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School of Graduate Studies
Faculty of Technology
Department of Civil Engineering**

**STREAM FLOW SIMULATION FOR
THE UPPER AWASH BASIN**

Shimelis Behailu

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SHIMELIS BEHAILU

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Discription of Symbols

Description	Symbol
Actual evapotranspiration	E_a
area upstream of the watershed discharge point	A_{up}
Average basin slope	S_B
Average channel slope	S_c
Average channel width	B_c
Average depth	D
Average field capacity	F_{av}
Average hydrologic active soil depth	D_{SH}
Average Length of the tributaries to the main channel	L_T
Average minimum soil water content	θ_{min}
Average runoff along the channel length	Q_{ch}
Average saturation capacity	SC
Average Slope	Y
Average water holding capacity of the soils	η
Bank full streamflow	Q_{BF}
Base Flow	Q_B
Brooks Corey Coefficient	β
Bubbling pressure	Ψ_b
Change in base flow	$\Delta\theta_B$
Change in interflow	$\Delta\theta_I$
Change in the stream reservoir	$\Delta\zeta_\sigma$
Change in the upper soil zone water content	$\Delta\theta_u$
Coefficient four	C_4
Coefficient one	C_1
Coefficient three	C_3
Coefficient two	C_2
Content of the ground water reservoir	V_G
Content of the stream reservoir	V_S
Curve numbe	CN
Curve number in the static file	CN_S
Depth of flow	D_F
Depth of soil	D_S
Direct Surface runoff	Q_S
Dry conditions	dc
Effective percentage of the watershed impervious	ξ

Excess precipitation	P_{ex}
Excess soil water	θ_{ex}
Field capacity of the soil zone	F
Ground water lag time coefficient	χ_{Γ}
Hydraulic Length of watershed	L
Initial water content in the lower root zone	θ_{lrz}
Input evapotranspiration data from the metrological data	E
Instream streamflow at the inlet	Q_{sin}
Interflow	Q_I
Interflow lag time coefficient	χ_I
Lag factor	LF
Lower soil zone water content	θ_l
Main channel length	CL
Maximum Retention in the watershed	S_S
Minimum soil water content of the soil layer	θ_{min}
Muskingum proportionality coefficient	K
Muskingum time step	Δt
Muskingum weighing coefficient	X
Overland flow lag coefficient	χ_o
Percentage of the soil depth in the upper soil zone	ζ_u
Percentage of the total soil zone depth in lower zone	ζ_l
Pore-size index	λ
Potential evapotranspiration	ξ
Precipitation	P
Roughness coefficient	n
Routing time steps	Δ
Saturation capacity	DT
Saturation soil hydraulic conductivity	K_{sat}
Saturation soil water content	θ
Soil hydraulic conductivity	k
Soil sorptivity	ϕ
Soil water content in the lower soil zone	θ
Soil water contour	Γ
Space step	ΔX
Streamflow	Q_S
Streamflow at the outlet	Q_s^{out}
Streamflow halfway down the channel	Q_s^{mid}
Streamflow into the basin	Q_s^{in}
Suction	Ψ

Surface runoff	Q_{sr}
Surface Storage	V_s
The potential transpiration from the lower soil zone	ξ_λ
Time step	Δt
Time step in seconds	$\Delta \tau_\sigma$
Total runoff	Q_T
Transpiration from lower soil zone	TR
Upper soil zone water content	θ
Watershed area	A
Wave celerity	c
Wet condition	wc

Abstract

The Awash Basin is the most utilized and most developed basin in Ethiopia. After the construction of the Koka dam the feature of the basin is changed in large extent. Heavy rainfall in the upstream catchments causes large inflow discharges to Koka Lake. At times where the water level is already close to the maximum water level, the excess water must be discharged through the spillways in order to prevent overtopping of the dam. The discharge through the spillway, together with the water discharged through the power plant turbines, has in the past caused flooding in the downstream areas, most notably in August 1996. To prevent the downstream areas from flooding, the water level in the lake could be lowered in advance provided the inflows could be forecasted.

For this reason, the FEWS-SFM was calibrated for the Upper Awash Basin using five years (1991-1995) of stream flow and rainfall records. The model was verified using another five years data (1996-2000). Ground observed data were used for the calibration for both the physical characteristics of the basin and the dynamic inputs: rainfall and potential evapotranspiration.

Simulation was done in three scenarios of defining the basin. First the basin is defined to have a single outlet at Melka Hombole hydrologic station. The second scenario divided the basin into six subbasins and the last scenario is made by dividing the catchment to thirty five subbasins. It is seen that the second scenario represented the rainfall runoff to an acceptable range both visually and statistically. The Nash and Sutcliff goodness of criteria (R^2) was used for testing the model performance. $R^2 = 0.63$ was obtained for the calibration and the verification yield $R^2 = 0.6$.

The simulation of the basin has underestimated the peak summer (July – August) and overestimated flow from March to June. The dry period flow is underestimated. However, further refinement of the DEM and investigation on the DEM and investigation on the way soil properties influencing the rainfall runoff process in the model may improve the model main rainy period flow and overestimation of the small rainfall period. From the results obtained further investigation on the way soil properties influencing the rainfall runoff process in the model is necessary.

Key words: Awash, calibration, DEM, FEWS-SFM, flood, Koka, rainfall runoff, simulation, verification.

INTRODUCTION

Problem Statement

Stream flow models are mathematical representations of a given watershed that replicate the natural hydrologic process to a pre set degree of acceptance. The importance of models lie on their capability to predict the extreme events: low flow or flood. Owing to its adverse effect, flood is the major concern in many of rainfall runoff models.

The potential flood hazard is obviously the result of a potential water resource that needs to be developed. Proper management to use the excess flow will be an enormous input for the dependable supply of water for various water resource projects in a basin. Models, therefore, will be a great tool both in predicting the amount of excess water leading to flooding as well as manage the shortage in case of drought.

The Awash basin is the most intensively utilized basin in Ethiopia. Extensive irrigation schemes have been functional for many years following the construction of the main structure, Koka dam in 1960. Now the reservoir is constantly filling up with sediment and has lost more than 30% of its water storage capacity. Due to this continuing reduction in capacity, the water management of the reservoir is becoming exceedingly difficult.

The basin has, therefore, faced recurrent flooding resulting from the water spilled downstream of the Koka reservoir that has caused huge destruction. Catastrophes, like the one in 1996, led to loss of life and heavy property damage in the downstream areas of Koka reservoir. The population density and the large amount of investment committed in the basin demands for a detailed flood warning and mitigation study. On the contrary, at the end of the dry season not enough water remains in the reservoir to meet the demand for power production, leading to power rationing and also rationing of water for the large irrigation farms downstream.

The Ministry of Water Resources Hydrologic Department uses radio communication with the Melka Hombole hydrologic station in July and August. The record made every three hours is routed to downstream reach. Based on the time the flow takes to arrive at the various sites warnings is being issued. There is no reliable forecasting model to do such analysis or use forecasted rainfall to obtain the stream flow in the Department. FEWS-

SFM was designed to produce a three days forecast for a forecasted rainfall and potential evapotranspiration.

Taking such events continent wise (3), the USGS/Earth Resources Observation Systems (EROS) Data Center in support of the Famine Early Warning System Network (FEWS NET), has undertaken efforts to enhance flood preparedness in the Southern Africa and Greater Horn of African countries. A stream flow model, Famine Early Warning System Stream Flow Model (FEWS-SFM), was developed by the USGS.

Objective

The general objective of this thesis is to evaluate whether the rainfall runoff pattern of the Awash basin could acceptably be simulated by the FEWS-SFM model.

The specific objectives of this thesis are, therefore,

- To calibrate the model with digitized inputs and historical observed meteorological data,
- To verify the model for observed data set.

Thesis Outline

This thesis documents the concepts, data requirements, data processing procedures, development and application of the FEWS-SFM for the upper awash basin. The first section of this thesis discusses the general condition of the basin as described in the latest Surface Water Master Plan Study of the Basin(1). This section also details the recent flood damages occurred in the basin and the loss both in human life and property.

Section two of the thesis gives a review about Rainfall Runoff process and modeling approach. The modeling approach of the rainfall runoff process is presented component wise, and discussion.

The detail description of the FEWS-SFM model is presented in section three. This includes the general concept, mathematical equations, and merits and demerits of the model.

Section four is devoted to the data requirement and data development for the model. Detailed information about the various data processing schemes is also discussed.

Section five provides the model calibration and verification process and the various techniques used to assess the model. The results of these were discussed in the sixth section. Conclusions and recommendations were drawn in the seventh section of the thesis.

1. The Awash Basin

1.1 Location and Accessibility

The Awash basin is part of the Great Rift Valley in Ethiopia located from 8.5⁰ N to 12⁰N. It covers a total area of 110 000 km² of which 64 000 km² comprises the Western Catchment, drains to the main river or its tributaries. The remaining 46 000 km², most of which comprises the so called Eastern Catchment, drains into a desert area and does not contribute to the main river course.

The Awash Basin has been traditionally divided into four distinct zones. These are; Upper Basin, Upper Valley, Middle Valley and Lower Valley.

Table 1-1 Division of the Awash Basin

Designation	From	To
Upper Basin	Headwaters	Koka Dam
Upper Valley	Koka Dam	Awash station
Middle Valley	Awash station	Gewane (d/s)
Lower Valley	Gewane (d/s)	Lake Abe

Source: Halcrow, 1989

The Awash Basin covers the central and northern part of the rift valley and is bounded to the west, southeast and south by the Blue Nile, the Rift Lakes and the Wabi Shebele Basins respectively. The main highway from Addis Ababa to Assab traverses the entire length of the Awash Valley. The other highway runs upto Awash where it continues eastward to Dire Dawa and further across the Wabi Shebele watershed to Harar and on to Jijiga. An alternative route linking with the Assab road at Mile, runs along the western escarpment from Addis Ababa, serving the larger industrial centers of Kombolcha and Desse. Furthermore, the main railway links Addis Ababa and the port of Djibouti.

1.2 Physiography and Geology

The topography of the Ethiopian Plateau is generally flat with elevations ranging generally from 2,500 m down to 2,000 m. The lowest elevation of the plateau, or uplands, is commonly considered to be at 1,500m. Geologically, the plateau comprises the denuded surface of Precambrian basement rocks on which lies the near horizontal

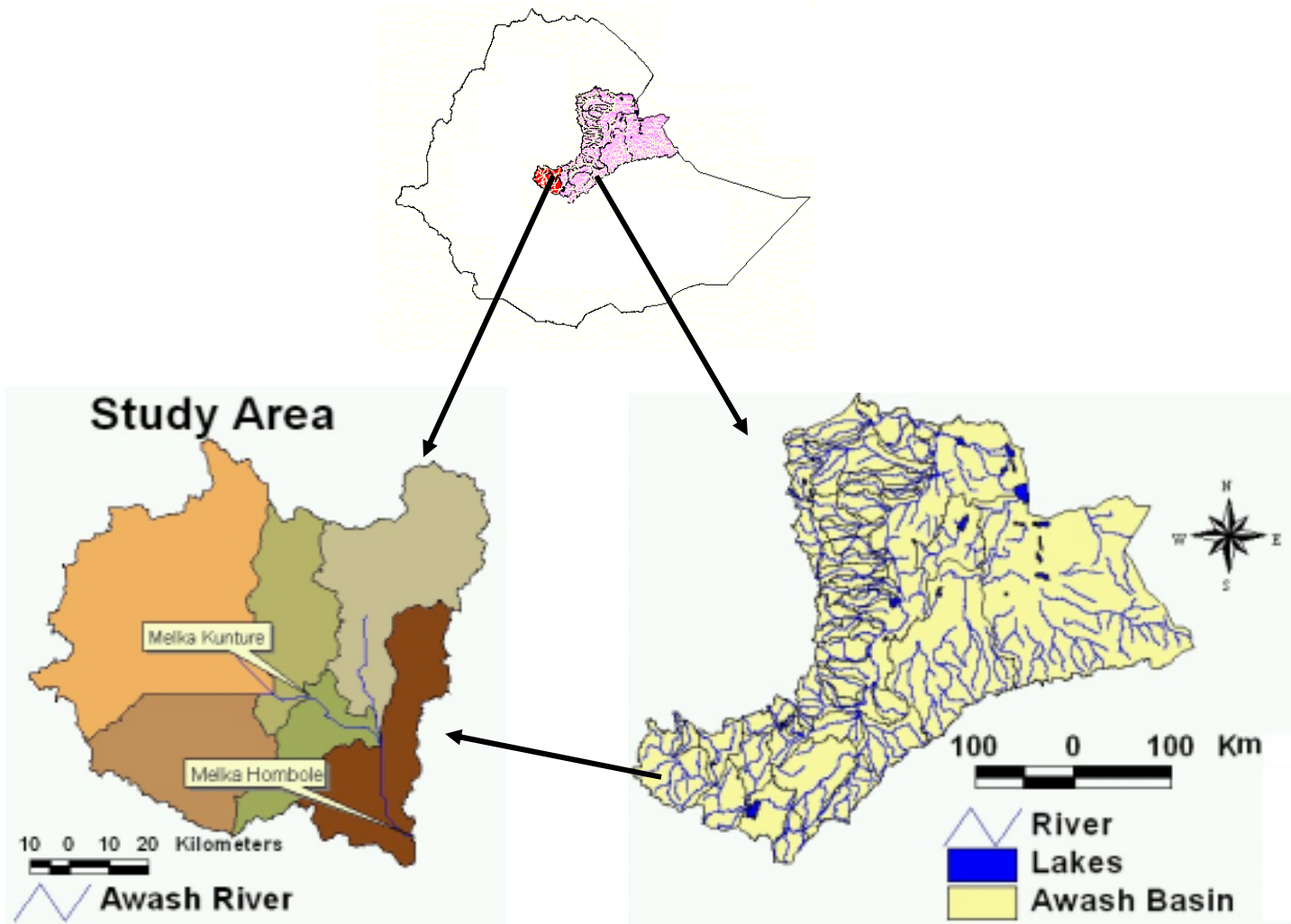


Figure 1-1 Awash Basin and The Study Area

Mesozoic sediments, covered in turn by the Tertiary flood basalt extrusions. Exceptions on this flat plateau area are the deeply incised river valleys and the volcanic masses, the latter rising to over 3,000m.

A series of fault scarps leads from the plateau to the floor of the Rift Valley which slopes north-east from the elevation of nearly 2 000 m at Lake Ziway to less than 400 m where it becomes the Afar Triangle. The flat floor of the Rift Valley is frequently broken by fault scarps and the effects of Pleistocene and Holocene volcanic activity. On the south-eastern side of the valley fault steps lead to the Ogaden Plateau. This slopes south east, draining towards the Indian Ocean and for that reason the Awash receives most of its tributaries from the western, Ethiopian Plateau, side(1).

1.3 Climate

The climate of the Awash Basin comes under the influence of the Inter-Tropical Convergence Zone (ITCZ) This zone of low pressure marks the convergence of dry tropical easterlies and the moist equatorial westerlies. The seasonal rainfall distribution within the basin results from the annual migration of the ITCZ. In March the ITCZ advances across the Basin from the south, bringing the small or spring rains. In June and July it reaches its most northerly location beyond the Basin which then experiences the heavy or summer rains. It then returns southwards during August to October, restoring the drier easterly airstreams which prevails until the cycle repeats itself in March(1).

The annual rainfall distribution resulting from this cycle is exhibited most clearly in the two distinct rainy periods which are characteristic of the northern plains of the basin. Moving southwards the more prolonged exposure to the moist air-stream is evident in the tendency for the two dominant rainy periods to merge into a more contiguous distribution. On the high plateau to the west of Addis Ababa the rainfall distribution shows a continuous increase from the spring rains to the summer peak rainfall. The distribution of rainfall over the highland areas is modified by orographic effects and is significantly correlated with altitude.

The mean annual rainfall varies from about 1 600 mm at Ankober, in the highlands north east of Addis Ababa to 160 mm at Asayita on the northern limit of the Basin. Addis

Ababa receives 90% of its annual rainfall during the rainy period March to September. At Dubti the same overall proportion is received during the two rainy periods, distributed 30% and 60% respectively. The mean annual rainfall over the entire Western Catchment is 850 mm and over the headwaters of the Awash, as gauged at Melka Hombole it is 1 216 mm. Over the Eastern Catchment the mean annual rainfall is estimated to be 456 mm. The annual and monthly rainfalls are characterized by high variability.

Potential evapotranspiration (PET) is also significantly correlated with altitude. At Wonji, in the Upper Valley, the mean annual PET is 1 810 mm, over twice the mean annual rainfall, with average monthly rainfall exceeding average monthly evapotranspiration only in July and August. At Dubti, in the Lower valley the mean annual PET is 2 348 mm which is over ten times the mean annual rainfall.

Mean annual temperatures range from 20.8 °C at Koka to 29 °C at Dubti, with the highest mean monthly temperatures at these stations occurring in June, at 23.8 °C and 33.6 °C respectively.

Mean annual wind speeds at Koka averages 1.2 m/s, the windiest months being June and July with mean monthly values of 1.9 and 1.6 m/s respectively. At Amibara the mean monthly wind speed values in June and July are over 2 m/s.

1.4 Surface Water Resources

The Awash river rises on the high plateau to the west of Addis Ababa, at an altitude of about 2 500 m. It then flows eastwards, through the Becho Plains area and is joined by several small tributaries before entering Koka reservoir, created by a dam, commissioned in 1960. At the outlet to Koka the total catchment area is some 11 500 km². The Awash then descends into the Rift Valley and flows north-eastwards to Awash Station, being joined by smaller tributaries draining from the eastern section of the watershed. Beyond Awash Station the river trends northwards receiving contributions from a number of sub-catchments from the western escarpments, most notably the Kesem and Kebena. The large expanse of catchment to the east of the river, accounting for some 40% of the total Basin area, does not contribute any surface runoff to the river. This area, of some 47 000

km² extent, known as the Eastern Catchment, loses all runoff into the vast expanse of desert plains which stretches from the escarpment northwards to the terminal lakes.

The main river channel passes adjacent to the Gedebassa swamp in a low flow channel with the main river floods passing into the swamp and partially returning, attenuated and reduced in amount, into the river channel downstream, which has a much reduced capacity. The main contributing sub-catchments in the lower part of the river are the Mile and Logiya rivers. After this the Awash turns abruptly eastwards and flows through a series of fresh water lakes, terminating in the salt Lake Abe, at an elevation of 250 m. The total length of the main river course is some 1 200 km.

The mean annual runoff into Koka reservoir amounts to some 1 660 Mm³. About 90% of this runoff occurs in the period July to October. This decreases to 1 390 Mm³ at Awash Station being depleted largely by losses from Koka and by Upper Valley irrigation diversions. Immediately upstream of Gedebassa Swamp, the mean annual flow is around 2 300 Mm³, given the level of irrigation abstraction. The mean annual flow is around 2 200 Mm³ at Tendaho. At Tendaho some 75%-80% of the mean annual runoff arrives during the periods March to May and July to October(1).

The total mean annual water resource of the Awash Basin amounts to some 4 900 Mm³ of which some 3 850 Mm³ is utilisable, the balance being largely lost to Gedebassa Swamp and elsewhere in the river system. This equates to a runoff coefficient of approximately 15 % from the Upper Basin.

The total area of the Western Catchment is 63 850 km² and the Eastern Catchment is 47 360 km². Within the Western Catchment there are a series of hydrologically closed basins which total some 5 050 km².

1.5 Recent Flooding Problem

The Awash basin and the flooding danger have become inseparable in hand for the past decade. Huge amounts destruction occurred in 1993 and 1996 resulting from the water spilled downstream of the Koka reservoir that caused huge destruction. According to the Ethiopian Disaster Prevention and Preparedness Commission (DPPC) estimation the number of people affected at different flooding events is shown in Table 1-2.

Table 1-2 Flood events at the Awash Basin and the estimated damage.

Zone/Wereda	Flood period	Remarks
Afambo,	1993	144,400
Dupti,	1994	154,900
Assaita	1995	145,700 people were affected.
Bure-Mudiatu,	1993	-
Gewanie	1994	-
	1995	-
	1996	Over 75,000 people were affected.
Dullecha, Amibara	1996	Over 47.56 m. Eth. Birr damage and expenditure.

In August 1996 a flood affecting (2) between 44000 and 58000 people occurred. At the Wonji Sugar Plantation alone (10km downstream of Koka Dam) the flood affected about 44000 people and caused the damage shown in Table 1-3

Table 1-3 Damages occurred at Wonji Sugar Plantation in 1996

Amount and type of damaged objects	Damage Extent	Cost of Damage (Birr)
339 living houses	Completely destroyed	10 862 000
1771 living houses	Partly destroyed or severely damaged	12 793 000
885 living houses	Damaged	2 615 000
Office materials	damaged	611 0000
1242 ha of land	Completely destroyed	3 577 000
Sugar and other sweets stored in the warehouse	Dissolved or destroyed	7 193 000
Other properties	Taken by flood	2 193 000
Dykes, roads irrigation canals, furrows	Damaged	7 351 000

All in all, a damage of 47 195 000 Birr occurred at the sugar plantation. Additionally, the damaged or destroyed private property of dwellers living in this area amounts to 2 500 000 Birr.

In the Upper Awash Agro Industry 761 employees were displaced. Houses, irrigation canals, and roads were also damaged. The reconstruction cost was 2 682 000 Birr, and an income of 237 000 Birr was lost.

At the Metehara Sugar Factory a dyke was broken and 1 200 ha of the plantation was flooded. However, only 50 ha of sugarcane that was recently planted were damaged. Several employees were displaced but no further damage was caused.

The “Middle Awash Valley Plantation” was not damaged; only minor deficits in income occurred due to postponements caused by the floods minor deficits in income occurred.

Summarized, the total damage caused by flooding in 1996 amounts to 52 578 000 Birr.

Additionally the health situation becomes an issue of concern once the water level regresses. Stagnant water and little lakes left behind in the crop field by the retiring flood become perfect breeding grounds for mosquitoes and are also a source of other diseases of which dysentery is the most frequent.

Flood damages further downstream along the Awash River, namely in the Afar Region, were not taken into account here, as the damage caused there can not be directly related to the release of water from Koka Reservoir. Tributaries to Awash River such as Kessem, Kebena, Hawadi, Ataya Jara, Mille and Logiya rivers which join the Awash downstream of koka reservoir contribute most to the lowland flooding in Afar.

In 1999 sections of the Awash River with village and agricultural plantations were affected by inundation in the Afar Region. Approximately 9 500 ha of cropped farmland were damaged and the estimation of people affected ranges between 3000 and 50000. Nevertheless that year no flood damage occurred in the upper reaches of the Awash towards the Koka Dam. It was unanimously agreed among experts, government officials and local farmers that the causes of flooding cannot be attributed to the partial release of water from the Koka Reservoir Upstream.

2. Review of Rainfall Runoff Process and Models

2.1 General

Hydrology (7) is concerned with study of the motion of the earth's waters through the hydrologic cycle, and the transport of constituents such as sediment and pollutants in the water as it flows. A hydrological model is a simplified simulation of the complex hydrological system.

Modeling (9) is one field of scientific activity which has developed the capability of delivering customized solutions through identifying a variety of arrangements or changes within a system to comply with both external and internal highly developed mathematical capabilities and versatile software tools.

The rainfall runoff process is a component of the hydrologic system; therefore, it is a valid approach to develop either 'detailed models' serving a wide range of modeling requirement, or "parsimonious models" meeting a specific requirement. Since rainfall data is generally in abundance in comparison to runoff data, the attempt has always been to convert rainfall to runoff.

2.2 Model Classification

Watershed models are generally classified according to the method they use to describe the hydrologic processes, the spatial and temporal scales for which they are designed, and any specific conditions or intended use for which they are designed, (18).

The model processes include all the hydrologic processes that contribute to the system output. Based on the description of those processes, in conjunction with the system characteristics, the models can be described as lumped or distributed, deterministic or stochastic or mixed. Lumped or lumped-parameter models treat an entire watershed as one unit and take no account of the spatial variability in processes, input, boundary conditions, or the hydrologic properties of the watershed. In contrast, distributed models ideally account for all spatial variability in the watershed explicitly by solving the governing equations, for instance, for each pixel in a grid. The description of the hydrologic processes within a watershed model can be deterministic, stochastic, or some

combination of the two. Deterministic models are models in which no random variables are used, i.e. for each unique set of input data the model will compute fixed, repeatable results. The governing equations describing the hydrologic and soil erosion processes in a deterministic model should be a major factor in selecting a model. Models with equations based on fundamental principles of physics or robust empirical methods are the most widely used in computing surface runoff and sediment yield. Stochastic models, in contrast, use distributions for each variable to generate random values for model input. As a result, the output from a stochastic model is itself random, with its own distribution, and can thus be presented as a range of values with confidence limits. Fully stochastic models, in which all components of the model are stochastic, are virtually non-existent.

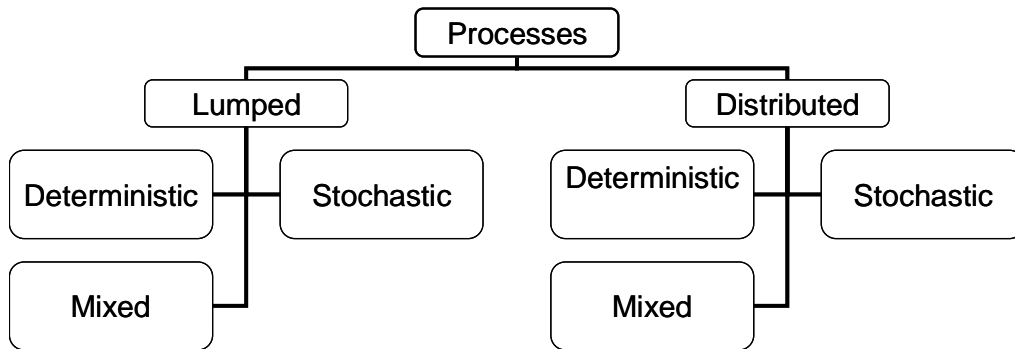


Figure 2-1 Classification of models based on process description

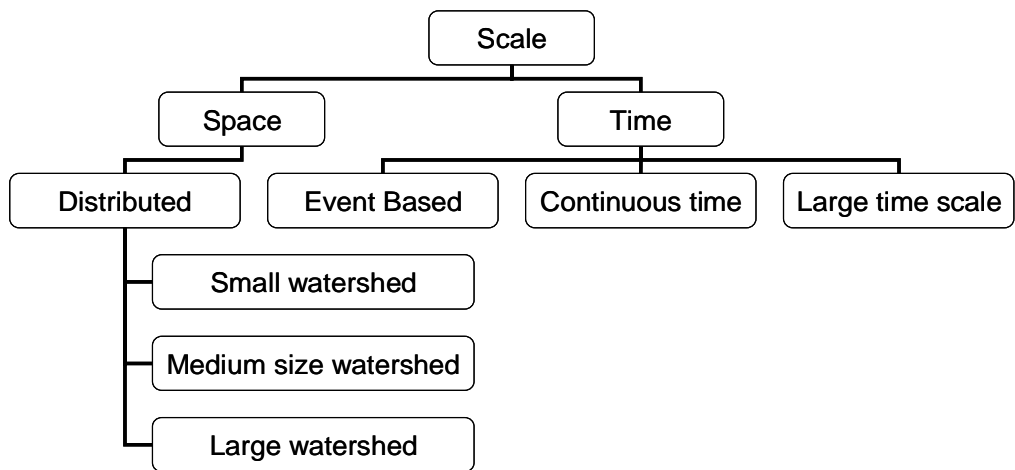


Figure 2-2 Classification of models based on space and time scale

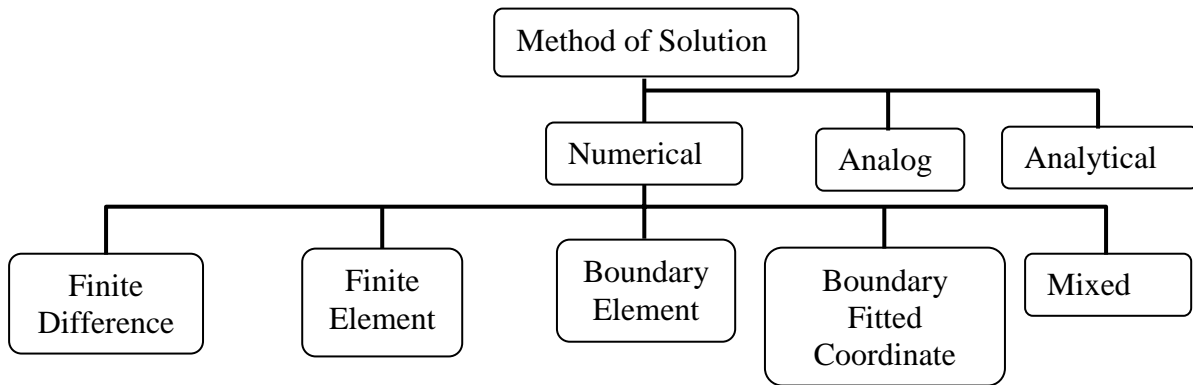


Figure 2-3 Classification of models based on solution technique

The watershed models can also be classified based on the time scale of models. The time scale can be defined as a combination of two time-intervals. One of the time intervals is used for input and internal computations. The second is the time interval used for the output and calibration of the model. Hydrologic processes may have to be computed at different time scales; therefore it is important to consider models that operate from event to daily to yearly time scales. At the event time scale, models typically do not compute inter-storm soil moisture conditions and therefore this information must be provided as an initial condition to initiate the model run. Event based models may be employed for storm events of relatively short duration or to finalize the design of technically complex structural and nonstructural management practices. On the other hand, continuous-time hydrologic models can simulate precipitation, available surface storage, snowmelt, evapotranspiration, soil moisture, and infiltration in a seasonal framework. These models typically operate on a time interval ranging from a fraction of an hour to a day. The principal advantage of continuous modeling is that it can provide long-term series of water and pollutants loadings.

The spatial scale can be used as a criterion to classify models into small-watershed, medium-size watershed, and large watershed models. Spatial scale is an important criterion in the selection of a model because the storage characteristics may vary at different watershed scales, that is, large watersheds have well developed channel networks and channel phase, and thus, channel storage is dominant. Such watersheds are less sensitive to short duration, high intensity rainfalls. On the other hand, small

watersheds are dominated by the land phase and overland flow, have relatively less conspicuous channel phase, and are highly sensitive to high intensity, short duration rainfalls.

2.3 Watershed Characteristics and Hydrologic Models

The watershed can be viewed as an aggregate of media between which flux of water, nutrients, energy, etc., occurs. Examples of such media are: the soil formation, the groundwater aquifers, the various water bodies, the plants, etc. It is exactly the description of movement of water and nutrients in and between these media that is sought in developing models.

2.3.1 Watershed Soil

The soil formation plays a fundamental role in the rainfall-runoff process. The precipitation that is received at the ground surface either infiltrates into the soil or gets stored temporarily on the ground surface, until it flows down into water courses or evaporates back into the atmosphere. Thus, it is mainly the characteristics of the soil formation that governs, for instance, how much of the rainfall becomes effective in producing runoff. As rainfall is intermittent, the soil formation experiences random periods of recharge by rainfall, and depletion by evapotranspiration as well as movement of water to deeper and down-the-slope layers.

The soil properties that have a direct influence on the movement of water are the hydraulic conductivity and the soil water-retention characteristics. Hydraulic conductivity under saturated condition is termed as saturated hydraulic conductivity while that under unsaturated conditions is called unsaturated hydraulic conductivity. The unsaturated hydraulic conductivity under field conditions, thus, is not a constant value but rather changes depending upon the water content of the soil. Moreover, the hydraulic conductivity is spatially variable in the watershed.

The soil water-retention property describes the ability of the soil to withhold or release water and is defined as the relationship between the soil moisture content and the soil-water suction or matric potential. The matric potential, thus, measures the relative ease with which water within the soil pores can readily flow at different moisture content and

as such a very important parameter of the soil formation in modeling soil water movement.

The watershed exhibits considerable spatial variability in soil properties. Often there are different soil types, and within the same soil type, variations have been observed in hydraulic as well as physical properties. Many research works have showed that there is a great deal of spatial variability in soil hydraulic properties. However, very limited information is available on the spatial variability of soil hydraulic properties in most watersheds. Thus, when it comes to the incorporation of the spatial heterogeneity of such soil hydraulic properties, then evaluation and modeling of the variability and efficient incorporation of the same into hydrologic models become important issues related to the overall model development and application exercises. With the development and proliferation of GIS, the capacity to handle spatial heterogeneity of model parameters has been significantly enhanced.

The two soil hydraulic properties discussed above are employed by physically-based models for soil-water movement, such as the Richards' equation. Many other models that fall in the conceptual models category rather use other derived soil properties among which Field Capacity (FC), and the Permanent Wilting Point (PWP), are very common. Although not necessarily in an efficient way, the FC has become one of the most important parameter used in conceptual models for describing the soil water movement. For instance, the ratio of actual evapotranspiration from a drying soil to the potential evapotranspiration is assumed to be a function of the soil moisture status. There have been many empirical functions describing the ratio; many of them use the FC as the upper limit of the soil moisture above which evapotranspiration proceeds at the potential rate, while the PWP is taken as the limiting soil moisture below which evapotranspiration is assumed to cease.

2.3.2 Watershed Vegetation

The land use/cover of a watershed greatly affects the hydrologic processes within the watershed. While land cover describes the type of vegetation in an area, land use refers to the type of use to which the land is made. Particularly, processes like interception,

transpiration, infiltration, and overland flow are the processes that are directly affected by the type of land use and cover in the watershed.

Exchanges of energy, mass, and momentum between the atmosphere and vegetation are controlled by plant canopies. The influence of the vegetation type and density on hydrologic processes has been studied by conceptualizing the same in some parameters. Primary vegetation characteristics which affect water and energy balance are the leaf area index (LAI), the stomatal conductance, the rooting depth, albedo and surface roughness. The interaction between vegetation in watershed and hydrologic processes may be summarized as: 1) the climate influences the soil moisture via evaporation and transpiration (which depend on the vegetation), 2) soil moisture and climate determine the type of vegetation that may grow in a region, and 3) the vegetation determines how it may control soil moisture (depending on the climate).

The effects of vegetation on hydrologic processes change with time, while at the same time, the vegetation characteristics may be viewed as parts of the responses of the watershed to moisture and energy input. This dynamic interaction is often not reproduced in most of the hydrologic models available today. Often seasonal indices are assigned to vegetation-dependent parameters affecting hydrologic processes.

2.4 Rainfall Runoff Processes and Component Models

The water that constitutes a streamflow may reach the stream channel by any of the several paths from the point where it first reaches the earth as precipitation. Some water flows over the soil surface as surface runoff and reaches the stream after the occurrences as runoff. Other water infiltrates through the soil surface and flows beneath the surface to the stream. This water moves more slowly than surface runoff and contributes to sustained flow of the stream during periods of dry weather.

When rain starts falling on more or less pervious areas, there is an initial period during which

- The rainfall is intercepted by buildings, trees, shrubs or other objects, and is thus prevented from reaching the ground: known as interception
- It infiltrates into the ground: known as infiltration

- It finds its way to innumerable small and large depressions, filling them to their overflow level: called depression storage.

The maximum rate at which a soil, when in a given condition, can absorb water is its infiltration capacity F . The storage may either evaporate or used by vegetation, or it infiltrates into the soil.

The difference between the total rainfall P and that which is intercepted is called effective rainfall. However, after the depression storage is filled, the rain intensity exceeds the infiltration capacity of the soil and the difference is then called rainfall excess, P_e . Runoff is obviously the residual of precipitation after the demands of interception; infiltration; depression storage and evapotranspiration are met. This precipitation is called rainfall excess.

During the period of rainfall excess, the actual route followed by a specific water particle from the time it reaches the ground until it enters a stream channel is devious. It is convenient to visualize three main routes of travel: overland flow or surface runoff is that water which travels over the ground surface to the channel. Once rainfall excess occurs, it first accumulates on the ground as surface detention, and then surface water originates as overland flow and begins to move down the slopes into small channels, then into larger channels, and finally as channel flow to the water shed outlet. This movement is called overland flow, and the water that thus reaches the stream channels is the surface runoff. Surface runoff can occur only as a result of storms having rainfall excess. All water contained within the permanent stream channel is called channel storage, S_c .

It has been mentioned earlier that the rainfall runoff process can be viewed as set of successive component processes. Most hydrologic models attempt to describe hydrologic processes in a detailed manner through combining these components. In each of the subsequent sections, process descriptions are given first followed by models developed in the past to simulate the process.

2.4.1 Interception

This is the process by which rain water is temporarily retained on leaves and stems of plants, roofs and other surfaces that are above the ground and are capable of holding

water. In particular for rural catchments the interception of water by vegetation is of prime importance. The following items are needed to be considered to describe the interception process mathematically in the overall phenomenon:

- Storage on leaves and stems of plants,
- Evaporation of stored water,
- Dripping of water from leaves and stems

Due to the complexity of the phenomenon and the parameters that influence it, it is very difficult to model interception. There are, however, few operational models that are used in practice. These models are designed for different uses and hence exhibit varying degrees of sophistication as well as data need.

One of the foremost models is that of (19) in which the interception loss is correlated to the storage capacity and the evaporation rate.

$$I_n = S_v + kE_v t_r \quad (2.1a)$$

where S_v is the storage capacity for the projected area of the canopy, which must be satisfied, k is the ratio of the vegetal surface area to its projected area, E_r is the rate of evaporation from the vegetal surface and t_r is the duration of the rainfall.

There are empirical models that relate the total interception loss to the total amount of rainfall above the vegetation. They are generally expressed as given in equation 2.1b

$$I_n = a + bP_c \quad (2.1b)$$

Where P_c is the precipitation over the vegetation, a , b , and n are parameters of the model, and n is often set to unity(18).

2.4.2 Infiltration

Infiltration refers to the movement of water into the soil formation. It is the main mechanism by which the soil formation gets replenished with water. The physics of unsteady infiltration rate into the soil formation can be described by the Richards' equation(20), who derived the partial-differential-equation describing the movement of

liquids in porous media by combining the Darcy equation with the law of conservation of mass. Darcy's equation is generally found in the literature for flow in anisotropic flow condition as shown in equation 2.2.

$$v = -K_{ij} \nabla \phi \quad (2.2)$$

Where v = the flux vector

K_{ij} = the hydraulic conductivity written as a tensor of second degree for anisotropic soil

$\nabla \phi$ = gradient of soil water potential

Equation (2.2) can be simplified for a case of isotropic medium and one-dimensional vertical flow condition as in equation 2.3

$$v = -K \partial \phi / \partial z \quad (2.3)$$

The other equation needed for the successful application of Darcy's law to practical problems is obtained by applying the principle of conservation of mass to the system. Hence,

$$\text{div } v = -\partial \theta / \partial t \quad (2.4)$$

Where div in equation (2.4) stands for divergence, and θ is the volumetric moisture content.

Combining Darcy's law with equation (2.4) results in the equation of unsaturated water flow in porous medium. This equation is given by (2.5) for the simpler case of one-dimensional vertical flow in isotropic medium.

$$\partial \theta / \partial t = -\frac{\partial}{\partial z} \left(K(\theta) \frac{\partial \phi}{\partial z} \right) \quad (2.5)$$

This is a simplified form of the well known Darcy-Richards equation(20).

The total potential, ϕ , is the gradient of the total potential that acts as the driving force for the movement of soil water.

The equation needs the hydraulic conductivity and water retention characteristics of the soil as a function of moisture content. It can be imagined how difficult it would be to use

the equation in hydrologic models for simulating, for instance, the rainfall-runoff process. The main difficulty arises from the lack of the necessary data to characterize the variability in the soil hydraulic properties and accurate simulation of the boundary conditions in the watershed. Moreover, the computational effort required to implement such models for watershed models makes them impractical. For this reason, until very recently the general three-dimensional Richards' equation has not been fully integrated into hydrologic models. In recent times, Richards' equation in one-dimensional form has been incorporated in few hydrologic models, for instance the MIKE- SHE model (17). In many of the watershed models to date, simplified models (known as operational models) of varying complexity have been employed.

Operational models of infiltration have been developed based on experiments as well as by adapting physically-based procedures. In addition, some rainfall-excess models, such as the SCS runoff model, may also be considered as infiltration models as they, indirectly, compute the amount of water lost into the soil formation. A description of some of the most common infiltration models is give below:

2.4.3 Empirical Infiltration Models

Empirical methods are usually in the form of simple equations, the parameters of which are derived by means of curve-fitting the equation to actual measurements of cumulative water infiltration. These equations only provide estimates of cumulative infiltration and infiltration rates, and do not provide information regarding water content distribution. Most are derived on the basis of a constant water content being available at the surface.

2.4.4 Physically-based Models

Green-Ampt Model: Green and Ampt (24) derived the first physically based equation describing the infiltration of water into a soil. The Green-Ampt model has been the subject of considerable developments in applied soil physics and hydrology owing to its simplicity and satisfactory performance for a great variety of hydrological problems. For many hydrological problems the use of more sophisticated approaches (*e.g.*, the models based on the nonlinear Richards equation,) is both impractical and inefficient due to more information on soil hydraulic parameters (*e.g.* water retention and hydraulic conductivity

functions) being required. In these methods, the entire soil moisture-pressure profile is generally evaluated, even though the main quantity of interest is the flux at one or both of the boundaries. Therefore, not surprisingly, the Green-Ampt equation has been the choice model of infiltration estimation in many physically-based hydrologic models. Also, the USDA's Agricultural Research Service (ARS) has done extensive work to develop empirical relations for obtaining the Green-Ampt model parameters, thus providing additional impetus for inclusion in many watershed models.

Green and Ampt assumed a piston-type water content profile (Figure 2-4) with a well-defined wetting front. The piston-type profile assumes the soil is saturated at a volumetric water content of θ_s (except for entrapped air) down to the wetting front. At the wetting front, the water content s drops abruptly to an antecedent value of θ_0 , which is the initial water content. The soil-water *pressure* head at the wetting front is assumed to be h (negative). Soil-water pressure at the f surface, h_f , is assumed to be equal to the depth of the ponded water.

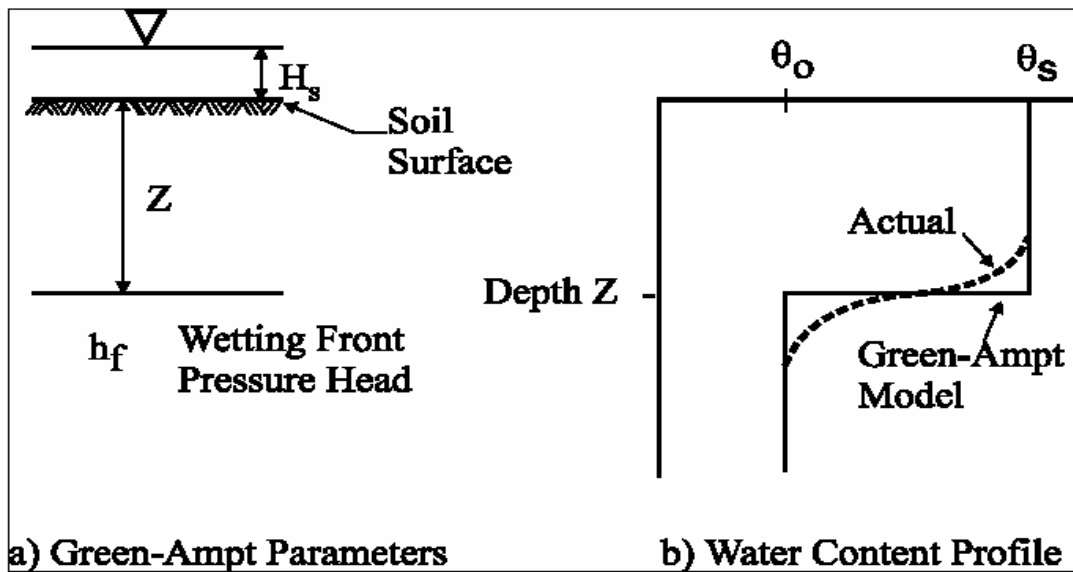


Figure 2-4 Illustration of Green-Ampt parameters and the conceptualized water content profile, which demonstrates the sharp wetting front.

At any time, t , the penetration of the infiltrating wetting front will be Z . Darcy's law can be stated as follows:

$$q = \frac{dI}{dt} = -K_s \left(\frac{h_f - (h_s + Z)}{Z} \right) \quad (2.13)$$

where K_s is the hydraulic conductivity corresponding to the surface water content, and $I(t)$ is the cumulative infiltration at time t , and is equal to $Z(\theta_s - \theta_o)$. Using this relation for $I(t)$ to eliminate Z from Eq. 2.13, and performing the integration yields,

$$I = K_s t - (h_f - h_s)(\theta_s - \theta_o) \ln \left[1 - \frac{I}{(h_f - h_s)(\theta_s - \theta_o)} \right] \quad (2.14)$$

Compilation of Green-Ampt Models

Even though originally developed for idealized conditions (*i.e.*, homogeneous soil and constant surface ponding depth), the Green-Ampt model has been extended to take into account more realistic features. Many infiltration models were derived based on the Green-Ampt approach, for instance Green and Ampt (24), Philip (22). They found quite reasonable results with the model used for the computation of rainfall excess. However, they found out that the hydraulic conductivity, which is highly variable in the watershed remains the most erratic constituent of the loss rate computation procedure.

The primary utility of the Green-Ampt approach lies in the estimation of the water flux, and it must be emphasized that the actual water content distribution with depth, $\theta(z)$, cannot be simulated, since the model formulation assumes a sharp wetting front.

Parameter Estimation for the Green-Ampt Models

The popularity of the Green-Ampt models is primarily due to simplicity, adaptability to varying scenarios, and the availability of characteristic parameter values for various soil textures and conditions. Extensive studies conducted by the USDA's Agricultural Research Service (ARS) have resulted in the development of empirical relations for the model parameters in terms of easily-measurable variables. This has provided an additional impetus for the inclusion of Green-Ampt models in many watershed models.

2.4.5 Rainfall-excess Models

The SCS (Soil Conservation Service) Model: The US Soil Conservation Service model is widely used for estimating floods on small to medium-sized ungauged drainage basins.

Together with the SCS triangular unit hydrograph, the method can be used to estimate peak floods from a known rainfall hyetograph. According to this method, the volume of direct runoff resulting from a rainfall of P is given by

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \quad (2.17)$$

Where I_a is the initial abstraction, and S is the potential retention in the basin, which equals the initial abstraction I_a plus the cumulative infiltration, F. No runoff occurs until rainfall equals an initial abstraction I_a is satisfied. After allowing for I_a the depth of runoff Q is the residual after subtracting F.

Commonly it is taken that the initial abstraction is about 20 % of the potential retention in any storm, i.e. $I_a = 0.2S$, hence

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (2.18)$$

The potential retention is expressed in terms of a dimensionless curve number CN, which depends on soil type and land use/cover in the drainage basin. In english units, where S is in inches. The value of CN depends on the soil, cover, and hydrologic conditions of the land surface, which are available in many standard hydrology books (15).

$$CN = \frac{25400}{254 + S} \quad (2.19)$$

2.4.6 Evapotranspiration

This process is responsible for the loss of water from the soil formation in the form of vapor. It is the sum total of evaporation of the water intercepted mainly by vegetation, direct evaporation from the soil surface, transpiration of plants. In the case of cracked soil, however, this amount is augmented by the evaporation of the water temporarily held in the crack space and the additional evaporation from the soil matrix through crack walls.

Potential evapotranspiration (more commonly known as reference crop evapotranspiration): is the rate of evapotranspiration from an extensive surface of 8 to 15

cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water'. Additional properties of the reference-crop, such as albedo and surface resistance, are specified in some definitions.

In practice, the computation of the actual evapotranspiration begins with the estimation of the potential (or reference crop) (15). This is then converted to the evapotranspiration of the given vegetation type under the given moisture conditions using some empirical methods.

2.4.7 Overland flow

This term refers to the flow rate on the ground surface before the water gets into the well-defined water courses in a watershed. It is mainly derived from the rainfall that is received in the watershed. The three main mechanisms through which water reaches a channel lead to three terms for the definition of components of stream flow. Part of the stream flow is generated from the rainfall excess, which is part of the rainfall that is greater than the infiltration capacity under the given conditions. This is known as overland flow. There are two ways by which overland flow is generated in the catchment: saturation overland flow and Hortonian overland flow. The former is generated, when soil becomes saturated from “below”, i.e. when either the ground water rises and saturates the soil, while the latter is generated when infiltration rates fall below the rainfall intensity. In both cases, rainfall on the saturated surface produces the surface runoff and the parts of the watershed that directly contribute to the runoff may be a small fraction of the watershed area.

Hydraulics of overland flow is highly variable depending upon the boundary conditions and the rainfall intensity and the infiltration rates. Generally, it may be laminar or fully turbulent, and it can exit as broad sheet flow, where the ground surface is covered with a thin film of water, or in small micro channels in which case it is known as rill flow. Sheet flow can reasonably be expected in urbanized environments on paved surfaces, such as streets, parking lots, airport runways, etc.

Water that entered the macropore system in the soil formation flows down the slope until it reaches the channel system. This contribution to the stream flow is known as the

interflow. There is still another component of the stream flow, which is applicable for the cases where the groundwater table intersects the channel section. In such cases there comes flow from the groundwater and this is known as the base flow.

Alternatively, saturation is assumed to occur whenever the subsurface drainage rate (from upslope area) exceeds the rate at which the soil profile can transmit it downstream.

2.4.8 Governing Equations

The derivation of the hydrodynamic equations governing overland flow under the most general boundary conditions makes use of the principle of conservation of mass and momentum. The equations are called St. Venant equations (25).

The general form of the St-Venant equations for two-dimensional flow are given below:

$$\omega \frac{\partial h}{\partial t} + \frac{\partial(uA)}{\partial x} + \frac{\partial(vA)}{\partial y} = I$$

and

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + g \frac{\partial h}{\partial x} = g(S_{ox} - S_{fx}) - \frac{uI}{h} \quad (2.20)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + g \frac{\partial h}{\partial y} = g(S_{oy} - S_{fy}) - \frac{vI}{h}$$

Where u and v are the depth averaged velocities in the x - and y - directions, respectively, A is the cross-sectional area normal to the flow, h is the mean depth of flow, ω is the flow width at the water surface, I is the lateral inflow rate per unit length, S_{ox} and S_{oy} are the bed slopes in the x - and y -directions, respectively, and S_{fx} and S_{fy} are the friction slopes in the x - and y - directions, respectively.

In many watershed models, overland flow is computed by means of simplified form of the St-Venant equations. One common simplification is to consider the flow to be essentially one-dimensional, in which case the equations take the forms:

$$\omega \frac{\partial h}{\partial t} + \frac{\partial Q}{\partial x} = I$$

and

$$Q = Q_n \sqrt{\left[1 - \frac{1}{S_o} \left(\frac{\partial h}{\partial x} + \frac{u}{g} \frac{\partial u}{\partial x} + \frac{1}{g} \frac{\partial u}{\partial t} + \frac{uI}{gh} \right) \right]} \quad (2.21)$$

Where Q is the discharge and Q_n is the normal discharge. The equation is further simplified into the kinematic-wave approximation, where inertia as well as the pressure terms are negligible, and diffusive-wave approximation, where only inertia terms are neglected.

In the subsequent sections, an application of the kinematic-wave approximation of overland flow in a GIS environment is described. The landscape is approximated by a series of planes as in a DEM approximation of the topography of the watershed. The model used for the overland flow in the present work makes use of the kinematic wave approximation to open channel flow in a simplified way. Manning's equation (26) offers the basic resistance relation which is then coupled with the continuity equation to solve the unknown variables. The method is illustrated for a single raster element in Figure 2-5 below.

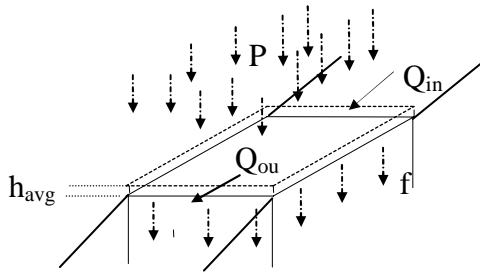


Figure 2-5 Overland flow: Definition sketch

In Figure 2-5, P denotes the precipitation in excess of interception in mm, Q_{in} is the sum of inflows coming to the element in question from upstream, h_{avg} is the average depth of flow over the element, f is the infiltration rate in mm/h and Q_{out} is the runoff leaving the element.

The continuity equation for the imaginary surface store looks

$$A \frac{\partial h}{\partial t} = (P - f) A - \frac{\partial Q}{\partial X} \Delta X \quad (2.22a)$$

where A is the planar area of the surface under consideration, Δx is length of the surface along the direction of flow.

With approximation of the rate of change of discharge with distance by the ratio of difference between outflow and inflow to element and the length of the element along the flow, and substituting the average depth of water over the element, an approximate equation have been formulated as given in (2.22b).

$$\frac{dh}{dt} = P - f - \frac{1}{A} \frac{(Q_{out} - Q_{in})}{L} B \quad (2.22b)$$

Where L and B denote the length and width of the element, respectively, which are in the case of raster elements equal.

Hence, the major changes made are that h is taken as the average value applicable over the whole of the element, and hence is only a function of time, and that the rate of change of Q along flow direction is taken as the difference between flows at outlet and inlet to the element in question.

With P and Q_{in} known and f determined as discussed in the section earlier, one needs one more equation to solve the equation (2.22b). This equation is normally provided by the momentum relationship, i.e. the principle of conservation of momentum. In the simplified form the Manning equation is used resulting in what is known as the kinamtic flow equation.

Manning resistance equation is given by

$$Q = 1/n * A_f * R^{2/3} S^{1/2}$$

where A_f is the area through which flow proceeds, R is the hydraulic radius, S is the slope of the energy gradient and n is the Manning resistance factor.

In the present case, $A_f = h_{avg} * B$, and R is approximated by h_{avg} since this is very small compared to B, i.e. a case of wide rectangular channel. Substituting these two and for a square element

$$\frac{dh}{dt} = P + \frac{Q_{in}}{A} - f - \frac{\sqrt{S} B}{n} h^{5/3} \quad (2.23)$$

This equation shall then be used to compute the overland flow in the model.

Although the elements are modeled as cascade of planes on which flow is modeled using the kinematic approach, the treatment of the flow discontinuity. The model does not consider flow discontinuity at boundaries of these elements.

The flow is assumed to occur as sheet flow with the water film being distributed uniformly over the entire surface of the grid cells. This is very approximate as the microrelief in the watershed is so rugged that flow tends to concentrate in very small channels called rills.

2.4.9 Channel Routing

The surface runoff that enters the channel network experiences now different flow situation. The geometry of water courses is entirely different from that under which overland flow occurs. Channels join each other and form the drainage network, a tree - shaped structure that converges at the catchment outlet. In flowing through this system of water courses the surface runoff hydrograph undergoes some modifications in its shape. Generally the peak gets reduced and the time base elongated. The computation of these changes to the inflow hydrograph is the subject of channel routing methods.

There have been developed in the past different routing methods that show varying degrees of complexity and data need. They generally fall into two groups. These are the hydrologic, or lumped, routing methods, where the change in the hydrograph along a channel reach is computed without considering what happens to it at intermediate points, and the hydraulic, or the distributed routing methods, where outflow hydrographs are computed at a mesh of points along the channel. Distributed models apply the physics of the flow more accurately than their lumped counterparts. However, they need detailed information that is not to be found especially for rural catchments. The treatment of such methods is beyond the scope of the present work.

An excellent example of hydrologic routing methods is the Muskingum method. This method assumes that the water temporarily stored in the channel reach is given by the relationship

$$S = K[XI + (1-X)Q]$$

Where, Q is the outflow discharge (assumed to be a single valued function of the stage), K, and X are coefficients, X lies in the range 0 to 0.5.

In the practice K and X are determined from measured inflow and outflow hydrographs for a given channel reach. For cases where only outflow hydrographs are available there is no other way than estimating them through calibration.

If one writes the rate of change of storage within the channel reach as a difference equation and combines it with the continuity equation, the following well-known routing equation is obtained

$$Q_{j+1} = C_1 I_{j+1} + C_2 I_j + C_3 Q_j \quad (2.24)$$

Where:

$$C_1 = \frac{\Delta t - 2KX}{2K(1-X) + \Delta t}$$

$$C_2 = \frac{\Delta t + 2KX}{2K(1-X) + \Delta t}$$

$$C_3 = \frac{-\Delta t + 2K(1-X)}{2K(1-X) + \Delta t}$$

and where $C_1 + C_2 + C_3 = 1$,

and $K/3 \leq \Delta t \leq K$ is the usual range of Δt

The Muskingum method has been extended by Cunge (27) and thereby enhanced the application of the method materially. This modified Muskingum method (known as the Muskingum-Cunge method), falls in the category of simplified distributed routing model. It is most effectively used as a distributed flow routing technique where the total channel

reach is subdivided into smaller ones with length Δx . The recursive equation applicable to each Δx_i sub-reach for each time step Δt^j is given by

$$Q_{i+1}^{j+1} = C_1 Q_i^{j+1} + C_2 Q_i^j + C_3 Q_{i+1}^j + C_4 \quad (2.25)$$

$$C_4 = \frac{q_l \Delta t \Delta x}{2K(1-X) + \Delta t}$$

where C_4 is the lateral inflow term which is given by

q_l is the lateral discharge, cu. m/s/m along the bank of the water course.

The coefficients K and X are computed from the channel and flow characteristics as given below:

$$K = \Delta x / c,$$

where c is the kinematic celerity of the flood wave computed at a discharge known as the

$$X = \frac{1}{2} - \frac{Q_R}{2cBS_e \Delta x}$$

reference discharge Q_R is the energy slope, but generally approximated by the channel slope, S_e , B is the top width of the wetted area.

The wave celerity is given by

$$c = 1/V dQ/dA$$

where V is the flow velocity and A the flow area.

Using the Manning's formula together with the reference discharge, the expression for the kinematic wave celerity looks in practice the one given below

$$\frac{dQ}{dA} = \frac{\sqrt{S}}{n} \left\{ \frac{5}{3} R_h^{2/3} - \frac{2}{3} R_h^{5/3} \frac{1}{B} \frac{dP}{dh} \right\} \quad (2.26)$$

Where R_h is the hydraulic radius (A/P), P is the wetted perimeter, and B the top width at a water depth of h . The equation applies to any channel shape.

For a trapezoidal channel section of side slopes $1:m_1$ and $1:m_2$

$$P = (\sqrt{1 + m_1^2} + \sqrt{1 + m_2^2})h$$

And

$$\frac{dP}{dh} = \sqrt{1 + m_1^2} + \sqrt{1 + m_2^2}$$

This can be used for rectangular and triangular sections as they can be treated as special case of the trapezoidal channel section.

Important in this method is the definition of the reference discharge upon which the values of the coefficients K and X depend. This flow has been defined as the initial steady-state flow in the channel. Hence, values of K and X remain constant throughout the routing period.

3 FEWS NET/USGS Stream Flow Model

3.1 Model description

The Famine Early Warning System Stream Flow Model (FEWS-SFM) is a physically based semi-distributed geospatial hydrologic model based on the use of satellite remote sensing, numerical weather forecast fields, ground observation, and geographic data sets describing the land surface

The FEWS-SFM (8) hydrological model was developed by the USGS/ EROS Data Center to provide a continuous simulation of stream flow, on a daily time step. It consists of a GIS-based module used for model input and data preparation, and the rainfall-runoff simulation model.

The Graphic User Interface (GUI) of the model is user friendly to prepare the necessary input data as well as routing of the flow and display of the outputs using the special analysis functions of the ArcView GIS software. Detailed data preparation of the model is presented in section 4.

The rainfall-runoff model is comprised of soil water accounting module that produces surface and sub-surface runoff for each sub-basin, an upland headwater basins routing module, and a major river routing module.

The runoff prediction module conceptualizes the soil as composed of two main zones: an active soil layer where most of the soil-vegetation-atmosphere interactions take place and a groundwater zone.

The active soil layer is divided into an upper thin soil layer where evaporation, transpiration, and percolation take place and a lower soil layer where only transpiration and percolation occur.

The runoff producing mechanisms considered in the model are surface runoff due to precipitation excess (including direct runoff from impermeable areas of the basin), rapid subsurface flow (interflow), and baseflow. The model has an upland headwater basins routing module and a major river routing module. The surface upland routing routine is a physically-based unit hydrograph method that relies on cell-based landscape attributes

such as drainage area, slope, flow direction, and flow length derived from a digital elevation model.

The interflow and baseflow components of the runoff are routed with a set of theoretical linear reservoirs. In the main river reaches water is routed using a nonlinear formulation of the Muskingum-Cunge routing scheme. Most of the model parameters have a physical meaning and are determined by the spatial distribution of basin characteristics. Parameterization of the basins' hydrologic properties is accomplished through the use of three data sets describing the Earth's surface: topography, land cover, and soils.

3.2 Data requirement

The FEWS-SFM model uses the following information of the catchment for simulation of streamflow.

Topography (Digital Elevation Model) of the catchment

The major input of the FEWS-SFM model is the topography of the catchment to simulate the geomorphology. The topography could be prepared from digitized topographic maps and be processed to produce a digital map of the area. For a digitized map, the map could be imported to ArcView GIS to be converted to shape file. The shape file of the catchment which contains the elevation, latitude and longitude with the necessary degree of resolution. The shape file containing the coordinates will then be converted to aerial coverage by using the 'Surface Interpolation' facility of ArcView. This will produce the DEM necessary for the model. It is also possible to use the DEM data of the area produced from satellite image and available through the Internet.

From the DEM the model generates additional input grid data by using the spatial analyst extension of ArcView. The input grid files include.

- Flow Direction: Possible flow direction value relative to the surrounding grid theme cells.
- Flow Accumulation: identifies the number of cells flowing into a particular cell
- Flow Length: the distance water would travel to reach this cell.
- Streams: a cell is taken to be a stream if the number of cells flowing to it is above the threshold value.

- Stream Link: assigns a unique value to sections of a stream between points of intersection
- Outlets: Identifies the outlet for a watershed, considering the most downstream point on a stream link.
- Basins: the drainage area above each of the watershed outlets.
- Hill Length: Hill length grid
- Slope: Terrain slope
- Downstream: Downstream ordering of basins.

These grid files are then further processed to produce the major text files necessary for the model. The data to be generated include the following

- Basin boundary
- River/Stream layout
- Subbasin slope
- Area of subbasins
- Channel Slope
- Channel Length
- Channel Width

Land use/cover data

The land use/cover information of the catchment is also necessary for the model. FEWS-SFM has a user friendly module to prepare this data from a geo-referenced spatial data made from ground measured data or it could be prepared from the satellite image files available in the Internet.

- Vegetation cover,
- Land use type,
- Overland flow velocity.

Soil data

The soil data can also be taken from the FAO Global soil data or could be prepared from available soil map and information if available for the catchments of interest in a refined scale. The soil data should be prepared in grid files.

- Texture
- Soil type
- Soil Depth
- Soil Water Holding Capacity
- Runoff curve number
- Overland flow velocity
- Hydraulic conductivity
- Hydrologic soil group

The land use/cover data combined with soil data to produce

- runoff curve number,
- maximum impervious cover

Rainfall and Potential Evapotranspiration

Meteorological data from ground installed instruments can be used to generate the aerial coverage of the catchment if available after being changed to a grid file. But the model also incorporates daily rainfall estimates obtained from satellite image.

Stream flow data.

In its present status the model does not incorporate the observed streamflow record in the calibration and verification process. But, the user uses these data in Ms Excel® spread sheet format to assess the performance of the model.

3.3 FEWS-SFM Simulation Process

Model initialization

The static data describing the physical characteristics of the watersheds and the precipitation and evaporation data for the watersheds are read and stored in arrays during the model's initialization phase. The application then creates the files required to

maintain the simulated streamflow and soil moisture contents. Define additional physical characteristics of the watersheds

Many characteristics describing the physical nature of the watershed are included in the input files. Additional characteristics are derived from this information and used by the model to simulate streamflow and soil-water conditions

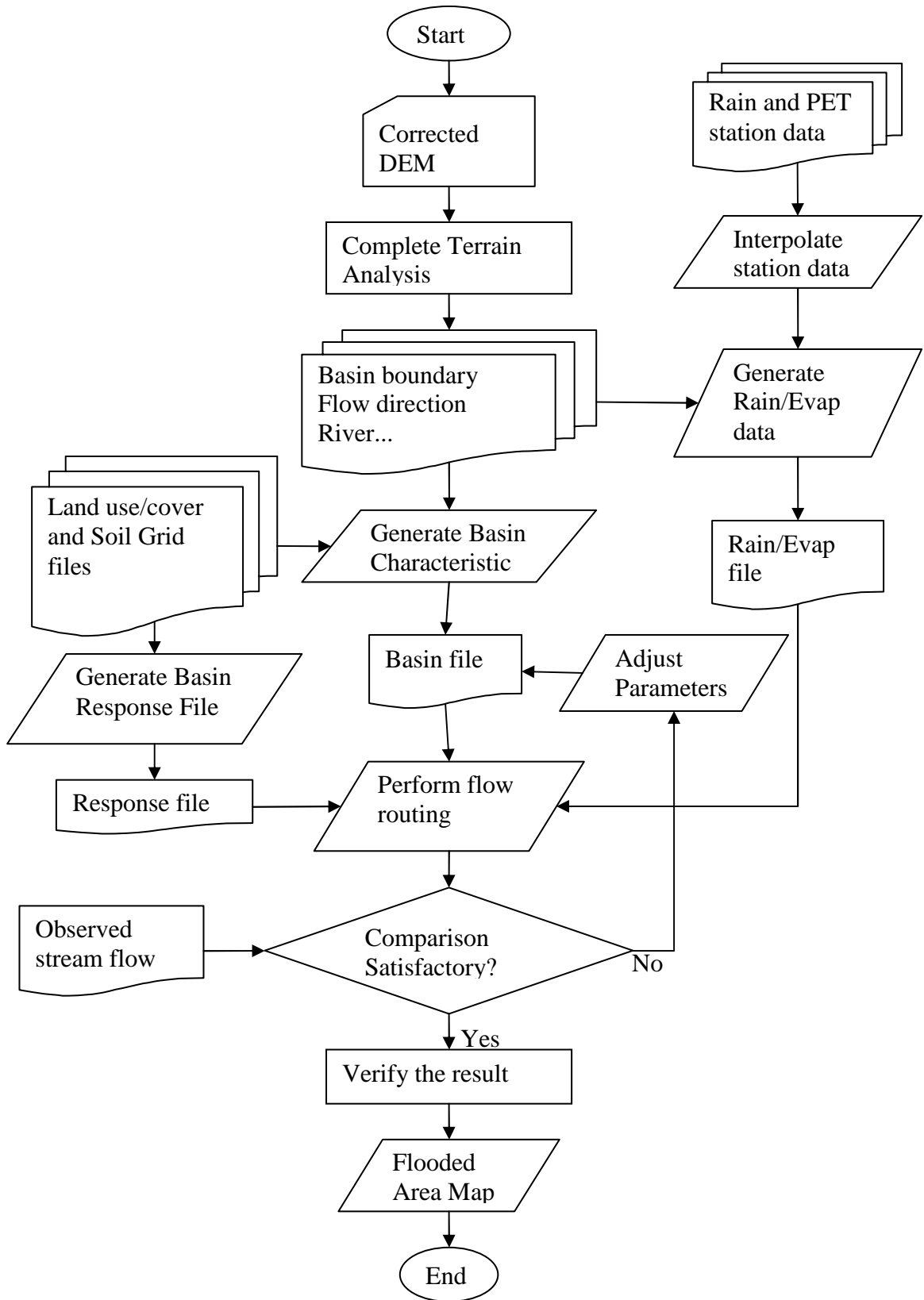


Figure 3-1. FEWS SFM layout.

Slope conversions and channel width

The channel widths are computed as

$$B_c = 0.006 * A_{UP} \quad \dots 3-1$$

If $B_c < 100\text{m}$ then

$$B_c = 100\text{m}$$

And if $B_c > 1500\text{m}$ then

$$B_c = 1500\text{m}$$

Values less than 100 meters are set to 100 meters and values greater than 1500 meters are set to 1500 meters.

Soil Layers

The model computes the minimum soil water content, field capacity, and saturation soil-water content for each watershed.

$$\theta = \gamma \eta DS \quad \dots 3-2$$

where γ is a constant based upon soil texture, and soil water content.

γ value for the different soil water content and texture

Texture	Minimum SWC	Field Capacity	Saturated SWC
Sandy soils	0.75	2.00	2.10
Loamy soils	1.00	2.10	2.25
Clay soils	1.25	2.20	2.50
Default	1.00	2.00	2.25

State Variables

The initial water content in the upper and lower root zones is a function of the average field capacity.

$$\theta_{urz} = 0.05 F_{av} \quad \dots 3-3$$

$$\theta_{lurz} = 0.75 F_{av} \quad \dots 3-4$$

The depth of water in meters, in the main channel is a function of the channel's width.

$$D_f = 0.01 B_c \quad \dots 3-5$$

The remaining initial water contents for the stream, soil moisture, and ground water reservoirs are set to zero.

Routing Coefficient

Excess precipitation and water in the stream channel is routed downstream using lag coefficients. Routing is based upon the Natural Resources Conservation Services (NRCS) Soil Conservation Service (SCS) Curve Number method.

$$L = \frac{L_T + L_M}{0.3048} \quad \dots 3-6$$

$$Y = \frac{S_B + S_C}{2} \quad \dots 3-7$$

$$LF = \frac{L^{0.8} * S^{0.7}}{31.67 * Y^{0.5}} (60\Delta t) \quad \dots 3-8$$

$$S = \frac{1000}{CN} - 9 \quad \dots 3-9$$

The lag factor must be greater than or equal to one.

$$\begin{aligned} \chi_O &= 1.0 / LT \\ \chi_I &= 1.0 / (3.0 / LF) \\ \chi_G &= 1.0 / (1000 / (K_{sat} * \Delta t)) \end{aligned} \quad \dots 3-10$$

Soil Percolation Coefficients

This model uses the Brooks Corey model for controlling the rate water percolates through the soil layer.

$$\begin{aligned} \Psi_b &= 0.12 \\ \lambda &= 0.252 \end{aligned}$$

$$K_{sat} = 1.058 \left[\frac{SC - \theta_{min}}{D_{SH}} \right]^{4.0} \quad \dots 3-11$$

A default value of 5000 meters is used if the file does not contain a length for a basin.

Water Balance

The model first determines the excess amount of precipitation. That is the amount of precipitation falling on the watershed that cannot be infiltrated into the soil layer or used by the evapotranspiration processes. The wet and dry soil conditions are calculated. The watershed's curve number is modified based upon soil moisture conditions.

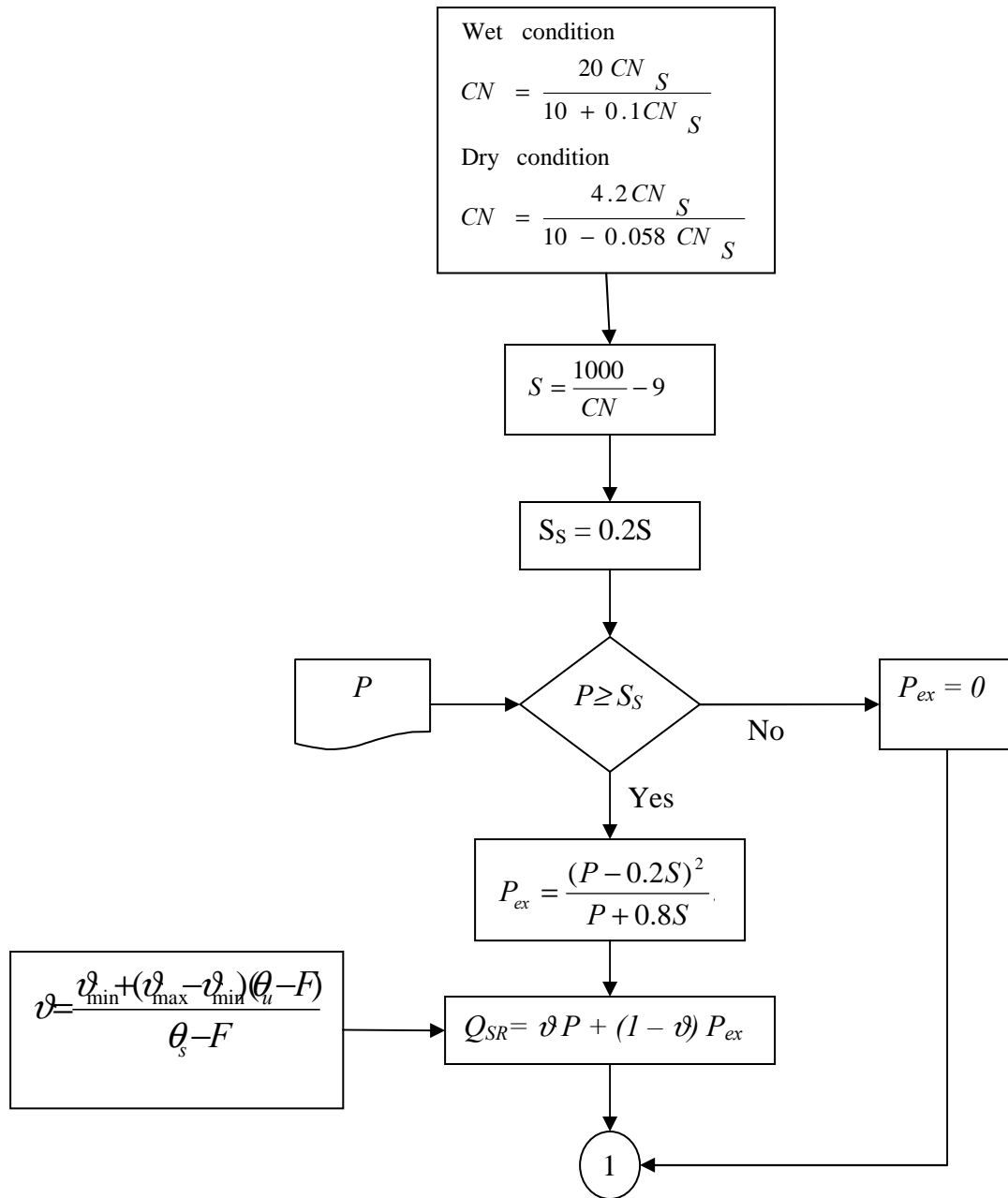


Figure 3-2 Surface Runoff computation of FEWS-SFM

The model next computes the quantity of water lost by evapotranspiration and the quantity of water in the soil layers is adjusted. The excess water from the upper soil layer is first computed.

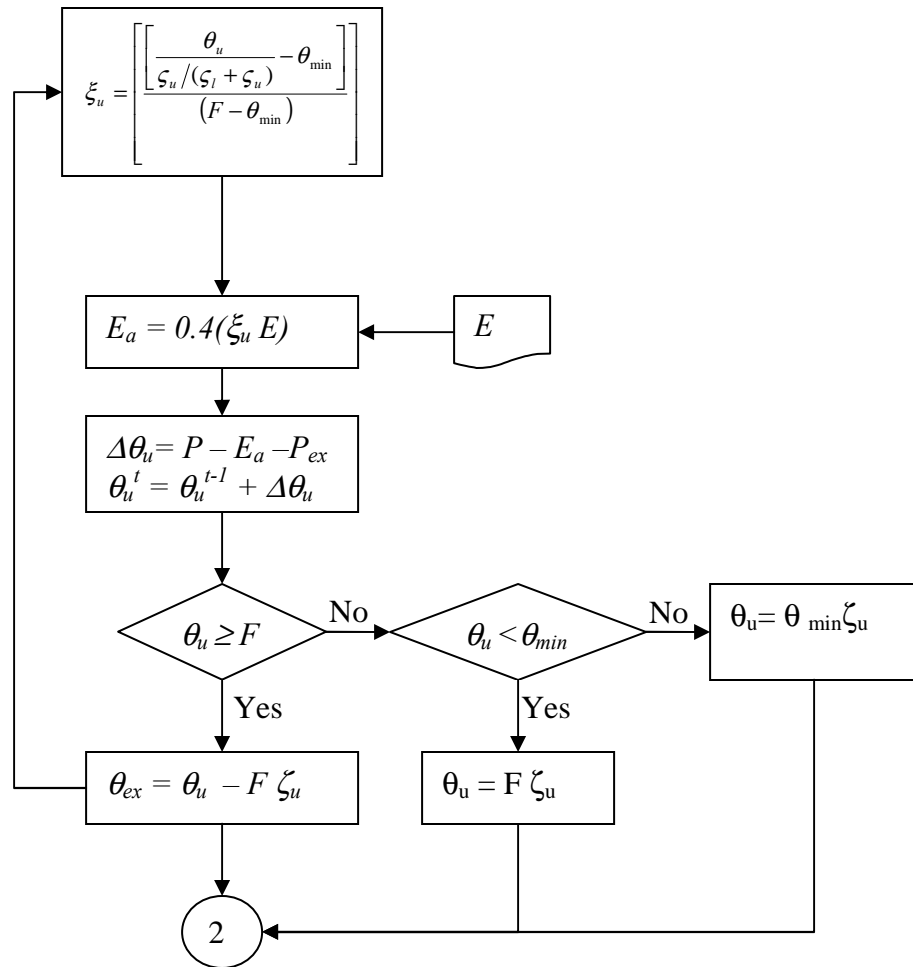


Figure 3-3 Soil Water in the Upper soil layer.

The excess soil water is partitioned into the amount that percolates to the lower soil zone and the amount available for interflow. The Green-Ampt model, an approximation of Darcy's law, is used to compute the portion of the excess soil water available for interflow.

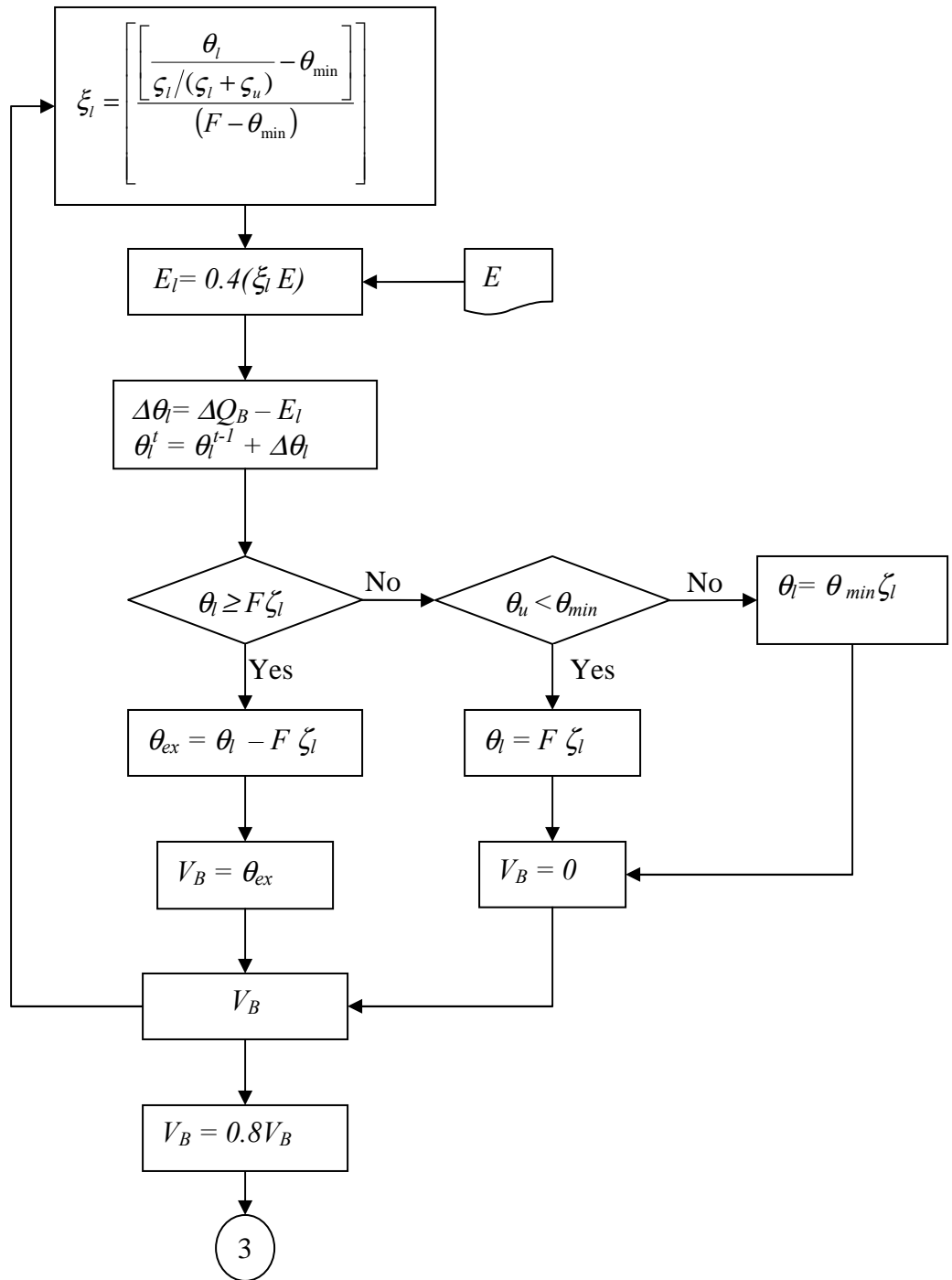


Figure 3-4 Soil Water in the Lower soil layer

The GreenAmpt model is used again to compute the excess water in the lower soil zone which acts as base flow. The FEWS Flood Model uses a linear reservoir concept. The first step in routing water inside a watershed is to add direct surface runoff, interflow, and base flow to their respective linear reservoirs and subtracting out the quantity of water

routed to the respective reservoirs associated with the downstream watershed.

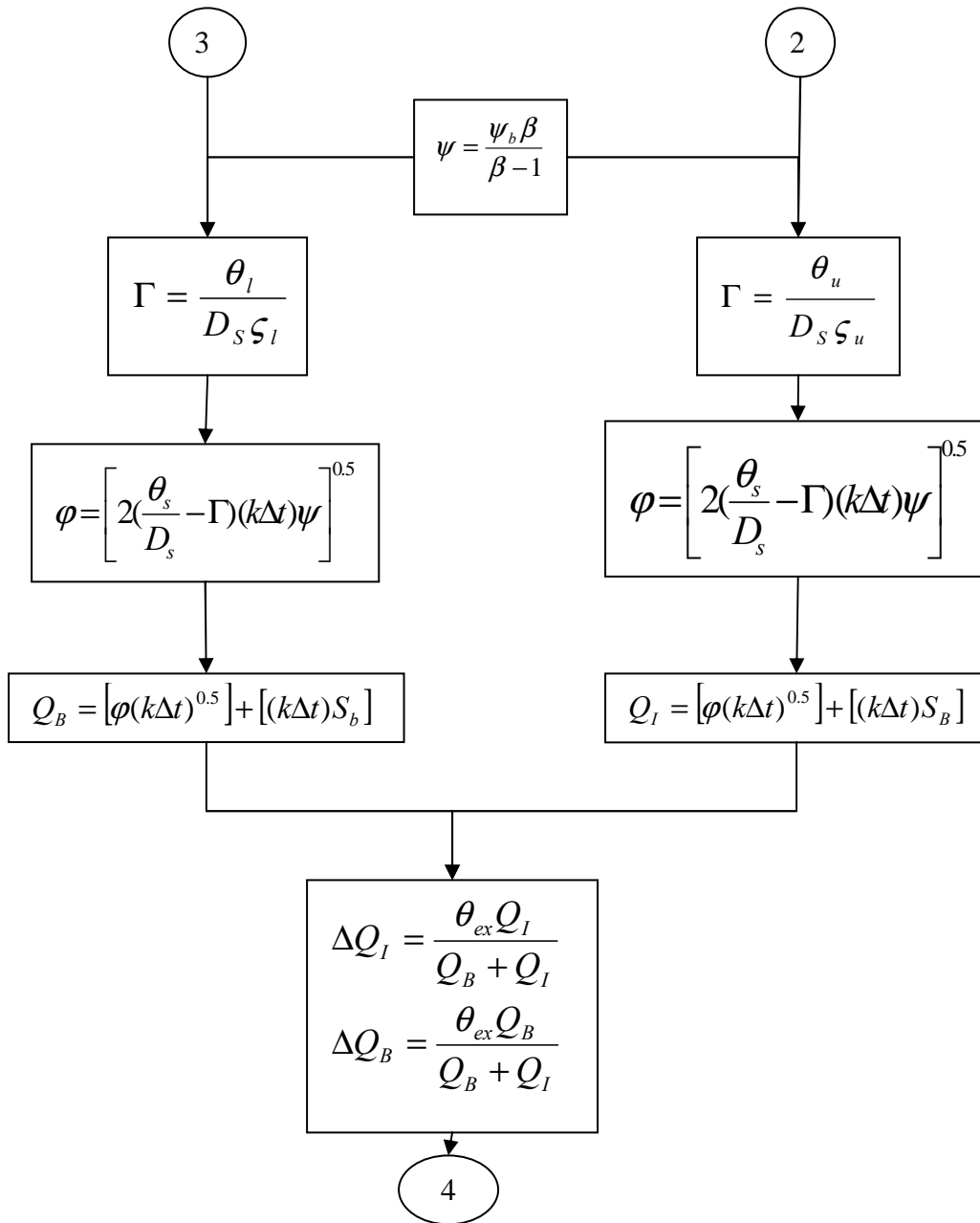


Figure 3-5 Green-Ampt model to separate soil water into the top and lower layers.

After the water within a watershed has been routed to the stream channel water must be routed between basins. The routing starts with the most upstream watershed.

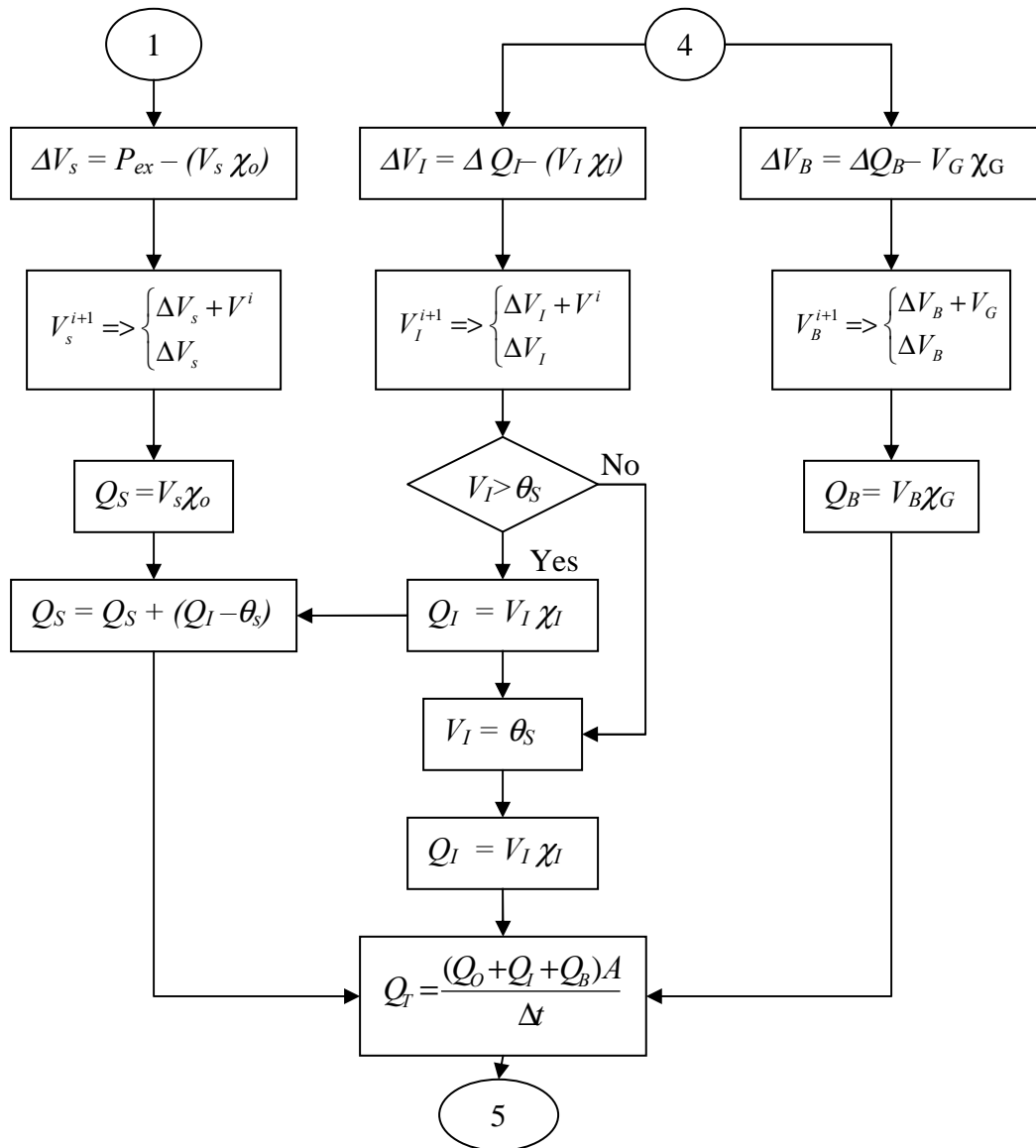


Figure 3-6 Flow routing within the watershed to the outlet.

The next step is to route the water down the channel using the MuskingumCunge model.

During each time step the model must simulate an existing discharge based upon information from the previous step. This information does not exist during the first time step estimates as being the streamflow needed to achieve a bank full condition.

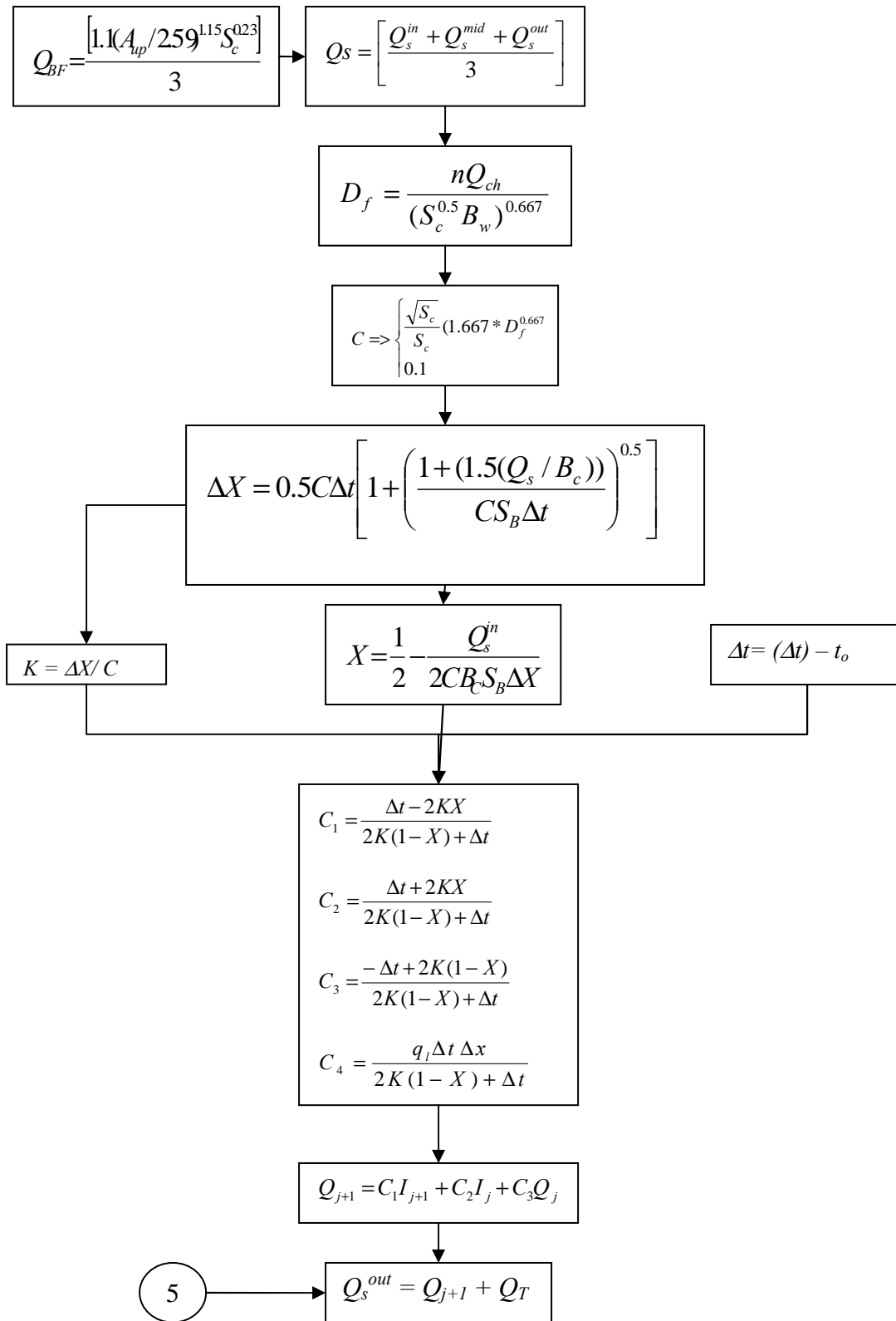


Figure 3-7 Stream flow at the outlet of the basin

The streamflow at each space step/time step is saved and used as the initial condition at the next time step. The simulation time step is then increased and the streamflow and soil-moisture conditions are simulated for the next day.

3.4 Merits and Demerits of FEWS SFM model

FEWS-SFM is developed for forecasting and early warning purpose typically for south and Great Horn of Africa. The model is intentionally made parsimonious to comply with the data scarcity of most African Nations. Its simplicity to run in personal computers and the easy Graphic User Interface for data preparation is suitable to use. Being spatial and GIS based, is the first advantage of FEWS-SFM which makes it preferable for interpretation and user friendly. Furthermore, the FEWS-SFM model is free of charge and it needs only ArcView® GIS software to prepare the input data.

Rain gauge record is scarce in the developing world. Even when available it is full of missing data and the conversion of the point record to an aerial coverage is full of uncertainties. Due to this fact, Radar estimates of rainfall are being increasingly applied to flood forecasting applications.

The FEWS SFM model though able to include observed rainfall records, its capability to be used with no difficulty for satellite rainfall estimates is far reaching. Once calibrated and verified the model can be run with the free available daily rainfall estimate and evapotranspiration data.

Only three classes of soil texture were used in the model, which necessitates the division of the soil into loam, sand or clay. Intermediate properties need to be entertained in the model.

The FEWS-SFM model at its present status couldn't be used for rivers having either natural or artificial reservoirs and/or abstractions. Structures are being built on many of the main rivers applying the model for the entire reach of such basins will be difficult.

Calibration of the FEWS-SFM need to be performed by opening the text files containing the parameters and adjust them manually. Despite its being parsimonious the number of model run depends on the number of subbasins considered with in the basin.

4 Data Acquisition and Preparation

4.1 Data Acquisition

4.1.1 Basin topographic map

Topographic maps of scale 1:250,000 were digitized in AutoCAD environment. The contour lines were reproduced digitally as polylines with a segment length of 0.001°. Each of these polylines was given the respective elevation. Spot elevations were also included to aid in the interpolation scheme. Besides, features such as rivers and streams, lakes and roads were digitized to help in checking and interpretation of the final result.

Areas which are susceptible to flood hazard are those plain areas at the banks of the river Awash. The 1:250,000 scale maps were unable to represent those plain areas as most of the contours were produced in an interval of 100m. Those areas were selected and the largest scale map available at the Mapping Agency, 1:50000, were digitized.

A simple Macro was written to extract the coordinate of segment end points for the polylines into a text file including the coordinate of the spot elevations. The text file was imported to the ArcView and the surface interpolation was easily carried out.

4.1.2 Soil Data

Among the inputs of any rainfall-runoff model, the soil data is most essential for the water balance. The infiltration, ground water recharge and surface runoff are determined in the FEWS-SFM model based on the soil data input.

For this reason the soil map of the entire basin was digitized from soil map of scale 1:500,000. The digitization was done in a similar way to the topographic maps except this involved replicating and making the polylines closed. A single line of each neighboring soil polygon was digitized and a closed polygon is then formed. The closed region generated from the closed polygons intersection is again used to produce a closed polyline which duplicates the boundary with those in its surrounding.

The drawback of the map was that it has only the soil unit name. A research report of soil research stations (6) in the basin and the FAO soil data base from Global Soil Data Products®(5) are used to relate the soil unit and the corresponding soil property.

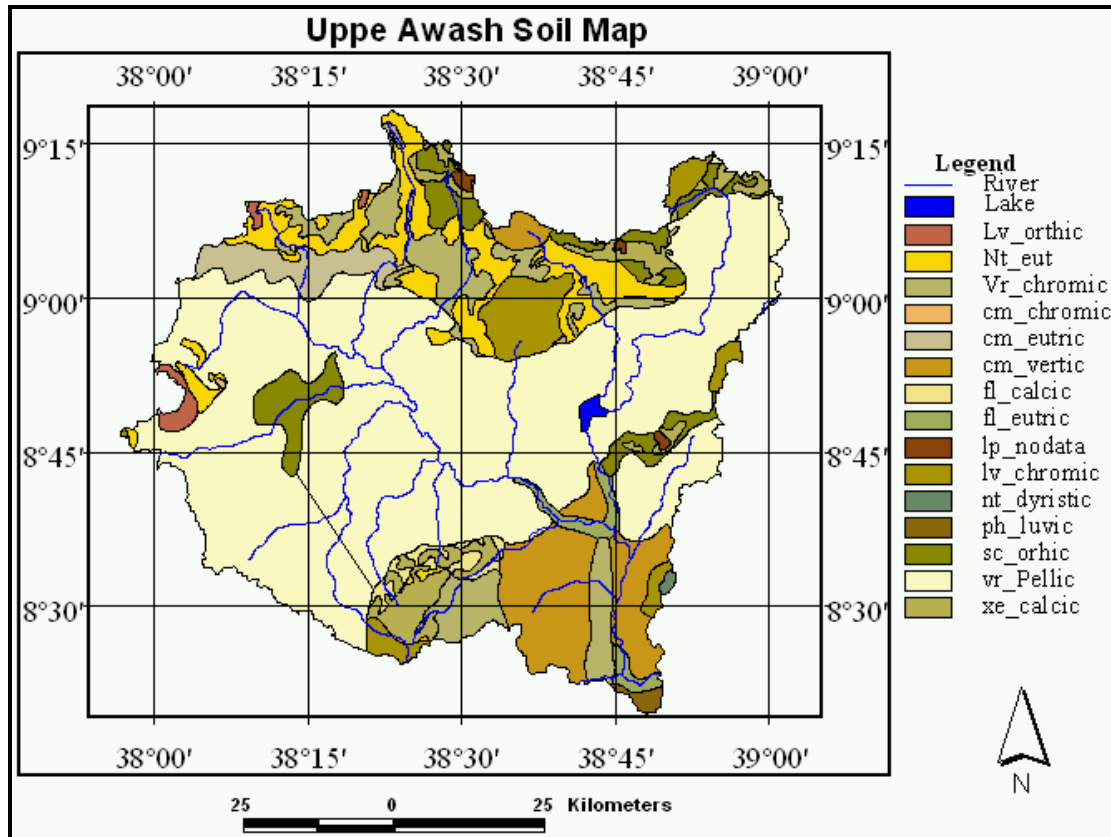


Figure 4-1 Soil Map of the Upper Awash Basin(16)

Table 4-1 Soil type and the respective property.

Soil Unit	Symbol	HSG	Rclfd	Texture	Ks	Depth	WHC
Chromic Cambisols	Bc	B	2	2	0.00012	86	0.1232
Eutric Cambisols	Be	B	2	2	0.000632	55	0.1727
Vertic Cambisols	Bv	C	3	2	0.00015		0.1211
Luvic Phaeozems	Hl	C	3	2	0.00062		0.1685
Lithosols ¹	I	D	4	2	0.001		0.06
Eutic Fluvisols	Je	B	2	2	0.00045	150	0.1621
Calcic Fluvisol ¹	Jk	B	2	3	0.0001		0.95
Chromic Luvisols	Lc	B	2	2	0.000575		0.1621
Orthic Luvisols	Lo	B	2	1	0.000752		0.179
Dystric Nitosols ¹	Nd	B	2	2	0.0008		0.1
Eutric Nitosols	Ne	B	2	3	0.00005		0.1028
Chromic Vertsols	Vc	D	4	2	0.00038	125	0.1302
Pellic vertisols	Vp	D	4	1	0.000036	123	0.0375
Water body	W			5	0.000001		0.01
Caloic Zerosols	Xk	B	2	1	0.000277		0.094
Orthic Slonchaks	Zo	B	2	1	0.000727		0.1798

¹ FEWS-Net data is assigned

Conversion formulas written in the manual of the FEWS-SFM (3) were implemented to obtain the representative values of the various soil properties as per the model requirement.

4.1.3 Landuse Landcover data

The land use land cover map of the basin is obtained from Woody Biomass inventory project), not yet finalized. The map was produced as per the need of the inventory project. Therefore, reclassification and adjustments were done (Table 4-2) before applying the data for the calibration of the model.

Table 4-2 Land use /cover data reclassification

Symb.	Raw Data Description	FEWS	Description
	Unclassified	0	
CI	Cropland with Few Stocks of Woody Plants	2	Dryland Cropland and Pasture
CRCB	Cropland with Few Stocks of Woody Plants	5	Cropland/Grassland Mosaic
CRCL	Cropland with Light Stocks of Woody Plants	5	Cropland/Grassland Mosaic
CRCM	Cropland with Moderate Stocks of Woody Plants	6	Cropland/Woodland Mosaic
CSL	Cropland with Light Stocks of Woody Plants	13	Evergreen Broadleaf Forest
CSM	Cropland with Moderate Stocks of Woody Plants	13	Evergreen Broadleaf Forest
FBO	Natural Forest	13	Evergreen Broadleaf Forest
FCO	Natural Forest	13	Evergreen Broadleaf Forest
FMO	Natural Forest	13	Evergreen Broadleaf Forest
FPD	Plantation Forest	13	Evergreen Broadleaf Forest
FPO	Plantation Forest	13	Evergreen Broadleaf Forest
FRO	Natural Forest	13	Evergreen Broadleaf Forest
GB	Grassland with Few Stocks of Woody Plants	7	Grassland
GL	Grassland with Light Stocks of Woody Plants	7	Grassland
GM	Grassland with Moderate Stocks of Woody Plants	7	Grassland
HH	Water	16	Water Bodies
HSP	Swamp	17	Herbaceous Wetland
HSS	Swamp	17	Herbaceous Wetland
SHD	Shrubland	8	Shrubland
SHO	Shrubland	8	Shrubland
TR	Rock	19	Barren or Sparsely Vegetated
TS	Bare Soil	19	Barren or Sparsely Vegetated
U	Others	1	Urban and Built-Up Land
WD	Woodland	6	Cropland/Woodland Mosaic
WO	Woodland	6	Cropland/Woodland Mosaic

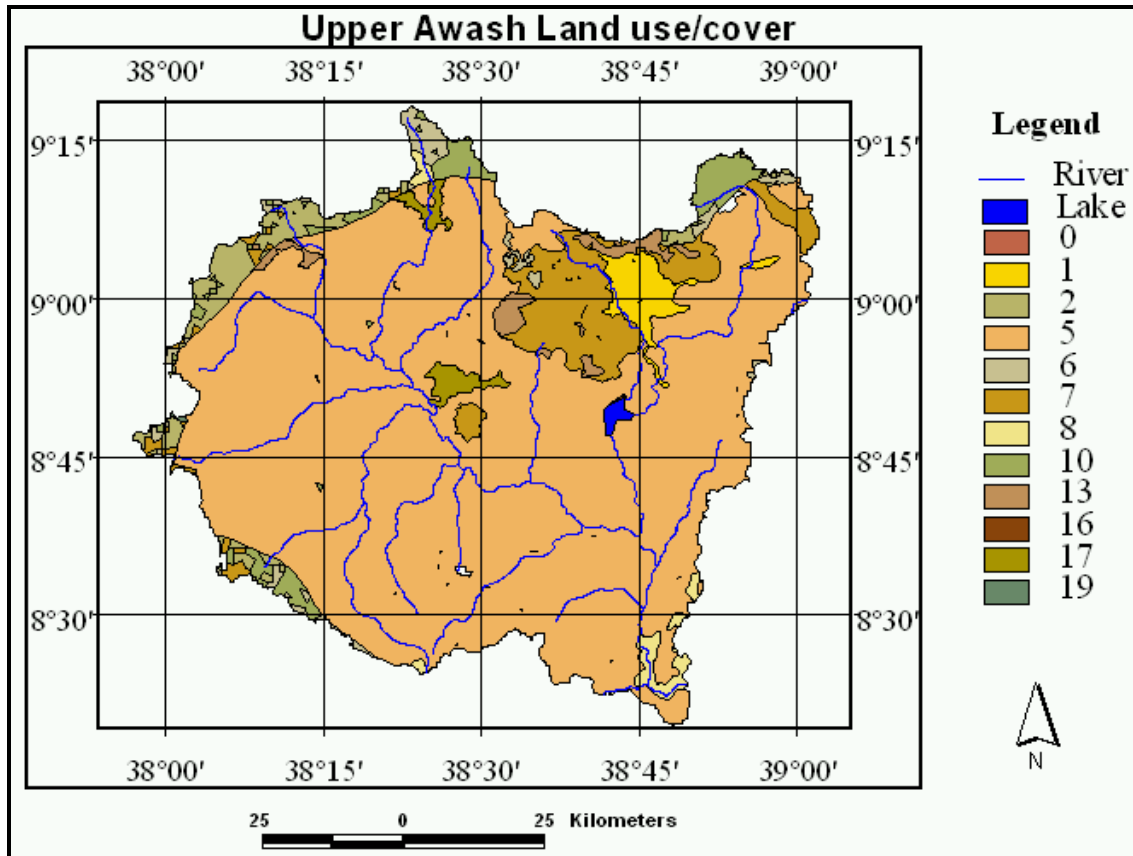


Figure 4-2 Landuse landcover of the Upper Awash Basin

Table 4-3 FEWS Landuse Landcover Classification and associated values

Value	Description	Mean curve number for hydrologic soil group				Velocityk
		A	B	C	D	
1	Urban and Built-up Land	73	82	88	90	6.3398
2	Dryland Cropland and Pasture	71	80	86	86	0.4572
3	Irrigated Cropland and Pasture	64	74	81	84	2.7737
5	Cropland/Grassland Mosaic	63	73	82	87	0.3962
6	Cropland/Woodland Mosaic	51	68	78	82	0.3962
7	Grassland	60	76	81	89	0.6401
8	Shrubland	48	62	73	78	0.4572
10	Savanna	44	65	77	82	0.4267
11	Deciduous Broadleaf Forest	55	66	74	79	0.4267
13	Evergreen Broadleaf Forest	55	66	74	79	0.2134
16	Water Bodies	100	100	100	100	6.3398
17	Herbaceous Wetland	100	100	100	100	4.7854
18	Woody Wetland	100	100	100	100	3.1394
19	Barren or Sparsely Vegetated	75	80	85	90	0.6706

Landuse and landcover data are needed to determine the response of the basin being modeled to precipitation. This data along with the soil data determine the response coefficients used by the FEWS-SFM to extract the amount of excess precipitation, the amount of recharge to the ground water system, and the amount of water held in storage in the soils. The response coefficients are determined using

Table 4-3.

4.1.4 Rainfall and Evapotranspiration Data

Another input file required by the FEWS-SFM model is the values for the forcing dynamic variables describing the daily total rainfall and potential evapotranspiration occurring over the watershed. A list of meteorological stations was used to see the aerial distribution within the basin and 35 stations were selected taking in to account the aerial coverage, orographic effect and the possible effect of a rainfall in that particular area on the flow of the Awash River.

Potential evapotranspiration data is almost not available. The only data obtained is the 10days average for the years 1987-1996. Almost all of the pans are not functional. The meteorological service uses piche readings to measure evaporation. No calibration is made to determine the amount of evapotranspiration from the Piche reading.

These decadal data was reorganized into a daily format and same data is used for generation of yearly data for the basin.

The encoding was done in Excel Spread sheet format, very similar to the meteorological service data sheet. A simple program is written to rearrange these data in a format suitable for the model which comprise of two files one containing data for the first 179 days and the other for the remaining days of the year.

Table 4-4 Raingauge stations used in the simulation.

ID	Station Name	Region	Latitude	Longitude	Elevation	Class	Beging_yea
1	Addis Ababa	SHEWA	9.03	38.75	2408	1	1955
17	Addis Ababa	SHEWA	9.03	38.72	2354	1	1980
26	Adis Alem	SHEWA	9.05	38.38	1600	4	1980
36	Akaki School	SHEWA	8.75	38.67	1600	2	1951
48	Aluta	SHEWA	9.2	39.15	2550	1	1977
111	Balchi	SHEWA	8.92	39.37	1600	4	1962
142	Bolo Giorgis	SHEWA	8.82	39.42	1600	4	1962
146	Buee	SHEWA	8.35	38.55	2020	1	1989
151	Bussa	SHEWA	8.83	38.12	2200	4	1962
154	Chefe Don	SHEWA	8.97	39.13	1600	4	
186	Debre Zeit	SHEWA	8.73	38.95	1900	1	1951
201	Dertulibe	SHEWA	8.68	38.98	1600	4	1963
208	Dilela	SHEWA	8.63	38.5	1600	4	1981
217	Dixis	ARSI	8.13	39.57	2680	3	1958
237	Etheya	ARSI	8.15	39.23	2060	3	1975
272	Ginchi	SHEWA	9.03	38.12	2290	1	1989
295	Guranda Meda	SHEWA	8.98	38.77	2245	4	1963
314	Holetta	SHEWA	9.07	38.48	2380	1	1954
322	Huruta	ARSI	8.15	39.37	2000	1	1974
363	Kimoy	SHEWA	9.03	38.35	2115	3	1983
366	KoKa	SHEWA	8.38	39.25		1	1991
375	Kulumsa	ARSI	8.13	39.13	2180	1	1963
386	Malkassa	SHEWA	8.4	39.3	1540	1	1977
401	Meki	SHEWA	8.15	38.8	1600	4	1965
403	Melka Kunture	SHEWA	8.72	38.62	2000	4	1962
411	Merti Jeju	ARSI	8.57	39.67	1250	1	1977
426	Mojo	SHEWA	8.62	39.15	1870	1	1963
434	Nazaret	SHEWA	8.55	39.27	1622	1	1989
444	Ogelcho	ARSI	8.07	39.03	1760	3	1967
457	Sebeta	SHEWA	8.92	38.65	2240	4	1954
461	Sendafa	SHEWA	9.15	39	2560	3	1954
482	Shola Gebeya	SHEWA	9.2	39.38	1600	1	1976
497	Teji	SHEWA	8.78	38.37	2110	4	1961
513	Tulu Bolo	SHEWA	8.67	38.22	2100	1	1962
523	Welenchit	SHEWA	8.65	38.22	1450	4	1960
524	Welenkomi	SHEWA	9.02	38.2	2300	4	1962
531	Wonji	SHEWA	8.48	39.25	1540	1	1951
551	Zuquala	SHEWA	8.55	38.83	3050	4	1962

Table 4-5 Potential Evapotranspiration Stations used in the simulation.

ID	Station Name	Region	Latitude	Longitude	Elevation	Class
1	A.ddis Ababa (cl.Ins)	SHEWA	9.03	38.75	2,408	1
17	Addis Ababa Bo	SHEWA	9.03	38.72	2,354	1
59	Ambo Hagerhiwot	SHEWA	8.98	37.83	1,600	1
89	Assela	ARSI	7.95	39.13	2350	1
186	Debre Zeit Af	SHEWA	8.73	38.95	1,900	1
187	Debre Zeit Arc	SHEWA	8.72	38.95	1,900	2
207	Diksis(SF)	ARSI	8.05	39.58	2680	1
264	Gibe Farm	SHEWA	8.23	37.58	1,110	1
314	Holetta	SHEWA	9.07	38.48	2,380	1
367	Koka	SHEWA	8.42	39.15	1,595	1
375	Kulumsa	ARSI	8.13	39.13	2180	1
411	Merti Jeju	ARSI	8.57	39.67	1250	1
426	Mojo	SHEWA	8.62	39.15	1,870	1
444	Ogelcho	ARSI	8.07	39.03	1760	3
482	Shola Gebeya	SHEWA	9.20	39.38	1,600	1
493	Sululta	SHEWA	9.17	38.72	2,610	1
506	Tikur Inchini	SHEWA	8.77	37.63	2,480	1
529	Wliso Giyon	SHEWA	8.55	37.98	2,000	1
531	Wonji	SHEWA	8.48	39.25	1,540	1
550	Ziway	SHEWA	7.93	38.72	1,640	1

4.1.5 Stream Flow Data

A list of Flow measuring stations was used to select two key stations of particular relevance to the model. Both stations were along the main river. The first station in the middle of the basin is known as Melka Kunture and the second at the outlet of the basin is Melka Hombole flow measuring station. Digital daily record of streamflow for both stations was obtained from the Hydrology Department of Ministry of Water Resources.

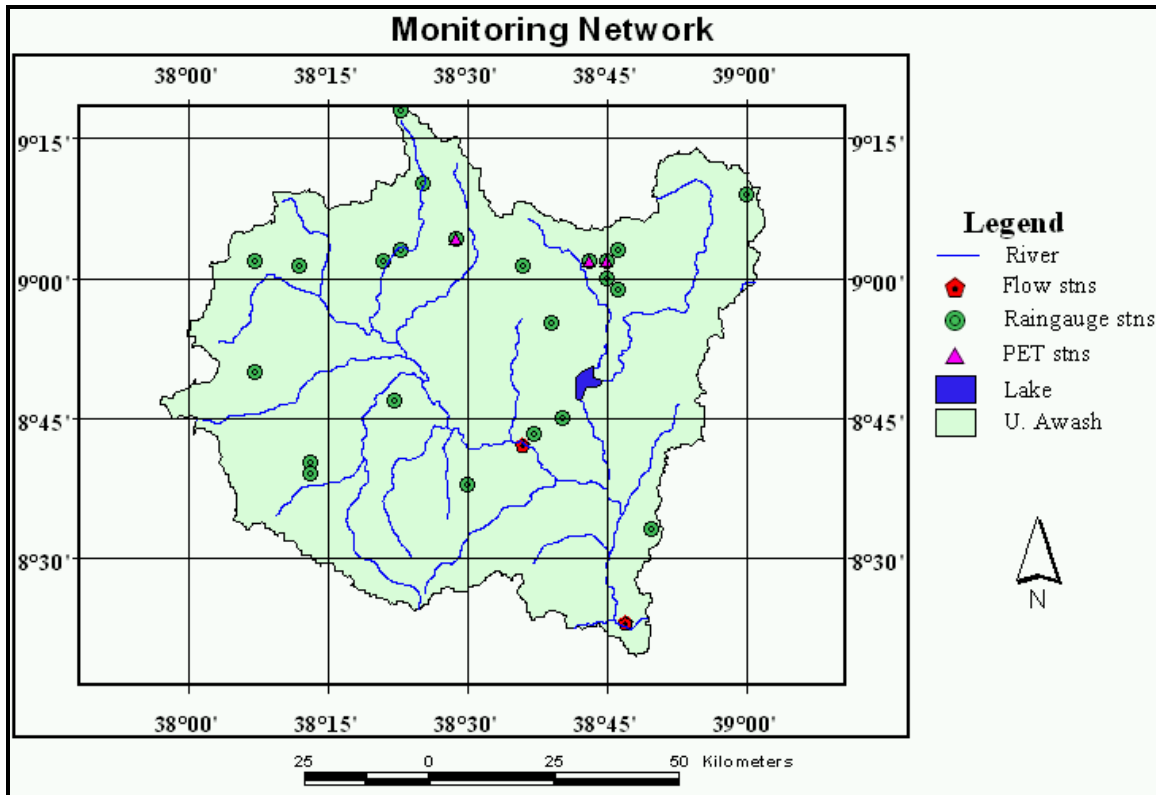


Figure 4-3 Monitoring Network of the Upper Awash Basin

4.2 Data preparation

The input data required for the FEWS-SFM is totally in grid format. Hence every input is converted to grid and the description is given below. The projection used in the preparation of all the geospatial data sets is Lambert Equal Area Azimuthal. This is because the Satellite image data which are intended to be used in the future are prepared and disseminated in the fore mentioned projection. Therefore, one can use the results obtained in this thesis for future reference and refinement.

4.2.1 Digital Elevation Model (DEM)

The DEM is crucial to obtain a well delineated basin, sub basins as well as the basin characteristics which will be an input for the model.

Topographic maps of scale 1:250,000 were bought from the Ethiopian Mapping Agency for the basin. The Agency produced these maps from aerial photographs taken at different time. This difference in the time frame is believed to be the cause for some of the mismatch encountered while joining contours from different sheets.

The FEWS-SFM model works on smooth terrain, therefore, sinks created in the surface interpolation procedure were filled by running a script. The output of these run will be used as a 'corrected DEM' grid data. This same conversion process was done many times after substantial addition of contour lines as a check. This intermediate check has been done using the interpolated Grid via converting into corrected DEM and crosschecking for acceptable representation of the basin topography.

Areas susceptible to flood hazard are those plain at the banks of the river Awash. The 1:250,000 scale maps were unable to represent such terrain as most of the contours were produced in an interval of 100m.

The largest scale map available at the Mapping Agency was 1:50,000 scale. These maps were bought and the digitized map was refined with these additional contour lines and spot elevations. Some of the contour lines of these maps were observed to cross with the contours digitized from the courser scale map. On such occasions the contours of the larger scale map were taken to represent the area.

A check was also done after inclusion of these refined contours. An improved DEM was obtained representing the basin. In the preparation of the corrected DEM, it was observed that the program cuts most of the spot elevation values and fills to the sink. This cut and fill procedure also extends to the plain areas with its adverse effect of removing the significance of contour lines of small interval and spot elevations added from the larger scale maps. An effort has been put to obtain the optimum value for this sink removal process.

The acceptance of the 'corrected DEM' is checked through comparison done after running the relevant module of the model. The river/stream shape file generated is then overlaid on the digitized river/stream shape file. This gives a quick view on how well the DEM is representing the actual basin topography.

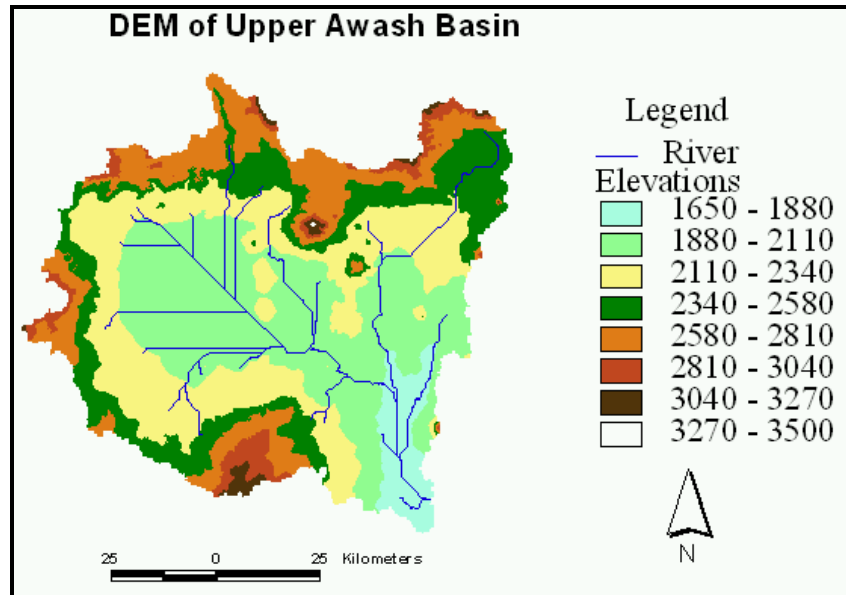


Figure 4-4 DEM of the Awash Basin

The ‘Complete Terrain Analysis’ module of the FEWS model is used to generate the necessary terrain related input grid files for the basin. The module uses the ‘Corrected DEM’ produced in the preparation of DEM for the watershed and the Spatial Analyst extension of ArcView. Complete Terrain Analysis was conducted using the ArcView FEWS Flood Model extension. The resulting sub-basins for each modeled basin are presented in Appendix A. The grid files generated and their respective description is shown in Table 4-6.

Table 4-6 Description of ‘Complete Terrain Analysis’ Grid themes

Grid theme	Description
FlowDir	Possible flow direction value relative to the surrounding grid theme cells.
FlowAcc	Flow accumulation grid identifies the number of cells flowing into a particular cell
FlowLen	Flow length is the distance water would travel to reach this cell.
Streams	Stream grid theme where a cell is taken to be a stream if the number of cells flowing to it is above the threshold value.
StrLinks	Stream link grid assigns a unique value to sections of a stream between points of intersection.
Outlets	Identifies the outlet for a watershed, considering the most downstream point on a stream link.
Basins	Basin grid shows the drainage area above each of the watershed outlets.
HillLength	Hill length grid
Slope	Terrain slope
Downstream	Downstream ordering of basins

4.2.2 Runoff curve number generation.

The FAO 1974 classification is used for the soil types. From this information the hydrologic soil group for each type of soil is determined. This classification of soil is based on the infiltration capacity of the soil which has a direct relation with the rainfall run off process.

In the original soil map of the basin, there were places of no specific soil categories. These areas were left with a “no data” category.

The land use land cover classification of the raw data obtained was reclassified according to the FEWS net grouping before hand. Geoprocessing tools were used to assign the curve number corresponding to the specific land use and land cover category of the entire basin.

The “no data” soil categories were also filled for a coherent determination of the curve number. The rcn.shp file from Africa data set is used to assign the curve number once more for such plots.

4.2.3 Vegetation cover

The data processing steps followed for the runoff curve number has already produced the intermediate shape file of the vegetation cover data of the entire basin. The field containing this specific information is converted to a grid and the input file is prepared.

4.2.4 Texture

The data CD obtained from Global Soil Data Task 2000(5) has a proportion of the amount of clay sand and loam soil in each soil type. This data is used to acquire the texture that corresponds to the soil types of the basin. A work of same approach as used for missing plots in the case of land use land cover was done to obtain the texture of plots of “no data” soil category.

4.2.5 Depth

Due to time constraint to collect actual soil depth for the soil units in the basin the soil depth grid data of the FEWS net Africa data is used for the model.

4.2.6 Hydraulic permeability

The hydraulic conductivity grid is prepared based on the amount of clay, loam and silt in each of the soil type. Where there was water, the grid was assigned the smallest value.

4.2.7 Soil water holding capacity

Soil water holding capacity was prepared from its relation with texture (12). Values for different soil types were listed in Table 4-1.

4.2.8 Maximum impervious cover

The maximum impervious surface soil parameter grid describes the ability of water to infiltrate through the land surface. In FEWS-SFM, this is used mainly to describe water bodies. The maximum impervious cover when taken from the FEWS-NET data set will not be erroneous as compared to the other data types. Therefore, the existing data was used as an input grid.

4.2.9 Rainfall and Potential evapotranspiration

Data processing was done by joining the two separate database tables in ArcView to get the yearly record and again joining with the attribute table of the shape file containing the station location. The final table is converted to another shape file and interpolated applying the “interpolate rainfall/evapotranspiration” module of the FEWS extension.

The inverse distance weight interpolation (15) is used to change the point reading to aerial coverage. Twelve neighboring stations and grid size of 2000m were considered for the interpolation result of a grid cell. The daily interpolated grid themes were saved in a separate folder for generation of rainfall data in the coming steps of the modeling procedure.

The potential evapotranspiration data was also prepared in the same procedure as of the rainfall data.

4.2.10 Velocity

The velocity grid is produced from the velocity attribute of the landuse landcover shape file. The velocity represents the runoff velocity that could be attained in the watershed for

the routing of the excess runoff. The velocity coefficient assigned to the various types of vegetation cover is shown in Table 4-3.

4.2.11 Basin file

The FEWS-SFM interface function “Generate Basin File” uses those prepared grid themes produces lumped average parameters describing the physical features of the sub-basins. The resulting sub-basins and their parameters are described in Appendix B

4.2.12 Response file

The “Compute Sub-Basin Response” function creates a “Unit Hydrograph” for the watersheds described in “complete terrain analysis”. The unit hydrographs are used to estimate the quantity of overland flow that reaches the stream channel. This Unit Hydrograph is mainly based on the grid theme “velocityk” which describes the overland velocity of flow of the watershed. The unit hydrograph is routed for 21 days in the FEWS-SFM.

5 Model Calibration and Verification

5.1 Model Input Organization

The prepared inputs were collected into the directory created for the model. The input files and their description is shown in Table 5-1

Table 5-1 infiles.txt description

File name	Description
basin.txt	Basin characteristics file
response.txt	Unit hydrograph parameter file
reservoir.txt ²	Basic reservoir characteristic file
parameter.txt	Model parameters data file
rain.txt	Time series file of the daily mean aerial rainfall
evap.txt	Time series file of the daily mean aerial potential evapotranspiration
initialize.txt	State variables initialization data file
streamflow.txt	Basin simulated streamflow output file with rainfall estimation
forecast.txt	Output file name for basins simulated steam flow with forecast rainfall
soilwater.txt	Output file name for basins mean areal soil moisture
riverstage.txt	Output filename for basins stream mean water depth
velocity.txt ²	File with the observed stream gauges data file names

5.2 Model Calibration

Most rainfall-runoff model structures being used today can be classified as conceptual, i.e. their structure is defined prior to any modeling being undertaken and model parameters have to be derived from calibration against one or more observed output variables, e.g. streamflow. These parameters usually have some physical meaning and accepted ranges for their values. Exact values for the parameters usually cannot be fixed in advance.

Identification of model parameters is based on the following three bases:

- Physical meaning
- Significance in the model
- Range of values

Being conceptual and parasimonous, FEWS-SFM currently has the following parameters:

² Not fully functional in the model.

- Soil water holding capacity
- Soil depth
- Top active layer of soil
- Saturated hydraulic conductivity, k_s
- Runoff Curve Number, CN
- Pan coefficient, K_c
- Manning's roughness coefficient. for river flow, n
- Basin loss, i.e. Ground Water recharge

The model calibration of the Upper Awash Stream Flow is done for five years of daily record (1991-1995). The calibration process of FEWS-SFM is purely manual and is made by trial and error. The result of the parameters sensitivity analysis and the physical properties of the basin were helpful in reducing the number of trial calibration runs. Three different scenarios based on the number of subbasins were also considered for the calibration of the model.

5.3 Sensitivity of Model Parameters

Sensitivity of the model parameters was done for the first scenario which represents the basin as a single watershed and hence single outlet. From the analysis done the water holding capacity of soil, the soil depth, the runoff curve number and the basin loss are found to be sensitive to change in parameter values and the remaining parameters are not so sensitive to change the hydrograph and the statistical measures as well. The default value of these less sensitive parameters is kept throughout the calibration.

5.4 Statistical measures used in the calibration process

The statistical measures used in this thesis to assess the model performance, as well as highlight the strengths and weaknesses of the model, are commonly used measures referenced in literature. This measures-oriented approach to model performance assessment focuses on several different aspects of overall accuracy or skill of the streamflow model.

The statistics used are intended to give a range of information (12). The correlation coefficient is used to measure how good the simulated result reproduces historical patterns. The root mean square statistics is sensitive to extreme events, such as high

streamflow peaks and flooding. A low root mean square result would indicate high performance at matching the peak flows. The mean absolute error gives a performance indicator that is more equally weighted between assessing the simulation of both low and high peaks.

The maximum absolute error shows the value of the largest deviation between the observation and the model, usually the largest high flow peak that was unable to be reproduced by the model. The bias statistic gives an indication if the model is systematically under or overestimating the streamflow. Because of the square of the differences in the Nash-Sutcliffe measure, it is extremely sensitive to high flow events. The range for the Nash-Sutcliffe is between one and negative infinity. If the Nash-Sutcliffe (16) result is a negative value, the mean of the observations is statistically better than the model results.

Statistical Measure

Formula

Correlation coefficient, r ,

$$\rho = \frac{\sum_{t=1}^n (O_t - \bar{O})(S_t - \bar{S})}{\sigma_o \sigma_s}$$

$$\text{where: } \sigma = \sqrt{\frac{\sum (y - \bar{y})^2}{n-1}}$$

Root mean square

$$rms = \sqrt{\frac{1}{n} \sum_{t=1}^n (O_t - S_t)^2}$$

Mean absolute error

$$mae = \frac{1}{n} \sum_{t=1}^n |O_t - S_t|$$

Maximum absolute error

$$\max ae = \max_{1 \leq t \leq n} |O_t - S_t|$$

Bias or mean daily error

$$mde = \frac{1}{n} \sum_{t=1}^n (O_t - S_t)$$

Nash-Sutcliff measure (R^2)

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

Where: S_t is the streamflow measurement data for each daily time step and O_t is the corresponding model estimations

5.5 Model Verification

After a model is calibrated for a given calibration period, its verification by independent historical data and the calibrated model parameters need to be carried out. Model verification for the Upper Awash Basin was done for the five years daily input data set (1996-2000).

6 Results and Discussion

The main objective of this thesis is to determine the value of the parameters for reliable estimation of daily runoff from daily rainfall record or daily rainfall estimate for the Upper Awash Basin. Simulation was done using the FEWS-SFM for the part of the Awash River Upstream of the Koka reservoir. The outlet of the basin is defined at Melka Hombole hydrologic station. This station is situated about 40Km upstream of the reservoir and has relatively consistent record of daily streamflow.

FEWS-SFM is a wide area continuous stream flow model. The model does a daily water accounting based on the moisture content of the soil and the ground water reserve. To avoid formation of single cell basin during basin delineation, the recommended minimum number of cells to generate a stream flow is 500. For this simulation the area for a single basin formed from grid cells of size 100m will be 5Km². But for a wide area stream flow model the area of the basins to be considered should be greater.

In simulation process the output of the model is only as good as the input data. The physical characteristics of the basin are entertained in the various parameter values of the subbasins. The accuracy of the default parameter obviously rely on the extent of detail of these input data. The DEM, for instance, was prepared from 1:250,000 scale topographic map with additional input from the largest scale map available (1:50,000). The watershed delineation, therefore, is as reliable as the topographic map. From the discussion in section 4, the DEM were corrected in Becho plains and in the plaine areas that separate the Awash Basin from the Rift Valley Basin based on the field observation and satellite image.

Soil as a major media in the rainfall runoff process, needs to be carefully prepared and its influence in the rainfall runoff process properly established. The soil data was compiled from digitized soil type map of 1:500,000 scale. For most of the soil types in the Upper Awash Basin, the corresponding globally averaged values of the different properties were assigned. The global average value could potentially introduce error unless supplemented by investigations made in the basin to determine such soil properties. Furthermore, FEWS-SFM is developed only for three classes of textures: clay, sand and loam. Constant

values for various soil properties such as the field capacity and soil moisture were functions of the texture. This leads to lumping of soils of different categories into one group, ultimately contributing to error in the output.

The land use/cover data was obtained from a pilot project under the Ministry of Agriculture. The raw data was processed to comply with the format of the FEWS-SFM as illustrated in section 4. The land use/cover data has no specific indication of the time it was prepared. Land use/cover is quite sensitive to the pertaining weather condition of each year. Hence, land use/cover is a semi-dynamic input. Effect of urbanization and other similar changes were not considered separately in the data preparation. A single value of land use/cover was used. Variations were taken care of in the model through adjustments of the runoff curve number for different seasons based on the soil water content.

To assess the models best performing module and the catchment property at different locations three simulation scenarios were considered based on the number of subwatersheds. In the first scenario the upper awash is lumped into a single basin with the outlet at Melka Hombole, generating single parameter value and is efficient in computation time and calibration. In this scenario the model generates the parameters for the entire catchment and the channel routing component was not dominant. The model uses the overland flow routing component to determine the flow hydrograph at the outlet.

The second scenario divides the Upper Awash Basin into six subbasins. Six values for each parameter were generated and these parameters were calibrated based on the physical properties of the subbasins (Figure 6-1). This scenario makes use of the channel routing module of the model to route the inflow from the outlet of the upstream subbasin(s) to the upstream end of the subbasin downstream.

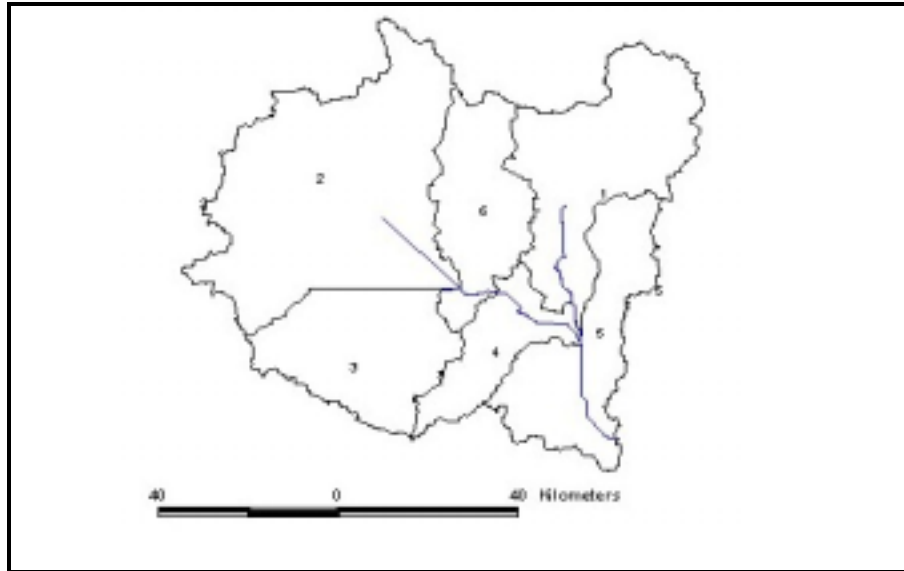


Figure 6-1 Scenario II of the watershed division.

Through further division the last scenario was established from thirty five subbasins. Here the features of the model obtained in the second scenario were amplified. For every increase of the number of subbasins the computation time becomes higher and hence this work is limited to thirty-five subbasins. The layout and division of the subbasins for the three scenarios is shown in Appendix A.

For the development of the model parameters ten years data (1991-2000) was considered. The data includes the daily record of stream flow at the Melka Hombole station and the daily record of rainfall of 34 stations and evapotranspiration ten stations. The first five years were used for the calibration and the remaining five years observed data were used for the verification of the model.

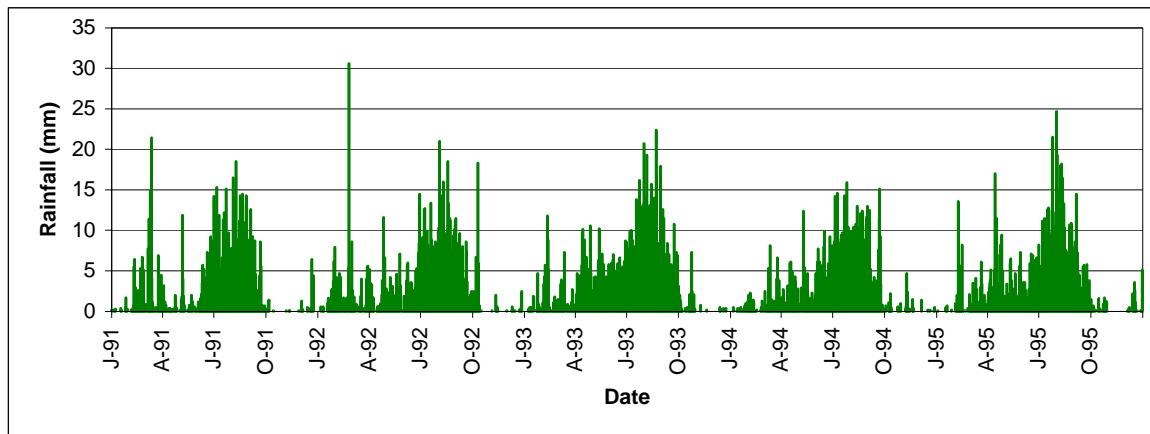


Figure 6-2 Daily Rainfall hytograph (1991-1995) of the upper awash catchment.

The interpolated rainfall and potential evapotranspiration (PET) data were used to obtain the subbasin average rainfall and PET values for the respective simulation scenario. However, the lumped result of the first scenario was used to visual comparison of the variation of the flow at the Melka Hombole outlet for all the cases.

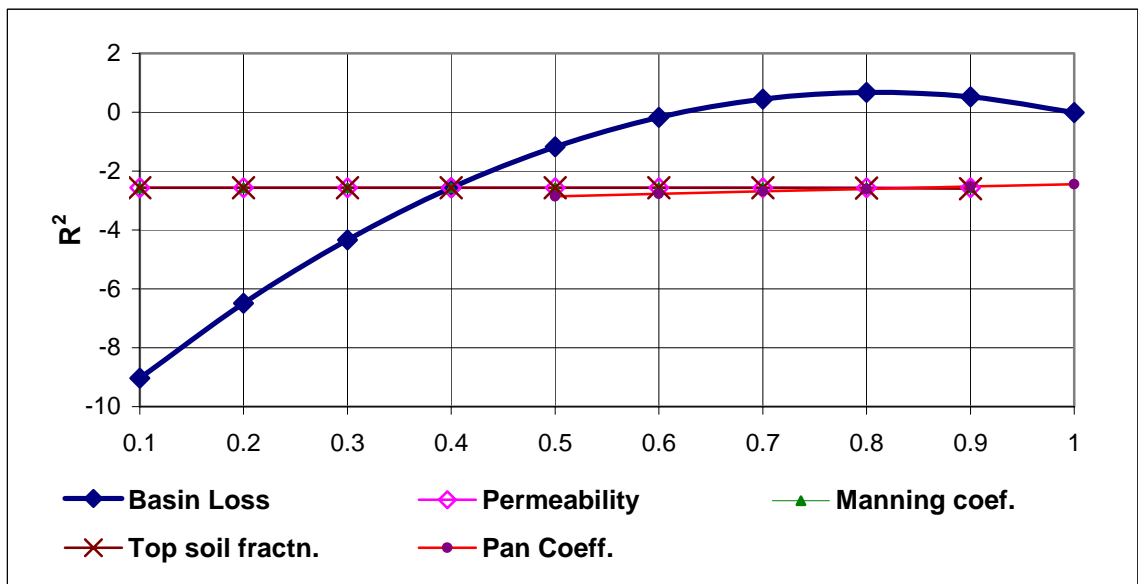
The simulated flow generally follows the rainfall pattern, but the calibration is dependent on how good the simulated runoff repeats the historical record. Anything wrong with either the rain gauge or reading its value affects the simulation result. Error in reading of the staff gauges or in the fitted rating curve of the hydrologic station end up in wrong “observed” flow value. It is quite difficult to trace which of these inputs had gone wrong in the calibration process. For instance peak flow of $526.2\text{m}^3/\text{s}$ has occurred in July 29, 1993 but the respective rainfall value was 4.2 mm in same day and 8.8 mm for the previous day as shown in Figure 6-8. Similarly, peak flows were simulated in 1992 where the observed flow is quite low. According to the observer assigned at Melka Hombole station, peak floods of the 1996 were not recorded due to the overflowing of the river above the staff gauges. Visual observation of the observed hydrograph in Figure 6-8 shows an error either in the rainfall record or stream flow record. The peak flow is not accompanied by a higher rainfall record, which could not happen for a deterministic model.

Comparison of daily flow records at Melka Hombole and Melka Kunture, upstream of Melka Hombole, also showed considerably higher flow records upstream than Melka Hombole for about two weeks, where it takes not more that a couple of days for a peak flow to to reach Melka Hombole, as shown in Table 6-1.

Table 6-1 comparison of flow records at Melka Hombole and Melka Kunture

Date	M. Hombole (m ³ /s)	M. Kunture(m ³ /s)
18-Aug-97	119.087	163.154
19-Aug-97	116.688	148.916
20-Aug-97	110.425	121.341
21-Aug-97	103.611	116.847
22-Aug-97	218.717	102.854
23-Aug-97	166.102	98.736
24-Aug-97	117.485	100.784
25-Aug-97	85.961	77.661
26-Aug-97	68.965	65.624
27-Aug-97	61.529	146.4
28-Aug-97	38.99	85.962
29-Aug-97	38.564	73.24
30-Aug-97	30.963	60.003

Sensitivity of the model parameters was done for the first scenario treating the basin as a single watershed and hence single outlet. The water holding capacity of soil, the soil depth, the runoff curve number and the basin loss are found to be sensitive to change in parameter values and the remaining parameters are not so sensitive to change the hydrograph and the statistical measures as well.



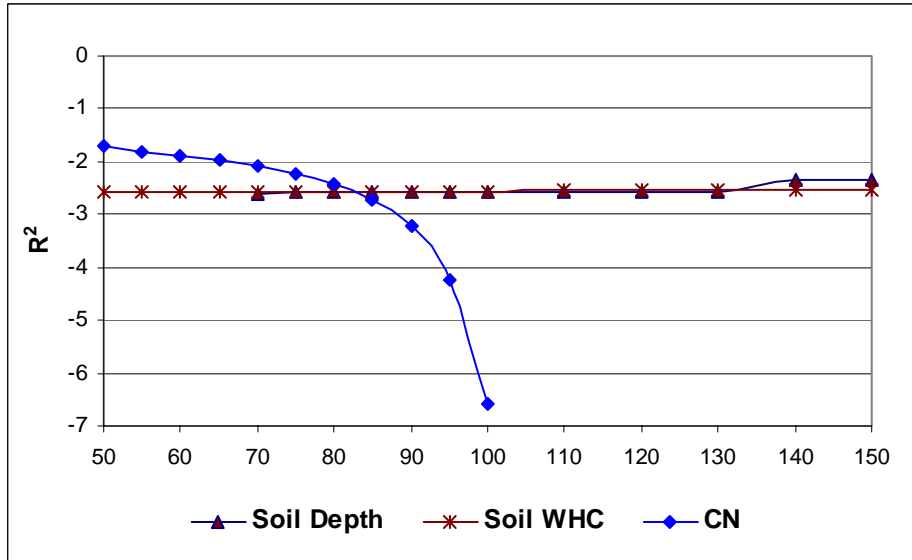


Figure 6-3 Sensitivity of FEWS-SFM parameter for the Upper Awash Basin.

The default run for all the three scenarios exaggerated the flow. From the parameters sensitivity investigation, the base flow or the ground water recharge coefficient plays a major role in the reduction and adjustment of this overestimated flow. The five years calibration period average observed flow was 42.69m³/s, while the model produces average flows of 148.69, 150.30 and 156.14 m³/s for scenario I, II and III respectively (Table 6-2).

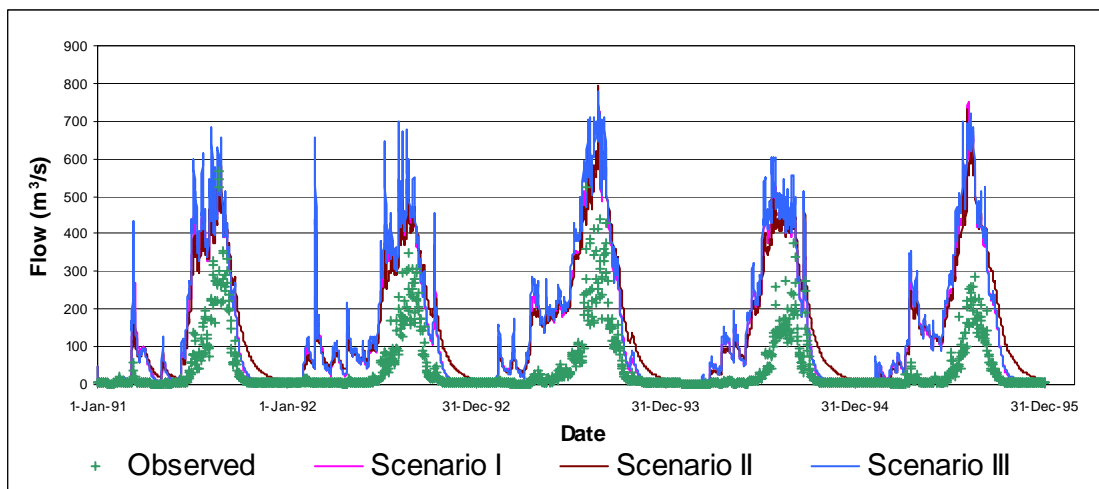


Figure 6-4 Historical flow Record and Default simulation Result

No particular stopping criteria were set to end the calibration process. However, Visual observation of the simulated and observed hydrographs plotted to same scale and daily

average rainfall of the basin in same base time scale was used to evaluate the performance of FEWS-SFM. For a satisfactory visual fit of the hydrographs, statistical performance investigation were further carried out and the best simulation parameters were selected based on the Nash and Sutcliff goodness of fit (R^2).

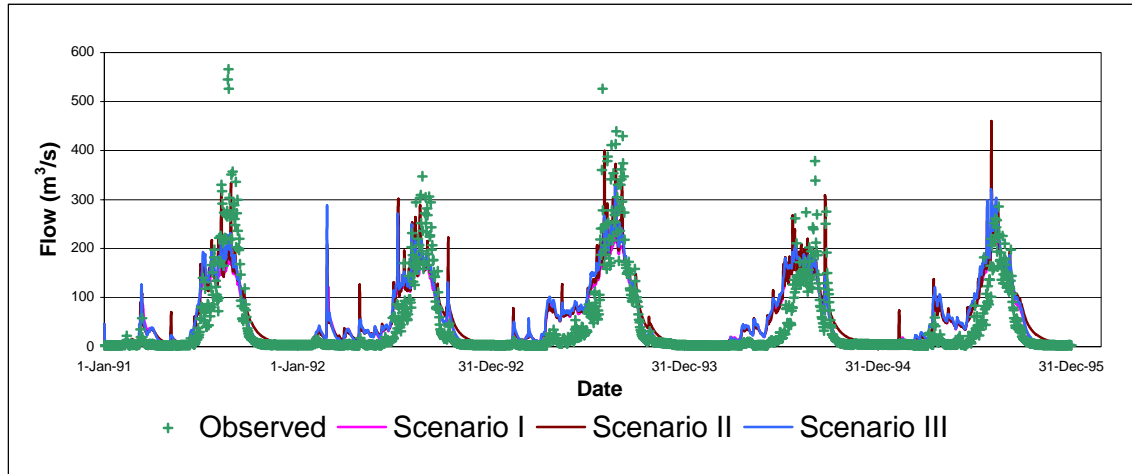


Figure 6-5 Historical flow Record and Calibrated simulation Result.

Table 6-2 Statistical results of default and calibrated results for the three scenarios.

Scenario	I		II		III	
	Default	Calibrated	Default	Calibrated	Default	Calibrated
Q_{omean}	42.69	42.69	42.69	42.69	42.69	46.84
Q_{smean}	148.67	51.23	148.81	60.29	172.43	49.00
Correlation	0.83	0.83	0.84	0.83	0.81	0.84
RMS	141.32	44.73	150.30	47.75	156.14	22.61
Mean_abs_err	0.0016	0.0016	0.0015	0.0015	0.0012	0.0012
Max_abs_err	589.59	397.37	533.81	359.88	647.65	365.17
Bias from mean	-98.40	-8.45	-107.36	-17.50	-113.20	-0.35
Nash and Sutcliff	-2.57	0.68	-2.57	0.63	-3.80	0.69

To maintain the low flow value for the first scenario was difficult because the model assigns zero value for peripheral subbasins and a minimum value of $0.1m^3/s$ for internal subbasins. Similar situation existed for the second scenario as well. Better result was observed for the third scenario.

In the calibration process the model performs better for the wet season, in particular rainfall periods of uniform distribution. As described thoroughly in section 2 of this document, the Upper Awash Basin exhibits two distinct rainy seasons. The 1993 simulated flow hydrograph (Figure 6-7) shows an overestimation during the low rainfall

periods (April-July) and a relatively good estimation of the runoff for the summer rainfall (July-September). The wet season flows of 1992 and 1994 were some how uniform hence appreciably simulated whereas peak flows such as the 1993 were not caught by the model. From such observations the rate of response of the model for low precipitation values is higher as compared to heavy summer rainfall. Figure 6-8 shows the flow hydrograph which caused severe damage downstream of the Koka reservoir. The 1996 flow was used for verification of the model parameters. Substantial underestimation of the peak flows was observed. The extent of over prediction for the small rain period is fair as compared to the other verification years.

The FEWS-SFM overestimated the streamflow for the first rain season (April – July) which has low amount of rainfall while the peak flow during heavy rainfall season (July – September) is generally underestimated. The simulated stream flow hydrograph crosses the observed flow hydrograph in the mid of September overestimating the flow in the recession limb. This could be the result of the good deal of rainfall that entered to the ground water reserve instead of producing the peak flow during the summer.

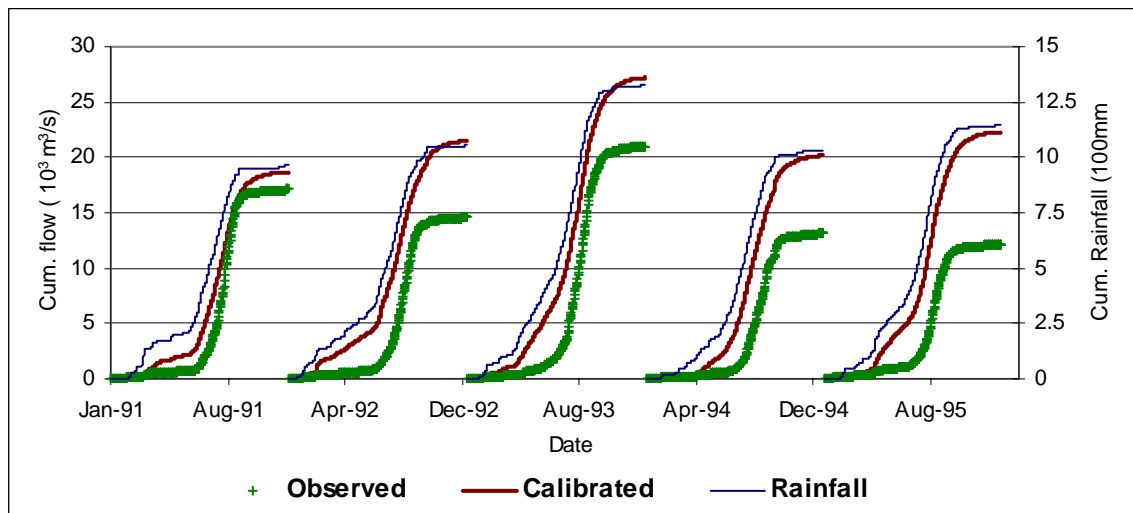


Figure 6-6 Mass curve for rainfall, observed stream flow and simulated stream flow

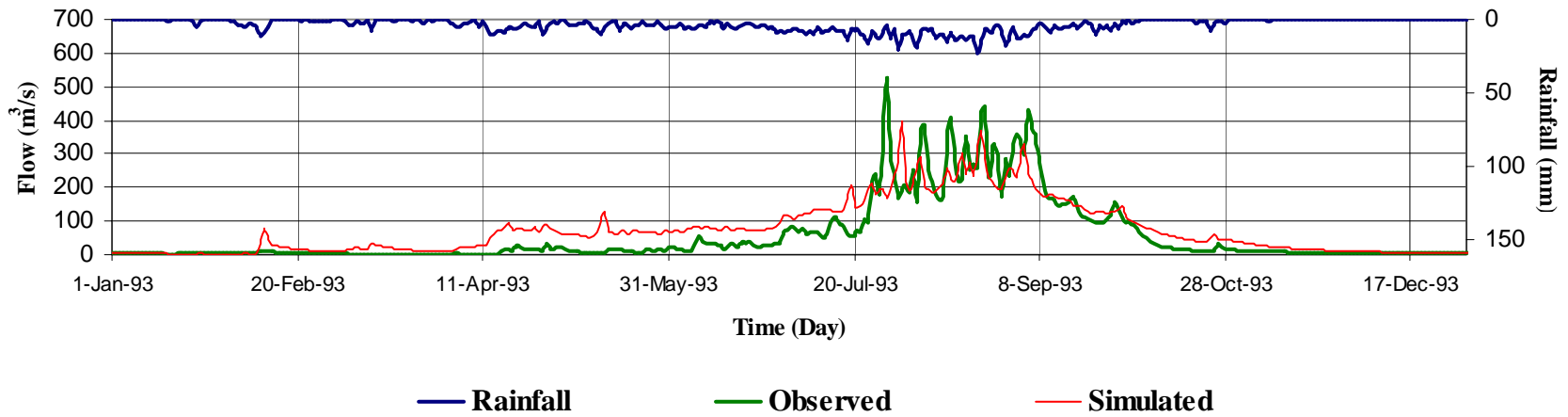


Figure 6-7 Simulated and observed hydrograph at Melka Hombole for the year 1993

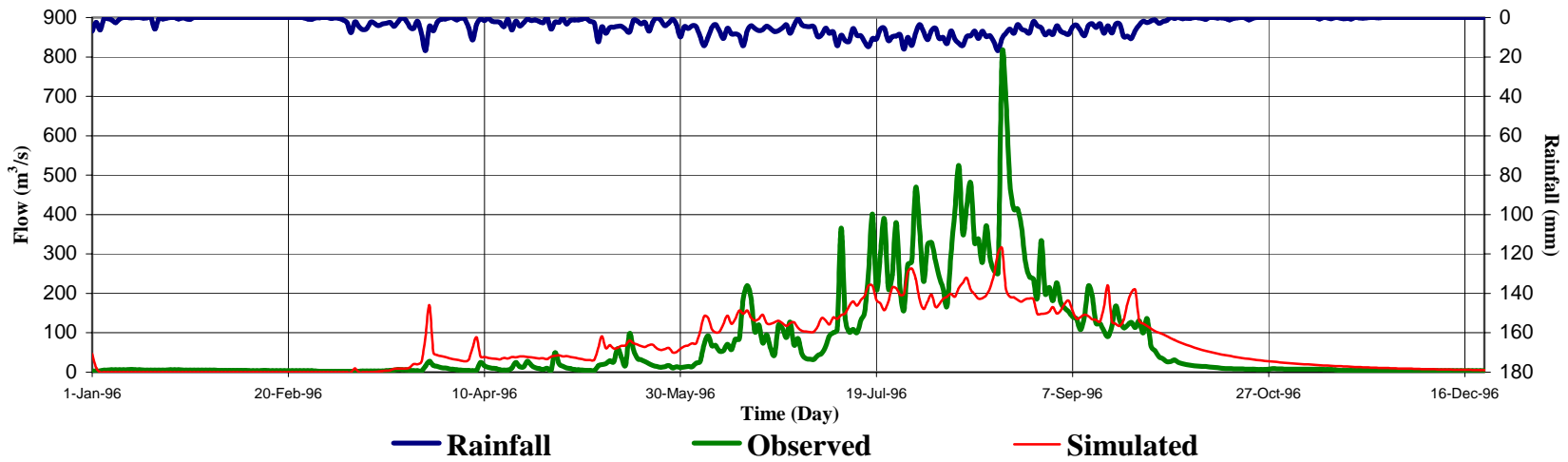


Figure 6-8 Simulated and observed hydrograph at Melka Hombole for the year 1996

The statistical measures employed for this study are devised to give wide range of information on the performance of the model. For the respective scenario three model results are considered based on the Nash and Sutcliff goodness of fit criteria (Appendix C). The remaining statistical measures are then compared and the best model parameter and basin combination is selected.

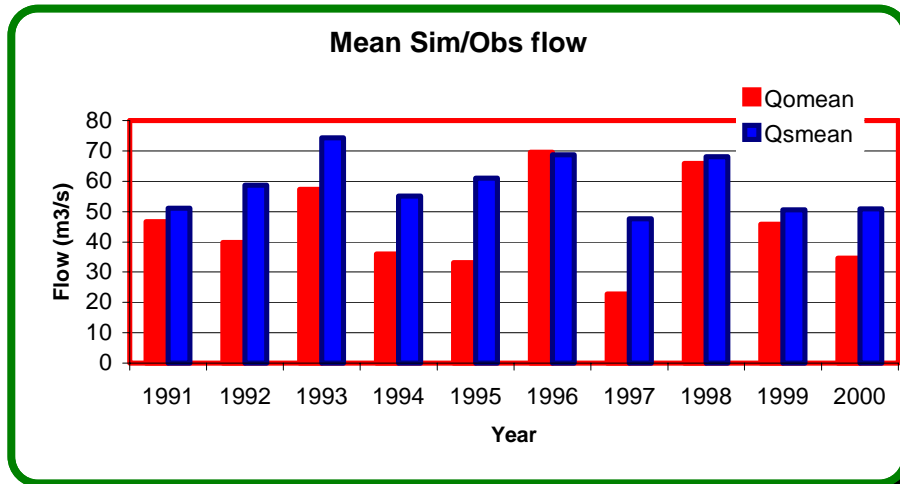


Figure 6-9 The annual average of observed flow and simulated flow.

The correlation between the historic and simulated streamflow values are with in the range of 0.80 –0.85, indicating that the model has captured the pattern of the historical record.

The root mean square (rms) value measures the models adequacy in matching the peak flows. The rms value obtained for the best run of scenario III is half of the other two scenarios. Hence, further division of the basin with a cost of computation time could result in a better rms value.

The maximum absolute error searches for the highest deviation of the historic record from the simulated flow. All the three scenarios showed very similar results as shown in Table 6-2. This value can be attributed to error in recording the rainfall data.

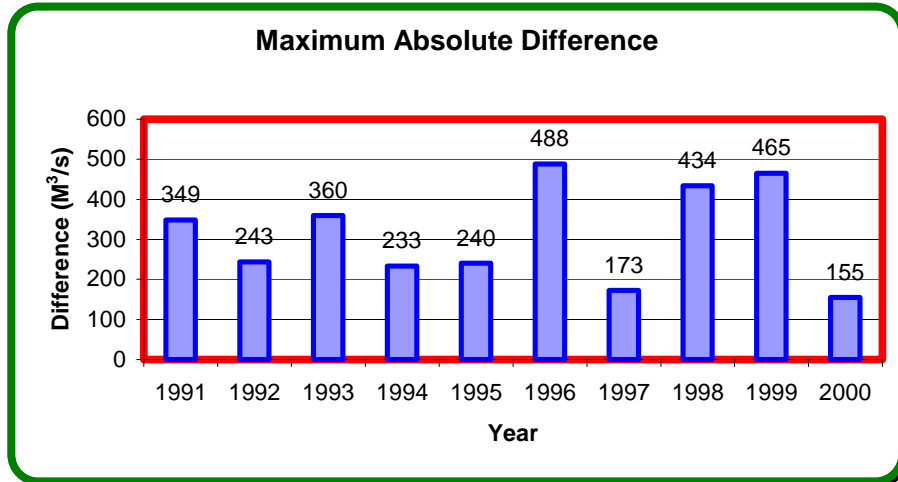


Figure 6-10 Maximum deviation of the simulated flow from the historical record.

Bias from the mean value simply indicates the variation of the mean of historical record and the simulated data. The model at its best calibration has given a higher average value for all the scenarios hence a negative value.

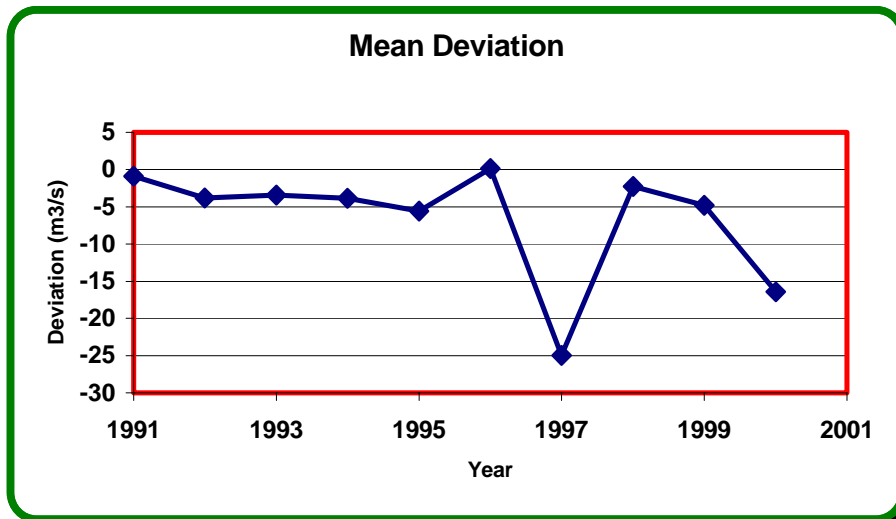


Figure 6-11 Deviation from the mean of each year of model run

The Nash and Sutcliffe goodness of fit criteria was the main statistical measure in the calibration. Though higher values were obtained for the third scenario, the second scenario ($R^2 = 0.63$) is taken for its better performance during verification ($R^2 = 0.60$) as shown in Figure 6-12. From visual observation, scenario II has given the best fit of daily extreme floods, while the other two cases produce a smooth hydrograph with better R^2 value but missing the daily variation.

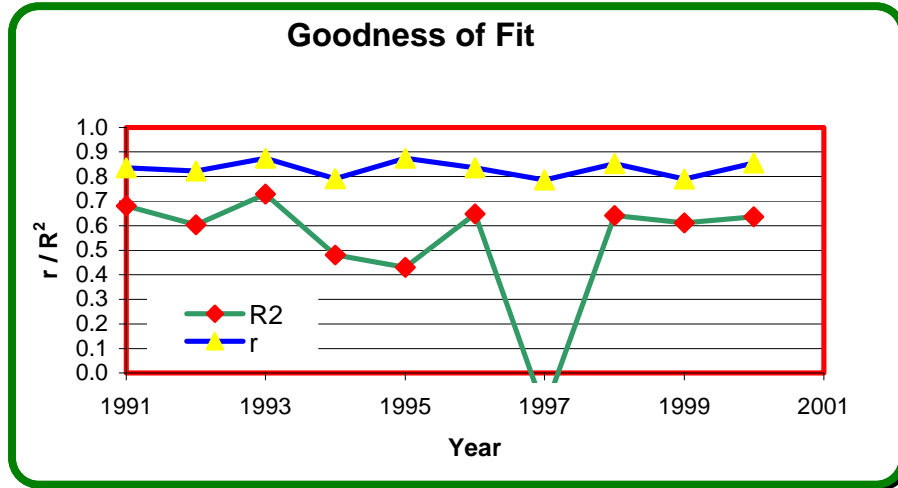


Figure 6-12 Yearly Correlation and Nash-Sutcliff coefficient for the simulation.

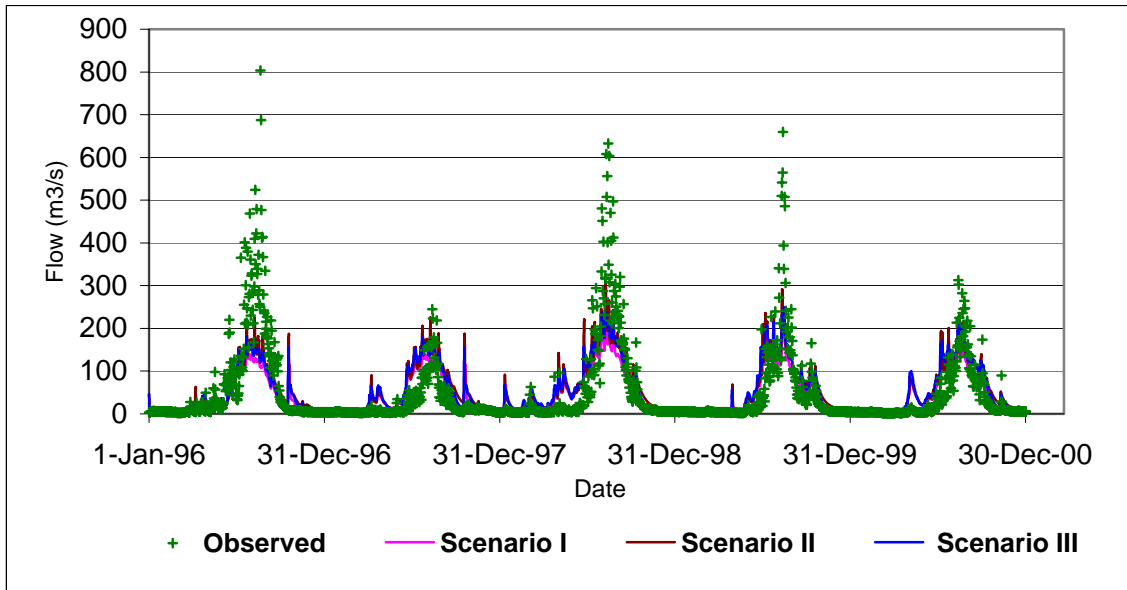


Figure 6-13 Historical flow record and verification result of the three scenarios.

Table 6-3 Model verification statistical result

Scenario	I	II	III
Q_{omean}	47.95	47.95	47.95
Q_{smean}	60.39	57.58	55.55
Correlation	0.80	0.81	0.80
RMS	36.65	36.44	35.97
Mean_abs_err	0.004	0.003	0.003
Max_abs_err	548.54	488.04	578.54
Bias from mean	-5.91	-4.83	-3.58
Nash and Sutcliff	0.60	0.60	0.61

7 Conclusion and Recommendation

While hydrologic models are used for important applications, such as forecasting and preparing for drought and/or flood hazards, they should also be considered as a tool for learning about a place. The uniqueness of each watershed must be captured in model parameters in order to properly represent the physical processes at work. At one level, the uniqueness of watersheds can be captured by use of distributed geo-spatial information from soil and land use databases. On the other hand, the resolution of model calculations developed to represent processes at the field scale will never exactly fit the applications at the basin scale.

The production of dependable stream flow model gives better knowledge of the surface water resource. Hence with a well calibrated model one can give satisfactory result to take care of the extreme events. For this particular work, though the main objective is to simulate the rainfall runoff process in the Upper Awash Basin. The data collected to define the problem of the basin in relevance to importance of stream flow simulation showed that the main challenge was the peak summer flow causing flooding downstream of the Koka dam. This flooding is due to the release of water from the reservoir during heavy summer inflows from the upper catchment at downstream and flood inundation in areas such as Teji, Tefki and Liben Ziquala.

The FEWS-SFM is a semi-distributed model. Basically the model first produces the parameters necessary for a watershed by using the different spatial analyst tools of the ArcView to obtain the average value of the parameters needed for the model. For such purposes the selection of the number of grids to generate the aerial extent of a basin is not provided to the users. The only information is that one has to use at least 500 grids for a grid size of 1kmx1km so as to get rid of the formation of single cell basins. Further investigation should be carried out on how to consider the basin topography and relate it to the basin boundary. Minimum criteria need to be set in explicit manner to decide the size of the subbasins.

In this simulation the major importance of simulation is at the downstream. The presence of a dam and hence an artificial lake poses a challenge as the model at it stands now

couldn't consider such structures. All the data for the entire catchment was collected and prepared for investigation and only the simulation was done for the upper part.

During simulation in the first scenario obtaining a single parameter that describes the response of the catchment within acceptable water balance was difficult. From the historical record at Hombole, quite sharp flood peaks prevail on a more gradually varying hydrograph. From the second scenario it was seen that the main hydrograph originates from the upper reaches of the catchment, whereas the peak flows result from runoff in the mountainous area upstream of the Hombole Station. Hence in the second scenario an improvement was made in the catchment response.

The third scenario though gives a much refined subbasin parameters, the adjustment of parameters was done only by incrementa values that apply to all the subcatchments by applying a macro made for this purpose. While adjusting these parameters the runtime was also a constraint as it takes much time for a single run to be completed, checked visually and statistically for its performance. Despite all the constraints the simulation was done and the result with the best statistical measure has less visual fit with the historical record. Furthermore, the size of some of the basins was small to be worked on with a wide area stream flow model like FEWS-SFM.

The FEWS-SFM overestimated the stream flow for the first rain season (April – July) which has low amount of rainfall while the peak flow during heavy rainfall season (July – September) is generally underestimated. The simulated stream flow hydrograph crosses the observed flow hydrograph in the mid of July and September overestimating the flow in the ascending and recession limb.

The underestimation and overestimation of the model for the dry and wet periods respectively can be attributed to its being parasimonous and its sensitivity to different ranges of rainfall records. From the overestimation of flow before July, it can be concluded that the model responds more to low rainfall values. On the other hand the overestimation after September is due to high precipitation that entered to the ground water reserve instead of producing the peak flow during the summer. Furthermore, the geomorphological data used for the model is a 100m DEM produced from maps of scale

1: 50,000 and 1: 250,000. Hence the basin characteristic such as the slope that affect the lag time and basin surface runoff are dependent on the value.

Vertisol is the dominant soil type in the Upper Awash Basin. Due the nature of this soil wide cracks form during the dry season increasing the infiltration rate. The soil volume keeps increasing till it fills all the cracks and during the heavy summer the soil attains its field capacity which leaves much of the precipitation to surface runoff generating higher streamflow. The catchment is mainly a grass land and hence detains most of the rainfall falling on the first rainy season. This could be one of the reasons that the model overestimates the streamflow in the first rainy season and underestimate the second. Therefore, the performance of the model in such soil types may need further investigation.

The annual simulated hydrograph result the model has captured the variation of the stream flow with the rainfall. From the visual observation as well as the statistical measures of uncertainty, the model simulated the flow of the basin to an acceptable range. However, considering the annual water balance the simulated flow has overestimated the total annual flow.

Only three classes of soil texture were used in the model, which necessitates the division of the soil into loam, sand or clay. Intermediate properties need to be entertained in the model. The constant values assigned to the description of soil-water relation based on soil texture also need further experiment to assign the appropriate value. An option can also be made for the user to assign that constant value at least in the calibration phase.

The model takes the topsoil depth to be 10% of the total soil depth, but during calibration changing these parameter has do not show any improvement, that seems this parameter is “hard coded” and the change has no effect internally even though The top soil depth is where the overland surface runoff, interflow and ground water recharge.

As a simulation model, the significant underestimation of peak flows and dry flows encountered is a major drawback of FEWS-SFM in the Upper Awash Basin. Therefore, the extent of accuracy of the model needed for the purpose it is intended for should be taken into consideration. For instance, in its present calibrated condition the model can be

used for assessing the general response of the catchment for a given rainfall and could also be used to evaluate the pattern of flow at the outlet.

The manual calibration process makes the model less attractive. Simple visual basic macros were used to link the various input, output and processing files so that the exchange of data between them is simplified. Such modules could easily be included in the main code of the model to make it semi automatic in the process of calibration.

However, the capability of FEWS-SFM to be used for both ground data and satellite derived data worth its modification. A 100m DEM and ground observed data were used for this study, but during the final stage of this work raw DEM of 85 m grid sizes were available for Africa free of charge. Updated Land use/cover data can also be downloaded from the Internet. Daily rainfall and potential evapotranspiration estimation is also becoming easily available. Hence, this model deserves further work on its soil-water interaction, so that its advantage in the country's context could be extracted.

It should be the commitment of users and designers of hydrologic models to constantly be improving the simulation of the physics of water flow, use of spatial data for basin-specific parameter estimation of the physics of water flow, use of spatial data conceptualization and implementation in order to improve the operations, reliability, and robustness of the model. Taking this fact into consideration, study is in progress at WRC to include the reservoir routing module for the FEWS-SFM model. This will enable routing the flow through the Koka dam and hence one can easily determine the flow condition downstream of the dam where the flood hazard is significant. Therefore upcoming researchers can use this result to include the reservoir routing and produce a refined model.

Lack of digital and consistent data is the cause for the delay of most Water Resources studies in Ethiopia. Building better data base from the various input data prepared for different researches reduces the burden of upcoming researchers through providing more time for the analysis than data input.

Finally, further study in the physical properties of the basin, the various coefficients can be adjusted in the model in a way to suit the countries situation. With a full coverage and

preparation of input data in a country wide basis, helps to evaluate different models and select the most appropriate one.

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Appendices

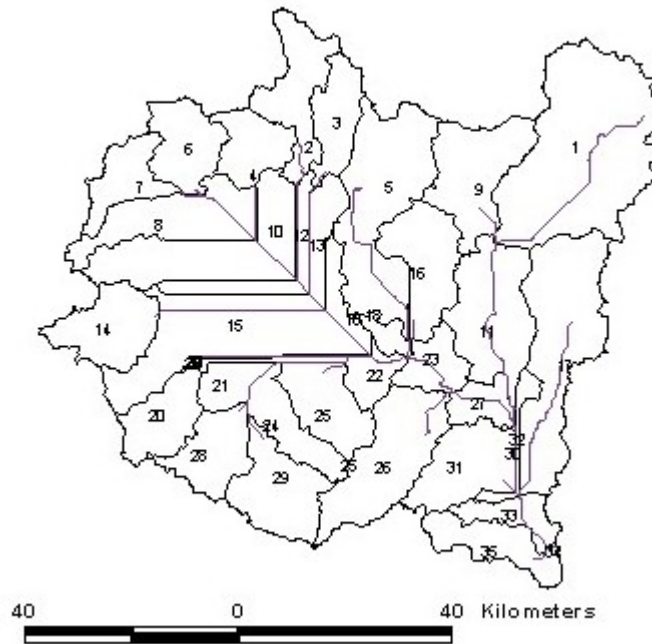
Appendix A Basin Shape file for the three scenarios.



Scenario I. Single basin



Scenario II. Division into Six Subbasins



Scenario III. Division into thirty five subbasins.

Appendix B Default and Calibrated Basin Parameters for the selected Scenario

Parameter.txt

Default

```
16      // MAXPAR, number of model static parameters, do not change
1826    // MAXTIME, number of days of model run
1991    // startyear, four digit year for the start of the simulation
1  // startday, day number (1-366) for the start of the simulation
1      // MAXSUBBASINS, number of subbasins
500     // MAXLINE , maximum length of an output printed line
1000    // MAXTOPOL, data level of the Pfafstetter topological system if the HYDR01K is used
0.1     // soil2top, fraction of the top soil layer of the hydrologically active soil layer
24.0    // hour2day, number of hours in a day
0.85    // Kc, pan evaporation coefficient
0  // model initialization mode, 0 for no initialization and 1 for initialization of state
variables from file
0.8     // InitialWetness, if no initialization, multiply field capacity by this number
```

Calibrated

```
0.35    // soil2top, fraction of the top soil layer of the hydrologically active soil layer
0.85    // Kc, pan evaporation coefficient
```

order.txt

```
BasinID
5
4
6
2
1
3
```

response.txt

BasinId	5	4	6	2	1	3
0	0.565507	0.645571	0.668735	0.279665	0.207358	0.391386
1	0.412182	0.354429	0.331265	0.700235	0.501652	0.608614
2	0.022311	0	0	0.0201	0.288964	0
3	0	0	0	0	0.002026	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0	0	0	0	0	0
11	0	0	0	0	0	0
12	0	0	0	0	0	0
13	0	0	0	0	0	0
14	0	0	0	0	0	0
15	0	0	0	0	0	0
16	0	0	0	0	0	0
17	0	0	0	0	0	0
18	0	0	0	0	0	0
19	0	0	0	0	0	0
20	0	0	0	0	0	0
21	0	0	0	0	0	0

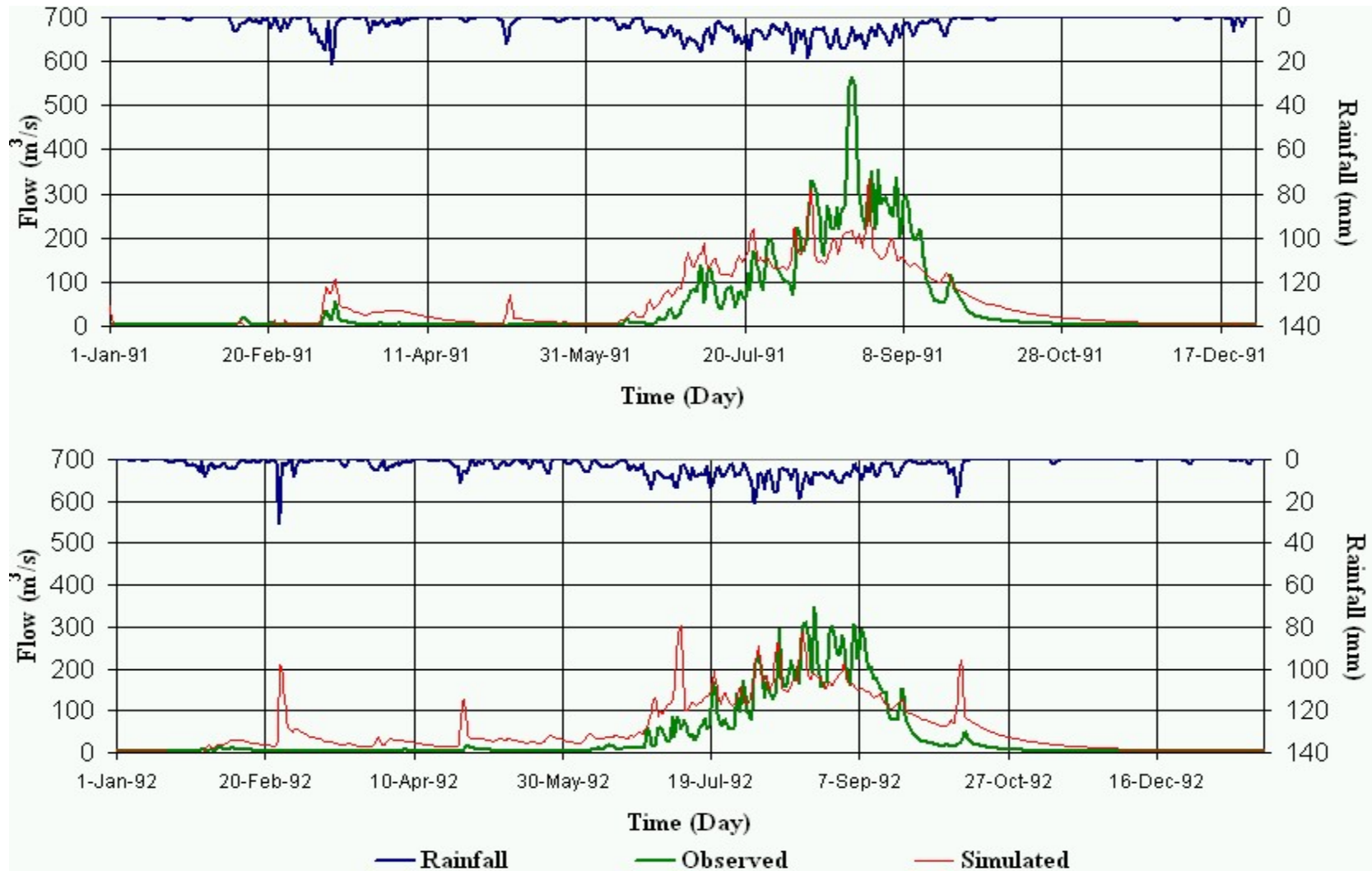
Basin.txt

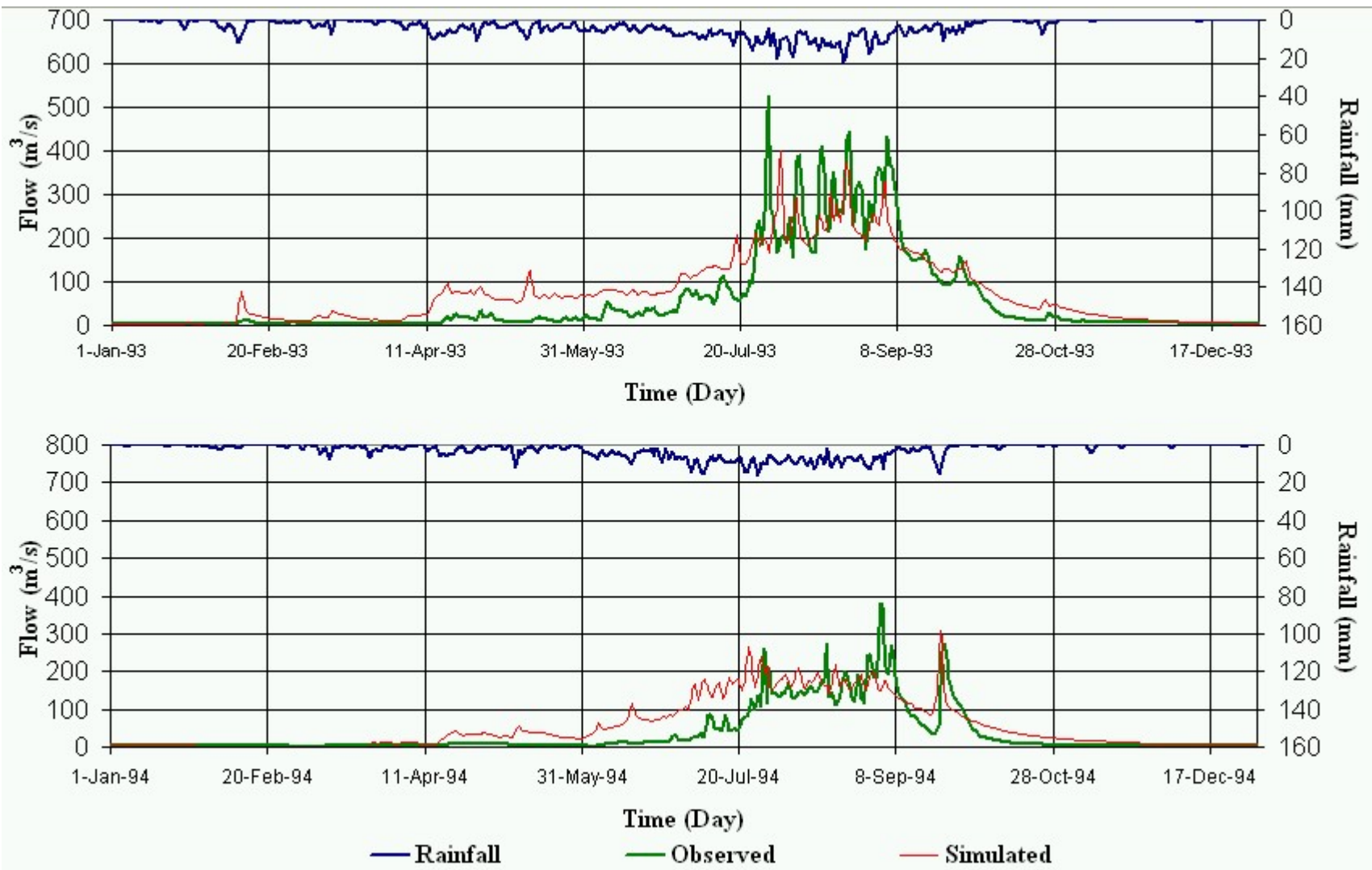
	Default (Measured)						Calibrated					
BasinID	5	4	6	2	1	3	5	4	6	2	1	3
SoilWHC	100.508	133.607	82.1552	78.1959	73.5189	80.9543	80.508	160.607	82	80	100.5189	80.9543
SoilDepth	143.779	152.801	141.134	129.839	139.506	142.208	123.779	180.801	141	100.839	160.506	160.208
Texture	2	2	1	1	1	1	2	2	1	1	1	1
Ks	0.204	0.207	0.178	0.186	0.167	0.081	0.204	0.207	0.178	0.186	0.167	0.081
Area	1065.39	556.2	876.92	2577.13	1440.95	1094.99	1065.39	556.2	876.92	2577.13	1440.95	1094.99
HLength	23594.9	15627.5	29387.8	27631.8	25097.8	33922.7	23594.9	15627.5	29387.8	27631.8	25097.8	33922.7
HSlope	0.9412	1.6862	0.9457	0.5009	1.0086	0.6769	0.9412	1.6862	0.9457	0.5009	1.0086	0.6769
UpArea	761157	510523	454903	257712	144094	109498	761157	510523	454903	257712	144094	109498
RivSlope	0.5255	0.7539	1.0121	0.001	0.7941	0.001	0.5255	0.7539	1.0121	0.001	0.7941	0.001
Elevation	1986.4	2317.4	2294.4	2325.6	2384.8	2356.1	1986.4	2317.4	2294.4	2325.6	2384.8	2356.1
RCNumber	82.5	82.4	83	82.8	82.9	84.3	60.5	65.4	75	85.8	75.9	65.3
RivLength	27968.1	26690.7	9759.81	23758.9	37779.4	3924.27	27968.1	26690.7	9759.81	23758.9	37779.4	3924.27
DownID	-9999	5	4	6	5	6	-9999	5	4	6	5	6
MaxCover	0	0	0	0	0	0	0	0	0	0	0	0
RivManning	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
BasinLoss	0.2	0.2	0.4	0.4	0.4	0.4	0.5	0.8	0.9	0.75	0.75	0.9
RiverLoss	0	0	0	0	0	0	0	0	0	0	0	0
HasDam	0	0	0	0	0	0	0	0	0	0	0	0

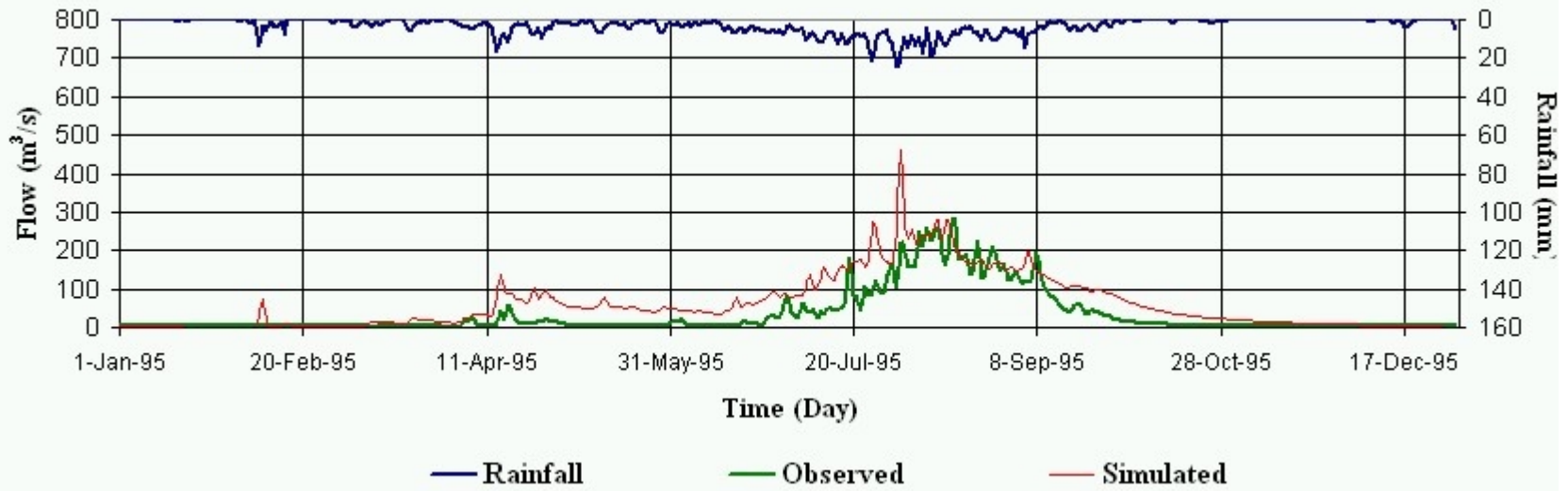
Appendix C Default and Calibrated Model Statistical results for the three Scenarios

Scenario	I				II				III			
	Default	177	145	41	Default	69	19	15	Default	6	8	13
Qomean	42.69	42.69	42.69	42.69	42.69	42.69	42.69	42.69	42.69	46.84	46.84	46.84
Qsimmean	141.32	50.52	48.37	51.23	150.30	49.11	56.14	60.29	156.14	50.48	49.00	51.96
rms	148.67	43.91	44.03	44.73	148.82	46.29	45.08	47.75	172.43	23.18	22.61	22.45
mae	0.0016	0.0016	0.0016	0.0016	0.0015	0.0015	0.0015	0.0015	0.0012	0.0012	0.0012	0.0012
max_abserr	589.59	402.77	387.07	397.37	533.81	394.47	392.87	359.88	647.65	364.07	365.17	356.07
Bias from mean	-98.40	-7.75	-5.60	-8.45	-107.36	-6.33	-13.35	-17.50	-113.20	-0.65	-0.35	-0.94
Nash and Sutcliff	-2.57	0.69	0.69	0.68	-2.57	0.65	0.67	0.63	-3.80	0.68	0.69	0.70
Correlation	0.83	0.84	0.84	0.83	0.84	0.82	0.85	0.83	0.81	0.83	0.84	0.84

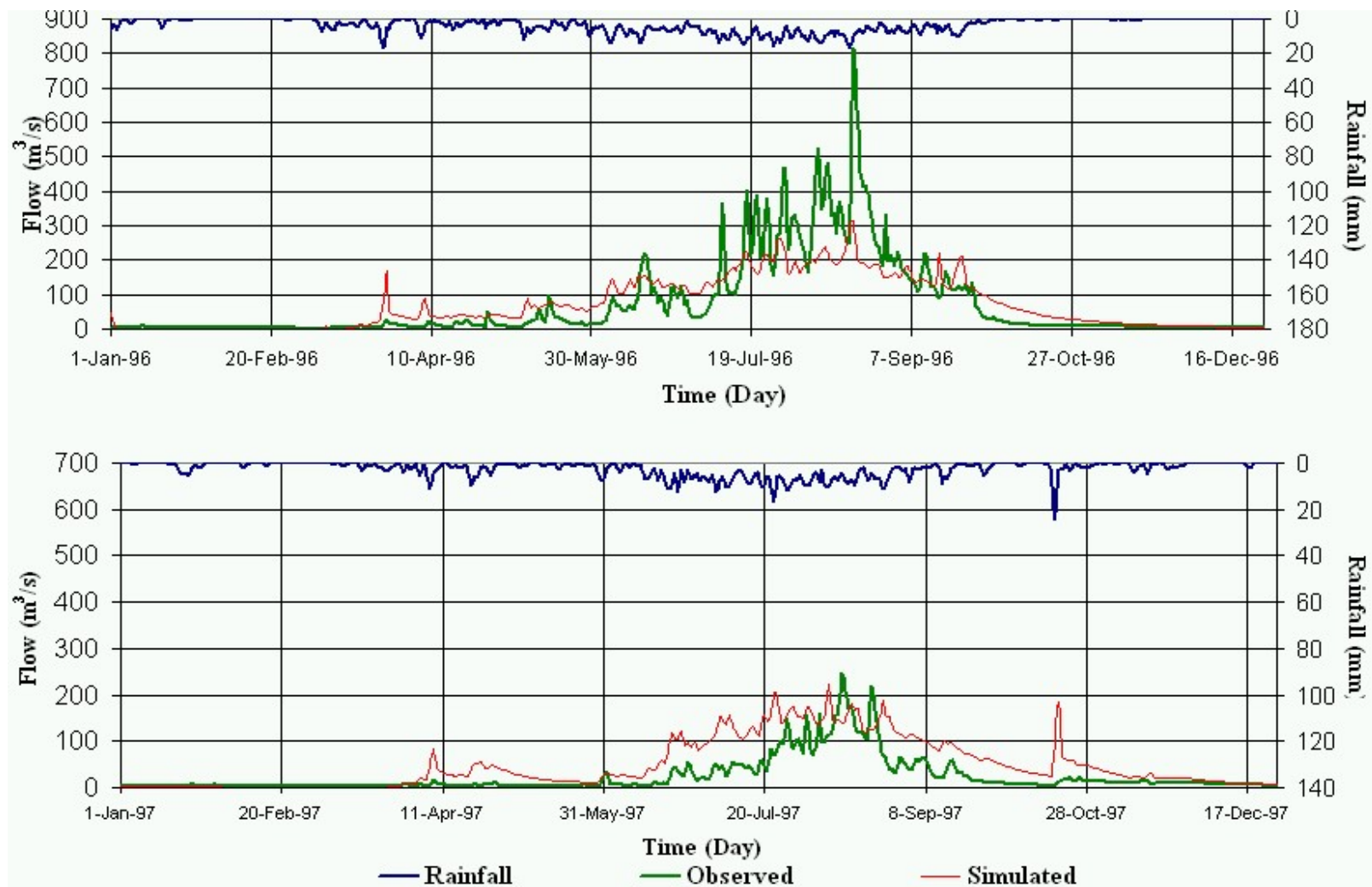
Appendix D Model calibration results

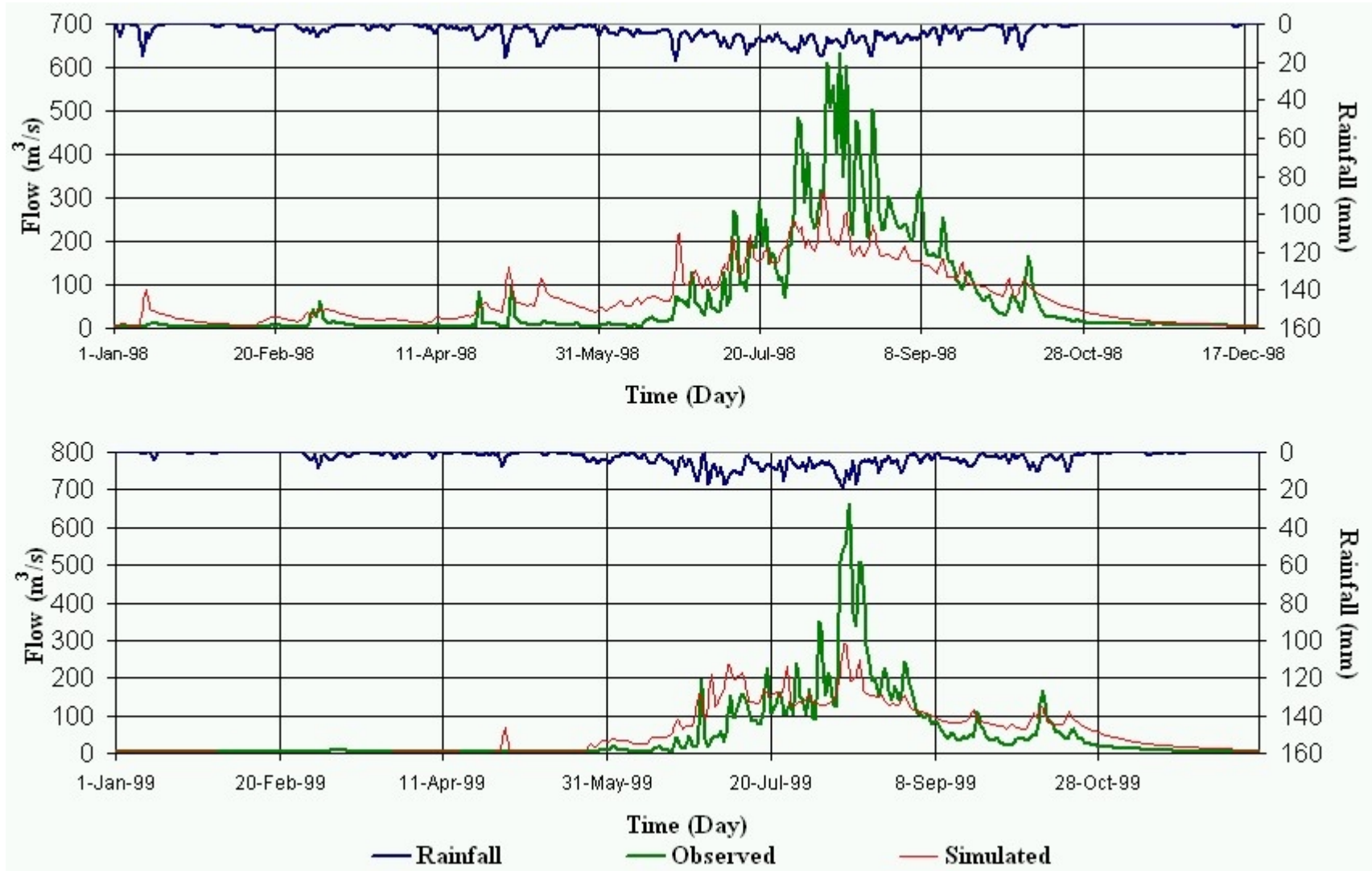


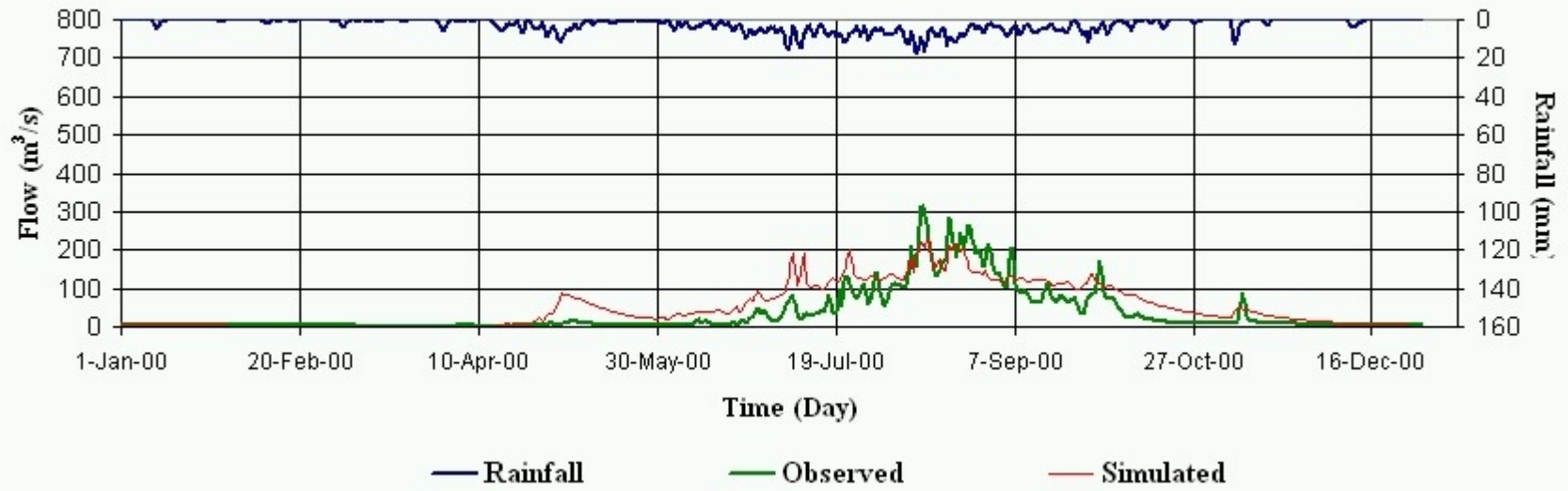




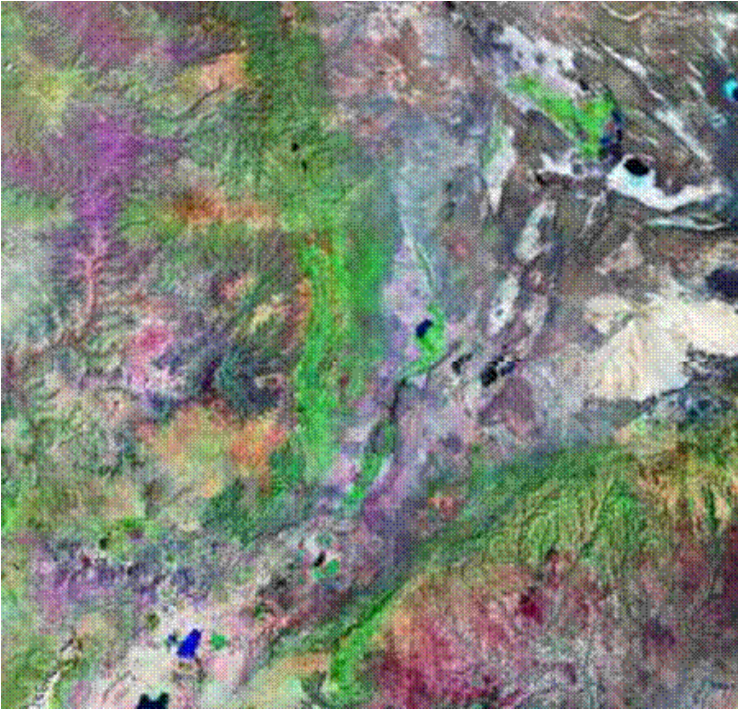
Appendix E Model verification result



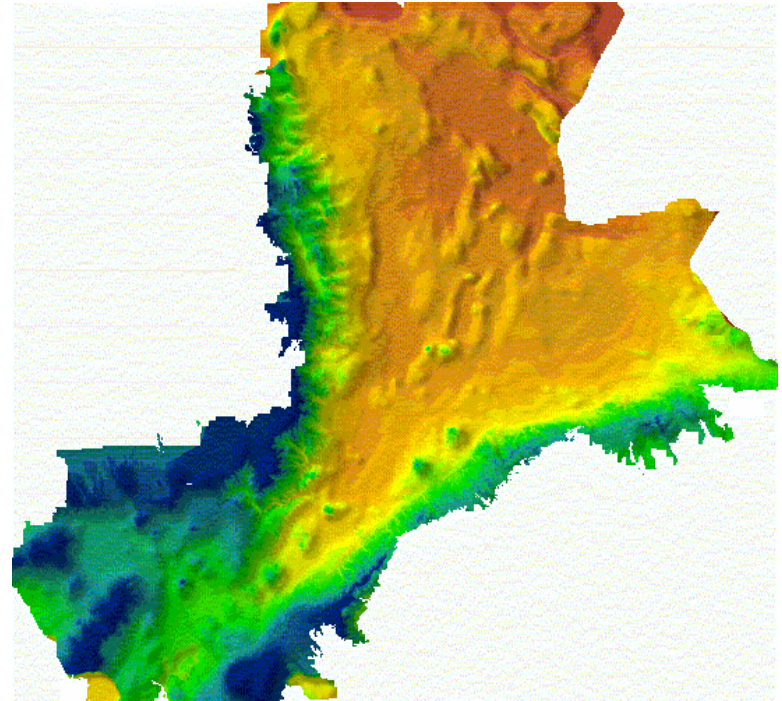




Appendix F Satellite image and DEM of Awash Basin.



i. Satellite image of Awash Basin



ii. DEM of Awash Basin

Appendix G Koka Dam



Pictures taken on June 4, 2004.

Appendix H Model output for the Calibration of the three Scenarios