ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
DEPARTMENT OF CIVIL ENGINEERING

Medium-Ranged Flood Forecasting for Upper Baro-Akobo River Basin:

Testing the applicability of European Flood Alert System (EFAS) methodologies to African small - medium scale river basins.

MSc Thesis

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

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Abstract

Flooding has always been a critical and common disaster in Ethiopia taking the lives of many people and livestock, displaced millions and destroyed a huge amount of the economy. The Baro-Akobo river basin - a trans-national river basin in Ethiopia located between latitudes of 5 ° 31` and 10 ° 54` N, and longitudes of 33 ° and 36 ° 17` E with an altitude range from 402m to 3106m - is one of the flood prone areas in the country which have been hit by different floods. In every rainy season news on floods in most of the river basins in the country is very common. Thus, establishing flood forecasting and early warning systems to the basin and the country as well is important.

In this paper, the methods of the European Flood Alert System (EFAS) are tested and adapted. EFAS is a medium range system to provide warning for flood hazards in European transnational rivers 3-10 days in advance of the floods. The LISFLOOD GIS based distributed hydrological model - underlying the EFAS system – was used with precipitation products from five different sources: TRMM (Tropical Rainfall Measuring Mission product of NASA), PRESSIAN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks product of University of Arizona), RFE (African Rainfall Estimation Algorism product of National Oceanic and Atmospheric Administration - climate prediction center), ERA-interim (product of European Center of Medium-Range Weather Forecasts (ECMWF's) and observed precipitation (interpolated by invers distance method).

Long time observed discharge data from the Ethiopian Minister of Water Resource and Energy were used for model calibration and verification. Additional input data are collected from 15 observed meteorological stations data around and in the basin from Ethiopian National Meteorology Agency, static data sets such as elevation data, leaf area index, soil data, land cover and others, and satellite precipitation data from Joint Research Centre (JRC) which were mapped for the African continent at 0.1^{o}grid scale. The model was calibrated using the SCE-UA (genetically adaptive approach for effective and efficient global optimization) algorithm. Both calibration and validation resulted in good scores for most precipitation datasets. Hindcasting results using ECMWF weather forecast data indicated that the EFAS method is capable to forecast small floods. Typical EFAS thresholds used in Europe need to be adjusted to allow for sending alerts already for smaller floods (return periods of 1 year). Hindcasting with adjusted thresholds yielded sound results and demonstrated the applicability of the system.

Key words: Flood forecasting and early warning, Baro-Akobo, LISFLOOD, EFAS

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List of Abbreviations

ERTA	Ethiopian Radio and Television Agency
UNICEF	United Nations International Children's Emergency Fund
UNDP	United Nations Development Program
WFP	World Food Program
JRC	Joint Research Center
EFAS	European Flood Alerts System
MoU	Memorandum of understanding
SCS	Soil Conservation Service
USDA	United States Department of Agriculture
GIS	Geographical Information Systems
ET0	Evapotranspiration ate from closed canopy
ES0	Potential evaporation from rate from a bare soil surface
EW0	Potential evaporation rate from an open water surface
LAI	Leaf Area Index
ANN	Artificial Neural Network
EDMWF	European Center for Medium Range Weather Forecasts
SNNPR	Southern Nations Nationalities and People's Region
MAR	Mean Annual Rainfall
PERSIANN	Estimation from Remotely Sensed Information using Artificial Neural Networks
RFE 2.0	African Rainfall Estimation Algorism
TRMM	Tropical Rainfall Measuring Mission
IDW	Inverse-Distance-Weighted
NOOA-CPC	National Oceanic and Atmospheric Administration – Climate prediction center
HWSD	Harmonized World Soil Database v 1.0
LDD	local drain direction maps

VGT4AFRICA	Vegetation for Africa project
UZTC	Upper Zone Time Constant
LZTC	Lower Zone Time Constant
GWLF	Ground Water Loss Fraction
PWPF	Power preferential flow
SCE-UA	Shuffled Complex Evolution method - University of Arizona
PSO	Particle Swarm Optimization
RMSE	Root Mean Squared Error
SD	Standard Deviation
SI	Sensitivity Index
RD	Relative Deviation
EPS	Ensemble Prediction System
COSMO-LEPS	Consortium for Small-scale Modeling - Limited Area Ensemble Prediction System
FOH	Frequency of Hit
POD	Probability of Detection
FOM	Frequency of Miss
SEBAL	Surface Energy Balance Algorism for Land
GLUE	Generalized Uncertainty Estimation

1. Introduction

1.1 Generals

Life in our perilous planet …, everybody feel deep sorrow when they watch or hear horrible news every day with natural disasters all over the world. Most of naturally occurring hazardous has dropped black point in human history in different parts of Earth. Among these floods, tsunamis, drought, earth quake, landslides, windstorms are common hazardous. Floods (focus of this paper) are the most frequent and costly natural disasters in terms of human hardship and economic loss which are climate related disaster (Liersch and Volk, n.d). Its impact ranges from loss of lives, destruction of property, destruction of infrastructures, and loss of agricultural productions. Vulnerability to floods is also increasing due to many reasons such as climate change (rainfall distribution disorder, sea water level rise) or land use change (urbanization, deforestation) which increases the need and necessity for different mitigation measures.

Floods, high levels of water submerging areas which are generally dry, it happens when the channels are supposed to carry discharge more than their normal capacity along river banks and due to seismic activities and land slids on shore of lakes and oceans. They have the possibility and capacity to happen everywhere even if topography is main determinant and its capacity, intensity and duration is also determined by many local conditions. Floods are commonly from prolonged storm rainfall and combination events of both hydrological and weather extremes. Since most people live in river banks and flood plain areas flood are common events in the past, today and in the future.

As almost all natural hazardous floods are not fully mitigated. However, the damage level can be highly managed by taking different measures. Structural measures include dams, levees, embankments, diversion weirs/channels, strengthening rivers to increase speed of discharge (REPORT ON DELAWARE RIVER FLOOD MITIGATION, 2006), and periodic cleaning of channels from sediments. Or/and non-structural techniques (or without earth work) mostly include polices linked to land use and land administration measures, watershed landscape management, an efficient flood forecast-warning system, increasing awareness of vulnerable communities (Zbigniew and Kundzewicz, 2002). Hence, flood forecasting and early warning systems nowadays are becoming from acceptable and commonly used mitigation measures due to many reasons such as environmentally fit, easily maintainable, non-disturbing the natural flow, rising confidence since structural measure everywhere might be impossible. These systems intend to minimize sufferings of humankind, globally many researchers are struggling to improve its effectiveness also became focus of this study.

1.2 Back ground

Flooding has always been a critical and common disaster in Ethiopia taking life of many people and livestock, displaced millions and destroyed huge amount of economy. Rainy seasons in Ethiopia (June to September) are linked with flooding in most of river basins in the country. Flood prone basins are: Baro-Akobo/Sobat River in western Ethiopia near the Sudanese border, Tekeze River in Tigray, Omo (draining into lake Turnkana) river in southern Ethiopia, Awash River in the rift valley, Wabi-Shebelle River in southeastern Ethiopia near the Somali border and lake Tana basin in north west of country are from the common ones (see figure 1.1).

Some seasonal flooding histories in different parts of the country are stated as follows: heavy rains in 2006 caused the Omo to flood its lower course, drowning at least 456 people and stranding over 20,000 people over the space of five days (ERTA NEWS, 2006). In Dire Dawa (sixth largest city 512 km towards east from the capital Addis Ababa), flood in August 1981 which killed about 80 people was previously considered as the worst in the town’s history (Tadesse, 2006?). However, the unprecedented August 6, 2006 flash flooding in deep sleep time was worst of all cases; more than 250 people died and more the 15,000 displaced and also in economical loose it surpassed all flood disasters that occurred in the city and around (News Dire, 2006; BBC NEWS, 2006). In general, there is always news from Ethiopia on flood hazards in every rainy season from different part of the county and from latest news in 2010 year from Oromia region, floods in mid-July displaced 400 households (2,500 people), according to an assessment carried out by the regional authorities with support from UNICEF, in Amhara region 400 people had been displaced due to flooding in Dera woreda, in Tigray floods killed two children, displaced approximately 250 people and caused extensive damage to household assets in Maichew and Alamata (ERTA NEWS, 2010: all.africa news, 2010) . In the future this may become chronic due to fast land - use and global climate change.

Flood in the Baro-Akobo River Basin in particular (study area): Western part of Ethiopia/Gambella region is endowed two large perennial rivers transecting Gambella region (Baro and Akobo) originate from the wet and fertile western highlands of the country. Like other rivers in the country they are also known for seasonal flooding. Even if, it has long-term benefit to agriculture along the river plains due to inundation depositing of alluvial sediments resulting to fertile land for cropping, it has serious socio-economic and environmental losses. The United Nation Development Programme (UNDP) Emergencies Unit reported in October 1999 flooding within the Baro River Basin displaced and made homeless 57,500 people, damaged household belongings, disrupted economic activities in Gambella, Itang and Jikawo weredas of the Gambella region. In 2006, floods in the region had killed two people and displaced more than 6,000.

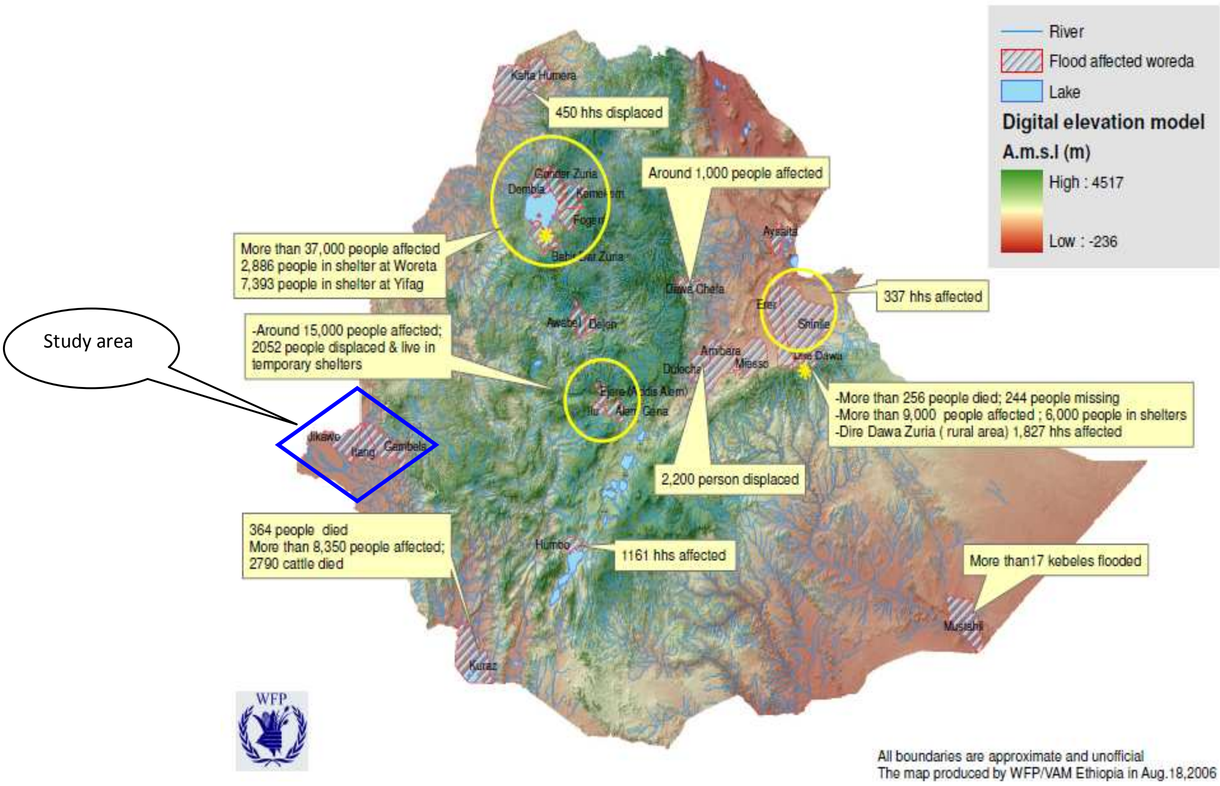


Figure 1.1 Flood Affected areas in Ethiopia as of August 18, 2006 (Source, World Food Program (WFP) for Ethiopia, August 18, 2006)

To end, what makes flooding of Baro River Basin in Gambella region worst are in the region which has relatively low human resource and infrastructure, 163,263 people of the region residing in 111 peasant associations are considered vulnerable to the effects of seasonal flooding (UNDP, Emergency unit for Ethiopia), due to intensive deforestation of the western Ethiopian highlands in the past few years as people seek to expand the land available for farming. And despite, some studies in (a) flood risk assessment by Ethiopian Ministry of Water and Energy, Gambella Regional state and UNDP emergency unit for Ethiopia, (b) general integrated flood management (Achameleh, n.d), (c) flooding and sustainable land management in the lower Baro-Akobo River basin by Woube (1999), (d) flood and health in Gambella region by Abay(2008). Studies on flood forecasting and early warning mechanisms in the river basin and in the whole country as well does not go far yet.

1.3 Study objectives

The main objective of this study is to test currently working European Flood Alert System applicability for African small-medium scale river basins and to adapt for Baro-Akobo River Basin. Flood forecasting and early warnings systems: flood mitigation measures used to inform the residence to evacuate themselves and their properties away.

Specific questions to address the above objectives are:

- What are realities and risks of the Baro River's flood history?
- Testing and comparing satellite-based precipitation data source with gauged ground precipitations.

1.4. Outline of the thesis

In this report medium-ranged flood forecasting and early warning system is developed for Baro river basin and methods of European Flood Alert System are tested and applied. First in chapter 2 insights are given in hydrological process and modeling by expounding the hydrological processes playing great role in rainfall-runoff generation. In addition, for hydrological model used (LISFLOOD) details for model components are stated (i.e meteorological input data, static input data, soil moisture routine, precipitation accounting, snow and frost, base flow routine, evapotranspiration accounting, surface and channel routing routine). Subsequently, in chapter 3 the study area with respect to physiographic (location, topography, soil & geology, land cover and land use), climatic (precipitation, temperature, evapotranspiration etc.) and hydrological realities is explained. In chapter 4 details in methodologies concerning data collection, process of model setting up, flood forecasting and early warning systems (applications of EFAS), uncertainties in flood forecast (including uncertainties raising from hydrological model, parameter sets and meteorological data) are addressed. In chapter 5 results of the model calibration and validation with different statistical skill measures are reviewed. And also results of flood hindcastes are stated. Finally summaries, recommendations and further extensions of the study are presented in Chapter 6.

2. Literature review

2.1. Hydrological processes

Hydrological cycle, describes the storage, state change and movement of water on, in, and above the ground. Even though, the water cycle has no end and no beginning, mostly its processes are started in literatures from the driver of the process: the sun. The sun heats water from different parts of earth. Evaporation is followed: as water vapors into the air from water bodies, straight from solid to gas (sublimate) from ice and snows, by combined evapotranspiration process from plants and soil covers. Rising air currents take the vapor up into the atmosphere where cooler temperatures cause it to condense into clouds (Legget , 1966). The condensed water in clouds will return back to ground as precipitation with different forms; mainly as rain but also as snow, sleet, and hail. The geographical location of specific area determines storage and form of precipitation. For locations near/around the poles and at high altitudes precipitation falls as snows or hail, and even can accumulate as ice caps and glaciers which will store frozen water for many years (Kuchment, n.d). In warm and most areas if solid form fall it will melt and with rainfall accumulate to make surface flow then to rivers and oceans while some part of it is infiltrating in to the ground for base flow or recharging ground water. Ground water will come out through openings as springs which will merge rivers, then to oceans or other water bodies. Finally ready for new steps and the cycle will repeat itself. Replacement and residence stay for water particles for rivers and atmosphere are very short while for large lakes, glaciers, oceans and deep groundwater will take from hundreds to thousands of years (http://www.physicalgeography.net).

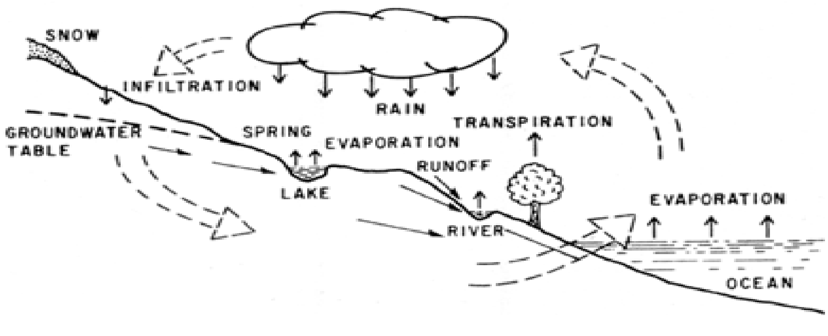


Figure 2.1 Hydrological process (Source: National Research Council Canada, www.nrc-cnrc.gc.ca)

2.1.1. Rainfall-runoff components at catchment scale

Runoff is defined as the portion of the precipitation that makes its way towards river, oceans or others; as surface or subsurface flow (Ragunath, 2006). The discharge flowing in a river is the runoff from its draining basin. Commonly discharge, stream flow and runoff are used interchangeably.

Raining time; before reaching the land surface a part of the precipitation will be intercepted by vegetation and/or other types of surface covers which will later evaporate or accumulate to fall (though, rainfall interception by vegetation varies with species composition, age, and density of vegetation cover). Some precipitation will be absorbed by the soil (the amount of which depends upon the soil moisture conditions at the time of precipitation). If rain continues and satisfies absorbing capacity of soils, the excess will collect in pits and puddles while part of it will either infiltrates to ground to recharge ground water or flow without joining water table as base flow. The accumulating water in pits and puddles leds to surface sheet flow and this part of water which is in transit overland flow which has not yet reached the stream channel is known surface detention or detention storage (Garg, 2006) and this excess water flowing overland joins the streams, rivers, lakes ocean etc. This will be the surface runoff part and together with base flow gives up full river discharge. River discharge will be covered from three different sources (Garg, 2006).

i. Surface runoff
ii. Base flow
iii. Direct precipitation over the river streams,

The second actor is important for minimum flow of the river and common character of perennial rivers; while the first factor important for the maximum flow of the river; and the third factor is negligible and generally can be ignore. Peak flows are generally linked with surface runoff.

Runoff commonly estimated by one of the following methods: (*i*) Empirical formulas, curves and tables like Ingli's, Lacey's and A.N Khosla's empirical formulas (ii) SCS curve number (USDA-SCS, 1972) method based on curve number an index combining hydrologic soil group and land use factors (iii) Infiltration method applied by reducing infiltration loss from the total precipitation or by using infiltration index.(iv) rational method simply and commonly used method introduced in 1889; determines peak discharge by using rainfall intensity, watershed area, and runoff coefficient. (v) Overland flow hydrograph as developed by C.F. Izzard (1948) essentially applies for uniform laminar sheet flow and to determine discharge it uses the kinematic viscosity of water, uniform depth of sheet flow and velocity of flow (vi) Unit hydrograph, concept first introduced by L. K. Sherman in 1932, it is based on the result from unit excess rainfall spread uniformly over a watershed for given duration.

As stated earlier, the term “hydrological cycle” is used to express the general circulation of water in its various forms from oceans to the atmosphere, to the ground from the atmosphere, and finally to oceans again. The “runoff cycle” is a descriptive term applied to part of this hydrological cycle, i.e. the part between the precipitation from the atmosphere to the land areas, and its subsequent discharge through stream channels.

Table 2.1 Runoff affecting factors (source, Ragunath, 2006; Garg, 2006, modified)

Factors affecting Runoff	
Storm Characteristics • Intensity • Duration • Areal extent(distribution) • Frequency • Antecedent precipitation • Direction of storm movement • Types of precipitation **Meteorological Characteristics** • Temperature • Humidity • Wind velocity • Pressure variation • Direction of prevailing storm	**Basin characteristics** • Size of the basin • Shape of basin • Average slope of the basin • Drainage network • Soil coverage • Land use coverage • Topography **Storage Characteristics** • Channels • Depressions • Flood plains, swamps • Streams • Upstream reservoirs**,** Ponds, lakes, sink

Almost all of factors listed above paly a role in determination of the peak flow. However, influencing level of each factors on peak discharge highly differs and dependent on many local conditions; sometimes there is possibility of neglecting some factors for some specific conditions.

2.2. Classification of hydrological models

Hydrological modeling, rainfall runoff modeling, and watershed modeling ……… all are methodologies having same destination; to solve the abstract relation between rainfall and runoff. Starting from 1950 and 1960 (SINGH and FREVERT, 2006) many scientific communities were struggling to solve the complex relation between rainfall and runoff. The progress in hydrological models is linked to computer technology and techniques to explore the hydrological environment. The advancement in computing speed, storage device, remote sensing, geographical information systems and radars technologies are now accelerating the improvements in hydrological models. And also the models will be improved as our understanding to hydrological process improves (Abbott et al., 1996?). Improvements in hydrological models mean directly improvements on the following its applications: effective watershed management, effective flood forecasting and warning systems, climate and land use change impact assessment, water balance, water quality, and for integrated river basin planning and management.

River basins need suitable models for their representations, as their basin characteristics are different by many criteria such as basin shape, slope, topography, stream network density, land use and land coverage, soil cover, ground water table. Difference in basin characteristics will become more when variation in weather and other criteria added. Generally, runoff formation process is believed to be highly non-linear, time varying, spatially distributed (Valadan B. and Keijzer, n.d , p. 331) thus, possibility of representing by one type of model will be difficult unless the model itself is highly flexible.

Hydrological modes have different classifications, commonly they are classified in to three groups: black box, conceptual and physical based (Wood and O'Connell 1985; Nemec 1994; Kachroo, 1992). In black box approach is based on systems theoretical approach, which depends mainly on some general relationship (empirical functions , simple mathematical expressions or artificial networks) are used to relate the input and output or rainfall and runoff. Conceptual type models attempts to represent major certain components of the hydrological cycle through interconnected mathematical functions. In physical based models to account the spatial variability of the processes, the variable and heterogeneous characters of the catchment are conserved by dividing (discretizing) the catchment into a number of relatively homogenous response unit (HRU) in which each parameter of the system has direct physical interpretation.

Model can also be classified by different criteria such as spatial and time scale discretization, method of solution, sub-process, and others. Figure 2.2 summarizes this and shows the characteristics of the model in use LISFLOOD (by grey color).

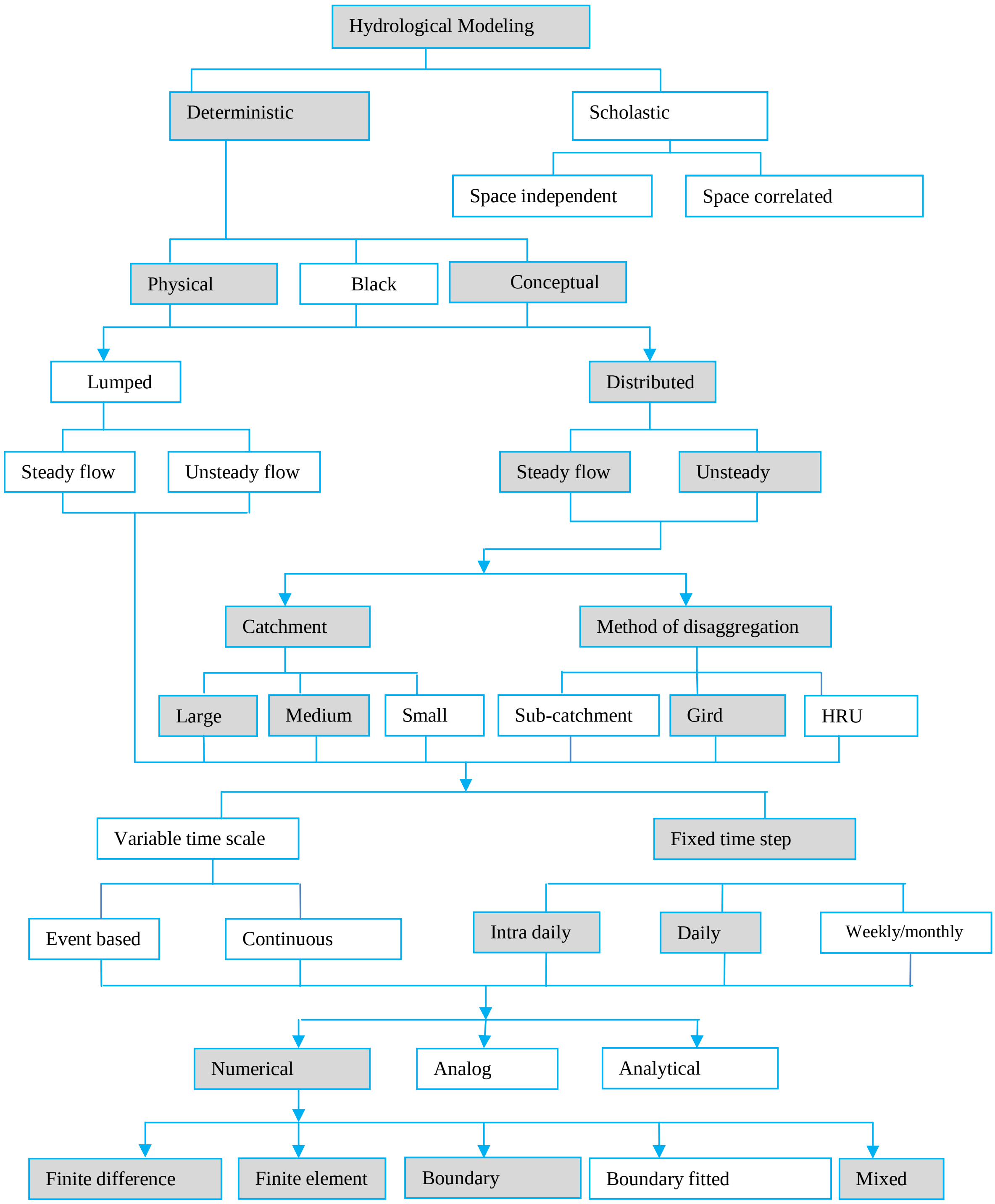


Figure 2. 2 Hydrological model classifications (source; Bruce Davison , 2003 p. 4, modified)

***Note the grey path shows the nature of LISFLOOD GIS based hydrological model. ***

Table 2. 2 Common watershed models and their characteristics (Jutla, 2004 p. 38)

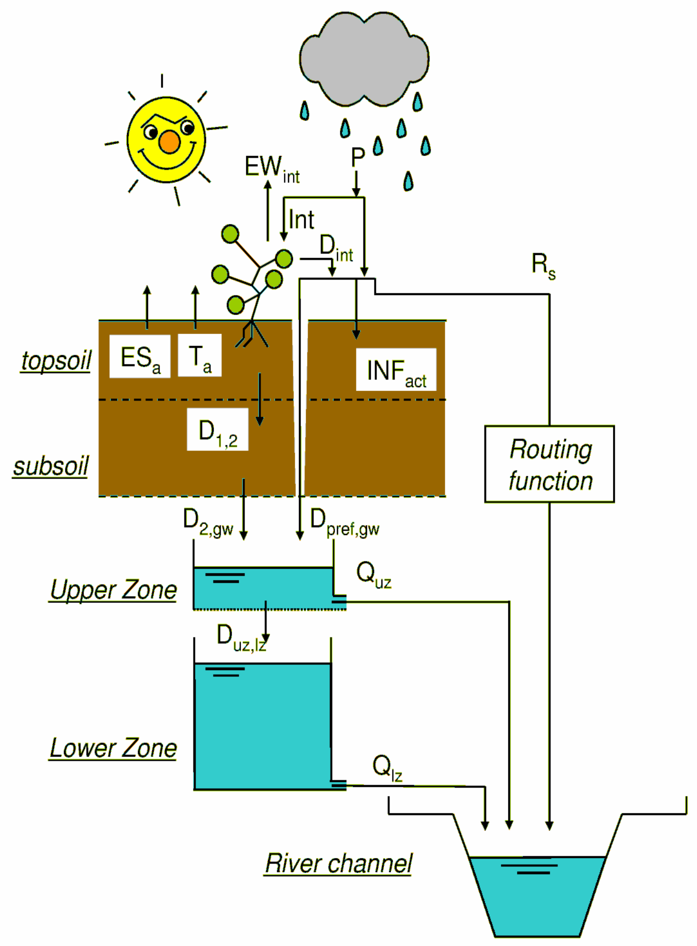
Model	Location of application	Time scale	Characteristics	Remark
Hydrological Engineering Center-Hydrological Modeling System (HEC-HMS)	USA	Event based	Physically based, semi-distributed	
National weather service(NWS)	USA	Continuous	Process based, lumped parameters	
Hydrological Simulation Package – Fortran(HSPF)	USA	Continuous	Physically based, semi-distributed	
University of British Columbia Model(UBC)	Canada	Continuous	Process based, lumped parameters	
Waterloo Flood System(WATFLOOD)	Canada	Continuous	Process based, Semi-distributed	
Simple lumped reservoir Parametric (SLURP)	Canada	Continuous	Process based, Semi-distributed	
Runoff Routing Model (ROBR)	Australia	Event based	Lumped	
Watershed Bounded Network Model (WBN)	Australia	Event based	Geomorphology based, lumped	
Physically Based Runoff Production Model (TOPMODEL)	Europe	Continuous	Physical based, Distributed	
System Hydrologique European (SHE)	Europe	Continuous	Physical based, Distributed	
Xinanjiang - Model	China	Continuous	Lumped, Process based	
LISFLOOD	Europe	Continuous	Physical based, Distributed	Study Model

2.3 LISFLOOD hydrological model

"Watersheds may be modeled by a lumped model using basin average input data and producing total basin stream flow. Such a model may produce reasonable result but because of the distributed nature of hydrological properties like soil type, slope and land-use, the model cannot be expected to accurately represent the watershed condition" (Narayan Shrestha, n.d). Such problems can be handled by distributed modeling, with help of geographical information systems to cover the link between topograph, soil cover, land use & cover and others. Distributed models are based on basic governing equations such as conservation of mass and momentum equations. Since most parameters and state variables are either directly measured in the field or reasonably assumed based on experimental work calibrating task will be minimized as additional advantage. The disadvantages of physically based models are that they require complicated numerical solving techniques and large amount of input data (Amir and Kouchak, 2009). A member of this group LISFLOOD is gird based physically distributed and bit conceptually lumped model written on PCRaster GIS environment which is developed by water quantity action (DER KNIJFF & DE ROO, 2008) of Land Management and Natural Hazard Unit of the Joint Research Centre.

LISFLOOD was designed for simulating the hydrological processes that occur in a catchment using any time interval and grid size (DER KNIJFF, DE ROO, 2008). The objectives of LISFLOOD was to produce a tool that can be used in large and transnational catchments for a variety of applications, including flood forecasting, water balance, operation for large lakes and reservoirs, climate change impact assessment, and integrated river basin management.

LISFLOOD mainly has been designed and tested for European river basins with resolution of 1 and 5 kilometers. Out of Europe it has been applied once in for the Lushi basin in China (BEVEN, K. J 2005) and once in Africa in Juba - Shabelle River Basin (Thiemig et al., 2010).



P: Precipitation

Int: Interception

WE_{int} : Evaporation of intercepted water

D_{int} : Leaf drainage

S_a : Evaporation from soil surface

Ta : transpiration (water uptake by plant roots)
INF_{act} : infiltration
R_s : surface runoff
$D_{1,2}$: drainage from top- to subsoil
$D_{2,gw}$:drainage from subsoil to upper groundwater zone
$D_{pref,gw}$ = preferential flow to upper groundwater zone
Duz,lz : drainage from upper to lower groundwater zone
Q_{uz} = outflow from upper groundwater zone
Ql = outflow from lower groundwater zone
D_{loss} : loss from lower groundwater zone

Figure 2.3 LISFLOOD model concept map (Der Knijff & De Roo, 2008)

Short explanations of the model concept map ranging from the meteorological data input, sub-process, outputs, etc. are summarized below. For more detailed description see LISFLOOD user's manual (De Roo, 2008).

2.3.1. Meteorological input data

Meteorological data are driving agents of hydrological models. Core meteorological input data are precipitation in mm per day, daily average temperature, evapotranspiration rate from closed canopy (ET0 in mm per day), potential evaporation rate from a bare soil surface (ES0 in mm per day), and potential evaporation rate from an open water surface (EW0 in mm per day) in which the last three (ET0, ES0 & EW0) variables are pre-proceeded by another independent sub-package LISVAP(Knijff, 2008). The calculation time step can be adjusted in model settings but, input variables are required to be set on daily basis.

2.3.2 Static data input

As the model is embedded with PCRaster Geographical Information System; terrain map, land use, soil map, leaf area index, stream drainage network, channel cross sections and generally, geographically linked data are facilitated by this package. These data can have different resolutions, but from the models prior objectives (to model large river basins) from 10-100 km gird resolution is recommended by the authors.

2.3.3 Snow and frost

Influences of frozen process (snow, frost etc.) in hydrological cycle are determined by both latitude and altitude. Its influence will increase as the geographical location of a basin or a system is far from equator and its altitude increases. To account the influence of snow and frost it can be set off (optional sub-process in the model) or it can be adjusted by the model itself according to the temperature data given. Precipitation is accounted as snow fall if the temperature is below 1°C (33.8 °F, with in average range for cut off for rainfall and snowfall in which in most literatures the range is stated from 30-34 °F (Mease, 1972)) and the melting rate is related with simulated full surface radiation balance as follows.

$$M = C_m (1 + 0.01 * R\Delta t)(T_{avg} - T_m) * \Delta t \qquad 2.1$$

Where, M is the rates of snow melt [mm]

C_m is a degree-day factor [mm $^oC^{-1}$ day^{-1}],

R is the rainfall intensity [mm day^{-1}],

Δt is the time interval [days],

T_{avg} is the average 24-hour temperature [^oC]

T_m is the temperature above which snowmelt occurs [^oC]

Frozen soils have influence in some hydrological elements such as evaporation from the soil surface, water uptake by vegetation, infiltration and flow of moisture through the soil matrix. It can be checked by the following equation.

$$F(t) = F(t-1) - (1 - A_f)F\Delta t - T_{avg} * e^{\frac{-0.04.kds}{wes}} \Delta t \qquad 2.2$$

Where, F is expressed in [^oC day^{-1}]

A_f: is a decay coefficient [day^{-1}]

K is a snow depth reduction coefficient [cm^{-1}],

d_s is the depth of the snow cover (expressed as an equivalent water depth [mm])

we_s is the equivalent water depth of a given depth of snow cover

The soil will be considered to be frozen, if F(t) is greater than or equal to 0.

2.3.4. Soil moisture routine

Mostly soil moisture fluxes in the unsaturated zone are simulated using Darcy's law for one and/or two dimensional flow. The flux (D) out of soil layer is then given by:

$$D = -K(\theta)\left[\frac{\partial h(\theta)}{\partial z} - 1\right] \qquad 2.3$$

Where, D is in $mmday^{-1}$

$K(\theta)$ hydraulic conductivity [$mmday^{-1}$]

θ is the soil's volumetric moisture content [mm^3 mm^{-3}]

$\frac{\partial h(\theta)}{\partial z}$ is matric potential gradient

Only downward flow which is driven by gravity is considered since influence of capillary rise is small. From the relationship between hydraulic conductivity and soil moisture status described by the van Genuchten equation (van Genuchten 1980) and from assumption matri potential gradient is zero (for fully downward flow), the flux simulated between from upper soil layer to lower soil layer ($D_{1,2}$) and from lower soil layer in to the ground layer ($D_{2,gw}$) (see fig. 2.3) is expressed as follows.

$$D = K(w) = K_s\left(\frac{w - w_r}{w_s - w_r}\right)^{\frac{1}{2}}\left\{1 - \left[1 - \left(\frac{w - w_r}{w_s - w_r}\right)^{\frac{1}{m}}\right]^m\right\}^2 \qquad 2.4$$

Where, Ks is the saturated conductivity of the soil [$mmday^{-1}$]

w : actual amount of moisture in the soil in [mm]

w_r : residual amount of moisture in the soil in [mm]

w_s : maximum amounts of moisture in the soil [mm]

Parameter m is calculated from the pore-size index, λ, which is related to soil texture:

$$m = \frac{\lambda}{\lambda + 1}$$

2.3.5 Loss routine

Loss computation is linked to computation of interception, infiltration, preferential flow, impervious area coverage and others to estimate the net excess rainfall which is effective in runoff generation.
The model accounts loss components as follows:

Canopy interception: rainfall interception in basins is influenced by properties of the canopy (species composition, age, and density of vegetation cover) that tend to vary over small distances (Katrin, et al., 2005). A portion of intercepted rainfall evaporates and the other portion may flow down on vegetation stems. Intensity and duration of rainfall determines the stay time of precipitation in leafs. According to Kuchment (n.d), dense conifer stand usually intercepts to 25 - 30 percent of the rainfall at the stem flow of 5-7 percent, The net rainfall interception by hardwood stand is about 15 percent for the period with leaves and about 7 percent for the period without leaves and rainfall interception losses by dense grasses and herbs is as great as for deciduous trees.
Interception is estimated from Aston (1979) and Merriam (1960) view:

$$Int = S_{\max}\left[1 - \exp\left(-k.R\Delta t / S_{\max}\right)\right] \qquad 2.5$$

Where, Int is the interception per time step [mm]

S_{max} is the maximum interception [mm]

R is the rainfall intensity [$mmday^{-1}$]

K is density of vegetation [m^2m^{-2}]

S_{max} is calculated using an empirical relation (von Hoyningen-Huene 1981 as sited on Der Knijff & De Roo, 2008)

$$\left.\begin{aligned} S_{max} &= 0.935 + 0.498LAI - 0.00575LAI^2 \quad (LAI > 0.01) \\ S_{max} &= 0 \quad (LAI \leq 0.1) \end{aligned}\right\} \qquad 2.6$$

Where LAI is average Leaf Area Index [m^2m^{-2}] of each grid pixel. The constant k is given by

$$K = 0.046LAI \qquad 2.7$$

Evaporation of intercepted water (EW_{int}) is simulated as potential evaporation rate from an open water surface (EW0).

$$EW\max = EW_o(1 - \exp(-k_{gb}.LAI))\Delta t \qquad 2.8$$

Where, EW_o is the potential evaporation rate from an open water surface [$mmday^{-1}$]

EW_{max} is maximum evaporation [in mm per time step]

k_{gb} constant the extinction coefficient for global solar radiation

Since amount of evaporation is determined by amount of water stored in leaves, which will be minimum of the actual evaporation from the interception stored (mm per time step) (EW_{int}), and the potential evaporation rate from an open water surface ($mmday^{-1}$)(EWo).

Then, leaf drainage is modeled as a linear reservoir with a time constant of one day (expecting within 24 hours precipitation in the leaves will fall or evaporate):

$$D_{in} = \frac{1}{T}.Int_{cum}\,\Delta t \qquad 2.9$$

Where D_{int} is the amount of leaf drainage per time step [mm]

T_{int} is a time constant for the interception store [day], which are set to one day

Infiltration: A process governed by gravitational force in which the water will enter to soil layer, determined by soil characteristics and its rate will decrease exponentially as the soil gets saturated enough. The model estimates infiltration capacity of the soil using the Xinanjian method, which accounts variations in infiltration capacity within in single pixel.

$$A_s = 1 - \left(1 - \frac{w_1}{w_2}\right)^b \qquad 2.10$$

Where, A_s : saturated fraction or pervious fraction

b: dimensionless empirical shape parameter,

W_1 : total moisture storage in the upper oil layer and

W_{s1} : maximum storage

Then, the infiltration capacity INF_{pot} (mm):

$$INF_{pot} = \frac{w_{s1}}{b+1} - \frac{w_{s1}}{b+1}\left[1 - (1 - A_s)^{\frac{b+1}{b}}\right] \qquad 2.11$$

However, the potential infiltration capacity may not always represent the actual infiltration rate see below.

Preferential flow: flow through soil channel (micro-pores, 0.9 - 5.0 mm or larger which acts as pipe), determined by many local conditions, cannot be governed by Darcy's law, and in general difficult to model (Schalk, 1990).

The amount of preferential flow per time step (mm) ($D_{pref,gw}$) is simulated in LISFLOOD as follows;

$$D_{pref,gw} = w_{av}\left(\frac{w_1}{w_{s1}}\right)^{c_{pref}} \qquad 2.12$$

Where, W_{va} : the amount of water that is available for infiltration

C_{pref} : empirical shape parameter (used as calibration constant)

The actual infiltration will be the smallest of infiltration capacity (INF_{pot}) and the difference between the amount of water available for infiltration and preferential flow (W_{av} - $D_{pref\,,\,gw}$).

Impervious area coverage: Impervious layer percentage coverage within the basin governs the amount of perception which will infiltrate to ground while the remaining will directly convert to runoff. The model accounts this effect by introducing parameter called ‘direct runoff fraction’ f_d which defines the percentage of pixel that is impervious**.**

2.3.6 Evapotranspiration accounting

Evapotranspiration is sometimes called as the consumptive use of plants: total water lost from vegetation due to evaporation from the soil and transpiration by the plants including water used for plants for tissue building. But, the last one can be neglected since its influence in quick-runoff generation is very low. The remaining two are modeled separately in the model based on the widely accepted FAO Penman-Monteith method.

The maximum transpiration per time step (mm):

$$T_{\max} = K_{crop} .ET0.[1 - \exp(k_{gb} .LAI)]\Delta t - EW\text{int} \quad 2.13$$

Where, ET0 is potential (reference) evapotranspiration [mm per day]

K_{crop} : crop coefficient

In case of water stress the actual transpiration is adjusted by a reduction factor (r_{ws}),

$$r_{ws} = \frac{w_1 - w_{wp1}}{w_{crit} - w_{wp1}} \quad 2.14$$

Where, W_1, is the amount of moisture in the upper soil layer in mm,

$W_{wpl,}$ is the amount of soil moisture at wilting point and

W_{crit1} is amount of moisture below which the water uptake is reduced in mm and expressed as:

$$W_{crit1} = (1 - p).(w_{fc1} - W_{wpl}) + w_{wpl} \quad 2.15$$

Where, W_{fc1} amount of soil moisture at field capacity

p, is the soil water depletion fraction

Then the actual transpiration, $T_a = r_{ws} . T_{max}$ [mm]

For evaporation from the soil surface: it is estimated to be equal to the maximum evaporation from a shaded soil surface (ES_{max}, in mm) and expressed as:

$$ES_{max} = ES0 \exp(-kgbLAI)\Delta t \qquad 2.16$$

Where, ES0 : the potential evaporation rate from bare soil surface [mm per day]

The actual evaporation rate is adjusted according to moisture available in the top soil layer by reduction factor which is linked to last rainfall date.

$$ESa = ES_{max}(\sqrt{D_{slr}} - \sqrt{D_{slr} - 1}) \qquad 2.17$$

Where, D_{slr}, represents the number of days since last rain event,

Since actual evaporation cannot be more than soil moisture available in the soil (difference b/n total amount of moisture and residual moisture); the moisture available in soil will be taken if ESa computed is more than it.

2.3.7 Base flow routine

Besides surface runoff, subsurface flow is also a main component of a river discharge; both storage and transport are modeled using two parallel linear reservoirs.
Flow in upper soil layer flows quickly, while the flow in the lower zone represents slow ground water flow and the amount or outflow from both of the layers to the river is expressed below (Q_{uz} and Q_{lz} respectively).

$$Q_{uz} = \frac{1}{T_{uz}}.UZ\,\Delta t \qquad 2.18$$

$$Q_{lz} = \frac{1}{T_{lz}}.LZ\,\Delta t \qquad 2.19$$

Where, T_{uz} and T_{lz} are reservoir constants [days]

UZ and LZ, amount of water stored in corresponding zones.

2.3.8 Surface and channel routing

The flow of water through the soil, surface and stream channels of a watershed is a distributed process because the flow rate, velocity, and depth vary in space and time throughout the watershed (Chow et al.1988). In fact, actual flow of water in channels is variable in three space dimensions, for instance velocity in the river varies along the river bed, across each cross-section and with depth (in which all these variations are determined by many local conditions such as bed slope, cross section shape, density of flowing water, different losses, bedforms etc).These phenomenons add complexity to model. However, the approximate representation is derived from Navier–Stokes general fluid flow equations, specifically for incompressible fluid water by Barre de Saint-Venant in 1871 (with some assumptions to describe one dimensional unsteady open channel flow). The Saint-Venant's general equation of non-conservation form for both continuity and momentum equation respectively are stated below.

$$v \frac{\partial y}{\partial x} + y \frac{\partial v}{\partial x} + \frac{\partial y}{\partial t} = 0 \qquad 2.20$$

$$\frac{\partial V}{\partial t} + V \frac{\partial v}{\partial x} + g \frac{\partial y}{\partial x} + g \frac{\partial y}{\partial x} - g\left(S_o - S_f\right) = 0 \qquad 2.21$$

Where, $\frac{\partial V}{\partial t}$ for local acceleration

$V \frac{\partial v}{\partial x}$ for convective acceleration

$g \frac{\partial y}{\partial x}$ for pressure force

gS_o for gravity force

gS_f for friction force

Kinematic wave routing which is mostly used considers only the last terms in momentum equation, from the assumption gravitational force will balance friction force. But, for subcritical flow (like in Ml profiles in which backwater profile could exist), and some other slope combinations the general dynamic wave that considers all local acceleration, convective acceleration , pressure force and friction force is recommended.

The LISFLOOD starts from plain routing, which is routed using a four-point implicit finite-difference solution of the kinematic wave equations (Chow et al.1988). Both subsurface flows from upper and lower layers are routed to the nearest downstream channel pixel by lumping in one time step. Then for channel routing, default set is kinematic routing (numerically solved by finite-difference). As an option, LISFLOOD includes also a dynamic model routing. However, to use this more data such as channel cross section, bed slope with high resolution need to be provided.

2.4. Flood forecasting and early warning systems

2.4.1 Floods in general

Floods have many classifications in which their type decides method of mitigation measures and extent of damage. From these, according to intensity they are classified low, medium, high and very high floods. According to their duration: slow-onset floods (usually last for longer period mostly weeks or months), rapid - onset floods (relatively shorter usually take from one up to three days), and flash floods (usually occur after minutes or hours of heavy rain fall, common in mountainous highlands). In reference to their location coastal floods, arroys floods, river floods (common type of floods) and urban floods (due to inadequate drainage facilities) (Hazrat , n.d). And classification by Kevin Sene (2008) in table below over comes all.

Table 2.3 Flood causes and types (source, Kevin Sene ,2008 p 21)

Type	Example	Typical types of flooding
Atmospheric	Frontal depressions	Extensive river flooding, coastal surge and wave over toping, estuary and delta flooding, urban and pluvial (surface water) flooding.
	Thunderstorms	Fast response/flash flooding and urban and pluvial (surface water) flooding
	Monsoon	Extreme prolonged rainfall causing a range of river and urban flooding issues
	Tropical cyclones	Coastal surge and wave overtopping, inland flooding, estuary and delta flooding
	Snowmelt	Extensive river flooding
	Ice jams	Rapid rises in river levels
	Glacial lake outburst flows	Fast moving, deep river flows
Geotechnical	Dam break	Fast moving, deep river flows
	Defense breach	Extensive inundation of coastal or inland areas
	Tsunami	Extensive inundation of coastal margins
	Debris flow	Destructive flows with high mud and rock content

2.4.2. Are floods predictable? To what extent?

The predictability of floods is highly dependent on many criteria even though floods are from groups of natural hazardous which can be predicted. Quality of meteorological forecast, performance of hydrological model and skills to cope with uncertainties are from the cores. Any *prediction is **uncertain**,* and in the mathematical modeling of hydrological and water resources systems this uncertainty has to be taken into account (Mohammad Karamouz, et al, 2003).The common river floods caused by atmospheric hazards and land use change have higher potential to be predicted than floods from geotechnical problems.

2.4.3 Flood forecasting systems:

"Structural measures keep the floods away from people and damageable property, nonstructural measures keep the people and damageable property away from the floods" [USACE, National Economic Development Manuals, ?]. Even though, priority is given to structural measures at reducing the impact of floods for the national water authorities and responsible bodies, it is unlikely that floods can ever be totally prevented (Thielen et al, 2006). So, effective flood forecasting and early warning systems can help and facilitate to evacuate people, livestock and properties, to regulate and operate reservoirs, generally to manage flood risk of vulnerable communities. There are many types of forecasting techniques used in different places, among these the simplest techniques are:

- Correlation based on stage-discharge data (can be performed in terms of river label and flow based on calculations of historical events to correlate the upstream and downstream flow nature), sometimes rainfall can be correlated with discharge and level.
- Time of travel or isochrones maps (World Meteorological Organisation 1994) (based on showing estimated or typical travel times from the onset, centroid or peak of a rainfall event, to the peak of flows being observed at various points in the river network).
- Simple routings by networking lateral flows
- Extrapolating rate of rise

From the advanced techniques:

- **Deterministic forecasting models**: single valued output based on combination of rainfall - runoff models real time meteorological and flow data. Such models tend to simulate the basin response to hydrological events and do not fully utilize information collected during an event. Originally developed to design studies, loose to foresee an exceedance probability which needs to be defined for the proportion of ensemble members which exceed that value (SINGH, n.d; Kevin Sene , 2008).

- **Probabilistic forecasting models**: models have potential to account uncertainties and possible ranges of future flow scenarios. Ensemble forecasting methodology (Jollife and Stephenson, 2003) is one which is widely used, based on ensemble members in which for well representation of the probability of events occurring; the median of the members is expected to be the deterministic one. Ensemble meteorological predictions are derivers to model uncertainty and propagations in flow.
- **Artificial Neural Network (ANN) and fuzzy logic:** recent methodology which is in detail studies for implementation which is based on artificial neural networks which are trusted to solve complex, non-linear and multivariate problems.

2.4.3.1 European Flood Alert System (EFAS)

European Flood Alert System aims at increasing preparedness in European transnational rivers towards flood hazard. EFAS gives medium-ranged system to warn the responsible authorities and communities at risk with a lead time of 3-10 days. It is currently under operation with close collaboration with different weather and hydrological service agencies and sited at European Joint Research Center, Italy (Thielen et al., 2009).

Short summaries for the overall system including input data set, methodologies, forecast verifications and skills assessments and others are stated as follows.

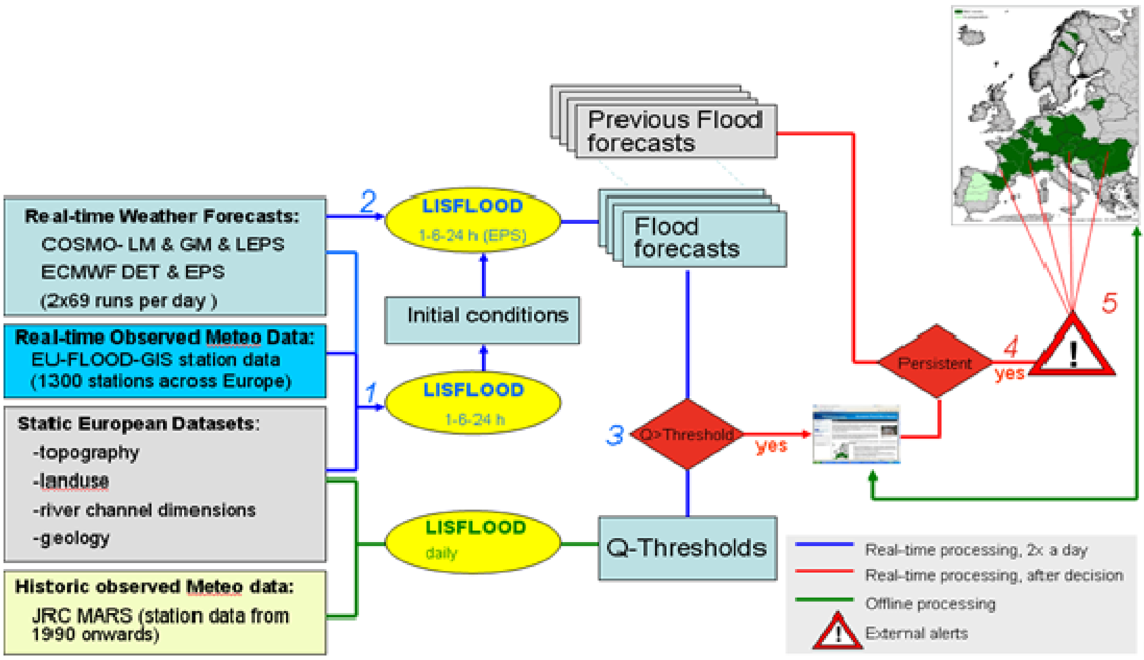


Figure 2.4 Schematic view of the EFAS (Source: Thielen & Bartholmes, 2007)

Input data sets:

System's input data include (i) static data set (land use, soil, topography, river stream network) with 1 and 5 kilometer resolution, (ii) meteorological database (JRC-MARS, since 1975 with daily update from more than 2000 stations across the whole continent), which are available in the Joint Research Center, (iii) historic hydrological observations data which are necessary for model calibration and verification from more than 800 stations are available in the center and some additional data were collected through the data bank of Global Data Runoff Center, (iv) weather forecasts which are provided from the European Center for Medium Range Weather Forecasts (EDMWF) and the German Weather Service (DWD), 10 days both deterministic and ensemble prediction from the first while 7 days deterministic only from the second.

Methodologies:

Thresholds: Thresholds are essentials to define a flood event, so warning and corresponding actions can be taken. In EFAS thresholds are grouped in four levels according to their water level and damage extent (see table 2.5), for the sake of visualization each level is coded with a respective color. One main task is how to determine these critical levels. They cannot be directly derived from observed flow history due to two reasons: (1) missing events since natural flows are mostly disrupted by artificial activities (ponds, reservoirs) they cannot be fully trusted for threshold derivation even if, this problem goes in model calibration with different data and model structure limitations to trust the simulated values for derivation. (2) Grid based threshold detection, getting an observed discharge record for each grid cell is impossible (but, it can be interesting view of the system, since critical flows can be detected for all paths of the river rather than on some gauged sites). To address both problems within EFAS (Thielen et al, 2009); long time series discharges are simulated with same parameterization setup for forecasting using LISFLOOD (see previous section). Each simulated discharge at each grid is ranked and statically evaluated to get threshold values. Then by quintile estimation critical thresholds' can be estimated based or parameters derived from long time series simulated discharges. In fact, the system is also using another parallel approach, from available simulated discharge (not too short) the highest will be the severe , flow corresponding to 99% to the high, 98% to the medium and 97% to the low threshold level.

Table 2. 4 EFAS thresholds levels, their color codes and associated hazard class (Source: Thielen et al, 2009)

EFAS threshold	Color	Hazard description
S (severe)	magenta	Very high probability of flooding, potentially severe flooding expected.
H (high)	red	High possibility of flooding, bankfull conditions or higher expected.
M (medium)	yellow	Water levels high but no flooding expected.
L (low)	green	Water levels higher than normal but no flooding expected.

Flood Forecasts and Persistency: Combined result of probabilistic and deterministic forecast with forecasts consistency (from different sources) and persistency are essentials for EFAS for managing flood events. Actually it will not wait for warn dissemination from both (deterministc and probabilistic) rather their individual threshold excedeence or flood definition determines. For probabilistic 10 EPS out of 51 members indicates event potential and exceedance during 24 hour duration for deterministic; for events persistently forecasted (from its twice per day forecasting rate, at 12:00 and 00:00, at least in two consecutive forecasts) and for more than 48 hours in advance the EFAS alert will be sent to the responsible partner organizations (Thielen et al, 2009). The alert messages are supported by different products like threshold exceedance maps (indicating probability of event for each grid), color-coded box (statistically summarized and simple to visualize the persistence of events) and hydrographs which will help for their decision.

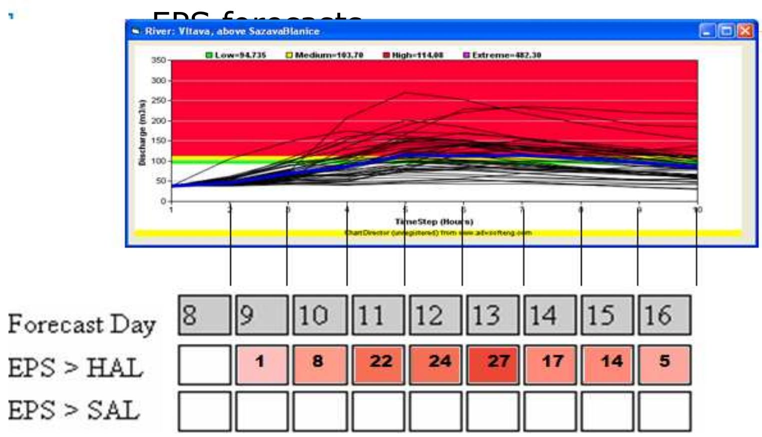


Figure 2.5 Ensemble Prediction Systems result (Source, EFAS training material, 2011)

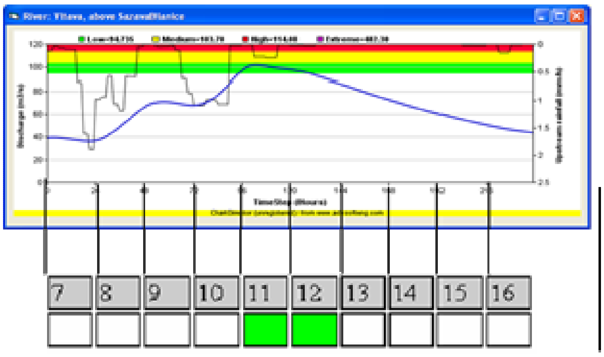


Figure 2.6 Single deterministic forecast result (Source: EFAS training material)

Table 2. 5 Overall EFAS forecasts (from different weather data source with over all 138 daily runs) (Source, http://efas-is.jrc.ec.europa.eu/home.html , 2011)

Forecast Name	Forecast [days]	N. of Ensembles	Spatial Resolution
Deterministic DWD (COSMO-EU + global model)	7 (3+4)	1	~ 7 km (for days 1 to 3) ~ 30 km (for days 4 to 7)
Deterministic ECMWF	10	1	~ 16 km
VAREPS ECMWF	10	51	~ 30 km
COSMO-LEPS	5	16	~ 7 km

Forecast verifications: EFAS results are verified on the basis of reported floods, in depth case studies for sever events and detail skill analysis of the performance of the model. In addition, detail performance of the system using different statistical skill (Hanseen-Kuipers, odds ratio, frequency of hits, frequency of miss, frequency bias, Brier skill score, reliability, probability of detection) tests are reviewed on Bartholmes et al. (2009) enclosing aggregate performance summary around 80%. Likewise the potential of flood event appearance (10 out of 51 ensemble members), persistency role, performance of probabilistic over deterministic forecasting system, forecast reliabilities verses lead time and others are resulted with good scores.

2.4.4 Warn dissemination

The most accurate flood forecast has no added value if it is not disseminated to the community. Hence, the dissemination of flood forecast information is an important issue. Thanks to technological advancement it is possible to reach the vulnerable communities by different means easily. Kevin (2008) has summarized the warn techniques in to indirect, community based and direct techniques. From indirect techniques televisions and radio broadcast, internet, teletext, telephone help lines, and newspapers. Under community based megaphones, helicopter loud hailers, bells, flags, motorcycles, electronic or manual billboard signs, road barriers, and flood wardens while telephone (voice and text), door knocking, fax, telex email and leaflet drops in direct techniques.

In EFAS the flood alert dissemination is based primarily on an online web-interface which is password protected and only accessed by EFAS partners (authorities that signed a memorandum of understanding). The results are well monitored by the EFAS team and in case of a particular situation an alert message will be sent out to the potentially affected partner via email. There are two types of messages: (1) EFAS flood alarm (Alert issued when a probability of exceeding critical flood thresholds are forecasted more than 2 days ahead in a river basin which is covered with an existing EFAS MoU.) and (2) EFAS flood watches (Alert issued when a probability of exceeding critical flood thresholds are forecasted in a river basin for which an EFAS MoU exists but the forecasted event does not satisfy the rules laid out in the MoU, e.g. regarding warning lead time, size of river basin, or location of event. An EFAS flood watch can also be issued if EFAS results are not conclusive but one of the multiple forecasts indicates risk of severe flooding.) (EFAS training material, 2011).

Timing of alarm dissemination is essential to rescue the vulnerable community and their properties. Figure 2.7 visualizes the distinction between catchment response time, forecast lead time and warning lead time. The overall time from rainfall event to flood peak covers the total catchment response time; the flood forecast lead time is the time period between the post-processed forecast and the flood event, while the real warning lead time is the time period after decision making and the flood event (Kevin, 2008). Forecast lead time could be delayed by some steps like rainfall data receiving and processing time, model run time (the taken to initialize mode states, run the model with probabilistic simulations), while warning lead time is delayed by some decision time which is required to send warning messages to responsible body. Hence, the effective time to warn or evacuate the affected community and their property is the time between warn received and peak flood reached is warning lead time. This warning lead time has to be as much as possible.

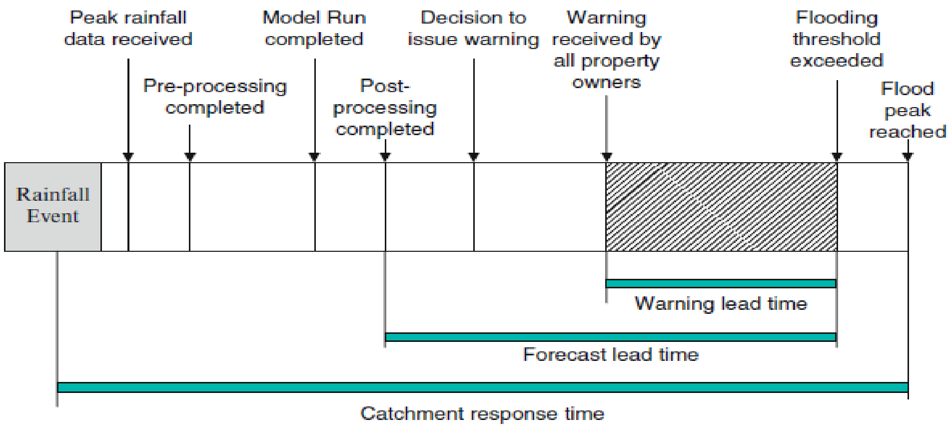


Figure 2.7 Flood forecast timings and delays in real time flood forecasting applications (Kevin Sene, 2008)

For the Baro-Akobo basin the dissemination realities are dependent on the life standard of the local community; radio broadcast, flags, bells and motorcycles are from the best recommended ones. For medium ranged forecasting systems i.e. minimum of three - four days in advance will be enough for the Baro-Akobo River basin inhabitants from their life patter point of view.

3. Study Area

3.1 Physiographic characteristics

3.1.1 Generals

Ethiopia is hydrologically divided into 12 basins: eight of these are river basins, one is a lake basin and three are dry basins (see Figure 3.1). The great East African Rift Valley is main determinant for the flow directions of the rivers as it divides the country. Most of the rivers will flow towards west to terminate at Mediterranean Sea (Abbay, Baro-Akobo, Mereb and Tekeze) or east to join Indian Ocean (Wabishebelle, Genale-Dawa and Ogaden), while the remaining ones will seep away inlands (Omo-Ghibe , Rift-valley Lakes, Aysha, Denakil and Awash).Most of them are trans-boundary river basins that radiate from the highland ridges of the Rift Valley and are endowed with high annual rainfall due to the Intertropical Convergence Zone in combination with orographic enhanced rainfall processes.

The Baro-Akobo Basin – focus of this thesis is a trans-national river basin shared by Ethiopia and Sudan. It is part of the White Nile River System having the name Sobat in Sudan. Baro-Akobo River Basin holds the second rank next to Blue Nile in runoff generation efficiency due to highest annual rainfall in western Ethiopia even though, the its catchment area is in the 7th position from 12 country's river basins. The river is characterized by high flows, extensive flooding, and high evaporation. Unlike to others rivers which are characterized by frequent ups and downs with falls Baro River is the only navigable river in the country with relatively stable channels.

3.1.2 Location and Basin characteristics

The Baro-Akobo Basin is located in the southwest of Ethiopia between 5 ° 31` and 10 ° 54` N, and 33 ° and 36 ° 17` E. The basin area is about 76,000 km^2, with altitude ranging from 3106 m to 402 MASL (50% below 1000, and 42 % between 1000 – 2000). The River Basin is divided by four administrative regions (i.e. 31% of the basin falls in Oromiya, 9.8% in Benshangul-Gumuz, 24.6% in SNNRP and 34.3% in Gambela), with around 2.2 million inhabitants (www.mowr.gov.et).

This study is limited to the Upper Baro-Akobo River above Gambella outlet (24,000 km^2) due to river discharge data constraint. The remotest gauging station with good river discharge record available in the basin is at Gambella (see fig 3.2).

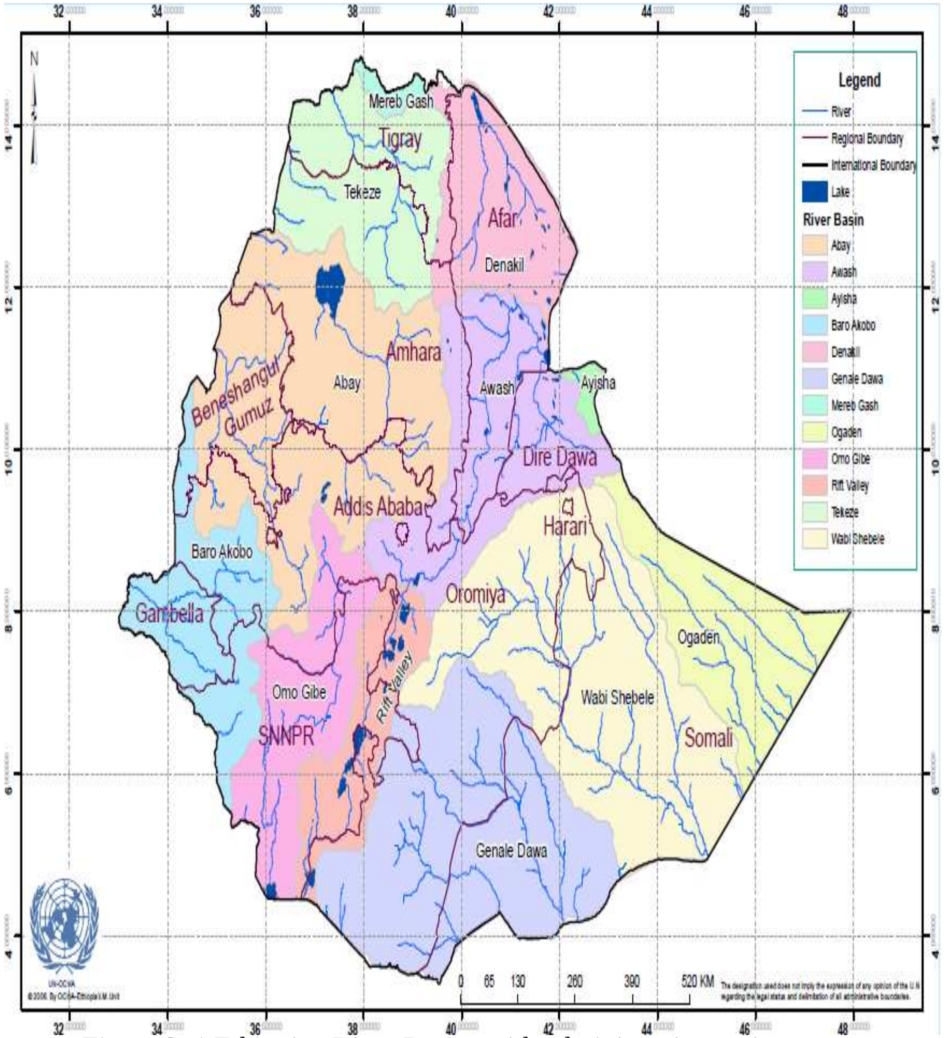


Figure 3. 1 Ethiopian River Basins with administrative regions

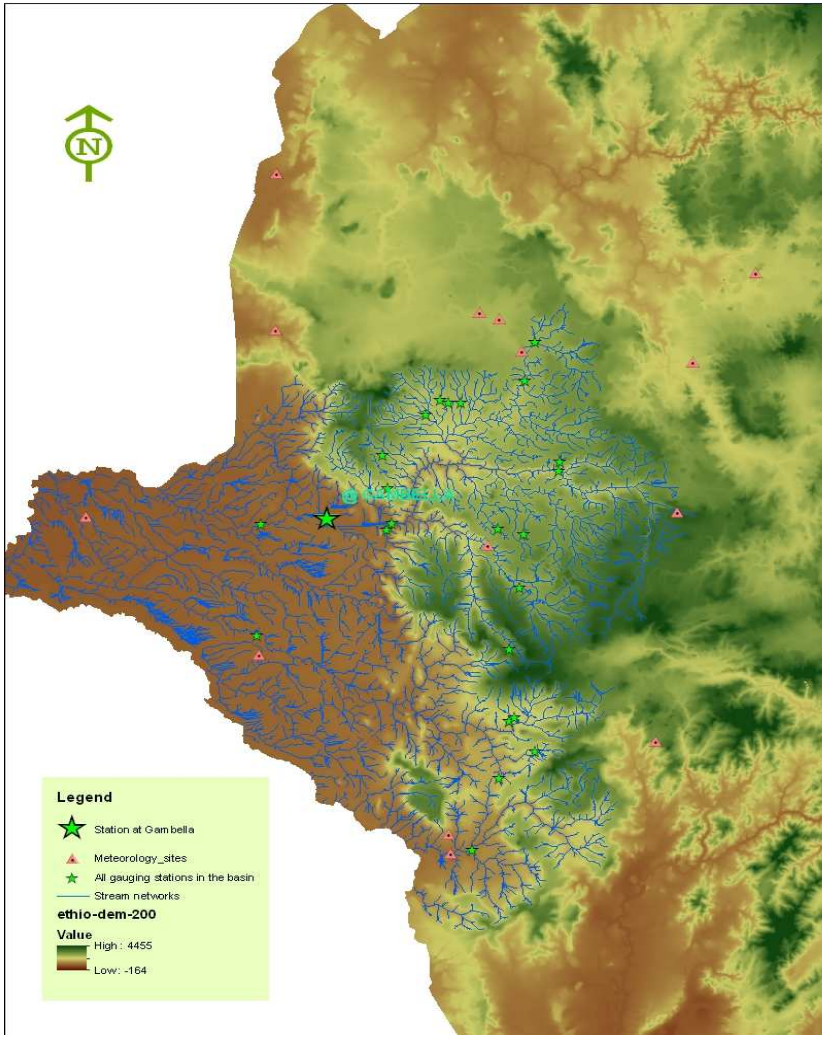


Figure 3.2 Western Ethiopia including Baro-Akobo River basin with all hydrological and meteorological stations.

3.1.3 Land cover and use

Land cover and land use are interconnected terms having high influence on the hydrological response Commonly, the first is linked with general physical materials on the surface (e.g forest, pavements, grass, etc), while the second is related to anthropogenic (farming and the like).

General coverage of the Baro Basin includes: grassland, low land and high land forests, bamboo forests, rain feed cultivation, wood land, shrub land (see Fig 3.3 below, J.P.Sutcliffe , 2009).

According to WBISPP (2001) and Chaffey (1978), within the Baro-Akobo basin the extent of the lowland forest, intermediate & montane forest covers, bamboo forest, and bamboo with montane forest mapped with area covering 3,670 km^2, 14,090 km^2 596 km^2, and 544 km^2 respectively. And due to high annual rainfall in the basin forests are floristically rich and higher percentage of the countries cash crop coffee Arabica product is covered by this area. And annual average deforestation rate in the basin is expected to be around 1.2 - 1.6 % (J.P.Sutcliffe, 2008 p. 2)

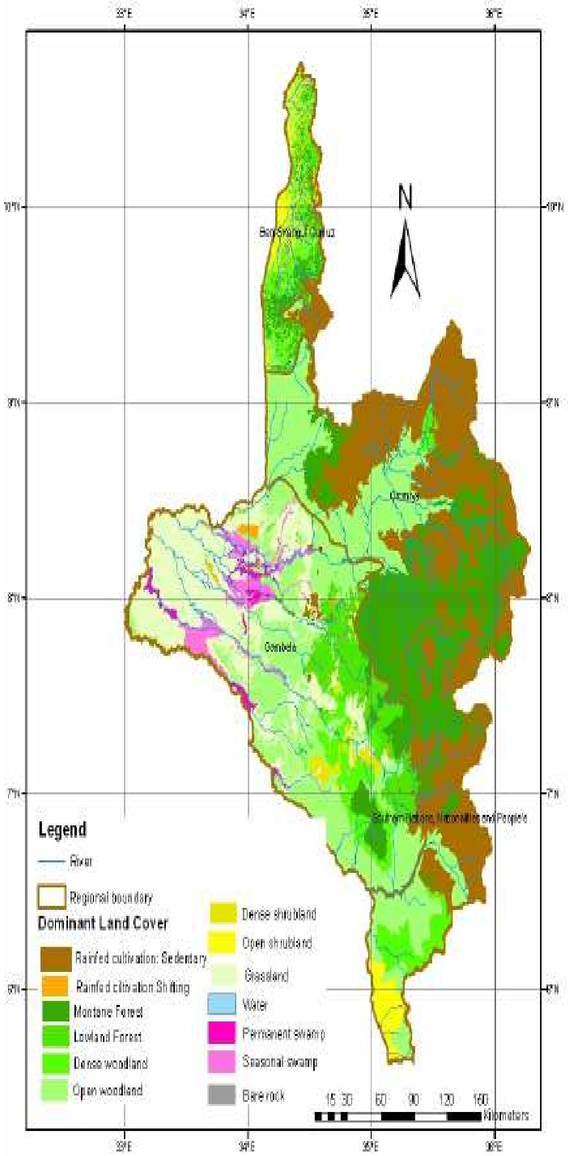


Figure 3.3 land Cover and Use for Baro-Akobo River Basin (Source: J.P.Sutcliffe , 2009)

3.1.4 Soil cover and geology

Geological and soil cover details (including layer depth, texture composition, and percentage area) are not surveyed well for the Baro Basin. However, Woube M. (2005) related all soil groups that are available within the basin to topographic, climatic, hydrologic and vegetative characteristics (see table 3.1).

For geological review, a large part of the basin is covered by shield basalt flows named as the Tepi basalt (up to 700m thick) (Davidson, 1983).In western Ethiopia, the high-grade gneissic terrains comprise various gneisses and migmatites, which are usually coarse-grained, well foliated and gray colored, often banded due to the injection of granitic material (Daniel M. et al., 2009). Woube M. (2005) also argued that rock outcrops occur in the eastern and northern part of the basin submerging westward and south west wards, soil materials founding at feet of the gentle slopes appear to have been formed from the basaltic lava flows from non-fragmented Oligocene - quaternary and deluvial, colluvial and elluvial fragments and as many formations around Gambella are depression filled with Alwero sandstone and it is water bearing.

Table 3.1 Soil types in the basin with topography and climate (Source: Woube M, 2005 pp. 150-151)

Soil types	Soil Characteristics’	Elevation and Topography	Parent Material	Climate
Nitosols	Laterised, humus, heavy clay, rich in base, thick and well aggregated, low EC, acid, Available p and K are mobile, sufficient N.	Steep slop, rolling surface, and 1000-2000	Basalt and other Quaternary deposits.	>1200mm annual rainfall, moderate temperature and good moisture.
Litosols	Immature brown soils, low humus, low fertility and lateritic pan, skeletal soils in combination with terrigenous tropical soils, rich in loams.	Formed under complicated topography, 800 - 1000 m a.s.l.	Loose rock	Moderate temperature
Ferralsols	Brownish-red, well drained, thick, deep surface craking, rich in clays, loams and humus, mobile P & K, sufficient N, Ca, EC, slightly alkaline and Fe-Mn concretion.	600 – 800m a.sl.	Quaternary deposits, iron cemented quartz, Fe-Mn corections.	1100 mm mean annual precipitation and ambient temprature.
Pellic Vertisols	Deep-black vertisols, heavy texture, deep cracking, moderate EC, low humus, mobile P & K, Ca, Mg as exchangeable cations,	400-500 m a.s.l	Lacustrine-alluvial clay	Rainfall and floods provide moisture for soil materials.

	slightly alkaline and nutrient deficient.			
Glay Vertisoils	Alluvial-meadow bog soils, heavy txture, high humus and EC, acidic, mobile P & K, fine silt, deep surface cracking, Fe-Mn concretion.	Flat plain, old riverbeds and hollows, 550-560m a.sl	Ancient deltaic deposits, river-bed alluvial sands.	800-900m annual precipitation, tropical ambient temprature.
Chromic Vertisols	Sandy loams poorly aggregated silty profiles, high humus content, reddish brown, clayey, surface compaction, Fe-Mn concretion.	Undulating plain, 500-550m a.s.l.	Alluvial loams and sandy loams	4-7 dry months and 1000 mm mean annual precipitation.
Fluvisols	Sandy, sandy loams, meadow, compacted fluvisols, deep gleyic, gley, heavy silt and clay texture gley, heavy silt and clay texture , high EC and humus mobile P and K, slightly acidic, Ca and Mn exchangeable cations.	Old riverbeds, flat land, 500 – 500m a.s.l	Alluvial clays, loams and sandy loams.	950 mm annual precipitation.
Forest Cambisols	Low humus, heavy texture, brown, dark – brown, high clay and humus content, low EC, Fe-MN content.	Denudation-aggradation landforms, 500-600 m a.s.l	Loose rock, basalt weathering products, grains gravel of quartz and feldspar.	950 mm annual precipitation and tropical ambient temperature.
Savannah Cambisoles	Shallow soils, low humus, heavy – light texture, compact, Fe-Mn concretion, low Ec and low nutrient supply.	Forest land, roll and ridges, 500-520 m a.s.l	Alluvial deposits.	950 mm annual precipitation.

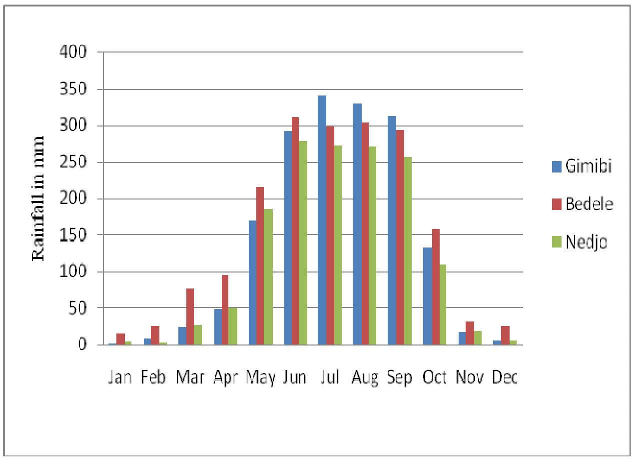
Table 3.2 Soil types in the basin with hydrological characteristics and vegetation cover (Source: Woube M, 2005 pp. 152)

Soil types	Hydrology	Vegetation	Land-use and land Suitability	Land potential
Nitosols	Ground water is deeper than 200 m but does not influence soil formation.	Tropical rainforest or ever green forest.	Arable land needs organic fertilizers.	Erosion on steep slope, denudation on plains and river valleys
Litosols	Low water table and availability of moisture depends on floods and rainfall.	Evergreen and deciduous tropical rainforest	Only a small area of land can be used for grazing but good for forest.	Less suitable for agriculture because of leaching
Ferralsols	Fresh group water (20 m deep)	Deciduous tropical forest, savannah grass and high in leaf litter decay products.	Partly arable land which requires organic and inorganic fertilizers.	High leaching and water erosion in gully forms.
Pellic Vertisols	Old and small rivers get lost in swampy areas.	Savannah grasses with different trees	Requires inputs due to waterlogged depression.	Lateral and sheet erosion in riverbeds.
Glay Vertisols	Swampy surface is connected with the river and ground water.	High grass savannah with scattered trees.	Unsuitable for agricultural activities	High leaching
Chromic Vertisols	>20-m ground water depth, water logging in depressions associated with rainfall	High grass savannah with scattered trees	Unsuitable for agricultural activities due to physical characteristics.	Leaching occurs
Fluvisols	Meanders, ox-box lakes and ancient delta origin, ground water are connected with river flow	Deciduous low trees and savannah grass.	Suitable for sprinkler irrigation	Erosion on river flood plains
Forest Cambisls	Drained and low water percolation areas.	Evergreen and deciduous tropical forest	Need organic and inorganic fertilizers	Erosion in combination with gullies.
Savannah Cambisols	Poorly drained areas and 20m ground water depth.	Deciduous forest and grass savannah.	Requires irrigation, organic and inorganic fertilizers.	Leaching occurs

3.2 Climate

Climate is broad term which is expressed in terms of rainfall, temperature, humidity, wind speed & direction, sunshine hours or with combination effects of these like evapotranspiration and others. It is mainly a function of altitude and geographical location.

In the basin the annual precipitation varies from about 1,500 mm to over 2,200 mm (www.mowr.gov.et), with two distinct seasons: dry from November to February and wet from June to October. Figure 4.3 indicates the rainfall pattern in the basin and western part of Ethiopia which is unimodal distribution with peak rainfall from mid-July to September. The mean annual temperature ranging from 17.5 °C on highlands to around 27.5 °C on the flood plains, with an overall maximum temperature range from 24 to 35 °C and minimum temperature from 10 to 20°C. Evapotranspiration in the basin is largely driven by the rainfall patterns with exception for the Machar Marshes. The Machar Marshes are wetland areas in north of Baro with complex hydrology which are feed by the spill from Baro and several streams from the Ethiopian foothills (Sutcliffe and Parks, 1999), here the evapotranspiration ranges from 300 - 1500 mm (www.waterwatch.nl).



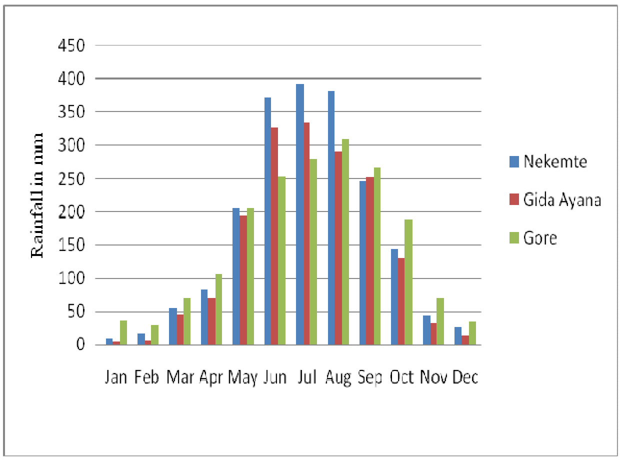


Figure 3.4 Long term mean monthly rainfall for some of meteorological stations.

3.3 Hydrological conditions

Generally the hydrology of the basin is characterized by a high runoff generation with average discharge of 9.7 liters/s/ km^2 (Gulilat B., n.d). The river discharge trends for the Gambella station can be seen in the graph below (figure 3.4).The data were collected since 1967 by the Ministry of Water and Energy (with the interruption between 1984 and 1989) . The minimum flow ranges from 7 - 20 m^3/s while, the maximum during peak rainy season is between 1200 – 1500 m^3/s. The total mean annual flow from the river basin is estimated to be 23.6 billion cubic meters (Sileshi et al, 2007. p.5).

Table 3.3 Details for hydrological gauging station at main outlet.

Station	LAT.	LON.	UTM		Upstream area in Km^2
			North	East	
At GAMBELLA	8d14'52"n	34d34'36"e	911951	673665	23461

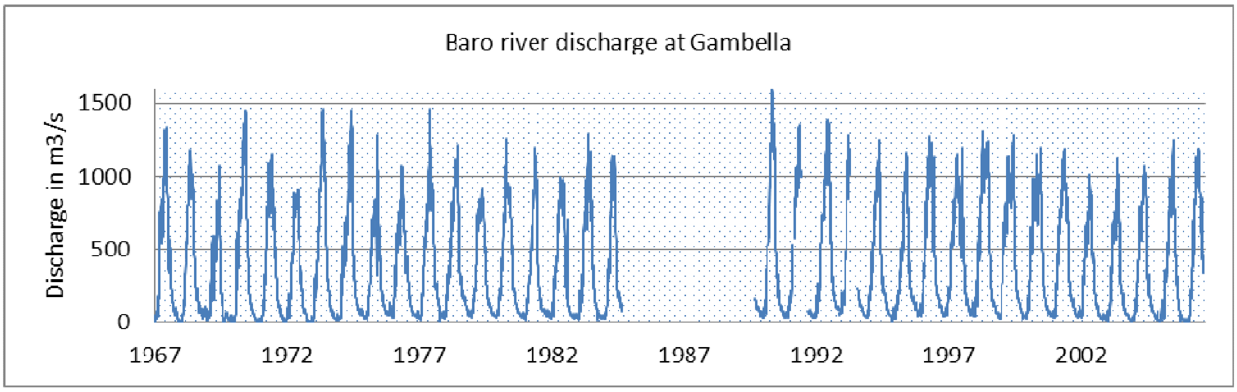


Figure 3. 5 long time series hydrograph for Baro River at Gambella station.

4. Data and Methodology

4.1 Used data

4.1.1 Meteorological data

4.1.1.1 Precipitation data

Two different precipitation information sources were used: (1) measurements from meteorological ground stations and (2) satellite-based rainfall estimates.

Measurements of 15 stations (located inside and around the basin) holding 15 years of daily record were made available by the Ethiopian National Meteorology Agency. Station characteristics can be seen in the table 4.1.

Four different satellite-based rainfall estimates were tested:

- Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN)
- African Rainfall Estimation Algorism, version 2 (RFE 2.0)
- ERA-interim
- Tropical Rainfall Measuring Mission, version 6 (TRMM 3B42)

The data were obtained from the University of Arizona, NOAA-CPC, ECMWF and NASA respectively. Detail for four of satellite data including source, spatio-temporal resolutions, methodology, spatial coverage and availability time are given in table 4.2.

Table 4.1 Meteorological stations in and around Baro-Akobo River Basin from Ethiopian National Meteorology Agency.

Station	Lat	Long	Elevation [m]	Period	% Missing	MAR [mm]	Remark
Assosa	10.01	34.31	1600	1987-2007	35	1118.507	
Begi	9.2	34.32	1650	1987-2007	55.17	1229.682	
Abobo	7.51	34.26	530				Not working
Gimibi	9.1	35.47	1970	1987-2007	8.27	1772.455	
Bebeka	6.49	35.16	1280				Not Working
Bedele	8.27	36.2	2030	1987-2007	0.97	1855.548	
Chiri	7.08	36.11	1500			1596.73	Partially working
Jinka	5.48	36.33	1430	1987-2007	0.96	1343.133	
Nedjo	9.3	35.27	1800	>>	5.6	1481.429	
Hena	9.27	35.36	1700	>>	44	2090.842	
Nekemte	9.05	36.27	2080	>>	4.39	2008.31	
Gida Ayana	9.52	36.56	1850	>>	4.31	1705.024	
Gore	8.09	35.32	2002	>>	0.92	1859.233	
Tepi	6.59	35.15	1540	>>	2.49	1535.171	
Jikawo	8.22	33.45	410	>>	60.48		Partially working

Table 4. 2 Detail for used satellites data sources

Satellite data	African Rainfall Estimation Algorism ,RFE 2.0	Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks, PERSIANN	ERA-interim	Tropical Rainfall Measuring Mission (TRMM)
Released by	National Oceanic and Atmospheric Administration – Climate prediction center NOOA-CPC	University of Arizona	European Centre for Medium-Range Weather Forecasts (ECMWF's)	NASA
Methodology	The rainfall algorism is uses the 85V GHz channel to detect the scattering of radiation by precipitation and ice within cloud layers. The returned scattering patterns are compared against previously derived rainfall amount and instantaneous rain rates. Due to difference in emissivity of land surface and water surface, emission algorism uses different wave frequencies. With source from different satellite, and finally Global Telecommunications Station (GTS) precipitation data is used for the algorism for obtaining the daily RFE values.	From information collected from whole cloud patch with the following four steps (Kuo-Lin Hsu et al., 2010) * Cloud image segmentation * Feature extraction from IR cloud patches * Similar cloud patches features are grouped to nearby cloud group. * Rainfall rates are assigned to pixels	Based on reanalysis from past decades in preparation and extending for the next–generation. ERA-interim uses the global analysis describing atmospheric and land ocean wave conditions for period 1957 – 2002. The assimilating model of ERA-interm uses T255 spherical harmonic representations for basic dynamic fields and it is based on 12 hourly four dimensional variational analyses (4D-Var) which include the adaptive estimation of biases in satellite radiance data.	From more physically - based microwave estimates and the remaining gaps are filled with HQ-calibrated infrared estimates.
Resolution (spatial, temporal)	0.1°x 0.1° daily	0.25°x 0.25° 0.5 - hourly	T255 (~80 km or 0.7 deg) 3-hourly	0.25° x 0.25° 3-hourly
Spatial coverage	40°N-S and 20°W-55°E	50° N-S	global	50° N-S
Available data	Since January 2001	Since March 2000	Since January 1989	Since January 1998
Source link	http://www.cpc.ncep.noaa.gov/products/fews/rfe.html	http://hydis.eng.uci.edu/gwadi/	http://www.ecmwf.int/research/era/do/get/era-interim	ftp://disc2.nascom.nasa.gov/data/TRMM/Gridded/Derived_Products/3B42_V6/Daily/

Station precipitation data are interpolated using Inverse-Distance-Weighted (IDW) method which is widely used, easy to program, fairly accurate under a wide range of conditions (Lam, 1983). i.e equation below:

$$P_i = \frac{\sum_{j=1}^{G} P_j \;/\; D_{ij}^{n}}{\sum_{j=1}^{G} 1 / D_{ij}^{n}} \tag{4.1}$$

Where p is precipitation at location i, Pj is the precipitation at sampled location j, D_{ij} the distance between i and j, G is the number of sampled locations and n is inverse-distance weighting power. Interpolation is done using the nearest five stations with weighting power 2 for 0.1 degree pixel size. For the case of missing values, interpolation can be conducted with other stations which hold values.

4.1.2 Static data

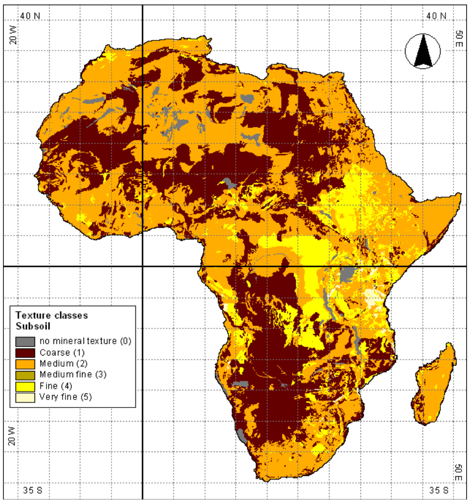
The following static data set are used as input into LISFLOOD. It includes soil, topography, slope gradient, local drainage, land cover, leaf area index, forest fraction, channel length information. Most maps were created by Bodis (2009). All data were aggregated to a 0.1 degree grid.

4.1.2.1 Soil

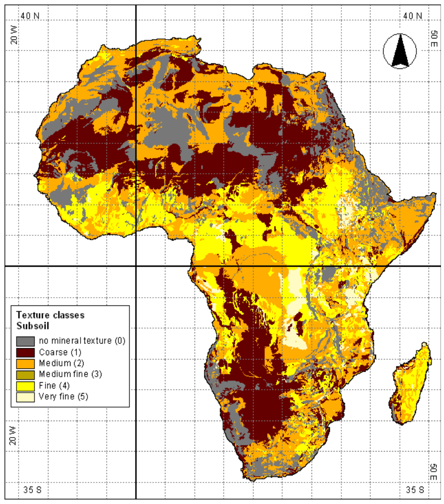
Two distinct soil informations are required by LISFLOOD: the soil texture and the soil depth.
Soil texture is derived based on the dominant soil for two layers (topsoil and subsoil) using information of the Harmonized World Soil Database v 1.0 (HWSD, FAO/IIASA/ISRIC/ISSCAS/JRC, 2009) (see figure 4.1 a and b). Soil texture classes for LISFLOOD according to percentage composition of clay, sand and silt are stated in table 4.3. The soil depth information is taken as given from the HWSD (see figure 4.1 c).

Table 4. 3 Soil texture classifications applied in LISFLOOD (source: Bodis, 2009)

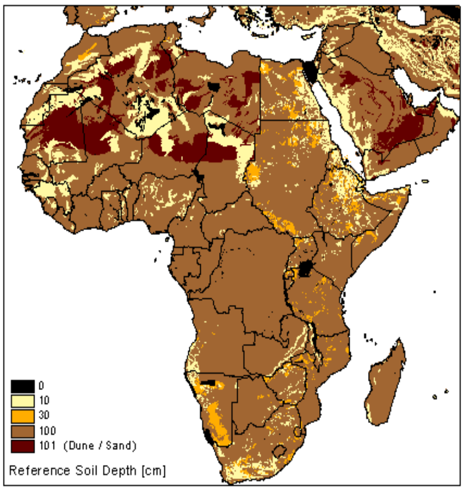
Class Codes	Description	Values for clay and sand contents
0	No mineral texture	peat soils, rocks, etc.
1	Coarse	Clay ≤ 18% and sand > 65%
2	Medium	18% < clay < 35 % and sand ≥ 15%,or clay ≤ 18% and 15 % ≤ sand ≤ 65 %
3	Medium fine	clay < 35 % and sand < 15 %
4	Fine	35 % ≤ clay ≤ 60 %
5	Very fine	clay > 60 %



(a). Soil texture for topsoil



(b). Soil texture for subsoil

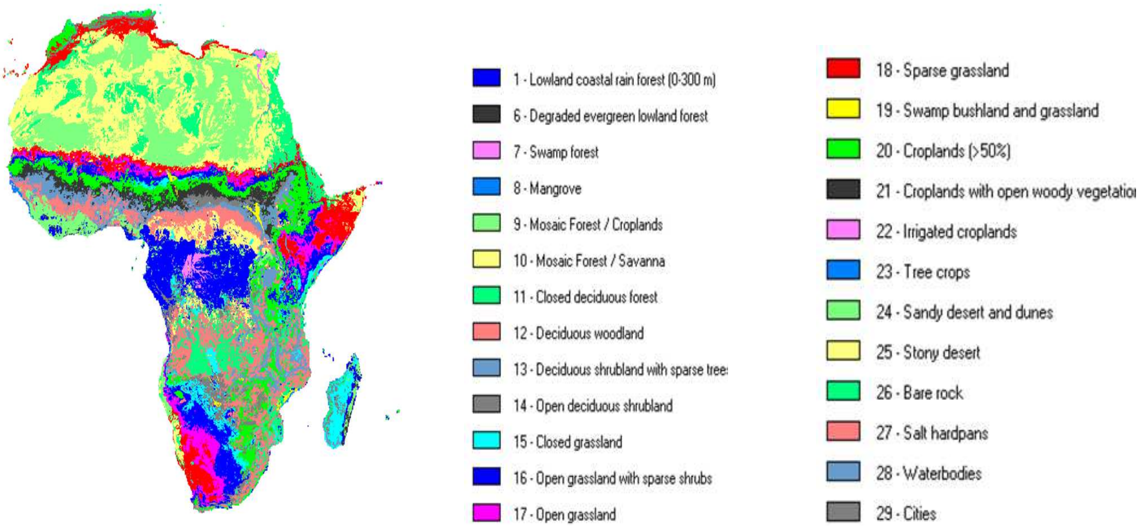


c. Soil depth map

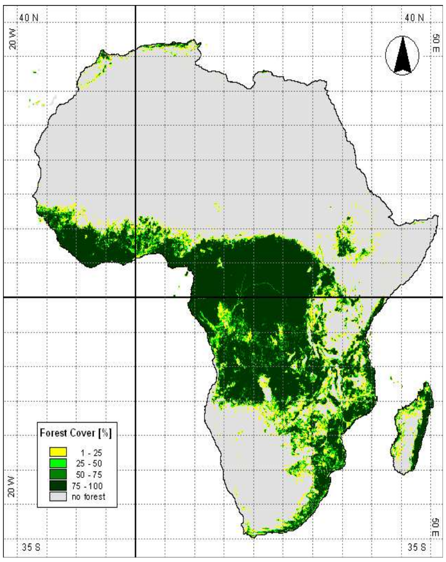
Figure 4. 1 LISFLOOD continental scale soil input maps (source: Bodis, 2009)

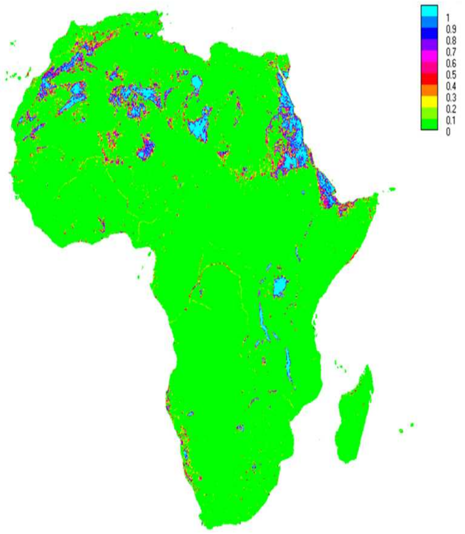
4.1.2.2 Land cover

Land cover related maps includes land cover, forest and direct runoff fraction maps. Land cover information were taken from the Global Land Cover 2000 data (Mayaux et al., 2006; GEM, 2003) and based on spatially dominant land cover type. The land cover is classified in to 25 classes (figure 4.2). Forest and direct runoff fraction maps are derived indirectly based on the land cover information as percentage area coverage for each pixel.



(a). land cover map





(b). Forest cover map

(c). Direct runoff fraction map

Figure 4. 2 land cover, forest fraction and direct runoff fraction map.

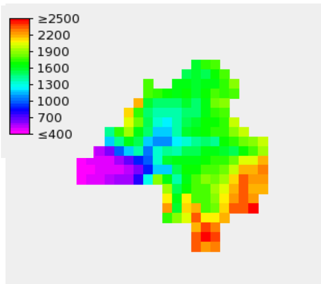
4.1.2.3 Leaf Area Index (LAI)

The Leaf Area Index, meaning the area of leafs per surface area (m^2/m^2), was extracted from the VGT4AFRICA Project (Baret et al., 2006). The data are provided for every tenth day, starting from 2007. Three years of data were used to create a reference year by averaging on an inter-annual basis, resulting in

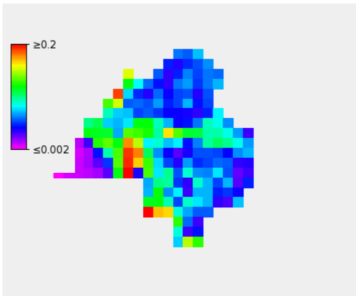
36 reference maps. Since it is difficult to show all sequence as an example two different season maps for the basin are shown in figure 4.3 i and j.

4.1.2.4 Others

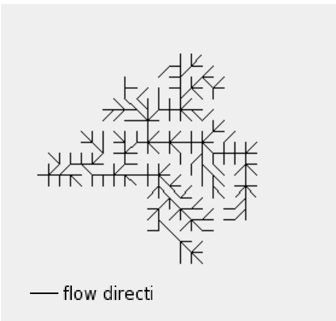
The remaining input maps such as local drain direction (LDD, essential components expressing fluid flow directions from each pixel to its steepest downs slope neighbor pixle), slope gradient (which shows the maximum rate of change in value from each cell to its neighbor), channel gradient (based on the terrain difference and estimated flow length with in a cell), channel bottom width (estimated based on representative river discharge with the assumptions of rectangular cross section), channel flow length and depth were derived indirectly based on the digital elevation data provided by the NASA-SRTM.



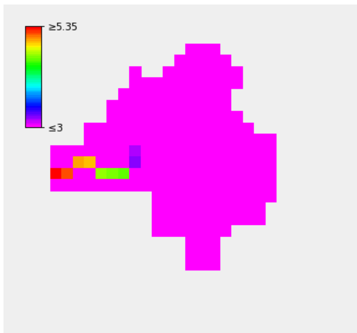
(a) mean dem



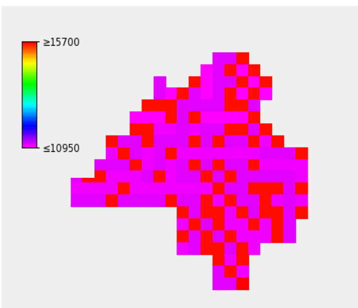
(b) gradient map

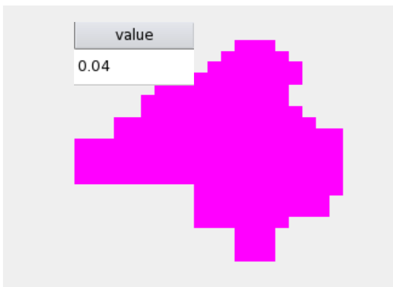


(c). local drain direction map

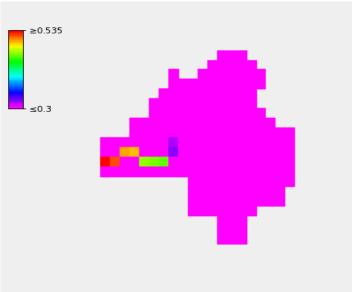


(d) channel bed width map

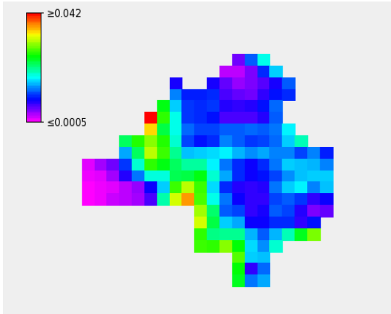




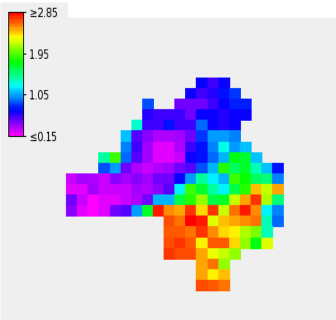
(e) channel length map



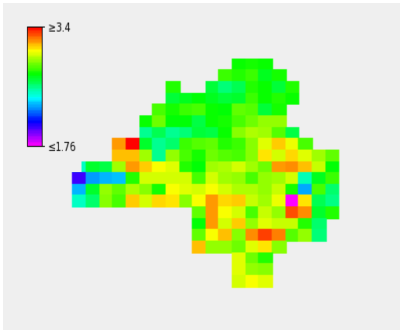
(f) channel manning coefficient map



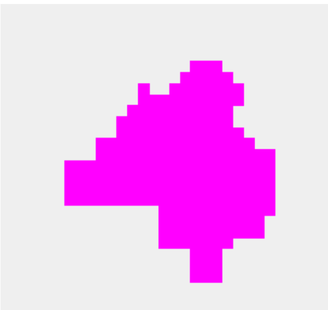
(g) channel bank full depth



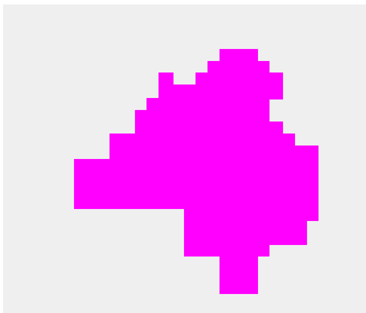
(h) channel gradient



(i) lai for time 02/01- 02/10/2000



(j) lai for time 09/10 - 09/20/2000



(k) channel map (each cell is considered as)

(h) channel side slopes (for all rectangular)

Figure 4. 3 Basin LISFLOOD input maps

4.2 Establishing LISFLOOD model

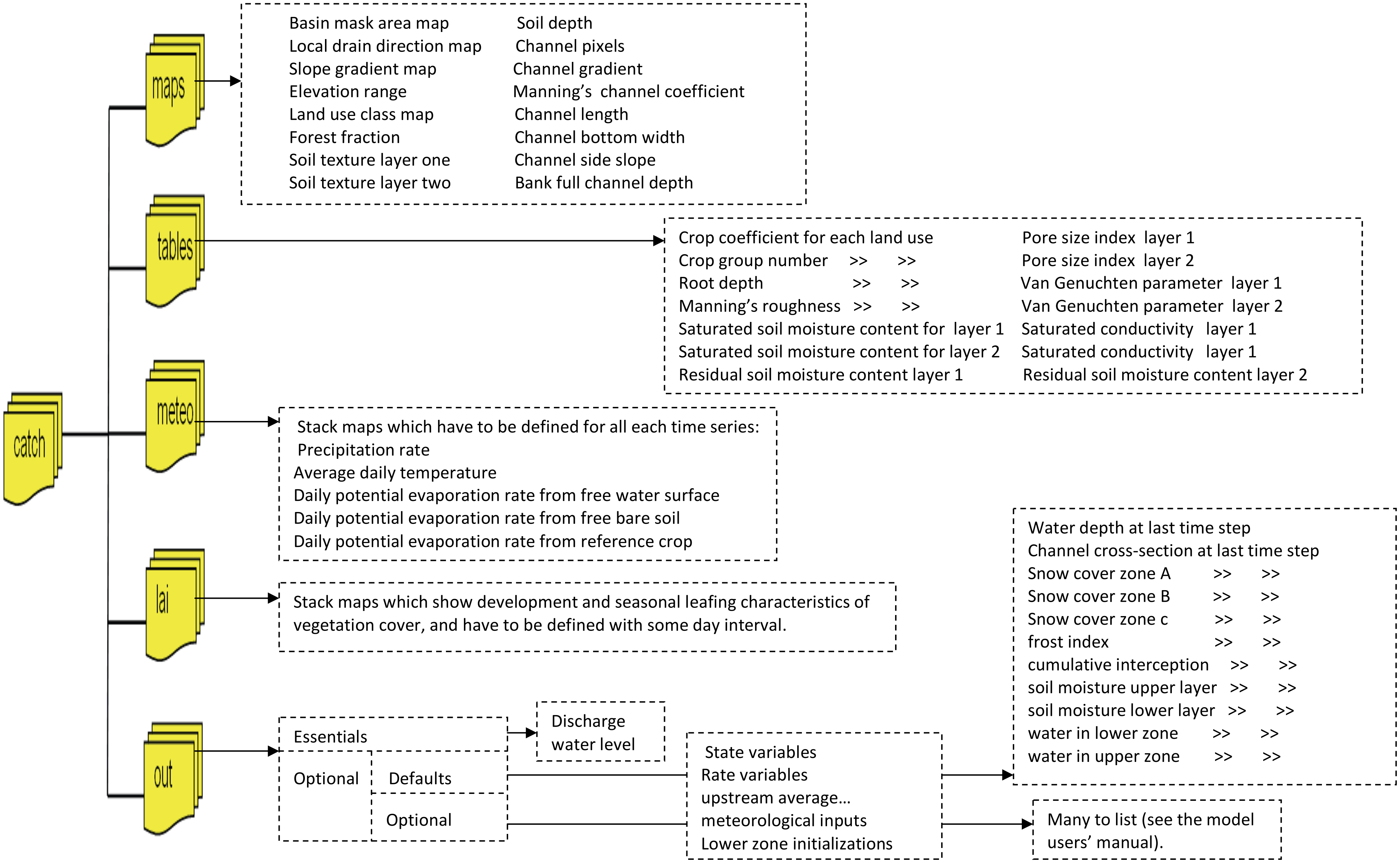
There are two essential phases within this study:

1. Establishment of the hydrological model and
2. Adaptation of the flood foresting and early warning system.

In this sub-section details for setting up of LISFLOOD model including parameterization, sensitivity analysis and calibration are stated. And in the next section, European Flood Alert System is adapted and tested (i.e. alert threshold determination, ensemble prediction systems, hindcasting, alert dissimilation).

4.2.1 Model structure

The following file structure diagram clarifies the model setting up which will lead to the first simulation with results stated at output below.


catch
maps
Basin mask area map
Local drain direction map
Slope gradient map
Elevation range
Land use class map
Forest fraction
Soil texture layer one
Soil texture layer two
Soil depth
Channel pixels
Channel gradient
Manning's channel coefficient
Channel length
Channel bottom width
Channel side slope
Bank full channel depth
tables
Crop coefficient for each land use
Crop group number >> >>
Root depth >> >>
Manning's roughness >> >>
Saturated soil moisture content for layer 1
Saturated soil moisture content for layer 2
Residual soil moisture content layer 1
Pore size index layer 1
Pore size index layer 2
Van Genuchten parameter layer 1
Van Genuchten parameter layer 2
Saturated conductivity layer 1
Saturated conductivity layer 1
Residual soil moisture content layer 2
meteo
Stack maps which have to be defined for all each time series:
Precipitation rate
Average daily temperature
Daily potential evaporation rate from free water surface
Daily potential evaporation rate from free bare soil
Daily potential evaporation rate from reference crop
lai
Stack maps which show development and seasonal leafing characteristics of vegetation cover, and have to be defined with some day interval.
out
Essentials
Optional
Defaults
Optional
Discharge
water level
State variables
Rate variables
upstream average…
meteorological inputs
Lower zone initializations
Water depth at last time step
Channel cross-section at last time step
Snow cover zone A >> >>
Snow cover zone B >> >>
Snow cover zone c >> >>
frost index >> >>
cumulative interception >> >>
soil moisture upper layer >> >>
soil moisture lower layer >> >>
water in lower zone >> >>
water in upper zone >> >>
Many to list (see the model users' manual).

4.2.2 Model parameters

LISFLOOD has more than 40 model parameters (see table 4.4). Generally, parameters are related to snow and frost activities, atmospheric processes, soil and ground water flow and routing. Most of them have a physical meaning and thus can be taken from literatures. Only a minor number needs to be determined through model calibration.

Table 4.4 LISFLOOD model parameters (source: Van Der Knijff et al., 2008)

Type	Parameter	Description	Units
Snow and frost related	f_{snow}	Snow correction factor	-
	T_{snow}	Temperature below which precipitation is treated as snow	^oC
	T_m	Temperature above which snow melt occurs	^oC
	C_m	Snowmelt degree-day factor	mm $^oC^{-1}$ day^{-1}
	L	Temperature lapse rate	$^oC\ m^{-1}$
	A_f	Frost index snow depth reduction coefficient	cm^{-1}
	k	Frost index snow depth reduction coefficient	cm^{-1}
	we_s	Snow water equivalent	-
	F_{crit}	Value of frost index above which soil is considered frozen land cover related parameters	$^oC\ day^{-1}$
Land cover related	f_{dr}	Direct runoff fraction	-
	LAI	Leaf Area Index (as function of time)	m^2m^{-2}
	k_{gb}	Extinction coefficient for global solar radiation	-
	K_{crop}	Crop coefficient	-
	T_i	Time constant of rainfall interception store	days
	W_{crit}	Threshold for resetting DSLR in soil evaporation reduction equation	mm
	n_s	Surface manning's roughness coefficient	-
	d_r	Rooting depth	cm
Soil and ground water related	b	Infiltration constant	-
	c_{pref}	Preferential flow constant	-
	K_{s1},K_{s2}	Saturated hydraulic conductivity layer 1,2	cm day^{-1}
	Θ_{s1}, Θ_{s2}	Saturated volumetric moisture content layer 1, 2	mm^3mm^{-3}
	λ_1, λ_2	Pore-size index layer 1,2	-
	α_1, α_2	Constant in soil water retention equation layer 1,2	-
	d_s	Soil depth	cm
	T_{uz}	Upper zone time constant	days
	T_{lz}	Lower zone time constant	days
	GW_{perc}	Maximum rate of percolation from upper to lower zone	mm day^{-1}
	f_{loss}	Ground water loss fraction	-
Channel related	g_{ch}	Channel bed gradient	mm^{-1}
	n_{ch}	Channel Manning's roughness coefficient	-

	l_{ch}	Length of channel element	m
	W_{ch}	Channel bottom width	m
	S_{ch}	Channel side-slope	mm^{-1}
	bf_{ch}	Channel bank full depth	m

4.2.3 Model parameter sensitivity

Sensitivity analysis for model parameter is essential for the following reasons:

(i) in calibration; to fix insensitive parameters at suitable value to decrease dimensionality of calibration problem (Mirshahi, 2010)

(ii) to detect and be sensitive at parameters and/or sub-process which are influential for hydrological response of the river basins for model formulation and parameter uncertainty,

(iii) for rough systematic check whether the parameters or sub-process are well defined (Wagener et al., 2004).

As the model sensitivity analysis is potentially useful in all phases of the modeling process (model formulation, model calibration and model verification)(McCuen**,** 2003), a simple trial and error method is applied for first reason (i.e dimensionality of calibration parameters), Generally for the remaining purpose it was done for first order (two times keeping others at optimized value and default value) and the result is presented on the next chapter.

4.2.4 Feasible parameter set and space

It is necessary to determine parameter sets (number of parameters which are to be calibrated) and their upper and lower boundaries for calibration. By simple trial and error sensitivity analysis the following eight parameters are set for calibration see table 4.5.

Table 4. 5 Feasible parameter sets and space for calibration

Parameter	description	Lower bound	Upper bound	Default values	unit
UZTC	Upper zone time constant	1	50	10	days
LZTC	Lower zone time constant	50	5000	1000	days
GWLF	Ground water loss fraction	0.1	1.5	0.0	-
bxinj	Power in Xinanjiang distribution function	0.1	1	0.5	-
PWPF	Power that controls proportion of preferential flow	1	6	3	
CCM	Multiplier factor for channel manning's n	0.1	15	1	
CalEvap	Multiplier for potential evapotranspiration rates	0.1	1.5	1	
CCM2	Multiplier applied to Channel Manning's n for second line of routing	0.1	15	1	

4.2.5 Initial conditions

LISFLOOD requires initial conditions prior to each run, to have a good replication of where, how much water is within the different storages (e.g. ground water or upper soil layer) at the time the model is launched. If initial conditions would not be provided, the model would first fill the storages before creating flow, which would result in a wrong representation of the actual situation.

The initialization of LISFLOOD is done in two steps. First, initial conditions for the storages holding a long response time (like ground water storage) are determined through a prerun of at least 6 to 8 years. The resulting state variables are stored within maps, which are loaded into the model for the actual run. Second, fast responding storages are calculated by using a warm up period of one year within the actual run. This one year is excluded from the analysis.

4.2.6 Calibration

Even if the esteemed procedure is testing each parameter independently and estimating directly the outputs, parameters are typically calibrated due to different limitations: technology, human capacity, uncertainty in nature, big temporal and spatial variations of parameters. Additionally having the boundaries of each parameter, calibration increases the confidence and reliability to trust the model.

Calibration means the adjustment of sensitive parameters within reasonable bounds to optimize the conformability of the observed and simulated discharge series. This process can be done either manual or automatically; both processes are described below.

4.2.6.1 Manual calibration

Optimal parameters are estimated by successive trial and error model simulations. This approach is time consuming, labour-intensive and increasingly complex as the number of parameters increases (Howard et al., n.d). Thus, it is an inefficient and limited approach to achieve an optimal parameter fit. However, it can be useful to gain insights on some catchment characteristics and sensitivity of model parameters by simple eye look and statistical values.

4.2.6.2 Automatic calibration

Optimal parameter is estimated using search algorithms and an optimizing objective function. Its efficiency is highly dependent on the chosen algorithm and objective function. Commonly used calibration algorisms are:

- AMALGAM (multi-algorithm, genetically adaptive multi-objective method),
- Quasi-Newton methods (algorism based on newton's method to find maxim or minima of a function based on gradient of functions),
- SCE-UA (genetically adaptive approach for effective and efficient global optimization), and
- Particle Swarm Optimization (PSO, is a population based stochastic optimization technique inspired by social behavior of bird flocking or fish schooling (Kennedy and Eberhart, 2001).

Further explanations are limited to the applied algorithm, SCE-UA.

SCE-UA (Shuffled Complex Evolution Method - University of Arizona) is grounded on genetic algorithm with intensive search, effective and efficient for global optimization in large parameter space developed by Duan et al. (1993). SCE-UA is developed to cope with the following five problems in optimization (1) having multiple regions of conversion (2), premature of optimization by many small local pits and bumps (3) the objective function surface in the multiparameter space may not be smooth and may not even be continuous (rough surface with discontinuity in derivatives) (4) high non- linear interaction between the parameters and (5) capability of handling high-parameter dimensionality.
The method applies a combination several existing methods that have been proven successful in the past. The overall principles of the algorisms are stated below.

I. Combination of deterministic and probabilistic approaches,

II. Systematic evolution of a complex of points spanning the parameter space, in the direction of global improvement

III. Competitive evolution;

IV. Complex shuffling.

The algorism flow chart and parameters taken for each step are stated below,

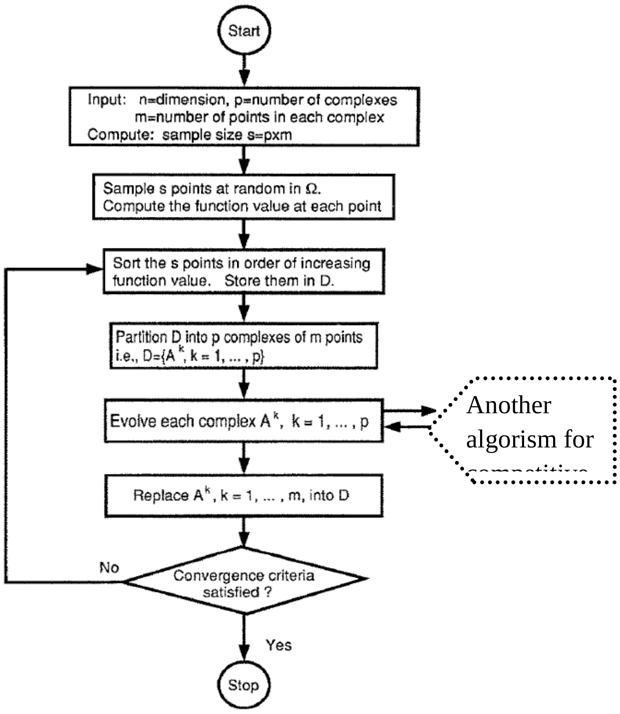


Figure 4.4 Flow chart of the shuffled complex evolution (SCE) method (Source, Duan et al., 1992,1993)

SCE-UA contains many probabilistic and deterministic components that are controlled by some algorithmic parameters (Duan et al., 1993). Thus, values of each parameter for the algorism determine effectiveness of the optimization. The recommended values by the authors are taken for all algorism parameters.

For initializing steps:

- n the number of model calibration parameters, n = 8
- p: number of complexes, recommended P $\geq$ 1, taken 3
- m: number of points in each complex , recommended m = 2*n +1, taken 17
- q: the number of points in each sub-complex, recommended n+1 , taken 9

- sample size will be m*p = 51

For competitive evolution:

- β: evolution steps taken by each complex before shuffling , recommended β greater than or equal to 1, taken 9
- α: number of offspring which each sub-complex generates before it put back into the complex, recommended value greater than one (if one only one will be replaced without effective search, and if more it will be more local search), taken 3

4.2.6.2.1 Objective functions

An objective function is a specific statistical skill score, such as for instance Nash-Sutcliffe or Pearson correlation coefficient. The target of the calibration algorithm is to find the parameter set that maximize the value of the objective function. Hence the search will continue till the objective function is not improving any further. Since each objective function has a distinct focus, the choice of the right objective function is determining for an optimal calibration result. It is possible to use one or multiple skill scores for the optimization.

For this study the Pearson's product - moment correlation coefficient (r) is set as objective function. Using the Pearson coefficient the main focus is on the correct reproduction of the dynamics of the hydrograph, and not on the reproduction of the correct water balance since this skill score is insensitive to proportional differences. Since the methodology of the flood alert system that we are testing on this basin is solely focused on the exceedance of pre-defined thresholds, this is the optimal objective function.

However, since the quantitative reproduction of the water balance within this test basin is feasible a different objective function, that is sensible to quantitative differences and to the general fit might serve better. For this reason the calibration was repeated using the coefficient of efficiency (Nash and Sutcliffe, 1970) as objective function, for the cases that the Person correlation coefficient was high, even if the graphs were quantitatively not in accordance.

The overall goodness fit is assessed by the following statistical skills scores:

- *Coefficient of efficiencies (Nash and Sutcliffe, E):* sensitive for extreme values, ranges from minus infinity to 1. Closer to one indicating better agreement.

$$E = 1.0 - \frac{\sum_{i=1}^{n} (O_i - S_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2} \quad 4.2$$

Where O_i observed discharge, S_i model simulated discharge with corresponding time step with observed, $\overline{O}$ is mean of observed discharge.

- *Pearson's product moment correlation coefficient and its square*: coefficient of determination: sensitive for extremes, insensitive for additive and proportional difference ranging from 0 to 1. Closer to one with better agreement.

$$R = \left[\frac{\sum_{i=1}^{n} (O_i - O_{avg}) * (S_i - S_{avg})}{\sqrt{\sum_{i=1}^{n} (O_i - O_{avg})^2} * \sqrt{\sum_{i=1}^{n} (S_i - S_{avg})^2}} \right] \quad 4.3$$

Where, S_i , S_{avg} , O_i , O_{avg} are model simulated, mean of simulated values, observed value and mean of observed values respectively.

Coefficient of determination R^2 is relatively easy to interpret the results (for instance R^2 = 0.8, 80% of model outputs can to be managed).

- *Root mean squared error (RMSE):* is the standard deviation of the simulation error and is used to measure the discrepancy between simulated and observed values on an individual basis (based on individual residues). It ranges from 0 to positive infinity, closer to zero better agreement.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (O_i - S_i)^2}{n}} \quad 4.4$$

- *Bias (BIAS):* it is a measure of unidirectional deviation of the simulated to the observed discharge. Ranging from negative infinity to positive infinity. Closer to zero indicating best fit , negative value for under estimations , and positive value for over estimation.

$$BIAS = \frac{O_i - S_i}{n} - \frac{\left(\frac{O_i - S_i}{n} + (O_i - S_i) \right)}{n} \quad 4.5$$

- *Water Balance:* The ratio between total simulated to total observed water amount with closer to one indicates best estimate.

  Water Balance = Total simulated water amount / Total observed water amount 4.6

4.2.6.2.2 Numbers of calibration runs

The total number of runs for calibration is mainly dependent on the optimizing algorism (including parameters of algorism), objective function and number of parameters. The maximum number of model iterations was set to 1000.

4. 3 Determination of alert thresholds

As abovementioned the European Flood Alert System (EFAS) issues a flood warning in form of an alert level (low, medium, high and severe) expressing the magnitude of the expected flood. Hence the determination of appropriate thresholds is crucial for a good flood warning. There are a number of different approaches of how to derive them, such

(1) Multiplying the average discharge value by some constants (i.e. 7*Qav, 5*Qav, and 3*Qav for high , medium and low respectively)
(2) Percentage or probability of occurrence (0.1%, 0.5%, and 1% for highest, medium and low discharge respectively)
(3) By quantile estimations or return periods (20, 5, 2, and 1.5 for highest, medium and low discharge respectively).

For the Baro-Akobo River Basin the thresholds are derived based on return periods. Unlike in Europe where the thresholds are calculated for each pixel, the thresholds have been calculated within this study at four sites: at the Gambella outlet and at each separate river string before confluencing (see table 4.6). The calculation has been executed using R (evir package), a freely available statistical program. The calculation has been executed using R (evir package, function for extreme value theory), a freely available statistical program which fits with extreme value distributions to fix extreme discharges at a given location from historic records.

Table 4. 6 Hindcasting outlet stations coordinate

Stations	Coordinate		Remark
	lat	long	
1	8.24	34.53	Main outlet at Gambella
2	8.64	35.71	
3	8.42	35.32	
4	8.16	34.95	

4.4 Hindcasting

Hindcastings are a common evaluation technique for forecasting systems. Hindcasting is a retrospective analysis of the hydrological situation in a river basin to determine the potential of the hydrological model to serve as a hydrological flood forecasting model. Therefore, historical meteorological forecasts are fed into the hydrological model to see how well the hydrological forecast matches with the known historical observation.

The main steps are:

- Running LISVAP to produce potential evapotranspiration from reference crops (et) , potential evaporation from bare soil surface (es) and potential evaporation from open water surface (eo) for all hindcastings days.
- Calculating precipitation i.e. adding both the large-scale precipitation (widespread, continuous precipitation produced by large-scale ascent due to frontal or topographical lifting or large-scale horizontal air convergence caused by different means) and convective (localized, rapidly changing, showery precipitation produced by cumulus-scale convection in unstable air) for the of case total precipitation is not given.
- Calculating initial conditions for all hindcasting periods
- Calculating long-term run to derive thresholds and to abstract the initial conditions for each day during the hindcast for all 4 sites.
- Calculating hydrological forecast; calculating the hydrological response for all 51 meteorological ensemble members for a lead time of 10 days
- Post processing: this is final step to present forecast outputs in understandable manner. Persistency table and hydrographs of ensemble members are main outputs of the system.

5. Results

5.1 Results of sensitivity analysis

Results of the sensitivity analysis are shown in figures 5.1 and APPENDEX I. From the figures it can be seen that the upper zone time constant (UZTC), the power in Xinanjiang distribution function (bxinj), and the power preferential flow (PWPF) are the most sensitive parameters. The ground water loss fraction (GWLF), the multiplier factor for potential evapotranspiration (CalEvap), and the multiplier for channel manning’s n (CCM) are from moderate sensitive; while the maximum rate for percolation from the upper layer to lower layer (GWPV), the channel Manning's n for second line of routing multiplying factor (CCM2) and the lower time zone constant (LTZC) are less sensitive. The tables complement the sensitivity analysis as they show the inter-dependencies between the parameters. The sensitivity of PWPF, GWLF, GWPV and LZTC are mutually dependent. The GWLF has for instance a high impact on the sensitivity of LZTC and GWPV; a large value of GWLF for instance results into an insensitivity of LZTC and GWPV.

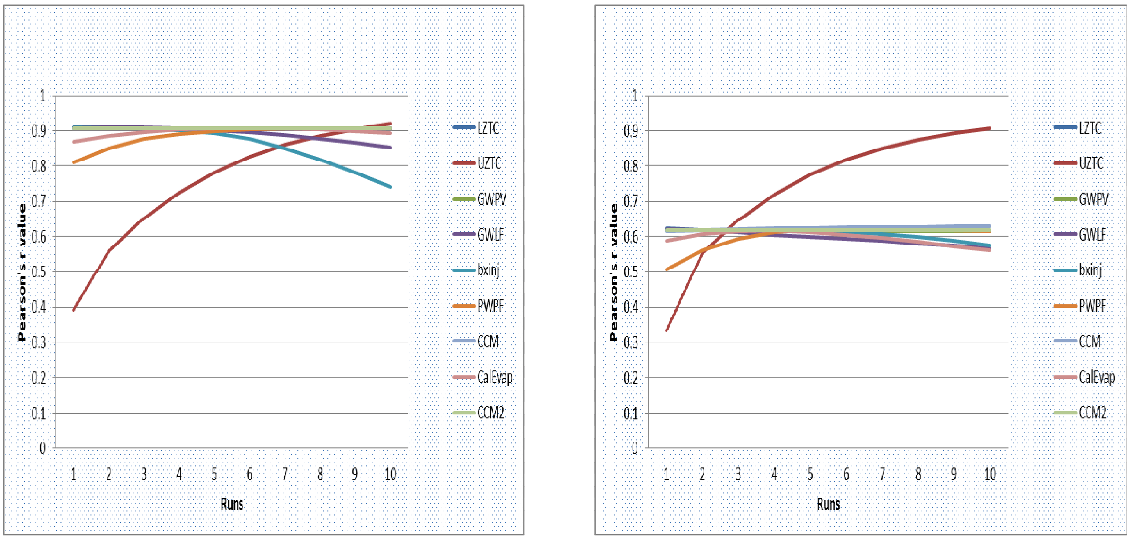


Figure 5. 1 Sensitivity analysis graphs, left keeping others at optimal value and right keeping others at default value

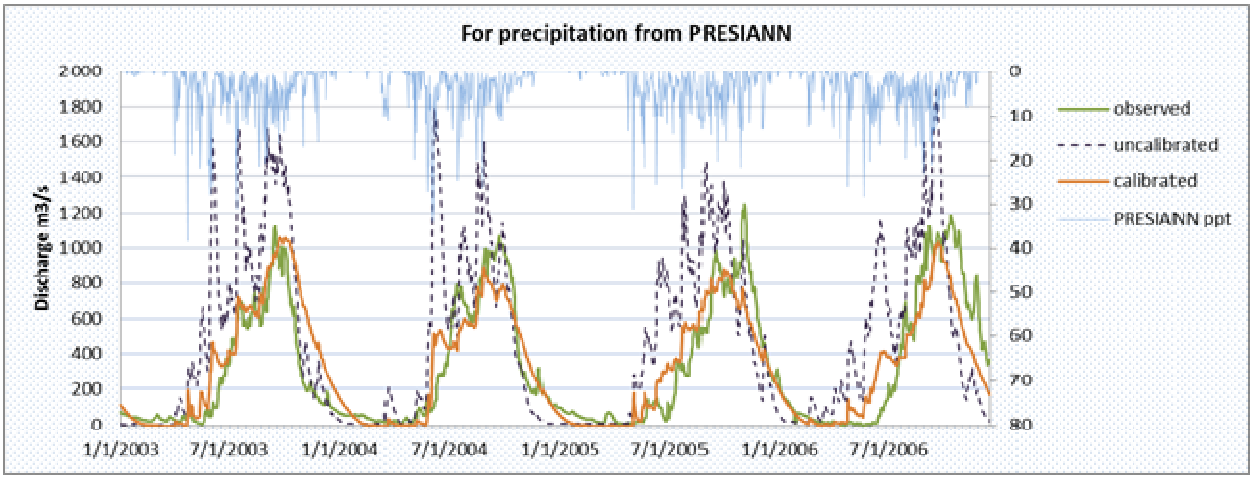
5.2 Results of calibration

The calibration was done twice for each of the five precipitation data sets (interpolated ground measurements, PERSIANN, TRMM 3B42, RFE 2.0 2.0 and ERA-interim) using once the coefficient of efficiency and once the correlation coefficient as objective function. A four year time period between 1/1/2003 – 12/31/2006 was chosen to run the calibration algorithm. However, the first year is considered as warm up period and thus is excluded from the visual and statistical evaluation.

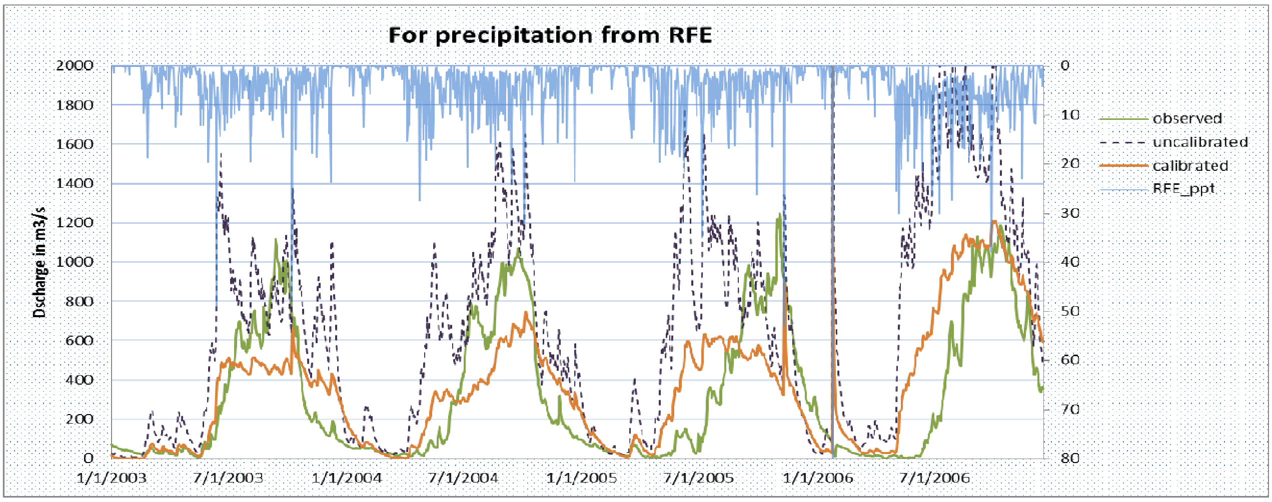
Table 5.1 summarizes the outcome of the calibration. Focusing on the evaluation of the coefficient of efficiency the best scores were achieved using PERSIANN, moderate scores using TRMM 3B42 or RFE 2.0 2.0 with 0.56 and 0.47 respectively, and rather poor scores using interpolated ground measurements or ERA-interim with -0.09 and -3.16 respectively. The poor scores of the last two data products may be explained on the one hand by the limited amount of ground measurement stations which may lead to an inadequate representation of areal rainfall patterns and on the other hand by the vast overestimation of discharge starting from September 2001. The water balance (WB) factor, which indicates the overall BIAS, supports the above stated outcome. Both, PERSIANN and TRMM 3B42, reach almost optimal values with 1.0 and 0.9, while ERA-interim is far off with 2.7. The results of the remaining skill scores such as correlation and root mean square error can be seen from table below. The last column states the number of iterations that the calibration algorithm needed to reach the optimum. It can be seen that the algorithm found the optimum well before the maximum number of iterations.

Table 5.1 Calibration statistical results for all precipitation sources

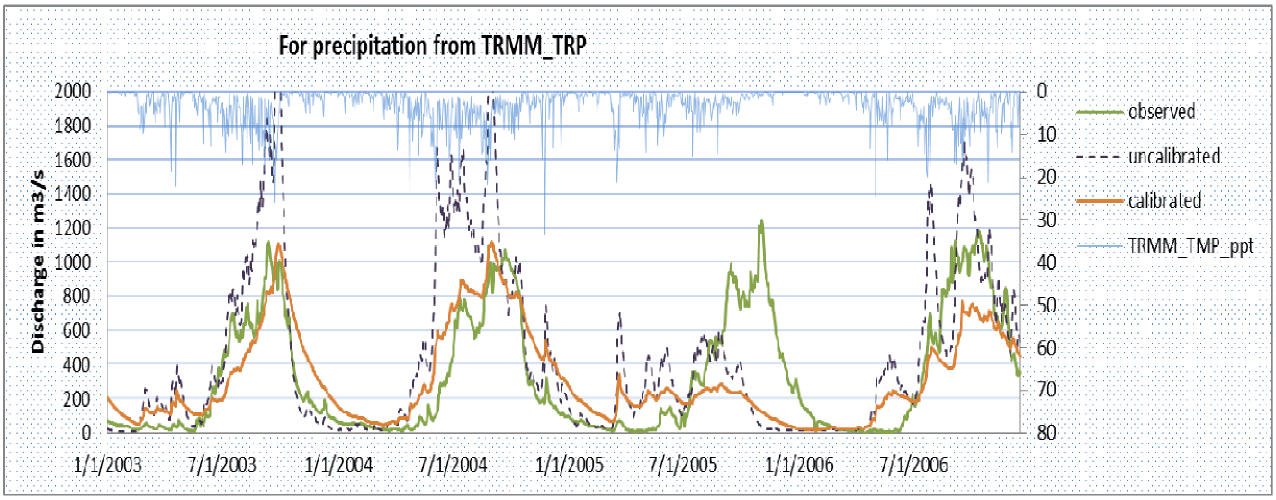
Precipitation source	Statistical skill scores								Objective function	No. of model iterations
	Water balance [m^3]	WB factor [-]	Average Q [m3/s]	Correlation	RMSE	BIAS [+]	BIAS [-]	Nash-Sutcliff		
Observed discharge	476382		329							
Observed precipitation	1389968	2.9	961	0.68	1059	949	-90	-8.12	(uncalibrated)	
	1344276	2.8	929	0.91	765	600	0	-3.75	R	238
	762522	1.6	527	0.88	367	418	-51.00	-0.09	CE	354
PERSIANN	690399	1.40	477	0.69	380	362	-129	-0.17	(uncalibrated)	
	505967	1.1	350	0.9	156	130	-88	0.8	R	240
	480897	1	332	0.89	157	135	-53	0.8	CE	277
TRMM 3B42	637467	1.3	441	0.69	373	280	-189	-0.13	(uncalibrated)	
	611540	1.3	423	0.78	287	217	-176	0.33	R	233
	335308	0.9	232	0.67	235	129	-305	0.56	CE	305
RFE 2.0	951788	2.0	658	0.60	547	404	-140	-1.43	(uncalibrated)	
	1014181	2.1	701	0.76	458	397	-114	-0.7	R	229
	528967	1.1	366	0.72	255	170	-195	0.47	CE	256
ERA interim	2242879	4.7	1550	0.56	1585	1267	-78	-19.39	(uncalibrated)	
	1612215	3.4	1114	0.82	939	785	0	-6.19	R	268
	1281732	2.7	886	0.8	753	611	-23	-3.61	CE	273



For precipitation from PRESIANN
Discharge m3/s
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
70
80
1/1/2003
7/1/2003
1/1/2004
7/1/2004
1/1/2005
7/1/2005
1/1/2006
7/1/2006
observed
uncalibrated
calibrated
PRESIANN ppt



For precipitation from RFE
Dscharge in m3/s
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
70
80
1/1/2003
7/1/2003
1/1/2004
7/1/2004
1/1/2005
7/1/2005
1/1/2006
7/1/2006
observed
uncalibrated
calibrated
RFE_ppt



For precipitation from TRMM_TRP
Discharge in m3/s
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
70
80
1/1/2003
7/1/2003
1/1/2004
7/1/2004
1/1/2005
7/1/2005
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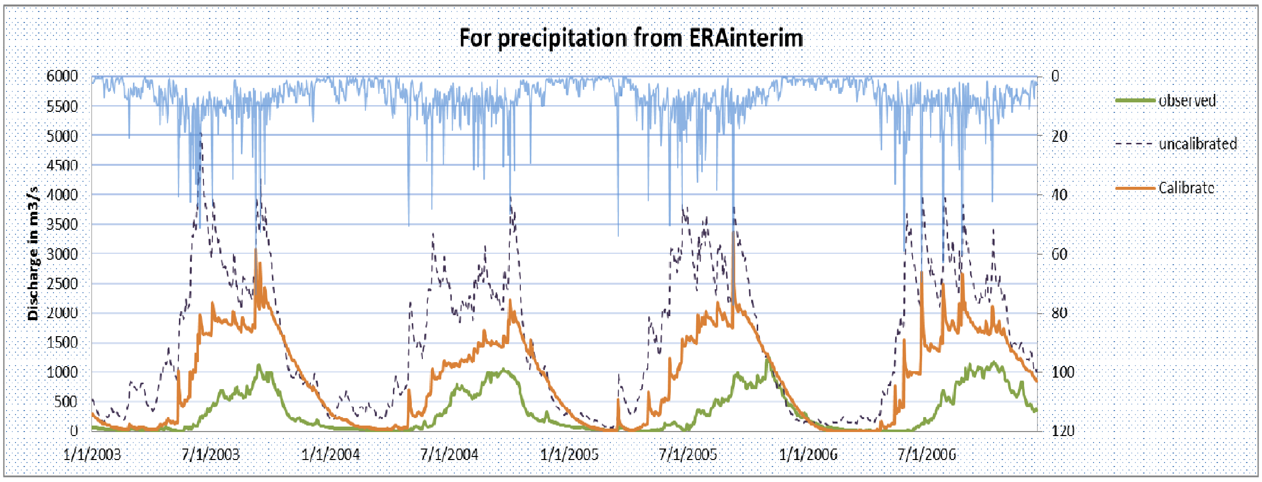
7/1/2006
observed
uncalibrated
calibrated
TRMM_TMP_ppt



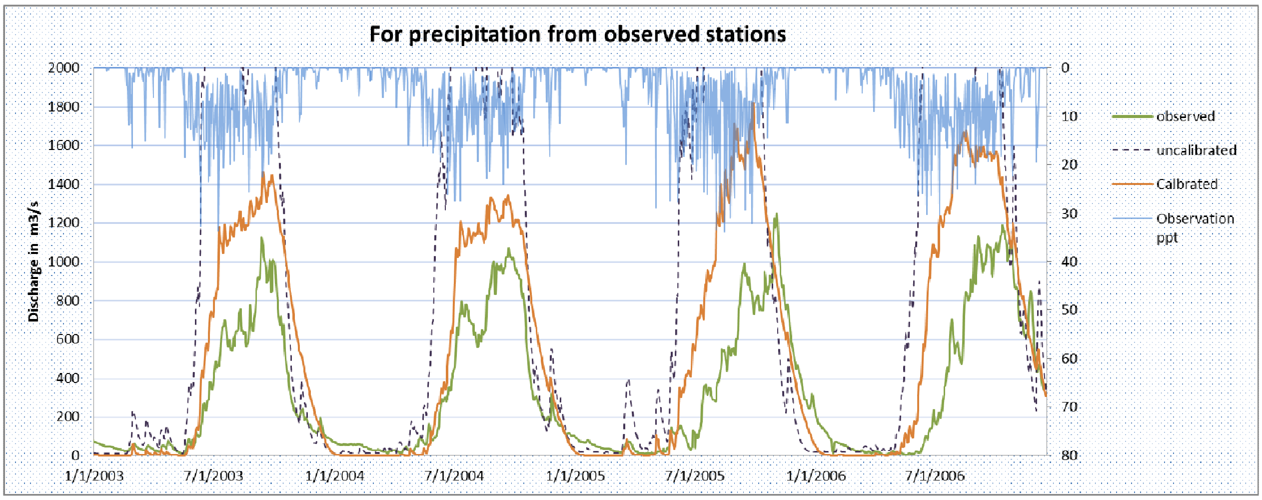


Figure 5. 2 Graphical results of calibration for all precipitation sources

Optimal parameter sets, which are results from the calibration, are stated for each individual meteorological data set in table 5.2.

Table 5. 2 Optimal parameter sets

Precipitation source	Optimized parameters							
	UPZTC	LZTC	GWLF	bxinj	PWPF	CCM	CalEvap	ChanMan2
Observed	49.88	640.72	1.48	0.43	3.07	7.3	1.48	14.77
PERSIANN	45.28	2477.63	0.43	0.2	4.51	10.06	1.02	11.82
TRMM 3B42	46.04	3567.16	0.01	0.39	2.08	12.33	1.49	11.33
RFE 2.0	49.84	3656.38	0.88	0.11	1.5	5.79	1.24	1.93
ERA interim	49.45	1190.02	1.43	0.36	3.25	0.78	1.48	7.7

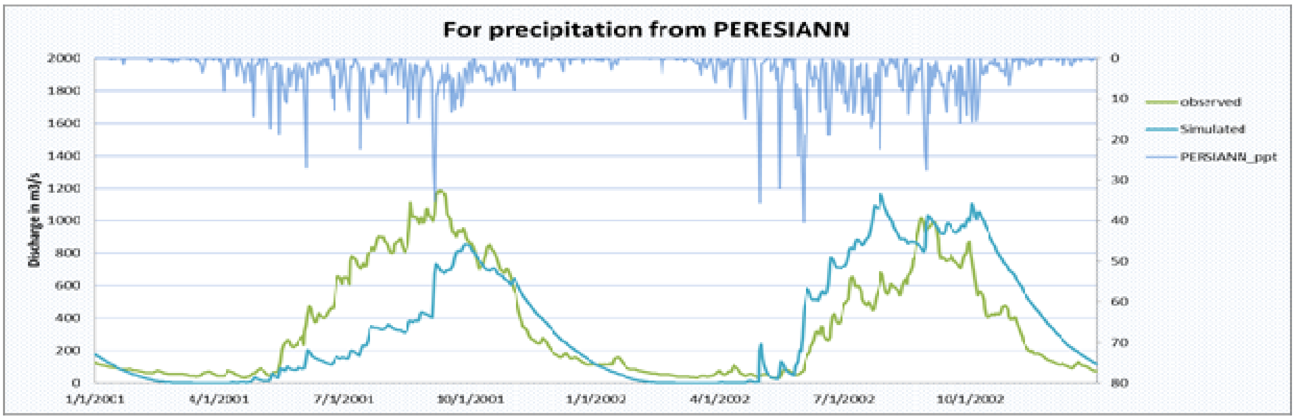
5.3. Results of Validation

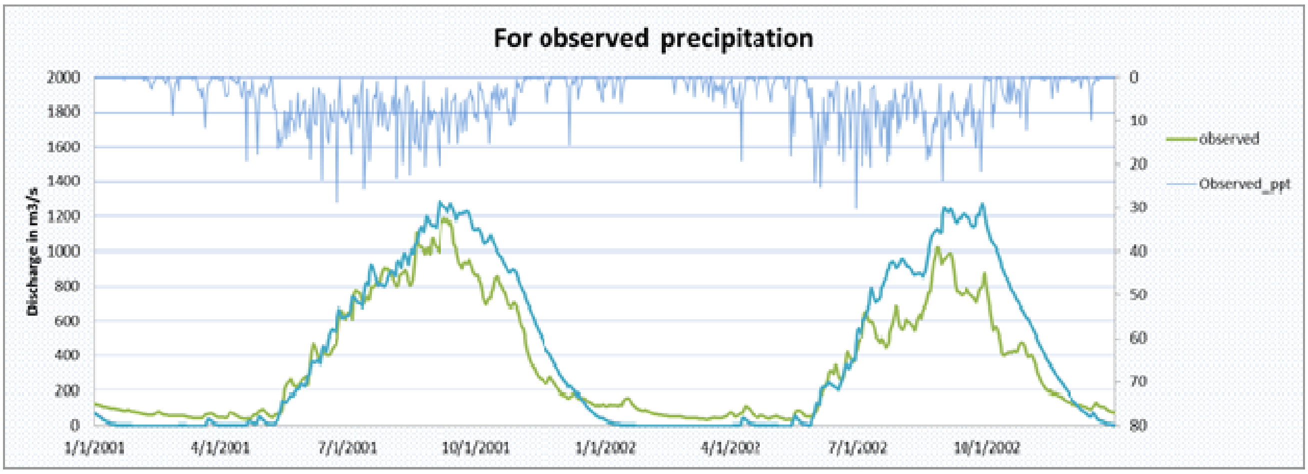
Validation is necessary to test if parameter values reflect the underlying hydrological processes, and are not a result of curve fitting (Klemes, 1986 and Refsgaard, 1996). For this study a simple split-sample validation is applied. Simple split-sample testing involves dividing the available measured time-series into two sets, one for calibration and one for validation. Thus, this test is based on temporal difference but not on spatial difference. The period from 2000 - 2002 is used for model validation (including one year warm up time). Statistical and graphical results are presented in table 5.3 and figure 5.3.

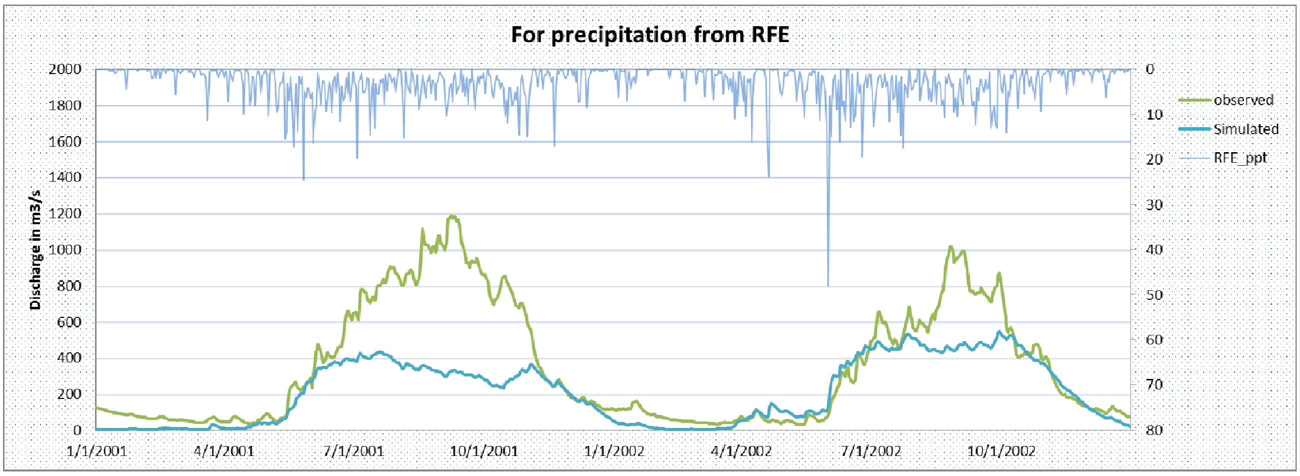
The coefficient of efficiency for the interpolated ground measurements, RFE 2.0, TRMM 3B42 PERSIANN, and ERA-interim are 0.74, 0.4, 0.66, 0.41, and -3.12 respectively. In comparison to the calibration results, the interpolated ground measurements achieved a higher score, PERSIANN a lower and the remaining ones (TRMM 3B42, RFE 2.0 and ERA-interim) a comparable one. Hence, the recommended product to use for initializing the model during a flood forecast is TRMM 3B42, due to its consistent high score. However, due to the fact that the EPS data (which will be used for the hindcasting) are delivered by the ECMWF, also the ERA-interim is considered for the initialization of the model during a flood event to see if it is possible to take different data sources for initialization and hindcasting or if those should be better taken from the same source.

Table 5. 3 Validation skill scores for all rainfall sources.

Precipitation source	Statistical skill scores								Remark
	Water balance [m^3]	WB factor [-]	Average Q [m3/s]	Correlation	RMSE	BIAS [+]	BIAS [-]	Nash-Sutcliff	
Observed discharge	255379		349.83						
Observed precipitation	300184	1.2	411	0.96	169	201	-57	0.74	
PERSIANN	250825	0.98	344	0.72	253	205	-164	0.41	
TRMM 3B42	342545	1.3	469	0.9	192	169	-64	0.66	
RFE 2.0	152907	0.6	209	0.81	255	39	-182	0.4	Lacks one year warm up time
ERA interim	420156	2.3	732	0.79	678	576	-63	-3.12	


For precipitation from PERESIANN
Discharge in m3/s
observed
Simulated
PERSIANN_ppt
1/1/2001
4/1/2001
7/1/2001
10/1/2001
1/1/2002
4/1/2002
7/1/2002
10/1/2002


For observed precipitation
Discharge in m3/s
observed
Observed_ppt
1/1/2001
4/1/2001
7/1/2001
10/1/2001
1/1/2002
4/1/2002
7/1/2002
10/1/2002


For precipitation from RFE
Discharge in m3/s
observed
Simulated
RFE_ppt
1/1/2001
4/1/2001
7/1/2001
10/1/2001
1/1/2002
4/1/2002
7/1/2002
10/1/2002

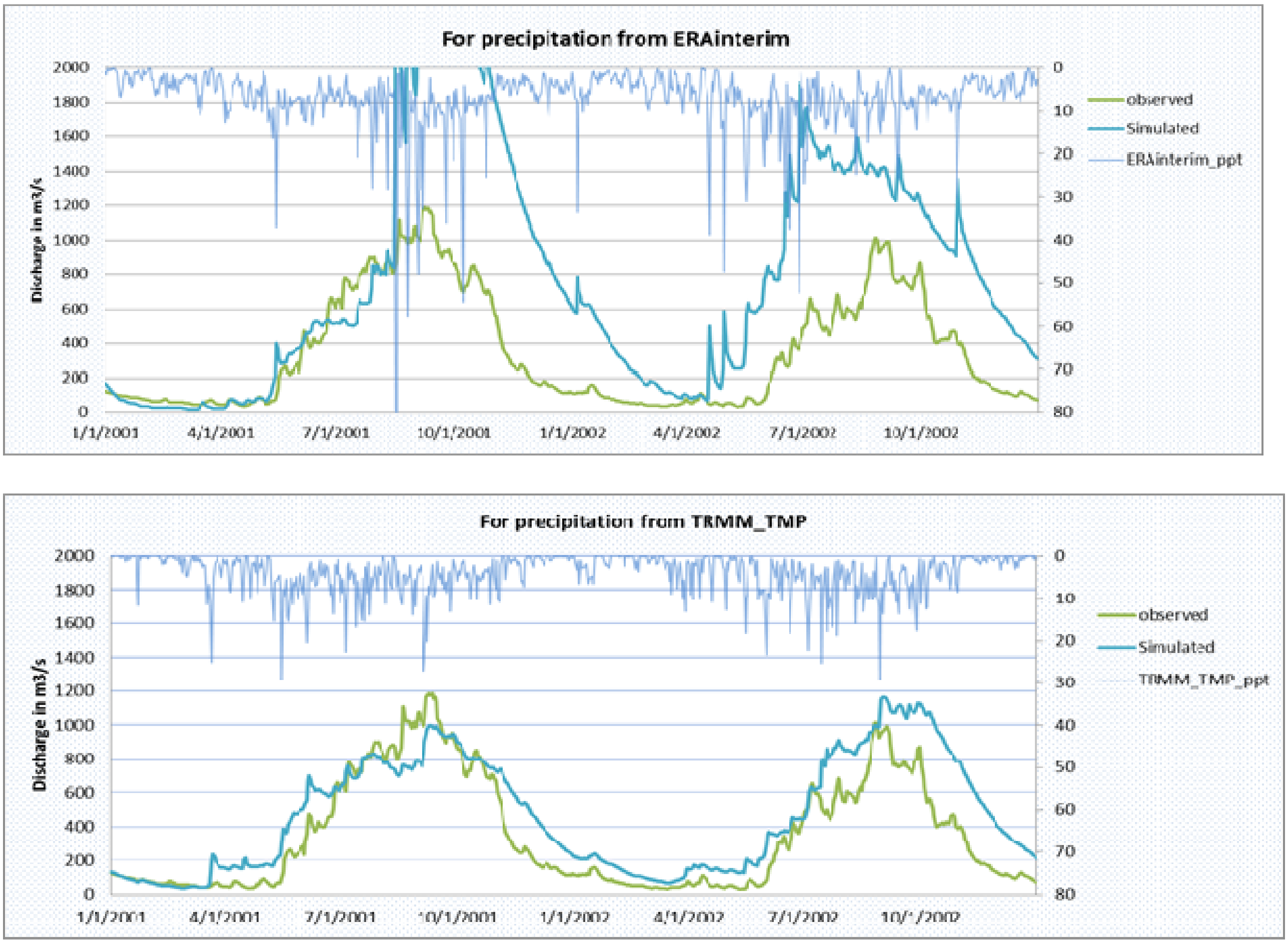


Figure 5.3 Graphical results for validation for all precipitation sources

5.4 Thresholds

For both of the chosen satellite products and the observations, alert thresholds need to be calculated. The thresholds were derived based on the simulated and observed long-term discharge series according to the procedure described in Section 4.3. The resulting thresholds are given in table 5.4.

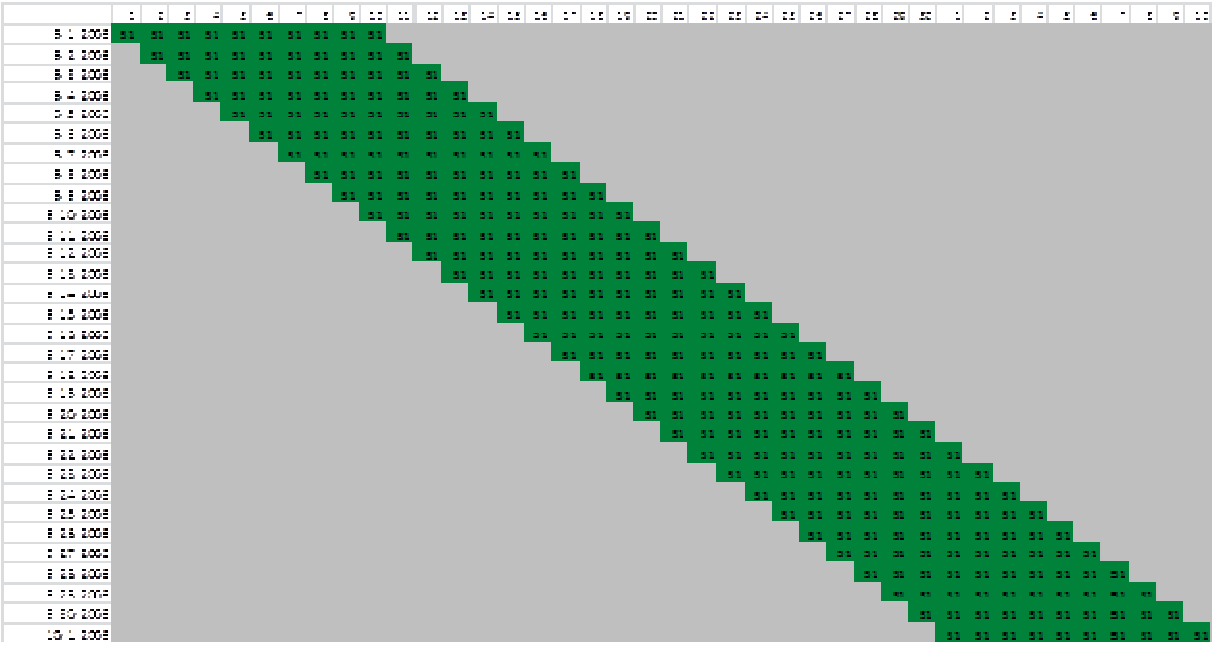
Table 5.4 Alert levels [m³/s]

From	Station	Low (T = 1.5 a)	Medium (T = 2 a)	High (T = 5 a)	Sever (T = 20 a)
TRMM 3B42 (1998-2006)	1	753	971	1210	1288
	2	270	330	397	420
	3	300	331	406	430
	4	167	211	273	305
ERA interim (1998-2006)	1	1747	2267	3411	4646
	2	481	627	953	1318
	3	602	771	1113	1436
	4	465	602	856	1059
Observed_ (1990 -2006)	1	1184	1237	1355	1480
Observed_ (1998 -2006)	1	1160	1206	1268	1297

5.5 Evaluations of hindcasting results

Equipped with the calibrated models and the respective alert thresholds the potential of LISFLOOD as flood forecasting model within the Upper Baro-Akobo Basin is tested. Two flood events of 1999 (01.09-31.10.1999) and 2006 (01.09-31.10.2006) are recalculated in a hindcasting mode to see how the model outcome complies with the known observation, or in this case with the PROXY hydrological record (which is the long term calculation). Each event was initialized individually using TRMM 3B42 and ERA-interim and then hindcasted using the meteorological ensemble forecasts (EPS). The outcome is a color-coded threshold exceedance matrix for each threshold as well as a spaghetti plot for each day.

The threshold exceedance matrix is a calendrical matrix; as such each row shows a 10-day forecast for a respective date, while each column shows the consecutive development of the hindcast. The number of EPS exceeding the alert threshold is shown within the matrix, while the period in which the PROXY exceeds the threshold is indicated using a blue cell border at the head of the matrix. Looking at the threshold exceedance diagrams, it can be seen that only the low threshold is continuous and with all ensembles exceeded, while the medium threshold shows only a minor number of ensembles exceeding the threshold and no ensembles exceeding the high or sever threshold. Applying the same decision rules as in Europe (consistent exceedance of the high alert threshold with a medium probability at least 15 ensembles for 3 consecutive forecasts) no flood alert would have been given in this case, since low or medium floods (lower than a 2 years return period) generally don't cause any damage in Europe. So, even though EFAS captured flood events adequately (measured and hindcasted the flood had a return period of 1-2 years), the system may need small adjustment for the Upper Baro-Akobo River Basin, since flood events that hold a return period of 1-2 years are not warned of, but create sever problems for the local community.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	1	2	3	4	5	6	7	8	9
10/1/2006	51	51	51	51	51	51	51	51	51	51																													
10/2/2006		51	51	51	51	51	51	51	51	51	51																												
10/3/2006			51	51	51	51	51	51	51	51	51	51																											
10/4/2006				51	51	51	51	51	51	51	51	51	51																										
10/5/2006					51	51	51	51	51	51	51	51	51	51																									
10/6/2006						51	51	51	51	51	51	51	51	51	51																								
10/7/2006							51	51	51	51	51	51	51	51	51	51																							
10/8/2006								51	51	51	51	51	51	51	51	51	51																						
10/9/2006									51	51	51	51	51	51	51	51	51	51																					
10/10/2006										51	51	51	51	51	51	51	51	51	51																				
10/11/2006											51	51	51	51	51	51	51	51	51	51																			
10/12/2006												51	51	51	51	51	51	51	51	51	51																		
10/13/2006													51	51	51	51	51	51	51	51	51	51																	
10/14/2006														51	51	51	51	51	51	51	51	51	51																
10/15/2006															51	51	51	51	51	51	51	51	51	51															
10/16/2006																51	51	51	51	51	51	51	51	51	51														
10/17/2006																	51	51	51	51	51	51	51	51	51	51													
10/18/2006																		51	51	51	51	51	51	51	51	51	51												
10/19/2006																			51	51	51	51	51	51	51	51	51	50											
10/20/2006																				51	51	51	51	51	51	51	51	51	51										
10/21/2006																					51	51	51	51	51	51	51	51	51	51									
10/22/2006																						51	51	51	51	51	51	51	51	51	51								
10/23/2006																							51	51	51	51	51	51	51	51	51	51							
10/24/2006																								51	51	51	51	51	51	51	51	51	51						
10/25/2006																									51	51	51	51	51	51	51	51	51	51					
10/26/2006																										51	51	51	51	51	51	51	51	51	51				
10/27/2006																											51	51	51	51	51	51	51	51	51	51			
10/28/2006																												51	51	51	51	51	51	51	51	51	34			
10/29/2006																													51	51	51	51	51	51	51	51	9	0		
10/30/2006																														51	51	51	51	51	51	51	34	0	0	
10/31/2006																															51	51	51	51	51	51	50	0	0	0

(a). For low alert level

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	1	2	3	4	5	6	7	8	9
9/1/2006	37	33	27	20	12	5	2	1	1	0																												
9/2/2006		0	0	6	6	6	4	3	3	4	5																											
9/3/2006			0	0	0	0	0	1	2	0	0	0																										
9/4/2006				0	0	0	0	1	0	0	1	1	1																									
9/5/2006					0	0	0	1	3	3	3	4	2	0																								
9/6/2006						0	0	2	2	2	2	3	3	3	4																							
9/7/2006							0	0	0	0	0	1	3	4	5	4																						
9/8/2006								0	0	0	0	1	2	2	5	7	7																					
9/9/2006									0	2	2	1	1	1	0	1	2	2																				
9/10/2006										0	0	0	0	0	1	1	2	2	1																			
9/11/2006											0	0	0	0	0	1	1	1	0	0																		
9/12/2006												0	0	0	1	1	0	1	2	1	2																	
9/13/2006													0	0	0	0	0	0	0	1	1	1																
9/14/2006														0	0	0	0	0	0	1	1	1	1															
9/15/2006															0	0	0	0	0	1	1	1	1	4														
9/16/2006																0	0	0	0	1	1	1	1	2	2													
9/17/2006																	0	0	0	0	0	1	1	1	1	1												
9/18/2006																		0	0	0	0	0	0	0	0	0	2											
9/19/2006																			0	1	2	4	3	2	2	1	1	0										
9/20/2006																				0	0	1	1	0	0	0	0	0	0									
9/21/2006																					0	0	0	2	2	2	2	1	0	0								
9/22/2006																						0	0	0	0	0	0	0	0	0	0							
9/23/2006																							0	0	0	0	0	0	0	0	0	0						
9/24/2006																								0	0	0	0	0	0	0	0	0	0					
9/25/2006																									0	0	0	0	0	0	1	1	1	1				
9/26/2006																										0	0	0	0	0	0	1	1	1	1			
9/27/2006																											0	0	0	0	0	1	1	1	1	1		
9/28/2006																												0	0	0	0	0	0	0	0	0	0	
9/29/2006																													0	0	0	0	0	0	0	0	0	0
9/30/2006																														0	0	0	0	0	0	0	1	0	0

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	1	2	3	4	5	6	7	8	9	10
10/1/2006	0	0	0	0	0	0	0	0	0	0																													
10/2/2006		0	0	0	0	0	0	0	0	0	0																												
10/3/2006			0	0	0	0	0	0	0	0	0	0																											
10/4/2006				0	0	0	0	0	0	0	0	0	0																										
10/5/2006					0	0	0	1	1	0	0	0	0	0																									
10/6/2006						0	0	0	0	0	0	0	0	0	0																								
10/7/2006							0	0	0	0	0	0	0	0	0	0																							
10/8/2006								0	0	0	0	0	0	0	0	0	0																						
10/9/2006									0	0	0	0	0	0	0	0	0	0																					
10/10/2006										0	0	0	0	0	0	0	0	0	0																				
10/11/2006											0	0	0	0	0	0	0	0	0	0																			
10/12/2006												0	0	0	0	0	0	0	0	0	0																		
10/13/2006													0	0	0	0	0	0	0	0	0	0																	
10/14/2006														0	0	0	0	0	0	0	0	0	2																
10/15/2006															0	0	0	0	0	0	0	0	0	0															
10/16/2006																0	0	0	0	0	0	0	0	0	0														
10/17/2006																	0	0	0	0	0	0	0	0	0	0													
10/18/2006																		0	0	0	0	0	0	0	0	0	0												
10/19/2006																			0	0	0	0	0	0	0	0	0	0											
10/20/2006																				0	0	0	1	0	0	0	0	0	0										
10/21/2006																					0	0	2	4	4	2	3	4	6	5									
10/22/2006																						0	0	3	5	4	8	7	6	4	3								
10/23/2006																							0	0	6	5	2	3	4	6	6	6							
10/24/2006																								0	0	1	0	1	2	2	2	2	1						
10/25/2006																									0	0	2	5	5	5	4	3	3	3					
10/26/2006																										0	0	0	0	1	1	1	0	0	0				
10/27/2006																											0	0	2	2	2	1	0	0	0	0			
10/28/2006																												0	0	3	0	0	0	0	0	0	0		
10/29/2006																													0	0	0	0	0	0	0	0	0	0	
10/30/2006																														0	0	0	0	0	0	0	0	0	0
10/31/2006																															0	0	0	0	0	0	0	0	0	0

b. Medium alert level

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	1	2	3	4	5	6	7	8	9
9/1/2006	0	0	0	0	0	0	0	0	0	0																													
9/2/2006		0	0	0	0	0	0	0	0	0	0																												
9/3/2006			0	0	0	0	0	0	0	0	0	0																											
9/4/2006				0	0	0	0	0	0	0	0	0	0																										
9/5/2006					0	0	0	0	0	0	0	0	0	0																									
9/6/2006						0	0	0	0	0	0	0	0	0	0																								
9/7/2006							0	0	0	0	0	0	0	0	0	0																							
9/8/2006								0	0	0	0	0	0	0	0	0	0																						
9/9/2006									0	0	0	0	0	0	0	0	0	0																					
9/10/2006										0	0	0	0	0	0	0	0	0	0																				
9/11/2006											0	0	0	0	0	0	0	0	0	0																			
9/12/2006												0	0	0	0	0	0	0	0	0	0																		
9/13/2006													0	0	0	0	0	0	0	0	0	0																	
9/14/2006														0	0	0	0	0	0	0	0	0	0																
9/15/2006															0	0	0	0	0	0	0	0	0	0															
9/16/2006																0	0	0	0	0	0	0	0	0	0														
9/17/2006																	0	0	0	0	0	0	0	0	0	0													
9/18/2006																		0	0	0	0	0	0	0	0	0	0												
9/19/2006																			0	0	0	0	0	0	0	0	0	0											
9/20/2006																				0	0	0	0	0	0	0	0	0	0										
9/21/2006																					0	0	0	0	0	0	0	0	0	0									
9/22/2006																						0	0	0	0	0	0	0	0	0	0								
9/23/2006																							0	0	0	0	0	0	0	0	0	0							
9/24/2006																								0	0	0	0	0	0	0	0	0	0						
9/25/2006																									0	0	0	0	0	0	0	0	0	0					
9/26/2006																										0	0	0	0	0	0	0	0	0	0				
9/27/2006																											0	0	0	0	0	0	0	0	0	0			
9/28/2006																												0	0	0	0	0	0	0	0	0	0		
9/29/2006																													0	0	0	0	0	0	0	0	0	0	
9/30/2006																														0	0	0	0	0	0	0	0	0	0

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	1	2	3	4	5	6	7	8	9	10
10/1/2006	0	0	0	0	0	0	0	0	0	0																														
10/2/2006		0	0	0	0	0	0	0	0	0	0																													
10/3/2006			0	0	0	0	0	0	0	0	0	0																												
10/4/2006				0	0	0	0	0	0	0	0	0	0																											
10/5/2006					0	0	0	0	0	0	0	0	0	0																										
10/6/2006						0	0	0	0	0	0	0	0	0	0																									
10/7/2006							0	0	0	0	0	0	0	0	0	0																								
10/8/2006								0	0	0	0	0	0	0	0	0	0																							
10/9/2006									0	0	0	0	0	0	0	0	0	0																						
10/10/2006										0	0	0	0	0	0	0	0	0	0																					
10/11/2006											0	0	0	0	0	0	0	0	0	0																				
10/12/2006												0	0	0	0	0	0	0	0	0	0																			
10/13/2006													0	0	0	0	0	0	0	0	0	0																		
10/14/2006														0	0	0	0	0	0	0	0	0	0																	
10/15/2006															0	0	0	0	0	0	0	0	0	0																
10/16/2006																0	0	0	0	0	0	0	0	0	0															
10/17/2006																	0	0	0	0	0	0	0	0	0	0														
10/18/2006																		0	0	0	0	0	0	0	0	0	0													
10/19/2006																			0	0	0	0	0	0	0	0	0	0												
10/20/2006																				0	0	0	0	0	0	0	0	0	0											
10/21/2006																					0	0	0	0	0	0	0	0	0	0										
10/22/2006																						0	0	0	0	0	0	0	0	0	0									
10/23/2006																							0	0	0	0	0	0	0	0	0	0								
10/24/2006																								0	0	0	0	0	0	0	0	0	0							
10/25/2006																									0	0	0	0	0	0	0	0	0	0						
10/26/2006																										0	0	0	0	0	0	0	0	0	0					
10/27/2006																											0	0	0	0	0	0	0	0	0	0				
10/28/2006																												0	0	0	0	0	0	0	0	0	0			
10/29/2006																													0	0	0	0	0	0	0	0	0	0		
10/30/2006																														0	0	0	0	0	0	0	0	0	0	
10/31/2006																															0	0	0	0	0	0	0	0	0	0

c. High alert level

Figure 5. 4 Persistency tables for hindcasting period from 01/09/2006 – 31/10/2006 for precipitation from ERA-interim (at Gambella main outlet)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	1	2	3	4	5	6	7	8	9
9/1/2006	0	0	0	0	0	0	0	0	0	0																													
9/2/2006		0	0	1	1	1	0	0	0	0	0																												
9/3/2006			0	0	0	0	0	0	0	0	0	0																											
9/4/2006				0	0	0	0	0	0	0	0	0	0																										
9/5/2006					0	0	0	0	0	0	0	0	0	0																									
9/6/2006						0	0	0	0	0	0	0	0	0	1																								
9/7/2006							0	0	0	0	0	0	0	0	2	2																							
9/8/2006								0	0	0	0	0	0	0	4	7	7																						
9/9/2006									0	0	0	0	0	0	0	1	2	2																					
9/10/2006										0	0	0	0	0	0	0	0	2	3																				
9/11/2006											0	0	0	0	0	0	1	1	1	0																			
9/12/2006												0	0	0	0	0	0	1	2	3	3																		
9/13/2006													0	0	0	0	0	0	0	1	1	3																	
9/14/2006														0	0	0	0	0	0	2	2	3	3																
9/15/2006															1	0	0	0	0	1	4	4	9	12															
9/16/2006																0	0	0	0	2	5	6	8	8	11														
9/17/2006																	51	0	0	0	2	4	11	9	10	11													
9/18/2006																		0	0	0	3	10	6	6	6	8	9												
9/19/2006																			51	8	13	15	18	18	23	23	24	26											
9/20/2006																				51	3	17	21	17	17	17	17	18	18										
9/21/2006																					51	19	17	13	14	17	19	17	16	17									
9/22/2006																						51	0	0	0	1	2	4	3	4	4								
9/23/2006																							51	1	2	3	3	2	2	3	5	6							
9/24/2006																								51	0	0	0	0	0	1	2	4	4						
9/25/2006																									51	1	0	0	2	4	14	19	20	20					
9/26/2006																										0	0	0	0	1	3	7	7	11	12				
9/27/2006																											0	0	0	1	1	2	3	4	4	4			
9/28/2006																												0	0	4	10	13	11	11	11	13	16		
9/29/2006																													51	0	4	7	8	3	4	7	12	11	
9/30/2006																														51	1	2	2	4	4	9	14	19	23

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	1	2	3	4	5	6	7	8	9
10/1/2006	51	0	0	0	0	0	1	4	7	11																														
10/2/2006		51	0	0	0	0	0	1	4	7	12																													
10/3/2006			51	0	0	0	0	1	2	4	6	6																												
10/4/2006				51	0	0	0	2	3	9	11	7	6																											
10/5/2006					51	0	2	3	6	11	12	10	9	7																										
10/6/2006						51	0	0	0	1	2	2	0	1	2																									
10/7/2006							51	0	3	4	5	5	4	4	4	4																								
10/8/2006								51	0	0	0	0	0	0	0	0	0																							
10/9/2006									51	0	0	0	0	0	0	0	0	0																						
10/10/2006										51	0	0	0	0	0	0	0	2	2																					
10/11/2006											51	0	0	0	0	0	0	0	0	0																				
10/12/2006												51	0	0	0	0	0	0	0	0	0																			
10/13/2006													0	0	0	0	0	0	0	0	0	0																		
10/14/2006														0	0	0	0	0	0	0	0	0	3																	
10/15/2006															0	0	0	0	0	0	0	0	0	0																
10/16/2006																0	0	0	0	0	0	0	0	0	0															
10/17/2006																	0	0	0	0	0	0	0	0	0	0														
10/18/2006																		0	0	0	0	0	0	0	0	0	1													
10/19/2006																			0	0	0	0	0	0	0	0	0	4												
10/20/2006																				0	0	2	2	2	1	1	0	3	3											
10/21/2006																					0	0	5	5	5	4	5	10	15	18										
10/22/2006																						0	1	12	14	15	16	20	20	23	23									
10/23/2006																							0	0	10	11	12	14	17	20	18	19								
10/24/2006																								0	3	6	9	11	16	17	19	19	18							
10/25/2006																									0	0	6	8	10	9	8	8	7	6						
10/26/2006																										0	0	6	7	10	10	8	7	6	4					
10/27/2006																											25	20	21	23	22	22	20	12	6	4				
10/28/2006																												51	10	19	18	11	7	6	4	0	0			
10/29/2006																													51	0	0	0	0	0	0	0	0	0		
10/30/2006																														51	0	0	0	0	0	0	0	0	0	
10/31/2006																															51	0	0	0	0	0	0	0	0	0

(a) Low alert level

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	1	2	3	4	5	6	7	8	9
9/1/2006	0	0	0	0	0	0	0	0	0	0																													
9/2/2006		0	0	0	0	0	0	0	0	0	0																												
9/3/2006			0	0	0	0	0	0	0	0	0	0																											
9/4/2006				0	0	0	0	0	0	0	0	0	0																										
9/5/2006					0	0	0	0	0	0	0	0	0	0																									
9/6/2006						0	0	0	0	0	0	0	0	0	0																								
9/7/2006							0	0	0	0	0	0	0	0	0	0																							
9/8/2006								0	0	0	0	0	0	0	0	0	1																						
9/9/2006									0	0	0	0	0	0	0	0	0	0																					
9/10/2006										0	0	0	0	0	0	0	0	0	0																				
9/11/2006											0	0	0	0	0	0	0	0	0	0																			
9/12/2006												0	0	0	0	0	0	0	0	0	0																		
9/13/2006													0	0	0	0	0	0	0	1	1	1																	
9/14/2006														0	0	0	0	0	0	1	1	1	0																
9/15/2006															0	0	0	0	0	0	1	1	1	1															
9/16/2006																0	0	0	0	0	0	0	0	0	1														
9/17/2006																	0	0	0	0	0	0	0	0	1	1													
9/18/2006																		0	0	0	0	0	0	0	0	0	0												
9/19/2006																			0	0	1	1	1	0	1	1	2	0											
9/20/2006																				0	0	0	0	0	0	0	0	0	0										
9/21/2006																					0	0	0	0	2	2	2	1	1	0									
9/22/2006																						0	0	0	0	0	0	0	0	0	0								
9/23/2006																							0	0	0	0	0	0	0	0	0	0							
9/24/2006																								0	0	0	0	0	0	0	0	0	0						
9/25/2006																									0	0	0	0	0	0	1	1	1	1					
9/26/2006																										0	0	0	0	0	0	1	1	2	2				
9/27/2006																											0	0	0	0	0	1	1	1	1	1			
9/28/2006																												0	0	0	0	0	0	0	0	0	0		
9/29/2006																													0	0	0	0	0	0	0	0	0	0	
9/30/2006																														0	0	0	0	0	0	0	1	1	0

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	1	2	3	4	5	6	7	8	9	10
10/1/2006	0	0	0	0	0	0	0	0	0	0																														
10/2/2006		0	0	0	0	0	0	0	0	0	0																													
10/3/2006			0	0	0	0	0	0	0	0	0	0																												
10/4/2006				0	0	0	0	0	0	0	0	0	0																											
10/5/2006					0	0	1	1	1	0	0	0	0	0																										
10/6/2006						0	0	0	0	0	0	0	0	0	0																									
10/7/2006							0	0	0	0	0	0	0	0	0	0																								
10/8/2006								0	0	0	0	0	0	0	0	0	0																							
10/9/2006									0	0	0	0	0	0	0	0	0	0																						
10/10/2006										0	0	0	0	0	0	0	0	0	0																					
10/11/2006											0	0	0	0	0	0	0	0	0	0																				
10/12/2006												0	0	0	0	0	0	0	0	0	0																			
10/13/2006													0	0	0	0	0	0	0	0	0	0																		
10/14/2006														0	0	0	0	0	0	0	0	0	1																	
10/15/2006															0	0	0	0	0	0	0	0	0	0																
10/16/2006																0	0	0	0	0	0	0	0	0	0															
10/17/2006																	0	0	0	0	0	0	0	0	0	0														
10/18/2006																		0	0	0	0	0	0	0	0	0	0													
10/19/2006																			0	0	0	0	0	0	0	0	0	0												
10/20/2006																				0	0	1	0	0	0	0	0	0	0											
10/21/2006																					0	0	2	3	1	1	1	1	1	1										
10/22/2006																						0	0	2	3	2	3	4	5	2	3									
10/23/2006																							0	0	6	2	1	2	4	5	5	6								
10/24/2006																								0	0	0	0	1	1	1	2	2	1							
10/25/2006																									0	0	2	5	5	3	3	3	3	2						
10/26/2006																										0	0	0	0	0	1	1	0	0	0					
10/27/2006																											0	0	0	0	0	0	0	0	0	0				
10/28/2006																												0	0	0	0	0	0	0	0	0	0			
10/29/2006																													0	0	0	0	0	0	0	0	0	0		
10/30/2006																														0	0	0	0	0	0	0	0	0	0	
10/31/2006																															0	0	0	0	0	0	0	0	0	0

b. Medium alert level

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	1	2	3	4	5	6	7	8	9
9/1/2006	0	0	0	0	0	0	0	0	0	0																													
9/2/2006		0	0	0	0	0	0	0	0	0	0																												
9/3/2006			0	0	0	0	0	0	0	0	0	0																											
9/4/2006				0	0	0	0	0	0	0	0	0	0																										
9/5/2006					0	0	0	0	0	0	0	0	0	0																									
9/6/2006						0	0	0	0	0	0	0	0	0	0																								
9/7/2006							0	0	0	0	0	0	0	0	0	0																							
9/8/2006								0	0	0	0	0	0	0	0	0	0																						
9/9/2006									0	0	0	0	0	0	0	0	0	0																					
9/10/2006										0	0	0	0	0	0	0	0	0	0																				
9/11/2006											0	0	0	0	0	0	0	0	0	0																			
9/12/2006												0	0	0	0	0	0	0	0	0	0																		
9/13/2006													0	0	0	0	0	0	0	1	1	0																	
9/14/2006														0	0	0	0	0	0	0	0	0	0																
9/15/2006															0	0	0	0	0	0	0	0	0	0															
9/16/2006																0	0	0	0	0	0	0	0	0	0														
9/17/2006																	0	0	0	0	0	0	0	0	0	0													
9/18/2006																		0	0	0	0	0	0	0	0	0	0												
9/19/2006																			0	0	0	0	0	0	0	0	0	0											
9/20/2006																				0	0	0	0	0	0	0	0	0	0										
9/21/2006																					0	0	0	0	0	0	0	0	0	0									
9/22/2006																						0	0	0	0	0	0	0	0	0	0								
9/23/2006																							0	0	0	0	0	0	0	0	0	0							
9/24/2006																								0	0	0	0	0	0	0	0	0	0						
9/25/2006																									0	0	0	0	0	0	1	1	1	0					
9/26/2006																										0	0	0	0	0	0	0	1	0	0				
9/27/2006																											0	0	0	0	0	0	0	0	0	0			
9/28/2006																												0	0	0	0	0	0	0	0	0	0		
9/29/2006																													0	0	0	0	0	0	0	0	0	0	
9/30/2006																														0	0	0	0	0	0	0	0	0	0

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	1	2	3	4	5	6	7	8	9	10
10/1/2006	0	0	0	0	0	0	0	0	0	0																														
10/2/2006		0	0	0	0	0	0	0	0	0	0																													
10/3/2006			0	0	0	0	0	0	0	0	0	0																												
10/4/2006				0	0	0	0	0	0	0	0	0	0																											
10/5/2006					0	0	0	0	0	0	0	0	0	0																										
10/6/2006						0	0	0	0	0	0	0	0	0	0																									
10/7/2006							0	0	0	0	0	0	0	0	0	0																								
10/8/2006								0	0	0	0	0	0	0	0	0	0																							
10/9/2006									0	0	0	0	0	0	0	0	0	0																						
10/10/2006										0	0	0	0	0	0	0	0	0	0																					
10/11/2006											0	0	0	0	0	0	0	0	0	0																				
10/12/2006												0	0	0	0	0	0	0	0	0	0																			
10/13/2006													0	0	0	0	0	0	0	0	0	0																		
10/14/2006														0	0	0	0	0	0	0	0	0	1																	
10/15/2006															0	0	0	0	0	0	0	0	0	0																
10/16/2006																0	0	0	0	0	0	0	0	0	0															
10/17/2006																	0	0	0	0	0	0	0	0	0	0														
10/18/2006																		0	0	0	0	0	0	0	0	0	0													
10/19/2006																			0	0	0	0	0	0	0	0	0	0												
10/20/2006																				0	0	0	0	0	0	0	0	0	0											
10/21/2006																					0	0	0	0	0	0	0	0	0	0										
10/22/2006																						0	0	1	1	1	0	0	0	0	0									
10/23/2006																							0	0	0	0	0	0	0	1	1	1								
10/24/2006																								0	0	0	0	0	0	0	0	0	0							
10/25/2006																									0	0	1	2	0	0	0	0	0	0						
10/26/2006																										0	0	0	0	0	0	0	0	0	0					
10/27/2006																											0	0	0	0	0	0	0	0	0	0				
10/28/2006																												0	0	0	0	0	0	0	0	0	0			
10/29/2006																													0	0	0	0	0	0	0	0	0	0		
10/30/2006																														0	0	0	0	0	0	0	0	0	0	
10/31/2006																															0	0	0	0	0	0	0	0	0	0

C . High alert level

Figure 5.5 Persistency tables for hindcasting period from 01/09/2006 - 31/10/2006 for precipitation from TRMM (at Gambella main outlet).

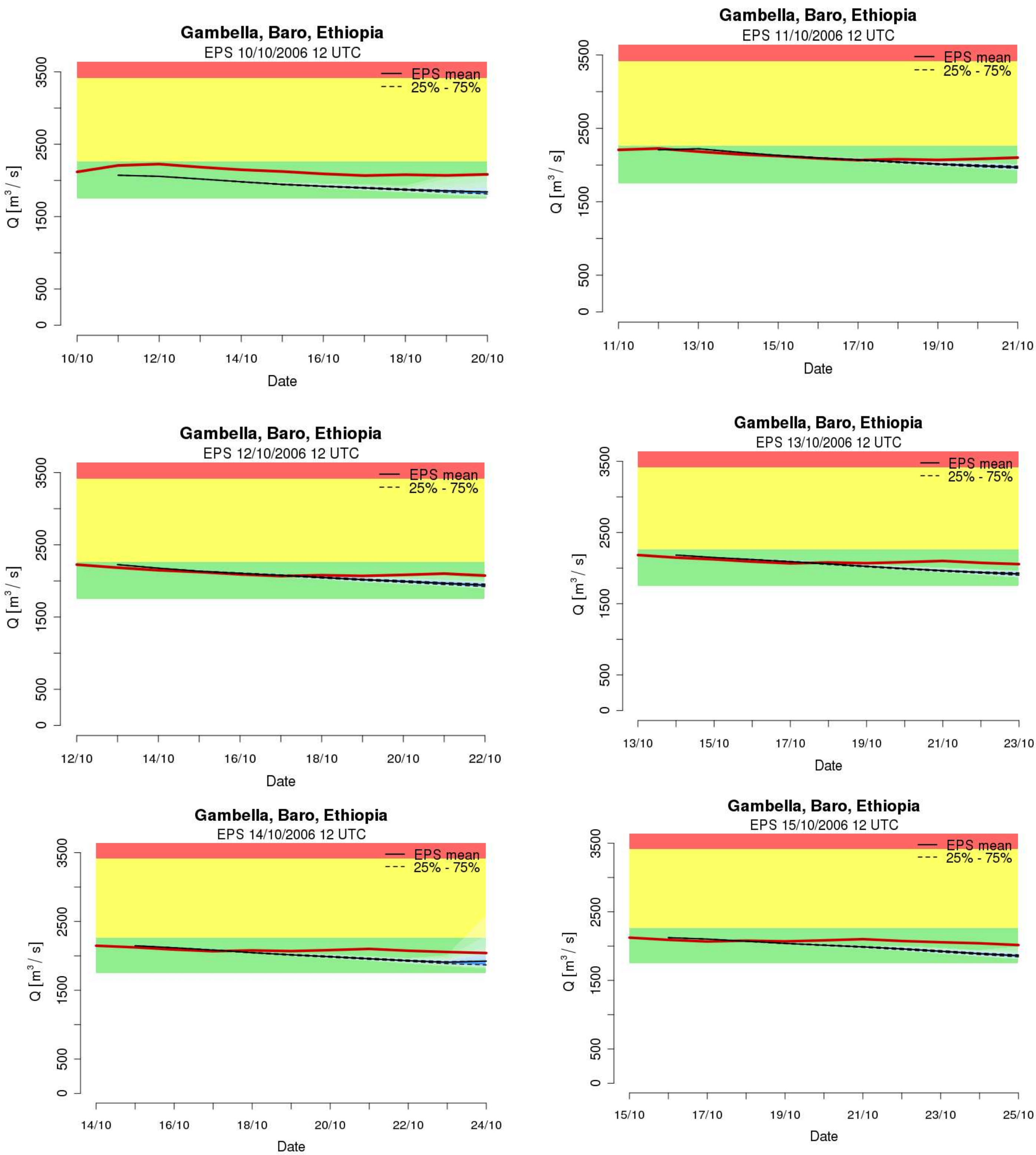


Figure 5.6 Forecast graphs for the next 10 days showing 75% and 25% boundaries of ensemble members for precipitation from ERA-interim

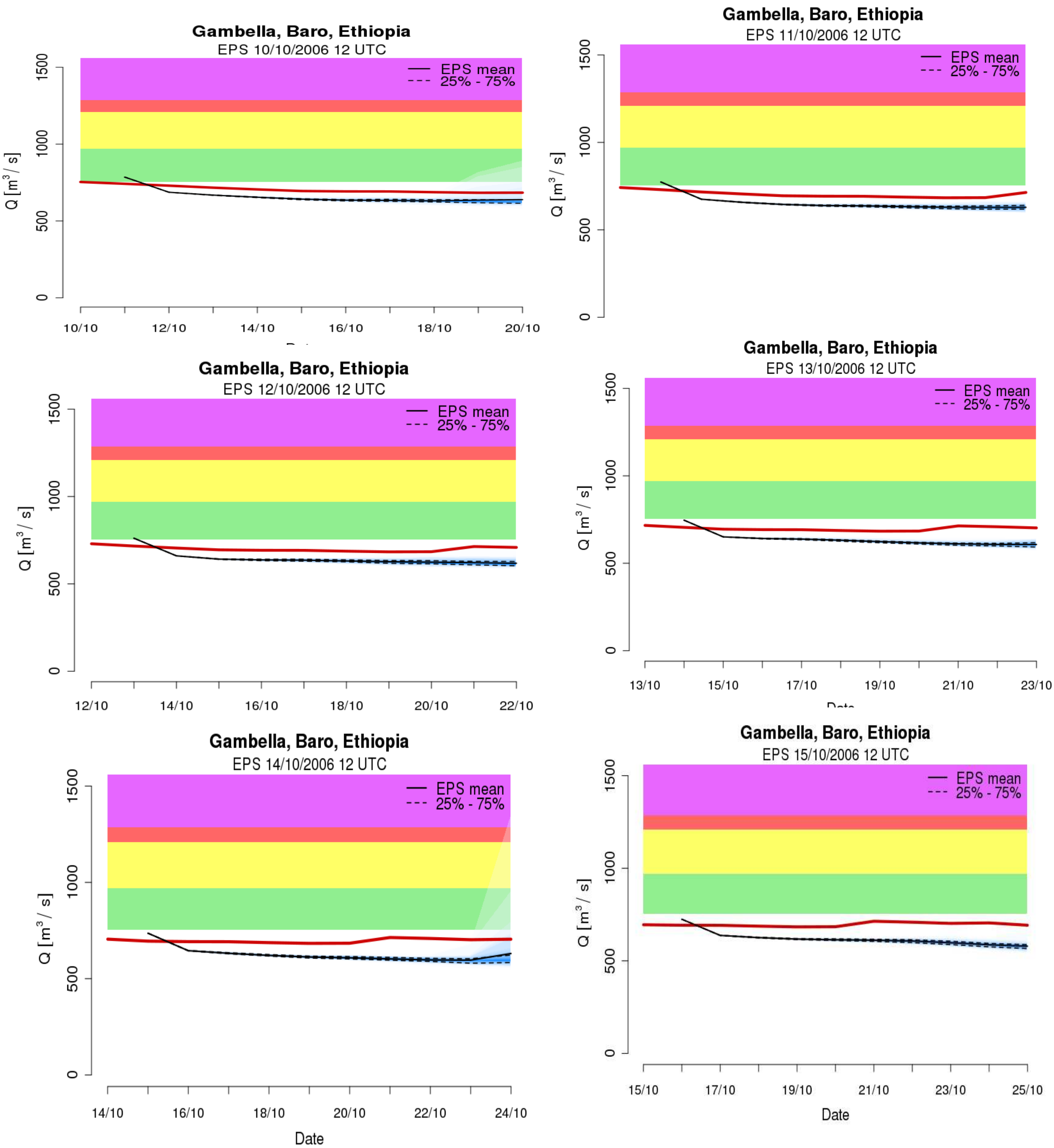


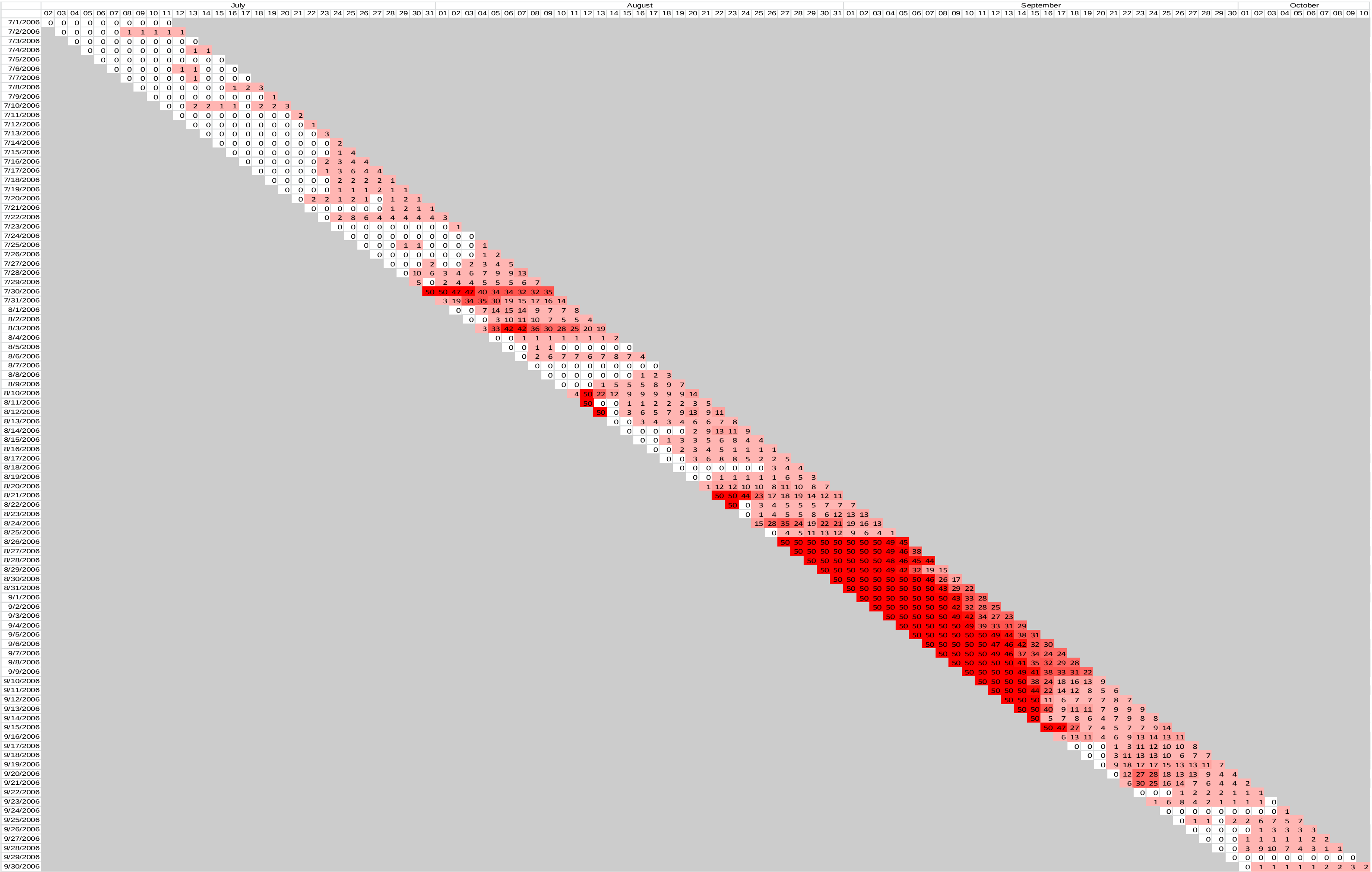
Figure 5.7 Forecast graphs for the next 10 days showing 75% and 25% boundaries of ensemble members for precipitation from TRMM

A possible solution to the above stated problem is the adjustment of the thresholds to values that are more representative to the hazard in this specific area. Hence new thresholds were derived based on the visual inspection of the long-term calculation. Attention was being paid that the low threshold indicate the offset of the flood, the medium the rising limb and the high threshold the peak (which is usually quite broad). Since in the previous setting the low threshold was already exceeded from the beginning of the forecast the forecasting period has been extended to four month, starting from 01.07.2006.

Results are presented in the threshold exceedance matrixes below (figure 5.8). The matrix shows an exceedance of the high threshold between 6 and 23 September 2006 detected with a lead time of 3 up to 10days.

	July																													August																															September																														October									
	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	01	02	03	04	05	06	07	08	09	10
7/1/2006	0	0	0	0	0	0	0	0	0	0																																																																																									
7/2/2006		0	0	0	0	0	0	0	0	0	0																																																																																							
7/3/2006			0	0	0	0	0	0	0	0	0	0																																																																																						
7/4/2006				0	0	0	0	0	0	0	0	0	0																																																																																					
7/5/2006					0	0	0	0	0	0	0	0	0	0																																																																																			
7/6/2006						0	0	0	0	0	0	0	0	0	0																																																																																		
7/7/2006							0	0	0	0	0	0	0	0	0	0																																																																														
7/8/2006								0	0	0	0	0	0	0	1	1	1																																																																													
7/9/2006									0	0	0	0	0	0	0	0	0	0																																																																												
7/10/2006										0	0	0	0	0	0	0	0	0	0																																																																										
7/11/2006											0	0	0	0	0	0	0	0	0	0																																																																									
7/12/2006												0	0	0	0	0	0	0	0	0	0																																																																							
7/13/2006													0	0	0	0	0	0	0	0	0	0																																																																				
7/14/2006														0	0	0	0	0	0	0	0	0	0																																																																			
7/15/2006															0	0	0	0	0	0	0	0	1	1																																																																	
7/16/2006																0	0	0	0	0	0	0	0	0	0																																																															
7/17/2006																	0	0	0	0	0	0	1	1	0	0																																																													
7/18/2006																		0	0	0	0	0	1	1	1	0	0																																																											
7/19/2006																			0	0	0	0	0	0	0	0	0	0																																																									
7/20/2006																				0	0	0	0	0	0	0	0	0	0																																																							
7/21/2006																					0	0	0	0	0	0	0	0	0	0																																																					
7/22/2006																						0	2	2	2	3	2	2	1	1	1																																																					
7/23/2006																							0	0	0	0	0	0	0	0	0	0																																																			
7/24/2006																								0	0	0	0	0	0	0	0	0	0																																																	
7/25/2006																									0	0	0	0	0	0	0	0	0	0																																																
7/26/2006																										0	0	0	0	0	0	0	0	0	0																																														
7/27/2006																											0	0	0	0	0	0	0	0	0	2																																													
7/28/2006																												0	0	0	0	0	1	1	1	2	4																																											
7/29/2006																													0	0	0	0	0	0	1	1	1	1																																										
7/30/2006																														0	1	4	6	6	4	5	6	8	10																																									
7/31/2006																															0	0	3	6	5	2	2	3	4	4																																								
8/1/2006																																0	0	0	0	0	0	0	0	0	0																																						
8/2/2006																																	0	0	0	0	0	1	1	0	0	0																																					
8/3/2006																																		0	5	12	13	9	9	9	10	9	7																																				
8/4/2006																																			0	0	0	0	0	0	0	0	0	0																																		
8/5/2006																																				0	0	0	0	0	0	0	0	0	0																																
8/6/2006																																					0	0	0	1	0	0	0	0	1	0																														
8/7/2006																																						0	0	0	0	0	0	0	0	0	0																													
8/8/2006																																							0	0	0	0	0	0	0	0	0	0																												
8/9/2006																																								0	0	0	0	0	0	0	0	0	0																											
8/10/2006																																									0	0	0	0	0	0	0	0	0	0																										
8/11/2006																																										0	0	0	0	0	0	0	0	0	0																									
8/12/2006																																											0	0	0	0	0	0	0	0	1	1																								
8/13/2006																																												0	0	0	0	0	0	0	0	2	2																							
8/14/2006																																													0	0	0	0	0	0	1	2	1	0																						
8/15/2006																																														0	0	0	0	0	0	0	0	0	0																					
8/16/2006																																															0	0	0	0	0	0	0	0	0	0																				
8/17/2006																																																0	0	1	2	0	0	0	0	0	0																			
8/18/2006																																																	0	0	0	0	0	0	0	1	1	1																		
8/19/2006																																																		0	0	0	0	0	0	0	0	0	0																	
8/20/2006																																																			0	0	0	0	0	0	0	0	0	0																
8/21/2006																																																				0	0	0	0	0	1	2	2	1	1															
8/22/2006																																																					0	0	0	0	0	0	0	0	0	0														
8/23/2006																																																						0	0	0	0	0	0	0	1	0	0													
8/24/2006																																																							0	1	3	3	1	2	2	2	1	1												
8/25/2006																																																								0	0	0	0	0	0	0	0	0	0											
8/26/2006																																																									50	50	26	16	12	12	9	7	5	6										
8/27/2006																																																										50	31	15	15	15	9	7	5	3	1									
8/28/2006																																																											0	32	36	37	35	30	27	26	23	18								
8/29/2006																																																												6	9	8	5	3	0	1	1	1	0							
8/30/2006																																																													50	40	3	2	3	7	6	3	0	0						
8/31/2006																																																														50	1	5	5	5	5	3	1	1	1					
9/1/2006																																																															11	23	16	9	6	4	1	0	0	0				
9/2/2006																																																																0	0	2	6	5	3	2	2	3	2			
9/3/2006																																																																	0	0	0	0	0	0	0	0	0	0		
9/4/2006																																																																		0	0	0	0	0	0	0	1	1	1	
9/5/2006																																																																			0	0	0	0	1	2	2	3	0	0
9/6/2006																																																																				0	0	2	2	2	2	3	2	2	2
9/7/2006																																																																					0	0	0	0	0	1	2	3	3	3
9/8/2006																																																																						0	0	0	0	0	1	2	5	7	6
9/9/2006																																																																							0	0	0	0	1	0	0	1	2	1
9/10/2006																																																																								0	0	0	0	0	0	0	0	1	1
9/11/2006																																																																									0	0	0	0	0	1	1	0	0	0
9/12/2006																																																																										0	0	0	0	0	0	1	1	1	2
9/13/2006																																																																										0	0	0	0	0	0	0	1	1	1
9/14/2006																																																																											0	0	0	0	0	0	1	1	1	1
9/15/2006																																																																												0	0	0	0	0	0	1	1	1	2
9/16/2006																																																																													0	0	0	0	1	1	0	0	2	2
9/17/2006																																																																														0	0	0	0	0	1	1	1	1	1
9/18/2006																																																																															0	0	0	0	0	0	0	0	0	0
9/19/2006																																																																																0	0	2	3	2	0	1	1	0	0
9/20/2006																																																																																0	0	1	1	0	0	0	0	0	0
9/21/2006																																																																																	0	0	0	1	2	2	0	0	0	0
9/22/2006																																																																																		0	0	0	0	0	0	0	0	0	0
9/23/2006																																																																																			0	0	0	0	0	0	0	0	0	0
9/24/2006																																																																																				0	0	0	0	0	0	0	0	0	0
9/25/2006																																																																																				0	0	0	0	0	0	1	1	1	1
9/26/2006																																																																																					0	0	0	0	0	0	1	1	1	1
9/27/2006																																																																																					0	0	0	0	0	1	1	1	1	0
9/28/2006																																																																																						0	0	0	0	0	0	0	0	0	0
9/29/2006																																																																																							0	0	0	0	0	0	0	0	0	0
9/30/2006																																																																																							0	0	0	0	0	0	0	1	0	0

(a) Sever alert level



(b) High alert level

July	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
7/1/2006	0	0	0	0	0	0	0	0	0	0																				
7/2/2006		0	0	0	0	0	1	1	1	1	1																			
7/3/2006			0	0	0	0	0	0	0	0	0	1																		
7/4/2006				0	0	0	0	0	0	0	0	1	2																	
7/5/2006					0	0	0	2	2	1	2	3	3	3																
7/6/2006						0	0	0	0	1	1	3	4	3	3															
7/7/2006							0	0	0	0	0	1	1	0	0	0														
7/8/2006								0	0	0	0	0	0	1	2	4	5													
7/9/2006									0	0	0	0	0	0	0	0	0	1												
7/10/2006										0	1	3	3	2	2	3	3	3	4											
7/11/2006											0	0	1	1	1	1	2	2	3	4										
7/12/2006												0	0	0	0	0	0	0	0	1	3									
7/13/2006													0	0	0	0	0	1	1	0	2	5								
7/14/2006														0	0	0	0	0	0	1	2	3	5							
7/15/2006															0	0	0	0	0	0	0	0	4	8						
7/16/2006																0	0	0	0	0	0	2	4	12	14					
7/17/2006																	0	0	0	0	0	2	7	9	11	7				
7/18/2006																		0	0	0	0	0	2	3	4	3	3			
7/19/2006																			0	0	1	1	2	3	3	3	2	2		
7/20/2006																				0	2	2	6	4	3	3	3	4	4	
7/21/2006																					0	0	0	0	0	1	2	2	2	2
7/22/2006																						0	4	9	10	8	8	8	6	6
7/23/2006																							0	0	0	0	0	0	0	0
7/24/2006																								0	0	0	2	3	0	0
7/25/2006																									0	0	0	1	1	1
7/26/2006																										0	0	0	1	1
7/27/2006																											0	0	6	8
7/28/2006																												44	50	50
7/29/2006																													50	50
7/30/2006																														50

August	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
7/22/2006	7																														
7/23/2006	2	2																													
7/24/2006	2	4	3																												
7/25/2006	1	1	2	2																											
7/26/2006	0	0	2	3	3																										
7/27/2006	5	6	7	7	11	10																									
7/28/2006	46	43	39	32	27	29	29																								
7/29/2006	50	47	41	34	25	20	20	19																							
7/30/2006	50	50	50	50	50	50	49	47	44																						
7/31/2006	50	50	50	50	50	46	45	38	34	32																					
8/1/2006		50	50	50	50	48	36	27	21	21	25																				
8/2/2006			50	50	50	50	48	35	25	19	17	19																			
8/3/2006				50	50	50	50	50	49	47	44	40	37																		
8/4/2006					50	50	50	35	28	24	14	11	7	9																	
8/5/2006						50	5	4	9	7	8	7	6	3	1																
8/6/2006							4	14	26	24	24	24	24	22	20	17															
8/7/2006								0	9	15	8	3	1	1	2	3	3														
8/8/2006									50	48	16	5	1	4	4	5	9	8													
8/9/2006										50	50	29	22	23	24	27	23	22	20												
8/10/2006											50	50	50	50	50	44	39	34	30	32											
8/11/2006												50	50	50	49	23	18	13	13	13	17										
8/12/2006													50	50	50	49	42	30	29	28	30	30									
8/13/2006														50	50	50	50	37	25	24	27	28	24								
8/14/2006															50	50	34	16	13	19	31	31	27	19							
8/15/2006																50	36	23	24	21	22	22	20	14	12						
8/16/2006																	50	29	15	23	23	19	17	17	10	8					
8/17/2006																		14	1	9	14	22	21	17	12	16	15				
8/18/2006																			0	0	2	4	4	4	4	8	8	9			
8/19/2006																				0	5	13	16	11	8	16	18	19	18		
8/20/2006																					50	50	50	43	35	29	32	32	31	26	
8/21/2006																						50	50	50	50	50	50	48	45	40	37
8/22/2006																							50	50	50	50	48	36	27	20	20
8/23/2006																								50	50	50	50	45	36	33	36
8/24/2006																									50	50	50	50	50	47	44
8/25/2006																										50	50	50	50	44	44
8/26/2006																											50	50	50	50	50
8/27/2006																												50	50	50	50
8/28/2006																													50	50	50
8/29/2006																														50	50
8/30/2006																															50

September	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
8/22/2006	20																													
8/23/2006	35	31																												
8/24/2006	42	38	32																											
8/25/2006	36	28	23	18																										
8/26/2006	50	50	50	50	50																									
8/27/2006	50	50	50	50	50	50																								
8/28/2006	50	50	50	50	50	50	48																							
8/29/2006	50	50	50	50	50	50	48	45																						
8/30/2006	50	50	50	50	50	50	50	50	48																					
8/31/2006	50	50	50	50	50	50	50	50	50	50																				
9/1/2006		50	50	50	50	50	50	50	50	50	50																			
9/2/2006			50	50	50	50	50	50	50	50	50	50																		
9/3/2006				50	50	50	50	50	50	50	50	50	49																	
9/4/2006					50	50	50	50	50	50	50	50	50	50																
9/5/2006						50	50	50	50	50	50	50	50	50	49															
9/6/2006							50	50	50	50	50	50	50	50	50	50														
9/7/2006								50	50	50	50	50	50	50	50	50	50													
9/8/2006									50	50	50	50	50	50	50	50	50	49												
9/9/2006										50	50	50	50	50	50	50	50	50	50											
9/10/2006											50	50	50	50	50	50	50	50	50	42										
9/11/2006												50	50	50	50	50	50	50	48	36	30									
9/12/2006													50	50	50	50	50	50	49	40	36	32								
9/13/2006														50	50	50	50	50	50	48	46	40	35							
9/14/2006															50	50	50	50	50	46	31	29	27	26						
9/15/2006																50	50	50	50	50	49	47	42	37	32					
9/16/2006																	50	50	50	50	49	43	41	40	35	35				
9/17/2006																		50	50	50	50	48	40	31	24	23	18			
9/18/2006																			50	50	50	50	49	34	30	25	22	20		
9/19/2006																				50	50	50	50	44	31	31	29	27	24	
9/20/2006																					50	50	50	50	45	41	37	30	24	17
9/21/2006																						50	50	50	50	47	38	36	29	20
9/22/2006																							50	50	50	50	25	13	4	6
9/23/2006																								50	50	50	46	28	17	14
9/24/2006																									50	50	50	47	26	12
9/25/2006																										50	50	50	46	19
9/26/2006																											50	50	50	49
9/27/2006																												50	50	44
9/28/2006																													50	50
9/29/2006																														50

October	01	02	03	04	05	06	07	08	09	10
9/21/2006	13									
9/22/2006	4	4								
9/23/2006	9	5	5							
9/24/2006	9	3	2	2						
9/25/2006	18	23	21	17	17					
9/26/2006	26	19	13	11	10	7				
9/27/2006	11	6	7	5	5	3	3			
9/28/2006	43	31	26	20	15	14	13	9		
9/29/2006	50	44	23	11	6	2	0	2	2	
9/30/2006	50	50	50	46	23	11	9	11	10	6

(c) Medium alert level

	July																														August																															September																														October									
	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	01	02	03	04	05	06	07	08	09	10
7/1/2006	0	0	0	1	0	0	0	0	0	0																																																																																											
7/2/2006		0	0	0	0	2	2	2	2	2	3																																																																																								
7/3/2006			0	0	0	0	0	0	0	0	1	2																																																																																						
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7/5/2006					0	0	1	4	7	7	11	14	19	19																																																																														
7/6/2006						0	0	2	5	8	13	15	20	17	20																																																																											
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7/12/2006												0	0	1	3	3	2	3	2	4	9																																																															
7/13/2006													0	0	2	2	2	3	4	4	5	9																																																													
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8/28/2006																																																											50	50	50	50	50	50	50	50	50	50										
8/29/2006																																																												50	50	50	50	50	50	50	50	50	50									
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9/29/2006																																																																																						50	50	50	50	50	50	50	50	49	46		
9/30/2006																																																																																							50	50	50	50	50	50	50	50	50	50

(d) Lower alert level

Figure 5.8 Persistency tables for test by adjusting thresholds for period from 01/07/2006 - 30/09/2006 for precipitation from ERA-interim (at Gambella main outlet).

6. Uncertainties in flood forecast

6.1 Generals

Uncertainty is a general concept that reflects impossibility to exactly describe existing state or future outcome due to more than one possible outcome. Uncertainty (conjugate of risk) generally expressed in terms of probability density. Uncertainty arises from the complexity of the system, from ignorance, from chance, from various classes of randomness, from imprecision, from lack of knowledge, from vagueness (UNESCO-IHE, Flood Management Education Platform, 2011). Generally any prediction is from highly uncertain daily activities. Thus, flood forecasting is uncertain due to many reasons which are eroding everyone's trust on forecast outputs. Error in flood forecast (whether timing or magnitude) may lead to either of the two problems (Smith and Ward, 1998): (1) under-preparation (due to forecasting low stage or late forecast inundation timing) will lead to high loss and (2) over-preparation (due to high sage forecast or prematuring of inundation time) leading to unnecessary expense, anxiety and loss of reliability for next forecasts. Therefore, forecast uncertainty estimation is becoming an increasingly important component of the forecasting procedure. Flood uncertainty estimation in the forecast can help the decision maker to enhance the reliability and credibility of both the forecasting and the warning system in real-time flood management (Shrestha and Solomatine, n.d).

There are a number of potential sources uncertainties in flood forecasting and early warning system and Maskey (2004) classified in to four major categories. (i) Due to model uncertainties (including assumptions in model equation, model structure, incomplete conceptualizing of real systems, ignorance of subsystems etc). (ii) Input or meteorological uncertainties (imprecise forecast, uncertainty in weather forecast). (iii) Parameter uncertainties (due to imperfect model parameters set, sub-optimal parameter). (iv) Natural and operational uncertainty (due to unforeseen causes landslides, dam break, human mistakes etc). And also uncertainties may rise from random or systematic errors in observed data which are used to measure simulation accuracy (Butts et al., 2005).

Basics and challenges in uncertainties (Butts et al., 2005)

- Quantification of uncertainty source and propagation.
- Impact evaluation of different source of uncertainties on forecast outputs
- How to compromise the uncertainties in forecast decision and management.
- Providing uncertainty for decision makers and users in easy and understandable manner.

6.2 Uncertainty from hydrological model

As modeling is mathematical gross simplification of reality (Leahy et al., 2007), it is impossible to represent every process. To achieve modeling it is common that we make many assumptions, neglect many sub-process, use analogues etc: leading to uncertainties which decrease the efficiency of the model. For simplified understanding of inherited uncertainties in modeling Khatibi et al (n.d) diagrammatically presented in figure 6.1. Models with high information content have capacity to minimize uncertainties.

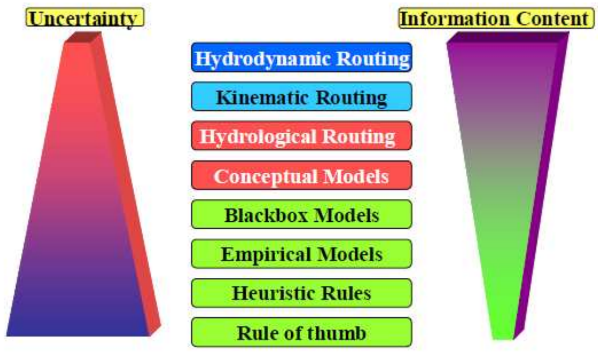

Figure 6.1Inherited uncertainty vs information content in modeling (source: Khatibi et al.,n.d)

Model uncertainty estimation needs deep investigation; here only highlights of methods used/LISFLOOD generals are assessed.

6.2.1 Flow Routing

Flood routing is needed for simulating the movement of water through the channel. It has no impact on the mass balance, but it is crucial for timing and magnitudes of the flood wave. As stated in section 2.3.8, flood wave propagation in open channel is approximated by the Saint-Venante's equations or by their simplifications such as kinematic wave, noninertia wave, gravity wave and quasi-steady dynamic wave (Tsia, 2003). Besides their physical wave propagation, their degree of computation highly differs. Kinematic routing (the most basic hydraulic routing) though, due to complex nature of river flow making simplification is a must for mathematical computations due to more assumptions stated below (Strelkoff, 1969) it is likely exposed to uncertainties:

- friction and bed slopes are equal ($S_o = S_f$)
- doesn't allow attenuation of flood wave (only translation is will be done)
- representing channels with straight line

- channels are stable (ignoring lateral degradation aggregation, frequent bed form change)
- flow resistance described by simple empirical equations of Chezy or Manning
- not considering for separation of main channel with overbanks

Dynamic routing due to more hydraulic information allows a higher degree of accuracy and a generally standard to which others are measured or compared. However, it is computational unstable, difficult to apply and requires more detailed data. However, diffusion wave (including the pressure term) with collaboration with local authorities for detail data seems realistic.

6.2.2 Evaporation and transpiration

Water losses in the basin by combination of transpiration from plants and evaporation from the soil surface have high potential of uncertainties in estimation of runoff generated in the basin, since these occur simultaneously and there is no simplified way to distinguishing between the two processes. Apart from the water availability in the topsoil, the evaporation from a cropped soil is mainly determined by the fraction of the solar radiation reaching the soil surface (Richard G. ALLEN, et al.,n.d). This fraction is dependent on growth stage of crops, some seasons evaporation is dominated by transpiration and on another period evaporation takes over. Although many approaches, empirical methods were developed and adapted over last many years due to weak input data, lack of global validity and high sensitivity for many local conditions still considerable uncertainties are recognized.

Though testing the accuracy of different ETo estimation methods under different climatically condition is not easy due to different constraints. In addition to method used (FAO-Penman-Monteith) satellite based estimation from two studies one from the Baro-Akobo river basin (WaterWatch, 2001) and second from Rift Valley including western and eastern highlands test (Ayenew T., 2006) SEBAL, Bastiaanssen (1998) method is recommended optionally.

SEBAL: Relying on advancement in remote sensing technology to improve determination of distributed areal actual evapotranspiration rate from spectral satellite data, and based on the energy balance approach (Parodi, 1993; Bastiaanssen et al., 1998). Surface Energy Balance Algorithm for Land (SEBAL) quantifies the energy balance using satellite spectra data as an input. The energy balance emphasizes in order to change water from liquids to vapor certain amount of energy is required which is mainly from solar radiation and can be determined by satellite data.

6.2.3 Ground water loss

Some fraction of infiltrating water percolates to the deep ground water zone, hence unavailable to feed rivers. Deep ground water loss covers around 1/20 of stream flow in terms of volume and globally annual basis, deep percolation constitutes 2% of precipitation (L'vovich, 1979). Thus it might be one cause for uncertainties due to difficulties to effectively estimate deep groundwater loss, in most operational hydrological models it is adjusted by calibration. Similarly in LISFLOOD ground water loss fraction is one calibration parameter.

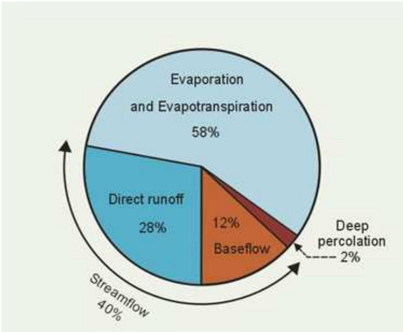

Figure 6.2 Global annual components of precipitation (source: Victor M. Ponce, n.d)

6.2.4 Transmission loss

It is mainly characteristic for arid areas that discharge decreases constantly in downstream reaches (contrarily, in some rivers the reveres may happen). This water loss is due evaporation as well as due to infiltrations into groundwater, river banks and floodplains. The most important factors affecting transmission loss are geology and soils of the valley, river characteristics (number, depth, gradient, size and meander of channels), soil-frost conditions, depth to the water table, soil moisture content, artificial activities (ponds, check dams, reservoirs, irrigation diversion canals) and vegetation along the channels (Florian Hacker, 2005). Transmission losses can be estimated by the following approaches (Joseph Cataldo et al., 2004) (i) Simplified regression (by using inflow and outflow volume data of number of reaches (ii) Simplified differential equation (using simplified differential equations to describe changes in flow rate over time) (iii) Combine use of differential equation and regression (iv) field observation and experimentation (v) stream flow routing (by examining shapes and timing of the hydrograph at different points downstream) (vi) hydrological budget (using basic equations describing changes in storage to account different factors). As transmission loss needs discharge measures at different reaches it is difficult to estimate due to lack of discharge data at different place but, from the climatological characteristics of the basin it will not be worst like that of arid regions.

6.3 Uncertainties from meteorological data

As meteorological data inputs are driving agents for hydrological modeling and flood forecasting they are also one main source of uncertainties. For precipitation (supreme agents) to test which precipitation source will be highly exposed to uncertainties the observed data are statically tested with satellite data which are extracted from the respective pixels for 8 years (2002 - 2010) interval. In addition to four satellite data sources used in calibration and validation one additional satellite data sources (CMORPH, due to shortage of discharge data for recent dates not used in calibration and validation) tested. From the tables below ranks by Nash-Sutcliff score differs mainly due to altitudes as some are good in highlands and others are good in lowlands. The average rank indicated that ERA-interim and PERSSIAN relatively exposed to high uncertainties and RFE 2.0, CMORPH & TRMM show less uncertainties in pixel to pixel test. In forecasting systems EPS are good for handling propagation but, they are sensitive for uncertainties, small error in errors in initial conditions will propagate and can make it to depart from the realistic one. To cope with this and estimating uncertainties conditions as stated earlier Taylor and Buizza (2003) recommendation generating an ensemble of different forecasts of atmospheric processes that differ by their initial conditions in addition to the main (deterministic) forecast is acknowledged.

Table 6. 1 Point to pixle test average rank (summary of APPENDEX II)

Station	ID	Altitude from dem_mean.map	Lat	Lon	ERAinterim	PERSIANN	CMORPH	TRMM 3B42	RFE 2.0	Remark
Assosa	1	809.91	10.01	34.31	5	4	3	2	1	
Begi	2	913.06	9.2	34.32	5	3	4	1	2	
Abobo	3	459.278	7.51	34.26						Station not working
Gimibi	4	1556.42	9.1	35.47	5	4	2	3	1	
Bebeka	5	647.63	6.49	35.16						Station not working
Bedele	6	2243.28	8.27	36.2	5	4	1	2	3	
Chiri	7	1900.76	7.08	36.11						Partially working
Jinka	8	553.913	5.48	36.33	3	4	1	5	1	
Nedjo	9	1549.38	9.3	35.27	5	4	3	1	2	
Hena	10	1509.76	9.27	35.36	5	3	4	1	2	
Nekemte	11	1333.19	9.05	36.27	4	4	2	3	1	
Gida Ayana	12	1405	9.52	36.56	5	4	1	3	2	
Gore	13	1614.46	8.09	35.32	5	4	3	2	1	
Tepi	14	798.64	6.59	35.15	5	2	4	1	3	
Jikawo	15	408.46	8.22	33.45	5	3	4	1	2	Partially working
Average rank					5	4	3	2	1	

6.4 Uncertainties from parameter sets

Parameter uncertainties are rising mainly from optimizing algorism, and due to imperfect parameters set/value. Model parameter uncertainties are explicitly accounted by use of GLUE (Generalized Likelihood Uncertainty Estimation) and Bayesian method. Application of statics is also vital to calculate the uncertainly limit and percentage of observation which fall within uncertainty bound. Here only frequency histograms and dotty plots of Pearson's r model efficiency were used to get insight on which parameters are highly exposed to uncertainties and the like.

From frequency histogram sharp and peaked distributions are associated with well definable parameters while flat distributions indicate more parameters uncertainty (Xiaoli et al., 2010). As seen from frequency histogram and dotty polts UZTC, GWLF, bxinj are from well-defined parameters. CalEvap and

CCM2 are bit skewed and both CCM and LTZC indicating with flat distribution exposure for high uncertainty.

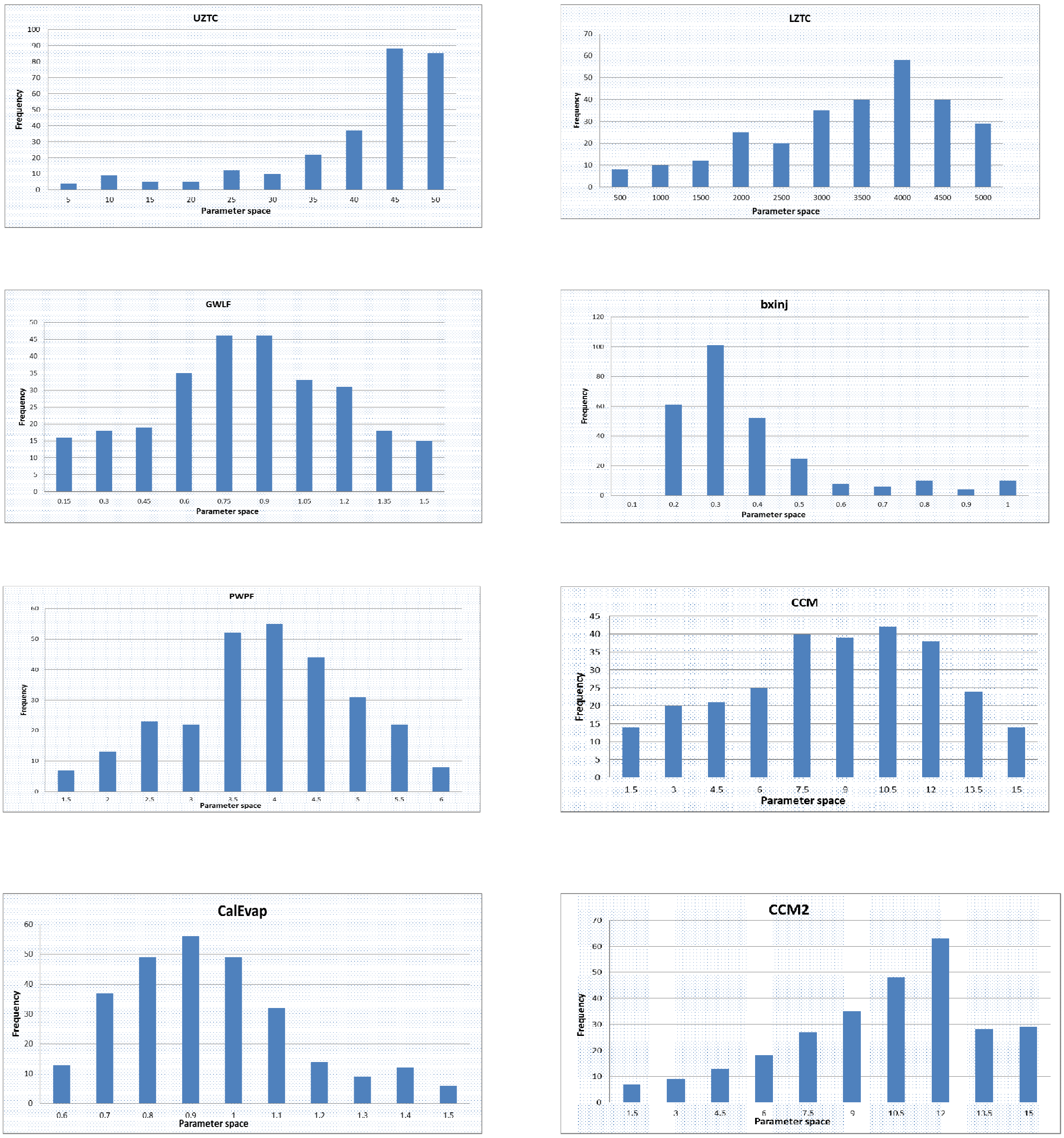

Figure 6.3 Frequency histogram

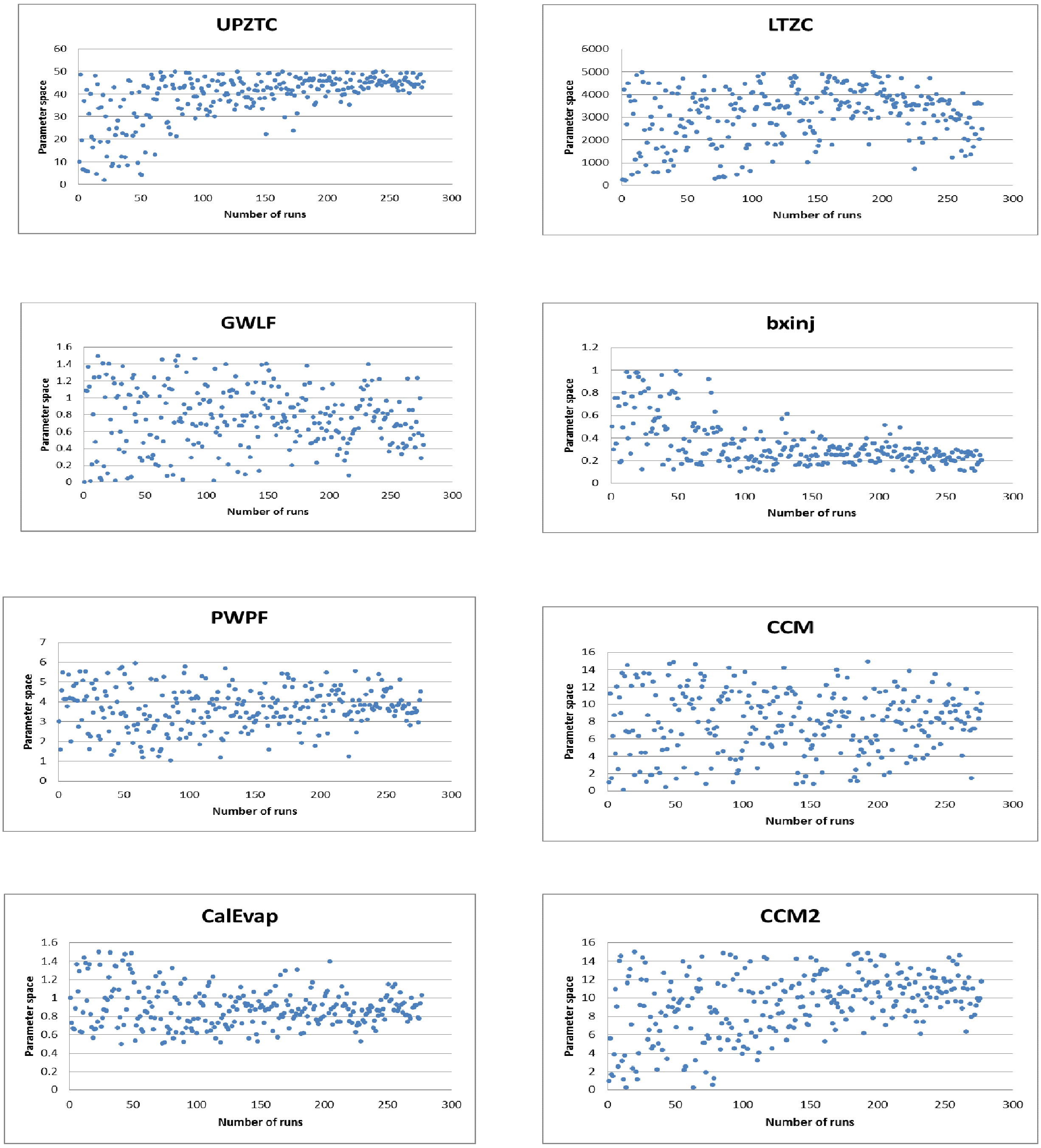

Figure 6.4 Dotty plot for evolution of optimized parameters’

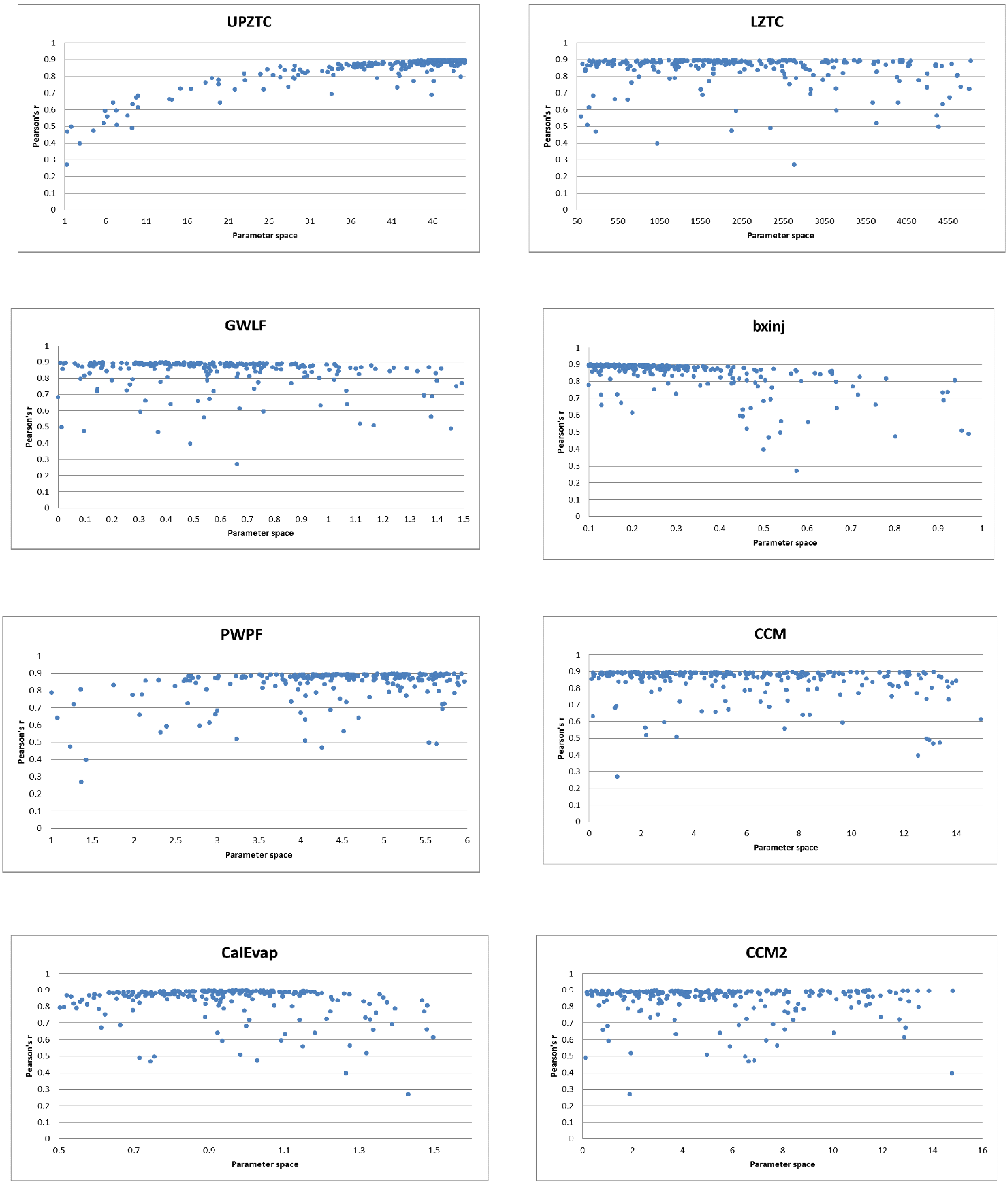

Figure 6.5 Dotty plots for Pearson's model efficiency vs parameter space

7. Summary, recommendations and study extensions

The mid-size transnational river basin Baro-Akobo, is one of Ethiopia's flood prone areas which have been hitten by different floods in the past. Within this thesis, methods of the European Flood Alert System (EFAS) are tested and adapted. EFAS is designed to give flood warnings for medium to large scale, transnational European rivers with a warning time of 3 to 10 days. LISFLOOD, a distributed hydrological model was applied with five different precipitation data sets: TRMM 3B42 (Tropical Rainfall Measuring Mission), PERSIANN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks), RFE 2.0 (African Rainfall Estimation Algorism), ERA-interim and ground observations (interpolated by inverse weighted distance method).

Observed discharge was obtained from the Ethiopian Minister of Water Resource and Energy, Meteorological stations data from the Ethiopian National Meteorology Agency, static data set (elevation model leaf area index, soil map, land cover and others) amongst others from the JRC and satellite products from NASA, University of Arizona, NOAA-CPC and ECMWF.

As model sensitivity analysis is potentially useful in all phases of hydrological modeling, to fix insensitive parameter for decreasing dimensionality of calibration parameters simple trial and error method is applied. For general purpose first order sensitivity analyses is done and for ranking in addition to graphs common techniques such as sensitivity index and relative deviation were used. First order sensitivity analysis (twice: one keeping others at optimal values and second keeping others at default value) resulted that UZTC, bxinj and PWPF are highly sensitive, GWLF, CalEvap and CCM are moderately sensitive, and GWPV, CCM2 and LTZC are less sensitive parameters.

LISFLOOD was calibrated using the SCE-UA (genetically adaptive approach for effective and efficient global optimization) algorithm. Excluding the first year for warm up, the period between 2002 and 2006 is taken from calibration. Eight parameters values are estimated: upper zone time constant, lower zone time constant, groundwater loss fraction, power taken for Xinajiang distribution function, power that control proportion of preferential flow, multiplier factor for channel manning's n, multiplier for potential evapotranspiration rates, multiplier applied to channel manning's n for second line routing. Likely, excluding one year for warm-up, the period from 2000 - 2003 is taken for validation. The calibration results (coefficient of efficiency) are 0.8, 0.56, 0.47, -3.61, -0.09 for PERSIANN, TRMM, RFE 2.0, ERA-interim and observed precipitation data respectively.

Warning thresholds are estimated based on return periods, derived from long term discharge simulations. Return periods of 20, 5, 2 and 1.5 years represent the alert level for a sever, high, medium and low flood respectively. These were calculated for the main outlet at Gambella station and for three other strategic points in the river path.

Finally, uncertainties rising from different sources are discussed: such as from some sub-process of model structure (flow routing, evapotranspiration, ground water loss, transmission loss), from meteorological data (point to pixel test for all of satellite data sources), from parameter set (frequency histograms, dotty plots for parameter space versus number of runs and for Pearson's r versus parameter space are used to assess which parameter likely exposed to high uncertainties).

7.1 Recommendations

- Precipitation is main input and driver of hydrological modeling their estimation has to be closest to the realistic. Since meteorological gauging stations are sparsely implemented in the basins (especially in developing nations) it's difficult to fully rely on those. Thus advancement of satellite technology is highly acknowledged as they hold potential to be an alternative to observed precipitation data.
- LISFLOOD model calibration and validation results for different input data sources ranged from 0.8 up to -2.7 coefficients of efficiency indicating influence of precipitation on model outputs and enclosing the model results for most of them with above 0.5 showing high potential of the model.
- Precipitation from Tropical Rainfall Measuring Mission (TRMM) showed relatively good and consistent scores for all calibration, validation and point to pixel tests in the basin.
- Due to the small size of the basin and other basin characteristics the high floods are having from 1 to 2 years return period resulting to be lower flood levels in EFAS flood definition and even though they are captured by EFAS they are out of the range for warning by the system. Commonly very short year returning period floods can have high possibility to be mitigated by infrastructure facilities unless the topography is highly exposed.
- The channel bed size and geometry of the cross section change has an impact on the timing of floods especially in long rivers. However, input data such as river cross section and bed width information would are usually not available. A closer collaboration with local authorities or/and high resolution satellite data may lead to improved model performance.
- Even if LISFLOOD inputs for continental scale 0.1^{o} is good increasing the scale raises the capacity of handling realities in spatial variations despite its high storage and computer processor need.
- Though, SCE-UA calibration algorism is highly acknowledged due to its probabilistic approach and from selection of appropriate algorism parameters still it may lose global optimal values. It is appreciated that the algorism will search optimal set with small runs. (for instance for rough optimal check by simple simplex for 6 parameters optimizing if discretized into ten between parameter space it will need running of model for 10! - 4! which is impossible by currently available computer capacity).
- Coefficient of efficiency has a better potential as optimizing objective function than the commonly used Pearson's r, since the later one is insensitive for additive and proportional differences.
- In most of calibration and validation results it's observed that mostly the average values are goodly estimated than extreme values since the optimizing algorisms optimizes based on average values. Therefore it might be better to introduce the use of variable optimal sets which are optimized independently.

- Using flood inundation maps with return period for thresholds derivation will increase the realities of flood definition/events. Sometimes due to local topography the flood with many return periods will not have any problem and vise verse.
- EFAS thresholds used in Europe need to be adjusted to allow for sending alerts already for smaller floods (return periods of 1-2 year), test was done by adjusting thresholds. It indicated reasonable results (highest discharges levels which led to flooding from 06 - 23 September 2006 were detected from 3-10 days in advance). Indicating the capacity of the system to apply to different basins with small adjustment.

7.2 Research contributions

Main contributions of this study are:

- ✓ Baro-Akobo River basin modeling for further different uses
- ✓ Testing LISFLOOD and EFAS for different climatic condition and catchment size
- ✓ Introducing and adapting medium ranged flood forecasting for Baro-Akobo river basin and Ethiopia as well.
- ✓ Testing satellite-based precipitation data and comparing with gauged precipitations.
- ✓ Reference for material for further studies in the basin.

7.3 Study limitations and possible research extensions:

Main limitations of the study include shortage of discharge and meteorological data spatially and temporally, high percentage of missing values which led to poor score for modeling using precipitation from observed stations. Furthermore due to lack of discharge data (i) forecasting was not done for downstream of Gambella town (ii) facing problem in switching the time period for calibration and validation time to access potentially different satellite data source for the basin and western part of the country (since most of satellite data are recent and having short period interval). Extending for other river basins in the country (which are more flood prone areas), for LISFLOOD by improving input data testing and applying in other basins having additional hydrological process.

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APPENDIX I Sensitivity analysis table

(a) first order keeping others at optimal value

	LZTC		UZTC		GWPV		GWLF		bxinj		PWPF		CCM		CalEvap		CCM2	
Runs	R, pear	E, co ef	R, pear	E, co ef	R, pear	E, co ef	R, pear	E, co ef	R, pear	E, co ef	R, pear	E, co ef	R, pear	E, co ef	R, pear	E, co ef	R, pear	E, co ef
1	0.9073	0.8105	0.3935	-0.9155	0.9074	0.8105	0.9100	0.8153	0.9084	0.8123	0.8093	0.6274	0.9073	0.8026	0.8697	0.5313	0.9074	0.8105
2	0.9073	0.8105	0.5597	0.0053	0.9074	0.8105	0.9096	0.8202	0.9073	0.8105	0.8516	0.7179	0.9073	0.8053	0.8851	0.6736	0.9074	0.8105
3	0.9073	0.8105	0.6511	0.2694	0.9074	0.8105	0.9086	0.8198	0.9055	0.8075	0.8764	0.7603	0.9073	0.8067	0.8967	0.7641	0.9074	0.8105
4	0.9073	0.8105	0.7237	0.4496	0.9074	0.8105	0.9061	0.7999	0.9018	0.8017	0.8908	0.7833	0.9073	0.8079	0.9035	0.8092	0.9074	0.8105
5	0.9073	0.8105	0.7810	0.5795	0.9074	0.8105	0.9020	0.7637	0.8931	0.7885	0.8996	0.7973	0.9073	0.8088	0.9066	0.8193	0.9074	0.8105
6	0.9073	0.8105	0.8259	0.6729	0.9074	0.8105	0.8962	0.7131	0.8765	0.7630	0.9046	0.8056	0.9073	0.8097	0.9074	0.8026	0.9074	0.8105
7	0.9073	0.8105	0.8602	0.7379	0.9074	0.8105	0.8882	0.6499	0.8516	0.7231	0.9069	0.8097	0.9073	0.8105	0.9062	0.7641	0.9074	0.8105
8	0.9073	0.8105	0.8860	0.7811	0.9074	0.8105	0.8780	0.5762	0.8195	0.6682	0.9077	0.8113	0.9073	0.8112	0.9035	0.7075	0.9074	0.8105
9	0.9073	0.8105	0.9052	0.8079	0.9072	0.8088	0.8659	0.4945	0.7819	0.5984	0.9075	0.8111	0.9073	0.8119	0.8992	0.6360	0.9074	0.8105
10	0.9073	0.8105	0.9193	0.8223	0.9065	0.8013	0.8520	0.4071	0.7411	0.5149	0.9066	0.8098	0.9073	0.8125	0.8936	0.5534	0.9074	0.8105
Sum	9.0734	8.1046	7.5056	4.2103	9.0725	8.0939	8.9166	6.8596	8.5867	7.2881	8.8611	7.7336	9.0734	8.0871	8.9713	7.0612	9.0735	8.1048
Mean	0.9073	0.8105	0.7506	0.4210	0.9073	0.8094	0.8917	0.6860	0.8587	0.7288	0.8861	0.7734	0.9073	0.8087	0.8971	0.7061	0.9074	0.8105
SD	0.0000	0.0000	0.1712	0.5387	0.0003	0.0029	0.0203	0.1491	0.0594	0.1035	0.0325	0.0594	0.0000	0.0031	0.0119	0.1050	0.0000	0.0000
Min	0.9073	0.8105	0.3935	-0.9155	0.9065	0.8013	0.8520	0.4071	0.7411	0.5149	0.8093	0.6274	0.9073	0.8026	0.8697	0.5313	0.9074	0.8105
Max	0.9073	0.8105	0.9193	0.8223	0.9074	0.8105	0.9100	0.8202	0.9084	0.8123	0.9077	0.8113	0.9073	0.8125	0.9074	0.8193	0.9074	0.8105
SI	0.0000	0.0000	0.5719	2.1134	0.0009	0.0114	0.0638	0.5037	0.1842	0.3661	0.1084	0.2266	0.0000	0.0122	0.0415	0.3514	0.0000	0.0000
RD	0.0000	0.0000	0.2281	1.2796	0.0003	0.0036	0.0228	0.2174	0.0691	0.1420	0.0367	0.0768	0.0000	0.0039	0.0133	0.1488	0.0000	0.0000
Rank	**9**		**1**		**7**		**4**		**2**		**3**		**6**		**5**		**8**	

*****Note: SD standard deviation*

SI Sensitivity Index

*RD relative deviation ********

(b) first order keeping others at default/average value

	LZTC		UZTC		GWPV		GWLF		bxinj		PWPF		CCM		CalEvap		CCM2	
Runs	R, pear	E, co ef	R, pear	E, co ef	R, pear	E, co ef	R, pear	E, co ef	R, pear	E, co ef	R, pear	E, co ef	R, pear	E, co ef	R, pear	E, co ef	R, pear	E, co ef
1	0.6220	-0.1331	0.6649	-2.3791	0.6185	-0.1488	0.6193	-0.1323	0.6178	-0.1041	0.5080	-0.4582	0.6157	-0.1104	0.5890	-0.7540	0.6178	-0.1041
2	0.6186	-0.1080	0.4468	-0.3514	0.6185	-0.1488	0.6165	-0.0938	0.6180	-0.1027	0.5623	-0.2444	0.6189	-0.1010	0.6063	-0.4484	0.6178	-0.1041
3	0.6176	-0.1032	0.3527	-0.0044	0.6185	-0.1428	0.6113	-0.0285	0.6179	-0.1026	0.5938	-0.1496	0.6207	-0.0960	0.6161	-0.2219	0.6178	-0.1041
4	0.6171	-0.1009	0.2810	0.2201	0.6182	-0.1176	0.6051	0.0362	0.6174	-0.1040	0.6120	-0.1108	0.6221	-0.0921	0.6175	-0.0618	0.6178	-0.1041
5	0.6169	-0.0995	0.2252	0.3833	0.6176	-0.0952	0.5992	0.0876	0.6163	-0.1075	0.6202	-0.1034	0.6233	-0.0889	0.6132	0.0512	0.6178	-0.1041
6	0.6167	-0.0987	0.1824	0.5043	0.6169	-0.0732	0.5932	0.1261	0.6135	-0.1171	0.6226	-0.1085	0.6244	-0.0861	0.6055	0.1285	0.6178	-0.1041
7	0.6165	-0.0981	0.1497	0.5936	0.6162	-0.0517	0.5870	0.1518	0.6077	-0.1389	0.6221	-0.1188	0.6253	-0.0835	0.5956	0.1787	0.6178	-0.1041
8	0.6164	-0.0976	0.1252	0.6580	0.6155	-0.0308	0.5805	0.1653	0.5993	-0.1735	0.6201	-0.1311	0.6262	-0.0811	0.5845	0.2081	0.6178	-0.1041
9	0.6163	-0.0973	0.1069	0.7030	0.6146	-0.0105	0.5735	0.1678	0.5882	-0.2203	0.6175	-0.1438	0.6271	-0.0788	0.5725	0.2208	0.6178	-0.1041
10	0.6163	-0.0970	0.0936	0.7328	0.6138	0.0093	0.5664	0.1612	0.5754	-0.2770	0.6146	-0.1567	0.6279	-0.0767	0.5601	0.2201	0.6178	-0.1041
Sum	6.1745	-1.0334	2.6285	1.0604	6.1684	-0.8101	5.9521	0.6414	6.0715	-1.4478	5.9932	-1.7252	6.2316	-0.8946	5.9602	-0.4787	6.1784	-1.0410
Mean	0.6175	-0.1033	0.2628	0.1060	0.6168	-0.0810	0.5952	0.0641	0.6072	-0.1448	0.5993	-0.1725	0.6232	-0.0895	0.5960	-0.0479	0.6178	-0.1041
SD	0.0018	0.0110	0.1815	0.9391	0.0017	0.0588	0.0182	0.1132	0.0149	0.0606	0.0371	0.1084	0.0039	0.0106	0.0194	0.3319	0.0000	0.0000
Min	0.6163	-0.1331	0.0936	-2.3791	0.6138	-0.1488	0.5664	-0.1323	0.5754	-0.2770	0.5080	-0.4582	0.6157	-0.1104	0.5601	-0.7540	0.6178	-0.1041
Max	0.6220	-0.0970	0.6649	0.7328	0.6185	0.0093	0.6193	0.1678	0.6180	-0.1026	0.6226	-0.1034	0.6279	-0.0767	0.6175	0.2208	0.6178	-0.1041
SI	0.0092	-0.3723	0.8592	4.2467	0.0076	16.9933	0.0855	1.7881	0.0689	-1.6997	0.1841	-3.4307	0.0194	-0.4390	0.0929	4.4145	0.0000	0.0000
RD	0.0029	-0.1064	0.6906	8.8564	0.0028	-0.7256	0.0307	1.7653	0.0246	-0.4187	0.0619	-0.6280	0.0062	-0.1185	0.0325	-6.9334	0.0000	0.0000
Rank	8		1		7		4		5		2		6		3		9	

*****Note: SD standard deviation*

SI Sensitivity Index

*RD relative deviation ********

APPENDIX II

Point to pixel satellite data test

Station	Assosa
ID	1
Lat	10.01
Lon	34.31
Altitude (m)	809.91

Skill scores	Observed	ERA-interim	PERSIANN	CMORPH	TRMM 3B42	RFE 2.0
mass balance [mm]	5086.5	8235	5649	6650	2848	4306
WB factor [-]		2	1.4	1.6	0.7	1.1
average ppt in mm	2.7855969	6	4	5	2	3
correlation [-]		0.23	0.16	0.4	0.25	0.42
RMSE [-]		11	10	9	8	7
BIAS [+]		7	9	6	4	5
BIAS [-]		-9	-9	-7	-8	-7
Nash-Sutcliff [-]		-1.73	-1.01	-0.76	-0.19	0.03

Station	Begi
ID	2
Lat	9.2
Lon	34.32
Altitude (m)	913.05

Skill scores	Observed	ERA-interim	PERSIANN	CMORPH	TRMM 3B42	RFE 2.0
mass balance [mm]	4908.6	10615	5684	7089	3525	4868
WB factor [-]		2.9	1.5	1.9	0.9	1.3
average ppt in mm	3.6934537	7	4	5	2	3
correlation [-]		0.22	0.18	0.35	0.22	0.16
RMSE [-]		13	9	9	8	9
BIAS [+]		8	8	6	4	6
BIAS [-]		-10	-10	-9	-10	-10
Nash-Sutcliff [-]		-2.38	-0.71	-0.84	-0.28	-0.66

Station	Gimibi
ID	4
Lat	9.1
Lon	35.47
Altitude (m)	1556.42

Skill scores	Observed	ERA-interim	PERSIANN	CMORPH	TRMM 3B42	RFE 2.0
mass balance [mm]	9469.8	10354	4820	7697	4548	5510
WB factor [-]		1.3	0.6	1	0.6	0.7
average ppt in mm	5.1860898	7	3	5	3	4
correlation [-]		0.3	0.2	0.47	0.34	0.51
RMSE [-]		12	12	11	11	9
BIAS [+]		6	8	6	6	5
BIAS [-]		-13	-12	-11	-11	-11
Nash-Sutcliff [-]		-0.31	-0.18	0.02	0	0.22

Station	Bedele
ID	6
Lat	8.27
Lon	36.2
Altitude (m)	2243.28

Skill scores	Observed	ERA-interim	PERSIANN	CMORPH	TRMM 3B42	RFE 2.0
mass balance [mm]	9246.7	8051	4163	6931	5190	5508
WB factor [-]		1	0.5	0.9	0.7	0.7
average ppt in mm	5.0639102	6	3	5	4	4
correlation [-]		0.26	0.15	0.58	0.36	0.33
RMSE [-]		11	11	8	10	10
BIAS [+]		5	6	4	3	5
BIAS [-]		-11	-12	-10	-12	-11
Nash-Sutcliff [-]		-0.19	-0.18	0.31	0.04	-0.02

Station	Jinka
ID	8
Lat	5.48
Lon	36.33
Altitude (m)	553.913

Skill scores	Observed	ERA-interim	PERSIANN	CMORPH	TRMM 3B42	RFE 2.0
mass balance [mm]	6628.6	4078	2499	4328	3445	3301
WB factor [-]		0.8	0.5	0.8	0.6	0.6
average ppt in mm	3.6723546	3	2	3	2	2
correlation [-]		0.26	0.01	0.34	0.21	0.29
RMSE [-]		8	9	9	10	9
BIAS [+]		4	5	4	9	6
BIAS [-]		-8	-9	-8	-8	-8
Nash-Sutcliff [-]		-0.12	-0.38	-0.14	-0.6	-0.14

Station	Hena
ID	10
Lat	9.27
Lon	35.36
Altitude (m)	1509.76

Skill scores	Observed	ERA-interim	PERSIANN	CMORPH	TRMM 3B42	RFE 2.0
mass balance [mm]	7422.3	9252	4794	7584	4539	5367
WB factor [-]		1.6	0.8	1.3	0.8	0.9
average ppt in mm	4.6946869	6	3	5	3	4
correlation [-]		0.21	0.27	0.42	0.39	0.29
RMSE [-]		13	10	11	9	10
BIAS [+]		7	6	6	4	6
BIAS [-]		-13	-13	-11	-12	-13
Nash-Sutcliff [-]		-0.84	-0.23	-0.34	0.04	-0.22

Station	Nekemtte
ID	11
Lat	9.05
Lon	36.27
Altitude (m)	1333.19

Skill scores	Observed	ERA-interim	PERSIANN	CMORPH	TRMM 3B42	RFE 2.0
mass balance [mm]	9694.8	8914	4733	7305	5060	5099
WB factor [-]		1.1	0.6	0.9	0.6	0.6
average ppt in mm	5.3151316	6	3	5	3	3
correlation [-]		0.34	0.21	0.41	0.35	0.52
RMSE [-]		11	11	11	11	9
BIAS [+]		6	7	5	5	4
BIAS [-]		-11	-11	-11	-11	-10
Nash-Sutcliff [-]		-0.15	-0.15	0.01	0	0.23

Station	Gida Ayana
ID	12
Lat	9.52
Lon	36.56
Altitude (m)	1405

Skill scores	Observed	ERA-interim	PERSIANN	CMORPH	TRMM 3B42	RFE 2.0
mass balance [mm]	7861.6	9738	3916	6746	4836	4890
WB factor [-]		1.5	0.6	1	0.7	0.7
average ppt in mm	4.7588378	7	3	5	3	3
correlation [-]		0.36	0.25	0.51	0.34	0.42
RMSE [-]		12	10	9	11	10
BIAS [+]		7	6	4	6	6
BIAS [-]		-12	-12	-11	-12	-11
Nash-Sutcliff [-]		-0.38	-0.06	0.14	-0.08	0.08

Station	Gore
ID	13
Lat	8.09
Lon	35.32
Altitude (m)	1614.46

Skill scores	Observed	ERA-interim	PERSIANN	CMORPH	TRMM 3B42	RFE 2.0
mass balance [mm]	7944.7	12049	4616	6989	4940	6349
WB factor [-]		1.9	0.7	1.1	0.8	1
average ppt in mm	4.4235523	8	3	5	3	4
correlation [-]		0.27	0.13	0.42	0.3	0.41
RMSE [-]		11	9	9	8	8
BIAS [+]		7	6	5	4	5
BIAS [-]		-8	-8	-7	-8	-7
Nash-Sutcliff [-]		-1.11	-0.35	-0.19	-0.1	-0.07

Station	Tepi
ID	14
Lat	6.59
Lon	35.15
Altitude (m)	798.46

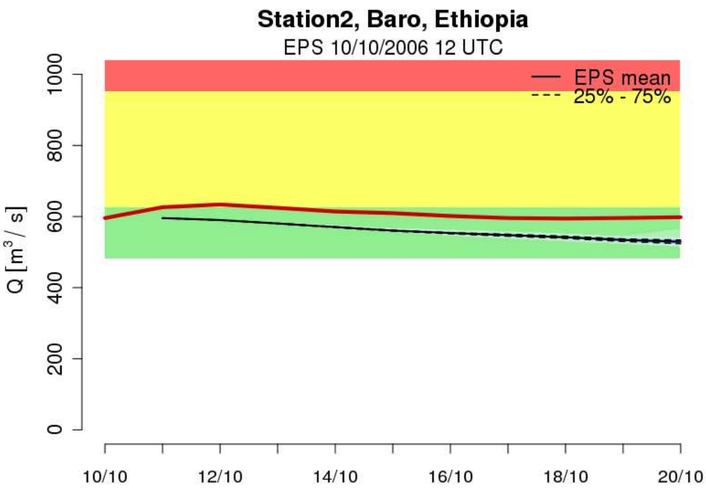
Skill scores	Observed	ERA-interim	PERSIANN	CMORPH	TRMM 3B42	RFE 2.0
mass balance [mm]	6918.1	8968	4082	7372	4328	5110
WB factor [-]		1.6	0.7	1.3	0.8	0.9
average ppt in mm	3.8540947	6	3	5	3	3
correlation [-]		0.09	0.05	0.25	0.2	0.13
RMSE [-]		13	9	10	9	9
BIAS [+]		6	6	5	6	6
BIAS [-]		-8	-8	-7	-7	-7
Nash-Sutcliff [-]		-1.95	-0.48	-0.71	-0.4	-0.62

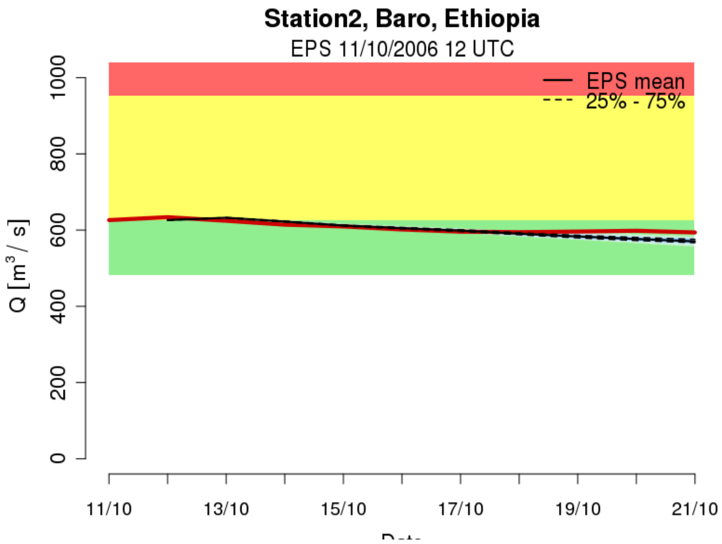
Station	Jikawo
ID	15
Lat	8.22
Lon	33.45
Altitude (m)	408.46

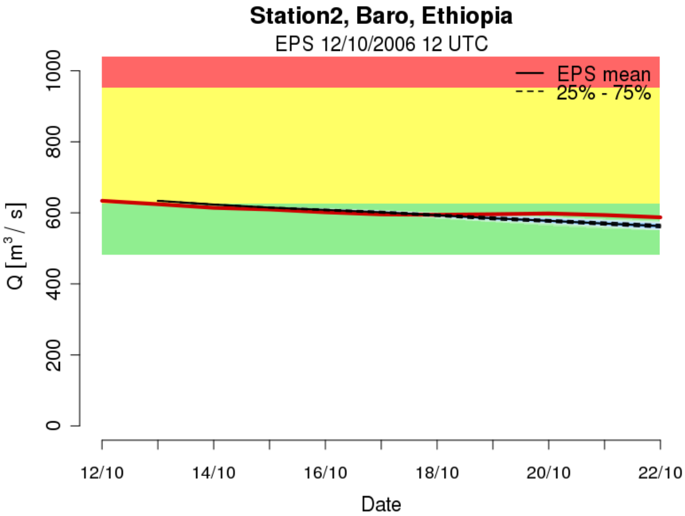
Skill scores	Observed	ERA-interim	PERSIANN	CMORPH	TRMM 3B42	RFE 2.0
mass balance [mm]	2293.9	8302	3902	5185	2584	3746
WB factor [-]		3.8	1.8	2.4	1.2	1.7
average ppt in mm	1.6891753	6	3	4	2	3
correlation [-]		0.07	0.03	0.12	0.15	0.07
RMSE [-]		13	10	11	8	9
BIAS [+]		6	7	5	4	5
BIAS [-]		-12	-12	-11	-11	-12
Nash-Sutcliff [-]		-2.57	-0.83	-1.51	-0.36	-0.69

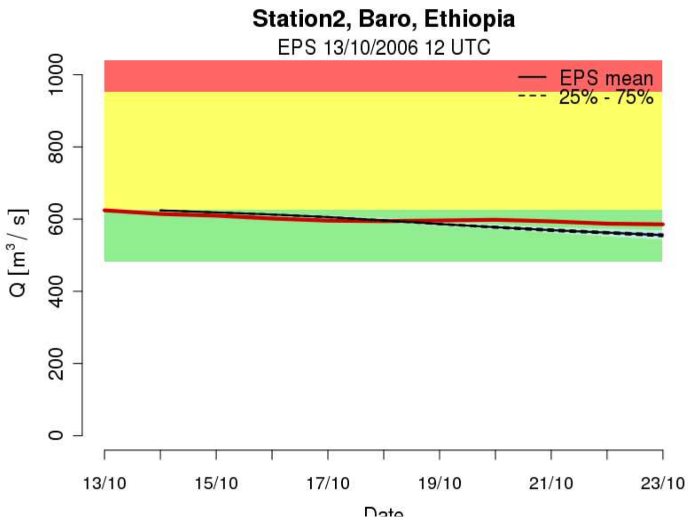
APPENDIX III

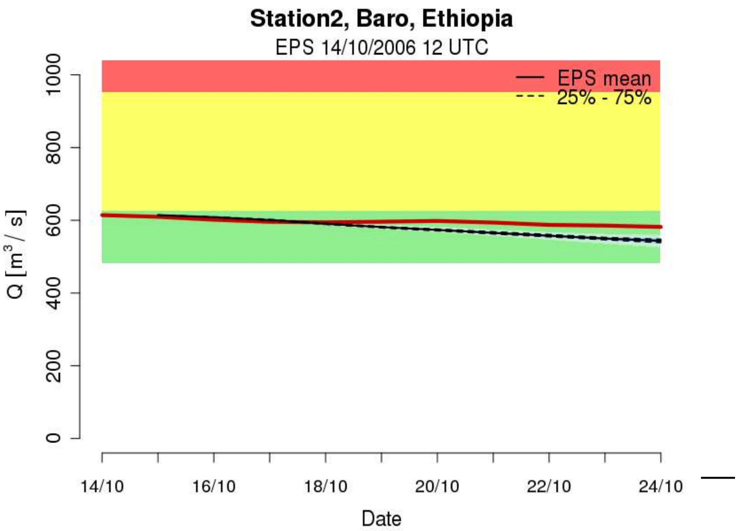
Hind cast graphs for the next 10 days showing 75% and 25% boundaries of ensemble members for precipitation from TRMM and ERA-interim for station 2 and 3 for the days 10/10/2006 to 15/10/2006)

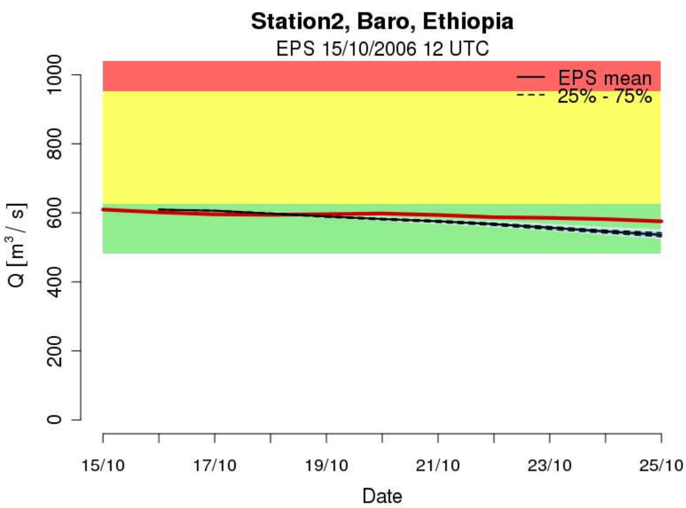


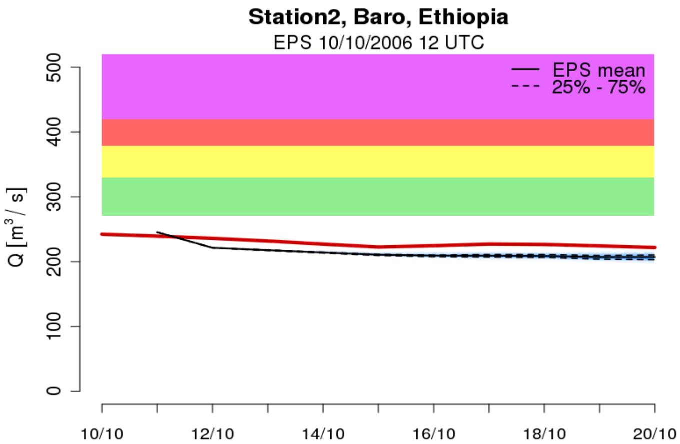


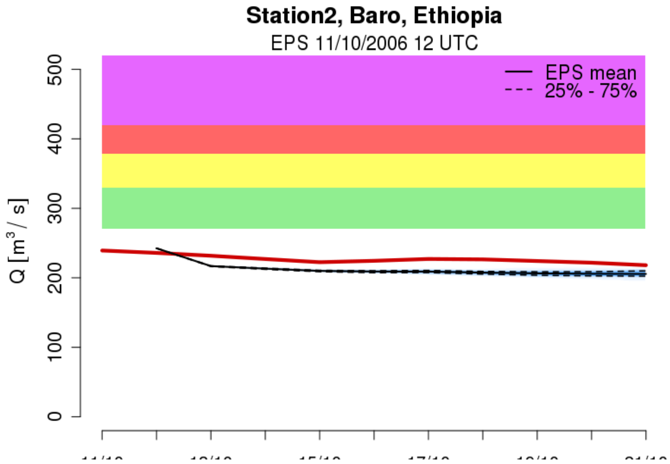


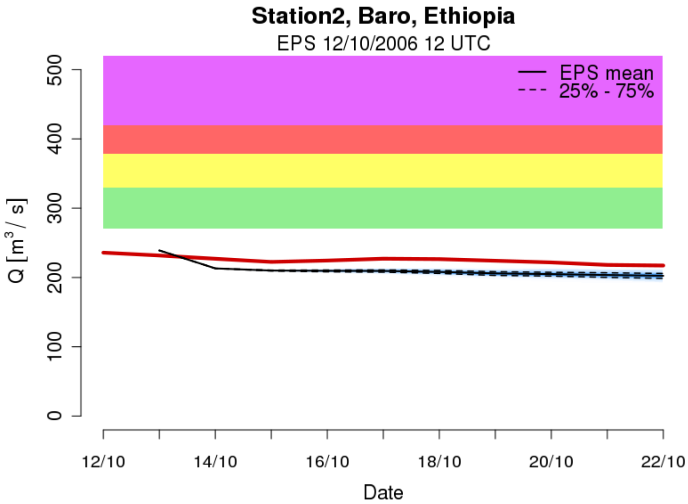


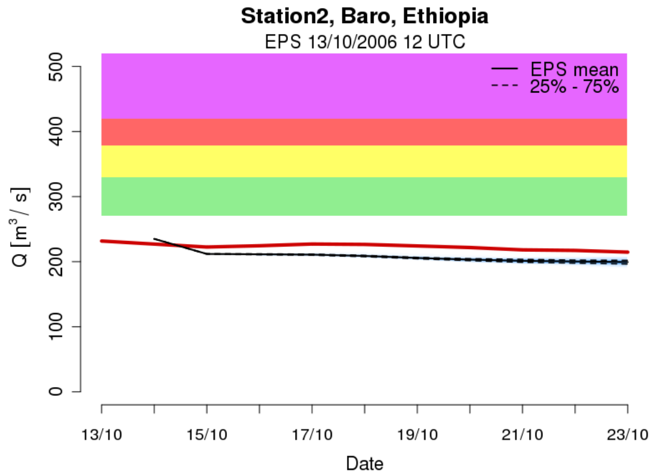


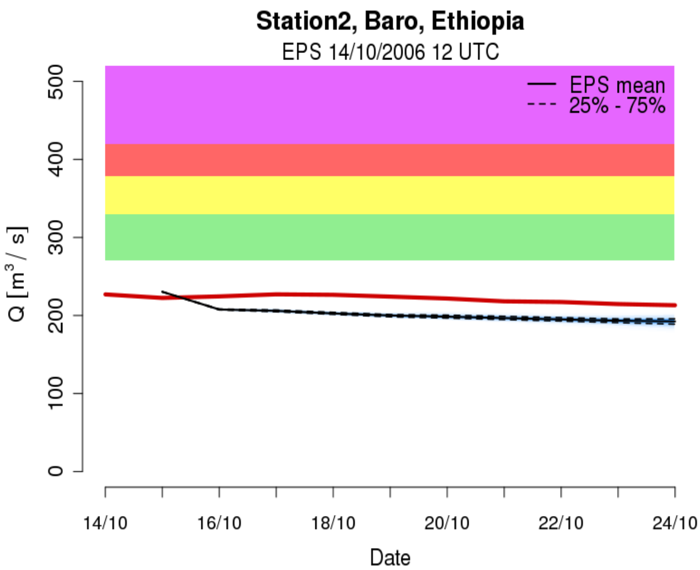


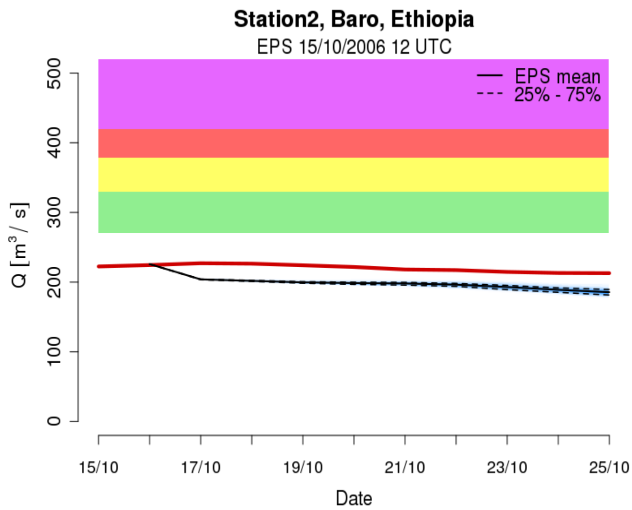

Station2, Baro, Ethiopia
EPS 10/10/2006 12 UTC
EPS mean
25% - 75%
Q [m³ / s]
0
100
200
300
400
500
10/10
12/10
14/10
16/10
18/10
20/10

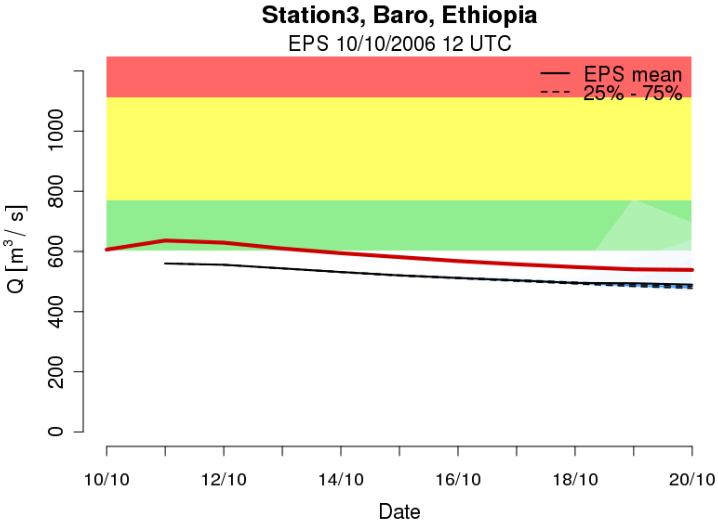

Station2, Baro, Ethiopia
EPS 11/10/2006 12 UTC
EPS mean
25% - 75%
Q [m³ / s]
0
100
200
300
400
500


Station2, Baro, Ethiopia
EPS 12/10/2006 12 UTC
EPS mean
25% - 75%
Q [m³ / s]
0
100
200
300
400
500
12/10
14/10
16/10
18/10
20/10
22/10
Date


Station2, Baro, Ethiopia
EPS 13/10/2006 12 UTC
EPS mean
25% - 75%
Q [m³ / s]
0
100
200
300
400
500
13/10
15/10
17/10
19/10
21/10
23/10
Date


Station2, Baro, Ethiopia
EPS 14/10/2006 12 UTC
EPS mean
25% - 75%
Q [m³ / s]
0
100
200
300
400
500
14/10
16/10
18/10
20/10
22/10
24/10
Date


Station2, Baro, Ethiopia
EPS 15/10/2006 12 UTC
EPS mean
25% - 75%
Q [m³ / s]
0
100
200
300
400
500
15/10
17/10
19/10
21/10
23/10
25/10
Date


Station3, Baro, Ethiopia
EPS 10/10/2006 12 UTC
EPS mean
25% - 75%
Q [m³ / s]
0
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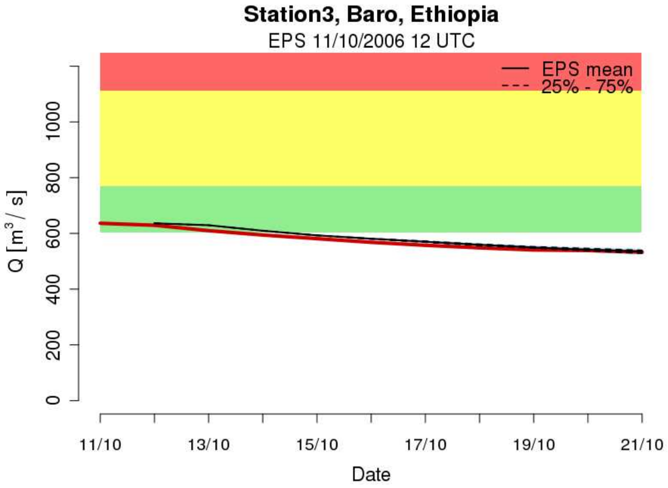
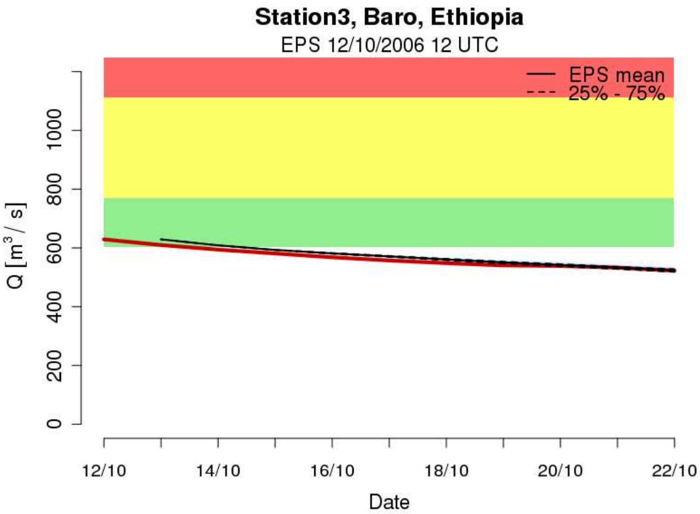
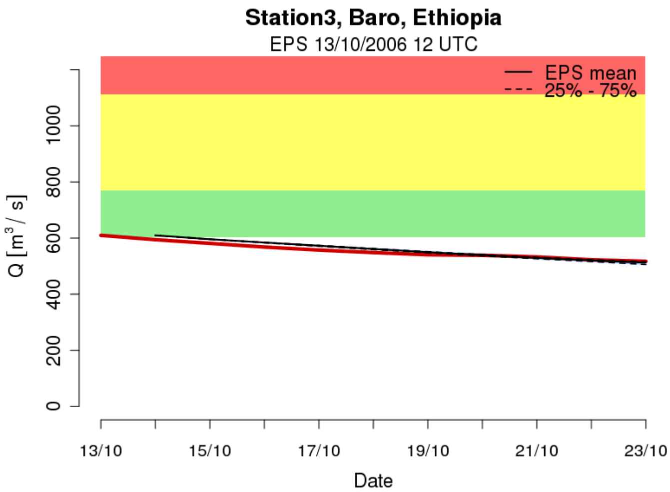
400
600
800
1000
10/10
12/10
14/10
16/10
18/10
20/10
Date


Station3, Baro, Ethiopia
EPS 11/10/2006 12 UTC
EPS mean
25% - 75%
Q [m³ / s]
0
200
400
600
800
1000
11/10
13/10
15/10
17/10
19/10
21/10
Date


Station3, Baro, Ethiopia
EPS 12/10/2006 12 UTC
EPS mean
25% - 75%
Q [m³ / s]
0
200
400
600
800
1000
12/10
14/10
16/10
18/10
20/10
22/10
Date


Station3, Baro, Ethiopia
EPS 13/10/2006 12 UTC
EPS mean
25% - 75%
Q [m³ / s]
0
200
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600
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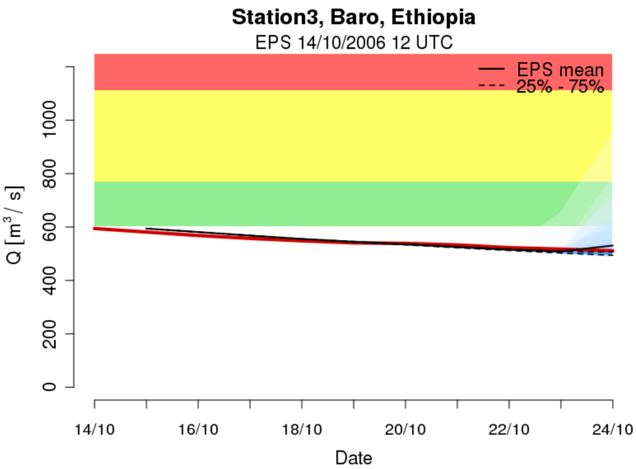
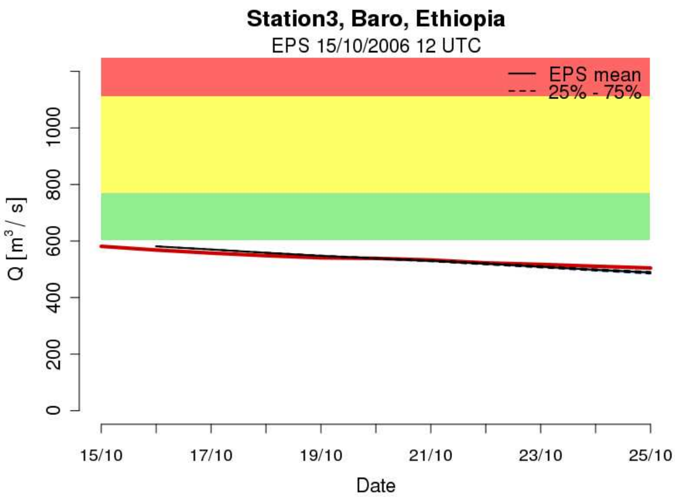
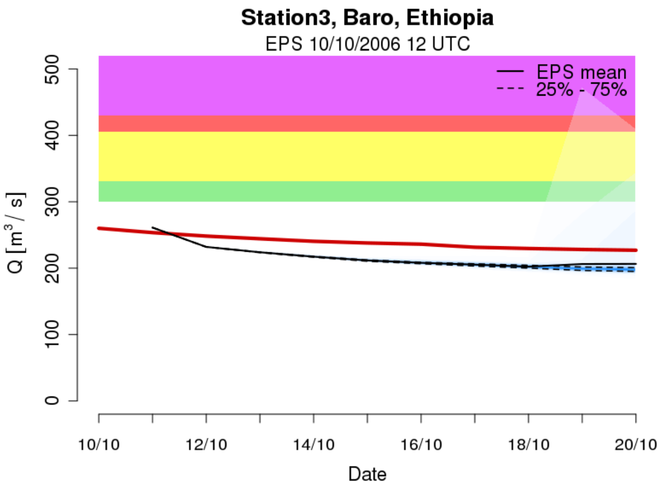
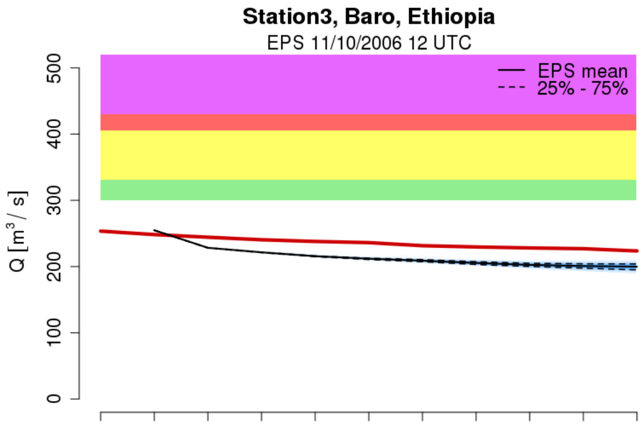
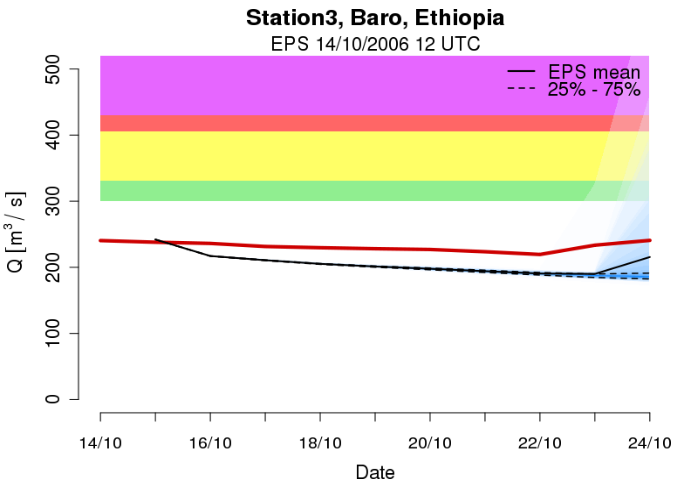
1000
13/10
15/10
17/10
19/10
21/10
23/10
Date

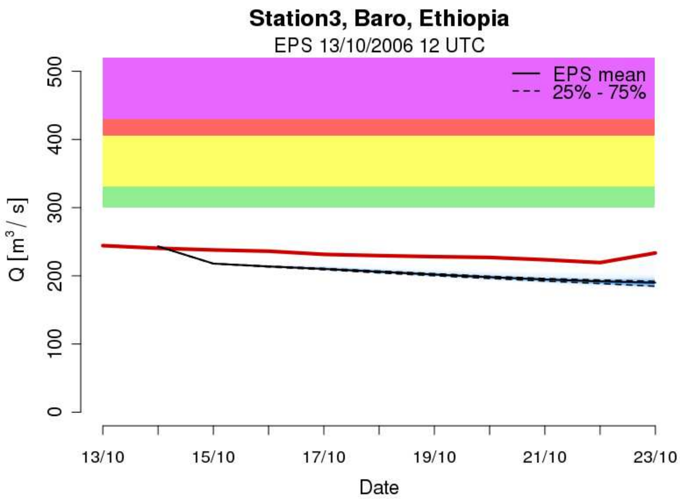

Station3, Baro, Ethiopia
EPS 14/10/2006 12 UTC
EPS mean
25% - 75%
Q [m³ / s]
0
200
400
600
800
1000
14/10
16/10
18/10
20/10
22/10
24/10
Date

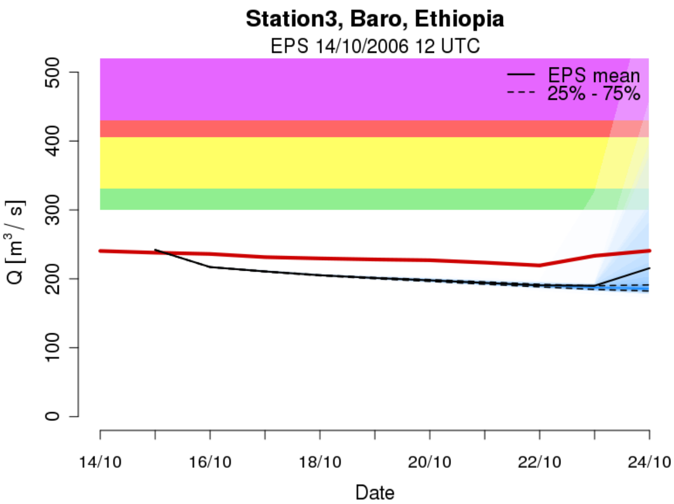

Station3, Baro, Ethiopia
EPS 15/10/2006 12 UTC
EPS mean
25% - 75%
Q [m³ / s]
0
200
400
600
800
1000
15/10
17/10
19/10
21/10
23/10
25/10
Date

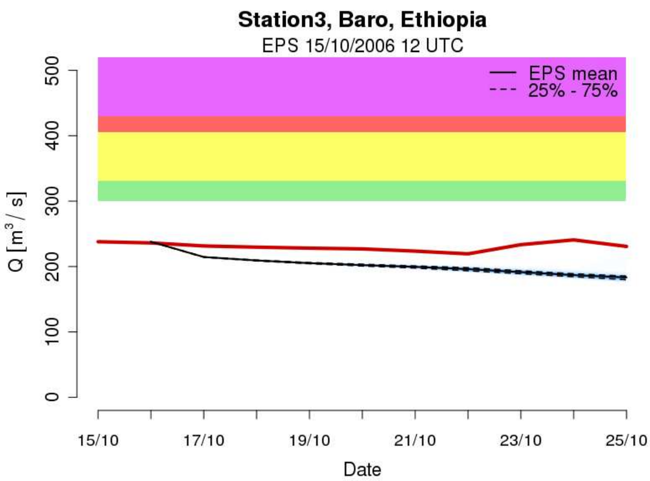

Station3, Baro, Ethiopia
EPS 10/10/2006 12 UTC
EPS mean
25% - 75%
Q [m³ / s]
0
100
200
300
400
500
10/10
12/10
14/10
16/10
18/10
20/10
Date


Station3, Baro, Ethiopia
EPS 11/10/2006 12 UTC
EPS mean
25% - 75%
Q [m³ / s]
0
100
200
300
400
500


Station3, Baro, Ethiopia
EPS 14/10/2006 12 UTC
EPS mean
25% - 75%
Q [m³ / s]
0
100
200
300
400
500
14/10
16/10
18/10
20/10
22/10
24/10
Date

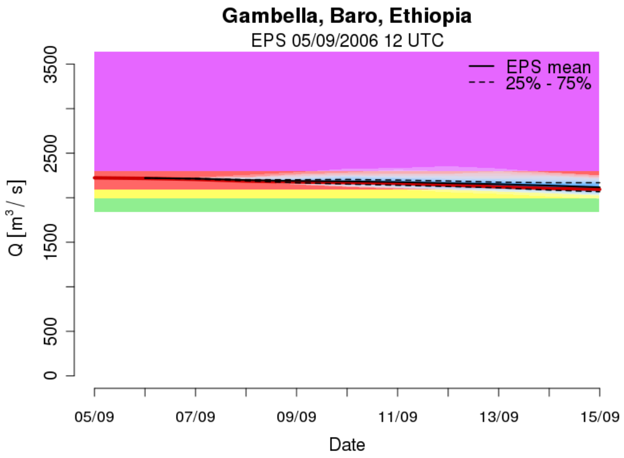

Station3, Baro, Ethiopia
EPS 13/10/2006 12 UTC
EPS mean
25% - 75%
Q [m³ / s]
0
100
200
300
400
500
13/10
15/10
17/10
19/10
21/10
23/10
Date

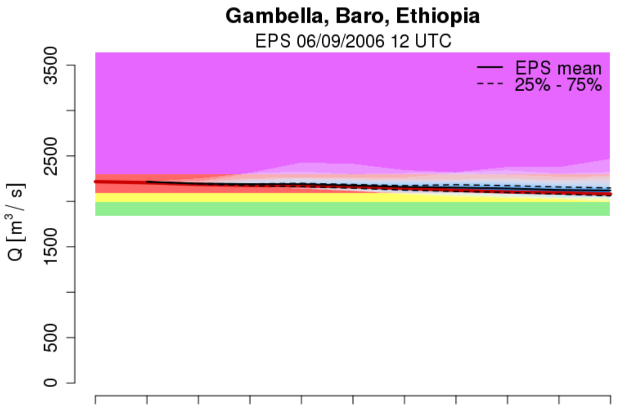

Station3, Baro, Ethiopia
EPS 14/10/2006 12 UTC
EPS mean
25% - 75%
Q [m³ / s]
0
100
200
300
400
500
14/10
16/10
18/10
20/10
22/10
24/10
Date

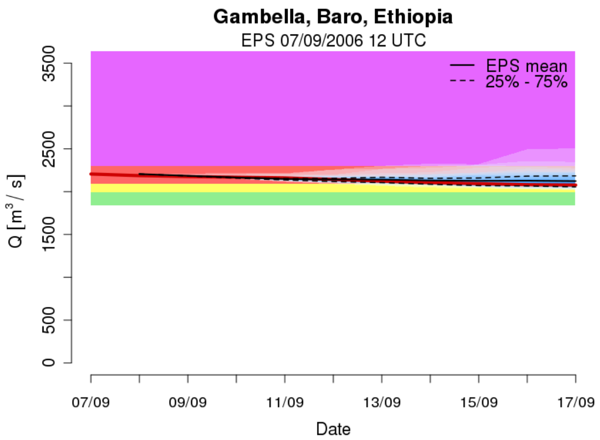

Station3, Baro, Ethiopia
EPS 15/10/2006 12 UTC
EPS mean
25% - 75%
Q [m³ / s]
0
100
200
300
400
500
15/10
17/10
19/10
21/10
23/10
25/10
Date

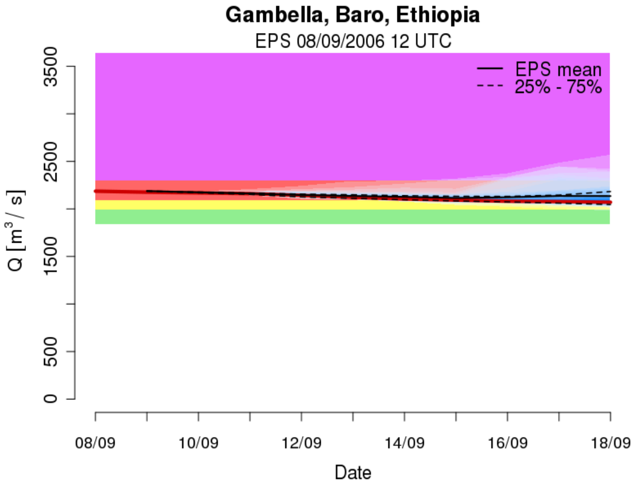
APPENDIX IV

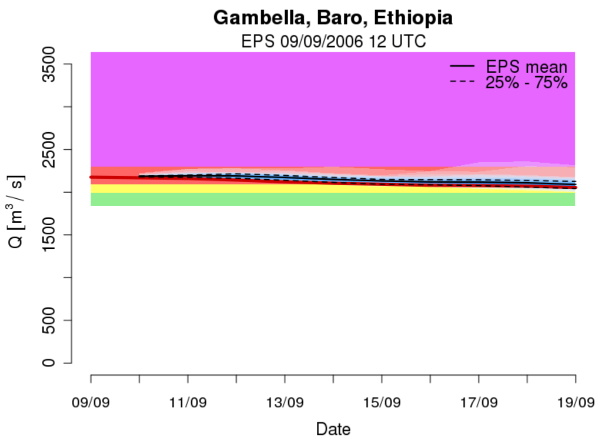
Test hind cast graphs for the next 10 days showing 75% and 25% boundaries of ensemble members for precipitation from ERA-interim for main outlet from time 05/09/2006 to 10/09/2006)

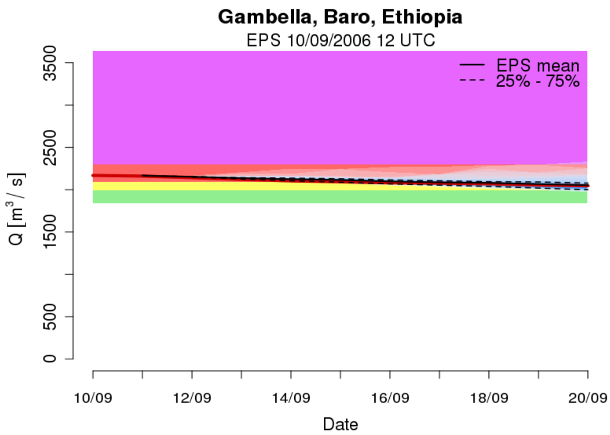






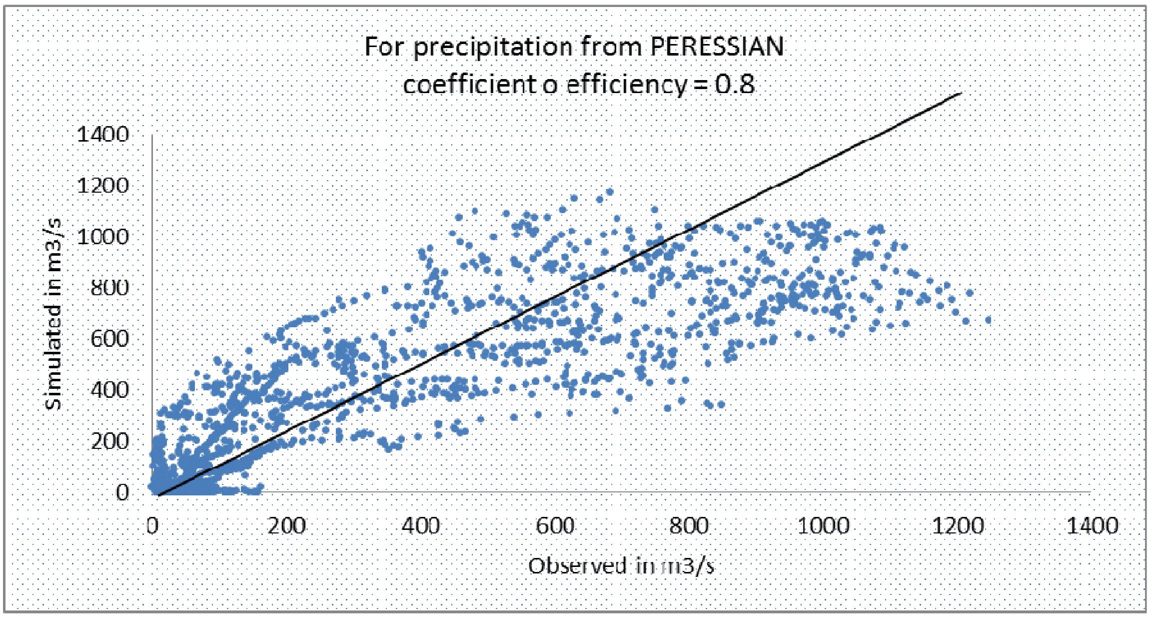


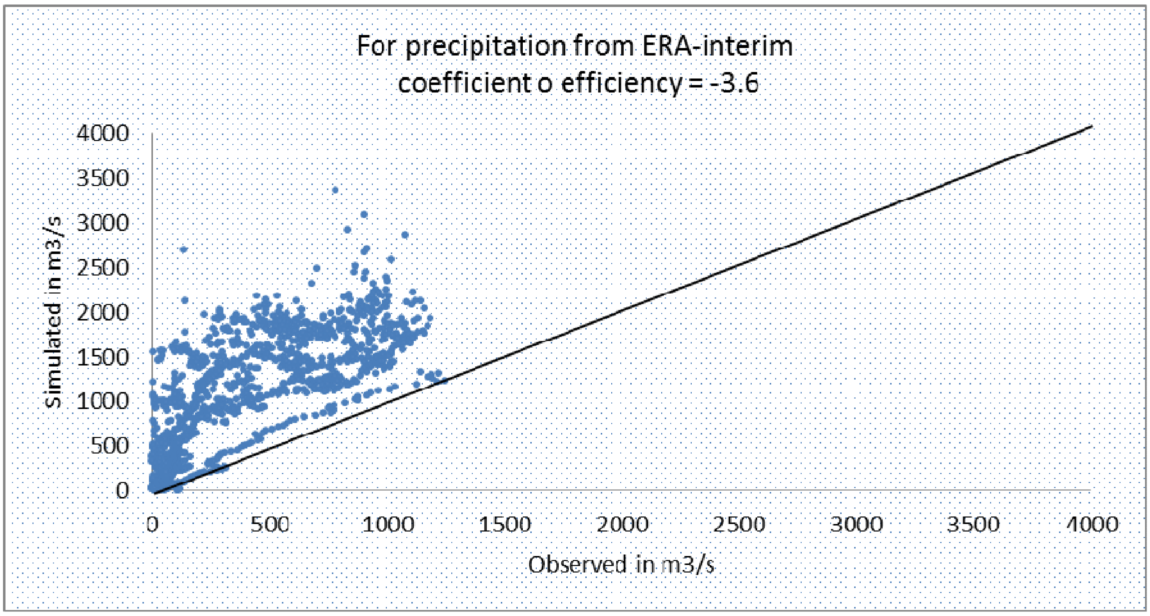


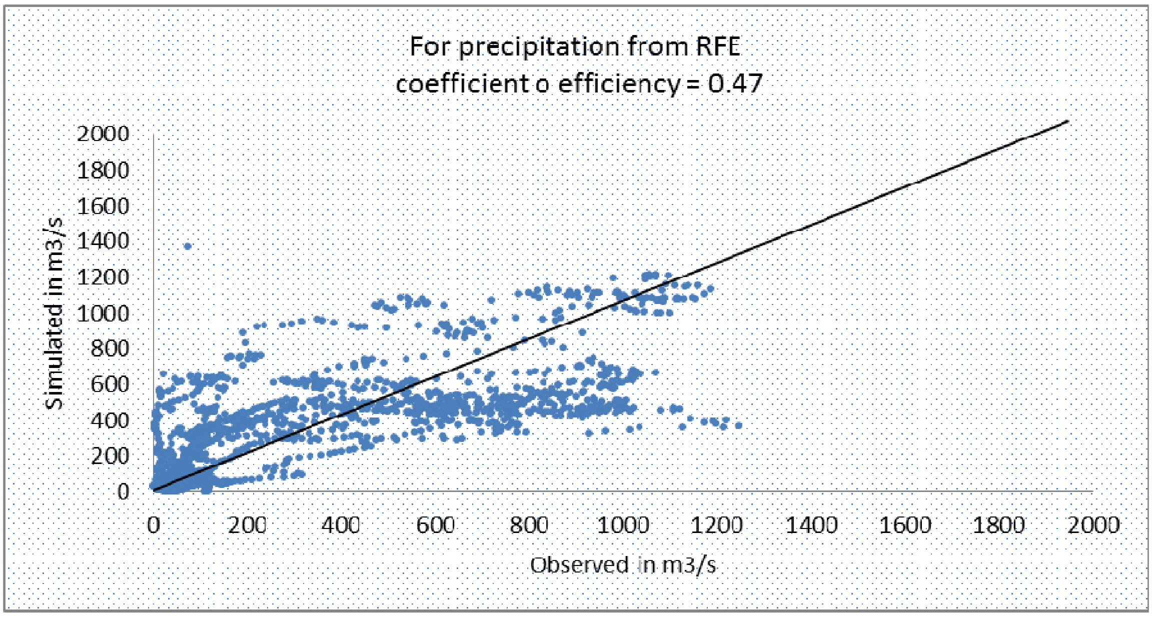


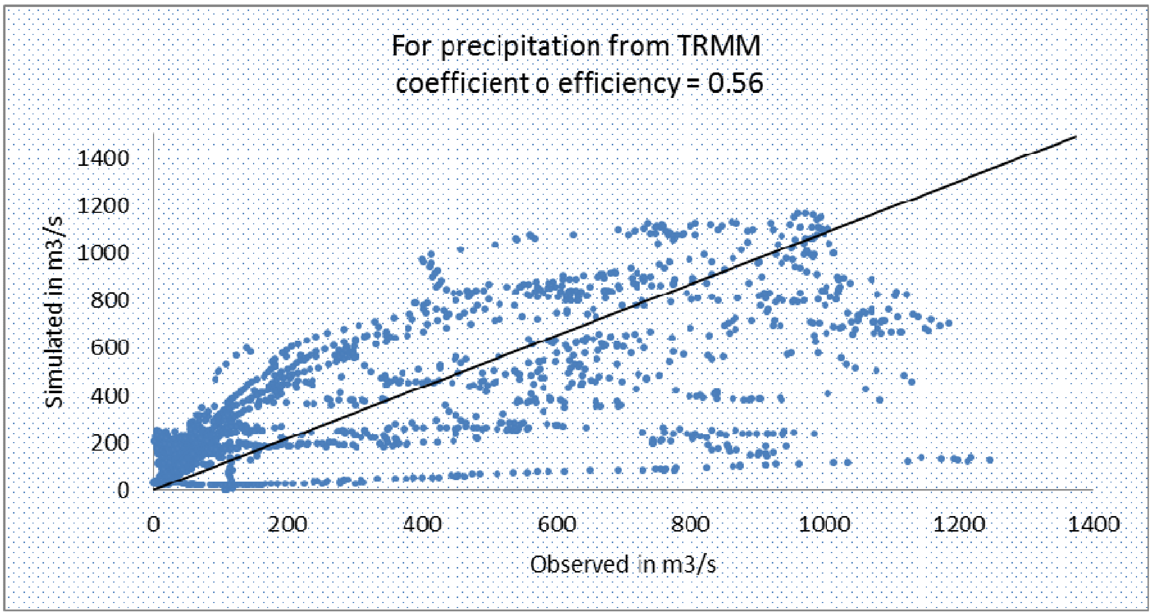
Appendix V

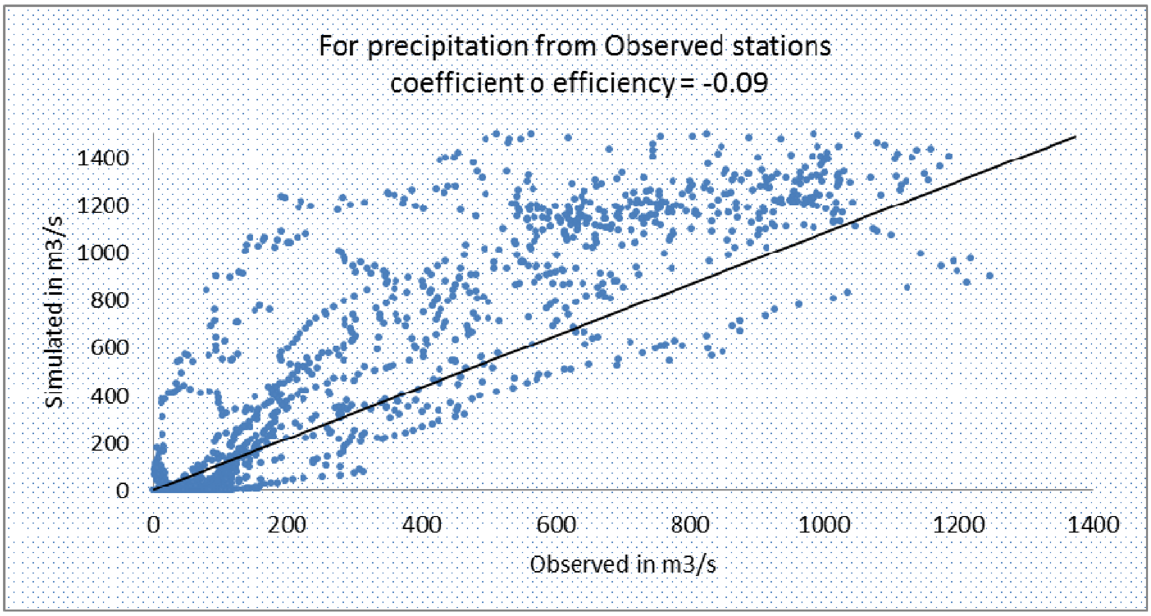
Observed vs simulated dotty plot for all precipitation data sources






For precipitation from RFE
coefficient o efficiency = 0.47
Simulated in m3/s
Observed in m3/s
0
200
400
600
800
1000
1200
1400
1600
1800
2000


For precipitation from TRMM
coefficient o efficiency = 0.56
Simulated in m3/s
Observed in m3/s
0
200
400
600
800
1000
1200
1400


For precipitation from Observed stations
coefficient o efficiency = -0.09
Simulated in m3/s
Observed in m3/s
0
200
400
600
800
1000
1200
1400

DECLARATION

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

Name: ________________________________

Signature: _____________________________