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Evaluation and Bias correction of Tropical Applications of Meteorology using SATellite (TAMSAT) daily rainfall estimates over the data-scarce region of Southern Ethiopia

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ABSTRACT

Precipitation data is an intrinsic parameter of rainfall-runoff simulation. since it is strongly hooked into the accuracy of the spatial and temporal representation of the precipitation. In regions where rainfall stations are scarce, additional data sources could also be needed. Satellite platforms have provided a satisfactory alternative because of their global coverage. Tropical Applications of Meteorology using SATellite (TAMSAT) is one such data source provided by the research group of the University of Reading, UK. This dataset provides rainfall estimates across Africa which captures the rainfall pattern in GenaleDawa River basin (southern Ethiopia) but with a magnitude bias of over-estimation and under-estimations. In this study, magnitude bias correction of the TAMSAT dataset with a linear scaling technique resulted in a rainfall grid of the area with ~4 km spatial resolution of a 35 year (1983–2017) daily rainfall dataset. Intercomparison between Satellite rainfall product and observed data were done using point to grid method selecting nine representative metrological stations.The average correlation R is 0.45 and the average NS is 0.028 and the Categorical index POD, FAR, FB and HSS, values were 0.49,0.4,0.84, and 0.4) before bias correction. After bias correction, these values were improved to the average value of R=0.87 and NS =0.764 and POD, FAR, FB, and HSS of (0.71,0.22, 0.92, and 0.66 respectively.

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Introduction

A precise analysis of water resources issues (e.g., flood, drought, extreme events, socio-economic analysis) entails accurate measures/estimations of hydroclimatic variables.For a comprehensive of the impact of rainfall on the environment, one must use appropriate spatial and temporal resolution for rainfall measurements [1]. Satellite-based precipitation estimates with high spatial and temporal resolution and enormous areal coverage provide a possible alternative source of data for hydrological models in areas where conventional rain gauge precipitation measurements are not readily available or sparsely available and no radar technology for measuring representative rainfall magnitude [1-4]. These applications would even have far-reaching effects for several developing countries whose ground-based rain gauges are sparse and no radar technology for measuring representative rainfall magnitude. However, there are errors associated with satellite-based rainfall estimates which prompt several questions [7]. How accurate are satellite-based rainfall products? Can high-resolution satellite rainfall products be used for hydrological applications? Lack of knowledge on the accuracy of those satellite products is a challenge to the hydrological community, especially under complex terrain.Satellite rainfall products are subject to the various sourceof errors related to temporal sampling, instrument, algorithm, gaps in revisit times, indirect relationship between remotely sensed signals and rainfall rate, and also its performance varies with region, elevation, and season [4-6]. A wide range of satellite-based estimations of precipitation isout there in high spatial and temporal resolution, which makes them useful for distributed hydrological models. However, not all the satellite products are suitable for all the regions (i.e., their suitability and performance vary from region to region) [7,8]. There is, therefore, a requirement to quantify their uncertainties before selecting the acceptable product for the region. Therefore, hydrologists are still uncertain in applying these products directly in hydrological applications knowing that many uncertainties are still involved in such techniques [9,10]. Given the practical limitations of the hydro-metrological station has brought about the utilization of satellite remote sensing as a potential method of quantifying rainfall such as visible and infrared techniques that derive qualitative or quantitative appraise of rainfall from satellite imagery. Inadequate hydro-metrological network coupled with inadequate maintenance of rainfall gauge measuring instruments, human error, and inaccessible areas such as sloping areas has resulted in the existence of gaps in rainfall measurements as most occasions are not recorded requires a means to improve on the available data accessible from the gauge precipitation network. Satellite precipitation estimation will, therefore, be important to address issues such as precipitation occurrence, magnitude, and apportionment at all-time scales for many applications in meteorology, climatology, hydrology, and environmental sciences. Besides this, it will provide much information required in the management of water resources and flood forecasting. To utilize these rainfall estimates appropriately it is essential to know their accuracy and expected error characteristics [11,12].

Several studies assessed the performance of satellite rainfall products on streamflow simulation capability, Bias correction, and Validation Worldwide. Regarding our country Ethiopia, some studies have been conducted to evaluate performance, validation, Inter-comparison of satellite-based rainfall products especially for the Blue Nile basin [1,13,6,14,7,8]. In other parts of Ethiopia high- resolution rainfall products have been evaluated for different purposes [15,16,2,10,5,7,8]. The rainfall data sets and the modeling activities were used to characterize and determine performance in input precipitation data; high-resolution satellite rainfall products bias-corrected TAMSAT. The main objective of this study is to evaluate and bias correct high-resolution satellite rainfall products (TAMSAT).

Materials and Methods

Study area description

GenaleDawa river basin lies in the southern part of Ethiopia, covering parts of Oromia, SNNP, and Somali regions (figure 1). Geographically located between 30 30' and 70 20' North latitude and 37005' and 430 20' East longitude. The basin covers an area of 172889 km2 [17]. It is the third-largest river basin, after Wabi Shebelle and Abbay river basins. Neighboring river basins are the Wabi Shebelle to the north and east, Rift Valley basin to the west. GenaleDawa river basin hasavery scarce metrological station and Mountainous topography and is provided as the area where satellite rainfall products are beneficial. The easterly and southeasterly moist air currents ascend over the highlands in spring, produce the main rainy season in southern Ethiopia in general, and in GenaleDawa basin in particular and bring "small rains" of spring (March to May) to most parts of the country. Southeast (GenaleDawariver basin), therefore, gets its first maxima rainfall during spring and receives the year's secondary maxima rainfall during autumn from the Indian Ocean easterlies. While the basin receives little rainfall in summer compared to spring (March to May) and autumn (September to November) due to the case that the Southerly Indian Ocean air currents lie in the lee side of the highlands in summer and Atlantic westerly's reach the southeastern lowlands (GenaleDawa) after losing their moisture on the highlands to the west.

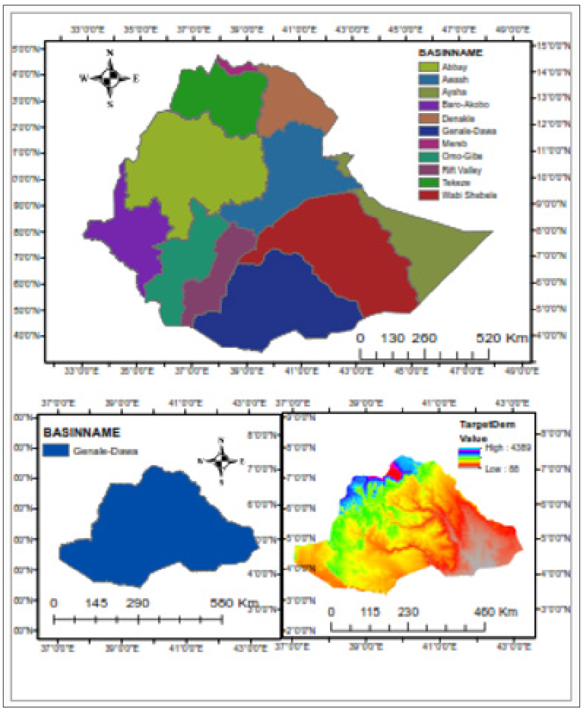

Figure 1: Study area map

Dataset

The TAMSAT daily rainfallestimates have been available for all of Africa since January 1983at a spatial resolution of0.0375° (about 4 km);The data was compiled in 9998 grid point file as time series excel file.The daily observed datasets for 9rain gauge stations throughout the area were accessed fromthe Ethiopian NMA (National Meteorology Agency).The climatic data and satellite data used for this study covers 22 years from January 1996 to December 2017.

Comparison/Evaluation

There are two commonly used methods for evaluating the satellite rainfall products, namely, point to grid (point-based) and grid to grid (interpolated grid to satellite grid) methods. Individual gauge stations-based rainfall is compared with grid-based satellite and reanalysis rainfall products in point-based comparison methods, while in the grid-to-grid comparison, the gauge-based observed rainfall is interpolated and then evaluated at the same resolutions of the selected grid-based satellite and reanalysis rainfall products. The grid-grid assessment approach is approved forthe area is covered with a high number and uniformly networked gauge stations. In the regionwhere the distributionnumber of rain gauge stations sparse and complex terrain as in the case of the present study, point to grid comparison method is the best way to evaluate each satellite and reanalysis rainfall product independently using their native resolution [10]. Hence, point to grid method is adopted for this study.

Bias Correction

Studies on the comparison of TAMSAT with ground-observed rainfall data confirmed that TAMSAT is excellent alternative data set for hydrological modeling on a large scale showing that TAMSAT precipitation can reproduce the observed rainfall pattern in Ethiopia, with magnitude variation. Therefore, a bias correction method that focuses mainly on the magnitude rather than the pattern or trend of the datasets is important. From among the various arrays of rainfall data bias correction techniques, most of which are statistical, the linear scaling (LS) bias correction method was selected for this study as it aims to match the monthly mean of corrected values as closely as possible with that of the observed ones. It operates with monthly correction values based on the difference between observed and raw data. The bias factor for precipitation is a multiplier that is computed from the ratio of the monthly mean of the observed to the raw dataset:

$$Pd, cor = Pd, raw * (\frac{\mu(Pm, obs)}{\mu(Pmraw)}$$

Where Pdcor is the corrected daily precipitation and Pdraw is the daily raw precipitation data from TAMSAT, μ (Pm,obs)is the long-term mean value of monthly rainfall of observed data, and μ(Pm raw)is the long-term mean value of the monthly raw rainfall data.

Performance Analysis

To evaluate the model simulation outputs relative to the observed data, model performance evaluation is necessary.Weuse both statistical indices and categorical statistical indices were adopted to evaluate the precision of the satellite rainfall products. Statistical indices evaluate the performance of the Satellite rainfall product in estimating the cumulative rainfall over a timeframe. The statistical indices are:

$$R = \frac{\sum(O-\overline{O})(S-\overline{S})}{\sqrt{\sum(O-\overline{O})^2}\sqrt{\sum(S-\overline{S})^2}}$$

$$RSME = \sqrt{\frac{1}{N}\sum(S-O)^2}$$

$$ME = \frac{1}{N}\sum(S-O)$$

$$MAE = \frac{1}{N}\sum(|S-O|)$$

$$NSE = 1 - \frac{\sum(O-S)^2}{\sum(O-\overline{O})^2}$$

$$Bias = \frac{\sum S}{\sum O}$$

Where O is the rainfall total at a reference gauging station, O¯is the average observed rainfall total at a reference gauging station, S is a rainfall total for a satellite product, and N is the number of data pairs compared. The dimensions of ME and MAE are mm, whereas NSE and Bias are dimensionless. ME and MAE both provide information on the average estimation error. ME ranges from –∞ to ∞, whereas MAE ranges from 0 to ∞, and a perfect score for both is 0. MAE was used here instead of the root mean square error to avoid the effect of extremely high rainfall values or outliers [18]. The Bias statistic indicates how well the mean estimate and gauge mean correspond; its value ranges from 0 to ∞, with 1 being a perfect score. Values of Bias >1 and positive ME values indicate an overestimation, whereas values of Bias <1 and negative ME indicate an underestimation. NSE shows the skill of the estimate relative to a reference (in this case, the mean of the gauge observations); it ranges from –∞ to 1, with higher values indicating better agreement between the Satellite rainfall and gauge measurements. Negative NSE values indicate that the reference mean is a better estimate than the SREs; 0 indicates that the reference mean is as good as the Satellite rainfall. A categorical statistical index assesses the rainfall detection capacities of satellite rainfall products. To assesses the rainfall detection capabilities of the Satellite rainfall estimate (rainfall product threshold ≥1 mm), we take a suite of binary skill scores that encapsulated information on rain/no-rain days in a contingency table (Table 1). The contingency table was constructed to calculate categorical statistics that included the probability of detection (POD), false alarm ratio (FAR), frequency bias index (FBI), and Heidke skill score (HSS) as follows:

Table 1: Contingency table for comparing rain Station-based measurements and satellite-based rainfall product

	Gauge >=1 mm	Gauge <1 mm
Satellite >=1 mm	A (Hit)	B (false detection)
Satellite <1 mm	C (Miss)	D (Correct No rain)

$$POD = \frac{A}{A+C}$$

$$(FAR = \frac{B}{A+B}$$

$$FBI = \frac{A+B}{A+C}$$

$$HSS = \frac{2(AD-BC)}{(A+C)(C+D)+(A+B)(B+D)}$$

Where A, B, C, and D showing hits (the satellite successfully detected rain), false alarms (the satellite failed to detect the no-rain case), misses (the satellite failed to detect rain), and correct negatives (the satellite successfully detected the no-rain case), respectively (Table 2). POD indicates the proportion of observed rainfall days that were correctly estimated by the satellite product. FAR is the proportion of satellite-estimated rainfall days when there was no rain. Both POD and FAR range from 0 to 1, with 1 being a perfect POD and 0 being a perfect FAR. FBI, ranges from 0 to ∞, compares the rainfall-day detection frequency of the Satellite rainfall product with that of the rain gauge measurements: an FBI of less than (greater than) 1 indicates an underestimation (overestimation) of rainfall days. HSS ranges from –∞ to 1, is a measure of the overall skill of the rainfall-day estimates after rain events detected by random chance have been removed: an HSS less than 0 indicates that random chance is better than the Satellite rainfall product; an HSS of 0 means the Satellite rainfall product has no skill; and an HSS of 1 indicates a perfect estimation of rainfall days by the Satellite rainfall product [4,5,7].

Result and Discussion

Bias Correction of TAMSAT Rainfall Product

Hydrometeorological datasets have significant importance on sustainable water resources management, as well as for differentsocio-economic activities. However, it is noted that acquiring an accurate and consistent set of precipitation data is a challengingtask throughout the world especially in Africa [7,19,8,10]. When comparing TAMSAT rainfall product with the in-situ rainfall of selected stations, it shows a large discrepancy. To use the bias-corrected dataset for hydrological modeling and other importance, the raw TAMSAT rainfall data were corrected with LS bias correcting techniques [20,7,21,4]. Both statistical and categorical tests clearly describe that the raw TAMSAT rainfall dataset has been biased in both directions (underestimation and overestimation) of the daily rainfall [4,11]. However, the overall magnitude of the raw TAMSAT rainfall dataset overestimates or underestimates the daily rainfall of the basin, indicated with a value of R, NSE, and RSME (0.26 - 0.58), (-0.41 - 0.26) and (5.21 - 10.3) respectively for all representative station (Figure 2 and 3). Categorically the values of POD, FAR, FBI and HSS (0.38 - 0.6), (0.26 - 0.65), (0.75 - 1.22), (0.25 - 0.47) respectively. The corrected TAMSAT rainfall dataset was the best fit with the observed dataset, with a small range of RMSE (1.77–5.6) and a strong range of NSE co-efficient (0.74 – 0.91) and a strong R (0.84 - 0.95). The bias correction gave a better result and lower values of PBIAS, ranging from 0.98 to 1.25. The categorical improvement is indicated by a strong value of POD, FAR, FBI and HSS (0.75 - 0.85), (0.17 - 0.3), (0.75 - 1.1) and (0.58 - 0.89) respectively.

Table 2: Comparison of categorical Evaluation Statistics for raw, bias-corrected TAMSAT

Evaluation Statistics		TAMSAT raw	TAMSAT Cor
Categorical	POD	0.49	0.71
	FAR	0.40	0.22
	FB	0.84	0.92
	HSS	0.41	0.66
Continuous	R	0.45	0.88
	ME	0.11	0.05
	BIAS	1.06	1.08
	RSME	7.6	3.70
	NSE	0.028	0.76

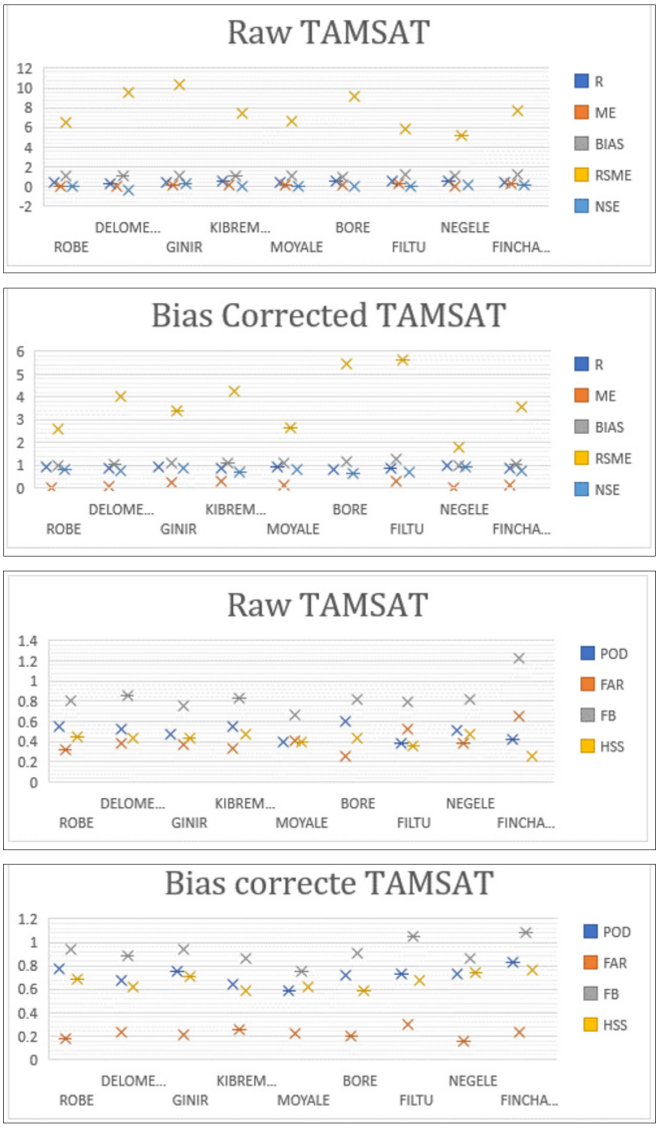

Figure 2: Statistical and Categorical index for raw and bias corrected TAMSAT

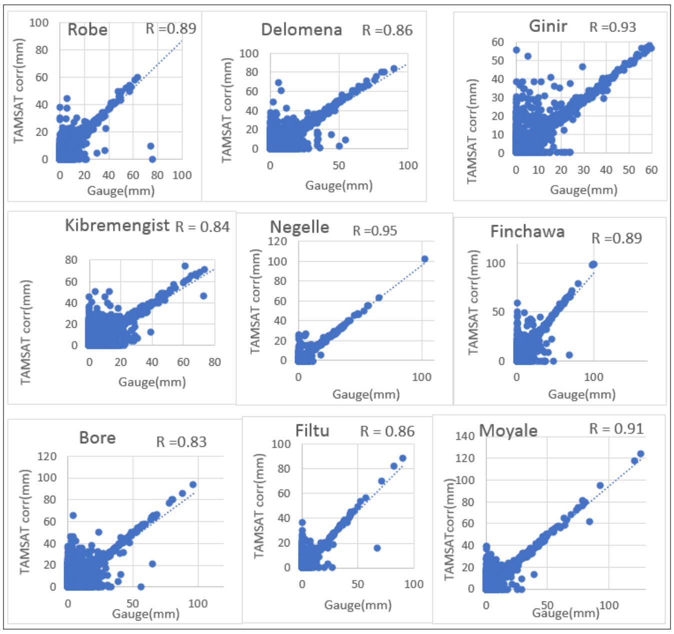

Figure 3: Intercomparison of daily rainfall TAMSAT and rain gauge

To use the corrected dataset for hydrological modeling and other purposes, the rawTAMSAT data was adjusted with Linear Scaling bias correcting techniques.However, the spatial distribution of the corrected TAMSATdataset shows a betterrepresentation of the observed rainfalldistribution of the area than the raw TAMSAT data. Comparingthe mean annual time series data for the threerainfall datasets using different statisticalmeasures (Figure 4 and 5). The statistical index clearly describes that the raw TAMSATdataset has biased in both directions (underestimation and overestimation) of the mean annual rainfall. However, the overall trend of the raw TAMSAT dataset underestimates the mean annualrainfall of the area, indicated with a negative value of PBIAS (-0.03- -0.35) and overestimates with a positive value of PBIAS (>0.04) and an NSE value of -0.4. On the other hand, the correctedTAMSAT data shows a positive and small PBIAS value, 0.98-1.25, anda strong NSE co-efficient, 0.67-0.95.

A bias correction performance test was also carried out usingthe statistical measures that include root-mean-square error (RMSE), Nash–Sutcliffe Efficiency (NSE), and percent bias (PBIAS) to evaluate the quality of the adjusted dataset on differenttime scales [20,10,1,5,22]. The annual performance assessmentindicated that the whole grid point and gave a strong NSE co-efficient (>=0.78),the positive low magnitude of PBIAS (>=0.98), and significantly smallRMSE, unlike the raw TAMSAT data. The monthlyand daily performance evaluationshave been found useful for sampleground-observation gauging stations that were distributedacross the basin.On daily time scales, the performance measures of RMSE,NSE, PBIAS, and R produced results in the range of 0.177–5.62,0.67–0.92,0.98–1.2, and 0.82-0.92 respectively, which are indicators ofthe good performance of the bias correction conducted.

The annual variation of rain observed by rain gauges was generally captured by both satellite rainfall products for all selected stations. TAMSAT product shows an overestimation of annual maximum rainfall from 84.4 to 2054.81mm/yr. for the whole study period when compared with Observed data. In capturing both magnitude and trend of annual rainfall bias-corrected TAMSAT shows best performance [20,23].

The trend of monthly rainfall observed at rain gauges iscorrectly captured by Biascorrected TAMSAT satellite rainfall products. Bias corrected TAMSAT overestimate monthly peak rainfall observed by rain gauge in the range of 0.75% to 3.94%for all stations except three stations; Robe, Bore, and Moyale Stations Which underestimate monthly peak by (2.16%,3.75%, and 5.89%) respectively.

An inter-comparison of daily rainfall estimates, the comparison statistics (R = Pearson's correlation coefficient) between TAMSAT rainfall values and rain gauge values were very good which ranges from 0.827 to 0.951for Selected representative stations.

The inter-comparison, especially the daily basis is vital. Therefore, bias-corrected TAMSAT rainfall estimates gave a very good result, and this result also consistent with findings in Eastern parts of Ethiopia [5,24,20,2,25,26]. There have been subsequent studies conducted in Ethiopia to evaluate satellite rainfall products in the estimation of rainfall, [1,5,11,27,23]; based on their studies and the result of this study, it is concluded that TAMSAT is much closer to the actual rainfall fields in Ethiopian basins [12,23,7,8].

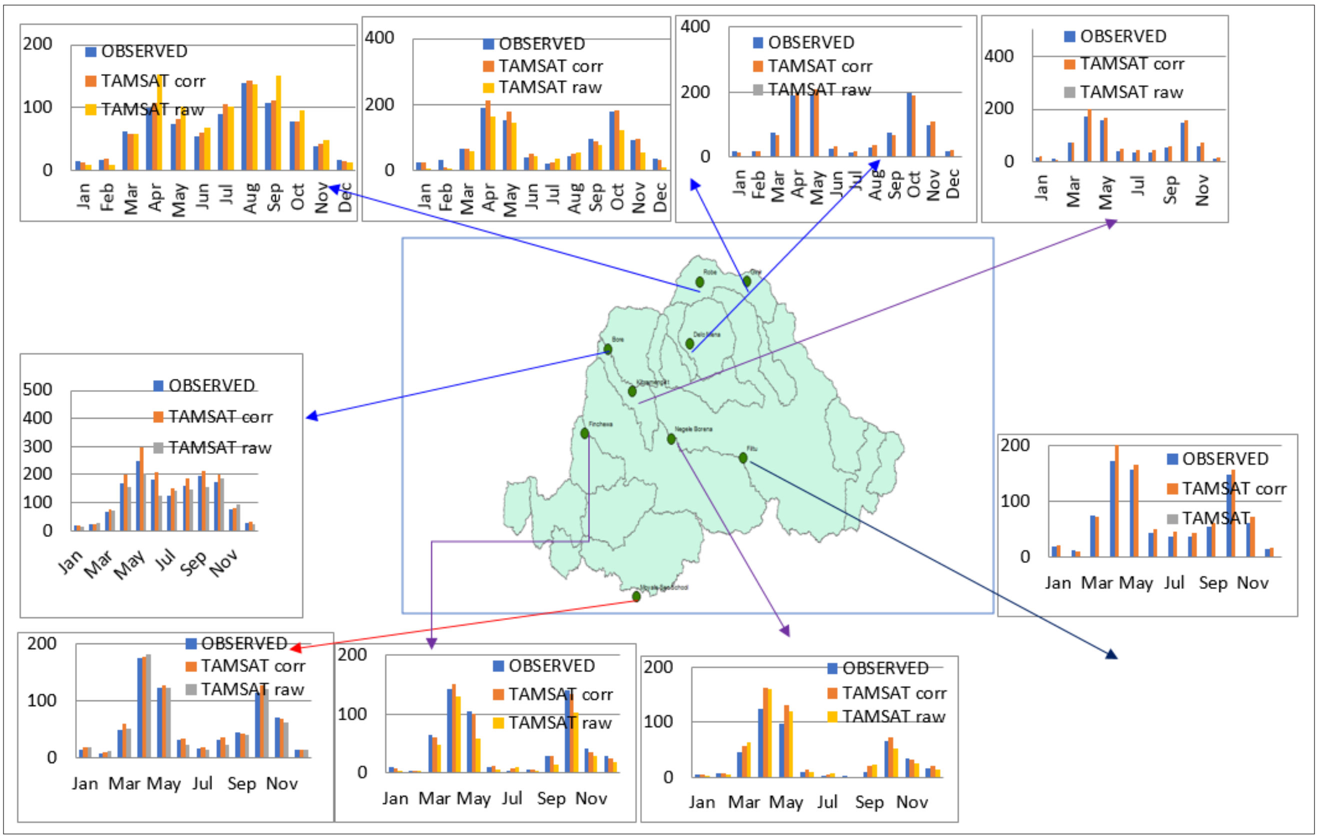

Figure 4: Inter- Comparison of Mean Monthly Rainfall

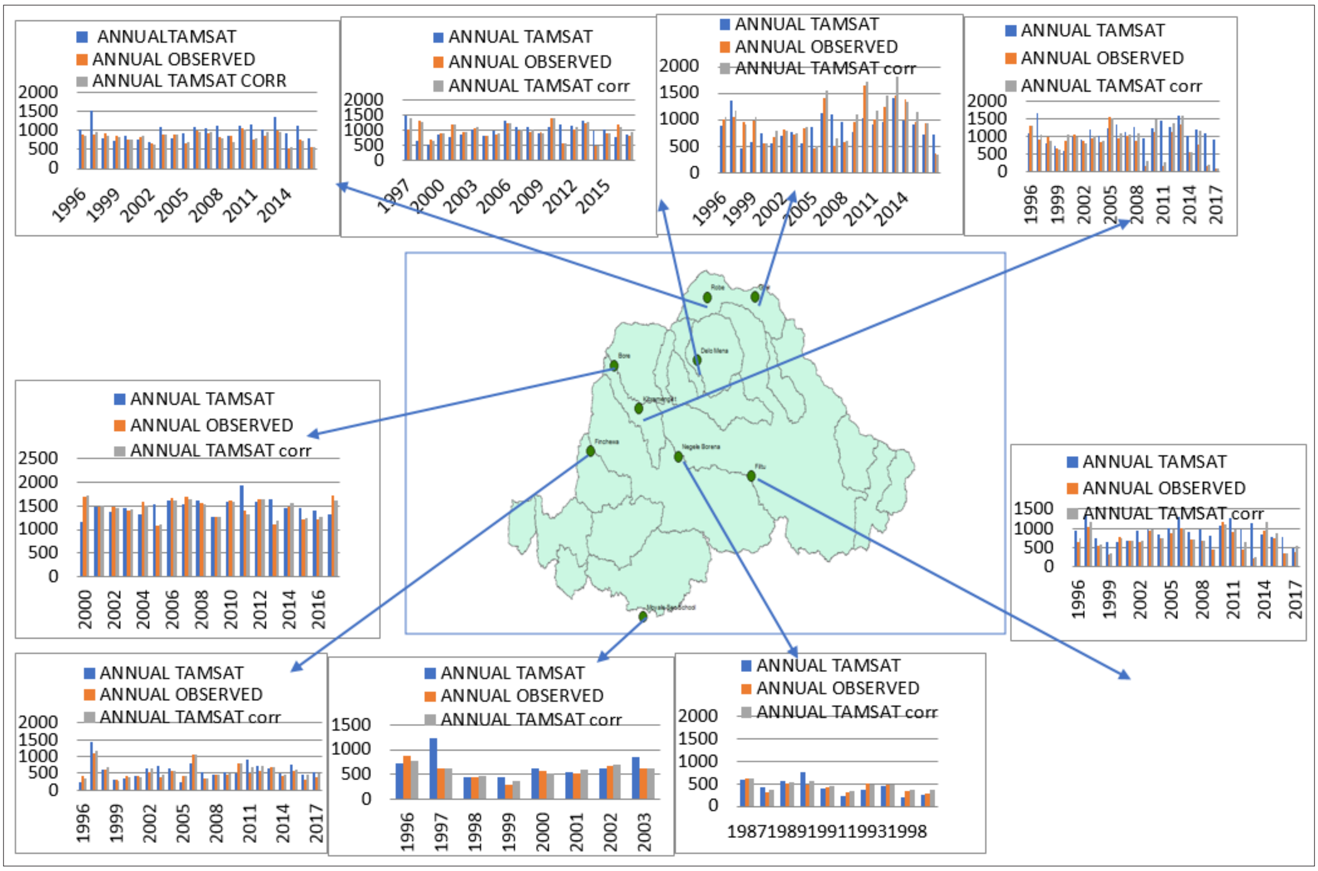

Figure 5: Inter-comparison of annual rainfall

Conclusion

High-resolution satellite rainfall product is getting very high recognitions as a source of rainfall data in data-scarce regions. The Southern part of Ethiopia (GenaleDawa river basin) can be provided as a good example where the use of satellite-derived precipitation could be beneficial. Satellite-based precipitation estimates exhibit large systematic and random biases. The biases persist when the estimates are aggregated over time and, hence, may cause large uncertainties. The study mainly focused on "Evaluation and Bias correction of Tropical Applications of Meteorology using SATellite (TAMSAT) daily rainfallestimates over the data-scarce region of Southern Ethiopia" Both statistical and categorical tests clearly describe that the raw TAMSAT rainfall dataset has biased in both directions (underestimation and overestimation) of the daily rainfall. However, the overallmagnitude of the raw TAMSAT rainfall dataset overestimates or underestimates the daily rainfall of the basin, indicated with a value of R, NSE, and RSME (0.26 - 0.58), (-0.41 - 0.26) and (5.21 - 10.3) respectively for all representative station. Categorically the values of POD, FAR, FBI and HSS (0.38 - 0.6), (0.26 - 0.65), (0.75 - 1.22), (0.25 - 0.47) respectively. The bias-corrected TAMSAT rainfall dataset was the best fit with the observed dataset, with a small range of RMSE (1.77–5.6) and a strong range of NSE co-efficient (0.74 – 0.91) and a strong R (0.84 - 0.95). The bias correction gave a better result and lower values of PBIAS, ranging from 0.98 to 1.25. The categorical improvement is indicated by a strong value of POD, FAR, FBI, and HSS (0.75 - 0.85), (0.17 - 0.3), (0.75 - 1.1) and (0.58 - 0.89) respectively, which are indicators ofthe good performance of the bias correction conducted.

Data Access and Format

The daily rainfall estimates (in mm per day) are freely available as netCDF files for each day from the TAMSAT website (http://www.tamsat.org.uk) and the University of Reading Research Data Archive. The spatial resolution is 0.0375° latitude by 0.0375° longitude with estimates provided for all land points in Africa, including Madagascar. In addition, the TAMSAT website contains quick look images for each day and a time series extraction tool can be used to extract area-averaged data for countries, administrative districts, and user-defined rectangular regions or user-defined pixels in CSV format.

The weather input data required for SWAT simulation includes daily data of Precipitation, maximum and minimum temperature, relative humidity, wind speed, and solar radiation. These were obtained from the Ethiopian National Meteorological Agency. The weather data used were represented from six stations inside GenaleDawa River basin. The climatic data used for this study covers 22 years from January 1996 to December 2017.

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