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S. I. – CEC FRAMEWORK

Performance evaluation of GPM-IMERG early and late rainfall estimates over Lake Hawassa catchment, Rift Valley Basin, Ethiopia

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Abstract

High resolutions of satellite rainfall products have been widely used for hydrometeorological and hydroclimatological studies over the globe. However, the performance of satellite rainfall estimates varies and is affected by topography and atmospheric characteristics. The assessment of satellite rainfall products is important over different regions. In this study, Integrated Multi-SatellitE Retrievals' performance for the Global Precipitation Mission version 6 (GPM-IMERG v6) was evaluated before and after bias correction, over the Lake Hawassa catchment. A linear scaling bias correction approach was used to correct the bias of GPM-IMERG early and late rainfall products. The satellite rainfall products were also compared with ground observed rainfall data in the Lake Hawassa catchment. Statistical performance assessing methods were used to evaluate both raw and bias-corrected IMERG early and late rainfall products. The percentage of bias (PBIAS) for early and late rainfall estimates was 91.54 and 77.03, respectively, for the entire periods before bias correction. It indicates that GPM-IMERG overestimated rainfall relative to ground-gauged rainfall. The results show that IMERG rainfall products are in good agreement with ground observed rainfall after bias correction. The correlation values (R) for IMERG early and late is 0.86 and 0.85, respectively, indicating a good correlation between IMERG's estimated rainfall and observed rainfall after bias correction. The performance of IMERG rainfall estimates varies with the seasons. The bias correction for only rainy season shows a good match with observed rainfall compared to all seasons. Bias-correction resulted in a good match between estimated and observed rainfall. Generally, evaluation of GPM-IMERG satellite rainfall products is essential prior to use for hydrological modeling and forecasting in data-scarce areas.

Keywords IMERG · Satellite rainfall · Linear scaling bias correction · Lake Hawassa · Rift Valley Basin · Ethiopia

Introduction

Rainfall plays a significant role in agriculture and water resource availability, particularly in developing countries where agricultural production depends on rainfed (Kawo and Karuppannan 2018). The Ethiopian Rift Valley Lakes Basin, including Lake Hawassa catchment, which spans from the south to the east of Ethiopia, has a dense population and mainly depends on rain-fed agriculture. The present study area, which is characterized by freshwater and suitable for agriculture and domestic use (Shankar and Kawo 2019; Haji et al. 2021a, b). However, rising temperature and the irregularities of weather conditions (Jansen et al. 2007; Olaka et al. 2010; Mohammed et al. 2019; Abraham et al. 2018) have had a significant impact on rainfed agricultural production (Deressa 2007; Hadgu et al. 2015; Zeray and Demie 2016; Asfaw et al. 2018) and reduced availability of freshwater (Olaka et al. 2010). Rainfall recharges the aquifer, whereas another part flows to streams as runoff. Fluctuation in rainfall affects water quantity (Seleshi and Zanke 2004) and alters the frequency of droughts and floods (Kumar et al. 2010; Frisvold and Murugesan 2013; Iqbal and Athar 2018). Therefore, understanding precipitation and its variations over time are essential for water balance studies and other hydrological applications. According to Hou et al. (2014), accurate observation or

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rainfall estimation is essential for hydrological modeling. Proper rainfall measures or estimates are required to forecast flood systems, drought monitoring, and water resources management. Due to the lack of rain gauge networks and a poor data collection system, the accuracy of measured rainfall data is low in developing countries (Haile et al. 2009; Fenta et al. 2018; Rivera et al. 2018; Gebremicael et al. 2019).

Nowadays, satellite-based rainfall products have been commonly used for hydrological studies (Bitew et al. 2012a, b; Hobouchian et al. 2017). Satellite rainfall products are very important in a limited number of active rain gauge networks, to investigate rainfall variability and its effects on water resource availability. In regions of Ethiopia, particularly around mountainous and over lake basins, a limited numbers of stations are available. Hence, satellite-based rainfall data is essential in the area of scare rain-gauged networks (Villarini 2010).

Satellite rainfall products have been widely used in different parts of the world (Alexander et al. 2006; Huffman et al. 2007a, b, 2014; Kucera et al. 2013; Hou et al. 2014). Satellite precipitation products have a systematic bias and random errors (i.e., temporal sampling and instrumental errors) (Yilmaz et al. 2005; Hossain and Anagnostou 2006; Dinku et al. 2007; AghaKouchak et al. 2012; Habib et al. 2012; Zhang et al. 2013; Maggioni et al. 2016), and its quality needs to be evaluated before to use for different applications. Due to this, performance evaluation against the rain gauge observed rainfall data and satellite rainfall products is vital in order to enhance their accuracy. It is very important to the users to understand the vagueness associated with the remotely sensed rainfall processing algorithms and the sensors' physical limitations. Infrared (IR) and passive microwave (PMW) sensors are the most used electromagnetic spectrum channels of satellite rainfall estimations (Huffman et al. 2007a, b). IR sensors use only top cloud temperature information from satellites to associate with a depth of rainfall, whereas PMW sensors directly collect information about rainfall (Todd et al. 2001).

Nowadays, numerous high-resolution satellite-based rainfall products have been developed and studied to assess their effectiveness. Integrated Multi-SatellitE Retrieval for Global Precipitation Measurement (GPM-IMERG) is one of the satellite-based rainfall products. Numerous researchers have assessed IMERG rainfall products with observed rainfall data and with other satellite-based rainfall products (Guo et al. 2016; Liu 2016; Sharifi et al. 2016a, b; Tang et al. 2016; Kim et al. 2017; Liu et al. 2017a, b; Skofronick-Jackson et al. 2017; Sungmin et al. 2017; Wang et al. 2019; Fuwan et al. 2020). Several studies have reported that IMERG rainfall estimates vary with seasons and elevations. For example, IMERG is best suited to detect summer rainfall in China (Tang et al. 2016), monsoon rainfall in India (Prakash et al. 2016), and heavy rainfall in Iran and Canada (Sharifi et al. 2016a, b; Asong et al. 2017).

Sungmin et al. (2017) evaluated GPM-IMERG early, late, and final products, and have reported that the satellite-based overestimate rainfall and produce very high values, which have a significant impact on the total rain volume. Wu et al. (2019) evaluated the performance of GPM IMERG v5 and TRMM 3B42 v7 precipitation products both spatiotemporally and concluded that the GPM IMERG v5 precipitation product was more accurate compared to the TRMM 3B42 v7 product. Alsumaiti et al. (2020) evaluated the performance of CMORPH and IMERG v6 rainfall products, and they found that both IMERG v6 and CMORPH have great potential for filling spatial gaps in rainfall observations. The assessement of satellite rainfall estimates can provide useful information to improve processes of satellite rainfall retrieval (Huang et al. 2013; Kirstetter et al. 2013; Lo Conti et al. 2014; Worqlul et al. 2018).

Several studies evaluated TRMM, ARC2, TAMSAT3, and CHIRPS precipitation products in Ethiopia (Bitew et al. 2012a, b; Gebere et al. 2015; Ayehu et al. 2018; Tesfamariam et al. 2019). Tesfamariam et al. (2019) evaluated the performance of CHIRPS, ARC2, and TAMSAT3 satellite-based rainfall products over the Ethiopian Rift Valley Lakes Basin. They found that CHIRPS rainfall products are better-estimated rainfall than ARC2 and TAMSAT3. This study aims to evaluate the performance of GPM-IMERG V06 early and late rainfall products' over Lake Hawassa catchment. Raw data and bias-corrected satellite rainfall products were compared with ground-based rainfall data. This study is significant to predict hydrological and climate change in subsequent studies using remote sensing precipitation products.

Materials and methods

Description of the study area

Lake Hawassa catchment is located in the Ethiopian Rift Valley Basin, and it lies between 6° 50′–7° 15′ latitude and 38° 17′–38° 44′ longitude. The study area has a total area of 1338 km^2, and it is located about 275 km south of Addis Ababa. The catchment is flat in the central part to slightly sloping lands, escarpments, and hills. Elevation of the catchment ranges between 3048 m.a.s.l. around ridges and 1665 m.a.s.l at the Lake Hawassa (Fig. 1). Topographically, Hawassa Lake is closed, with few streams flowing from the northwest and west to the lake. Tikur Wuha River is the Perennial River, which fed the lake from the northeast side of the catchment. The discharge of Tikur Wuha River in 1999 is shown in Fig. 2. According to historical data in 1999, the river discharge is high between June and October and low from October to May. Currently, the station is not functional.

Rainfed farming is the primary source of income for people in the study area. According to Dessie (1995), the catchment

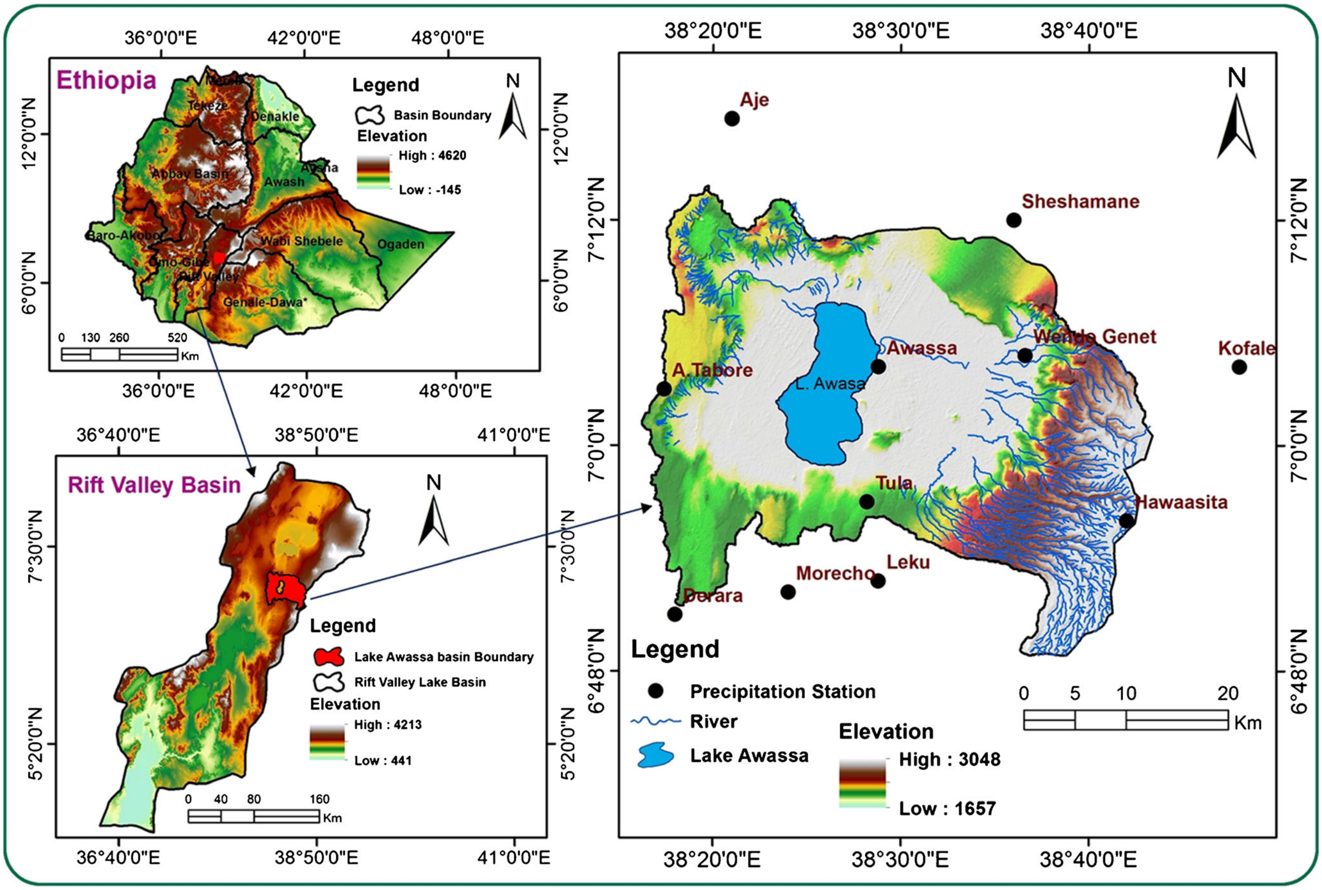


Fig. 1 Location map of Hawassa catchment

climate varies from dry to subhumid, based on the definition of the climate or humidity regions of the Thornthwaite system. Legesse et al. (2003) reported that the catchment has three seasons: (1) the primary rainy season between June and September (locally known as kiremt); (2) the dry season (locally known as baga) between October and February; (3) the limited rainy season between March and May (locally known as Belg).

The mean monthly precipitation observed at each station between 2007 and 2012 is shown in Fig. 3. The locations of the stations are shown in Fig. 1. Figure 4 shows the distribution of average monthly rainfall at Lake Hawassa catchment from 2007 to 2012. It can be seen in Figs. 3 and 4 that the distribution of rainfall in the Lake Hawassa catchment area is high in kiremt between June and September, although low rainfall occurs between October and February. The belg

Fig. 2 Mean monthly river discharge of Tikur Wuha in 1999

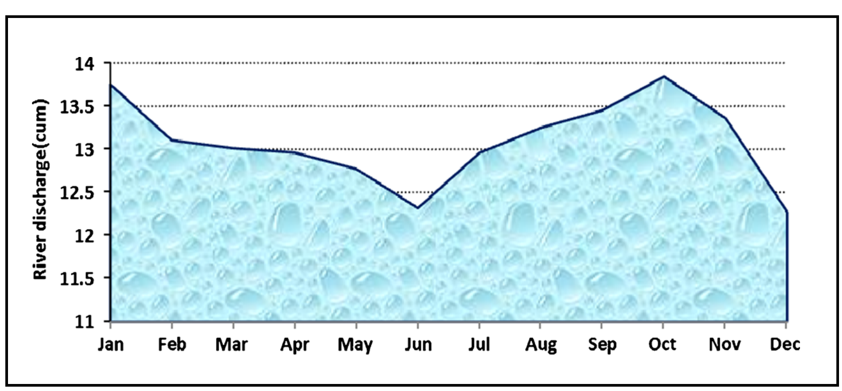
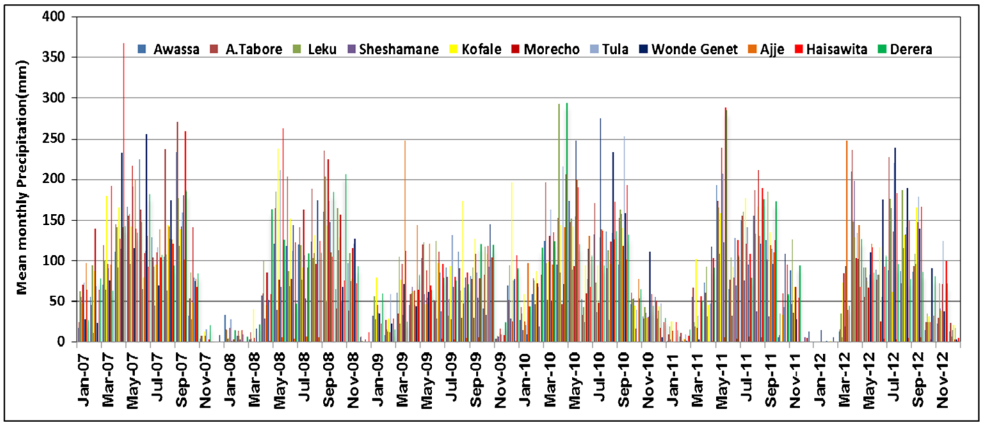


Fig. 3 Mean monthly rainfall recorded at different stations in the study area (2007–2012)



season has mild rainfall. However, in some stations, the highest rainfalls were recorded in this season.

Data sources

Ground-based rainfall data

For this study, monthly rainfall data (2007 to 2012) obtained from the National Meteorological Agency of Ethiopia (NMA) were used to evaluate GPM-IMERG rainfall products over Lake Hawassa catchment. Eleven rain gauges located in and around the study area were used to calculate the mean monthly rainfall using the polygon system. Table 1 shows the latitudinal (degree-minute) and longitudinal (degree-minute) position and elevation of 11 stations (m).

GPM-IMERG product dataset

GPM-IMERG is a multi-satellite precipitation product from the GPM house generated by the combined observations of GPM and its counterpart. The GPM is an international satellite mission precisely designed to unify and improve precipitation measurements from research and operational microwave sensors to deliver next-generation global precipitation data products (Sunilkumar et al. 2019). Spatial resolution and time resolution estimates of GPM-IMERG precipitation are 0.1° and half-hour, respectively. The early, late, and final runs are three GPM-IMERG products. The periods for early and late are 6 and 18 h respectively. GPM-IMERG product can be downloaded free of charge using http://pmm.nasa.gov/data-access/downloads/gpm or https://giovanni.gsfc.nasa.gov/giovanni/. For this study, area-averaged daily accumulated early and late rainfall products of GMP-IMERG were downloaded using https://giovanni.gsfc.nasa.gov/giovanni/. In this study, Lake Hawassa catchment geographic coordinates were used to download IMERG version 6 (V06) products for the periods between 1 January 2007 and 31 December 2012. Mean-GPM-3IMERGDE-06-precipitationCal and mean-

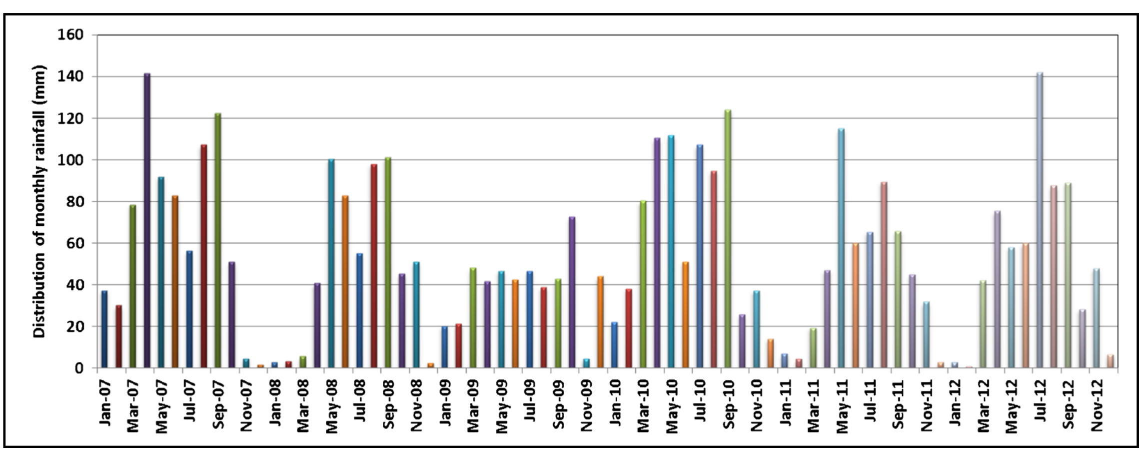


Fig. 4 Mean monthly rainfall at Hawassa catchment (2007–2012)

Table 1 Coordinates and elevation of the stations

Station name	Longitude	Latitude	Elevation
Awassa	38.48	7.07	1694
A.Tabore	38.29	7.05	1750
Leku	38.48	6.88	1879
Sheshamane	38.6	7.2	1727
Kofale	38.8	7.07	2620
Morecho	38.4	6.87	1831
Tula	38.47	6.95	1973
Derara	38.3	6.85	1950
Wendo Genet	38.61	7.08	1742
Aje	38.35	7.29	1846
Hawaasita	38.7	6.93	2240

GPM-3IMERGDL-06-precipitationCal were downloaded for early and late rainfall for IMERG, respectively.

Methods

Average rainfall computation for the study area

There are scarce and unevenly distributed rain gauge stations in the study area. In addition, some of the stations have missing data. The scarce distribution and a small number of rain gauge stations in the catchment make it challenging to characterize rainfall patterns based on ground observations. Therefore, to compare ground-based rainfall data with the GPM-IMERG rainfall product, daily precipitation was converted to the monthly average areal rainfall. The area-average rainfall was calculated using the Thiessen polygon method in ARC-GIS. The Thiessen polygon method is the weighted average method and the area of each rain gauge was therefore obtained using Arc-GIS (Fig. 5). The rainfall recorded at each rain gauge station in the study area was then weighted according to the area it represents. The average monthly rainfall area of Lake Hawassa was then calculated. The average monthly rainfall reported by the Thiessen polygon was met. The average monthly rainfall calculated by the Thiessen polygon method for the period between 2007 and 2012 is shown in Fig. 3.

GPM-IMERG product analysis

In this study, the average daily accumulated rainfall over the Lake Hawassa catchment area between 2007 and 2012 was obtained from GPM-IMERG. The GPM-IMERG rainfall products were compared with ground-based observed monthly area-averaged rainfall between January 2007 and December 2012.

Statistical evaluation of GPM-IMERG rainfall estimates

Error statistics were used in this analysis to evaluate the GPM-IMERG raw and bias-corrected rainfall products. Statistical assessments were calculated for both the rainy seasons and the full seasons between 2007 and 2012. At the Lake Hawassa catchment scale, four error statistics such as Pearson correlation coefficient (R), percentage relative bias (PBIAS), Nash-Sutcliffe efficiency (NSE), and root mean square error (RMSE) were calculated, for GPM-IMERG raw and bias-corrected precipitation products at monthly time frames. In addition, GPM-IMERG raw and bias-corrected rainfall products were also compared to ground-based rainfall data.

PBIAS

According to Araújo (2006), BIAS shows how satellite rainfall estimates (P_{sat}) relate to observed rainfall (P_{obs}). Negative BIAS values indicate that the satellite overestimates rainfall relative to recorded rainfall, whereas positive values indicate that GPM-IMERG underestimates rainfall relative to recorded rainfall. Bias was computed using Eq. (1) and the relationship between precipitation derived from GPM-IMERG (P_{sat}) and mean areal precipitation calculated using rain gauges (P_{obs}) in the catchment area of Lake Hawassa was compared.

$$\mathrm{PBIAS} = \sum_{i=1}^{n} (P_{sat} - P_{obs}) * \frac{1}{\sum_{i=1}^{n} P_{obs}} * 100 \quad (1)$$

Root mean square error

RMSE was calculated (Eq. 2) to evaluate the error variance of the GPM-IMERG rainfall products (P_{sat}) and the rain gauge (P_{obs}). The values of the RMSE range from 0 to ∞. According to Santos (2014), the RMSE value equal to zero shows no errors, whereas greater than zero shows errors between the estimated rainfall of GPM-IMERG and the measured rain gauge.

$$\mathrm{RMSE} = \sqrt{{}^{1}/_{n} * \sum_{i=1}^{n} (P_{sat} - P_{obs})^2} \quad (2)$$

Coefficient of correlation (*R*)

The R measures the extent to which the estimated values correspond to the observed values (Tang et al. 2020). In this study, R was calculated using Eq. (3) to evaluate how the precipitation estimated by GPM-IMERG corresponds to the measured precipitation in the catchment area of Lake Hawassa.

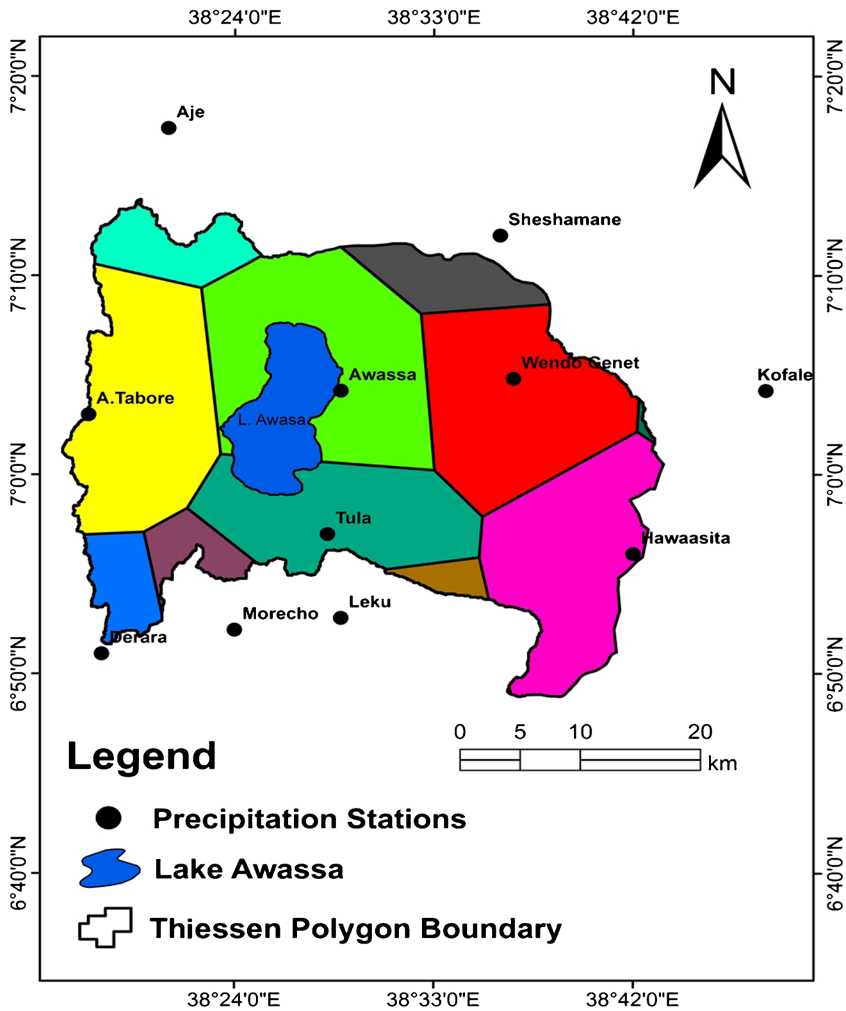


Fig. 5 Thiessen polygon constructed over Lake Hawassa catchment

$$R = \frac{\sum_{i=1}^{n}(P_{\text{obs}} - P_{\text{obsmean}})\sum_{i=1}^{n}(P_{\text{sat}} - P_{\text{satmean}})}{\sqrt{(P_{\text{obs}} - P_{\text{obsmean}})^2}\sqrt{(P_{\text{sat}} - P_{\text{satmean}})^2}} \quad (3)$$

Nash-Sutcliffe efficiency

NSE was used to evaluate the performance of the estimated rainfall by GPM-IMERG with the rain gauges observed in the catchment area of Lake Hawassa. The NSE was computed using Eq. (4). The value of the NSE ranges between − ∞ and 1.0, where the value of the NSE = 1 indicates a perfect match between the GPM-IMERG rainfall estimates and the observe rainfall (Liu et al. 2017a, b; Wei et al. 2018). In general, a higher NSE value indicates good performance.

$$\text{NSE} = 1 - \sum_{i=1}^{n} \frac{(P_{\text{sat}} - P_{\text{obs}})^2}{(P_{\text{sat}} - P_{\text{obsmean}})^2} \quad (4)$$

GPM-IMERG satellite bias correction

Satellite rainfall products contain enormous systematic (bias) and random errors (Habib et al. 2014). Bias persists when the estimates of satellite precipitation are aggregated over time. Errors in satellite precipitation products may cause significant uncertainty for hydrological use. Correction and quantification of bias in satellite rainfall estimates are important for hydrological modeling and design. Daily bias correction (DBC), daily translation (DT), distribution mapping (DM), empirical quantile mapping (EQM), local intensity scaling (LOCI), linear scaling (LS), and power transmission (PT) (Beaufort et al. 2019) are some of the approaches used to address bias in satellite precipitation forecasts. Bias correction techniques are divided into mean-based (LS and LOCI) and distribution-based (DT, DBC, and EQM) techniques (Chen et al. 2013a, b). According to Habib et al. (2014), there are three bias correction schemes: pixel-based, time-and-space-fixed, and time-variable bias corrections. Details and comparisons of the different methods of bias correction are available in Luo et al. (2019) and Chen et al. (2013a, b).

The technique used in this study to correct bias was the LS method. The LS bias correction was applied on a monthly basis to GPM-IMERG late and early rainfall. GPM-IMERG late and early rainfall was adjusted using Eq. (5). According to Teutschbein and Seibert (2012), LS is capable of adjusting perfectly for climatic factors when monthly mean values are included.

$$P_{\mathrm{mcorsat}} = P_{\mathrm{moldsat}} * \left(\frac{\mu P_{\mathrm{mobs}}}{\mu P_{\mathrm{msat}}} \right) \quad (5)$$

where P_{mcorsat} denotes the corrected rainfall of the mth month, P_{moldsat} denotes the rainfall from raw GPM-IMERG products for the study periods, and μ is the mean.

Results and discussion

Evaluation of GPM-IMERG rainfall estimates before bias correction

Results of statistical analysis prior to bias correction for all periods of study are shown in Table 2. The statistical study shows that the area-averaged rainfall from GPM-IMERG early and late is well associated with the area-averaged rain gauges. Correlation coefficients for IMERG early and IMERG late with rain gauges are 0.74 and 0.76, respectively. PBIAS of both IMERG products shows that GPM-IMERG overestimates rainfall over the catchment area of Lake Hawassa compared to the observed rainfall values. Remarkable overestimation has been observed in all seasons, and bias is evident (PBIAS 91.54% positive for IMERG early and 77.03% positive for IMERG late). IMERG early products have been found to be highly overestimated as compared to IMERG late rainfall estimates over catchments at Lake Hawassa. The statistical analysis for the main rainy seasons (July to September) was also calculated in this study (Table 3). The degree of bias varies slightly with the seasons, with a bias of 41.62% for early IMERG and 29.10% for late IMERG rain products for rainy seasons only. Overestimated rainfall in rainy seasons in relation to observed rainfall in the Hawassa Lake catchment is evident from PBIAS of both rainfall derived from IMERG. Sun et al. (2018, b) agreed that performance of GPM products in summer and autumn is better than that in winter and spring. The performance of GPM products in the wet season at a monthly scale was better than in the dry season. RMSE decreases in rainy seasons due to the difference in time scales relative to full-time rainfall estimates. However, a low correlation coefficient was observed for both IMERG early (0.35) and IMERG late (0.39) rainy seasons with rain gauges. It is observed from Fig. 6b that the correlation is good for longer average time scales (all periods) than for short periods (rainy seasons) (Fig. 6a). In the rainy seasons and all periods, there was a wide scatter for both IMERG, which shows a discrepancy between uncorrected GPM-IMERG rainfall and observed rainfall.

Figure 7 shows the cumulative rainfall and GPM-IMERG estimates for early and late rainfall from January 2007 to December 2012. Total precipitation from the gauge, early IMERG, and late IMERG was 3869.31 mm, 7411.22 mm, and 6849.78 mm, respectively, during the study period. The cumulative precipitation from IMERG early is high and relatively close to IMERG's estimates of late rainfall. The cumulative precipitation from IMERG in early and late is higher than that of the observed rainfall in the Lake Hawassa catchment. The cumulative rainfall from the early estimate is 3541.90 mm higher and late is 2980.46 mm higher than the observed rainfall.

Figure 8 shows a comparison of the monthly rainfall from the GPM-IMERG satellite (early and late) and the observed rainfall at the Lake Hawassa catchment area prior to the bias correction for the period from January 2007 to December 2012. Overall, both early and late IMERG had a very good follow-up to the seasonal cycle of observed rainfall. However, the GPM-IMERG satellite (early and late) overestimates rainfall in all seasons compared to the ground-based rainfall. The IMERG product was found to have performed

Table 2 Comparison of mean monthly observed rainfall and the GPM-IMERG satellite estimates before bias correction for periods between 2007 and 2012

GPM-IMERG	NSE (−)	PBIAS (%)	R (−)	RMSE (mm)
Early	− 2.47	91.54	0.74	66.93
Late	− 1.62	77.03	0.76	58.01

Table 3 Comparison of mean monthly observed rainfall and the GPM-IMERG satellite estimates before bias correction for only rainy sessions (kiremt) (July–September) from 2007 to 2012

GPM-IMERG	NSE (−)	PBIAS (%)	R (−)	RMSE (mm)
Early	− 1.76	41.62	0.35	27.17
Late	− 0.93	29.10	0.39	22.66

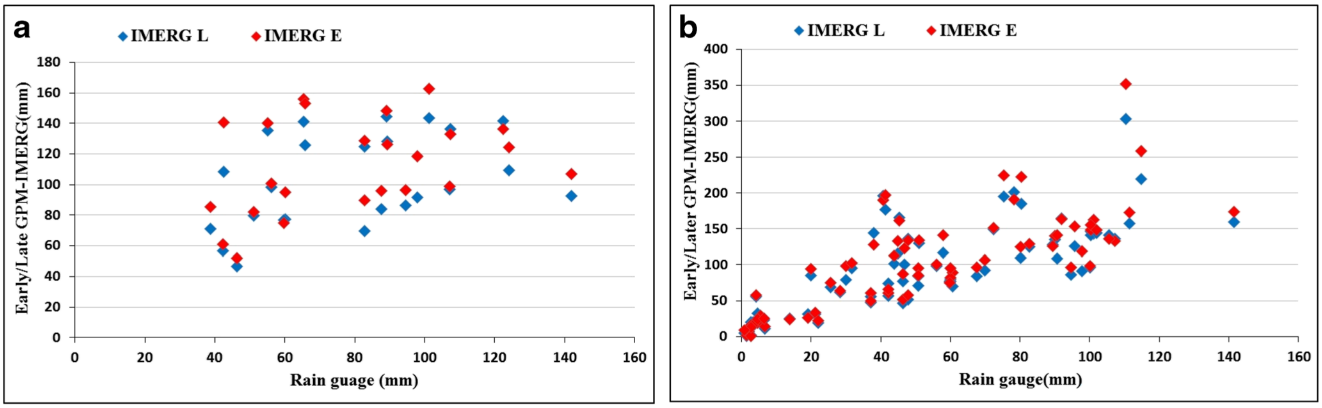


Fig. 6 Scatter plots of main rain periods (**a**) and all periods (**b**) for monthly rainfall between station and GPM-IMERG for the period 2007–2012 in the Lake Hawassa catchment

slightly poor at all seasons over the Lake Hawassa catchment area. The early IMERG showed slightly worse performance (higher peak) in some years than the late IMERG but still generally followed a similar pattern of variation of the ground-based rainfall data (Fig. 8).

Statistical evaluation of GPM-IMERG rainfall estimates after bias correction

Table 4 shows the statistical analysis of the observed mean monthly rainfall and the GPM-IMERG satellite rainfall estimates after the bias correction. It is observed that both IMERG early and late have good performance after a bias correction. The early and late R values for IMERG are 0.86 and 0.85, respectively, indicating a strong correlation of IMERG rainfall estimates with observed rainfall. The results show that the correlation varies from season to season. The GPM-IMERG rainfall products are depending on rainfall intensity (He et al. 2017). The IMERG rainfall products are inclined to provide an overestimate of light rainfall and underestimate of heavy rainfall (Xu et al. 2017). In rainy periods, the early and late IMERG shows a good correlation (R = 0.83 and 0.84, respectively) with observed rainfall (Table 4). However, the PBIAS result shows that GPM-IMERG overestimated (PBIAS positive) for all seasons and underestimated (PBIAS negative) for the rainy season over Lake Hawassa catchment. It could be due to the estimated rainfall during the dry

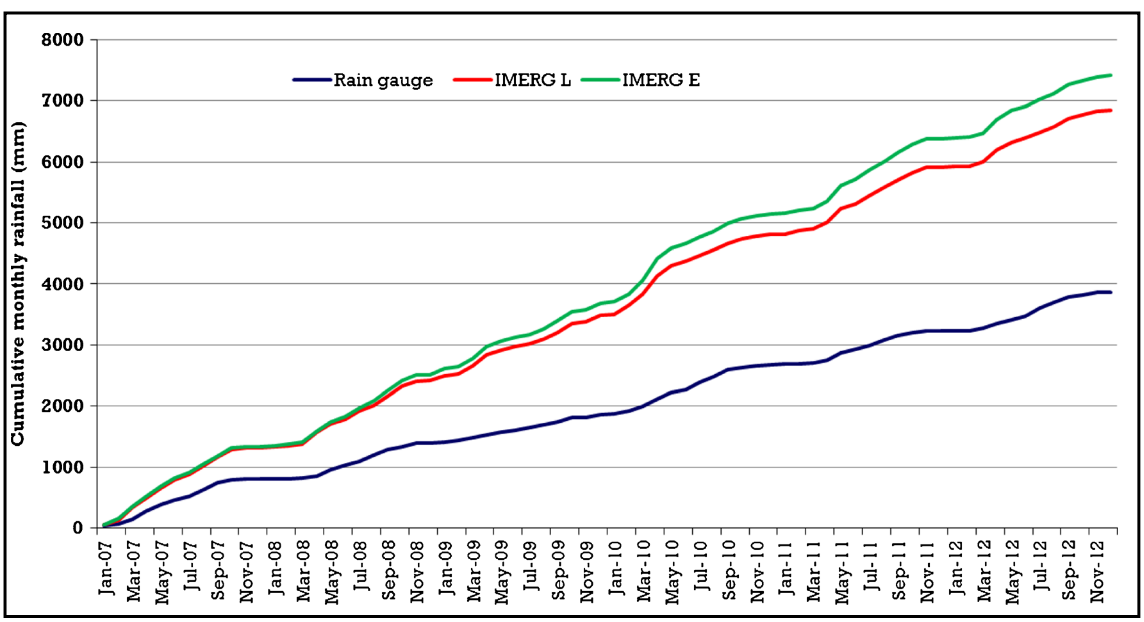


Fig. 7 Time series cumulative precipitation over Lake Hawassa catchment (2007–2012)

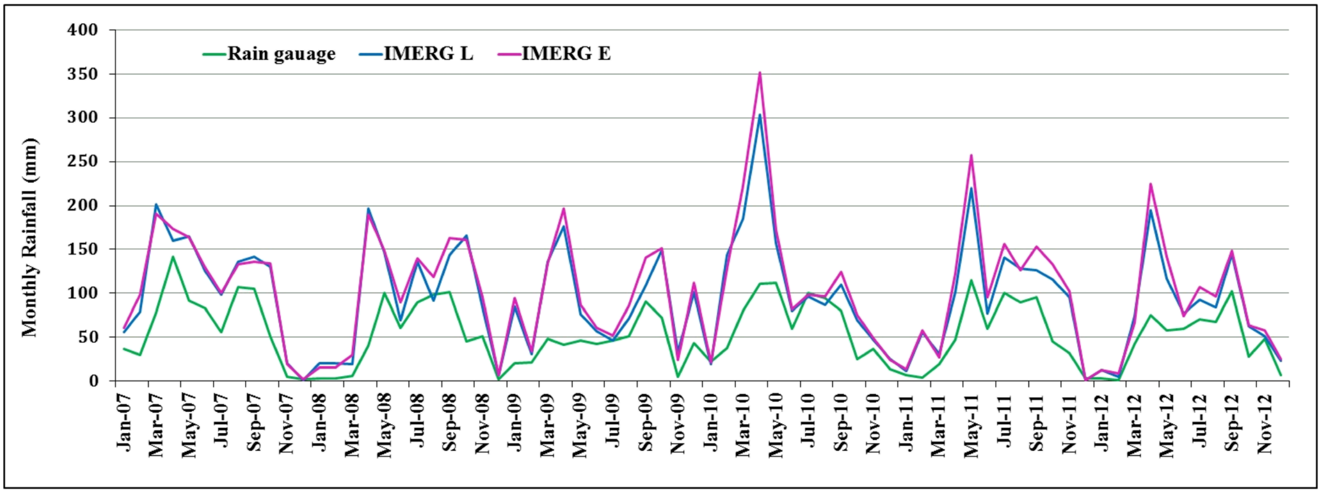


Fig. 8 Comparison of monthly rainfall from the GPM-IMERG satellite and the rain gauges at Lake Hawassa catchment before bias correction for the periods from January 2007 to December 2012

season and the elevation effect that was not investigated in this study. In rainy periods, the RMSE is relatively smaller compared to all seasonal performance measures following a bias correction. However, the NSE is similar in magnitude for both IMERG early and late in the rainy seasons and all periods (Tables 4 and 5).

The scattering plots in Fig. 9 compares the GPM-IMERG rainfall after bias correction and the average monthly rainfall recorded in the catchment areas of Lake Hawassa. Data plots are shown for the area average at the catchment level, covering the period from 2007 to 2012 for all periods and rainy periods. It can be seen from the figure that there is no wide scattered after bias correction for all periods and rainy periods. It shows a strong correlation between both GPM-IMERG products and observed precipitation following a bias correction (Gingyu et al. 2020). Overall, the performance of GPM-IMERG rainfall is good after a bias correction over the catchment area of Lake Hawassa. However, the performance of IMERG early-run and IMERG late-run products varies with the seasons.

Figure 10 shows the cumulative ground-based rainfall and GPM-IMERG rainfall products of early and late rainfall from January 2007 to December 2012 after bias correction. Total observed rainfall, early IMERG, and late IMERG was 3869.31 mm, 4367.58 mm, and 4386.90 mm, respectively, for the study period. The cumulative rainfall of both IMERGs is fairly similar to the observed after a bias correction for the catchment of Lake Hawassa. Figure 11 shows the comparison of monthly rainfall from the GPM-IMERG satellite (early and late) and observed rainfall in the Lake Hawassa catchment area after bias correction. The results showed that, following a bias correction, the mean monthly rainfall better captured the trend of observed rainfall. Overestimation and underestimation of IMERG products were observed in some months of 2010 and 2007, respectively. It is observed that both IMERG early and late were satisfactorily captured the gauged rainfall amount after bias correction especially in 2008, 2009, and 2011 years. It is also observed that both IMERG products have well captured observed rainfall during the

Table 4 Statistical analysis of mean monthly rainfall observed and GPM-IMERG satellite estimates after bias correction from 2007 to 2012.

GPM-IMERG	NSE	PBIAS	*R*	RMSE
Early	0.66	12.88	0.86	20.99
Late	0.65	13.38	0.85	21.17

Table 5 Statistical analysis of mean monthly rainfall observed and GPM-IMERG satellite estimates after bias correction for only rainy seasons (kiremt) (July–September, 2007–2012)

GPM-IMERG	NSE	PBIAS	*R*	RMSE
Early	0.66	− 3.3E-14	0.83	6.84
Late	0.64	− 6.68E-15	0.84	7.06

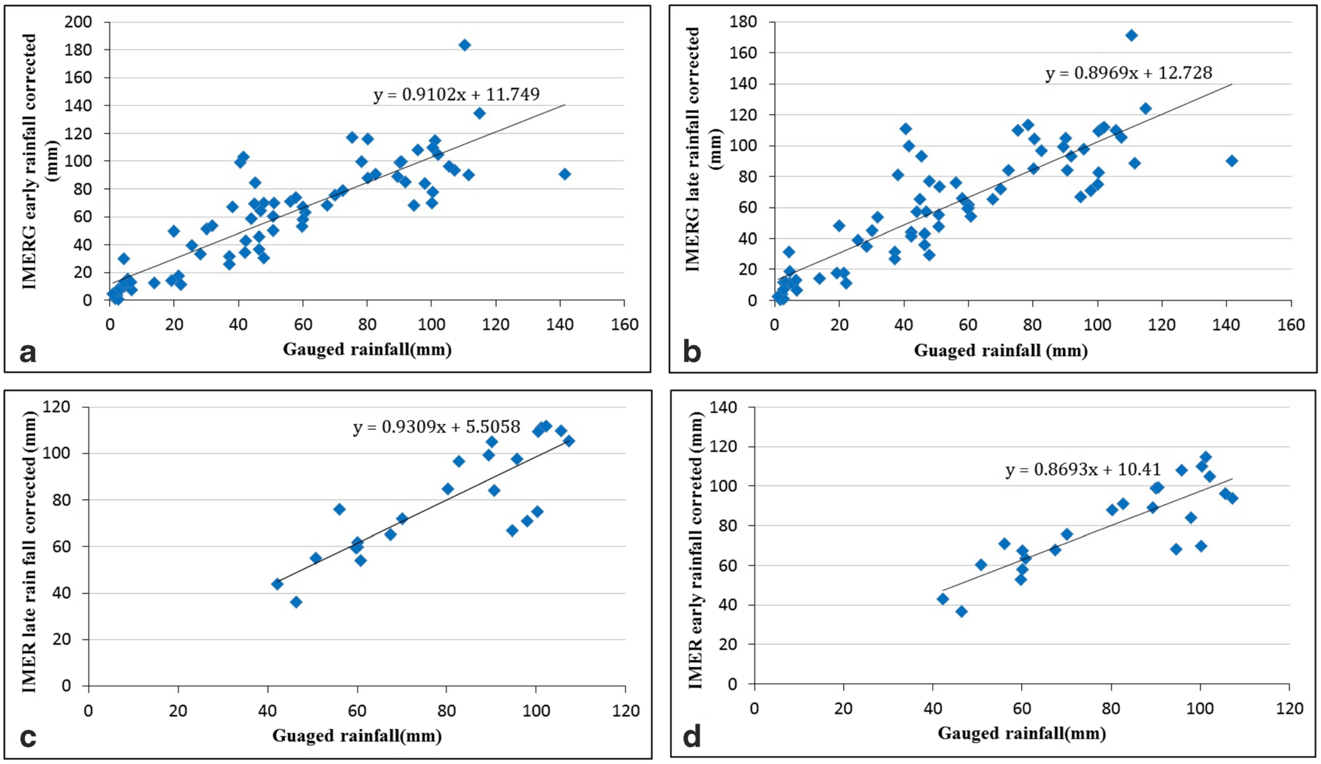


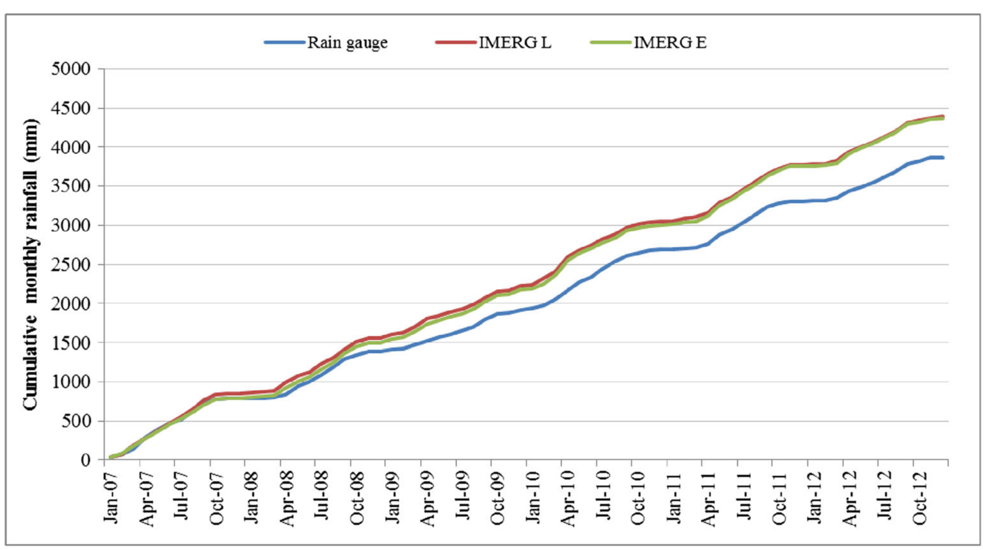
Fig. 9 Scatter plots of GPM-IMERG satellite rainfall products against rain observed rainfall from 2007 to 2012, for early (**a**), late (**b**), late in rainy periods (**c**), and early in rainy periods (**d**)

rainy season (June–September) compared to all seasons (Fig. 12). However, in some months during dry periods and in some months during small rainfall periods, IMERG overestimates rainfall compared to the measured rain gauge. The GPM-IMERG satellite rainfall estimates provided excellent performance during the major rainy seasons in the study area (Fig. 12).

Conclusions

The IMERG rainfall products early and late was evaluated before and after bias correction using error statistics. In this study, the performance of GPM-IMERG rainfall products was evaluted on a monthly scale for all periods, for only rainy periods and cumulative rainfall from 2007 to 2012. The

Fig. 10 Time series of cumulative precipitation over Lake Hawassa catchment (2007–2012)



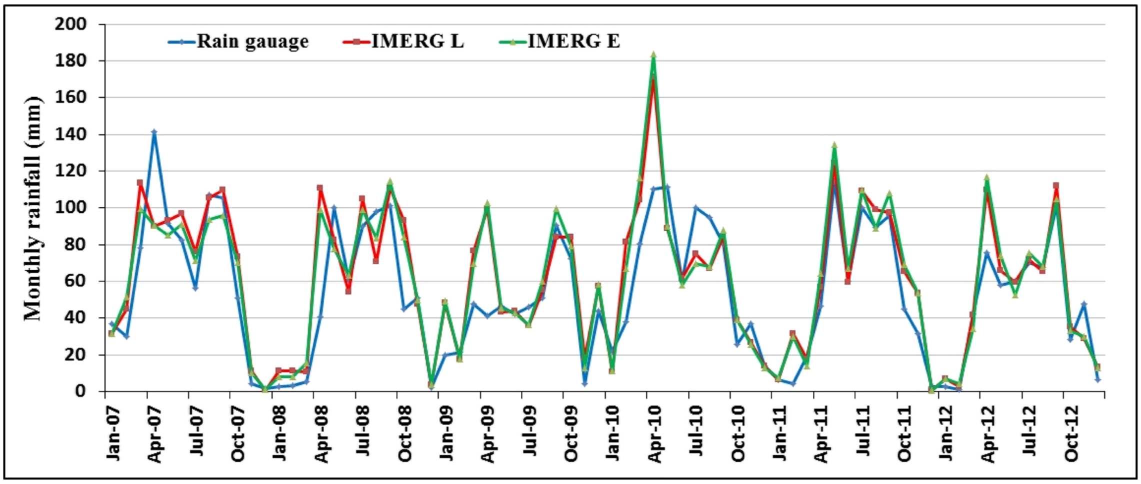


Fig. 11 Comparison of monthly rainfall from the GPM-IMERG satellite and the rain gauges at Lake Hawassa catchment after bias correction for the periods from January 2007 to December 2012)

IMERG early rainfall estimates have a bias with percentage of bias (PBIAS) 91.54 for early rainfall estimates and 77.03 for late rainfall estimates. It shows that during the analysis period, GPM-IMERG overestimated the rainfall as compared to ground-based rainfall. Correction of the GPM-IMERG precipitation estimate effectively reduced bias and resulted in a reasonable match between the predicted GPM-IMERG precipitation and the measured rainfall. The correlation value (R) for IMERG early and late is 0.86 and 0.85, respectively, indicating a strong correlation between the predicted IMERG precipitation and the measured precipitation after the correction of bias. Results also indicated that the estimated rainfall performance of IMERG is variable over the seasons. Bias correction of the rainy season shows a strong correlation between IMERG's estimated rainfall and observed rainfall over the catchment area of Lake Hawassa compared to other full sessions. Bias correction improves the performance of both early and late IMERG products. The impact of topographical characteristics such as elevation on the output of GPM early and late rainfall estimates over the study region should be explored in future studies. In addition, different bias correction methods should be applied and compared to evaluate performance of GPM-IMERG rainfall estimates over the study area.

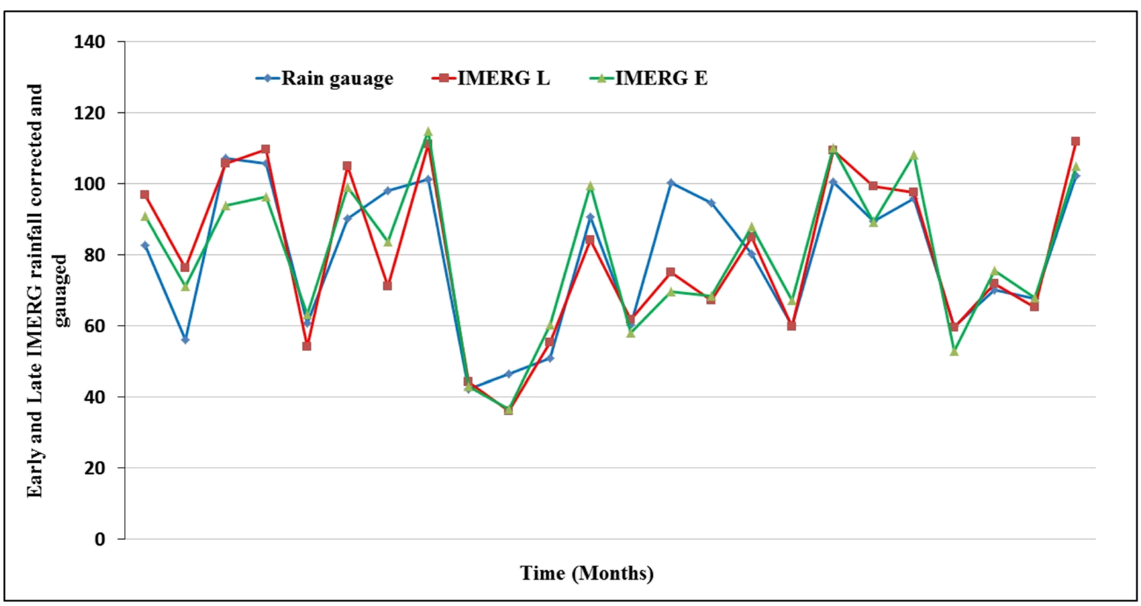


Fig. 12 Comparison of monthly rainfall from the GPM-IMERG satellite and the rain gauges at Lake Hawassa catchment after bias correction for the rainy periods from June to September for 2007–2012

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Declarations

Conflict of interest The authors declare that they have no competing interests.

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