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Flood simulation using public domain data for a data scarce transboundary basin: the case of Gash River Basin, Horn of Africa

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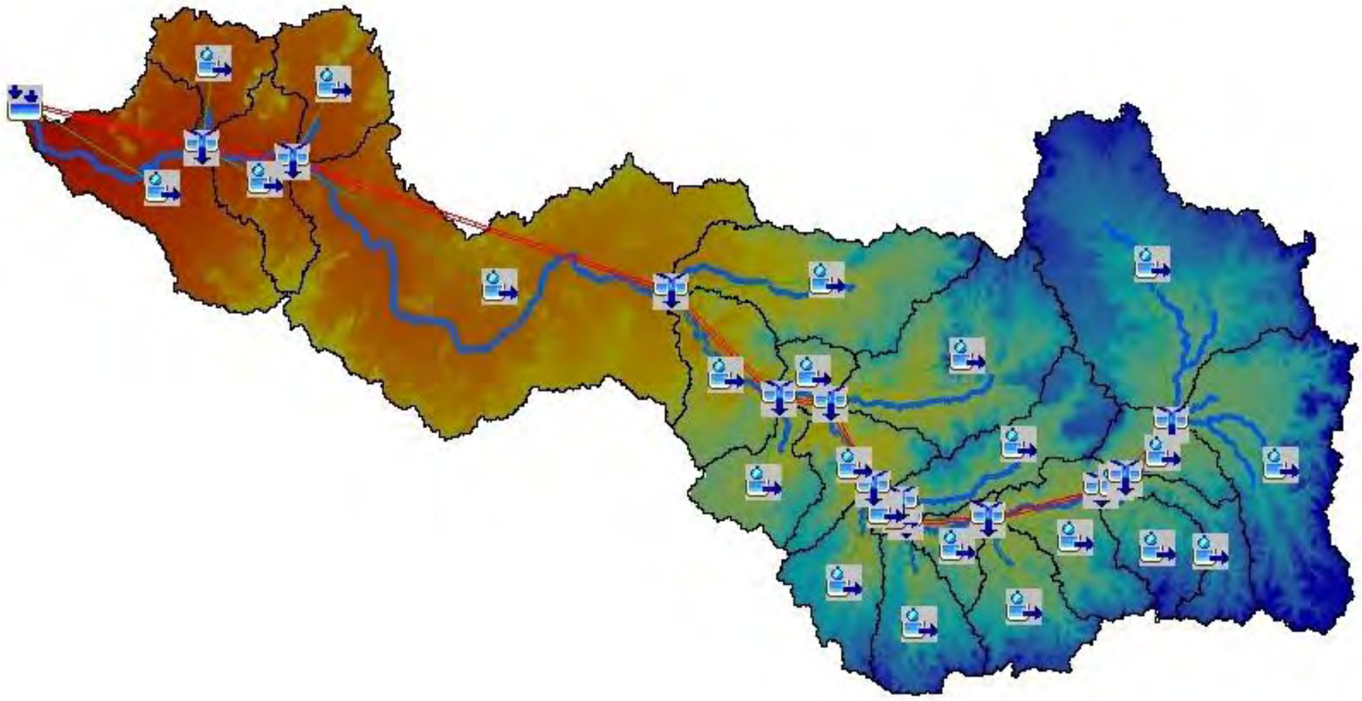
MSc Thesis WM-WRM. 14.19



Flood simulation using public domain data for a data scarce transboundary basin: the case of Gash River Basin, Horn of Africa

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This research is done for the partial fulfilment of requirements for the Master of Science degree at the UNESCO-IHE Institute for Water Education, Delft, the Netherlands

Delft
April 2014

Dedicated To

All the hydrologists, flood modellers, and water resource managers who work day and night under environmental uncertainty, political (management) pressure, limited resources, and peoples' expectation to save lives, and livelihood.

Abstract

This study was undertaken to investigate the possibility of developing a reliable rainfall-runoff model for flood forecasting using public domain datasets for the Gash River in eastern Sudan. The Gash is a transboundary river starts in Ethiopia, Eritrea and ends up in Sudan. Five satellite based rainfall estimates (SBRE) viz. TRMM, ECMWF, ARC-2, RFE-2 and TAMSAT were assessed to evaluate which rainfall product represents better the actual rainfall pattern and intensity of the basin. After evaluation based on performance measures such as the: Root Mean Square Error (RMSE), Mean Average Error (MAE) and Correlation coefficient (R^2), TRMM, ARC-2 and ECMWF were selected for rainfall-runoff simulations. Model simulations were carried out using HEC-HMS model. Among six years of available discharge data from 2007 to 2012, period of 2007 to 2010 was used for calibration with 2007 as warming up period whereas data from 2011-2012 were used for validation. In additional to continuous daily rainfall-runoff model development using HEC-HMS, an event based flood model was also developed which was used for flood modelling with 72 hours lead time. TRMM and ARC-2 rainfall data were taken as two cases of rainfall inputs for these simulations, based on their superior performance in the earlier analysis. Also simulations based on daily TRMM versus 3-hourly TRMM were compared to evaluate effect of input time-step on the results.

The study shows that SBRE products provide important insights of the rainfall pattern in this data scarce region of Gash River Basin, both in terms of spatial and temporal resolutions. However, the results indicate better correspondence between observed rain gauge data and SBRE at longer time step such as monthly, while daily time step shows poor correspondence. However, the availability of only one rain gauge data for the whole Gash basin remains a limiting factor for making general conclusions. The SBRE based rainfall-runoff model (HEC-HMS) could not simulate the time series of flows, in particular daily peak discharges, with desired level of accuracy. This may limit potential use of these data for flood forecasting before accuracy can be improved further. Nevertheless, the model could be useful in computation of monthly or longer time scale rainfall-runoff process and estimation of water balance components which could helpful to guide water management practice in the basin. However, the event based HEC-HMS model developed using SBRE data with shorter time steps (3-hourly) showed good capability to simulate daily peak discharges. It is expected that accuracy of the forecast could be improved with further enhancement of SBRE against ground measurements.

Key Words: Flood, Forecast, satellite based rainfall estimates, hydrological modelling, HEC-HMS

Acknowledgements

This research has been possible because of the support of so many people personally and professionally. I would like to extend my sincere gratitude to everyone who contributed to this research in many different ways: by sharing their experience, thoughts and opinions on the research, and by contributing time, advice and hospitality. I would like to thank Netherlands Fellowship Programme for sponsoring my academic and living costs for this Masters Degree, and Hydraulic Research Centre, Sudan for travel allowance during the field work.

I am enormously indebted to my mentors, Dr Yasir A. Mohamed and Dr Ilyas Masih for trusting me with this research, and providing unwavering support, enthusiastic encouragement and constructive advices throughout the entire research period. This research would not have been possible without their active contribution. I am also particularly grateful to Professor Pieter van der Zaag for his motivation and valuable feedback.

I also really appreciate the advice and assistance of Dr Biswa Bhattacharya, Dr Schalk Jan van Andel and Dr Shreedhar Maskey who provided valuable guidance with HEC-HMS and satellite data processing. Ms Patricia Trambauer Arechavaleta deserves a huge thank for helping me with ECMWF data processing. I would also like to remember the kind assistance provided by the staff members from Gash River Training Unit, Kassala and Hydraulic Research Centre, Wad Medani during the field work.

I would also like to express my sincere gratitude to Mr Giriraj Amarnath from IWMI for providing HEC-HMS model, necessary datasets and valuable feedback. His resource and advice saved lot of time as well as help in understanding the modelling better. Special thank goes to Dr Hatim Sharif from University of Texas for his valuable feedback to my research proposal, and helping me to be more precise with my research objectives and methodology.

I am also very thankful to friends and colleagues at UNESCO-IHE, particularly Krishna Upadhyay, Bishnu Gurung, Manisha Shakya, Mjawa Shenduli, Zaza Dashniani, Marilou Baino-Salingay, Akewaq Gobosho, Temesgen Alem, and Maria Clemens who helped in different ways, and created the homely environment making life easier in the Netherlands.

Finally, I would like to thank my beloved mother Subhadra Rokaya and girlfriend Sujata Budhathoki for their love, support and patience which provided me strength and encouragement during my study.

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Abbreviations

amsl	above mean sea level
CMAP	CPC Merged Analysis of Precipitation
ECMWF	European Centre for Medium-Range Weather Forecast
EPS	European Prediction System
ET	Evapotranspiration
FEWS-NET	Famine Early Warning Systems Network
HEC-HMS	Hydrological Engineering Center-Hydrologic Modeling System
IWMI	International Water Management Institute
MAE	Mean Absolute Error
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NSE	Nash-Sutcliffe Efficiency
PVE	Percent Volume Error
RMSE	Root mean square error
R^2	Coefficient of determination
SCS	Soil Conservation Service
SMA	Soil Moisture Accounting
SBRE	Satellite based rainfall estimate
TRMM	Tropical Rainfall Measuring Mission
CMORPH	Climate Prediction Centre Morphing Technique
TAMSAT	Tropical Applications of Meteorology using SATellite data & ground-based observations
USACE	United States Army Corps of Engineers

CHAPTER 1

Introduction

The Introduction Chapter briefly describes the overview of this research. It discusses on study area, explain research problem and states research objectives and questions.

1.1. Background

Runoff prediction and river flow forecast are important hydrological studies for water resource development, planning and management among other uses. Rainfall-runoff models, which aim at simulating the catchment response and flow hydrograph, are extensively used to support flood forecasting (Nayak et al., 2013) and water resources planning (Laurent et al., 1998). The need for predicting runoff from specific catchment remains large, especially in densely populated and flood-prone areas (Cabus, 2008) such as Gash River basin in Eastern Africa (Bashar et al., 2005). Its hilly and mountainous catchment with high rainfall intensity and relatively sparse vegetation cover makes Gash more prone to flooding (Wheater et al., 2007).

A flood forecasting and early warning systems are very important tools for managing floods and lessening damages (Burlando et al., 1993). Timely forecast provides authorities sufficient time to make informed decisions (Werner et al., 2013) and evacuate people to safer places (Akhtar, 2006) whereas inaccurate and late forecasts will just waste the efforts of management (M. G. Anderson & Burt, 1985).

The simple and commonly used practice is to record the real time rainfall data using rain gauges, and then apply the measured rainfall for discharge forecast at the point of interest using a rainfall-runoff model (Burlando et al., 1993). However, for small catchments with small hydrological response time, flood forecasting with real time rainfall data is not enough for disseminating the flood warnings at required lead time, to take necessary measures. In such cases, the use of the forecasted rainfall, instead of measured rainfall, in the rainfall-runoff model provides additional lead time for early warning (Maharjan, 2013).

A typical flood forecasting procedure predicts runoff using rainfall data and other relevant hydro-meteorological parameters using rainfall-runoff models (Fotopoulos et al., 2010). Rainfall being the major driver of any hydrological models, its quality and quantity play a key role in the model performance (Bhattarai, 2013). However, in many situations, the river catchments are located across country borders. Competing interests make sharing data among nations more difficult (Thinh, 2010). Often data sharing protocols are not adequately in place, and rainfall-runoff computation become difficult with ground station data. Furthermore, the networks of ground-based hydro-meteorological observations are sparse in developing countries. Part of the reason is the inadequate resources available in countries which have more pressing economic and social issues. Conversely, these are also the countries where improved estimates of water resource availability are required (Hughes, 2006).

Remote sensing (RS) can potentially close some of the gaps in data availability (Stisen et al., 2008). Satellite-based rainfall monitoring is widely used because of its increasing global coverage. It has great importance for operational purposes in data scare regions such as Africa. It also has potential benefits such as input to hydrological models because of their real time availability, low cost and good spatial coverage (Teo & Grimes, 2007). Radar has also played an increasingly important role in technologically developed countries, particularly with regard to provision of data in real time (Grimes et al., 1999).

However, selecting appropriate precipitation data set for hydrological modelling is quite challenging. Users often face dilemma in selecting an appropriate model among large pool of models or even a suitable method to represent a particular process within one hydrologic model. And these types of studies are relatively limited in developing nations (Verma et al., 2010).

Most river flood forecasts are carried out using a two-step process. First, hydrological models are used to study rainfall-runoff process. Then hydraulic models are used to convert resulting flood hydrographs to water level forecasts (Hicks & Peacock, 2005). This research is limited to only the first step of rainfall-runoff modelling. The second phase of flow (hydraulic) routing of flood wave is recommended for the future research in the Gash basin.

1.2. Problem Definition

Figure 1.1 The Gash River Basin in Eastern Africa

A detailed review of different studies and reports suggests three major issues in the Gash basin. The first and the most prominent one is frequent flooding. In the last three decades, several devastating floods were recorded in the years 1975, 1983, 1988, 1993, 1998, 2003 and 2007. The most damaging one occurred in year 2003, where almost half the Kassala city was washed out affecting approximately 60-70% of the city's population (OCHA, 2003). The total loss is estimated to amount to US$ 150 Million (Artan et al., 2007). Another big flood event in 2007 took lives of 20 people and damaged 16300 houses affecting more than 20,000 people (IFRC, 2007).

The second issue is inconsistent data on the Gash basin. Some research argues that the river originates only from Eritrea (Hamid & Malla, 1930; Elsheikh et al., 2009) whereas others claim it originates from Eritrean-Ethiopian high lands (Artan et al., 2007). Similarly different scholars have indicated different precipitation range in Gash, i.e. 50-200 mm (Hielkema et al., 1986) and 340 mm (Elsheikh et al., 2009). Hence, there is no consistency on data and information on the Gash basin.

Finally, the third issue in the Gash basin is the trans-boundary nature of the river, and the absence of data sharing mechanism. Most of the river catchment lies in Eritrea but there is no data sharing protocols which makes rainfall-runoff computation impossible from ground stations. In the context of competing interests, sharing data among nations becomes even more difficult (Thinh, 2010).

1.3. Research objectives

Considering the major issues discussed above, it is very important to develop a proper flood forecasting system for early warning that can help save lives and livelihood of people. Hence, the main objective of this research is to study the possibility of developing a reliable rainfall-runoff model for flood forecasting using public domain datasets in the Gash River.

Therefore, the specific objectives of this research are to:

- Test different options of public domain climate datasets (rainfall, temperature, etc.) as input conditions for accurate rainfall-runoff modelling.
- Develop a flood forecasting model using remote sensing and ground data
- Study the possibility to increase the flood forecast lead time through the use of forecasted rainfall data.

1.4. Research Question

Based on the research objectives stated above, the following research questions have been formulated:

- Which freely available satellite precipitation data source is more reliable, accurate and valid compared to ground measurement for the Gash River Basin?
- How reliable and accurate is HEC-HMS for flood model and/or rainfall-runoff using remote sensing and ground data in the Gash basin?
- How much lead time can be increased using forecasted rainfall data, and how reliable are those forecasts?

1.5. Structure of the thesis

Chapter two discusses on the research area, the Gash river basin. It mainly focuses on its location and topography, and climate and hydrology. A literature review on previous studies in the Gash basin is also included.

Chapter three reviews different SBRE products used in this study as well as on rainfall-runoff models including HEC-HMS, and flood forecasting.

Chapter four discusses materials and methods used in this study. It describes rainfall data acquisition, SBRE data processing, hydrological model set up, model simulation, and model performance.

Chapter five discusses on validation of different SBRE products with ground based rainfall measurement at different time scale as well generation of rainfall maps of the Gash basin.

Chapter six focuses on rainfall-runoff modelling using TRMM and ARC-2. Statistical performance measures such as NSE, PVE and R^2 are used to evaluate the performance of the model. This chapter also discusses runoff generation at different time steps such as daily and monthly.

Chapter seven discusses flood simulation using different rainfall products for three different events in 2011, 2010 and 2009. An evaluation on difference on time of peak and peak discharge is carried out with respect to actual discharge measurement. This chapter also include a comparison between rainfall inputs using daily TRMM and 3-hourly TRMM along with peak time and discharge evaluation.

Chapter eight discusses the conclusions derived on the basis of the whole study. It also consists of the recommendations for further study based on the results and limitations encountered.

CHAPTER 2

Research Area – The Gash River Basin

This Chapter discusses on the Gash river basin. It mainly focuses on its location and topography, and climate and hydrology. A literature review on previous studies in the Gash basin is also included.

2.1. Location and Topography

The Gash River basin is a trans-boundary basin shared among Ethiopia, Eritrea, and Sudan. The river originates from the Eritrean and Ethiopian highlands in an area characterized by steep slopes. The upper course of the river in Eritrea is known as the Mareb River (Artan et al., 2007). Historically, the basin used to be part of the Nile River System. However, tectonic activities, sedimentation and other morphological developments have dramatically changed the course of the river (Elsheikh et al., 2009).

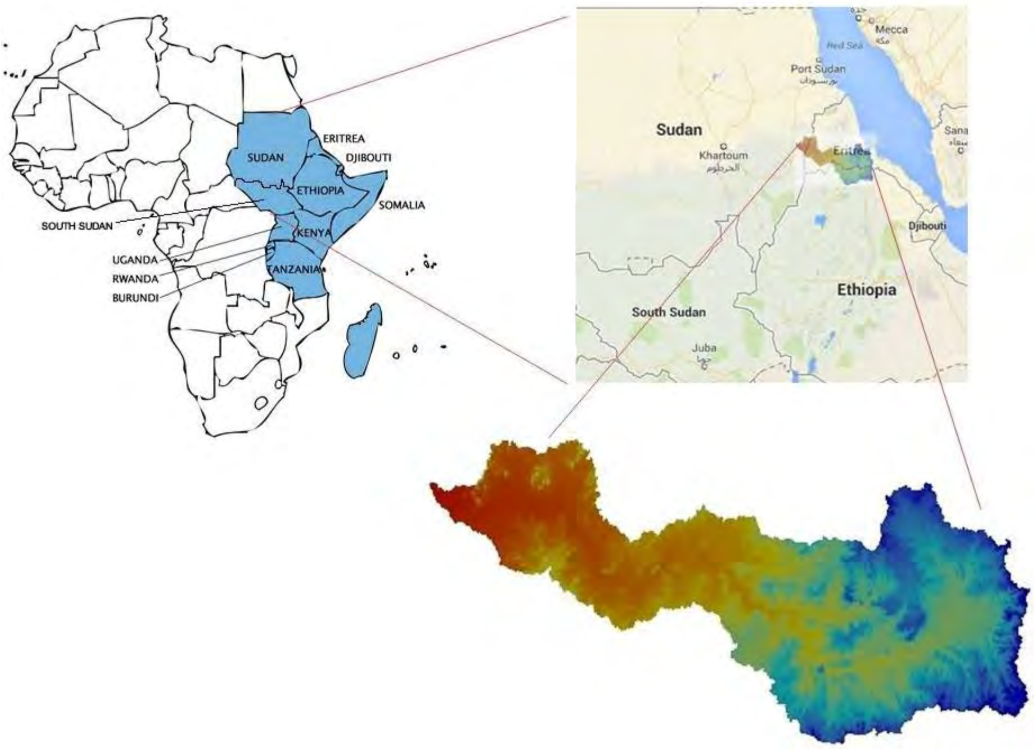

Figure 2.1 The Gash River Basin in Eastern Africa

The Gash River basin is located at 36°20′−39°50′E and 14°07′−15°47′N with a total catchment area of 21,000 km^2 (Figure 2.1).The length of the river is 280 km (Elsheikh et al., 2009) with an average slope of 200 cm/km. The course of river is varied with catchment width varying from 30 meters to 90 meters (Alredaisy, 2011). The average annual discharge is 1,056 Mm^3 at El-Gira, upstream gage station and 587 Mm^3 at Salam-Alikum, downstream gage station (Elsheikh et al., 2009).

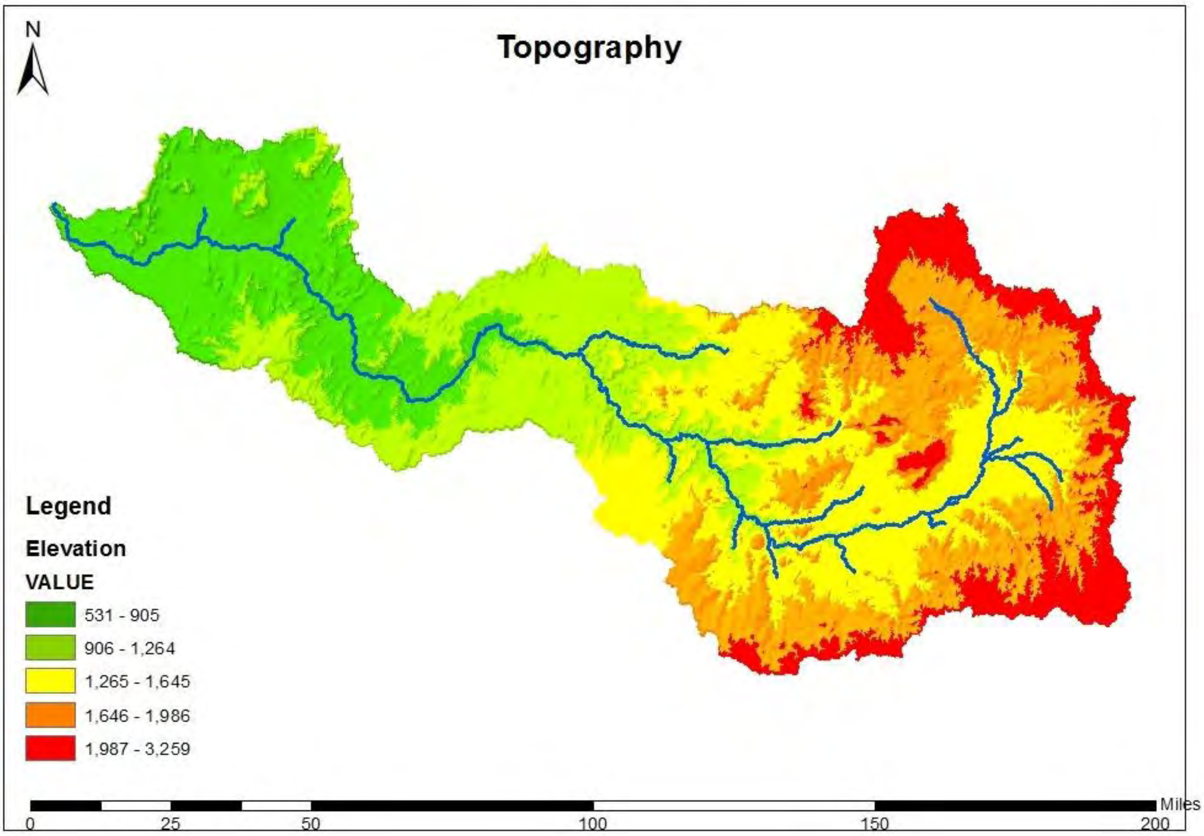

Figure 2.2 Elevation map of the Gash basin (in meters)

The digital elevation map (Figure 2.2) shows that the topography of the basin varies from 531 meters above mean sea level to 3259 meters above mean sea level. The part of river in Sudan falls in lower elevation zone whereas the origin of river in Ethiopia and Eritrea are highlands with higher altitudes.

2.2. Climate and Hydrology

The Gash basin is characterized by semiarid climate. Two main seasons can be distinguished, i.e. winter season that starts from November to March, and hot and dusty summer season that starts from April to October. The winters have average temperate of 25°C whereas in summer, temperature exceeds 45°C. The average rainfall in the basin is 350 mm which starts in July and lasts till September (Elsheikh et al., 2009).

The discharge data were collected from Gash River Training Unit, Kassala and Hydraulic Research Centre, Wad Medani for the years 2002 to 2012 for the station El-gira. The figure 2.3 shows the location of the discharge station.

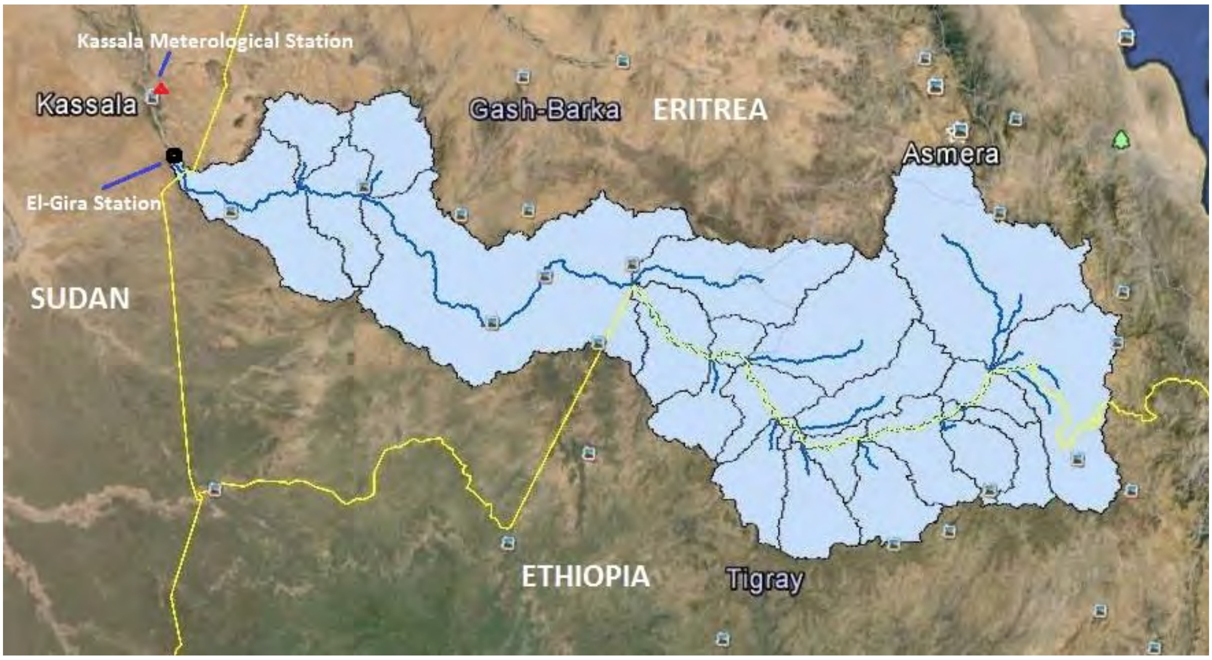

Figure 2.3 El-gira station in the Gash River in google map

The discharge data for the year 2004 was not available. The rest of the data shows that the annual average discharge is around 860.95 Mm^3. Though comparatively higher discharges are observed in years 2003, 2005 and 2006, the latter years show more or less consistent flow hydrology of the Gash.

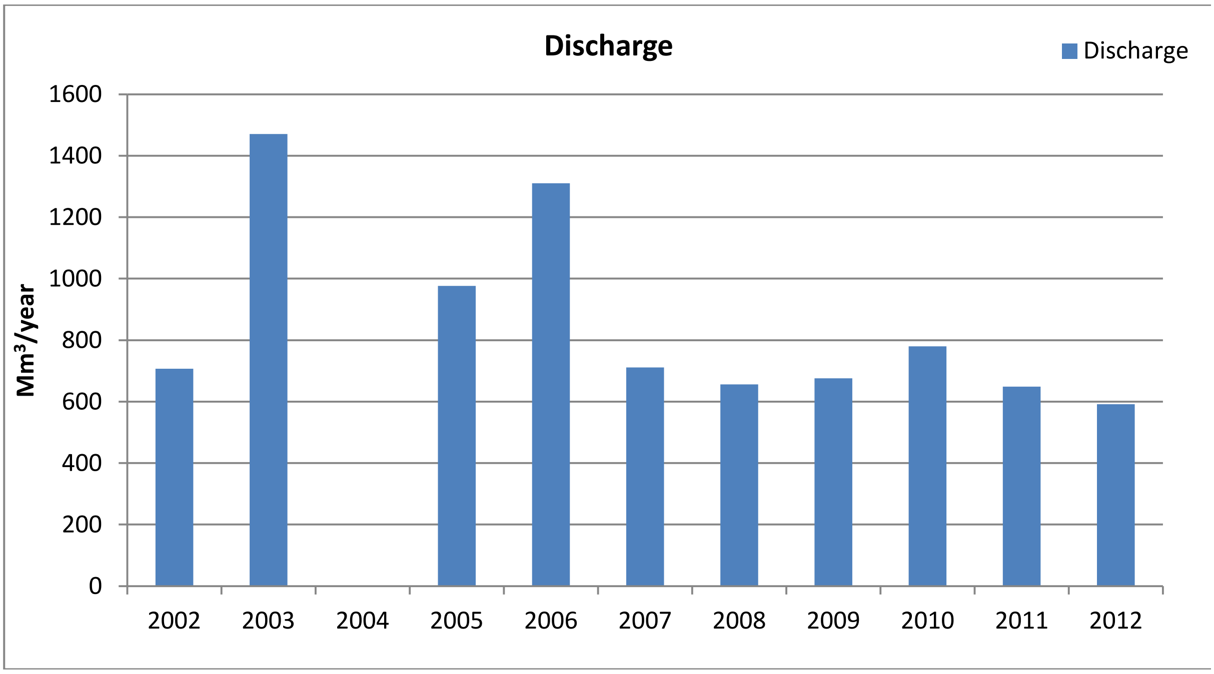

Figure 2.4 Annual discharge in Gash as measured in El-gira

The average monthly discharge for the last ten year shows that the major runoff in the river is only in four months of rainy season, i.e. June, July, August and September. The figure 2.5 also shows that August is the month with highest runoff.

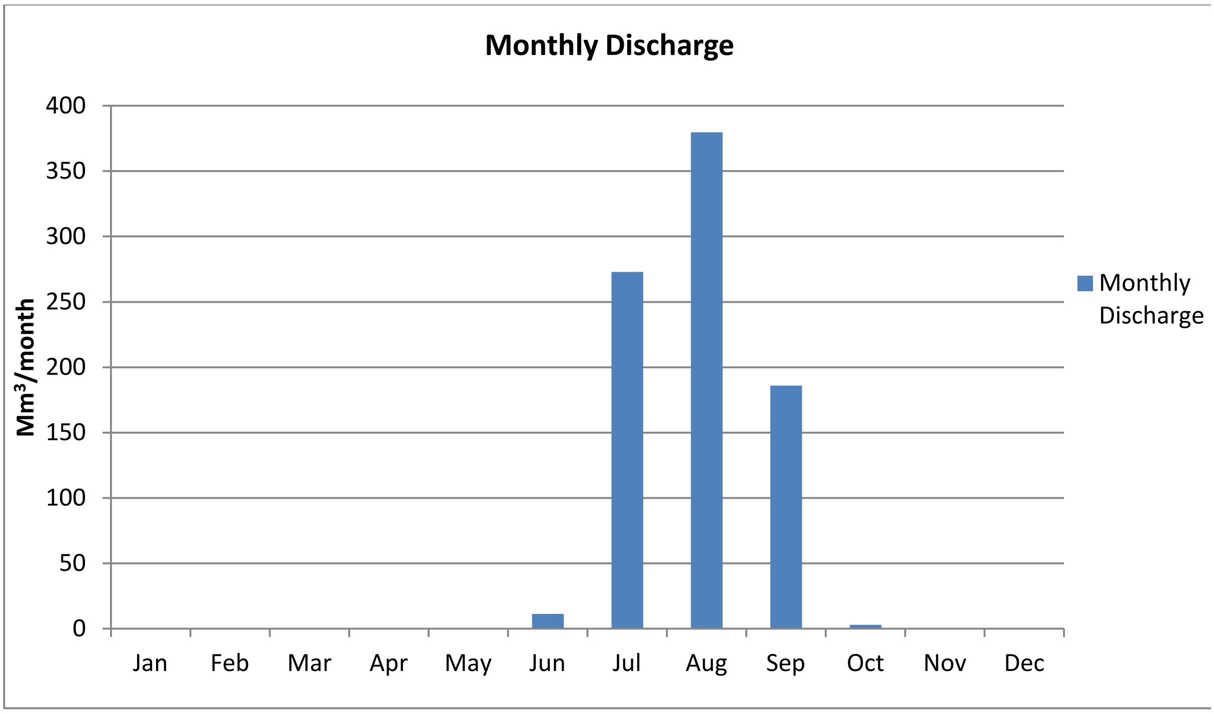

Figure 2.5 Average Monthly discharge in Gash as measure in El-gira from 2002-2012

2.3. Other Studies in the Gash Basin

Several studies have been undertaken at the gash basin on its different aspects. Most of them are focused on groundwater. Elkrail and Ibrahim (2008) carried out groundwater modelling determining water permeability zones, and identifying water storage sites. They also calculated abstraction rate. Another study was performed on groundwater budget by Elsheikh et al. (2009) also identified groundwater storage capacity at different locations and also calculated extraction rate. Different geomorphologic characteristics from source to delta with high rainfall variability between catchment and basin was found during a study of catastrophic impact of the Gash River (Alredaisy, 2011). Similarly, a study on Evolution of the gash river was performed which attempted in explain the morphological river course change (Elsheikh et al., 2009).

A study on adequacy of satellite derived rainfall data for stream flow modelling was also carried out (Artan et al., 2007). This study carried out in four basins including the Gash basin investigated the usefulness and uncertainty of SBRE of Famine Early Warning Systems Network (FEWS-NET) for hydrologic modelling. When SBRE and gauge estimated basin-wide mean area rainfalls were compared, authors found a very weak correlation at daily scale but excellent match at monthly scale. This suggested the usefulness of SBRE for monthly and longer time scales rainfall-runoff computation. Authors also concluded that SBRE data are only useful if hydrologic model is calibrated with such data but not rain gauge measured rainfall unless the model is recalibrated.

CHAPTER 3

Literature Review

Chapter two reviews different SBRE products used in this study as well as on rainfall-runoff models including HEC-HMS, and flood forecasting.

3.1. Satellite precipitation data sets

Rainfall inputs are increasingly available in a spatially distributed fashion. This is significant since the location of rainfall relative to the runoff contributing areas is crucial for making accurate forecasts (Blöschl et al., 2008). There are several SBRE ranging from near real time to monthly averages for different spatial resolutions. A main advantage of these products is that they overcome data shortages due to low density of installed rain gauges (Syed et al., 2004), incompatibilities in equipment and measurement methodology, and most importantly discontinuities and lack of immediate access to data due to political boundaries that divide trans-boundary catchments (Hossain et al., 2007). Table 3.1 shows list of SBRE used in this study.

Table 3-1: List of satellite based rainfall products used in this study

SN	Type of SBRE	Availability	Resolution		Period of Record	Source
			Spatial (lat/lon)	Temporal		
1	TRMM (3B42)	50S to 50N	0.25°	3 hrs	Jan 1998 - Jul 2008	(Huffman et al., 2007)
2	FEWS-NET RFE-2	Africa	0.1°	daily	Jan 2001 to present	http://www.cpc.ncep.noaa.gov/products/fews/RFE2.0_desc.shtml
3	FEWS-NET ARC-2	Africa (20.0W-55.0E & 40.0S-40.0N)	0.1°	daily	Jan 1995-Present	(Novella & Thiaw, 2012)
4	TAMSAT	Africa	0.0375°	10 days	1983 - present	(Grimes et al., 1999)
5	ECMWF	89.5S- 89.5N, 0E - 359.3E	0.125°	Daily	1 August 1979 – Present	http://www.esrl.noaa.gov/psd/data/gridded/data.erainterim.html

3.1.1. Tropical Rainfall Measuring Mission

The Tropical Rainfall Measuring Mission (TRMM) is a joint mission between National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency designed to measure rainfall for weather and climate research. It has been designed in a way to improve understanding on precipitation distribution and variability within the tropics. It was first launch on 27th November, 1997 and has been sharing data since 1st January, 1998 (http://pmm.nasa.gov/TRMM). It is intended to provide a best estimate of quasi-global precipitation. Estimates are provided at relatively fine scales (0.25° × 0.25°, 3-h) in both real and post-real time to accommodate a wide range of researches (Huffman et al., 2007). TRMM has been widely used in different parts of world ensuing different results. Some researches (Thinh, 2010; Collischonn et al., 2008) have found TRMM just an alternative to no rain gauge improving runoff simulations when merged with rain gauge but not resulting satisfactory performance in itself. A study from Bangladesh shows that it is suitable for only long-term monthly averages and not for short-term hydrological application like flood forecasting (Islam & Uyeda, 2007). Another study from Pangani River Basin in Tanzania also argues that TRMM performed well in yearly basis capturing both spatial and temporal rainfall pattern but failed to detect higher intensity rainfall close to mountainous part of basins (Haque, 2009).

On the contrary, TRMM after bias adjustment was found to improve flood prediction in Upper Cumberland River in south eastern Kentucky (Harris et al., 2007). It was also found useful to monitor heavy rainfall for Yangtze River Basin, China (Minghu et al., 2001) and to predict peak discharge quite accurately in Nepal showing possibility of using in operational flood forecasting (Hazarika et al., 2007). However, there is no uniform acceptance of TRMM as a potential data source for flood forecasting. The results differs case by case depending upon catchment conditions, and spatial and temporal resolutions. Table 3.2 summarizes some researches on TRMM.

Table 3-2: Literature review on TRMM

Publication	Description of application	Author's conclusion
Tobin and Bennett (2014)	TRMM 3B42 and Climate Prediction Centre Morphing Technique (CMORPH) were applied in hydrological modelling of 10 watershed in diverse locations across the globe	TRMM 3B42 resulted acceptable results in most of the watersheds and hence can potentially support watershed modelling whereas CMORPH results were not satisfactory.
Collischonn et al. (2008)	Daily values were aggregated from three hourly TRMM rainfall and compared with daily rain gauge measurement	TRMM rainfall is not precisely accurate but when average over basin, results are quite similar and seasonal variability is well represented. TRMM can contribute in identifying non-functional or aberrant rain gauges at basin level.
Kidd and McGregor (2007)	Distribution of rainfall over Hawaiian Island chain and surrounding oceans as observed by TRMM PR instrument was investigated	Satisfactory quantitative rainfall estimates matching surface observation were found as well as fact that PR instrument provides vertical profile of precipitation along with spatial information.
Islam and Uyeda (2007)	Different products of TRMM (3B42 V5, 3B43 V5 and 3B43 V6) were compared with ground based rain gauge network for five years	3B43 V6 (monthly product) performed well among other products. TRMM could help in better understanding of rain climatology of tropical climatic countries like Bangladesh as shown by long periodic analysis.
Dinku et al. (2007)	10 different satellite rainfall products were evaluated. Comparison was made in two clusters; first one with low spatial and temporal resolution and	TRMM 3B43 and CMAP from first group and TRMM 3B42, TAMSAT and CMORPH from second group performed reasonably well.

	second one with high spatial and temporal resolution.	
Hazarika et al. (2007)	TRMM and Observed data were compared in different climatic regions of Nepal	Close resemblance to areal average rainfall was found. However, TRMM overestimated rain in dry seasons and underestimated in monsoon periods.
Barros et al. (2000)	Rain gauge and TRMM precipitation were compared in mountainous central region of Nepal from 1999 monsoon	Better rain detection was observed at lower altitude stations as compared to higher elevation stations.

3.1.2. FEWS-NET Products

In 1998, the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) developed the Rainfall Estimator (Herman et al., 1997) in response to the need for higher-resolution operational daily rainfall estimates to support FEWS-NET. FEWS-NET supports and informs disaster relief decisions that impact millions of people and involve billions of dollars (Funk & Verdin, 2010). FEWS-NET monitors the rainfall and moisture availability conditions with the help of NOAA RFE data (Jayanthi et al., 2013). As of January 1, 2001, RFE version 2.0 has been implemented which replaces previous version 1 that was operational from 1995 to 2000 (http://www.cpc.ncep.noaa.gov/products/fews/RFE2.0_desc.shtml).

Since RFE-2 did not allow deriving meaningful rainfall anomalies to assess the current state and evolution of the climate, African Rainfall Climatology (ARC) was developed based on the same algorithm employed in the RFE-2 algorithm (Xie & Arkin, 1996). From 2001, ARC version 2 has been introduced with acquisition of historical, calibrated IR imagery and daily summary gauge data. "It is a unique product relative to other satellite rainfall estimators because of its high, 0.18^0 gridded spatial resolution, and its ability to blend gauge and satellite information on a near-real-time basis to provide daily (0600–0600 coordinated universal time) rainfall estimates over the African continent" (Novella & Thiaw, 2012).

Table 3-3: Literature review on FEWS-NET products

Publication	Description of application	Author's conclusion
Mashingia et al. (2013)	Gauge corrected RFE-2 and TRMM-3B42 were tested over a data scarce tropic complex region in Tanzania. Accuracy was assessed comparing with available gauge data on sub-basin level and pair-wise (point to point pixel) with the reproduction of rainfall volume, rainfall intensity and consistency of rain and no-rain days	Both of the products performed reasonably well detecting rainfall occurrence. Local calibration of satellite derived rainfall estimates and merging with local rain gauge could eliminate overestimation and underestimation. Though, strong correlation was not observed, products have high prospective to supplement gauge observation in data sparse basins.
Thiemig et al. (2013)	Four SBRE (CMORPH, RFE 2.0, TRMM-3B42 and PERSIANN) and one re-analysis product (ERA-Interim) were evaluated over two river basins (Volta and Baro-Akobo) for the time period 2003–2008 with focus on the individual and combined effect of SBRE-specific calibration and bias correction on the hydrological performance, the level of complexity required regarding bias correction and interpolation to achieve a good hydrological performance	Model calibrated to respective SBRE rather than to interpolated ground observations always gives higher performance. Bias corrections are essential prior calibration but specific model calibration is adequate for SBRE with good intrinsic data quality. Sophisticated bias correction generated superior hydrological performance while sophisticated spatial interpolation resulted added value only over mountainous region.

Jayanthi et al. (2013)	At district level, RFE-2 was statistically regressed with drought-induced yield losses in the months of January, February and March	Analysis showed that most damage in maize yield is due to drought condition in February and early March. Regional maize vulnerability model for Southern Malawi was obtained. The result would assist in developing early monitoring mechanism for drought impact evaluation and identify potential food related hazard.
Novella and Thiaw (2012)	ARC-2, a new gridded daily 29-yr precipitation estimation dataset centered over Africa at 0.18 degree spatial resolution is described.	Results show that ARC-2 is a major improvement over ARC1. It is consistent with other long-term datasets, such as Global Precipitation Climatology Project and CPC Merged Analysis of Precipitation (CMAP). ARC-2 is expected to provide users with real-time monitoring of the daily evolution of precipitation, which is instrumental in improved decision making in famine early warning systems.
Beyene and Meissner (2010)	Monthly RFE and rainfall record from weather stations were analyzed. Spatial-temporal analysis was undertaken to see if RFE can reliably analyze seasonal rainfall variability	RFE images can be reliably used for early warning systems, and to empower decision makers on the impacts caused by the changes in the magnitude, timing, duration, and frequency of rainfall deficits on different spatial and temporal scales.

3.1.3. Tropical Applications of Meteorology using SATellite data and ground-based observations

Tropical Applications of Meteorology using SATellite data and ground-based observations (TAMSAT) is a product of TAMSAT Research Group, University of Reading, United Kingdom. The main purpose of this satellite imagery is to estimate rainfall and other surface water budget components particularly in Africa. Routine products of the group are a ten-daily (dekadal), monthly and seasonal rainfall estimates for Africa derived from Meteosat thermal infra-red (TIR) channels based on the recognition of convective storm clouds and calibration against ground-based rain gauge data. This methodology is used by AGHRYMET and by a number of African Meteorological Services to provide vital, up to the minute information on the state of the rainy season. The spatial resolution is 0.0375° and data is available from 1983 (http://www.met.reading.ac.uk/tamsat/about/).

Table 3-4: Literature review on TAMSAT

Publication	Description of application	Author's conclusion
Asadullah et al. (2008)	TRMM 3B42, CMORPH, TAMSAT, RFE 2.0 and PERSIANN, five satellite products are compared against historical monthly rainfall data in four regions of Uganda	Seasonal and spatial patterns are reasonably reflected by all the products. TRMM 3B42, CMORPH and TAMSAT show most promise in the application. Use of multiple products is recommended as products differences are large.
Teo and Grimes (2007)	The TAMSIM algorithm with rainfall estimates derived from Meteosat cold cloud duration fields was compared with rain gauge data from Gambia in west Africa at daily scale	The distribution of rainfall from the simulations agreed well with that from rain gauge both when averaged larger areas and at pixel scale. However, tendency of overestimating the probability of rainfall coverage was observed when zero cold cloud dominated the domain.
Grimes et al. (1999)	Estimates from satellite information and rain gauge were optimally merged using weightage. Block Kirging was used to estimate uncertainty developing a novel	More reliable results both for the spatial and mean areal distribution were observed from merging. The result is promising and should be studies further in other areas and seasons as well

	regression approach for satellite uncertainties. Then the algorithm was tested used Estimation of Precipitation by SATellite dense rain gauge network in Niger.	as different integration intervals to understand performance with broader spectrum of rainfall patterns.
Dinku et al. (2007)	10 different satellite rainfall products were evaluated using station network over complex topography varying from below sea level to 4620 meters. Comparison was made in two clusters; first one with low spatial (2.5u) and temporal (monthly) resolution and second one with high spatial (0.1u to 1u) and temporal (3-hourly to 10-daily) resolution.	TRMM 3B43 and CMAP from first group and TRMM 3B42, TAMSAT and CMORPH from second group performed reasonably well.

3.1.4. European Centre for Medium-Range Weather Forecasts

European Centre for Medium-Range Weather Forecast (ECMWF) aims the development of computer models to mimic the behaviour of the atmosphere, and to create the collection and storage of meteorological data (www.ecmwf.int). The spatial resolution has changed from about 120 by 120 km to about 50 by 50 km over the period 1997–2006 (Bürger et al., 2009). Forecasts are available for lead times of up to 10 days.

In regards to quantitative precipitation forecast, skill in ensemble predictions over Europe was found to be persisted into the medium range for low thresholds, but not for high ones (Buizza et al., 1999). In a comparative study of ECMWF, National Centers for Environmental Prediction (NCEP) and MSC Global Precipitation System, the spread of ensemble forecasts was found insufficient to systematically capture reality, suggesting that none of them is able to simulate all sources of forecast uncertainty. But, most verification measures indicate that the ECMWF ensemble forecast system has the best overall performance, with the NCEP system being competitive during the first, and the MSC system during the last, few days of the 10-day forecast period (Buizza et al., 2005).

Table 3-5: Literature review on ECMWF

Publication	Description of application	Author's conclusion
Verkade et al. (2013)	First the biases in the mean spread and forecast probabilities were evaluated to see how these biases propagate to streamflow forecast. Then multiple post-processing techniques such as quantile-to-quantile transform, linear regression were used. Then both pre and post-processed ensemble was tested with hydrological model of river Rhine.	Forcing ensembles creates significant biases that cascade streamflow ensembles. These biases improvement differs with forecasted lead time, spatial scale and amount but are generally moderate.
Kneis et al. (2012)	Different numerical weather predictions were used as input for operation hydrological model. Downscaled ECMWF was used with lead time of +120 hours at	Both NWPs gave lower than 50% of probability of event detection which in many cases was in range of 20-30% whereas false alarms ratio was considerably high. Uncertainties were originated from both deficiencies in hydrological modelling and quantitative

	daily scale for 8.5 years and Consortium for Small-scale Modeling- European Union was tested with lead time of +72 hours for 3.5 years	rainfall estimation as well as insufficient quality of rainfall forecasts. However, studies shows that in many cases, s major runoff related to snowmelt can be successfully predicted in 4-5 days' advance.
Buizza et al. (2005)	The methodologies of ECMWF, MSC and NCEP used to simulate effect of initial and model uncertainties in ensemble forecasting were compared for a 3 month period between May and July 2002.	Quality of data assimilation used to create initial condition and numerical model strongly determines the performance of ensemble prediction system. Both the initial and model related uncertainties on forecast errors should be simulated by successful European Prediction System (EPS). None of systems is able to simulate all forecast uncertainty sources. However, relative strengths and weakness analyzed in this study can offer guidelines for future development of EPS techniques.
Mullen and Buizza (2001)	EPS for probabilistic forecast of 24 hour accumulated precipitation was assessed over the eastern United States using rain gauge data for verification.	EPS forecasts were observed more skilful in winter than summer. Skillful forecasts to past 1 week were found for threshold of 1mm in both seasons. However, the accuracy decreased with the increase in threshold until forecasts of 50 mm are not significantly skillful at one day.

3.2. Rainfall-runoff modelling

Modelling has become a guiding tool for hydrological simulation in the last few decades. With the advanced development of computer science and extensive research in hydrology, hydrological modelling has become powerful and flexible. This has been boost by free availability of some non-commercial software. This has opened a incredible opportunity especially to developing nations (Thinh, 2010).

With increasing popularity and use, different types of models have been developed. They can be classified as fully distributed, semi-distributed and lumped models based on their fundamental principles. (Thinh, 2010). The major rainfall-runoff models are based on numerical models in which parameters are built-in so that they meet local basin conditions. Some examples of these kinds of models include LISFLOOD (De Roo et al., 2000), TOPKAPI (Liu et al., 2005) and models from MIKE family (Plate, 2007).

Different studies have been conducted to evaluate specific rainfall-runoff models using lumped watershed models such as HSPF, SWRRB, and SWMM; distributed models such as SWAT, MIKE SHE, and HEC-HMS, and watershed-scale models such as ANSWERS and AGNPS, among others (Verma et al., 2010). A summary of such models and methods have been provided in the Encyclopaedia of Hydrological Sciences (Werner et al., 2005). The fundamental bases of most hydrological models are same basic formula of rainfall-runoff hydrology. They only difference is in the complexity of process descriptions (Plate, 2007).

3.2.1. Model Selection

The varieties of models available in market especially non-commercial ones not only increase the access to the model but also amplify the confusion in selection of right model. However, few points can be considered in selecting appropriate models. At first, the model should not demand long time series data as in many countries especially in developing nations, such long time series might not be available. This can restrict the use of data driven models. Secondly, the model should be user friendly and simple to use. Especially for flood forecasting, model should not require long simulation period. This restricts the use of fully distributed models which requires longer simulations. At third and importantly, the models should be non-commercial, available at free of cost. Hence, commercial models are often out of choice. Finally, the priority should be given to the models currently being used in the same basin. Based on above selection criteria, HEC-HMS was identified as one of the appropriate rainfall-runoff models for upper Blue Nile (Elfeta, 2010).

3.2.2. HEC-HMS

HEC-HMS is a Hydrologic Modelling System, developed by the Hydrologic Engineering Center of the US Army Corps of Engineers in Davis, California, that is designed to estimate the runoff and stream flow from a given catchment (Feldman, 2000). It is a deterministic, semi-distributed conceptual model. The physical properties of river basins along with the meteorology are well defined in this model. It can also be used for flood forecasting (Knebl et al., 2005; M. L. Anderson et al., 2002).

"Event hydrological modelling and continuous hydrological modelling is possible in HEC-HMS. The former one reveals how a basin responds to an individual rainfall event (e.g. quantity of surface runoff, peak, timing of the peak, detention) whereas latter one synthesizes hydrologic processes and phenomena (e.g. synthetic responses of the basin to a number of rain events and their cumulative effects over a longer time period that includes both wet and dry conditions" (Chu & Steinman, 2009).

Soil Moisture Accounting model incorporated in HEC-HMS aids continuous hydrological modelling including flood forecasting (Chu & Steinman, 2009). It was possible to increase the lead time of forecasts to 24 hours using different rainfall scenarios with HEC-HMS in a study carried out at Madagascar (Simon, 2010).

3.3. Flood Forecasting

After the blueprint paper by (Freeze & Harlan, 1969), flood modelling has rapidly advanced. The latest advancement in technology such as SBRE using next generation radar, geographic information system, high resolution digital elevation models, and advanced hydrological models has led to improved flood modelling (Garrote & Bras, 1995).

Different types of flood model have been developed and applied in varied river basin with diverse characteristics. Among them, mathematical hydrological models have also been widely used (Xiong et al., 2001). "Recently, more physically based models have been popular which consist of an input: areal averaged rainfall, gage levels or discharges at upstream gages, measured in real time and transferred to the regional forecasting centre, where they are converted, by means of suitable hydrological and hydraulic models, into future water levels and discharges at some critical points" (Plate, 2007).

Different studies have been conducted applying different models. LARSIM, an applied rainfall-runoff model is used for operational flood forecasting at several centres in Germany and Austria (Kneis et al., 2012). Similarly, artificial neural network have been used in Ganges in Bangladesh for flood forecasting to increase the lead time by additional 3 days (Akhtar, 2006).

CHAPTER 4

Data and Methodology

The Chapter Three discusses materials and methods used in this study. It describes rainfall data acquisition, hydrological model set up, model simulation, and performance of the model.

4.1. General

The quality and quantity of input data largely determines the performance of any hydrological model (Bhattarai, 2013). The model used in this research is Hydrological Engineering Center-Hydrologic Modeling System (HEC-HMS). The basic data required to develop a hydrological model in HEC-HMS are climatic datasets, land cover, soil types and topography. The details of data used and methodologies are discussed in this chapter.

4.2. Rainfall Data

4.2.1. Measured Rainfall

Rainfall data are crucial inputs for hydrological modelling. However, rainfall data of catchment from Eritrea and Ethiopia were not available due to inadequate data sharing mechanisms among Sudan, Eritrea and Ethiopia. Different levels of efforts were done to access rainfall data from some of the existing rain gauges from Eritrea. One rainfall station was however available in the Gash Basin in Kassala city, Sudan. Daily rainfall data from January 2002 to December 2012 was collected from Kassala Meteorology Office. The rainfall station is shown in figure 5.1.

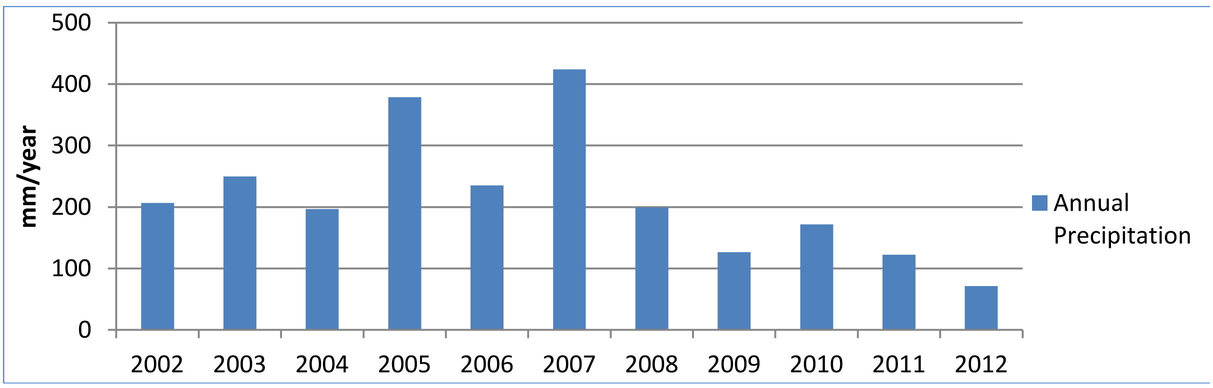

Figure 4.1 Annual rainfall recorded in the rain gauge station at Kassala, Sudan

4.2.2. Satellite Based Rainfall Estimates

Five different SBRE products were downloaded for this study. Table 4.1 provides the links to their sources.

Table 4-1: List of SBRE with sources

SN	SBRE	Source
1	TRMM Daily	http://disc2.nascom.nasa.gov/Giovanni/tovas/TRMM_V7.3B42_daily.2.shtml#description
2	TRMM 3-hourly	http://disc2.nascom.nasa.gov/Giovanni/tovas/TRMM_V7.3B42.2.shtml
3	RFE-2	ftp://ftp.cpc.ncep.noaa.gov/fews/fewsdata/africa/rfe2/
4	ARC-2	ftp://ftp.cpc.ncep.noaa.gov/fews/fewsdata/africa/arc2/
5	TAMSAT	http://www.met.reading.ac.uk/~tamsat/data/rfe.html
6	ECMWF	http://apps.ecmwf.int/datasets/data/interim_full_daily/

4.3. SBRE Data Processing

SBRE data accessed from the respective web sites were processed with set of ArcGIS tools using Model Builder. Iterate Raster tool was used to batch process all the individual daily rainfall images at one step. The coordinate of the images were defined as GCS_WGS_1984 which were then projected to WGS_1984_UTM_Zone_37N. Finally, the projected images were extracted for the required catchment using Spatial Analyst tool, Extract by Mask. Then daily rainfall images for the basin were obtained.

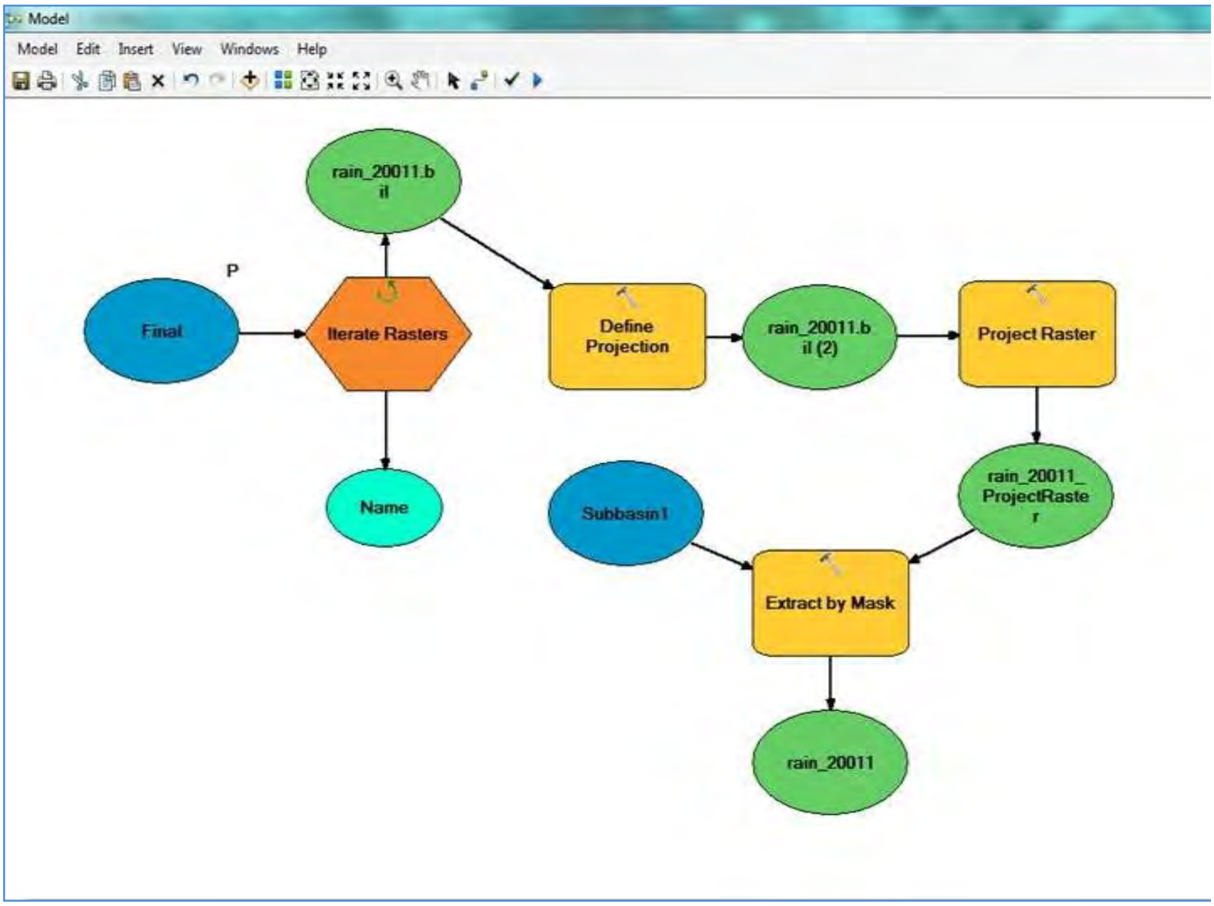

Figure 4.2 SBRE processing steps in Model Builder

4.4. Hydrological Model HEC-HMS[1]

The HEC-HMS program was developed at the Hydrological Engineering Center (HEC) of the US Army Corps of Engineers (Feldman, 2000). It is a deterministic, semi-distributed conceptual model. The modelling system is designed to simulate the rainfall-runoff processes of dendritic watershed systems. This includes large river basin water supply and flood hydrology, and small urban or natural watershed runoff (USACE, 2009a). The physical properties of river basins along with the meteorology are well defined in the model. It provides separate models to represent various components of rainfall and runoff processes. Several methods are provided for loss, transform, baseflow, and channel routing to adapt the available data and a broad range of topographic conditions (Thinh, 2010). The Figure 4.3 shows a system diagram of the runoff process at local scale.

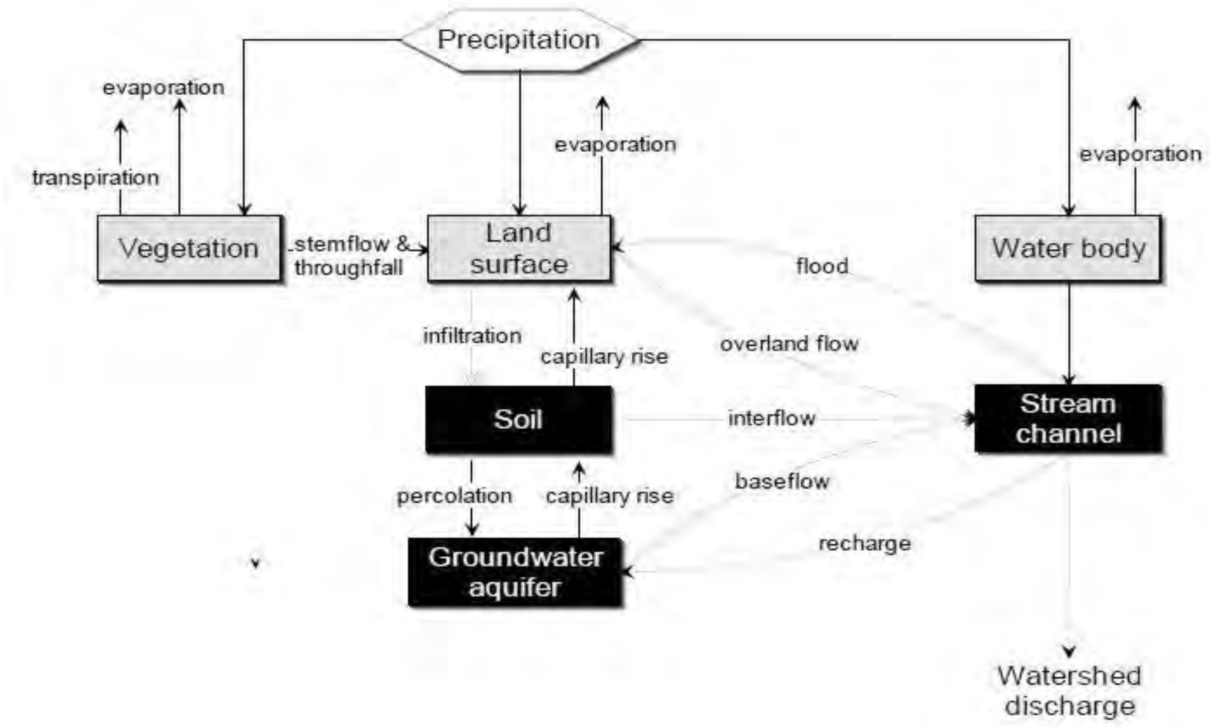

Figure 4.3 System diagram of the runoff process at local scale (HEC-HMS Technical Manual)

Precipitation is the key input for the model which is in the form of rainfall. Such rainfalls are either intercepted by vegetation cover or fall straight on ground. Rainfall in water body will contribute to the stream channel flow with certain amount being evaporated. Rainfall on the ground could be stored temporarily as surface storage such as lakes and ponds which are either evaporated or infiltrated into the soil. But certain volume of falling rainfall becomes over land flow when soil is saturated and contributes to the stream flow. The infiltrated water from the land surface is percolated to the lower soil layer and aquifer. However, capillary rise can uplift the water from soil and aquifer back to the land surface. Ground water aquifer can contribute as baseflow to stream channel or sometimes stream channel can also recharge the ground water depending on place and time. Hence, the stream channel flow from water body, overland flow, soil interflow and ground water baseflow gives the total discharge of the watershed.

[1] This section is written with a reference from a HEC-HMS User's Manual and HEC-HMS Technical Manual

4.5. Model Setup

HEC-HMS version 3.5 was used in this study. This section of the chapter describes the appropriate processes, methods and components used. The existing basin model developed by International Water Management Institute (IWMI) was used for this study to develop own hydrological models. Two types of hydrological model, i.e. continuous and events based models were developed. The Table 4.2 explains the key methods used in these two models.

Table 4-2: Methods used in two HEC-Models

Hydrological Processes	Methods	Rainfall-runoff model	Event based flood model
	Canopy	Simple Canopy	Not used
	Surface	Simple Surface	Not used
Basin Model	Loss	Soil Moisture Accounting	SCS Curve Number
	Transform	Clark Unit Hydrograph	Synder Unit Hydrograph
	Baseflow	Linear Reservoir	Recession
	Routing Method	Muskingum-Cunge	Muskingum-Cunge
Meteorological Model	Precipitation	Specified hyetograph	Specified hyetograph
	Evapotranspiration	Monthly average	Not used

4.5.1. Basin Model

The basin model includes elements like sub-basins, reaches, junctions, reservoirs, discharge diversions, source and sink elements. This study only includes sub-basins, reaches and junction. The three major processes in the sub-basin are:

a. Loss Method

Precipitation on the pervious surface is subject to losses. There are several options available to account losses for both continuous and event simulations. Two types of loss methods were used for this study. Soil Moisture Accounting (SMA) and SCS Curve Number method were used for continuous and event based modelling respectively. SMA method provides an advantage to compute continuous simulation for both dry and wet behaviour compared to other methods (USACE, 2009b). The specific values used in both loss methods are provided at table A.2 and B.1 respectively.

b. Transform

Transform is the process that converts excess precipitation computed by the loss model to direct surface runoff. Seven different methods of transform are available in HEC-HMS. In this study, Clark Unit Hydrograph and Synder Unit Hydrograph were used for continuous and event based modelling respectively. Table A.4 and B.2 summarizes the parameters and range of value used in each method respectively.

c. Baseflow

Baseflow is a major component of river flow in dry season or in a period without any precipitation. It is mainly contributed by groundwater flow. In this study, linear reservoir model was used for continuous modelling whereas recession method was used for event based modelling. The specific values used in both methods are provided in Table A.5 and B.3.

d. *Routing*

Routing methods models the flow through a river reach. Upstream hydrograph is used as boundary condition to compute downstream hydrograph using continuity equation. Various such types of routing methods are available in HEC-HMS. Muskingum-Cunge is one of the most common routing methods, and was used in this study for both continuous and event based modelling. Table 4.3 summarizes the data such as channel's length, width, roughness and bed-slope, etc used in Muskingum-Cunge method.

Table 4-3: Parameters used in Muskingum-Cunge Method

Reaches	Length (M)	Slope (M/M)	Manning's n	Shape	Width (M)
R20	21249	0.0018	0.045	Trapezoid	147.37
R40	42400	0.0021	0.045	Trapezoid	240.4
R60	92389	0.0027	0.04	Trapezoid	264.61
R90	34938	0.0026	0.035	Trapezoid	128.67
R100	12018	0.0027	0.035	Trapezoid	80.66
R180	16127	0.0048	0.035	Trapezoid	26.88
R210	21993	0.0029	0.035	Trapezoid	136
R220	6241	0.0038	0.035	Trapezoid	28.86
R230	6883	0.0031	0.03	Trapezoid	61.28
R260	27660	0.0041	0.03	Trapezoid	12.47
R270	2489	0.0036	0.03	Trapezoid	46.55
R290	18910	0.0035	0.03	Trapezoid	29.98

4.5.2. Meteorological Model

Meteorological model provides meteorological boundary conditions for the sub-basins such as precipitation and potential evapo-transpiration. In terms of precipitation, model computes actual water available at the land surface. If precipitation is rain then all precipitation is readily available which is not case when precipitation is in form of snow.

a. *Precipitation*

Among several methods to input precipitation, specified hyetograph method was used for this study. This method is advantageous when a single precipitation gage can be used to represent the precipitation over a basin. The daily rainfall time series in an excel file processed externally was copied and pasted in the precipitation gauge table. Several options are available to increase control over how the data is processed.

b. *Evapo-transpiration*

Evapo-transpiration is another meteorological methods used in this study. It is sum of both evaporation from the group surface, and transpiration by vegetation. It is usually used with continuous simulation. Monthly average method was used in this study which is designed to work with measure pan evaporation data. However, it can also be used with data collected with the eddy correlation technique or other modern methods. The values used in each sub-basin are provided in table A.6.

4.5.3. Control Specification

Control Specification specifies the time period for the model simulation with the time step of computation. In continuous rainfall-runoff model, two time controls were used. The year 2007-2010 was used as calibration period and year 2011-2012 was used for validation. The model was run with a time-step of 1 day. In case of event based model, three events, each from year 2011, 2010 and 2009 were simulated. Model was run both with time-step of 1 day and 1 hourly to simulate both daily and hourly peak flows.

4.6. Model Simulation

A combination of basin and meteorological model and control specifications is used to make simulations. Basin model manages runoff volume, direct runoff, baseflow and channel routing. Similarly, meteorological model comprises of ET and rainfall data while control specification deals with simulation period and time step.

In developing rainfall-runoff model two SBRE products, i.e. TRMM and ARC-2 were used based on their reasonable performance in validation with ground based rainfall measurement. Only 6 years data from 2007 to 2012 were used for rainfall-runoff modelling though discharge data were collected from 2002. The only reason for that was for the period 2007-2012, calibrated discharge data were available which was more accurate. Among the six years data, the year 2007 to 2012 were taken as calibration period with year 2007 considering warming up period whereas year 2011 and 2012 were considered as validation period. Automatic calibration was done to optimize the parameters. In flood forecasting, the model was developed for the year 2011 and was subsequently tested for the year 2010 and 2009.

4.7. Evaluation of Model Performance

The performance of the model was evaluated comparing daily and monthly simulated discharge with the observed discharge. The statistical tools such as Nash-Sutcliffe Efficiency (NSE), Coefficient of determination (R^2) and Percent Volume Error (PVE) were used measure the model outputs.

a. Nash-Sutcliffe Efficiency:

It is calculated as,

$$NSE = 1 - \frac{\sum (Q_{obs(t)} - Q_{sim(t)})^2}{\sum (Q_{obs(t)} - \overline{Q_{obs}})^2}$$

Where,

NSE is Nash-Sutcliffe Efficiency, $Q_{obs(t)}$ is observed discharge at time t, $Q_{sim(t)}$ is simulated discharge at time t and $\overline{Q_{obs}}$ is average observed discharge. The "t" used in the calculation is the time period used (Nash & Sutcliffe, 1970). The value varies from - ∞ to 1. With the increase in performance, the numerical value increases and becomes maximum 1 in ideal case when simulated and observed hydrograph exactly match each other (Bhattarai, 2013).

b. Coefficient of determination

Another widely used statistical measures Coefficient of determination (R^2) is given by,

$$R^2 = \frac{(\sum (Q_{obs(t)} - \overline{Q}_{obs}) \sum (Q_{sim(t)} - \overline{Q}_{sim(t)}))^2}{\sum (Q_{obs(t)} - \overline{Q_{obs}})^2 \sum (Q_{sim(t)} - \overline{Q}_{sim(t)})^2}$$

Where,

Q_{obs} and Q_{sim} are observed and simulated discharge; $\overline{Q_{obs}}$ and $\overline{Q_{sim}}$ are mean observed and simulated discharge. Coefficient of determination varies from 0 to 1 where higher value denotes better fit of the regression line between simulated and observed discharges. When simulated and observed discharges exactly match each other, a value of 1 is obtained. These objective functions are widely used in hydrological modelling (Masih et al., 2011).

c. Percent volume error

Finally, the volume balance was also calculated by using another statistical method called Percent Volume Error (PVE) which is given by,

$$PVE = \frac{(V_{sim} - \overline{V}_{obs}}{\overline{V}_{obs}} * 100$$

Where,

$\overline{V_{sim}}$ and $\overline{V_{obs}}$ are average simulated and observed volume of stream flow. PVE shows by what percentage the simulated flow is underestimated or overestimated. Positive value means over estimation and negative shows underestimation. If simulated and observed flow is exactly same then an ideal case of 0 is obtained.

The objective of the model improvement was set based on statistical tools as maximising NSE and R^2, and minimising PVE.

CHAPTER 5

Validation of satellite rainfall

This Chapter discusses on validation of different SBRE products with ground based rainfall measurement at different time scales as well generation of rainfall maps of basin.

5.1. Comparison of rainfall products in the Gash basin

One of the constraints in hydrological modelling in the Gash River is its inadequate availability of rainfall data. In the absence of adequate rain gauge measured data, acceptable interpolation was not possible for the Gash basin. The data available for this study was only one rain gauge data from Kassala city. This single station data could be neither interpolated nor generalized for the whole basin. Also the topography varies greatly in the Gash basin from 531 meters amsl in Sudanese plains to 3259 meters amsl in Eritrean and Ethiopians highlands. And rainfall pattern is known to vary with topography. Usually higher rainfall rates are observed in mountain regions compared to plains and only available rainfall stations was in Sudanese plains.

Though some rain gauges were known to operate in Eritrean part, data could not be accessed despite continuous efforts. In many trans-boundary rivers such as Gash especially in developing countries, data sharing is still a challenge, and data are often considered as secret information. This makes rainfall-runoff computation with ground station data difficult. However, RS can close of these gaps of data unavailability (Stisen et al., 2008). It has great importance for operational purposes, especially in data scare regions such as Africa (Teo & Grimes, 2007).

Five different satellite based rainfall products, i.e. TRMM 3B42 V7, ARC V2, RFE V2, TAMSAT, and ECMWF were used for this study. However, there were several limitations in comparing these satellite based products. Firstly, the comparison was being made between point rainfall and areal rainfall. The point rainfall records at small area whereas area and spatial resolution of satellite based rainfall products were quite higher, for instance, 625 km^2 for TRMM. The values were compared at daily, monthly and annual scales (shown in below figure 5.1) though there is likely to have poorer performance at daily scale than at monthly. The main reason is that with the larger time scale the error will be minimized. Studies have also shown that comparison at monthly scale is better than daily scale for satellite based rainfall products (Li et al., 2012; Arias-Hidalgo et al., 2012). Secondly, the rainfall products were compared at their own spatial resolutions. TRMM had 0.25^0, ARC and RFE at 0.1^0, TAMSAT at 0.0375^0 and ECMWF at 0.125^0.

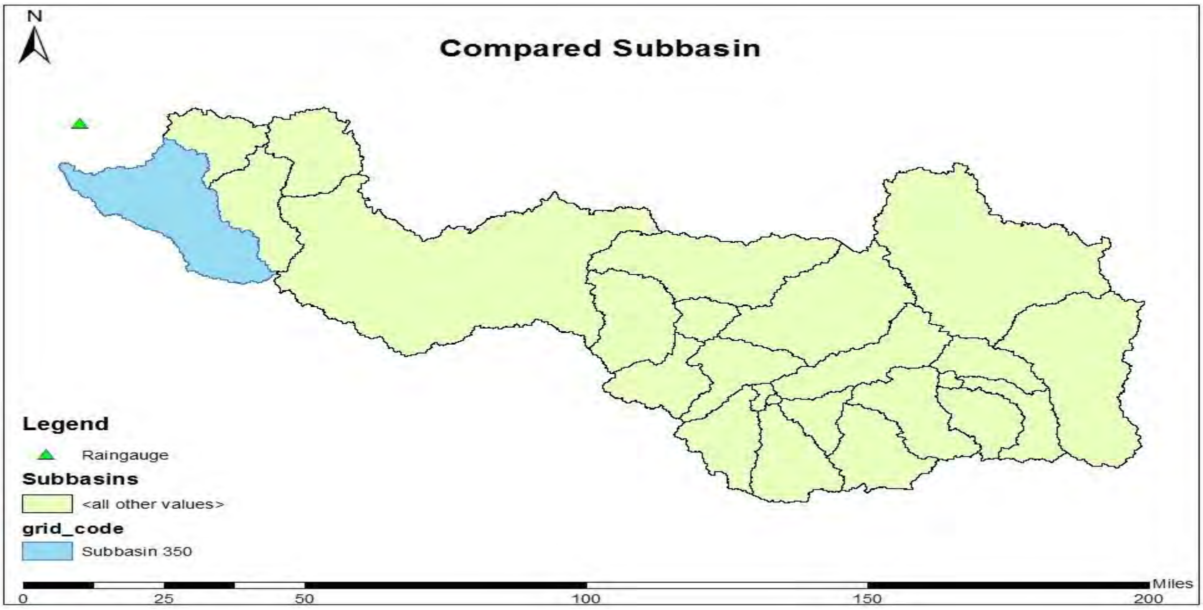

Figure 5.1 Compared sub-basin and rain gauge station

The performance of rainfall products were evaluated comparing daily, monthly and annual rainfalls. The four statistical tools NSE, R^2, Root Mean Square Error (RMSE), and Mean Absolute Error (MAE) were used for the comparison.

5.1.1. Daily Correlation

At daily scale, four rainfall products, TRMM, ARC-2, RFE-2 and ECMWF were compared with ground based rainfall station using different performance measures. TAMSAT was not compared as it doesn't have daily resolution. None of the products showed higher performance in terms of RMSE, MAE and R^2 (Table 5.1). However, results were obvious as different studies have shown that satellite based rainfall products correlates better at larger temporal scale such as monthly than at daily level. A study done by Li et al. (2012) in Xinjiang catchment, Poyang lake basin using TRMM also showed that there is better linear relationship with TRMM rainfall and rain gauge rainfall data at monthly scale compared to daily. Another study by Arias-Hidalgo et al. (2012) conducted in Ecuadorian coastal foothills using TRMM also showed that monthly resolution is the finest with high correlation compare to daily or yearly.

Table5.1 shows that at daily scale, TRMM has highest R^2 but ECMWF outperforms it in RMSE and MAE. RFE-2 performs worst in terms of all the performance measures.

Table 5-1: Rainfall products performance measure at daily scale

SN	Rainfall Products	Performance Measure as compared with Rain Gauge data		
		RMSE (mm/day)	MAE (mm/day)	R^2
1	TRMM	5.3	1.3	0.0488
2	ARC-2	5.2	1.4	0.0283
3	RFE-2	9.6	5.8	0.0007
4	ECMWF	4.3	0.7	0.0349

However, it is to be noted that the value obtained from processing RFE-2 data were quite suspicious. The poor performance could also be partially due to some error in data processing though all of the data were carefully processed using same standard procedure as mentioned in section 4.3 SBRE data processing.

5.1.2. Monthly Correlation

The figure 5.2 shows that the average monthly rainfall for four major rainfall months, i.e. June, July, August and September from period 2002 to 2012. It is observed that TRMM, ARC-2 and RFE-2 consistently exceeds station based rainfall measurement in all four months. TAMSAT highly overestimates for August but underestimates for June and July with slightly overestimating for September whereas ECMWF consistently highly underestimates for all the rainfall months. The poor performance of ECMWF could also be associated with possible error in data processing though as mentioned above, a standard procedure was applied for the processing of all of the SBRE.

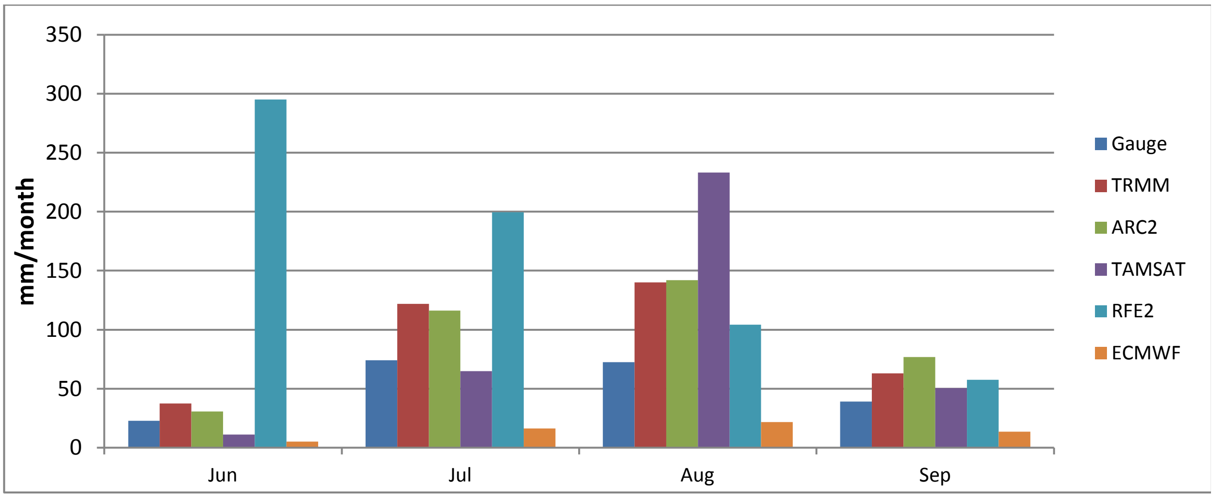

Figure 5.2 Average monthly rainfall for major rainfall months from 2002 to 2012

Table 5.2 shows the overall summary of the rainfall products performance. It is observed that the RMSE is lowest in TRMM and highest in RFE-2 which indicates the magnitude of the error. However, there is not a significant difference among different products at monthly scale except for RFE-2. The biasness which describes the tendency of the satellite product to report higher or lower daily rainfall across the comparison period was found to follow similar pattern where besides RFE-2, all other datasets have more or less close values. Coefficient of determination was found to be good fit in TRMM and ARC-2, i.e. 0.85 and 0.70. However they were lower than 0.5 in TAMSAT and ECMWF and very poor with RFE-2.

Table 5-2: Rainfall products performance measure at monthly scale

SN	Rainfall Products	Precipitation (Jun-Sept)			Performance Measure as compared with Rain Gauge data		
		P_{min}	P_{max}	P_{avg}	RMSE (mm/month)	MAE (mm/month)	R^2
1	Gauge	0.35	173.1	52.13			
2	TRMM	19.0	273.19	90.50	29.9	16.1	0.85
3	ARC-2	0	240.28	91.37	33.9	19.2	0.70
4	RFE-2	29	378	164.07	180.8	149.7	0.002
5	TAMSAT	5	284	89.88	50.8	21.1	0.47
6	ECMWF	1.40	56.55	14.11	32.1	14.7	0.41

5.1.3. Yearly Correlation

The figure 5.3 shows that at annual scale, except ECMWF, all other rainfall datasets over estimates rainfall consistently in all the years whereas ECMWF largely underestimates in terms volume of rainfall. The pattern is also more or less similar in all of the rainfall data sets. It is also observed that the annual rainfall has significantly decreased in last five years. This is confirmed by both rain gauge measurement as well as satellite datasets except RFE-2 which show slight increase in 2012. Though it is not possible to study rainfall trend with 11 years of data, it suggest there could be some implications on water resource management if the trend continues. Since RFE-2 estimates were too high making difficult to clearly observed pattern of other rainfall products, it has been omitted in the below figure 5.3.

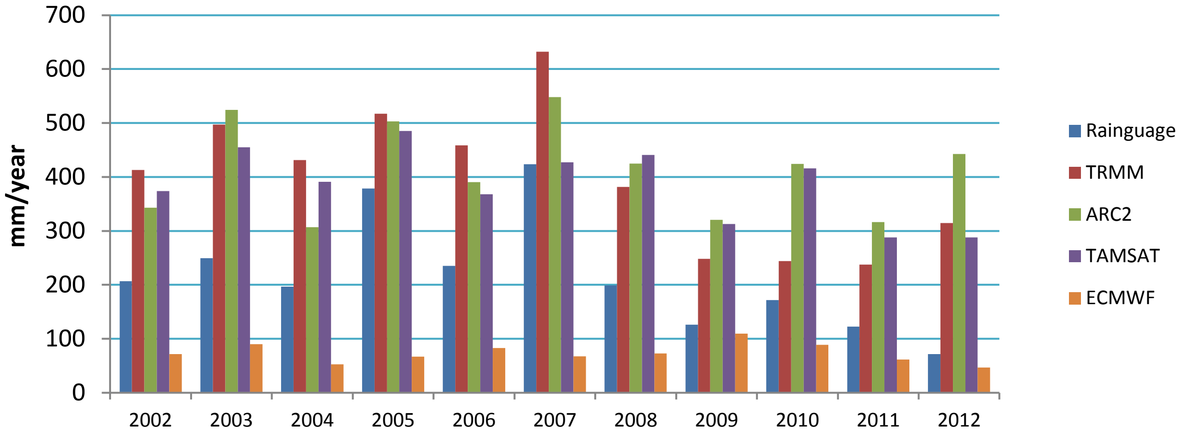

Figure 5.3 Annual rainfall observed with different rainfall products except RFE-2

In terms of statistical performance measure, the yearly comparison follows the monthly pattern except for ECMWF (please refer to table 5.3). Interestingly, though RMSE and MAE are better than any products with ECMWF, the R^2 has the worst agreement.

Table 5-3: Rainfall products performance measure at annual scale

SN	Rainfall Products	Precipitation			Performance Measure as compared with Rain Gauge data		
		P_{min}	P_{max}	P_{avg}	RMSE (mm/year)	MAE (mm/year)	R^2
1	Gauge	71.5	423.8	216.5	-		
2	TRMM	237.8	632.4	397.8	210.3	176.7	0.71
3	ARC-2	306.8	548.1	413.1	210.9	196.7	0.45
4	RFE-2	1626	2284	1971.7	1763.2	1755.2	0.44
5	TAMSAT	288	485	386.0	182.0	169.5	0.59
6	ECMWF	46.6	109.7	73.8	175.5	142.7	0.00002

5.2. Rainfall in the Gash

One of the key challenges in the Gash basin was to understand the precipitation pattern of the basin. Understanding the intensity, pattern and frequency of the whole basin is very essential for better water resource management as well as for flood forecasting. The highlands in Eritrea and Ethiopia and plains in Sudanese part indicate a varied topography within the basin which ranges from 531 m amsl to 3259 m amsl. The researches have shown that there is high variability of precipitation distribution with altitudes. Varikoden et al. (2012) in their study of Indian summer monsoon found that the rainfall and frequency of rain events are more pronounced at coastal belts and foothills of Himalayas. Another study done in Kenyan highlands also shows that there is even difference in length and timing of rainy season among high altitude areas and low altitude areas (Ngetich et al., 2014). However, another study by Al-Ahmadi and Al-Ahmadi (2013) showed that not necessarily high altitudes receive more rain. In their study they found that a low altitude locations facing windward side received more rainfall. Hence, it can be concluded that there is high spatial and temporal variability in rainfall intensity and frequency.

Unfortunately, ground based rainfall data was available from only one rainfall station at Sudanese plain in Kassala city. This one rainfall station data could not be extrapolated for the whole catchment of size 21000 km^2 with high altitudinal variation. Hence, precipitation maps based on satellite rainfall estimates were used to generate average rainfall maps for the basin to understand spatial variability of rainfall. This is also particularly important for flood forecasting as the time of travel from places receiving high intensity of rainfall influences lag time of peak flood.

Data from four rainfall sources TRMM, ARC-2, ECMWF and TAMSAT were used to generate the average annual rainfall map for years 2002 to 2012. Inverse distance weighted method; a Spatial Analyst tool in GIS was used to interpolate point average rainfall from each sub-basin. Maps for basin were extracted using another Spatial Analysis feature 'extract by mask' using sub-basin feature.

5.2.1. Rainfall with TRMM

TRMM 3B42 version 7 was used to generate rainfall for the whole catchment. The derived map shows there is high rainfall variability. In terms of spatial distribution, the whole catchment can be divided into five rainfall zones. It is observed that the eastern and western part of the basin receives comparatively lower precipitation than central region. For instance, the lowest rainfall class is with range of 340 mm to 445 mm per year which lies in western part of the catchment near Sudanese and Eritrean border. The second class is from 446 to 541 mm per year in an average and this zone lies mostly in eastern front in Eritrea whereas small part lies in western part as well. The figure 5.4 also shows that highest rainfall rates are at South-central part of the basin receiving rainfall range of 721 to 859 mm per year. Most of this part receiving high rainfall lies in Ethiopian highlands.

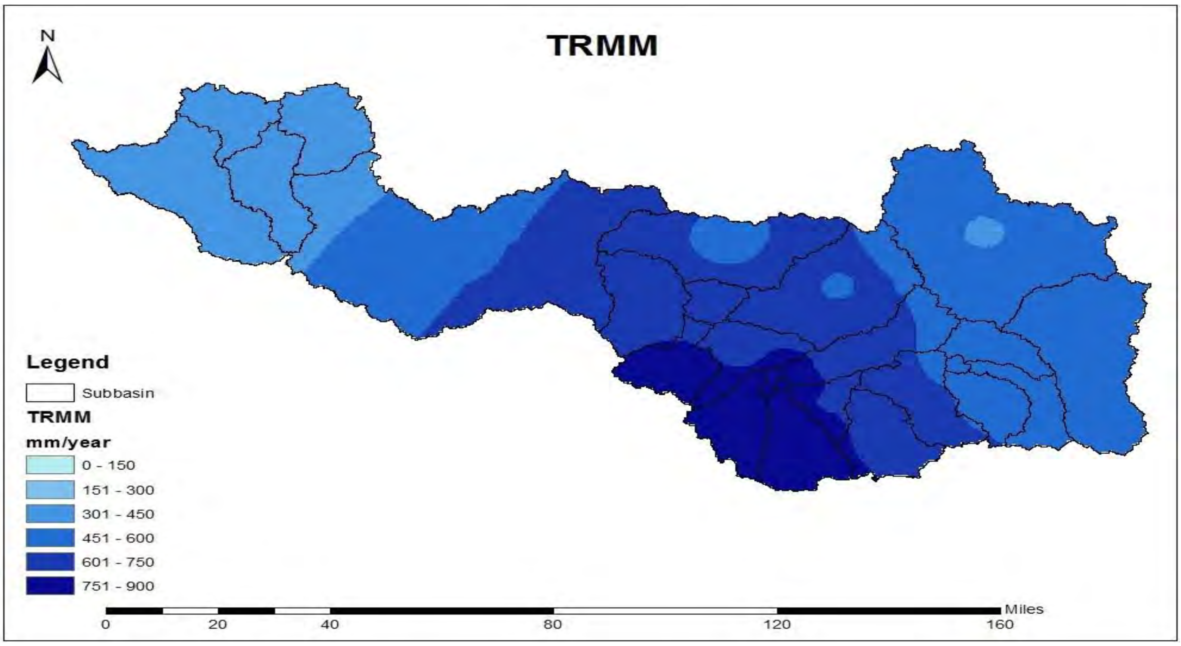

Figure 5.4 Average annual rainfall distribution from years 2002 to 2012 based on TRMM

5.2.2. Rainfall with ARC

The rainfall distribution pattern of ARC-2 aligns with that of TRMM showing similar spatial variability with low rainfall in eastern and western parts, and high amount in south-central part of the basin. Though the minimum rainfall in basin is comparatively similar, for instance, 340 mm per year for TRMM and 338 mm per year for ARC-2, the highest amount varies with around 150 mm per year. TRMM ranges reaches to 850 mm per year and 708 mm per year is of that of ARC-2. Though there is some difference in range, distribution pattern are quite comparable.

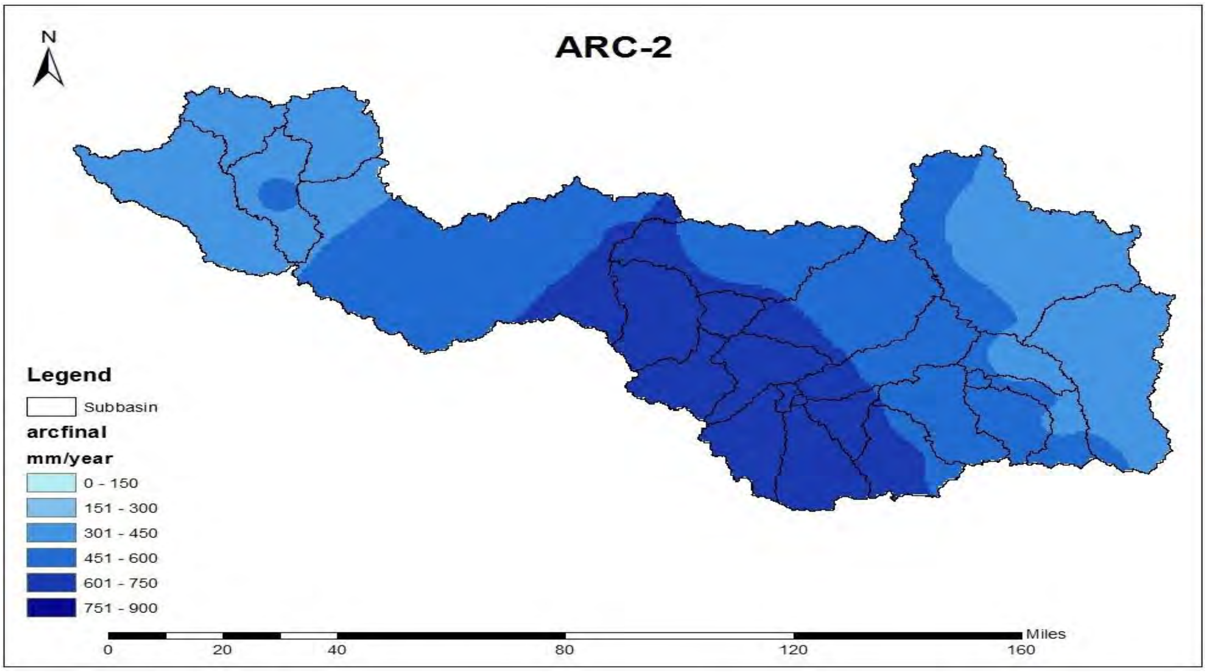

Figure 5.5 Average annual rainfall distribution from years 2002 to 2012 based on ARC-2

5.2.3. Rainfall with TAMSAT

Rainfall distribution map based on TAMSAT was also generated. However, it is to be noted that unlike TRMM and ARC-2, TAMSAT has a temporal resolution of dekadal, i.e. every 10 days. But interestingly, TAMSAT also shows the similar pattern of rainfall distribution in different region. However, the minimum and maximum rainfall ranges recorded in TAMSAT are slightly lower than both TRMM and ARC-2. The minimum rainfall range starts with 202 mm per year and reaches to 659 mm per year only.

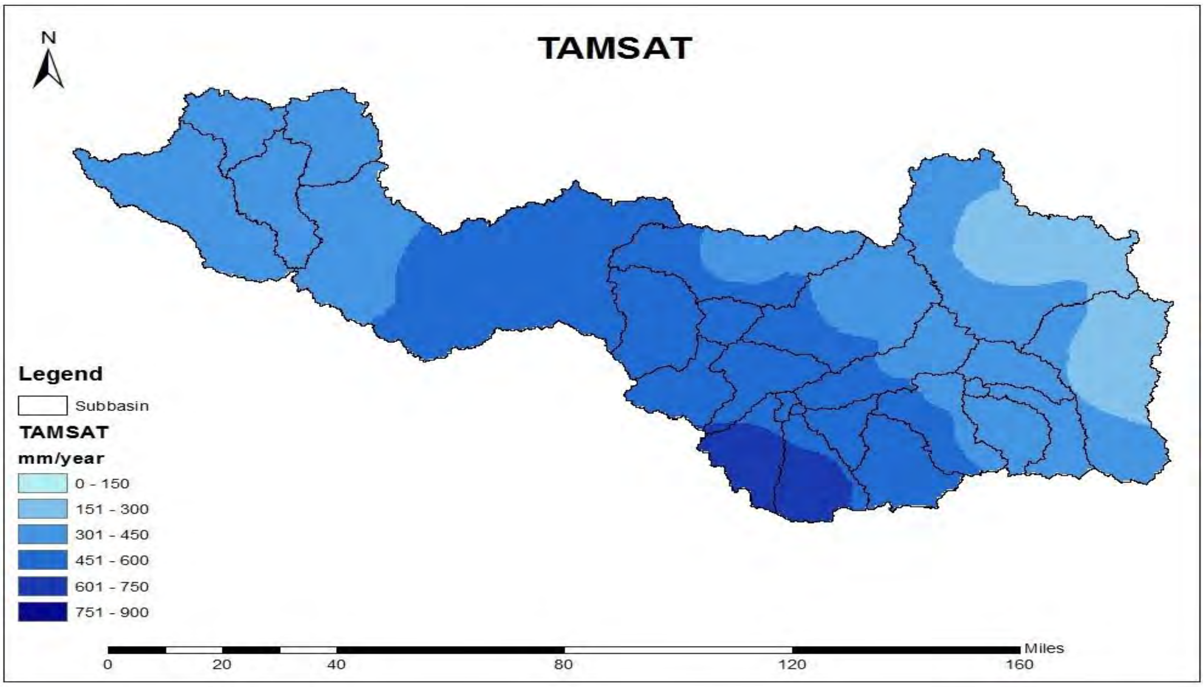

Figure 5.6 Average annual rainfall distribution from years 2002 to 2012 based on TAMSAT

5.2.4. Rainfall with ECMWF

The rainfall range showed by ECMWF Interim Analysis is the lowest out of four satellite rainfall products. The rainfall range starts with as low as 51 mm per year and reaches only 167 mm per year. This range is quite low compare to measured rainfall in Kassala ground based rainfall station. Though the volume of rainfall measure differs greatly with other satellite rainfall products and ground based measurement, the spatial pattern is quite similar indicating low rainfall rates in western part and higher rainfall intensity in south central region.

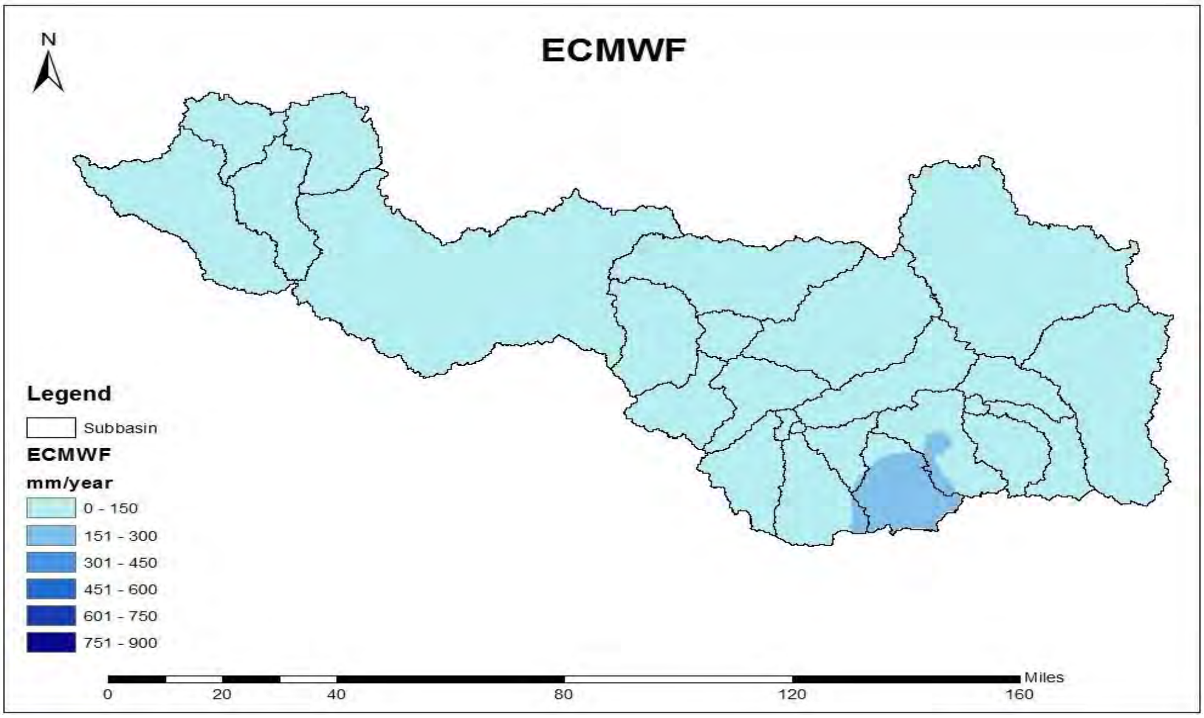

Figure 5.7 Average annual rainfall distribution from years 2002 to 2012 based on ECMWF

5.2.5. Temporal Rainfall distribution in Gash

The monthly rainfall for four major rainy months June, July, August and September for year 2012 was studied to get some insights on temporal rainfall distribution in the whole catchment. Rainfall maps were derived based on TRMM, ARC-2, ECMWF and TAMSAT. All of the rainfall products except ECMWF showed that the highest rainfall received month is August whereas for ECMWF for the year 2012, July was the month with highest rainfall.

There is also high variability in total rainfall in each month with each rainfall products. There is also no consistency in rainfall pattern over areas and volume of rainfall among different rainfall products. However, TRMM, ARC-2 and TAMSAT show more or less similar range of rainfall over months. ECMWF shows quite lower range of rainfall volume compared to other three products.

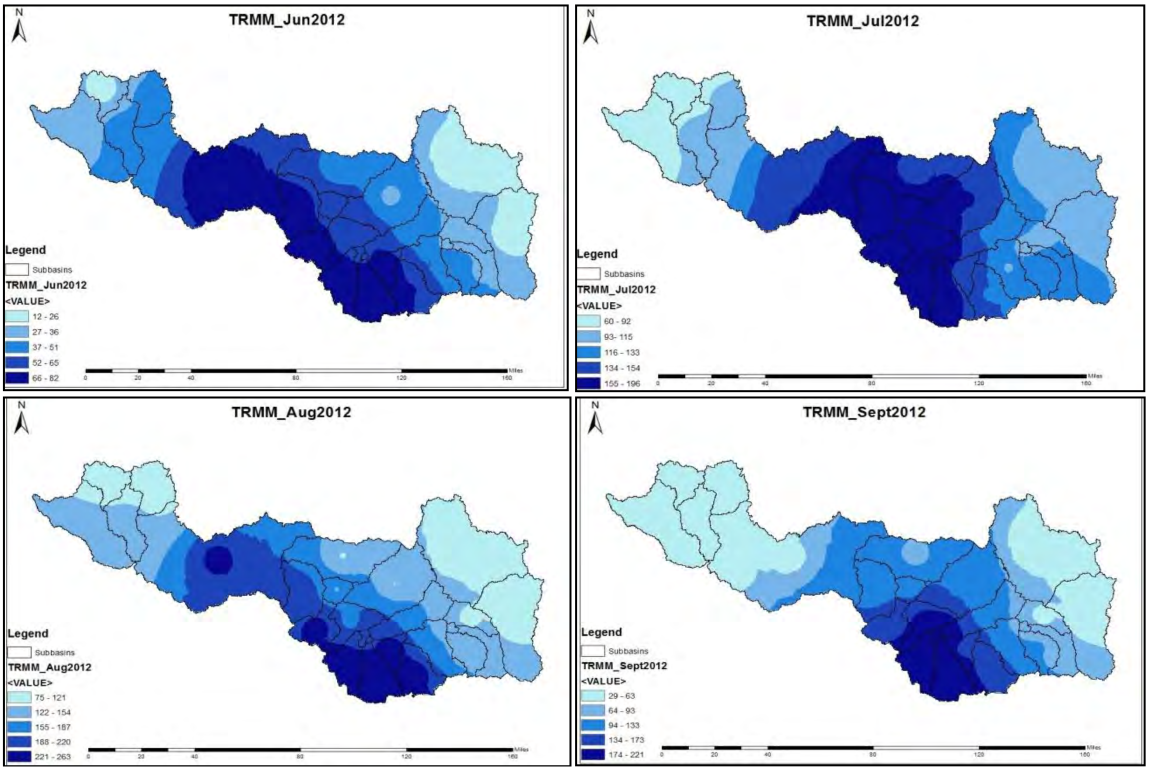

Figure 5.8 TRMM monthly rainfall distribution for major rainy months in 2012

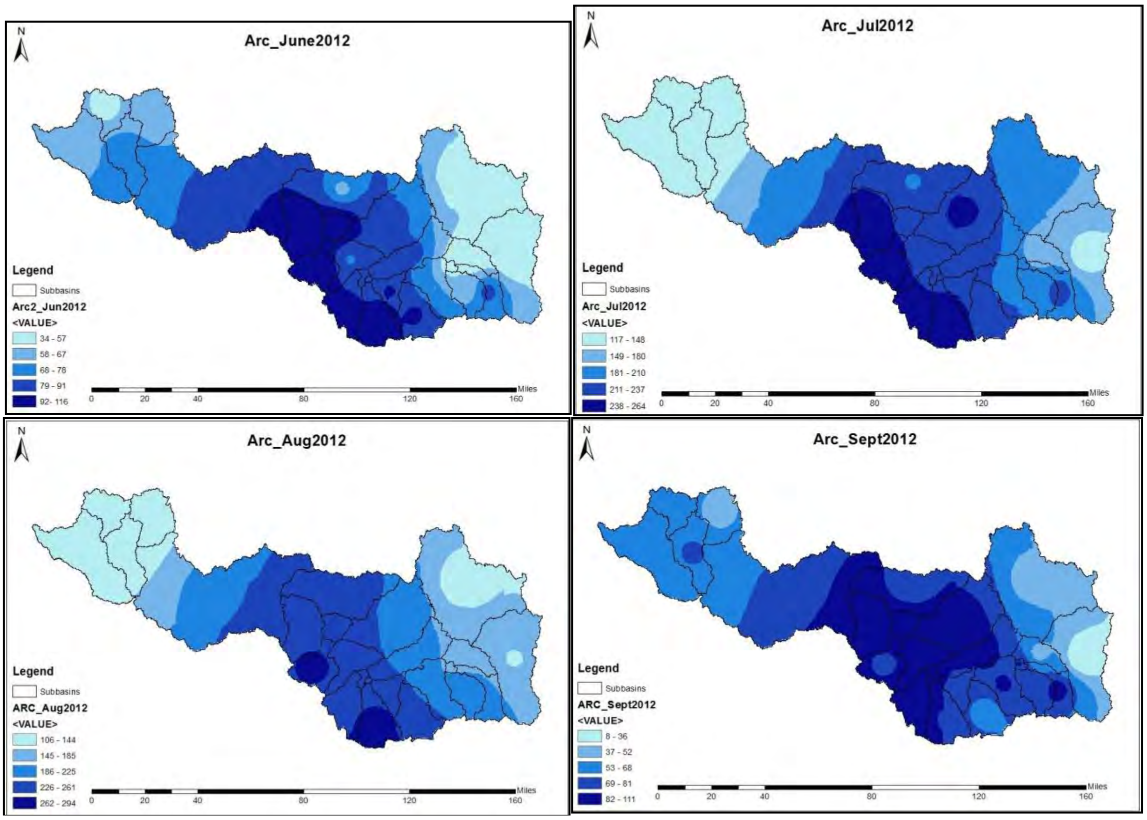

Figure 5.9 ARC-2 monthly rainfall distribution for major rainy months in 2012

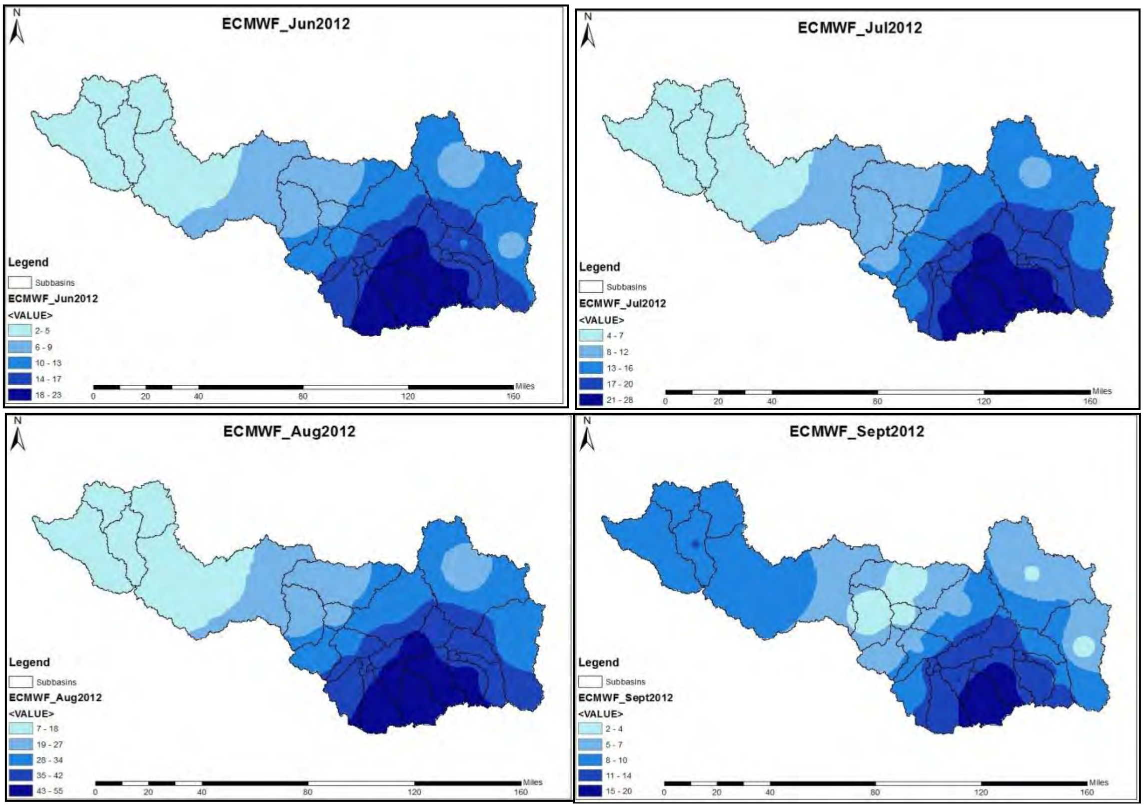

Figure 5.10 ECMWF monthly rainfall distribution for major rainy months in 2012

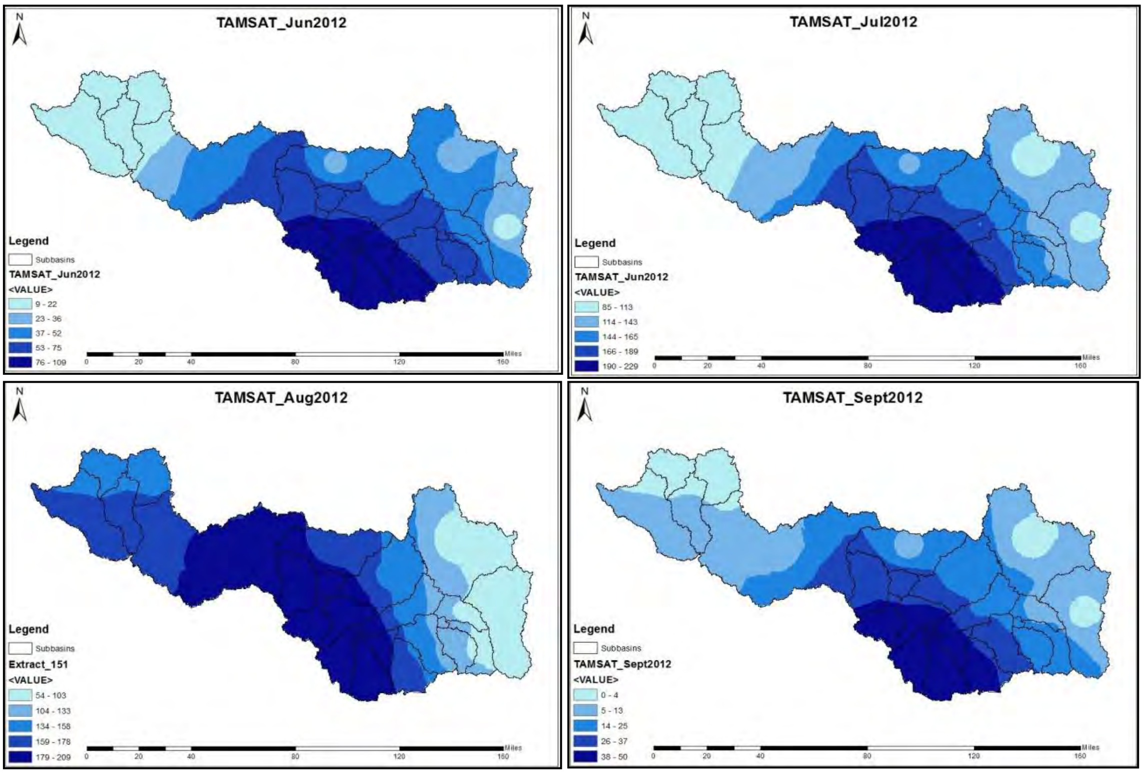

Figure 5.11 TAMSAT monthly rainfall distribution for major rainy months in 2012

CHAPTER 6

Simulating rainfall-runoff process

This Chapter focuses on rainfall-runoff generation derived using TRMM and ARC-2. Statistical performance measures such as NSE, PVE and R^2 are used to evaluate the performance of the model.

6.1. Comparing runoff from different rainfall products

6.1.1. Comparison at Daily Scale

Three rainfall products viz. TRMM, ECMWF and ARC-2 that performed comparatively better in rainfall validation were used for rainfall-runoff modelling. Though TAMSAT had reasonable performance, it was not used as it doesn't have temporal resolution at daily scale. Though the total rainfall at different time scale yielded by ECMWF was lowest, it performed better in terms of statistical performance measures such as RMSE, MAE and R^2. However, when modelled in rainfall-runoff models, it gave almost negligible discharge so has been avoided in discussion.

Figure 6.1 and 6.2 shows the runoff generated by TRMM, and ARC-2 respectively compared with actual daily discharge measured at El-gira station. Though the models were run separately for calibration period (2008-2010) and validation period (2011-2012); the results are jointly present in the below figures. Considering the statistical performance measure such as NSE, PVE and R^2, TRMM performs slightly better than ARC-2. Though they show good correlation, none of the products could capture the peak flows at daily scale.

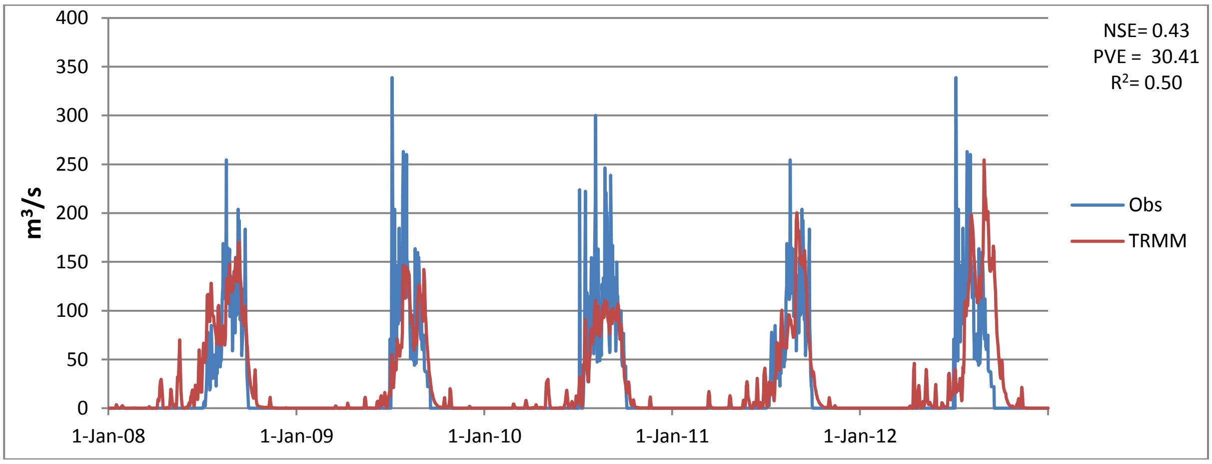

Figure 6.1 Simulated and observed hydrograph using TRMM

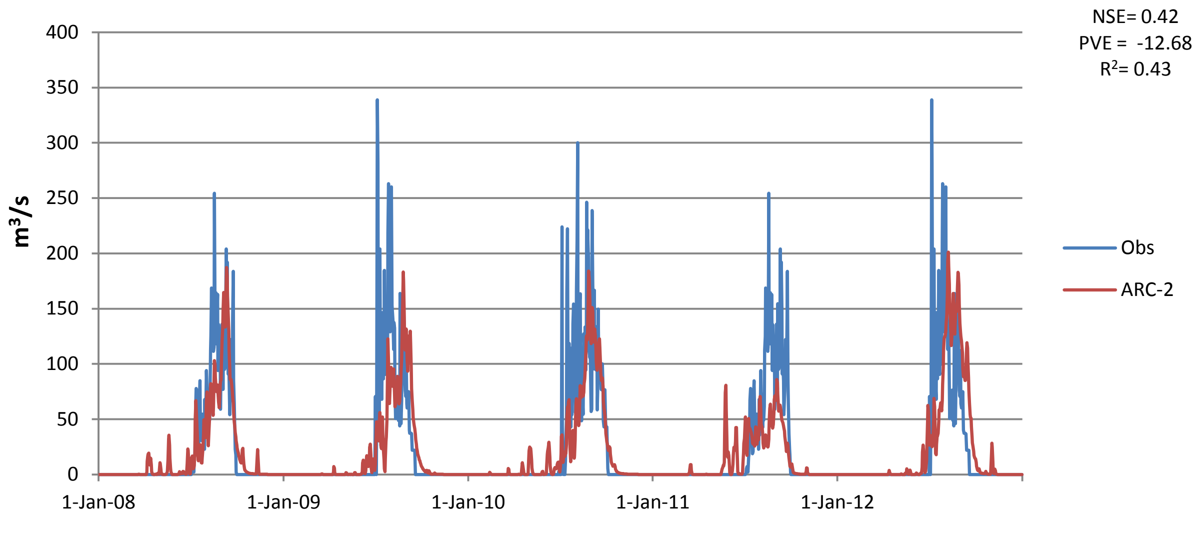

Figure 6.2 Simulated and observed hydrograph using ARC-2

The table 6.1 show the overall statistical summary of the model performance with different rainfall inputs. The values calculated are for both the calibration and validation years. Observing the discharge hydrograph and statistical performance measures, it can be seen that TRMM performs comparatively better than ARC-2 but there is no big significant difference in the performance measures.

Table 6-1: Rainfall-runoff performance measure at daily scale

SN	Rainfall Products	Performance Measures		
		NSE	PVE	R^2
1	TRMM	0.43	30.41	0.50
2	ARC-2	0.42	-12.68	0.43

6.1.2. Comparison at Monthly Scale

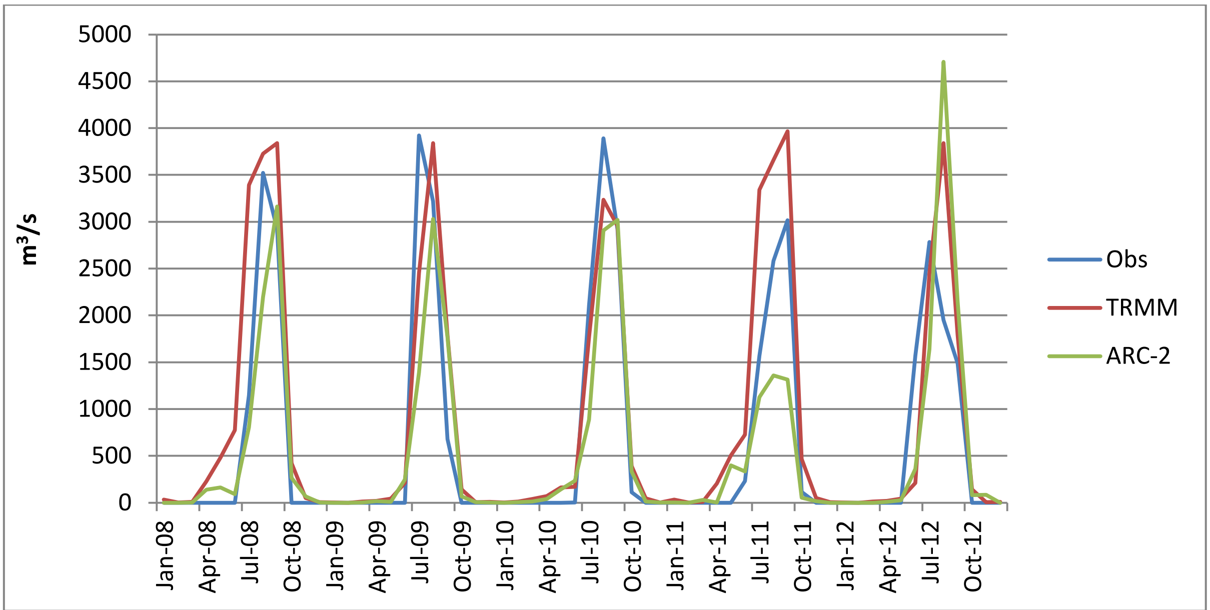

Figure 6.3 Simulated and observed hydrograph using three different rainfall products

Figure 6.5 shows the discharge yielded by each of the product along with actual discharge observed at station El-gira. At monthly scale, all of the SBRE products generated rainfall when compared with actual discharge performs quite better compared to daily scale. Table 6.2 shows that NSE of TRMM increased from 0.43 to 0.73 and ARC-2 from 0.42 to 0.67. Similarly, R^2 increased from 0.50 to 0.81 for TRMM and from 0.43 to 0.68 for ARC-2. The performance at monthly scale follows the pattern of daily scale. TRMM has quite better performance than ARC-2.

Table 6-2: Rainfall-runoff performance measure at monthly scale

SN	Rainfall Products	Performance Measures		
		NSE	PVE	R^2
1	TRMM	0.73	30.41	0.81
2	ARC-2	0.67	-12.68	0.68

CHAPTER 7

Event Based Flood Modelling

This Chapter discusses discharge forecasts using different rainfall products for three different events in 2011, 2010 and 2009. An evaluation on difference on time of peak and peak discharge is carried out with respect to actual discharge measurement. This chapter also include a comparison between rainfall inputs using daily TRMM and 3-hourly TRMM along with peak time and discharge evaluation.

7.1. Comparing flood simulation with different rainfall inputs

An event based hydrologic model was developed for flood modelling. Event based hydrologic model in HEC-HMS are better known for their ability to simulate peak discharges compared to continuous model. According to Chu and Steinman (2009), event based hydrologic model responds better individual rainfall event (e.g., quantity of surface runoff, peak, timing of the peak, detention) whereas continuous hydrologic model reproduces better hydrologic processes and phenomena (e.g. several rain events and their cumulative effect) over longer period in both dry and wet seasons.

TRMM and ARC-2, two SBRE were used for peak discharge simulation at the outlet, El-gira. Three highest peak events were chosen from the year 2011, 2010 and 2009 respectively for the comparison. Generally though forecasts are made for future, historical events were chosen in order to validate the forecast made with actual discharge measurement at outlet.

The figure 7.1 shows that in the year 2011, there was peak flood event on July 22 as measured in El-gira gauge station ARC-2 gives quite close results in term of volume of peak discharge and time of peak compared to other rainfall products. Similar comparatively good results are obtained for the year 2009 as well (figure 7.3). However, ARC-2 performs worst in year 2010 where it gives very high discharge and in a very different date then observed in outlet. The quantitative evaluation of two SBRE products is given in next sub-section, i.e. summary of evaluation.

TRMM performs reasonable in all of the three events (figure 7.1, 7.2 and 7.3). More importantly, it has consistent performance in overall three cases unlike ARC-2 which performs better in some years and not in others.

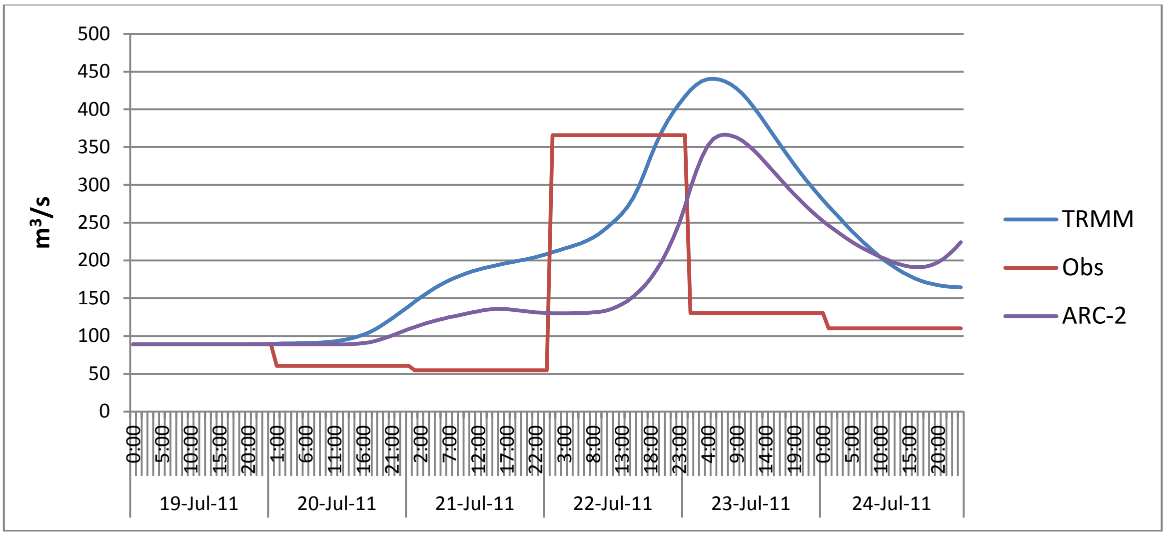

Figure 7.1 Results of peak discharge simulation with two cases for flood event in July 22, 2011

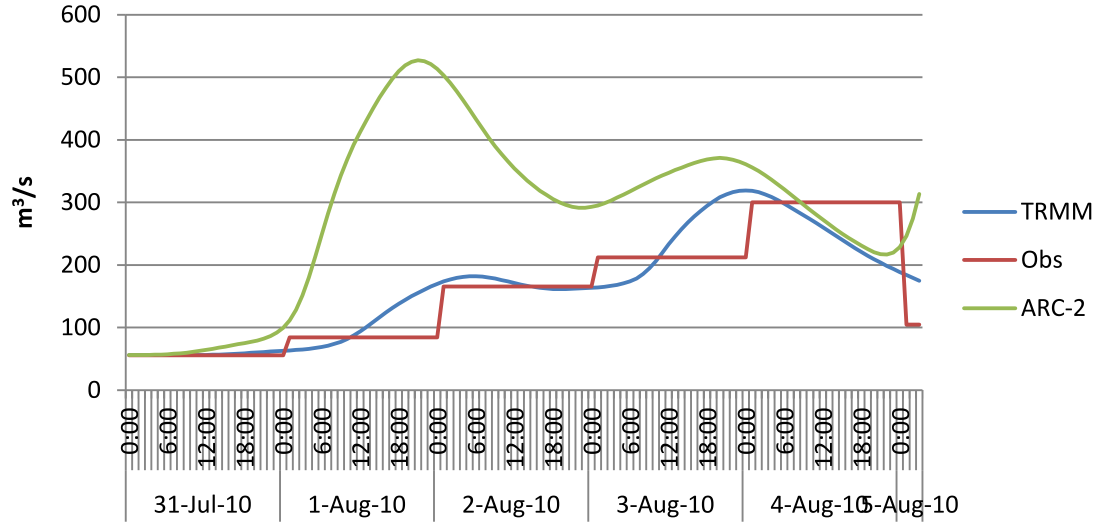

Figure 7.2 Results of peak discharge simulation with two cases for flood event in July 22, 2011

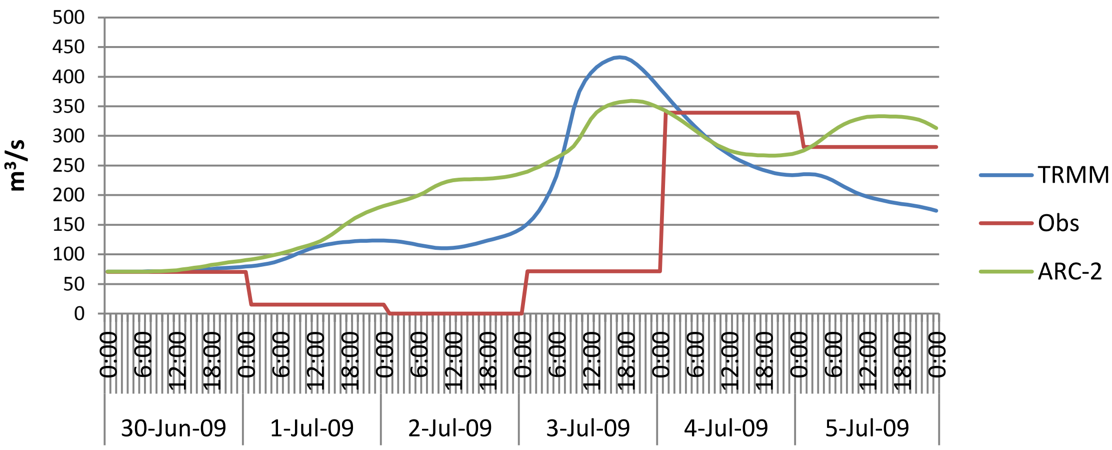

Figure 7.3 Results peak discharge simulation with two cases for flood event in July 4, 2009

Summary of Evaluation

The table 7.1 summarizes quantitative forecast quality in terms of time of peak and peak discharge. As it was daily model, peak hour could not be estimated so time of peak is evaluated based on days. Exact peak hours are calculated in next section where model is run at hourly scale. For the event in 2011, though it looks like observed peak discharge is on 22nd July and forecasted from TRMM and ARC-2 are on 23rd July, there is not a difference of day but rather only hours as can be clearly seen from figure 7.1. In terms of volume of discharge, it can be seem that ARC-2 gives quite good estimate. It only exceeds by 0.8 m^3/s.

However, ARC-2 doesn't give consistent performance when compared to the event in 2010. It largely overestimates the volume of peak discharge as well date of peak discharge is not coherent with actual observed discharge. TRMM gives rather satisfactory performance both in terms of date and peak discharge. It only exceeds the peak volume by 19.1 m^3/s and date of peak discharge is same as to the observed one, i.e. 4th August. In 2009, ARC-2 again performs superior than TRMM with least difference in peak volume discharge. TRMM also performs reasonable though it slightly overestimates the peak discharge.

Table 7-1: Quantitative forecast quality comparison

Events	Dataset	Date of Peak Discharge	Discharge (m^3/s)	Difference in Discharge (m^3/s)
2011	Observed	22July	366	
	TRMM	23 July	440.6	+74.6
	ARC-2	23 July	366.8	+0.8
2010	Observed	04 August	300.1	
	TRMM	04 August	319.2	+19.1
	ARC-2	01 August	527	+226.9
2009	Observed	04 July	339	
	TRMM	03 July	432.8	+93.8
	ARC-2	03 July	359	+20

7.2. Comparing flood simulation with different time-step rainfall inputs

The same flood events of the year 2011, 2010 and 2009 were compared with three hourly TRMM data against daily TRMM rainfall data. The hourly discharge at outlet was used instead of daily discharge to see if these products will be able to capture the hourly peak discharges. It was observed that the daily scale TRMM input rainfall though exceeds daily peak flows in above simulations; they underestimated the peak flows when compared at hourly discharge. In the contrary, it is seen from figure 7.4, 7.5 and 7.6 that the 3-hourly rainfall inputs gives better performance compare to daily rainfall input in the model. The quantitative performance measures are explained in next sub-section, summary of evaluation.

3-hourly TRMM rainfall inputs gave a very good result in 2011 where amount and time of peak hours are almost exact. In the event of August 4, 2010, there was some time lag in the peak discharge between 3-hourly based simulated discharge and observed discharge. Also, three hourly based simulated discharge has slightly lower peak volume discharge compared to observed discharge. However, compared to peak discharge simulated by daily TRMM, 3-hourly performs much better. The similar result follows for the year 2009 as well as shown in figure 7.6.

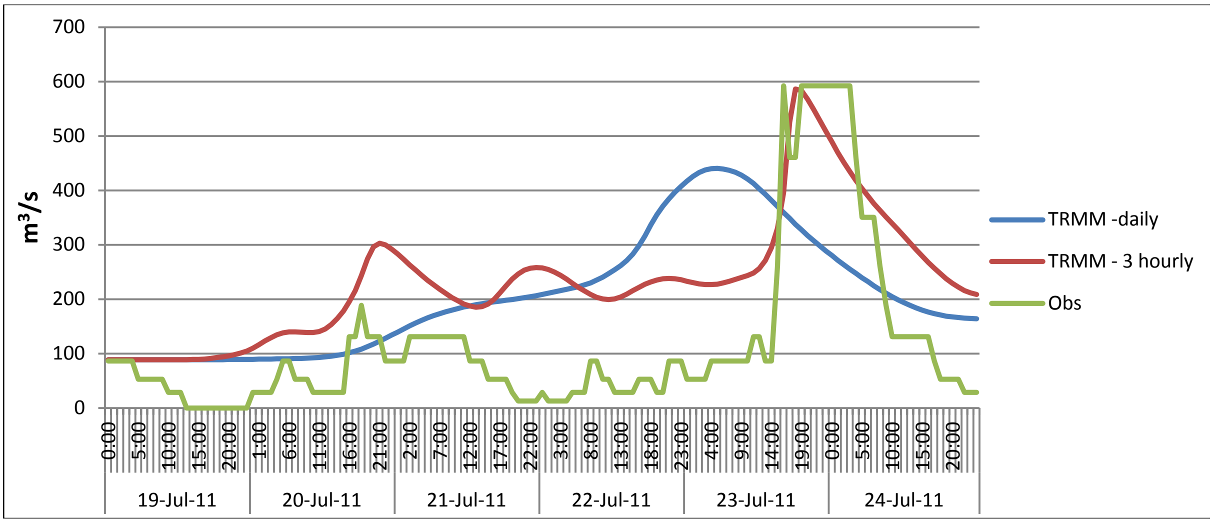

Figure 7.4 Results of peak flood simulation with two cases for flood event in July 22, 2011

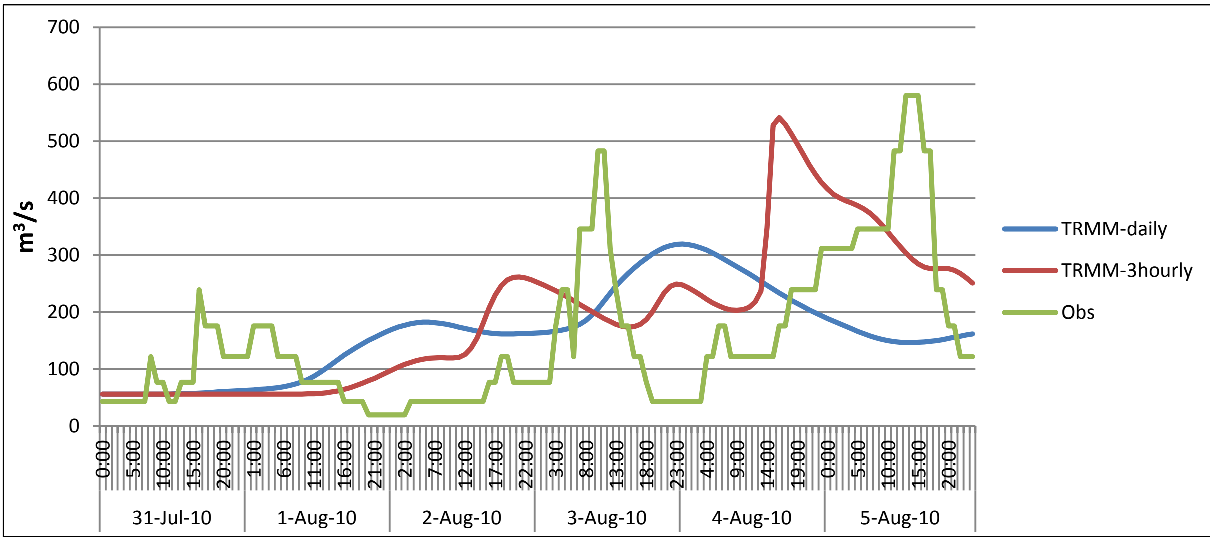

Figure 7.5 Results of peak flood simulation with two cases for flood event in August 4, 2010

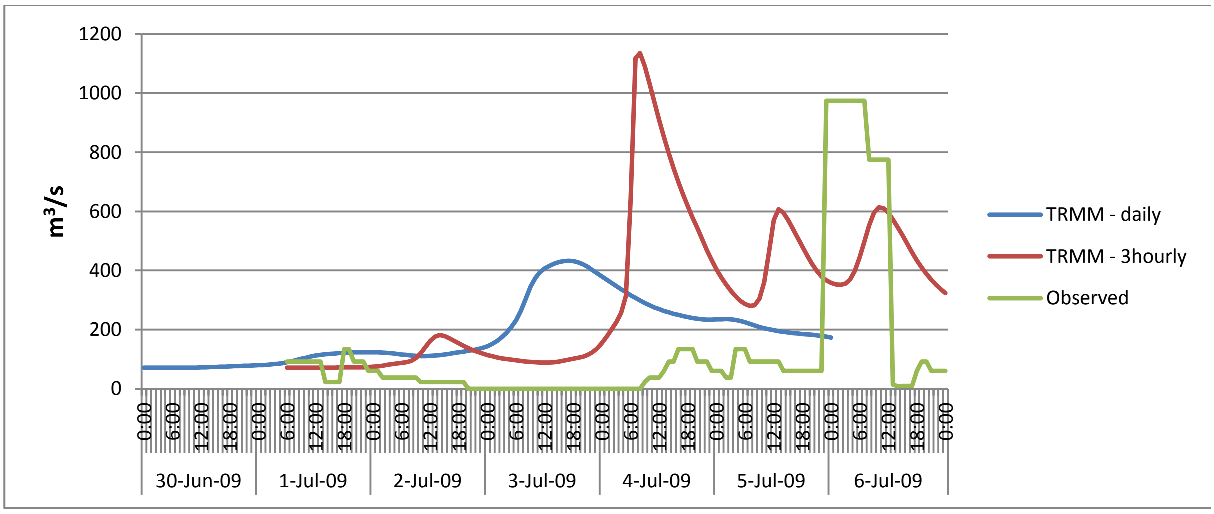

Figure 7.6 Results of peak flood simulation with two cases for flood event in July 6, 2009

Summary of Evaluation

From the table 7.2 it is obvious that 3-hourly TRMM rainfall outperforms daily TRMM in all aspects viz. time of peak discharge and volume of peak discharge. For the events in 2011 and 2010, 3-hourly corresponds well with actual observed discharge as well. There is very less difference in volume of peak discharge as well as time. However, it is not the case in 2009 when both of rainfall products don't simulate actual discharge. But this could also be due to reason that hourly discharge data was not available for 3rd July. There could also have been another big peak event in that day which daily and 3-hourly TRMM suggests but it is missing due to lack of measured data of that day.

Table 7-2: Quantitative forecast quality comparison between daily and 3-hourly TRMM

Events	Dataset	Date of Peak	Hour of Peak	Difference in time (hrs)	Discharge (m^3/s)	Difference in Discharge (m^3/s)
2011	Observed	23 July	16:00		592.3	
	TRMM Daily	23 July	05:00	+ 11	440.6	-151.7
	TRMM 3-hourly	23 July	18:00	- 2	586.2	-6.1
2010	Observed	05 August	13:00		580.3	
	TRMM Daily	04 August	0:00	+ 37	319.2	-261.1
	TRMM 3-hourly	04 August	16:00	+21	541.3	-39
2009	Observed	5 July	23:00		974.3	
	TRMM Daily	3 July	17:00	+54	432.8	-541.5
	TRMM 3-hourly	4 July	08:00	+39	1136.1	+161.8

CHAPTER 8

Conclusion and Recommendation

This Chapter discusses the conclusions derived on the basis of the whole study. It also consists of the recommendations for further study based on the results and limitations encountered.

8.1. Conclusion

i. The comparison of five SBRE at nearest sub-basin with observed rain gauge showed that TRMM outperforms RFE-2, ARC-2 and TAMSAT at daily[2], monthly and annual temporal resolution in terms of RMSE, MAE and R^2. RFE-2 gives unexpectedly high values whereas ECMWF indicated very low rainfall. Therefore rainfall estimates from RFE-2 and ECMWF were considered highly uncertain and were not used in further process of rainfall-runoff modelling. The reason for high RFE-2 is not clear, and could be related to data processing.

ii. The rainfall data comparison also shows that the performance of rainfall products increases over longer time period. For instance, R^2 increased from 0.04 to 0.85 for TRMM, from 0.283 to 0.70 for ARC-2, from 0.0007 to 0.002 for RFE-2 and from 0.03 to 0.04 to ECMWF. This finding corresponds with several studies in other regions given by literature.

iii. Average annual rainfall maps were derived for the whole basin based on four SBRE, i.e. TRMM, ECMWF, ARC-2 and TAMSAT. Though the range of rainfall measured in all of the four products vary greatly both in terms of volume of rainfall, they all have comparable spatial and temporal pattern throughout the basin, indicating highest rainfall in the middle parts compared to upper and lower regions. This matches mean annual rainfall measured by ground stations.

iv. The TRMM and ARC-2 rainfall were used in rainfall-runoff modelling using HEC-HMS model. The TRMM daily results were satisfactory with acceptable NSE, PVE and R^2. ARC-2 though had a good correlation with observed discharge, showed very poor NSE. The model performance greatly improves at monthly scale compared to daily scale. NSE of TRMM increased from 0.43 to 0.73 and ARC-2 from 0.42 to 0.67 from daily to monthly. Similarly, R^2 increased from 0.50 to 0.81 for TRMM and from 0.43 to 0.68 for ARC-2. It suggests that SBRE products could be very useful for monthly or longer time scale Rainfall-Runoff computations and water balance analysis.

[2] TAMSAT was not compared at daily scale

v. TRMM and ARC-2 Rainfall were used for event based flood modelling. TRMM gives consistent result compared to ARC-2, that for three different events in years 2011, 2011 and 2009. ARC-2 though performs better than TRMM in year 2011 and 2009, cannot maintain consistent result for 2010.

vi. Using daily TRMM data, the model captures daily peak discharge, but misses hourly peaks. Interestingly, 3-hourly TRMM rainfall input in event based HEC-HMS model could simulate well those hourly peak discharges both in terms of time of peak and flow rate.

vii. The study concludes SBRE products provide important insights to understand rainfall pattern in data scarce basin such as the Gash River Basin both in terms of spatial and temporal scale. SBRE based Rainfall-Runoff modelling could be useful in the computation of water balance components at monthly or longer time scale which could help to improve water management practice in the basin especially for agriculture in case of the Gash basin. Though daily SBRE products provides good daily discharge forecast, they still will miss the peak hourly discharges. Furthermore, carrying out continuous simulation using sub-daily data might offer better prospects for the flood forecasting but need further research.

8.2. Recommendation

i. The comparison of rain gauge measurement and nearby basin areal rainfall measurement showed that some products performed better than the others. However, to generalize this conclusion for the whole basin, it is important to access rainfall measurement from rain gauges in Eritrea and Ethiopia which were not available for this study. Hence, it is recommended to develop a cross-country data sharing mechanism as well as maximum use of available ground rain-gauges for the comparison.

ii. TRMM showed quite promising results both in rainfall validation and runoff computation. However to reduce biases, a further study to derive suitable correction factor is recommended.

iii. The daily TRMM rainfall could not generate well the peak daily flows. However, the use of 3-hourly data showed promising results in event based flood modelling. Hence, the use of 3-hourly TRMM rainfall in continuous rainfall-runoff model is recommended for operational flood forecasting. However, real time version of TRMM should be used instead of research version for operational purpose.

iv. This research is limited to only the first step of rainfall-runoff modelling. The second phase of flow (hydraulic) routing of flood wave is recommended for the future research in the Gash basin.

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Appendices

Appendix A Parameters used in continuous rainfall-runoff model

Table A.1 Canopy and Surface

	Canopy		Surface	
Sub-basins	Initial Storage (%)	Max Storage (mm)	Initial Storage (%)	Max Storage (mm)
W620	0	1	0	47.79
W610	0	1	0	47.75
W600	0	1	0	20.83
W590	0	1	0	1.05
W580	0	1	0	32.65
W570	0	1	0	3.53
W560	0	1	0	51.07
W550	0	1	0	42.03
W540	0	1	0	2.73
W530	0	1	0	30.32
W520	0	1	0	56.96
W510	0	1	0	129.18
W500	0	1	0	40.24
W490	0	1	0	28.08
W450	0	1	0	38.61
W430	0	1	0	16.79
W420	0	1	0	109.11
W410	0	1	0	201.20
W400	0	1	0	57.82
W380	0	1	0	98.93
W370	0	1	0	324.63
W350	0	1	0	106.86
W340	0	1	0	50.77
W330	0	1	0	49.92
W320	0	1	0	36.14

Table A.2 Parameters used in Soil Moisture Accounting

Sub-basins	Soil (%)	GW 1 (%)	GW 2 (%)	Max Infiltration (mm/hr)	Impervious	Soil Storage (mm)	Tension Storage (mm)	Soil Percolation (mm/hr)
W620	0	0	0	4.5	25.6	300	200	3
W610	0	0	0	4.5	9	300	200	3
W600	0	0	0	4.5	11	300	200	3
W590	0	0	0	4.5	12	300	200	3

W580	0	0	0	4.5	11	300	200	3
W570	0	0	0	4.5	10	300	200	3
W560	0	0	0	4.5	10	300	200	3
W550	0	0	0	4.5	14.5	300	200	3
W540	0	0	0	4.5	15.5	300	200	3
W530	0	0	0	4.5	10	300	200	3
W520	0	0	0	4.5	10	300	200	3
W510	0	0	0	4.5	11	300	200	3
W500	0	0	0	4.5	9	300	200	3
W490	0	0	0	4.5	10	300	200	3
W450	0	0	0	4.5	22	300	200	3
W430	0	0	0	4.5	8	300	200	3
W420	0	0	0	4.5	8	300	200	3
W410	0	0	0	4.5	9	300	200	3
W400	0	0	0	4.5	10	300	200	3
W380	0	0	0	4.5	7	300	200	3
W370	0	0	0	4.5	5	300	200	3
W350	0	0	0	4.5	2.5	300	200	3
W340	0	0	0	4.5	4	300	200	3
W330	0	0	0	4.5	3	300	200	3
W320	0	0	0	4.5	3.5	300	200	3

Table A.3 Parameters used in Soil Moisture Accounting

Sub-basins	GW 1 Storage (mm)	GW 1 Percolation (mm/hr)	GW 1 Coefficient (hr)	GW 2 Storage (mm)	GW 2 Percolation (mm/hr)	GW 2 Coefficient (hr)
W620	80	2	150	45	1	350
W610	80	2	150	45	1	350
W600	80	2	150	45	1	350
W590	80	2	150	45	1	350
W580	80	2	150	45	1	350
W570	80	2	150	45	1	350
W560	80	2	150	45	1	350
W550	80	2	150	45	1	350
W540	80	2	150	45	1	350
W530	80	2	150	45	1	350
W520	80	2	150	45	1	350
W510	80	2	150	45	1	350
W500	80	2	150	45	1	350
W490	80	2	150	45	1	350
W450	80	2	150	45	1	350
W430	80	2	150	45	1	350

W420	80	2	150	45	1	350
W410	80	2	150	45	1	350
W400	80	2	150	45	1	350
W380	80	2	150	45	1	350
W370	80	2	150	45	1	350
W350	80	2	150	45	1	350
W340	80	2	150	45	1	350
W330	80	2	150	45	1	350
W320	80	2	150	45	1	350

Table A.4 Parameters used in Clark Unit Hydrograph

Sub-basins	Time of concentration (hr)	Storage Coefficient (hr)
W620	2.3514	7.0541
W610	2.5134	7.5401
W600	1.6904	5.0712
W590	0.46988	1.4096
W580	2.1533	6.4599
W570	0.89328	2.6798
W560	2.2986	6.8959
W550	2.7056	8.1168
W540	0.69584	2.0875
W530	1.7601	5.2803
W520	3.0925	9.2774
W510	2.6397	7.9192
W500	2.0372	6.1117
W490	1.2967	3.8901
W450	2.5163	7.5488
W430	1.5228	4.5685
W420	3.7653	11.296
W410	3.36	10.08
W400	2.9243	8.7728
W380	4.176	12.528
W370	5.6936	17.08078
W350	4.6688	14.006
W340	2.5923	7.777
W330	3.0666	9.1997
W320	2.8466	8.5397

Table A.5 Parameters used in Linear Reservoir

Sub-basins	GW 1 Initial (M^3/S)	GW 1 Coefficient (hr)	GW 1 Reservoirs	GW 2 Initial (M^3/S)	GW 2 Coefficient (hr)	GW 2 Reservoirs
W620	0.02	150	1	0.01	350	1
W610	0.02	150	1	0.01	350	1
W600	0.02	150	1	0.01	350	1
W590	0.02	150	1	0.01	350	1
W580	0.02	150	1	0.01	350	1
W570	0.02	150	1	0.01	350	1
W560	0.02	150	1	0.01	350	1
W550	0.02	150	1	0.01	350	1
W540	0.02	150	1	0.01	350	1
W530	0.02	150	1	0.01	350	1
W520	0.02	150	1	0.01	350	1
W510	0.02	150	1	0.01	350	1
W500	0.02	150	1	0.01	350	1
W490	0.02	150	1	0.01	350	1
W450	0.02	150	1	0.01	350	1
W430	0.02	150	1	0.01	350	1
W420	0.02	150	1	0.01	350	1
W410	0.02	150	1	0.01	350	1
W400	0.02	150	1	0.01	350	1
W380	0.02	150	1	0.01	350	1
W370	0.02	150	1	0.01	350	1
W350	0.02	150	1	0.01	350	1
W340	0.02	150	1	0.01	350	1
W330	0.02	150	1	0.01	350	1
W320	0.02	150	1	0.01	350	1

Table A.6 Parameter used in PET

Months	Rate (mm/month)	Coefficient
January	100.6364	0.7
February	113.9455	0.7
March	171.1545	0.7
April	191.9636	0.7
May	208.7909	0.7
June	172.9455	0.7
July	130.3909	0.7
August	85.873	0.7
September	92.118	0.7
October	142.4455	0.7

November	121.7818	0.7
December	111.1909	0.7

Appendix B Parameters used in the event flood modelling

Table B.1 Parameters used in SCS Curve Number

Sub-basin	Initial Abstraction	Curve No.	Impervious
W620	3.24	94	0
W610	3.24	94	12.5
W600	5.02	91	10
W590	5.02	91	11
W580	3.24	94	14
W570	5.02	91	10
W560	3.24	94	13
W550	5.02	91	9
W540	3.24	94	10
W530	3.24	94	11
W520	5.02	91	11.5
W510	3.24	94	12
W500	5.02	91	8
W490	5.02	91	12
W450	5.02	91	8
W430	3.24	94	15
W420	3.24	94	22
W410	8.27	86	11.6
W400	3.24	94	7
W380	3.24	94	13
W370	5.02	91	5
W350	8.27	86	3.5
W340	8.27	86	4
W330	8.27	86	2.5
W320	8.27	86	3

Table B.2 Parameters used in Synder Unit Hydrograph

Sub-basin	lag time	Peaking Coefficient
W620	2.9392	0.9
W610	3.1417	0.9

W600	2.113	0.9
W590	0.5873	0.9
W580	2.6916	0.9
W570	1.1166	0.9
W560	2.8733	0.9
W550	3.382	0.9
W540	0.8698	0.9
W530	2.2001	0.9
W520	3.8656	0.9
W510	3.2997	0.9
W500	2.5465	0.9
W490	1.6209	0.9
W450	3.1453	0.9
W430	1.9036	0.9
W420	4.7067	0.9
W410	4.2	0.9
W400	3.6554	0.9
W380	5.22	0.9
W370	7.117	0.9
W350	5.836	0.9
W340	3.2404	0.9
W330	3.8332	0.9
W320	3.5582	0.9

Table B.3 Parameters used in Recession

Sub-basin	Initial Discharge	Recession Constant	Threshold type	Ratio to Peak
W620	2.617195	1	Ratio to Peak	0.25
W610	2.614987	1	Ratio to Peak	0.25
W600	1.14093	1	Ratio to Peak	0.25
W590	0.057426	1	Ratio to Peak	0.25
W580	1.788073	1	Ratio to Peak	0.25
W570	0.193123	1	Ratio to Peak	0.25
W560	2.797046	1	Ratio to Peak	0.25
W550	2.301934	1	Ratio to Peak	0.25
W540	0.149425	1	Ratio to Peak	0.25
W530	1.660692	1	Ratio to Peak	0.25
W520	3.119895	1	Ratio to Peak	0.25
W510	7.075134	1	Ratio to Peak	0.25
W500	2.204099	1	Ratio to Peak	0.25
W490	1.538008	1	Ratio to Peak	0.25

W450	2.114656	1	Ratio to Peak	0.25
W430	0.919762	1	Ratio to Peak	0.25
W420	5.975914	1	Ratio to Peak	0.25
W410	11.01949	1	Ratio to Peak	0.25
W400	3.166985	1	Ratio to Peak	0.25
W380	5.418496	1	Ratio to Peak	0.25
W370	17.77997	1	Ratio to Peak	0.25
W350	5.852508	1	Ratio to Peak	0.25
W340	2.780827	1	Ratio to Peak	0.25
W330	2.733938	1	Ratio to Peak	0.25
W320	1.979486	1	Ratio to Peak	0.25