Available online at www.ejournals.uofk.edu
UofKEJ Vol. 9 Issue 2 pp. 25- 31 (August-2019)

UNIVERSITY OF KHARTOUM ENGINEERING JOURNAL (UofKEJ)

Potential of Satellite Rainfall Estimates as Inputs for Flood Forecasting: Case Study Gash River, Sudan.

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ABSTRACT: This study is an attempt to test the potential of using real time Satellite Rainfall Estimates (SRE) data for hydrological modeling. Tropical Rainfall Measurement Mission (TRMM-3B42RT V7) SRE was evaluated against observed rain gauge data in Gash river catchment. The TRMM was evaluated against intensity as well as elevation dependency. The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) software of the Army Corps of Engineering of the USA was used to simulate the rainfall - runoff process. The performance of TRMM was found to underestimate the rainfall for most of the events, the underestimation increases with the increase in elevation. TRMM data set was biased corrected and used as input to derive the hydrological model. Observed hydrographs at the catchment outlet were compared to the simulated flow hydrographs using events and continuous modeling. The results of hydrological modeling showed that events based modeling performed better, the coefficient of determination (R^2) vary between 0.87 to 0.96 while Nash-Sutcliffe Efficiency (NSE), vary from 0.84 to 0.96 and Root Mean Square Error (RMSE) vary from 45 to 118.3 m^3/s. While the same statistics for continuous modeling showed, (NSE = 0.65) and (RMSE 44.5 m^3/s). These results reflect the high potential of TRMM data set as inputs for hydrological modeling and flood forecasting in the Gash river and other basins with similar characteristics.

Keywords: *Gash basin; flash flood forecasting; rainfall validation; HEC-HMS; TRMM-3B42RT.*

1. INTRODUCTION

Floods problems have drawn more attention worldwide as they occur more frequently and affect more than 75% of the world's countries [1]. Compared to other natural disasters, flooding has the potential to cause the greatest loss of life and damage to properties [2]. Flooding can be managed through two approaches; structural and/or non-structural [3]. Structural approach depends on building of protection or training works and non-structural approach depends on building of flood forecast systems. The former is very expensive and laborious that is why most of the time building flood forecast system is the most effective and easiest way for managing flooding. Flood forecasting can be defined as estimating the future stages or flows and their time sequences at selected points along the river course [2, 4].

Rainfall data is the most crucial input for analyzing rainfall-runoff relationship and drives flood forecast models [5, 6]. Decline of rain gauge networks encourage researchers to investigate the utility of SREs as alternative in hydrological modeling [7, 8, 9, 10]. However, there were many uncertainties associated with the SRE products, they cannot be used for any hydrological modeling without validation [11]. This study is an attempt to validate one of the SRE products which is Tropical Rainfall Measurement Mission (TRMM-3B42RT) in Gash river basin.

Gash in eastern Sudan, is a flashy (seasonal) river. The river frequently breaches the embankment and strikes Kassala city and its surrounding areas causing large damages to lives and properties. The existence of dense settlement around Gash river and the location of the city itself on the flood plain, make it vulnerable to high flooding. Over 50% of the urban land in the Gash plain is still under threat of flooding [12, 13]. Absence of observed hydro-meteorological data in the catchment, made rainfall-runoff simulation a challenging task [14], few studies addressed the issue. Bashar, et al. [3] tested the utility of Space Technology in managing the water resources in Gash river. The study used geo-spatial stream flow model, as simulation tool and Rain Fall Estimate (RFE) data set as input, which was not validated with ground rainfall. The model captures the peak with reasonable accuracy. The reproduced hydrograph is comparable to the observed one (R^2= 0.56). Rokaya, [14] tried to simulate rainfall-runoff process and develop flood simulation model for flood forecast and irrigation water management in Gash basin. He used four different SREs; RFE, TRMM, ARC-2 and ECMWT as inputs to run HEC-HMS model. TRMM and RFE showed good performance as well as events hydrological modeling, the only limitation of the study he used data from Kassala station only for the validation of SREs, which is outside the effective catchment area. Giriraj and Sharma, [15] tried to develop a flood simulation model for best water allocation for spate irrigation in Gash scheme. In general, the absence of reliable observed discharge and rainfall data were the common limitations among these studies.

Regarding validation of SREs in eastern Sudan catchments in general (Ethiopia & Eritrea), Habib el. al. [16] studied Climate Prediction Centre Morphing Technique (CMORPH) in the Blue Nile River catchment where three different bias correction schemes were used. Significant changes on the model parameters were obtained which improve the model output.

This is the first study that addresses the issue of validating TRMM data, in eastern Sudan in general and Gash basin in particular. For the first time, the observed rainfall data from upper catchment and reliable discharge data were used to calibrate SREs over Gash basin. TRMM-3B42RT was bias-corrected using ground rainfall and used as an input to drive a hydrologic model developed in HEC-HMS software. New reliable discharge data for the years 2015-2018 were obtained for calibration of the hydrological model.

2. MATERIALS AND METHODS:

2.1 Study Area

The Gash river is a braided stream of fluent type with a shallow alluvial bed and wide flood plains [17]. The catchment of the river lies between longitudes of 36°00′ and 40°00′ E and latitudes of 14°00′ and 16°00′ N in the highlands of Eritrea & Ethiopia (Fig. 1). The Gash river crosses Kassala city, capital of Kassala state, and divides it into two parts. Flood frequently breaches the embankment and invades the city causing great damages. Recently, flooding has become a recurrent phenomenon, the most serious floodings were experienced during the years 1975,1983,1988,1993,1998, 2003, 2007,2014, and recently in 2016. The topography of the catchment area is very complex, with elevation varying from more than 3000 meters above mean sea level in Eritrea and Ethiopia to 500 meters in the Sudanese plain. The flow of the river is highly variable, with an average annual discharge of 650×10^6 m^3 at Gera gage station, at the Eritrean-Sudanese border. The mean annual rainfall over the basin is about 500 mm/year, and the main rainy moths are June to September with maximum in July and August.

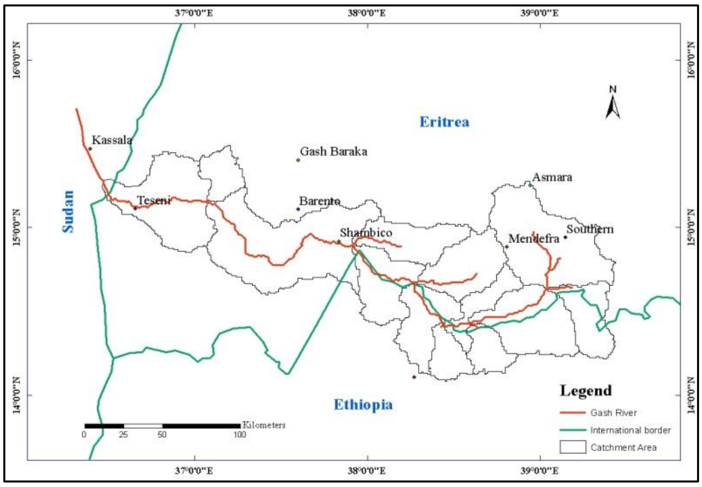

Fig. 1. Location map of Gash river catchment and rain gauges

2.2. Data Availability

2.2.1. Ground rainfall

Daily rainfall data are available for Kassala station from Sudanese Meteorological Authority (SMO) for the period from 2000 to 2018, but Kassala station is out site the effective catchment of the river besides it is in low elevation while the whole catchment is hilly area. However, monthly rainfall data are available for the period from 2014-2016, from seven Eritrean stations within the catchment (Asmara, Southern, Teseni, Barento, Shambico, Gash baraka and Mendefra) as shown in fig. 1. The monthly data were last accessed in September 2017 from the web site (http://www.eritrea.be/old/eritrea-climate.htm). It is the only available ground rainfall data, which was used for the validation of SRE.

2.2.2. Tropical Rainfall Measuring Mission (TRMM)

TRMM-3B42RT V7 data set, which has been used in this study, are available since 1998 up to date. It is freely available in public domain, with spatial resolution of (0.25°X 0.25°) grids and temporal resolution of 3 and 24 hours. The data accessed through the link www.giovanni.gsfs.nasa.gov/giovanni/#service. TRMM was aggregated from daily to monthly data to be used for the analysis.

2.2.3. Discharge data

Discharge measurements in flashy rivers is a challenging task. The only applicable methods for discharge measurements in Gash river is the traditional float method. Observed discharge data are available from the Gash River Training Unit (GRTU) of the Sudanese Ministry of Water Resources, Irrigation and Electricity (MoWRI&E) for the period from 1999 up to date. Many studies indicated that these data are not reliable [3, 14, 15]. New reliable discharge data were obtained for the years 2015 to 2018 at Gera & Kilo 1.5 stations using float method. This new data was used in this study for calibration of the model.

2.3 Comparison of TRMM with Ground Measurements

SRE were contaminated, the products should be evaluated against ground observation prior uses for any hydrological studies [10, 18, 19]. There are two ways for validating SRE data; either through ground truthing or hydrological modeling [20]. The former is to compare the SRE data set to ground observation, and the later based on the ability of SRE to reproduce the outflow hydrograph at the basin outlet. Both methods were used in this study.

2.3.1. Ground truthing

There are three methods for ground truthing [20]; point to grid, grid to grid and area-average. Two methods were used here; point to grid and area-average. The third method was not used because average ground rainfall over single grid is not available due to poor network.

Point vs grid analysis

Point-grid method has been used to compare SRE data to gauge rainfall observations. Point rainfall data at the seven stations within the Gash basin were compared to the corresponding grid of TRMM rainfall dataset. The analysis was carried out for the period of overlapping between TRMM and available ground rainfall data (i.e. 2014-2016).

Area-average analysis

In this method area-average SRE is compared to area-average gauge data in the whole basin. Among the different interpolation techniques available to compute area-average rainfall, Thiessen polygons method were used here to generate area-average ground rainfall [21, 22]. The area-average SRE was downloaded directly from the source link as time series data.

2.3.2. Hydrologic modeling.

The ground truthing procedure for rainfall validation work good if dense network is available [20]. The available rainfall data was used here for computing the rainfall bias and to correct SRE. The corrected SRE was used as input for hydrological modeling. The hydrological modeling is based on the ability of the SRE to reproduce the runoff hydrograph at the catchment outlet. Accurate measurement of the discharge at the outlet (Gera) is required for this method. New discharge measurements for the years 2015 to 2018 were conducted to be used in the validation of the SRE.

HEC-HMS software is used for building the hydrological model to simulate the rainfall-runoff processes. HEC-HMS was developed by the Hydrologic Engineering Center of Army Corps of Engineering of the USA [23]. It is a numerical model that includes a large set of methods to simulate watershed, channel, and water-control structure behavior, thus predicting flow, stage, and timing [24]. The model developed to simulate the precipitation-runoff processes and to be applicable in a wide range of geographic areas for solving the widest possible range of Hydrological problems. The physical representation of a watershed is accomplished with a basin mode. Hydrologic elements are connected in a dendritic network to simulate runoff processes. Meteorological data analysis is performed by the meteorological model and includes precipitation, evapotranspiration, and snowmelt. Assortments of different methods are available to simulate infiltration losses and transform excess precipitation into surface runoff. The software also includes hydrologic routing methods for simulating flow in open channels. The catchment pre-processing was done in Arc-hydro tools extension imbedded in ArcGIS software then imported to HEC-HMS.

2.3.3. Elevation zones

Rainfall estimates are sensitive to orography [7, 10]. Since the catchment topography is relatively complex (elevation is ranging between 500 m to more than 3000 m above mean sea level), TRMM data set need to be checked for elevation dependency. Earlier studies that evaluated the performance of satellite-based precipitation products indicated that the algorithms were still challenged at high elevations [16, 21]. Two elevation zones were considered in this study for the elevation dependency; less than 600 m (low land) and greater than 2000 m (high land).

2.4. Bias Correction for TRMM Data

Systematic and random errors are some of the contaminants that significantly affect the performance of SRE, especially in flash flood forecast [16]. Therefore, such products should be refined before being used for hydrologic analysis. Efforts has been made by many researchers to employ different bias-correction schemes to validate the SRE [22]. In this study, a multiplicative bias was used, TRMM was compared to ground rainfall as given in equation (1) and the bias factor was calculated at monthly basis because daily ground data are not available in the catchment.

Equation (2) explains how TRMM were corrected.

$$Bias\ factor_m = \frac{\mathrm{TRMM}_m}{\mathrm{GR}_m} \qquad (1)$$

Where:

Bias factor $_m$, is the bias factor for a specific month (m)

TRMM $_m$ is the monthly raw TRMM for the month (m)

GR $_m$ is the monthly ground rainfall for the month (m)

The correction for TRMM was made using following equation:

$$\mathrm{TRMM_m\ (corr.)} = \frac{\mathrm{TRMM_m}}{\mathrm{Bias\ factor}\ _m} \qquad (2)$$

Where:

TRMM $_m$ (corr.) is the corrected monthly TRMM for month (m)

TRMM $_m$ is the monthly raw TRMM data

The computed monthly bias factor is used to validate the daily and hourly data. The percentage bias is calculated as shown in equation 3 below:

$$\text{Percentage bias}\ _m = \frac{(\mathrm{TRMM}_m - \mathrm{GR}_m)}{\mathrm{GR}_m} * 100 \qquad (3)$$

Where:

TRMM $_m$ and GR $_m$ as explained above

2.5. Evaluation of Rainfall Data

Three statistical tests of error functions were used to evaluate the performance of the satellite rainfall data namely; Nash-Sutcliffe Efficiency (NSE), Root Mean Square Error (RMSE) and Coefficient of determination (R^2). The equations for the statistical test of error functions were shown in the following equations (equations 4 to 6):

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(Q_{i\ obs} - Q_{i\ sim})2}{\sum_{i=1}^{n}(Q_{i\ obs} - \bar{Q}_{obs})2} \qquad (4)$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Q_{i_{sim}} - Q_{i_{obs}})^2} \qquad (5)$$

$$\mathrm{R} = \frac{\sum_{i=1}^{n}(Q_{i\ sim} - \bar{Q}_{sim})(Q_{i\ obs} - \bar{Q}_{obs})}{\sum_{i=1}^{n}((Q_{i\ sim} - \bar{Q}_{sim})^2)^{0.5}\ X \sum_{i=1}^{n}((Q_{i_{obs}} - \bar{Q}_{obs})^2)^{0.5}} \qquad (6)$$

Where, Q_{obs} is the observed values, Q_{sim} is the estimated values, $\bar{Q}_{sim}$ is the average simulated values, $\bar{Q}_{obs}$ is the average observed values and n is the number of data.

3. RESULTS AND DISCUSSIONS:

3.1. Point Rainfall Analysis

The monthly TRMM single grid rainfall data were compared to the monthly ground point rainfall data for each individual station. The rainy season (June to September) was selected for the analysis, for the period 2014 to 2016. Most of the stations showed under-estimation of rainfall except Shampico which showed overestimation. The results of statistical analysis showed good correlation between SRE and the observed rainfall for all stations except Shampico (less than 0.50) (fig. 2). The value of R^2, is deteriorating with the increase in elevation (i.e. low elevation station; Teseni, Barento, & Gash Baraka) showed higher R^2 values than the high elevation stations (Asmara & Southern).

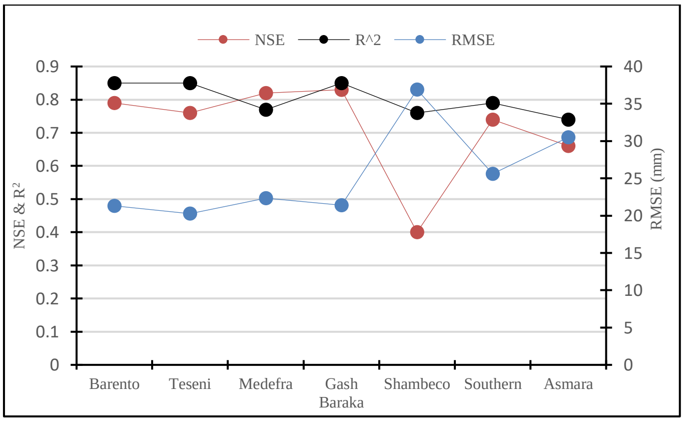

Fig. 2. Statistical measures of performances for different gauging stations in Gash basin

The bias factors along with percentage bias were calculated for each individual month for the period 2014 to 2016. The results for each single station were given in (figs. 3 & 4) for July and August months.

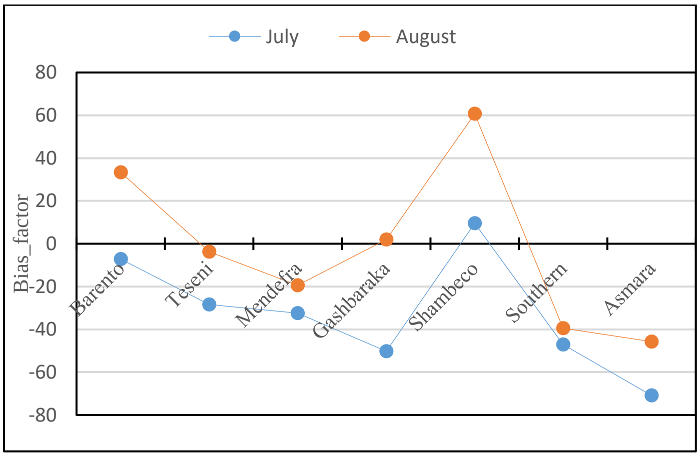

Fig. 3. Bias factor for July and August for different gauging stations in Gash basin

3.2. Area-average Rainfall Analysis over Whole Basin

The area-average SRE data were compared to area-average gauge rainfall data, the performance measures were given in table 1. For monthly bias, the four months of the rainy season were selected namely; June, July, August and September. The values of percentage bias and bias factor were shown in table 2. In general, the SRE tends to underestimate the rainfall over the whole basin (Percentage bias = -0.88).

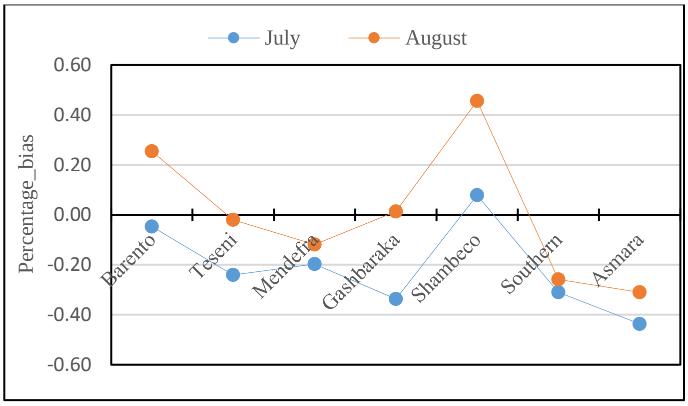

Fig. 4. Percentage bias for July and August for different gauging stations in Gash basin

Table 1. Performance measures for area-average rainfall

Performance measure	value
R^2	0.95
NSE	0.87
RMSE (mm)	2.55

Table 2. Percentage bias and bias factor for whole basin for rainy months

Month	Bias factor	Percentage bias
June	0.75	-0.25
July	0.84	-0.16
August	0.96	-0.04
September	0.97	-0.03
average	0.88	-0.12

A multiplicative bias scheme was adapted to correct TRMM data sets using monthly bias factor. Statistical measures of performances were shown in table 3, for raw and corrected TRMM. Values of statistics showed noticeable improvement between raw and corrected TRMM data. The values of R^2, NSE, and RMSE over the basin are 0.95, 0.87 and 16.5 mm, respectively for raw TRMM data sets. While the corresponding values for corrected TRMM are 0.96, 0.91 and 13.4 mm, respectively.

Table 3. Statistical measures of performance for raw and corrected TRMM data sets.

Statistics	TRMM-3B42RT	
	Raw	Corrected
R^2	0.95	0.96
NSE	0.87	0.91
RMSE (mm)	16.5	13.4
Percentage Bias	-0.12	0.01
Bias factor	0.88	1.01

3.3. Elevation Dependency

Point rainfalls in two different elevation zones (low and high) were checked for elevation dependency. The statistical measures of performance for low land gave the values for R^2 (0.85), NSE (0.79) and RMSE (21.31 mm), while for high land the same statistics gave the values of (0.66), (0.74) and (30.5 mm) respectively. This result indicates that TRMM performance is better in low land and it is coinciding with other analyses which were carried in Turkey and South Korea [21]. The percentage bias and bias factor also were deteriorated with increase of elevations as shown in table 4.

Table 4. Statistical measures of performance for selected elevation zones

Statistics	Elevation zones	
	Low <= 600 m (Teseni @ 600 m)	High > 2000 m (Asmara @ 2070 m)
R^2	0.85	0.66
NSE	0.79	0.74
RMSE (mm)	21.31	30.5
Percentage Bias	-0.13	-0.37
Bias factor	0.87	0.63

3.4. Continuous Modeling with HEC-HMS

To understand catchment hydrology, continuous monitoring is required, continuous modeling was used to study the continuity of hydrological process over long period of time [24]. Corrected TRMM rainfall product was used as input for continuous rainfall-runoff modeling. Runoff generated by corrected TRMM was compared with actual daily discharge measured at Gera station (outlet of the catchment). HEC-HMS models were run separately for calibration period (2015-2016) and validation period (2017-2018), the results were presented separately in figs. 5 & 6. The model captured the peak flows and time to peak well. Saber and Yilmaz, [21] used the same concept of hydrological modeling for reproducing runoff hydrograph for more validation of SREs in Turkish catchment. They used Global Satellite Mapping of Precipitation products (GSMaP) as input to HydroBEAM model, there were noticeable improvement in the output hydrograph after bias correction of SREs.

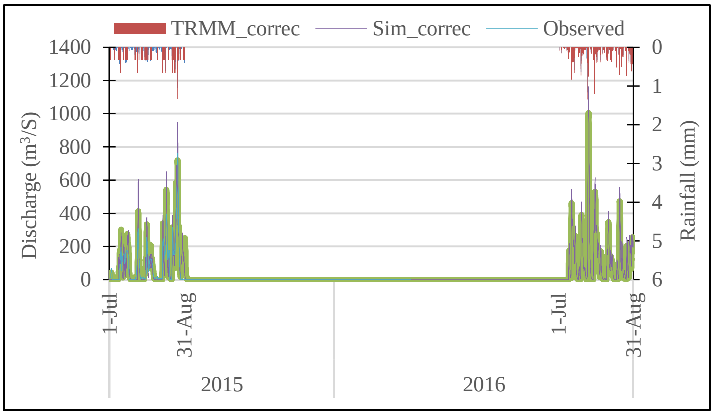

Fig. 5. Simulated and observed hydrograph for calibration period (2015-2016) using corrected TRMM

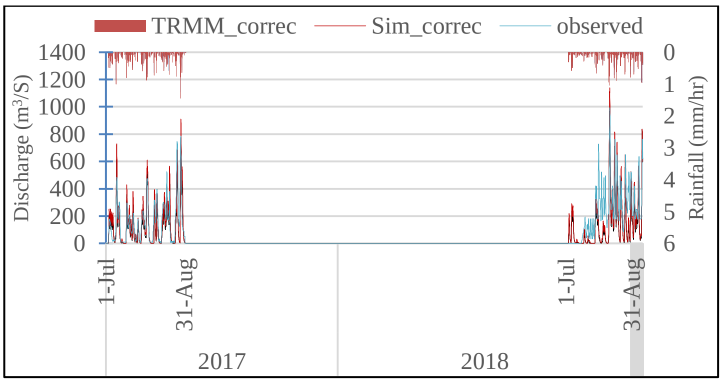

Fig. 6. Simulated and observed hydrograph for validation period (2017-2018) using corrected TRMM

The performance of the model was increased slightly with the validation scheme adopted, for both calibration and validation periods. Table (5) shows the statistical measure of performance such as NSE, RMS and R^2, for corrected TRMM. The model was able to detect the peak & time to peak reasonably.

Table 5. Details of model performance for continuous modeling using corrected TRMM

Statistics	Calibration	Validation
NSE	0.79	0.66
RMSE (m^3/s)	44.5	74.1
Simulated peak (m^3/s)	1162	1139
Observed peak (m^3/s)	1062	992
Date & time to peak (sim.)	25/7/2016 17:00	4/8/2018 19:00
Date & time to peak (obs.)	25/7/2016 18:00	4/8/2018 15:00

3.5. Event Modeling with HEC-HMS

Event hydrologic modeling is useful for better understanding of the underlying hydrologic processes, it reflects the basin respond to individual rainfall event (peak, time to peak and volume) [24]. Event modeling increases the utility of both event and continuous modeling in real time flood forecast. Since the Gash river is a flashy river, the flow of the river more or less depends on individual storm events.

During the span period of available discharge data, twenty events has been selected for event modeling for both calibration and validation, ten events each. The selected events include the peaks of the year's 2015, 2016, 2017 and 2018. The peaks of the years 2015 and 2017 were used for calibration (figs. 7 & 8), and the years 2016 and 2018 for validation (figs. 9 & 10). Analysis of storm events showed average lag time for the basin about 20 hrs.

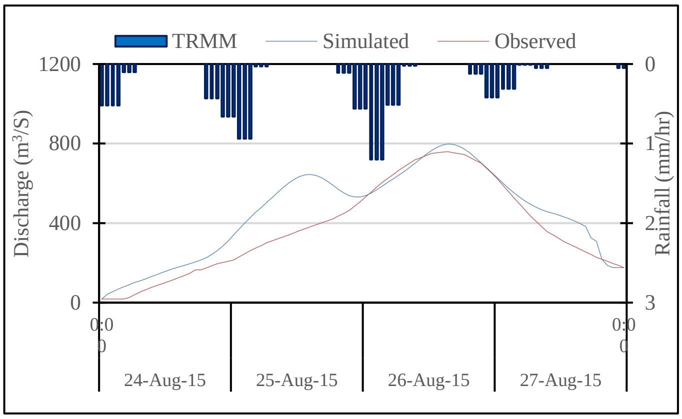

Fig. 7. Simulated & observed hydrographs (calibration-2015)

The performance of the event model was also increased with the validation scheme adopted, for both calibration and validation periods. Table (6) shows the statistical measure of performance for the selected peak events. The model simulates the peaks and time to peaks reasonably, the performance measure and other details were given in table 6.

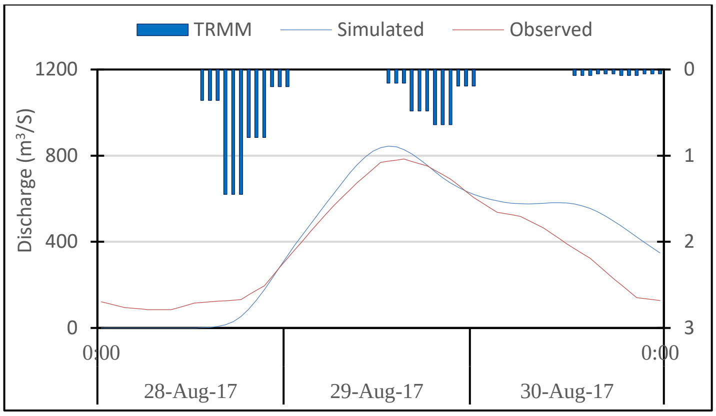

Fig. 8. Simulated & observed Hydrographs (calibration-2017)

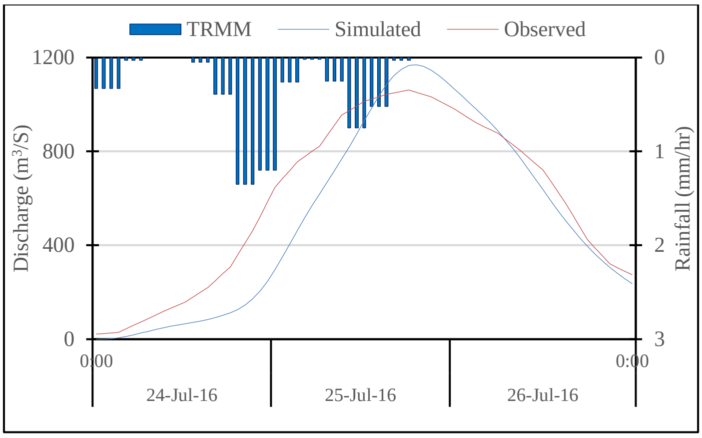

Fig. 9. Simulated and observed hydrographs (validation-2016)

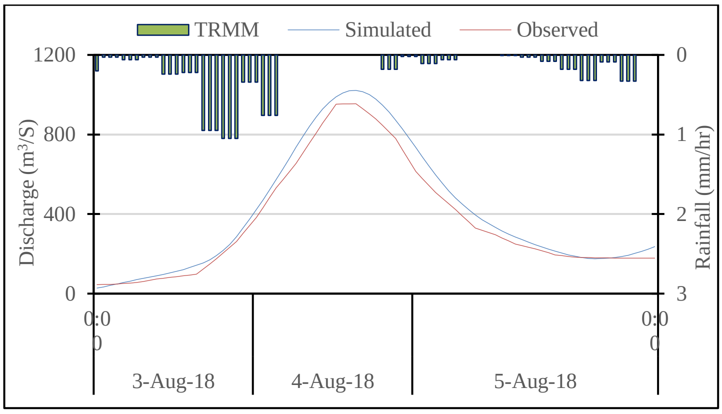

Fig. 10. Simulated and observed hydrographs (validation-2018)

Table 6. Details of model performance for events modeling using corrected TRMM data

Statistics	Calibration		Validation	
	2015	2017	2016	2018
NSE	0.92	0.96	0.96	0.84
RMSE (m^3/s)	110	45	101	118.3
R^2	0.87	0.96	088	0.94
Simulated flow (m^3/s)	798	746	954	844
Observed flow (m^3/s)	754	784	1062	954
Date & time to peak (sim.)	26/8 18:00	29/8 17:00	25/7 18:00	4/8 16:00
Date & time to peak (obs.)	26/8 18:00	29/8 17:00	25/7 18:00	4/8 15:00

It was observed that from table 6, the TRMM data sets were able to capture most of the rainfall peaks. The peaks of rainfall were most of the time coincided with the peak flows at the catchment outlet. This results strengthen the utility of TRMM for flood forecast in Gash river basin.

4. CONCLUSIONS

This study was aimed at testing the potential of using satellite derived rainfall data for hydrological modelling and flood forecasting in the Gash river catchment. SRE data set from the source TRMM-3B42RT V7 was selected to be used as alternative for ground rainfall and HEC-HMS software was used as rainfall-runoff simulation tool.

Monthly ground rainfall data from seven stations in the catchment were used for validation of SRE. The SRE was compared to ground rainfall data from the seven stations as individual stations and at area-average over the basin. TRMM data sets tend to under estimate the rainfall, in general, for both individual and area-average scale. A multiplicative bias scheme was used to correct the SRE at monthly basis.

Satellite rainfall estimates were checked for elevation dependency. The performance of TRMM data sets were found to be deteriorating with the increase of elevation, the lower altitude stations showed better performance than the higher altitude stations in terms of R2 and NSE statistics.

HEC–HMS was used for the hydrological modeling, hourly TRMM data sets were bias corrected and used as input to the hydrological model. Both continuous and event-based model were developed, a noticeable improvement was obtained in the simulated hydrograph after SRE data sets were bias correct.

Two statistical measures of performance were used namely; NSE and RMSE. The results of statistics indicated that events-based hydrological modeling performed better than continuous hydrological modeling in Gash river basin.

One of the interesting results was that, TRMM data sets were able to capture the peaks of rainfall events, most of the TRMM data sets peaks were coinciding accurately with the peak runoff at the catchment outlet. In general, the study concluded that TRMM-3B42RT V7 showed promising results to be used as input for hydrological modeling and flood forecasting in Gash river catchment.

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