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ORIGINAL ARTICLE

EVALUATING THE PERFORMANCE OF SATELLITE RAINFALL PRODUCTS IN UPPER GILGEL ABAY CATCHMENT, BLUE NILE BASIN, ETHIOPIA

Assayew Nebere Ambaw[1]

ABSTRACT

Evaluation of performances of satellite rainfall estimates (SREs) for representing the spatial and temporal variability of rainfall in data-poor catchments such as Upper Gilgel Abay is vital. Hence, the focus of this study was to test the effectiveness of satellite rainfall estimates at high spatial and temporal resolutions in Upper Gilgel Abay Catchment. The study period of 2006-2010 was used for downloading the 1-hr temporal and 8 km × 8 km spatial resolution CMORPH (Climate Prediction Centre Morphing Method) data (selected from SREs). For correcting the systematic biases, time and space variant bias correction algorithm was applied for a time window of 7 days and a minimum rain accumulation of 5 mm within these days. Bias correction selected for this study aimed at correcting both in space and time domains. Based on the findings of this study, CMORPH underestimates rainfall up to 18% during the analysis period (2006-2010). Spatially, there are clear variations on the performance of CMORPH across rain gauging stations.

Keywords: CMORPH; bias factor; satellite rainfall estimates; optimum window size.

INTRODUCTION

Spatial and temporal distribution of rainfall are important for water resources management, flood prediction and warning services, and drought monitoring (Bajracharya et al., 2015).Rainfall variability in the Upper Gilgel Abay study area isreported by Haile et al. (2009), which reveals the variability between mountainous areas and flat areas. In Upper Gilgel Abay catchment rain measuring stations are sparse in distribution and most are located outside the catchment. Observations from rain gauge stations are available daily with some of series incomplete. Hence, Satellite rainfall products can be considered as an option for rain gauge measurements.

Satellite-based rainfall estimates have become available at high resolutions and are expected to offer an alternative to represent the variability of rainfall estimates in data-sparse and ungauged catchments (Sawunyama & Hughes, 2008). In this regard, different products have been produced with the development of earth observation techniques. One of the products that

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[1] Lecturer, Department of Geography and Environmental Studies, University of Gondar, P.O. box 196 Gondar, Ethiopia, Email: sayew.nebre@uog.edu.et, assayew@gmail.com.

is available at a global scale with high spatial (8 km × 8 km) and temporal (30min) resolution is Climate Prediction Centre morphing method (CMORPH).

The accuracy of the 1-hr, 8 km × 8 km CMORPH product for a Lake Tana basin, which is characterized by large topographic variability and significant rainfall variation, is shown by Haile et al. (2013). Findings show the poor rain detection capability of CMORPH which led to significant underestimation of the seasonal rainfall depth with large amounts of hit rain bias as well as missed rain and false rain biases. The findings also indicated the effect of the spatial differences in highlands and lowlands in rain event properties which are reflected on spatial differences in CMORPH accuracy (Haile et al., 2013).

Errors as such can be random or systematic. It is the systematic error that is commonly referred to as bias and reflects errors which are systematically distributed over time and space. Different bias correction algorithms are proposed in research to minimize the systematic error which exists in satellite rainfall estimates. In Lake Tana Basin specifically, Habib et al. (2014) applied three bias correction schemes which are space-time fixed, time variable and space-time variable bias factors to correct the bias of CMORPH and found the bias which needs most important correction is the temporal variation of CMORPH.

The quality of the rainfall input can be achieved from continuous rainfall measurements on sub-daily or hourly basis, from sufficient number of rainfall gauging stations over the area of application. Unfortunately, this is not always the case in many developing countries including Ethiopia, where such an observation network is yet to be developed. For example, the catchments discussed in this study are poorly gauged and in some cases the daily time series data from the gauging stations may even exhibit significant gaps (Seyoum, van Andel, Xuan, & Amare, 2013). Hence, this study evaluates the practical applicability of SREs in data-sparse catchments like Upper Gilgel Abay as alternative source of rainfall data for hydrological and water resource management applications using time and space variant correction algorithm.

Study area and data availability

Upper Gilgel Abay Catchment is located in north-western Ethiopia with geographical coordinates of 10°56' to 11°51'N latitude and 36°44' to 37°23' E longitude. The catchment represents the gauged part of Gilgel Abay River Basin. The total area of Upper Gilgel Abay catchment is 1657km^2.The river originates in a place known as Gish Abay which is near a small town Sekela and it is the largest contributor to the inflow of Lake Tana (Rientjes et al., 2011). The topography of catchment is characterized as rugged with highest elevation around 3504 meters and lowest around 1892 meters.

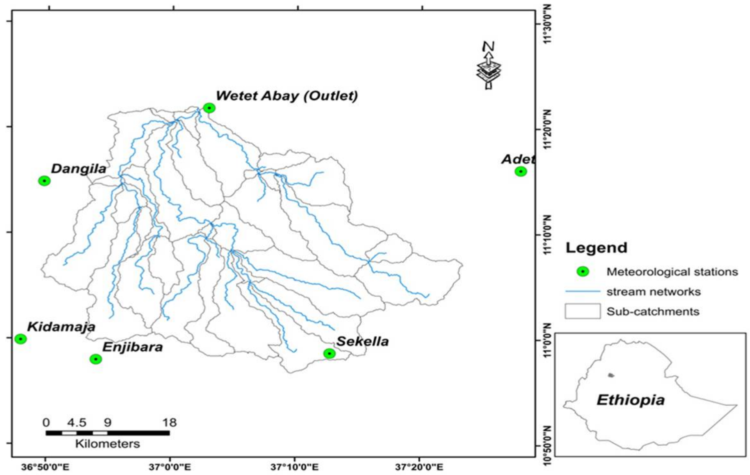

Figure 1: *Location of meteorological and gauging stations considered in Upper Gilgel Abay catchment*
Source: Author's own data

Meteorological data

In the area inside and outside of the study catchment meteorological stations of different level are found and collected from Regional Meteorological Office in Bahir Dar. Based on the classification of the office there are principal, also termed level one stations, where precipitation, air temperature, wind speed, relative humidity and sunshine duration measurements are taken every three hours. Another set of stations are class three stations (ordinary), where precipitation and air temperature measurements are taken daily. In addition to this class four stations only serve for precipitation measurements at daily base. Based on this classification Adet, Dangila and Bahir Dar are principal stations. Class three stations are Kidamaja and Wetet Abay and class four stations includes Enjibara and Sekela.

Remote sensing data

Satellite-based data products collected and used for this study are CMORPH (Climate Prediction Center morphing methodrainfall products.Satellite rainfall estimate of CMORPH product was downloaded for 5-year period (2006-2010) through ISOD (In Situ and Online Data Toolbox) extension of Ilwis software having 1-hour temporal resolution and 0.07277 degrees (approximately 8 km) spatial resolution. CMORPH estimates are derived from the passive microwaves aboard the DMSP 13, 14 & 15 (SSM/I), the NOAA-15, 16, 17 & 18 (AMSU-B), and AMSR-E and TMI aboard NASA's Aqua and TRMM spacecraft, respectively (Joyce et al., 2004).

Materials and methods

Processing satellite rainfall estimates

The CMORPH (1-hr, temporal and 8 km × 8 km spatial resolution) product is chosen for this study for representing rainfall distribution over the Upper Gilgel Abay catchment. CMORPH produces global precipitation estimates at high spatial and temporal resolution. CMORPH uses half-hourly interval geostationary satellite Infrared imagery to propagate the relatively high-quality precipitation estimates derived from passive microwave data (Joyce et al., 2004). The product can provide rainfall estimates at hourly time step which is finer than gauge measurement frequencies (daily) and for 8 km × 8 km grid element.

The procedure that was used to prepare the satellite rainfall estimates for model input is the following:

Extraction of SREs

A point map showing the location of rain gauging stations was created for the meteorological stations which measure rainfall daily. With the aid of *maplist* and Ilwis script, SREs for pixels where rain gauging locations fall was extracted for comparing with surface based rain gauge measurements.

Bias correction scheme

Scatter plots and statistical indices like mean, standard deviation and coefficient of variation were used for evaluating the performance of CMORPH against gauge measurements. This helps to get an overall impression of the performance of CMORPH in the study period and site. The correction factors have been applied for correcting systematic errors of satellite rainfall estimates of CMORPH. The total bias is estimated in the formula below.

$$\text{Total bias}=\sum_{i=1}^{n} R_S - \sum_{i=1}^{n} R_G \text{ ....(1)}$$

Where R_S and R_G represents CMORPH and gauge rainfall estimates respectively.

The bias correction scheme that was applied to correct satellite rainfall estimates is time and space variant because it enables to apply correction over time and space depending on the variability of rainfall estimate and is adapted from Habib et al. (2014). The algorithm was applied in Upper Gilgel Abay catchment and performs better than time-invariant, and time-variant and spatially invariant correction schemes.

For a selected day (*d*) and gauge (*i*), the multiplicative daily Bias Factor (*BF*) at a certain CMORPH pixel with a collocated gauge can be formulated as follows.

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Where *G* and *S* represent daily gauge and CMORPH rainfall estimates, respectively, *i* refers to gauge location, *t* refers to a Julian day number; and

$$BF_{TVS} = \frac{\sum_{t=d}^{t=d-L} S_{(i,t)}}{\sum_{t=d}^{t=d-L} G_{(i,t)}} \quad (2)$$

L is the length of a time window for bias calculation. The time window used for this study is selected as 7 days with minimum 5mm gauge rainfall accumulation based on preliminary analysis of the dataset and previous studies in the area by Habib et al. (2014). If the rainfall accumulation is less than 5mm, no bias correction was applied to that specific time window.

Measurements from gauging stations (point) were compared to pixel values (size 8km ×8km), which indicates that the correction scheme ignores the possible error that can be produced by point to area comparison. However, the spatial correlation assessment of point-grid element in the study catchment indicates0.91 for seven-day accumulation period, which can be taken as reasonable to use point to pixel comparison for seven-day time window (Habib et al., 2014).

RESULTS AND DISCUSSION

Performance of satellite rainfall estimates (SREs) in Upper Gilgel Abay Catchment

The rainfall estimates acquired from CMORPH product were evaluated based on information from ground measuring stations. Comparison aimed at daily estimates for which descriptive statistics are calculated like mean, standard deviation and coefficient of variation. The period for analysis is from 2006-2010 (1826 days) but only those days with rain estimates larger than 0 for either CMORPH or the rain gauge are selected. Results of the analysis are shown in Table 1.

Based on mean values, Enjibara station indicated a wider difference between gauge and CMORPH when compared to other stations which is 2.39 mm/day. CMORPH underestimates in Adet (1.67 mm/day), Dangila (0.37 mm/day), Sekela (2.01 mm/day), Wetet Abay (1.62 mm/day) and Kidamaja (1.53 mm/day). Mean values for all stations are higher than from CMORPH and thus indicate that on multi-annual time scale CMORPH underestimates rainfall systematically across the Upper Gilgel Abay Catchment.

Based on standard deviation values, Enjibara, Wetet Abay and Kidamaja stations indicated higher values (> 2 mm/day) while Adet, Dangila and Sekela stations show a standard deviation value of less than 1.79 mm/day. According to statistics of standard deviation, which is a measure of the spread of the rainfall estimates from the mean, CMORPH has underestimated rainfall than the gauge and follows the pattern of mean.
Coefficient of variation can show the degree of variation from CMORPH and gauge data and is the ratio of standard deviation to mean. As shown in Table 1, less variation is indicated in Kidamaja and Wetet Abay stations than
Source: Author's own data

Table 1. Summary statistics of gauge and CMORPH daily rainfall (2006-2010)

Stations	Rain estimates	Mean (mm day)	Std. dev.	CV	sample size(days)
Adet	CMORPH	5.24	7.27	1.39	914
	Gauge	6.91	9.06	1.31	
Dangila	CMORPH	8.70	10.80	1.24	945
	Gauge	9.07	11.70	1.29	
Sekela	CMORPH	5.77	8.46	1.47	1312
	Gauge	7.78	9.56	1.23	
Enjibara	CMORPH	8.39	10.19	1.21	1105
	Gauge	10.79	12.59	1.17	
Wetet Abay	CMORPH	7.45	10.02	1.35	1031
	Gauge	9.07	12.19	1.34	
Kidamaja	CMORPH	9.66	11.34	1.17	1076
	Gauge	11.20	13.33	1.19	

other stations. Less variability is also reported in CMORPH than gauge rainfall estimates, which indicated the less temporal variability of CHORPH that gauge estimates. Overall, since underestimation shows consistency, the systematic error, or bias, can be calculated. Before the CMORPH estimates can be used for rainfall-runoff modeling in this study, bias correction must be applied.

Scatter plot were prepared to get the general impression of how CMORPH rainfall estimates compared with gauge measurements (see Figure 2). A cluster of points which fall in x-axis shows missed hits where satellite misses and gauge indicates rainfall. There are even higher values (>30mm/ day) of SREs which are missed by the satellite which indicates the CMORPH might not give a better estimate in high rainfall events. Points which fall in y-axis indicates false hits where no rainfall indicated in the gauge and satellite specifies the value. The false hit does not match with missed biases in pattern and density. The pattern which is observed from the scatter plot also varies spatially. It shows the spatial variations in the performance of CMORPH estimates in Upper Gilgel Abay Catchment. In stations Enjibara, Sekela and Kidamaja satellite misses the rainfall which is indicated in the gauge than other station visually. These can be associated with the topography. Sekela and Enjibara stations are located in mountainous areas where elevation is above 2500 m. Assuming some kind of error in measuring with gauging , it clearly shows the poor performance of CMORPH in detecting rainfall in mountainous areas of Upper Gilgel Abay catchment,.(Fig 2).

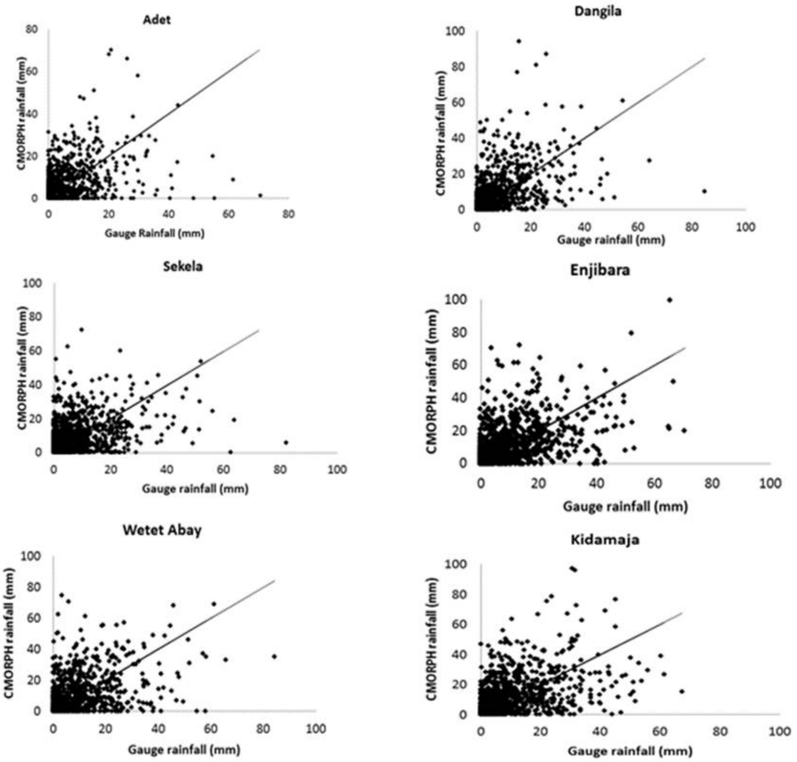

Figure 2. *Scatter plots of CMORPH and gauge daily rainfall (2006-2010)*
Source: Author's own data

On mean annual time scale, CMORPH underestimates rainfall in all of the

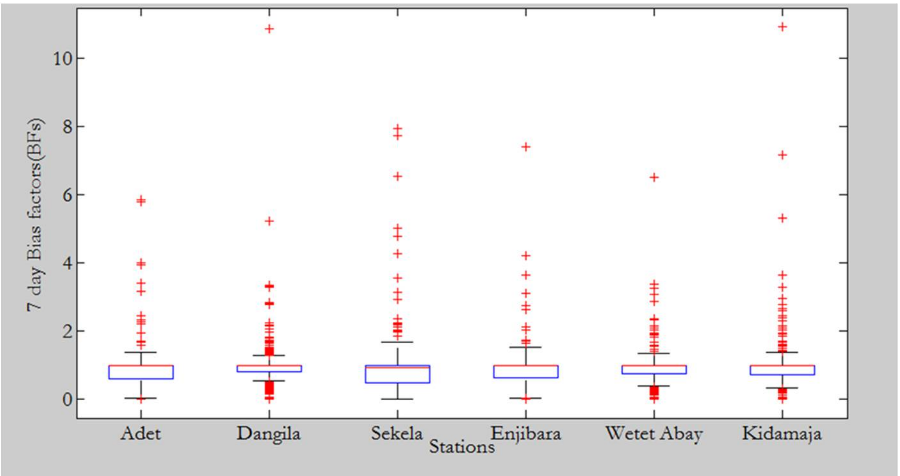

Figure 3. *Whisker plot showing comparison of BF'S obtained from 7 days sampling window (2006-2010)*
Source: Analytical output

stations as indicated in Table 1, which directs the need to apply bias correction before using the CMORPH for modelling runoff. Bias correction selected for this study aimed at correcting both in space and time domains. Bias factors are estimated for time windows of seven-day time window for each grid element of the CMORPH image so to correct the satellite estimates over space as well. The calculated bias factors are described in box plot in figure 3 to show the variability and extent of correction factors applied. The ends of Boxes indicate upper and lower quartiles and the horizontal line inside shows the median, while the whiskers show the upper and lower extreme values within 1.5 times the interquartile range (width of the box) from the ends of the box, the red symbols shows outliers.(Fig 3)

Table 2. Summary statistics of CMORPH daily rainfall before and after TSV bias correction

Stations	Rainfall estimates	Mean (mm/ day)	Standard Deviation	Coefficient of Variation	Maximum (mm/day)	Sum	sample size(days)
Adet	Gauge	3.46	7.28	2.103	70.20	6320	1826
	Uncorrected CMORPH	2.62	5.77	2.201	61.65	4786	
	Corrected CMORPH	3.04	6.69	2.199	70.58	5553	
Dangila	Gauge	4.69	9.56	2.037	94.00	8571	1826
	Uncorrected CMORPH	4.51	8.90	1.976	68.15	8226	
	Corrected CMORPH	3.88	7.73	1.993	84.71	7080	
Sekela	Gauge	5.59	8.83	1.579	72.30	10212	1826
	Uncorrected CMORPH	4.15	7.63	1.840	65.35	7570	
	Corrected CMORPH	4.49	8.35	1.862	82.32	8192	
Enjibara	Gauge	6.53	11.12	1.704	99.40	11919	1826
	Uncorrected CMORPH	5.08	8.93	1.758	69.95	9273	
	Corrected CMORPH	5.59	9.77	1.746	70.55	10216	
Wetet Abay	Gauge	5.12	10.21	1.992	74.50	9355	1826
	Uncorrected CMORPH	4.21	8.39	1.994	63.50	7679	
	Corrected CMORPH	4.47	8.88	1.989	84.28	8155	
Kidamaja	Gauge	6.60	11.62	1.761	97.20	12056	1826
	Uncorrected CMORPH	5.69	9.92	1.741	85.35	10399	
	Corrected CMORPH	5.57	9.70	1.741	67.36	10178	

It is found that the lower whisker is at the same level (BF = 0) for stations Adet, Sekela and Enjibara, with no outliers found in the lower quartile for Sekela. A wide range of bias factors values are observed for stations Sekela and Enjibara (see figure 3). In Dangila and Kidamaja high BF values (explained in outliers) are reported. The whiskers indicate the extent of bias factors applied in 7-day sampling window. Where a narrow BFs values are applied in Dangila, Wetet Abay and Kidamaja stations. Larger outliers are identified in Dangila and Kidamaja stations. Outliers will contribute in creating the maximum rainfall estimates while using these BFs in bias correction scheme and indicated in Table 2.

Effects of bias correction

After applying bias correction, findings revealed the bias corrected CMORPH estimates at multi-annual base are closer to the gauge measurements as shown in Table 4. For instance, the mean rainfall estimate for Adet in uncorrected CMORPH was 2.62 mm/day and after correction the value changed to 3.04 mm/day which is closer to gauge rainfall (3.46 mm/day). For Enjibara station where there was 1.45 mm/day bias the correction applied reduces the bias to 1.1mm/day. Based on mean statistics the correction applied enhanced the CMORPH estimates in Adet, Enjibara, Sekela and Wetet Abay stations (see Table 2). The correction scheme which was applied also deteriorated the rainfall estimates in Dangila and Kidamaja stations.

The standard deviation follows the pattern of the mean in all stations. As shown in Table 2, CV values improved in Adet, Dangila and Enjibara stations while in Sekela the value deteriorated when compared to gauge. However, the CV statistics not clearly depicted the improvements like mean and standard deviation when corrected and uncorrected CMORPH are compared. Overall, the underestimation is improved and mean values are closer to gauge measurements after the correction applied. The pitfall of the correction scheme applied is indicated by the maximum value of rainfall estimate. In Sekela and Wetet Abay the maximum rainfall estimate is increased after applying bias correction (see Table 2).

CONCLUSION

CMORPH SREs has underestimated rainfall systematically (up to 18%) throughout the catchment. Spatially, there are clear variations identified on the performance of CMORPH across rain gauging stations, where in Dangila station SREs has performed better and in Enjibara and Sekela stations relatively higher biases are found. This can be associated with the impact of topography on the performance of SREs as Enjibara and Sekela stations are located in the mountains. The applied bias correction scheme (time and space variant) has reduced the systematic errors of CMORPH, and improved the underestimation reported in most of the stations. CMORPH SREs at high spatial and temporal (1-hr and 8 km × 8 km) resolution has reasonably represented rainfall amount and distribution after bias correction. Hence combining SREs with gauge measurement may lead to get advantage of information from both gauge and satellite rainfall estimates for using them in various hydrological and water resource applications.

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