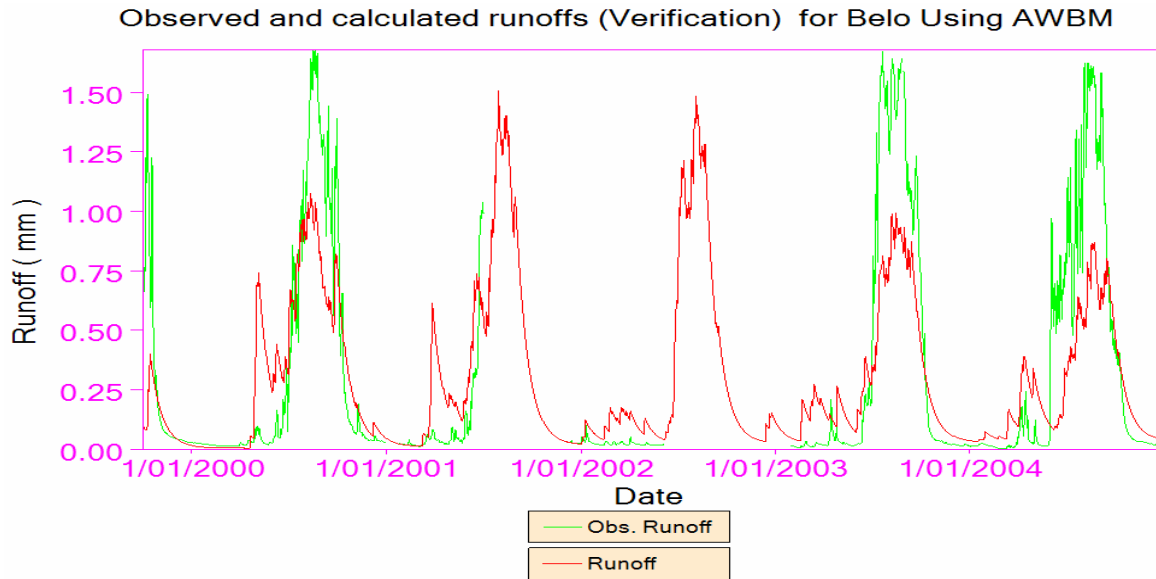
Appendix B.15: Calibration Results for Melka Kunture Catchment Using AWBM



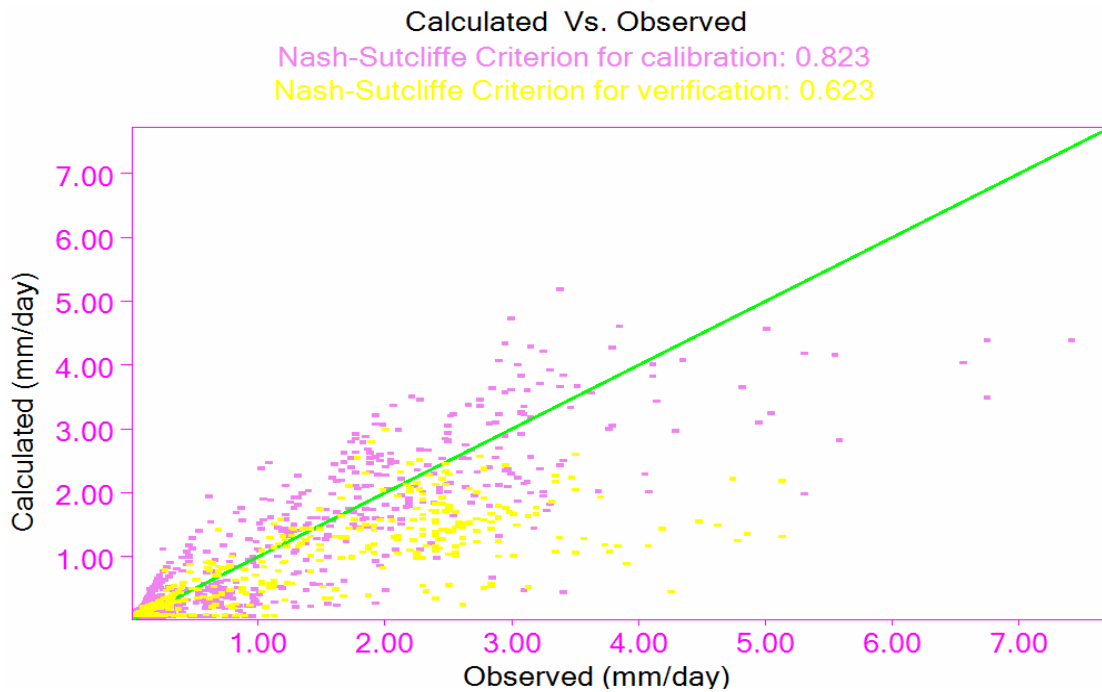
Appendix B.16: Simulated and Observed Flow for Melka Kunture Catchment (Verification Period) Using AWBM



Appendix B.17: Simulated and Observed Flow for Bello Catchment (Verification Period) Using AWBM



Appendix B.18: Calibration Results for Melka Kunture Catchment Using SMAR

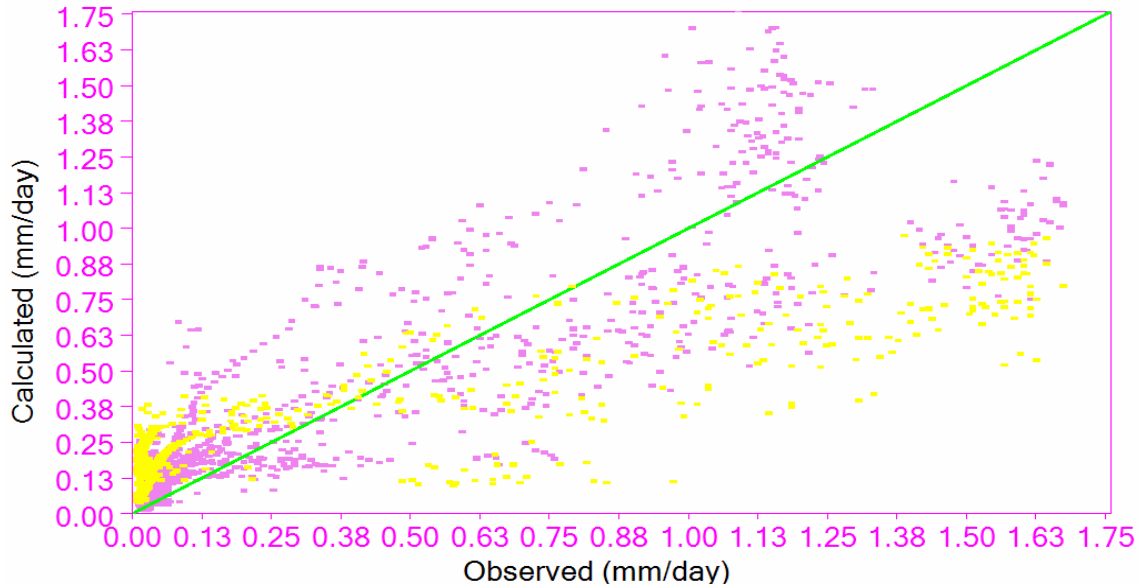


Appendix B.19: Calibration Results for Bello Catchment Using SMAR

Calculated Vs. Observed runoff for Bello Catchment Using SMAR Model

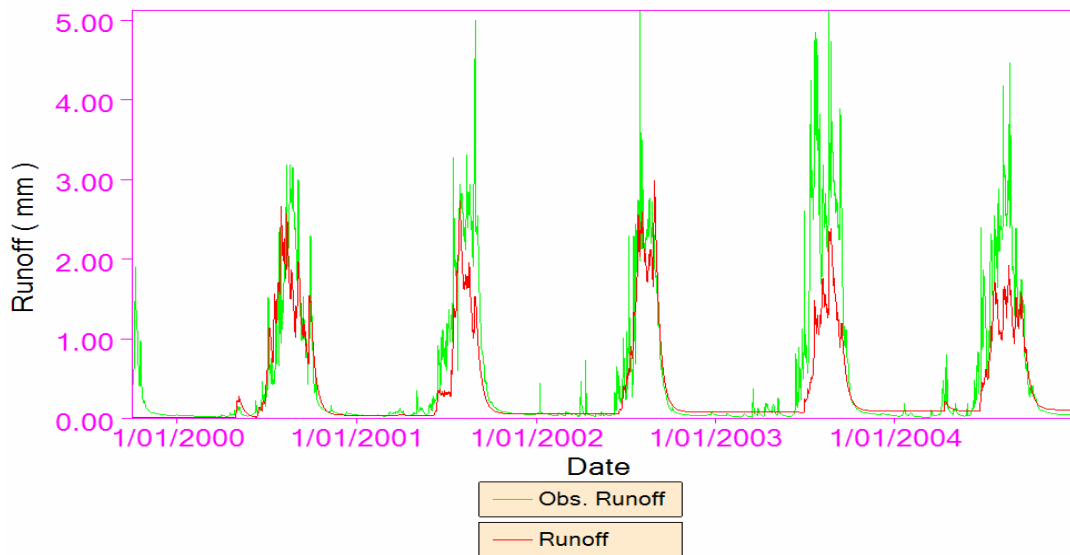
Nash-Sutcliffe Criterion for calibration: 0.793

Nash-Sutcliffe Criterion for verification: 0.603

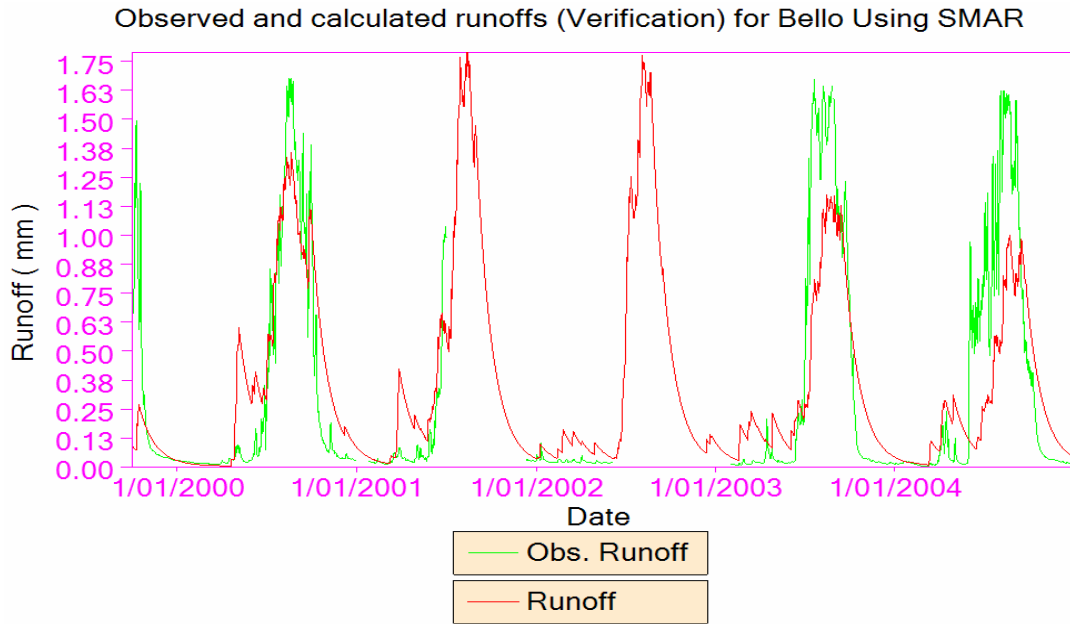


Appendix B.20: Simulated and Observed Flow for Melka Kunture Catchment (Verification Period) Using SMAR

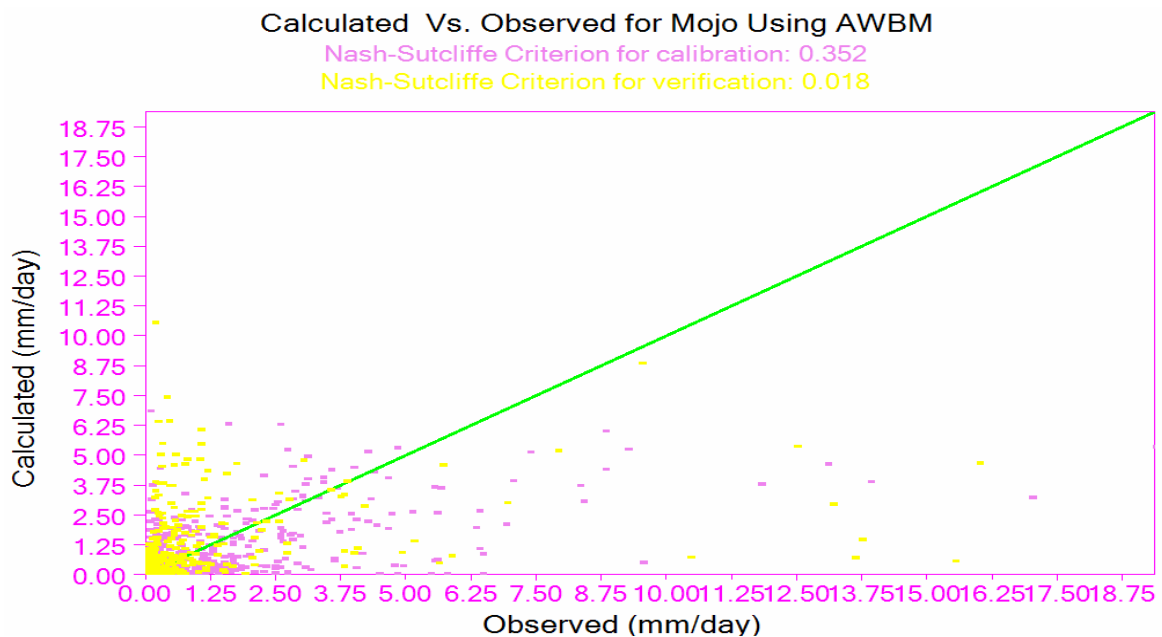
Observed and calculated runoffs (Verification) for Melka Kunture Using SMAR



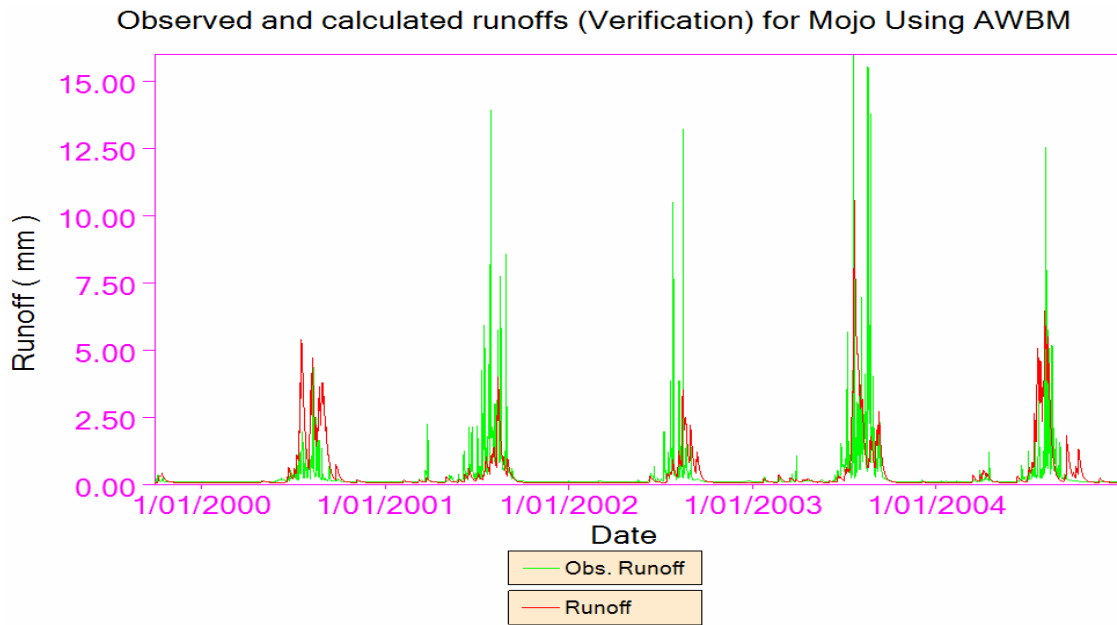
Appendix B.21: Simulated and Observed Flow Bello Catchment (Verification Period) Using SMAR



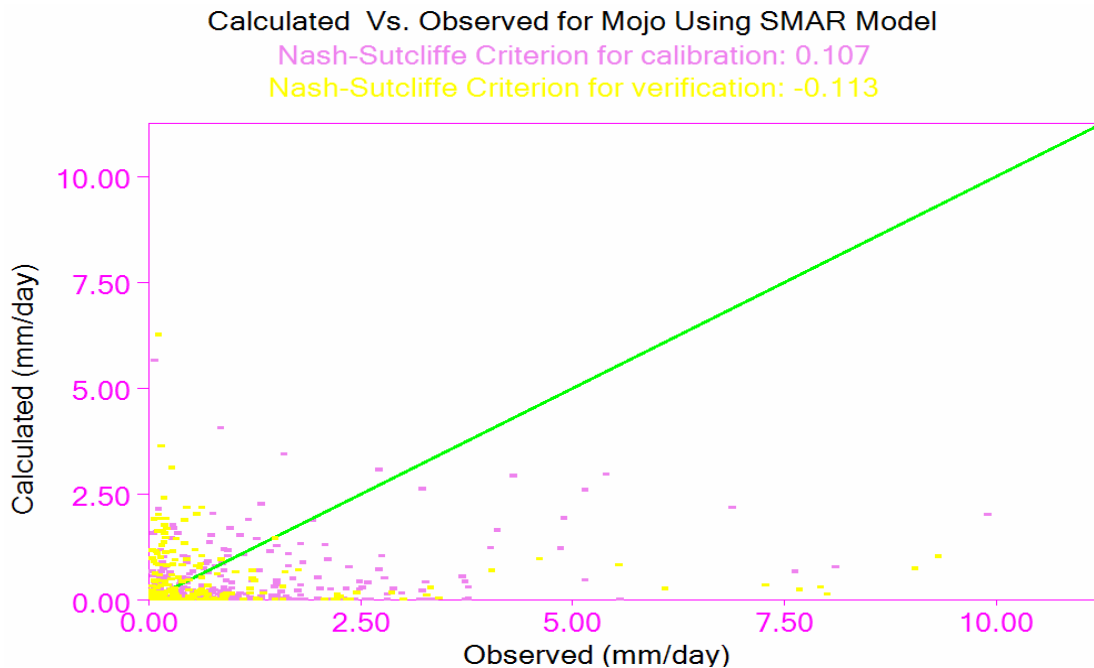
Appendix B.22: Calibration Results for Mojo Catchment Using AWBM



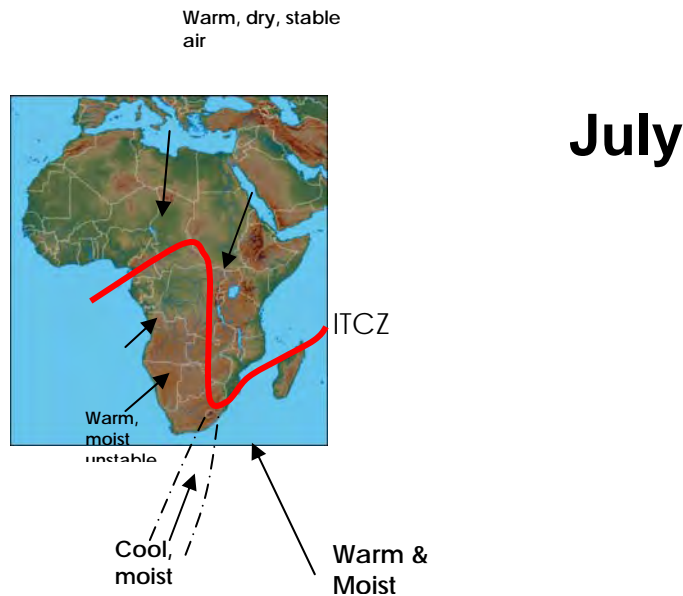
Appendix B.23 Simulated and observed flow Mojo Catchment (Verification Period) Using AWBM



Appendix B.24: Calibration Results for Mojo Catchment Using SMAR models



Appendix B.25: Inter Tropical Convergence Zone(ITCZ)



Inter Tropical Convergence Zone (ITCZ)

Appendix C: Overview of Catchment Modeling Toolkit and Rainfall Runoff Library

Appendix C.1:Modelling Platforms Available with Catchment Modeling Tool Kit

- **CHUTE** – a spreadsheet programme for the design of rock chutes. These are used in rivers and channels to stabilise erosion (similar to riprap).
- **MUSIC** – a decision support system for evaluating urban storm water design.
- **RAP** – models river condition and river restoration design.
- **RRL** – is the Rainfall Runoff Library that contains five different models that can be used to simulate runoff at a range of different scales.
- **SCL** – is a library of stochastic models for generating climatic data (e.g. rainfall and potential evapotranspiration) at a site.

- **SedNet**- constructs sediment budgets for river networks.
- **TIME** – is not a model as such but is a model development platform for creating and testing new models.
- **TREND** – a time series analysis package designed specifically for hydrological data.

Appendix C.2: Optimization Algorithms and Objective functions Available in Rainfall Runoff Library (RRL)

There are seven optimization algorithms available

- Genetic algorithm
- Uniform random sampling
- Pattern search
- Multi start pattern search
- Rosenbrock search
- Rosenbrock multi-start search
- Shuffled Complex Evolution (SCE-UA)

There are options of having both a primary and secondary objective function. Eight primary objective functions are available in RRL:

- Nash-Sutcliffe criterion (Coefficient of efficiency)
- Sum of square errors
- Root mean square error (RMSE)
- Root mean square difference about bias
- Absolute value of bias
- Sum of square roots
- Sum of square of the difference of square root
- Sum of absolute difference of the log

There are four secondary objective function options:

- None
- Runoff difference in %
- Flow duration curve
- Base flow method 2

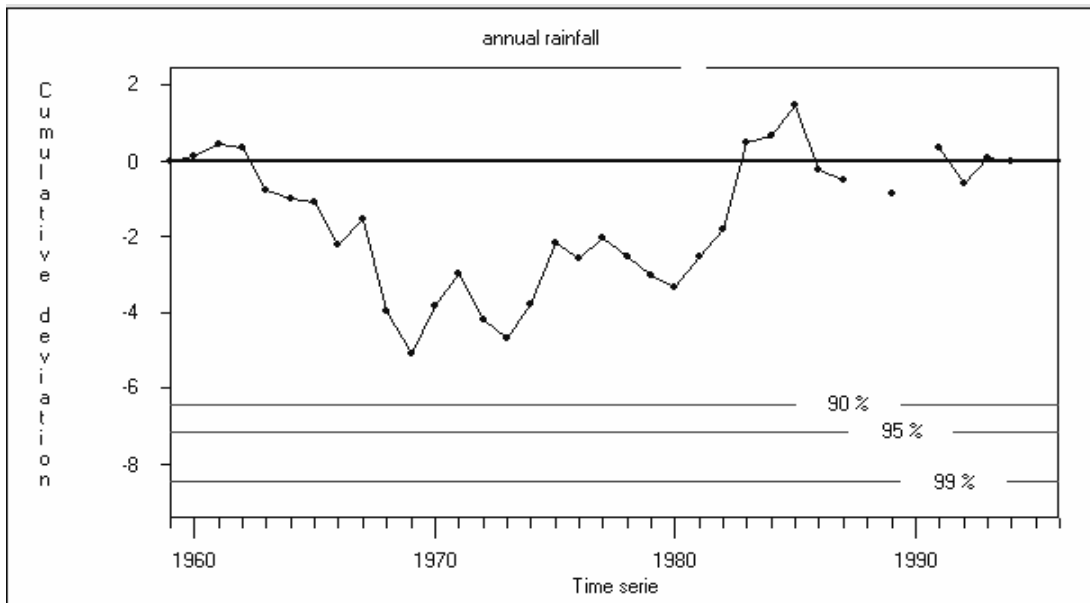
When using two objective functions, specified weightings are applied to each objective function and then these weighted functions are combined to create a single objective function that is used by the optimizer.

Appendix D: Overview of Rainbow22

The restriction of homogeneity assures that the observations are from the same population. One of the tests of homogeneity (Buishand, 1982) is based on the cumulative deviations from the mean:

$$S_k = \sum_{i=1}^k (X_i - \bar{X}) \quad k=1, \dots, n$$

where X_i are the records from the series X_1, X_2, \dots, X_n and \bar{X} the mean. The initial value of $S_k=0$ and last value $S_k=n$ are equal to zero (Figure below). When plotting the S_k 's (also called a residual mass curve) changes in the mean are easily detected. For a record X_i above normal the $S_k=i$ increases, while for a record below normal $S_k=i$ decreases. For a homogenous record one may expect that the S_k 's fluctuate around zero since there is no systematic pattern in the deviations of the X_i 's from their average value \bar{X} .



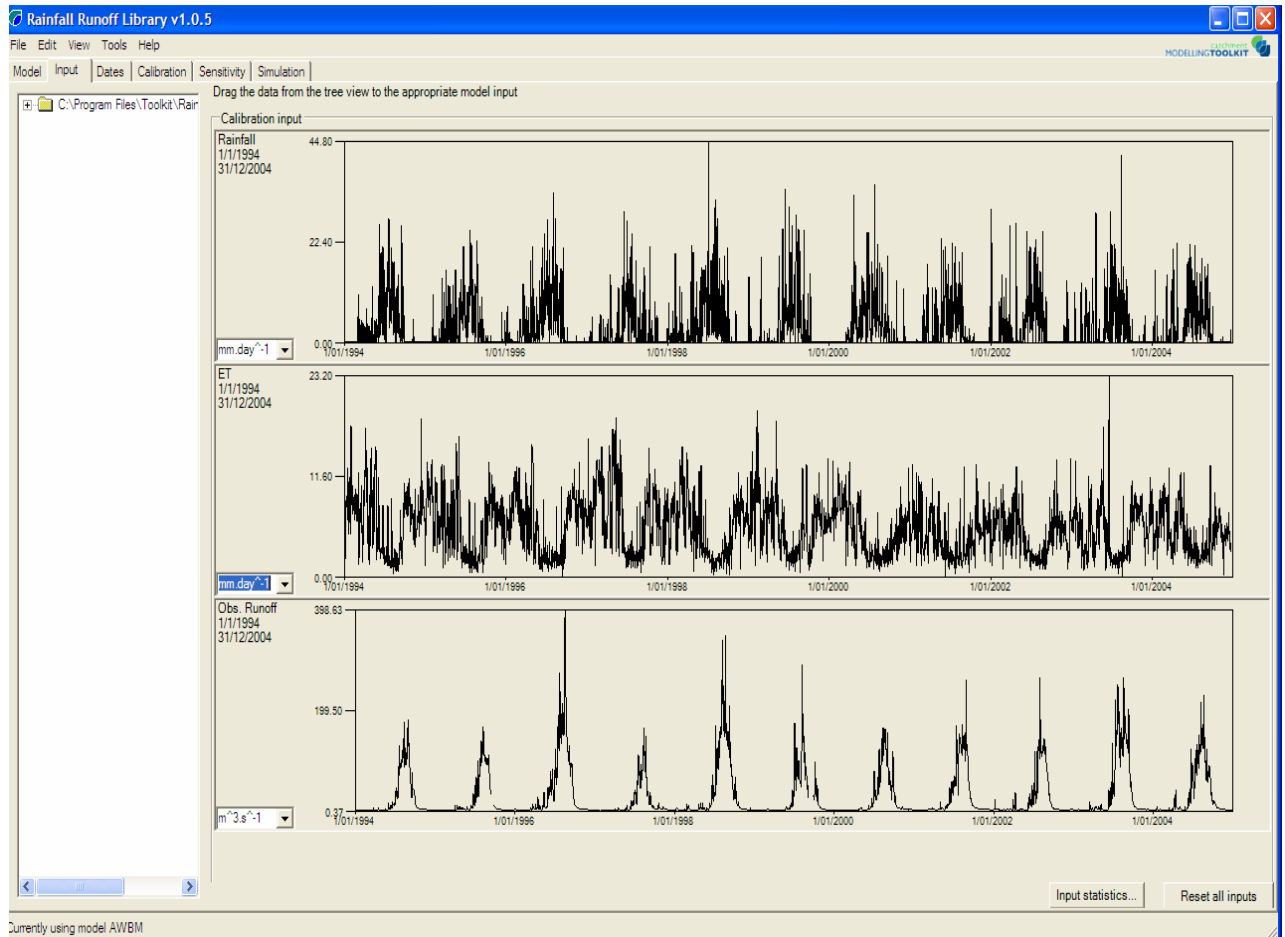
The above figure shows Rescaled cumulative deviations from the mean for the total annual rainfall (1960 – 1996). When the deviation crosses one of the horizontal lines the homogeneity of the data set is rejected with respectively 90, 95 and 99% probability.

To test the homogeneity of the data set, RAINBOW rescales the cumulative deviations by dividing the Sk 's by the sample standard deviation value. By evaluating the maximum (Q) and the range (R) of the rescaled cumulative deviations from the mean, the homogeneity of the data of a time series can be tested. High values of Q or R are an indication that the data of the time series is not from the same population and that the fluctuations are not purely random. Critical values for the test-statistic which test the significance of the departures from homogeneity are plotted as well (Figure above).

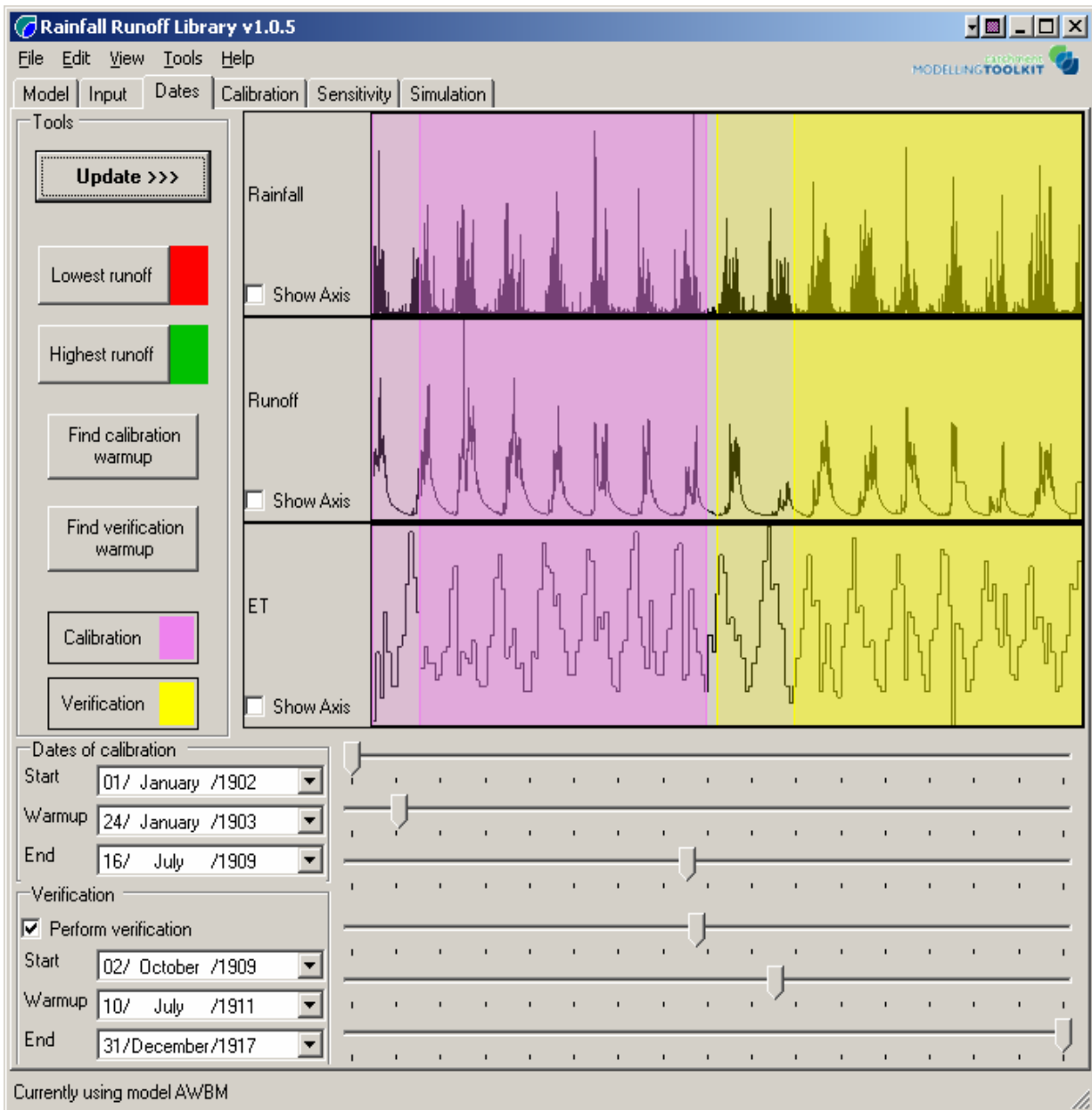
Appendix E: Evaporation Factors

Monthly	Jan	Feb	Mar	Apr	May	J	Jul	Aug	Sep	Oct	Nov	Dec
Factor	0.65	0.7	0.7	0.8	0.8	1.0	0.8	0.8	0.7	0.7	0.7	0.65

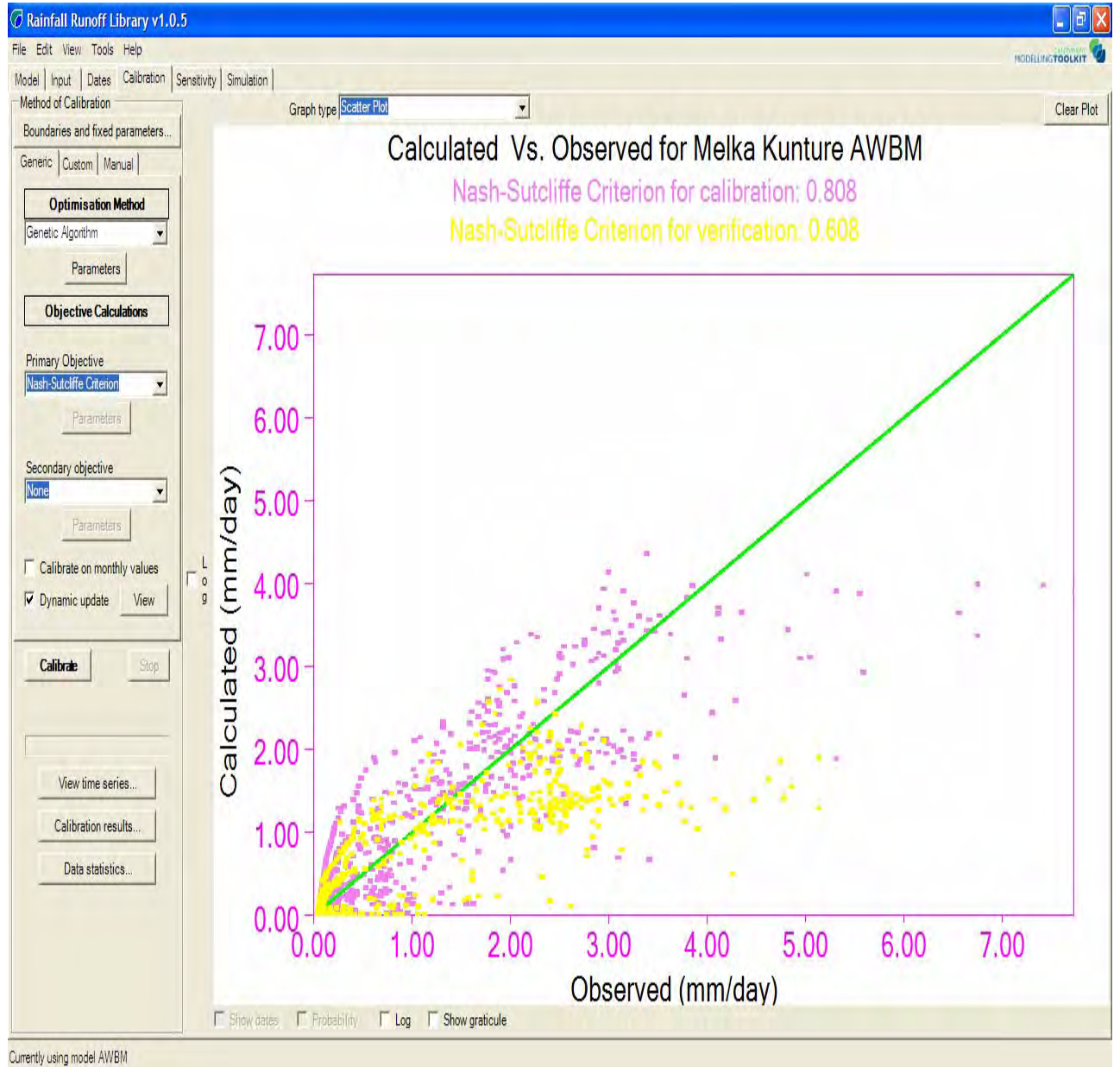
Appendix F: Input dialogue



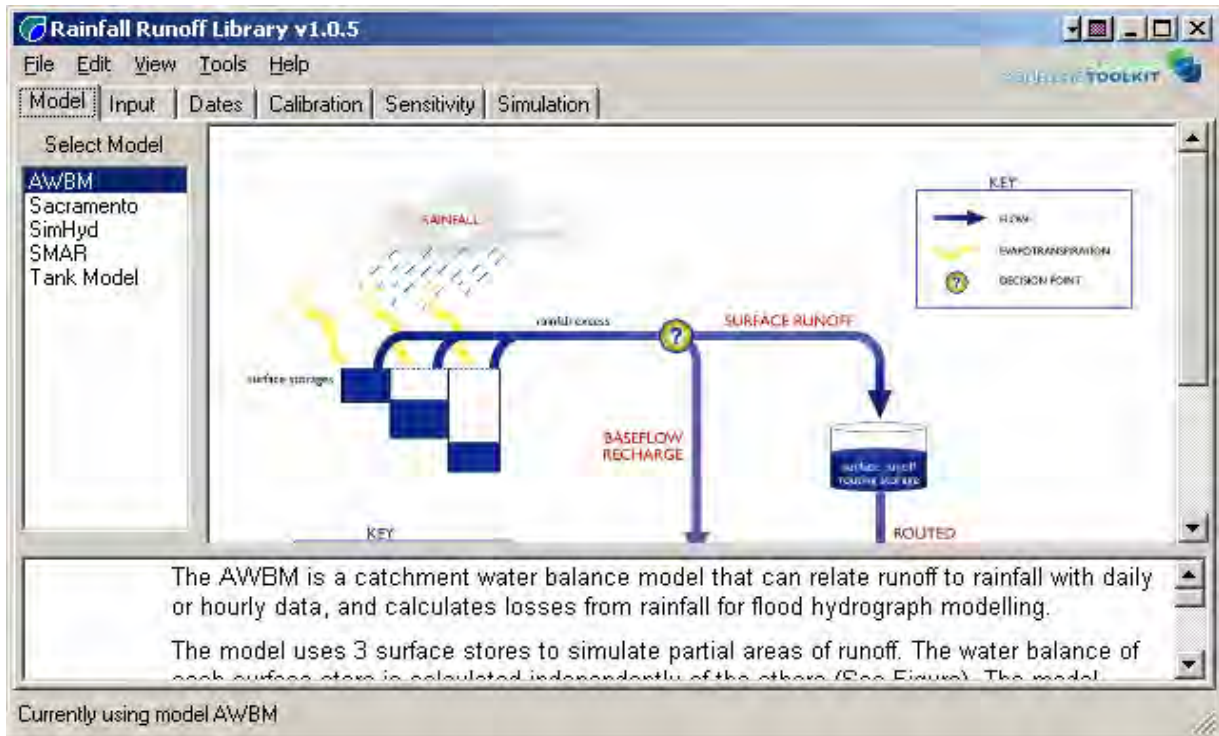
Appendix G: Dates dialogue



Appendix H: Calibration dialogue(Optimization and objective function selection dialogue)



Appendix I: Model dialogue



Appendix J: Sensitivity dialogue

