



**Comparison of TRMM, MPEG and CFSR rainfall estimation**

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# Comparison of TRMM, MPEG and CFSR rainfall estimation with the ground observed data for the Lake Tana Basin, Ethiopia

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## Abstract

Planning of drought relief and floods in developing countries is greatly hampered by lack of a sufficiently dense network of weather station measuring precipitation. In this paper we test the utility of three satellite products to augment the ground based precipitation measurement to provide improved spatial estimates of rainfall. The three products are: Tropical Rainfall Measuring Mission (TRMM) product (3B42), Multi-Sensor Precipitation Estimate-Geostationary (MPEG) and Climate Forecast System Reanalysis (CFSR). The accuracy of three products is tested in the Lake Tana Basin in Ethiopia where in 2010 38 weather stations were available with a full record of daily precipitation amounts. Daily grid satellite based rainfall estimates were compared to: (1) point observed ground rainfall (2) areal rainfall in the major river sub-basins of Lake Tana. The result shows that, the MPEG and CFSR satellite provided most accurate rainfall estimates. On the average for 38 stations 78 and 86 % of the observed rainfall variation is explained by MPEG and CFSR data respectively while TRIMM explained only 17 % of the variation. Similarly, the areal comparison indicated a better performance for both MPEG and CFSR data in capturing the pattern and amount of rainfall. MPEG and CFSR have also a lower RMSE compared to the TRMM satellite rainfall. The Bias indicated that, the MPEG is consistent in underestimating the observed rainfall while the TRMM and CFSR were not consistent; they overestimated for some and underestimated for the others.

## 1 Introduction

Precipitation is a major component of the water cycle, and is responsible for depositing approximately  $505\,000\text{ km}^3$  (or on the average 990 mm) of the fresh water on the planet. It is one of the major water balance component of the global water balance. Although the spatial and temporal variability of precipitation is important, unless large numbers of rain gauge stations are available, capturing variability is difficult (Sharma et al., 2012).

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Though, ground rainfall observation station networks are often unevenly and sparsely distributed in the developing countries and this situation is not likely to improve in the near future. In Rahad, Dindir and Welaka Sub-basins in the Blue Nile Basins in Ethiopia there are only three stations for each sub-basin an area of greater than 5000 km<sup>2</sup>. This is far below the World Meteorological Organization (WMO) standard of one station for 100 to 250 km<sup>2</sup> of area for mountainous region (WMO, 1994). The poor coverage of rain gage hinders drought forecasting for food deficits, and is of great hindrance of accurately predicting discharge (both low flows and floods), sediment discharge and nutrient fluxes. Unavailability of good rainfall estimates might also be the reason that as noted by Baveye (2013) that hydrologists, seem reluctant to deal with pressing and unprecedented societal questions such as food deficits related to water resources.

The growing availability of high-resolution (and near real time) satellite rainfall products can help hydrologists to obtain more accurate precipitation data particularly in developing countries and remote locations where weather radars are absent and conventional rain gauges are sparse (Bitew et al., 2012). Satellite derived rainfall estimates have become a powerful tool to supplement the ground based rainfall estimates. Recently, the availability of earth observation data for environmental or societal purposes is increasingly available through earth observation (EO) data provision services. Some of the freely available spatially distributed rainfall estimates are Tropical Rainfall Measuring Mission (TRMM) (Simpson et al., 1988), EUMETSAT's Meteorological Product Extraction Facility (MPEF) Multi-Sensor Precipitation Estimate-Geostationary (MPEG), Climate Forecast System Reanalysis (CFSR), the NOAA/Climate Prediction Centre morphing technique (CMORPH), Precipitation Estimation from Remotely Sensed Information using Artificial Neural Network (PERSIANN), the Naval Research Laboratory's blended product (NRLB), and more.

Passive Microwave (PM) and Thermal Infrared (TIR) sensors are the most widely used channels of the electromagnetic spectrum for satellite rainfall estimation (Dinku et al., 2010, 2011; Negri et al., 1984). A TIR sensor provides useful information on storm clouds based on top cloud temperature. The assumption in the TIR is that

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relatively cold clouds are associated with thick and high clouds that tend to produce high rainfall rates (Haile et al., 2010). One of the limitation with TIR sensor is, it only uses the top cloud temperature from which the depth of the cloud is inferred (Dinku et al., 2010) and also underestimates warm rain and misidentifies cirrus clouds as raining (Dinku et al., 2011). Microwave sensors are more direct way of retrieving precipitation from satellite; they gather information about the rain rather than the cloud (Dinku et al., 2010). The absorption of microwave radiation by liquid water and its scattering by ice particles can be related to rainfall over ocean and over land (Ferraro, 1997). The disadvantage of PM sensors is that, they are not available on geostationary satellites, which make them to have a longer re-visit time (Heinemann et al., 2002). A combination of both, microwave (MW) data from polar orbiting satellites and IR data from geostationary systems is an obvious approach to overcome some of the shortcomings in the estimation of precipitation. In this study, a validation of satellite rainfall estimation using a combination of MW and IR data TRMM, MPEG and CFSR will be done by comparing with the ground observation rainfall data for the Lake Tana Basin, Ethiopia.

Validation of satellite rainfall products in the Ethiopian highlands will give an insight into how the different products perform over such regions. A number of TRMM rainfall product validation have been done for the Ethiopian highlands (Dinku et al., 2010; Tsidu, 2012) are among others, all of them are focused on comparison of gridded satellite rainfall estimation to a ground rainfall observation data. This study validates satellite rainfall products in two ways: comparing satellite gridded rainfall data to point observation data and satellite areal rainfall to areal observation for the major sub-basins of Lake Tana, and in addition to TRMM, CFSR and MPEG are also validated using ground rainfall stations in and around the Lake Tana Basin. Lake Tana Basin is selected to take the advantage of a relatively higher rainfall observation station density and availability of daily rainfall data. These rainfall products are selected for comparison because, all of them are the state of the art algorithms, and have been widely used and freely available in Africa. For example, Bahir Dar University, Ethiopia in collaboration with Tana Sub-Basin Office and University of Twente, Faculty ITC, the Netherlands



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stations did not record the rainfall consistently on a daily basis or for other stations the location and the elevation were not known. Thirty eight stations remained that have continuous daily rainfall data for the selected study period (2010). The satellite rainfall estimates used for this study includes: MPEG from MPEF, TRMM product (3B42) Version 7 and CFSR. Part of the MPEG data, at 15 min temporal interval is acquired in near real time from the low-cost satellite image reception station established at Bahir Dar University, Institute of Technology (Wale et al., 2011). The daily aggregated MPEG data from 00:00 till 23:45 UTC, in  $\text{mm day}^{-1}$ , is available online at: <ftp://ftp.itc.nl/pub/mpe/msg/>. TRMM gridded rainfall estimates are collected from the ftp site, available at: [ftp://disc2.nascom.nasa.gov/data/s4pa/TRMM\\_L3/TRMM\\_3B42\\_daily/](ftp://disc2.nascom.nasa.gov/data/s4pa/TRMM_L3/TRMM_3B42_daily/). The daily gridded CFSR rainfall data can be collected from <http://rda.ucar.edu/datasets/ds094.1/>.

## 2 Methods

The predicted satellite rainfall estimate and observed gauged rainfall data have different spatial and temporal scales. The ground observation consists of a 38 daily observations of point rainfall amounts irregularly distributed across the Lake Tana Basin (Fig. 1). The MPEG, TRMM and CFSR rainfall consists of spatially distributed time series regular gridded data with a spatial resolution of 3 km,  $0.25^\circ$  ( $\approx 27$  km at the equator) and 38 km respectively. A detailed description of TRMM, MPEG and CFSR data is provided in the Appendix A. The average annual rainfall from 1994 to 2008 is plotted against the station elevation to see the stations likely affected by convective precipitation and those very much affected by a combination of orographic and convective precipitation. Backwards elimination technique was used to obtain the linear trends with elevation in the long term average rainfall. The backward elimination technique successively eliminates the weakest independent station (variable) after which the regression will be recalculated (Xu and Zhang, 2001). If removing the variable significantly weakens the linear model then the variable is re-entered otherwise it is deleted. This procedure is then repeated until only useful variables remain in the linear elevation-rainfall model.

The gridded satellite rainfall estimation is linked to the ground rainfall observations in two ways:

- Point to grid comparison: the grids of satellite rainfall estimation (MPEG, TRMM and CFSR) are compared to the ground rainfall observation data within the satellite grid box. This means, a point ground observation data is compared against a satellite grid data of size of 3 by 3 km, 0.25 by 0.25° and 38 by 38 km for MPEG, TRMM and CFSR respectively. It is done by extracting the satellite rainfall estimation for the ground rainfall station locations. Finally the comparison on monthly and annual basis is done applying standard statistics.
- Areal comparison: satellite rainfall estimation is compared with the interpolated observed rainfall stations. The ground rainfall observations are interpolated adopting a Thiessen Polygon method and compared with the respective satellite rainfall estimation for the major gauged river basins of Lake Tana; the accuracy is measured using standard statistics. The major river basins in the Lake Tana used for this study are Gilgel Abay, Gumara, Ribb and Megech, according to Kebede et al. (2006) these rivers contribute approximately 93 % of the surface water inflow.

## 2.1 Ground Rainfall Observation Station (GROS)

There are 51 meteorological stations operated by ENMA in the study area. Some of them have no location information and/or the actual elevation provided is not considered reliable. For the 38 selected stations daily rainfall is available in 2010 study period. Monthly rainfall amounts for selected stations are given in Fig. 2. Long-term annual average rainfall varies between 830 mm to 2500 mm year<sup>-1</sup> from 1994 to 2008. Approximately eighty six percent of the annual rainfall falls between June to September.

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## 2.2 Statistical measures

Three statistical measures were used to compare the satellite rainfall estimates with the ground rainfall observations consisting of the Coefficient of Determination (*R*-Squared), Multiplicative Bias (Bias) and Root Mean Square Error (RMSE).

The Coefficient of Determination (*R*-Squared): is used to evaluate the goodness of fit of the relation. *R*-Square address the question on how well the satellite rainfall estimates correspond to the ground rainfall observations, it is the degree of linear association between the two terms see Eq. (1).

$$R^2 = \left( \frac{n \sum(G_i S_i) - (\sum G_i)(\sum S_i)}{\sqrt{(n(\sum G_i^2) - (\sum G_i)^2)(n(\sum S_i^2) - (\sum S_i)^2)}} \right)^2 \quad (1)$$

where:  $R^2$  = coefficient of determination,  $G_i$  = ground rainfall measurements,  $S_i$  = satellite rainfall estimates, and  $n$  = number of data pairs.

Root Mean Square Error (RMSE) measures the difference between the distributions of the ground observed rainfall and the distribution of satellite rainfall estimation and calculates a weighted average error, weighted according to the square of the error. RMSE is useful when large errors are undesirable. The lower the RMSE score, the closer the satellite rainfall estimation represents the observed ground rainfall measurement see Eq. (2).

$$RMSE = \sqrt{\frac{\sum(G_i - S_i)^2}{n}} \quad (2)$$

where: RMSE = root mean square error,  $G_i$  = ground rainfall measurements,  $S_i$  = satellite rainfall estimates, and  $n$  = number of data pairs.



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Bias (Dinku et al., 2008) is a measure of how does the average satellite rainfall magnitude compared to the ground rainfall observation. It is simply the ratio of the mean satellite rainfall estimation value to the mean of ground rainfall observed value. A bias of 1.1 means the satellite rainfall is 10 % higher than the average ground rainfall observations see Eq. (3).

$$\text{Bias} = \frac{\sum S_i}{\sum G_i} \quad (3)$$

where:  $G_i$  = ground rainfall measurements and  $S_i$  = satellite rainfall estimates.

### 3 Result and discussion

The long-term annual average rainfall from 1994 to 2008 is plotted against station elevation to see the rainfall–elevation relation (Fig. 3). Two clear trends can be observed; the first one shows a 50 mm of rainfall increase for every 100 m elevation increase and the second trend observed was a 125 mm rainfall increase for every 100 m elevation increase. These two relations can be explained by stations likely affected by convective rainfall only (rectangles) and those very much affected by a combination of orographic and convective precipitation (in circles) in Fig. 3.

#### 3.1 Point to grid comparison

The satellite rainfall estimates are aggregated to monthly temporal intervals and the monthly satellite rainfall estimation was extracted for the 38 stations locations. The observed ground rainfall and the extracted satellite rainfall for all 38 stations is depicted for the three standard statistical techniques in Fig. 4a–c.

As shown in Fig. 4a, the monthly MPEG and CFSR have a strong correlation with the Ground Rainfall Observations Stations (GROS). For MPEG the coefficient of determination ranges from a maximum of 0.99 (Enfranz Station) to a minimum value of 0.53

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(Yismala Station). On average 78 % of the total observed rainfall variation is explained by the MPEG satellite rainfall estimate. The CFSR has a coefficient of determination ranging from 0.63 to 0.99 for Gassay and Shembekit respectively, on average 86 % of the total observed rainfall variation is explained by CFSR rainfall data for the 38 stations. The correlation between TRMM and GROS on monthly basis is weak, with a maximum coefficient of determination of 0.29 (Addis Zemen Station) and a minimum value of 0.00. Multiple stations did not show a correlation with TRMM data. On average only 7 % of the total observed rainfall variation is explained by the TRMM satellite rainfall estimates. The root mean square error in Fig. 4b gives very much the same trends as in Fig. 4a. The MPEG and CFSR have a much better RMSE (ranging from 0.63 to 9.5 mm day<sup>-1</sup>) while TRMM has a RMSE ranging from 3.8 to 11.8 mm day<sup>-1</sup>.

Thus MPEG and CFSR rainfall estimate are clearly better related to gauged rainfall than TRMM. This is in agreement with the findings of Dinku et al. (2008), where on average TRMM-3B42 captures only 15 % of the rainfall variability for the whole Ethiopia.

Finally if we look at the rainfall distribution throughout the year we found that the rainfall estimates of MPEG and CFSR agree with the ground based observation of 84 to 86 % of the annual rainfall occurs in the rainy monsoon phase from June to September as exemplified in Fig. 5, for Addis Zemen and Agre Genet Stations. In contrast TRMM finds that only 30 % rainfall is during the rainy season.

The Bias calculated (Fig. 4c) for MPEG, TRMM and CFSR ranging from 0.2 to 0.9, 0.5 to 1.9 and 0.24 to 2.69 with an average value of 0.43, 1.0 and 1.3 respectively. The MPEG is consistent in under-predicting the observed rainfall, on average it underestimates by 57 % . The TRMM overestimates for 15 stations and it underestimates for the remaining. The CFSR also overestimates for 24 stations and it has the largest standard deviation of Bias indicating the spread of the Bias between stations. The MPEG seems consistent in underestimating the ground observed rainfall while the TRMM and CFSR are not consistently in estimating the observed rainfall.

Stations likely affected by convective rainfall (22 stations, marked in rectangles in Fig. 3) have a better correlation coefficient and a smaller RMSE than the stations

likely affected by a combination of orographic and convective precipitation (16 station, marked in circle in Fig. 3). The Bias also indicated that, stations likely affected by both convective and orographic rainfall have a higher bias than the likely stations affected by convective rain only. This is quite reasonable, because due to the result of orographic lifting of the moist air, leading to precipitation while the cloud top is still relatively warm. Satellite rainfall products may not detect the rainfall from the warm clouds as the cloud-tops would be too warm for TIR thresholds (Dinku et al., 2008), and there will not be much ice aloft to be determined by PM senses. But, both sensors can detect the rainfall from the deep convection (Tsidu, 2012).

### 3.2 Areal comparison

Stations likely affected by convective rainfall are interpolated using a Thiessen Polygon method and their weights on areal rainfall for the major watersheds is determined (Fig. 6). Gilgel Abay watershed has two stations likely affected by convective rainfall; Megech has three, Gumara six and Ribb seven stations. The areal observed rainfall is compared with the areal satellite rainfall estimation for the major gauged rivers basins in the Lake Tana. Figure 9, shows the correlation and RMSE of areal Ground Rainfall Observation Station (GROS) vs. MPEG, areal GROS vs. TRMM and areal GROS vs. CFSR for the major river basins of Lake Tana.

The areal MPEG and CFSR satellite rainfall estimation have a very high coefficient of determination above 0.8, on average both MPEG and CFSR captured 93 % of the areal observed rainfall variability on the major river sub-basins of lake Tana (Fig. 7). Overall, the areal satellite rainfall estimates for the major river basins have a smaller RMSE and a higher  $R$ -Squared compared to the result of point to grid comparison. This is because the stations used for areal observed rainfall estimations are the likely station affected by convective rainfall only and the satellite observation data is an average value over the grid area. The areal Bias computed indicated that the MPEG rainfall consistently underestimates the observed rainfall by an average of 60 %, while the areal CFSR overestimates for Gilgel Abay and Ribb (on average by 40 %) and underestimates for

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Megech and Gumara (on average by 5 %). The areal RMSE of MPEG is smaller than areal CFSR estimation. The areal TRMM rainfall indicated a very small  $R$ -Squared and a very high RMSE. The Bias for TRMM rainfall estimation is not constant; it overestimates for Gilgel Abay and Gumara by 40 and 10 % respectively and underestimates for Ribb and Megech watersheds by 10 %. Thus, the consistence Bias with an excellent correlation for MPEG rainfall estimate, there is a necessity to use scaling factors for the rainfall Bias correction.

#### 4 Conclusion

This study evaluated EUMETSAT's MPEF Multi-Sensor Precipitation Estimate-Geostationary (MPEG), Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis TRMM 3B42 data version 7 and Climate Forecast System Re-analysis (CFSR) rainfall estimation, using data of 38 ground rainfall observation stations in and around the Lake Tana Basin for 2010. The comparison was done using two approaches: point to grid and areal comparison for the major river sub-basins. Areal observed rainfall is estimated by interpolating the stations likely affected by convective rainfall, interpolation is done by Thiessen Polygon method with a grid size of  $0.25^\circ$ , 3 km and 38 km for the major river basins in the Lake Tana Basin. The performance of MPEG and CFSR satellite rainfall estimation both for point to grid and areal comparison was far better than the TRMM satellite rainfall estimation. The MPEG satellite rainfall is consistent in underestimating the ground observed rainfall by an average of 60 % for both point to grid and areal rainfall comparison and it has captured the rainfall pattern. CFSR satellite rainfall also captured the observed rainfall pattern but it has showed some inconsistency, it overestimates for some and underestimates for the other stations. TRMM rainfall was not consistent in estimating the ground rainfall observation for both point to grid as well as areal comparison and did not capture the observed rainfall pattern at all. TRMM underestimates for some and overestimates for the others both for the point to grid and areal comparison.

The ground observation data indicated 86 % of the annual rainfall to occur from June to September and the MPEG and CFSSR indicated approximately the same percentage. The TRMM indicated only 30 % of the annual rainfall to occur during the rainy season June to September. Based on the study period for the study area, MPEG has performed better in capturing the spatial and temporal pattern of observed rainfall. The result suggested that there should be further calibration for the TRMM 3B42 rainfall product for the Lake Tana area before the data is used for any kind of study.

## Appendix A:

### A1 Multi-Sensor Precipitation Estimate-Geostationary (MPEG)

MPEG is one of the products from MPEF as part of the Meteosat Second Generation (MSG) Ground Segment. The MPEF primary function is to generate meteorological products from the Level 1.5 image data supplied like those from the SEVIRI instrument onboard of the MSG series of geostationary satellites by the Image Processing Facility (IMPF) (EUMETSAT, 2008). Multi-sensor Precipitation Estimate (MPE) is an instantaneous rain rate product which is derived from the Infrared data (IR-data) of the geo-stationary EUMETSAT satellites by continuous re-calibration of the algorithm with rain-rate data derived from polar orbiting microwave sensors.

The algorithm is based on a combination of MSG images from the Infrared IR10.8 micro m channel and passive microwave data from the Special Sensor Microwave Imager (SSM/I) instrument on the United States Defence Meteorological Satellite Program (DMSP) polar satellites. The role model for the MPE algorithm was the algorithm developed by Turk et al. (1999). The product is most suitable for convective precipitation, and is intended mainly for areas with poor radar coverage (Heinemann and Kerényi, 2003). The MPEG data is available through the GEONETCast near real time, global network of satellite-based data dissemination systems designed to distribute space-based, air-borne and in-situ data. A ground GEONETCast reception station is

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established at the compound of Bahir Dar University, Engineering Faculty (Wale et al., 2011) in collaboration with Tana Sub-basin Organization (TaSBO) and with the University of Twente, Faculty ITC, the Netherlands. The MPEG data is available at a temporal resolution of 15 min with a spatial resolution of 3 km for the whole field of view of MSG.

The 15 min MPEG data is aggregated to daily, monthly and annual rainfall for the study area for 2010, using a daily aggregation time between 00:00 and 23:45 UTC.

## A2 Tropical Rainfall Measuring Mission (TRMM)

TRMM, Tropical Rainfall Measuring Mission, was launched by the H-II rocket from Tanegashima Space Centre of The National Space Development Agency of Japan (NASDA), on 28 November 1997. This satellite has been developed as a joint project between Japan and US, which is the first space mission dedicated to measure rainfall (NASDA, 2001).

TRMM works by combining both TIR and MW sensors (Dinku et al., 2011). The MW channel carefully measures the minute amounts of microwave energy emitted and scattered by the Earth and its atmospheric constituents. TRMM also operates in active radar. TRMM satellite orbits the earth at a 35° inclination angle with respect to the equator. TRMM covers an area of the earth's surface that extends well beyond the tropics, covering a swath between 38° N to 38° S. TRMM makes these data available in both near-real time and delayed research-quality formats. The TRMM rainfall product has a spatial resolution of 0.25° and a temporal resolution of 3 h. For this study the TRMM product 3B42 version 7 is used. The TRMM-3B42 estimates are produced in four steps (Dinku et al., 2010): (i) the PM estimates are adjusted and combined, (ii) TIR precipitation estimates are created using the PM estimates for calibration, (iii) PM and TIR estimates are combined, and (iv) the data is rescaled to monthly totals where by gauge observations are used indirectly to adjust the satellite product (Dinku et al., 2010). The major inputs into the 3B42 algorithm are IR data from geostationary satellites and PM data from the TRMM microwave imager (TMI), special sensor microwave imager (SSM/I), Advanced Microwave Sounding Unit (AMSU) and Advanced

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Microwave Sounding Radiometer-Earth Observing System (AMSR-E) (Ouma et al., 2012). In February 2014 the successor is like launched, the GPM mission with advanced radar and passive microwave sensors and will provide continuous precipitation estimates for the next years to come.

### 5 **A3 Climate Forecast System Reanalysis (CFSR)**

The CFSR was designed and executed as a global, high-resolution coupled atmosphere–ocean–land surface–sea ice system to provide the best estimate of the state of these coupled domains for the study period (Saha et al., 2010). New features in the CFSR according to Wang et al. (2011) include: (1) it is the first reanalysis system  
10 in which the guess fields are taken as the 6 h forecast from a coupled atmosphere–ocean climate system with an interactive sea ice component; and (2) it assimilates satellite radiances rather than the retrieved temperature and humidity values. In addition, the CFSR is forced with observed estimates of evolving greenhouse gas (GHG) concentrations, aerosols, and solar variations (Wang et al., 2011). The CFSR global atmosphere data has a spatial resolution of approximately 38 km and the data is available  
15 from 1979.

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20 edged.

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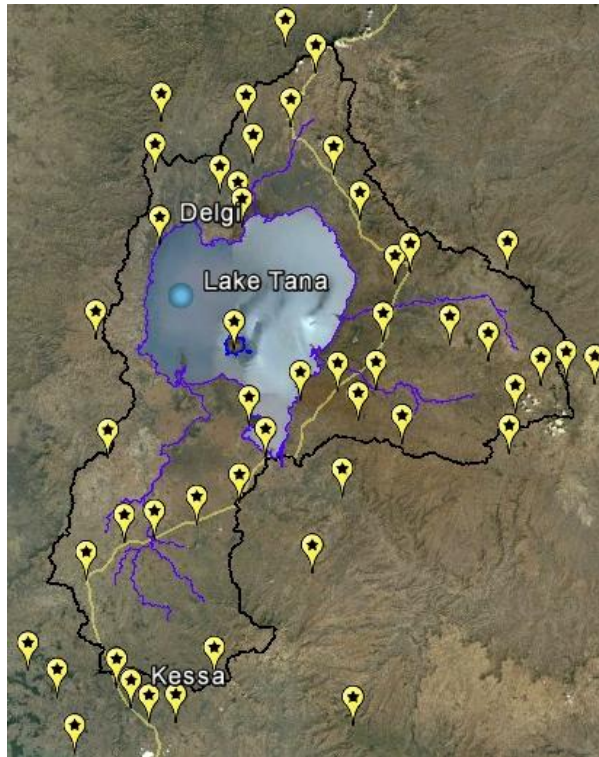
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**Figure 1.** Lake Tana watershed and spatial distribution of ground rainfall observation stations (Google Earth map as background).

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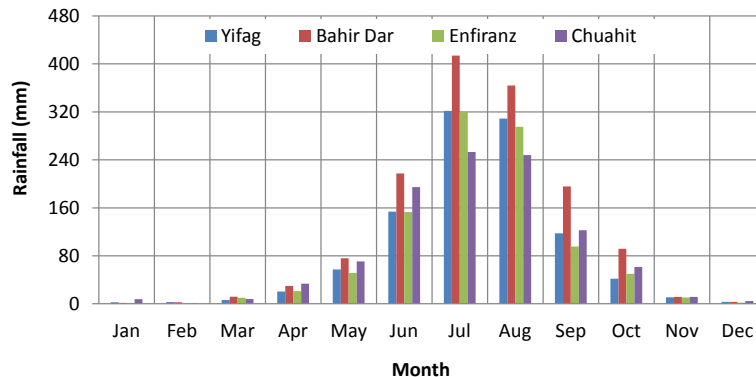
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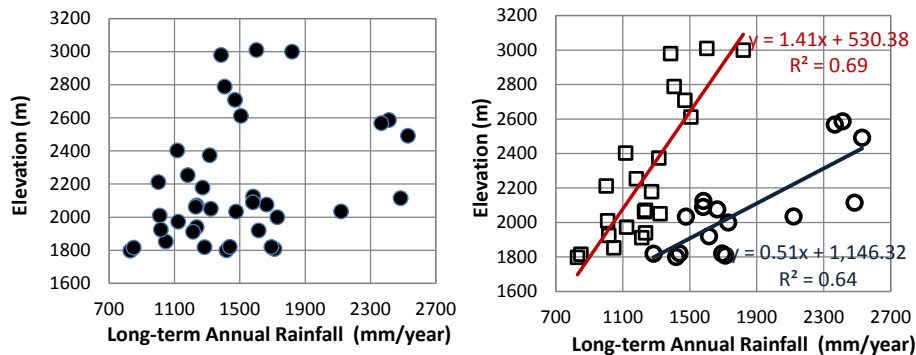


**Figure 2.** Averaged monthly gauged rainfall distribution of selected stations in the Lake Tana Basin (from 1994–2008).

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**Figure 3.** Elevation versus long-term annual average rainfall relations in the Lake Tana Basin (38 stations from 1984 to 2008).

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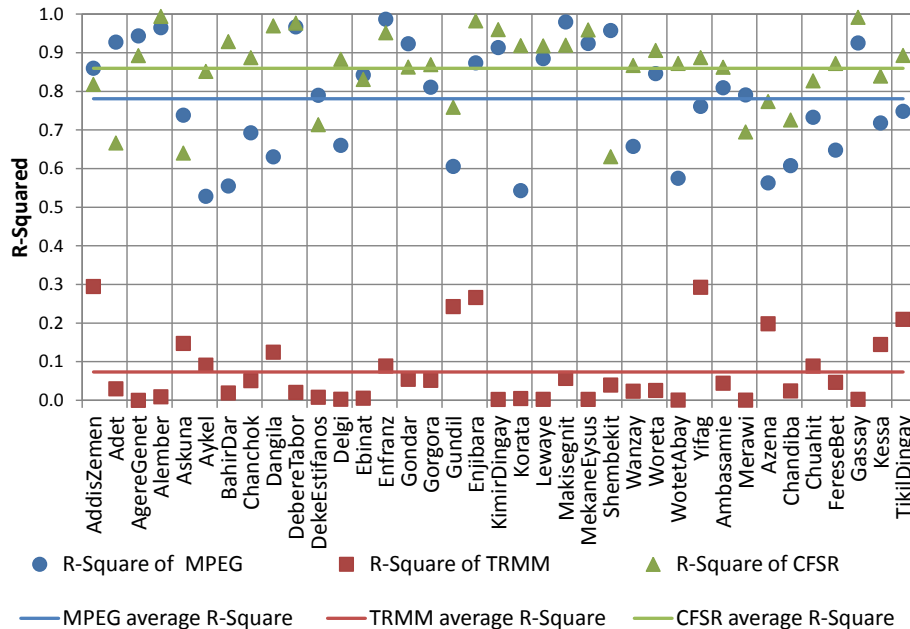
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**Figure 4a.** *R*-Squared of MPEG, TRMM and CFSR vs. 38 Ground Rainfall Observation Stations (GROS) in the Lake Tana Basin. The lines represent the average *R*-Square of MPEG, TRMM and CFSR data compared with the 38 gauged rainfall observation stations in Lake Tana Basin.

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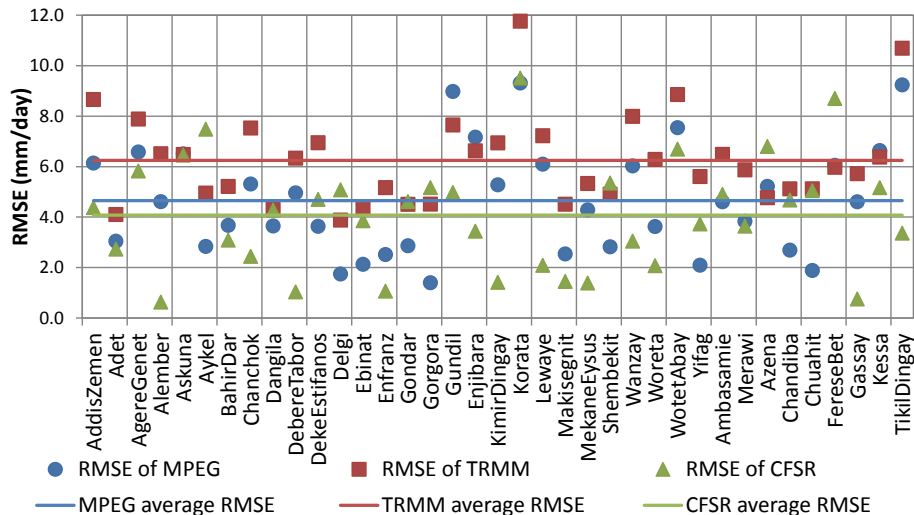
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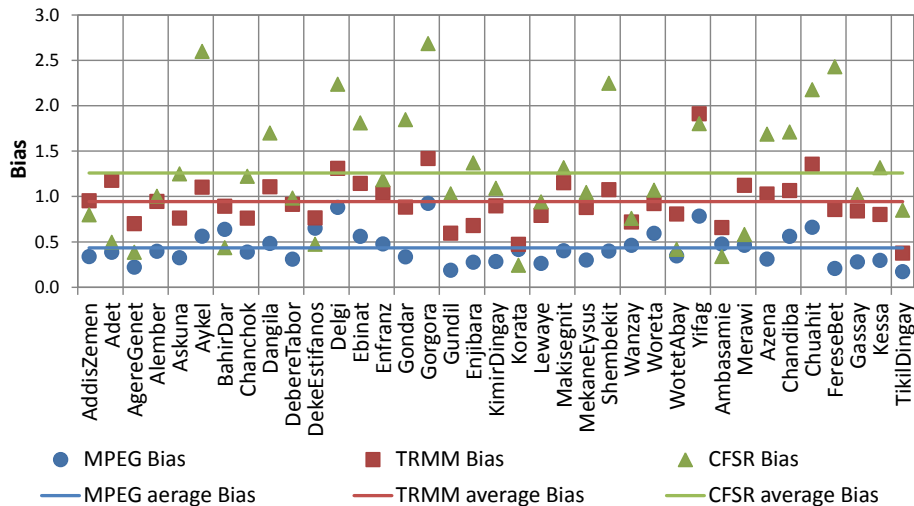


**Figure 4b.** RMSE of MPEG, TRMM and CFSR compared with the 38 Ground Rainfall Observation Stations (GROS) in the Lake Tana Basin. The lines represent the average values of Root Mean Square Error of MPEG, TRMM and CFSR data compared with the ground rainfall observation stations in the Lake Tana Basin.

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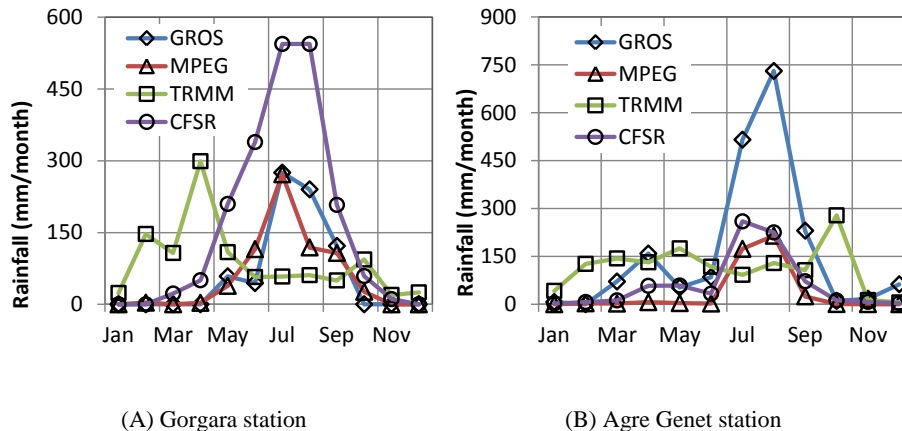


**Figure 4c.** Bias of MPEG, TRMM and CFSR versus 38 Ground Rainfall Observation Stations (GROS) in the Lake Tana Basin. The lines indicate the average values MPEG, TRMM and CFSR Bias compared with the ground rainfall observation stations.

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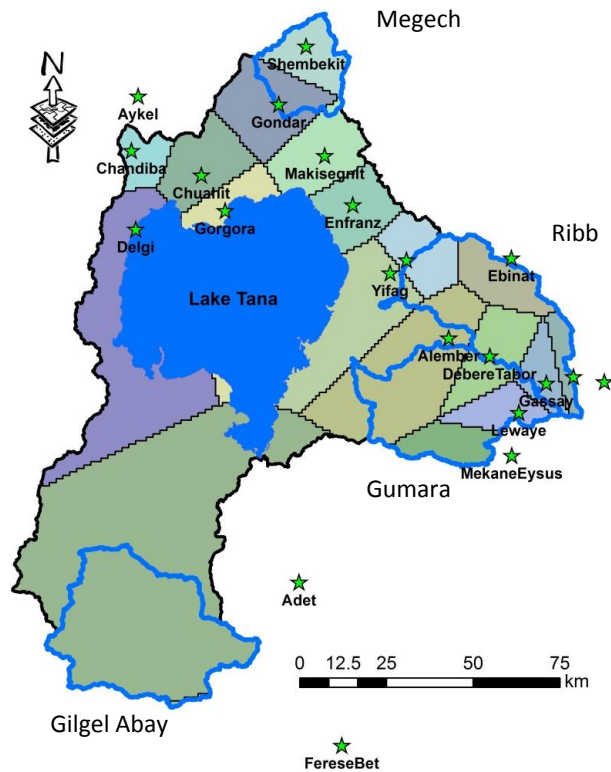
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**Figure 5.** Temporal distribution of gauged rainfall and satellite rainfall estimation from Tropical Rainfall Measuring Mission's (TRMM), Multi-Sensor Precipitation Estimate-Geostationary (MPEG) and Climate Forecast System Reanalysis (CFSR) for Gorgara and Agre Genet stations (year 2010).

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**Figure 6.** Thiessen Polygon of stations likely affected by convective rainfall in the Lake Tana Basin. The green stars represent the rainfall stations likely affected by convective rainfall alone.

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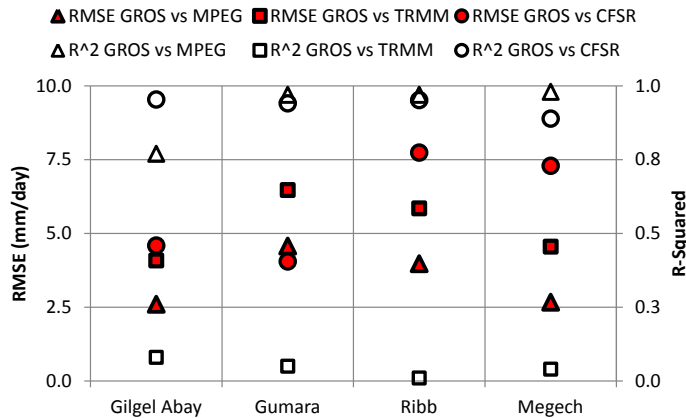
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**Figure 7.** *R*-Squared and RMSE of areal ground observed rainfall vs. satellite rainfall estimate for the major river basins in the Lake Tana.

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