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Evaluation of the satellite-based and reanalysis-based rainfall for the data poor region in assessing basin level water resources: a case study on the Brahmaputra river basin

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Abstract

Bangladesh a South-Asian country faces different types of natural disaster such as flood, drought, river bank erosion, tropical cyclone, earthquake and landslides, etc. Out of which water born disaster is very acute here. The country faces major floods in 1987, 1988, 1998, 2004, 2007 and 2017 where major drought in 1994. Thus proper hydro-meteorological data and information are very important for the management of water borne disaster. Several researchers work on evaluation, comparison and validation of several satellite products of precipitation. This study is to evaluate and subsequently check the applicability of the different satellite-based rainfall products (TRMM, CMORPH & GsMap) and reanalysis-based rainfall products (WFDEI & MSWEP) in relatively finer spatial resolution such as in sub-catchment scale of the basin at a daily and monthly temporal resolutions. Evaluation of the satellite and reanalysis based rainfall products over observed rain gauge datasets have been done using several performance indicators such as Probability of Detection (POD), False Alarm Ratio (FAR), coefficient of determination (R^2), bias and Root Mean Square Error (RMSE), etc. From the outcome of the study, it has been found that reanalysis-based rainfall products such as WFDEI and MSWEP datasets show better correlation than satellite-based rainfall products such as TRMM, CMORPH and GsMap datasets. Again TRMM product show better performance even than GsMap and CMORPH datasets. Overall, the rainfall products evaluated in this study are rationally good in detecting the rainfall events rather poor in quantitative estimation of daily rainfall. In conclusion, the reanalysis-based rainfall products such as WFDEI and MSWEP provides better rainfall estimation than satellite-based rainfall products over the Brahmaputra basin. Thus, global earth observation products open a new horizon of hydrological data generation which would supplement the existing monitoring system specially for data poor remote hilly areas. Reanalysis-based rainfall products evaluated under this study are very promising in assessing the basin level resources.

Keywords: Satellite-based, rainfall, Brahmaputra river, basin.

1. Introduction

Bangladesh a South-Asian country faces different types of natural disaster such as flood, drought, river bank erosion, tropical cyclone, earthquake and landslides, etc. Out of which water born disaster is very acute here. The country is a highly flood prone area as geographically located in the flood plain delta of three major rivers Ganges-Brahmaputra-Meghna (GBM) (Mirza, 2003). Here 80% of the total annual rainfall has been occurred in monsoon over the basins which is one of the main causes of floods as the country is the main corridor of those basins runoff (Bajracharya et al., 2015; Mirza, 2011). The country faces major floods in 1987, 1988, 1998, 2004, 2007 and 2017 where major drought in 1994. Based on the statistics 2.32 million hectares of land affected during Kharif where 1.2 million hectares of land during Rabi seasons due to drought. A comparison statement revealed that 2.18 million tons of rice damaged due to drought where 2.38 million tons of crop loss due to flood disaster within the periods of 1973-1987 (Dey et al., 2011).Thus proper hydro-meteorological data and information are important for the management of water borne disaster.

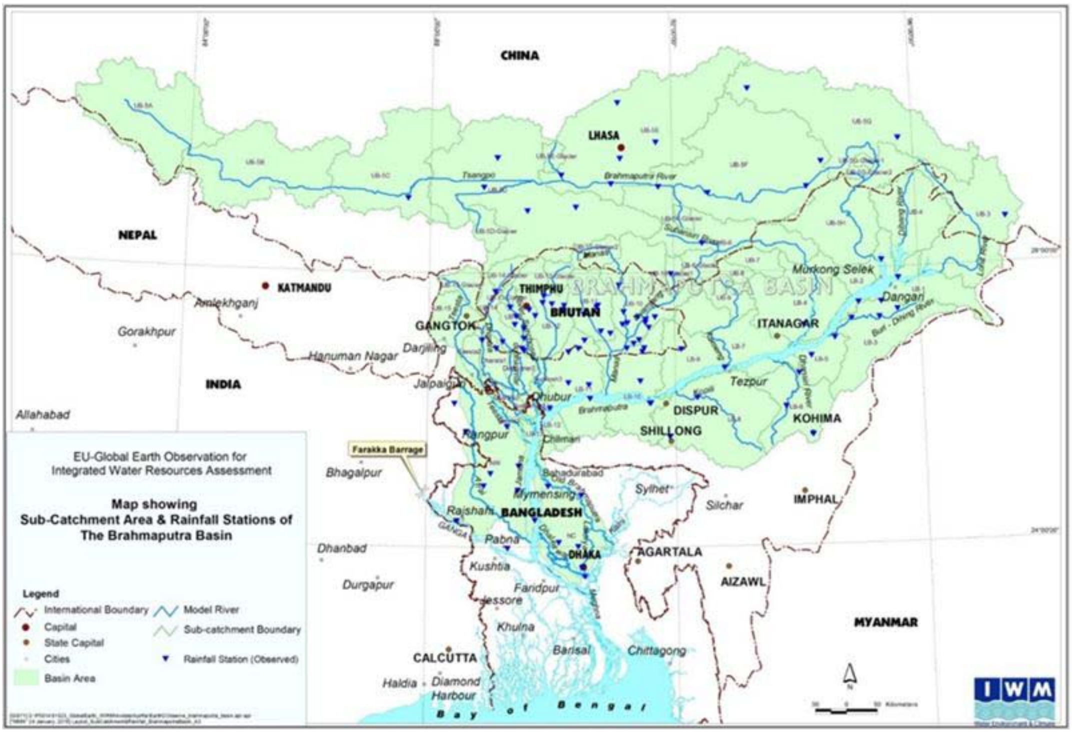

Fig. 1. Map of the Brahmaputra river basin (Source: IWM).

Again land-use change, climate change, demographic development and socio-economic development are the drivers and pressures creating stress, insecurity and quality degradation in water resources in various region of the world. Quantity and quality of water resources as well as their changes & trends over time are also not known in various regions of the world due to lack of observation and monitoring of the important meteorological and hydrological variables. Earth Observation data from different sources such as research institution, academic institution, and operational agencies, in high spatial & temporal resolution are one of the source for data poor region in the world for particularly area influenced by orography (Bajracharya et al., 2015). Several researchers work on evaluation, comparison and validation of several satellite products of precipitation with observe rain gauge data in different spatial and temporal scale range in different area (Liu et al., 2015; Bajracharya et al., 2015; Gao et al., 2013; Liechti et al., 2012; Dinku et al., 2009).Bajracharya et al. (2015) evaluated different satellite products over the Brahmaputra river basin in different temporal scales such as daily, decadal, monthly and seasonal where the spatial scale is entire basin. And the rationale of this study is to check the applicability of the earth observed (satellite and reanalysis-based) products in relatively finer resolution such as in sub-catchment scale of the basin. The main objective of this study is to evaluate different satellite-based and reanalysis-based rainfall products for the basin scale modelling. These satellite rainfall products are freely available in concern website of research institute. And reanalysis-based rainfall products are available under the EU-FP7 project “Global Earth Observation for Integrated Water Resources Assessment”. Applicability of these data sets for local hydrological model application is tested by the case-studies of Brahmaputra basin consisting 54nos. of data-poor sub-catchments.

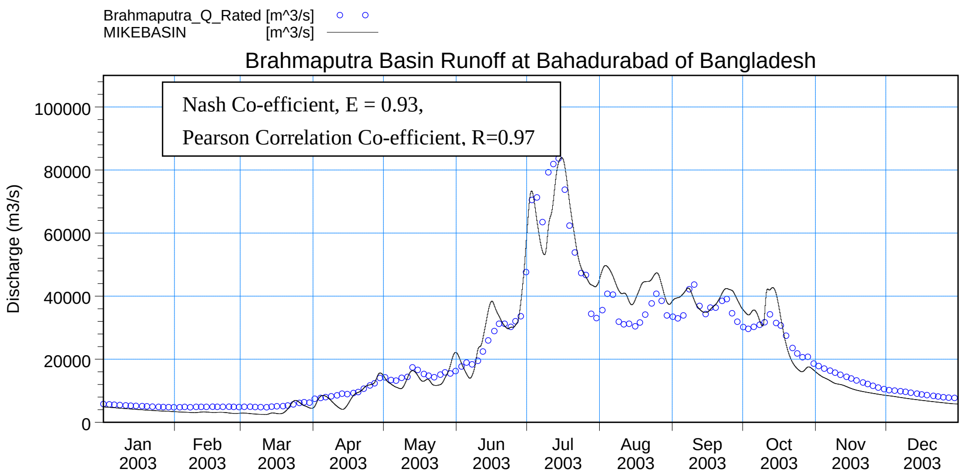

Fig. 2. Comparison of model runoff with rated discharge at Bahadurabad for 2003.

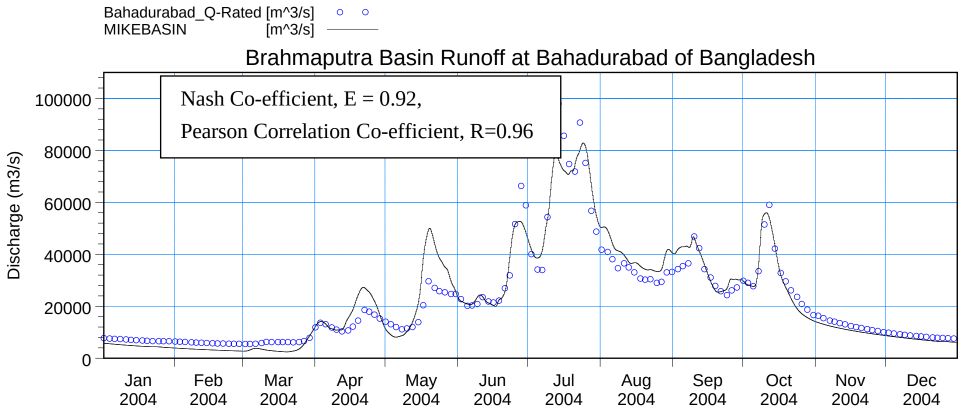

Fig. 3. Comparison of model runoff with rated discharge at Bahadurabad for 2004.

2. Study area and data

2.1 The Brahmaputra basin

The Brahmaputra is one of the world's largest rivers with a drainage area of 554,554 sq. km. It originates from Chema-Yung-Dung glacier mass located at the south-east of the Mansarovar lake of in the Kailas range of southern Tibet, which traverses China, India and Bangladesh to drain into the Bay of Bengal (Bajracharya et al., 2015; Goswami, 2008). Being a unique river, it coversdifferent wide-ranging environments like Tibet which is the cold dry plateau, the Himalayan slopes which is drenched by rain, Assam which is landlocked alluvial plains and finally Bangladesh which is the vast deltaic lowlands (Goswami, 2008). Out of the entire basin 50.4%, 34.9%, 7.4% and 7.2% lands are administratively covered by China, India, Bangladesh and Bhutan respectively. Its basin in China is entirely included in Tibet Autonomous Region (TAR). Its basin in India is shared by Arunachal Pradesh (41.88%), Assam (36.33%), Nagaland (5.57%), Meghalaya (6.10%), Sikkim (3.75%) and West Bengal (6.47%). In Bangladesh, the basin is shared by North West Region (4.5%) and North Central Region (3.6%). The extent of the basin under different countries is shown in Figure 1.

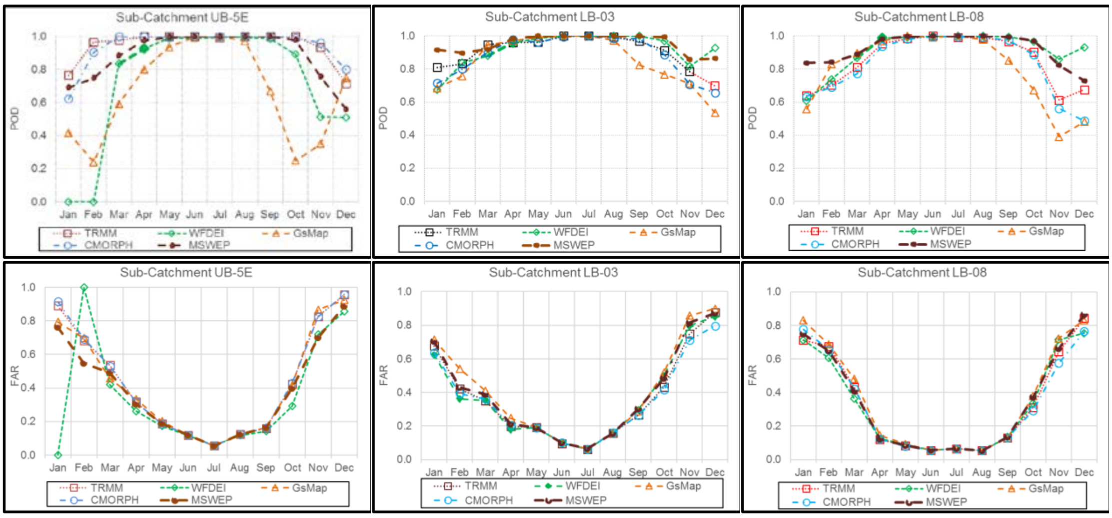

Fig. 4. Plotting of POD (top sets) and FAR (bottom sets) for sub-basin UB-5E (left) LB-03 (middle) and LB-08 (right).

The shape of the basin is irregular. The maximum east-west length is 1,540 km and the maximum north-south width is 682 km. The basin lies between 23°N to 32°N latitude and 82°E to 97°50’ E longitude. The part of the Tibetan plateau falling under the basin has an elevation varying from 3,000 to 5,000 m and is dotted with numerous glaciers. The Brahmaputra basin, excluding the Tibetan portion, forms an integral part of the southeast Asian monsoon regime with a mean annual rainfall of 2,300 mm. Distribution of rainfall over the basin varies from 1,200 mm. in parts of Nagaland to over 6,000 mm. on the southern slopes of the Himalaya.

2.2 *Source of rainfall data*

2.2.1 *Gauge rainfall*

Rainfall data for 114 nos. of station has been collected from various public domain which exists in India (28 nos.), Bhutan (66 nos.) and China (20nos.). Rainfall data at 16 stations of Bangladesh have been collected from BWDB. Available data is varied in duration for different stations. Data collected for India and China is ranged from 2002 to 2014 whereas it ranges from 2002 to 2007 for the stations of Bhutan. For Bangladesh, rainfall data are available more than 30 years from 2014 and backward.

2.2.2 *TRMM 3B42 rainfall*

The TRMM 3B42 rainfall is the product of TRMM Multi-satellite Precipitation Analysis (TMPA). The purpose of the 3B42 algorithm is to produce Tropical Rainfall Measuring Mission (TRMM) merged with high quality (HQ)/infrared (IR) precipitation and root-mean-square (RMS) precipitation-error estimates. The 3B42 estimates are produced in four stages; (1) the microwave precipitation estimates are calibrated and combined, (2) infrared precipitation estimates are created using the calibrated microwave precipitation, (3) the microwave and IR estimates are combined, and (4) rescaling to monthly data is applied. Each precipitation field is best interpreted as the precipitation rate effective at the nominal observation time (Huffman et al., 2007).

Table 1
Spatial and temporal resolution of different earth observation data investigated in the study

Product Name	Spatial Resolution	Temporal Resolution	Domain	Duration
TRMM-3B42	0.25˚x0.25˚	3-hour	50˚N-50˚S	1998-2013
CMORPH	0.25˚x0.25˚	Daily	60˚N-60˚S	1999-2013
GSMaP	0.1˚x0.1˚	Hourly	60˚N-60˚S	2000-2010
WFDEI	0.5˚x0.5˚	Daily	90˚N-90˚S	1979-2012
MSWEP	0.25˚x0.25˚	Daily	90˚N-90˚S	1979-2015

2.2.3 CMORPH rainfall

The Climate Prediction Center (CPC) MORPHing technique (CMORPH) produces global precipitation analyses at very high spatial and temporal resolution. This technique uses precipitation estimates that have been derived from low orbiter satellite microwave observations exclusively, and whose features are transported via spatial propagation information entirely obtained from geostationary satellite IR data (Joyce et al., 2004).

2.2.4 GsMap_MVK rainfall

The Global Satellite Mapping of Precipitation (GsMap) MVK product produces global precipitation distribution with high temporal and spatial resolution. The technique uses the Kalman filter to compute the estimates of the current surface rain fall rates at each 0.1-degree pixel of the infrared brightness temperature by the GEO-IR satellites. The filter predicts the precipitation rate from the microwave radiometer and its morphed product obtained in a similar way as the Joyce et al. (2004), and then refine the prediction based on the relationship between the IR brightness temperature and surface rainfall rate. The rain rates from the passive microwave radiometers are generated by Aonashi and Liu (2000).

2.2.5 WATCH Forcing Data ERA Interim (WFDEI)

The earth2observe project aims to develop a global water resources re-analysis based on state-of-the-art meteorological re-analysis, improved with earth observations and extended with output from hydrological and land surface models that should be off value for multi-scale water resources assessments and research projects. The technical description of the Tier-1 data is available in WP5 report. For the meteorological forcing, it was decided to use a recent state-of-the-art dataset: the WATCH (Water and Global Change FP7 project) Forcing Dataset ERA-Interim hereafter WFDEI (Weedon et al., 2014). WFDEI is based on the ECMWF ERA-Interim reanalysis with several bias corrections using gridded observations (Dee et al., 2011).

2.2.6 Multi-Source Weighted-Ensemble Precipitation (MSWEP)

The Multi-Source Weighted-Ensemble Precipitation (MSWEP) is a global precipitation dataset. The datasets were specifically designed for hydrological modelling and described in detail by Beck et al. (2017). The long-term mean of MSWEP is based on the CHPclim dataset (Funk et al., 2015) but replaced with more accurate regional datasets where available (over USA and New Zealand). Additionally, a correction for gauge under-catch and orographic effects was also applied by inferring catchment-average precipitation from streamflow observations at 13762 stations across the globe. Overall resolution, domain and duration of the collected different earth observed data in this study are listed in Table 1.

3. Methods

3.1 Evaluation of estimated rainfall

Rainfall products were analyzed and evaluated at a daily and monthly temporal resolutions. Scatter plots were plotted and several performance indicators were computed between the earth observations and observed precipitation estimates, including Probability of Detection (POD), False Alarm Ratio (FAR), coefficient of determination (R^2), bias and Root Mean Square Error (RMSE). POD and FAR indices are the proper analyses to check the ability for each of the rainfall products to detect rainfall events (Liechtiet al. 2012). For each rainfall, it is estimated to have rained or not. This leads to three outcomes: hit, h, false alarm, f and miss, m. The indicators are derived from these outcomes:

$$\text{POD} = \text{h} \,/\, (\text{h+m}) \tag{1}$$
$$\text{FAR} = \text{f} \,/\, (\text{h+f}) \tag{2}$$

Here,
hit, h = count of estimated rain over observed rain
miss, m = count of estimated no rain over observed rain
false alarm, f = count of estimated rain over observed no rain

The co-efficient of determination (R^2),for a linear regression model is simply the square of the correlation coefficient between two variables. The bias reflects the degree to which the measured value is over or under estimated. The RMSE is a frequently used measure of differences between two variables. The RMSE% is computed as RMSE divided by the mean precipitation of rain gauge data, and it can be used to evaluate the reliability of satellite precipitation product. When RMSE% is less than 50%, the satellite precipitation data are considered to be reliable, while they are unreliable when RMSE% is equal to or is greater than 50%. The formulas of the four indictors are described as follows:

$$R^2 = \left[\frac{\sum_{i=1}^{n}(M_i - \bar{M}) - (P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(M_i - \bar{M})^2}\,\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}}\right]^2 \tag{3}$$

$$Bias = \frac{\sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} M_i} - 1 \tag{4}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - M_i)^2}{n}} \tag{5}$$

$$RMSE\% = \frac{RMSE}{\bar{M}} \tag{6}$$

Here,
P_i = aggregated satellite rainfall in sub-catchment scale
M_i = aggregated observed rainfall in sub-catchment scale
n = total no of data
i = index of data
$\bar{P}$ = average value of P_i
$\bar{M}$ = average value of M_i

Total 54 nos. of sub-catchment has been delineated for the entire Brahmaputra river basin using SRTM land elevation data. Thiessen polygon method has been used to compute mean areal precipitation in each of the delineated sub-catchments from the observed point gauge data. For the grid-scale rainfall of earth observation (satellite and reanalysis-based precipitation), mean areal precipitation has been computed using the area weighted sum method for each sub-catchment. Overall, the evaluation of the earth observed rainfall data sets over observed rainfall has been done in sub-catchment scale for the Brahmaputra basin for the period of 2002 to 2012. Results were interpreted in GIS mapping for the entire Brahmaputra River basin and plots & graphs for the three selected sub-basins upon different hydro-meteorological characteristics.

3.2 Local scale hydrological model

For the local-level hydrological model development, MIKE 11 NAM (Nedbør Afrstrømnings Model) in combination with MIKE BASIN has been used. MIKE BASIN is a water management tool developed by Danish Hydraulic Institute (DHI Water & Environment) for addressing water allocation, conjunctive water use, reservoir operation, or water quality issues (DHI, 2007). And NAM is a rainfall-runoff model typed as physically based lumped, deterministic and conceptual model which is developed in 1973 by the DHI (Nielsen and Hansen, 1973).Development of model using MIKE BASIN includes several steps: (i) sketching of the river system, (ii) delineation of sub-catchments, (iii) computation of mean rainfall and evaporation for each sub-catchment, (iv) set up hydrological / rainfall runoff model, (v) set up of MIKE BASIN model, and (vi) simulation as well as calibration of the model. Hydrological model for the Brahmaputra river basin has been developed using MIKE Basin which contains 54 nos. of sub-catchments, Muskingum routing of the sketching river systems. Initially the input data such as rainfall and evaporation has been considered from the observed stationed datasets. And the model has been calibrated by comparing the model result against rated/measured discharges at Bahadurabad of Bangladesh. Some comparison plots of model result against rated/measured discharge at Bahadurabad of Bangladesh are shown in Figure 2 and Figure 3. Finally, the calibrated model has been applied to estimate the runoff for the different satellite and reanalysis -based rainfall for the period 2002 to 2012 as described earlier. And comparison has been made for the earth observation over observed rainfall regarding water resource assessment.

4. Analysis and results

4.1 Performance of storm capturing

Performance of the capturing storm has been evaluated using POD and FAR statistics. Monthly average of daily categorical statistics from the period 2002 to 2012 has been estimated for each of the 54 sub-catchments of the entire Brahmaputra river basin (shown in Figure 1). Sample plotting of the POD and FAR is shown in Figure 4for the datasets of TRMM, CMORPH, GsMap, WFDEI and MSWEP over observed gauge dataset for UB-5E, LB-03and LB-08 sub-basins. From the observation of the plotting, it is clear that during monsoon the POD varies from 0.9 to 1 and moderately same for all sub-catchments in Brahmaputra basin. The EO products has more or less similar result for FAR estimation. Thus storm capturing is better during monsoon rather dry season for the satellite estimation and reanalysis-based rainfall datasets.

4.2 Evaluation of rainfall estimate

Rainfall datasets of TRMM, GsMap, CMORPH, WFDEI and MSWEP has been evaluated with observed data in sub-catchment scale after computation of mean areal rainfall for the entire Brahmaputra river basin for the period 2002 to 2012. Different statistics has been used

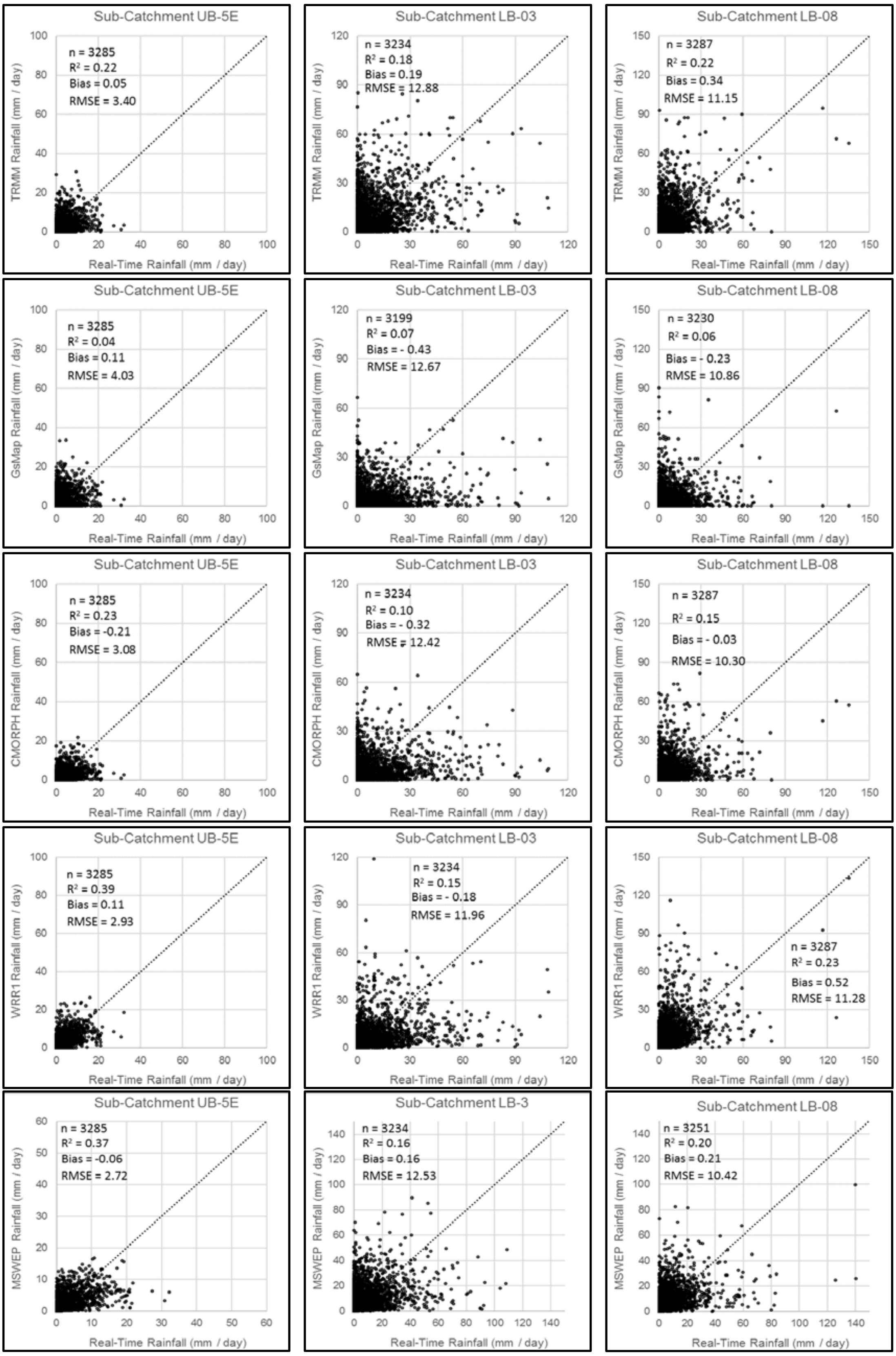

Fig. 5. Sample scatterplots of daily average rainfall of sub-catchment UB-5E (left), LB-03 (middle) and LB-08 (right) for TRMM, GsMap, CMORPH, WFDEI (WRR1) and MSWEP rainfall datasets over observed rainfall.

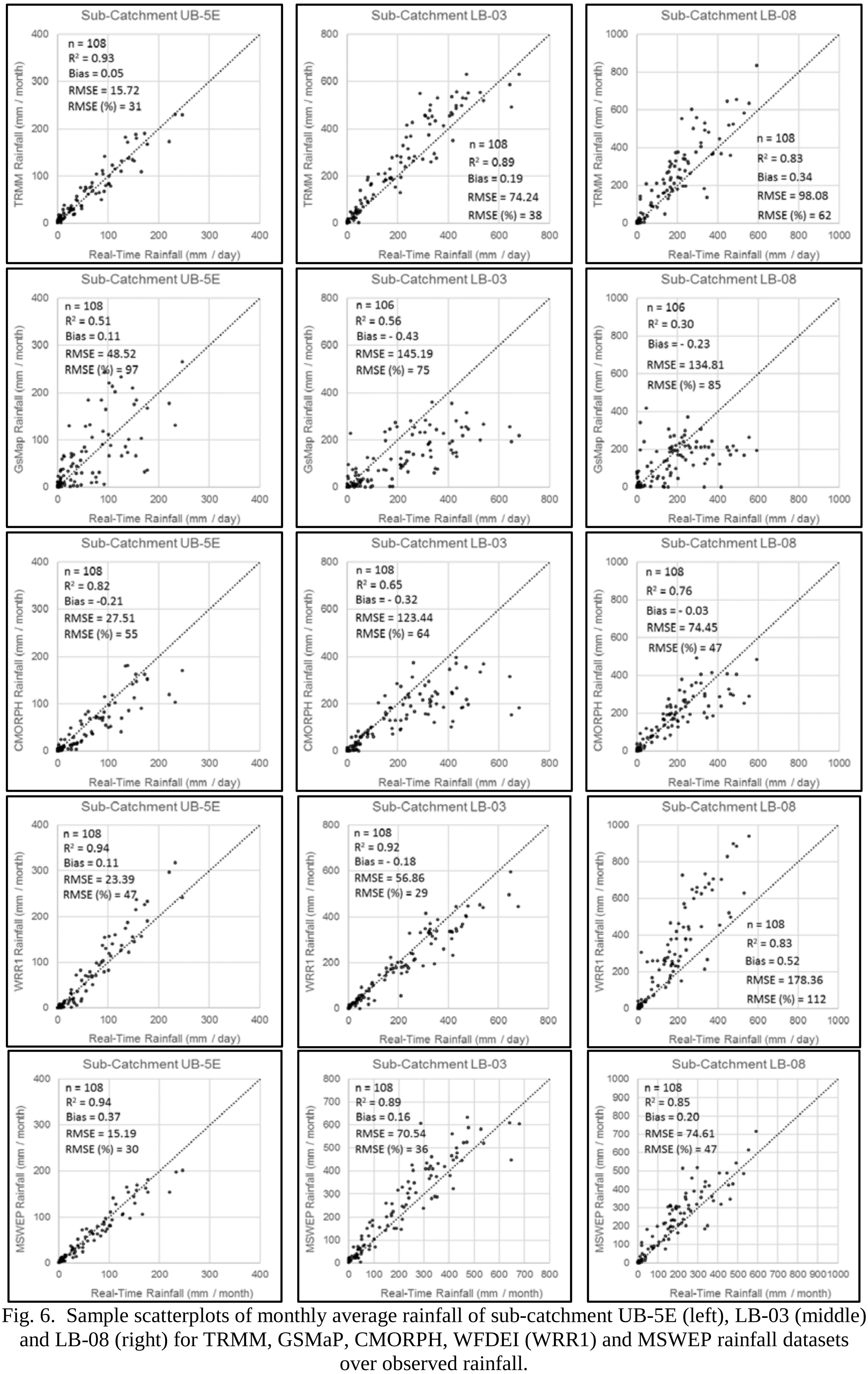

Fig. 6. Sample scatterplots of monthly average rainfall of sub-catchment UB-5E (left), LB-03 (middle) and LB-08 (right) for TRMM, GSMaP, CMORPH, WFDEI (WRR1) and MSWEP rainfall datasets over observed rainfall.

for this evaluation test such as R^2, Bias and RMSE, etc. Figure 5 and Figure 6 shows the sample scatterplots of daily and monthly average statistics respectively for three sub-catchments UB-5E, LB-03 and LB-08. For the sub-catchment UB-5E, R^2 value varies from 0.05 to 0.39 for mean daily statistics where from 0.51 to 0.94 for mean monthly statistics. For the sub-catchment LB-03, R^2 value 0.07 to 0.18 for mean daily statistics where from 0.56 to 0.92 for mean monthly statistics.

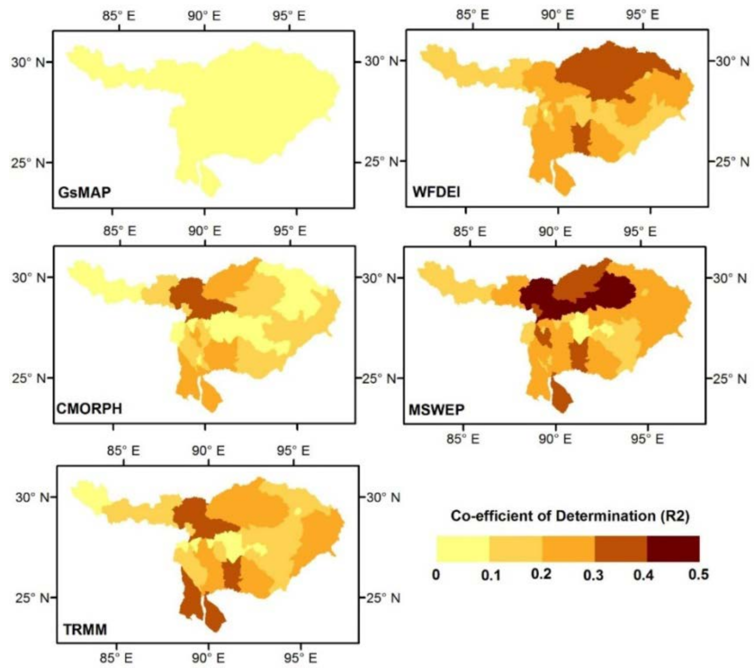

Fig. 7. Spatial variation of coefficient of determination (R^2) in the Brahmaputra basin for mean daily statistics.

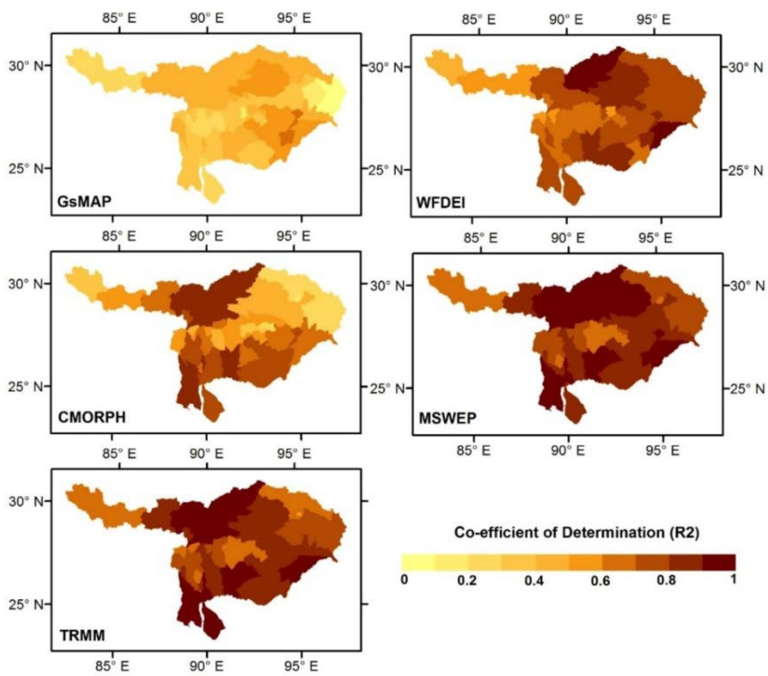

Fig. 8. Spatial variation of coefficient of determination (R^2) in the Brahmaputra basin for mean monthly statistics.

Again for the sub-catchment LB-08, mean daily statistics for R^2 value shows the range of 0.06 to 0.34 where the range of 0.30 to 0.85 for mean monthly statistics. Overall, co-efficient of determination (R^2) represents that monthly rainfall is better correlated than daily rainfall dataset as rainfall is a random meteorological event which has severe heterogeneity in nature. For three sub-catchments, overall GSMaP & CMORPH rainfall datasets shows underestimation where TRMM, WFDEI and MSWEP shows over estimation due to negative (-) and positive (+) bias respectively.

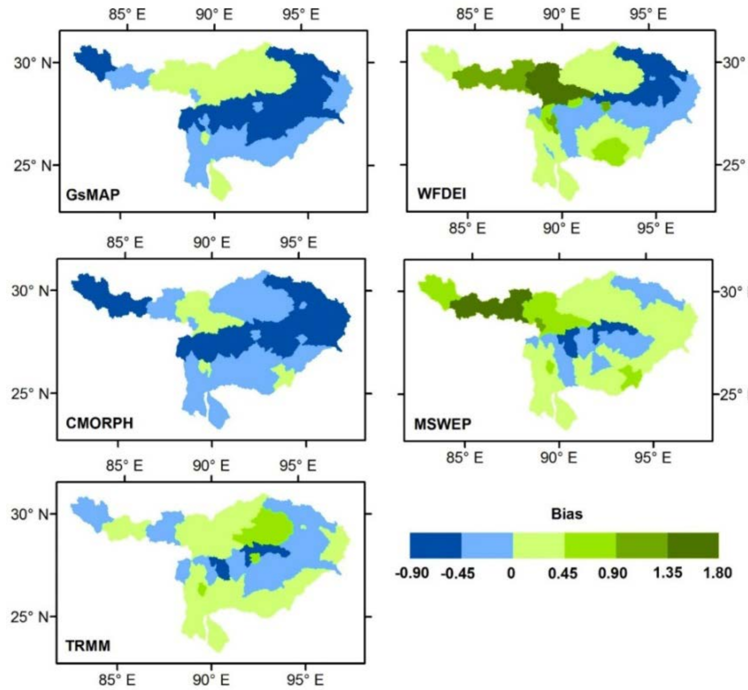

Fig. 9. Spatial variation of bias in the Brahmaputra basin for mean monthly statistics.

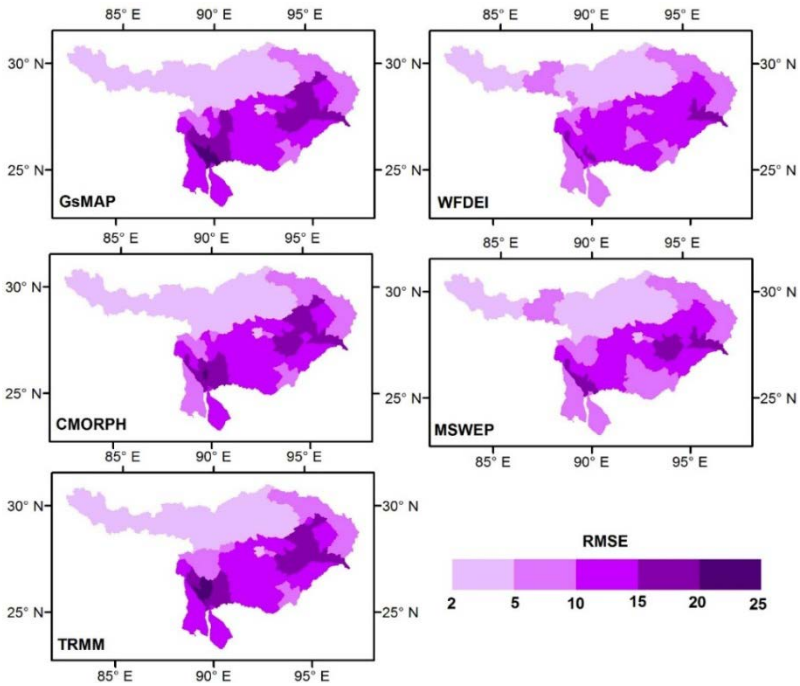

Fig. 10. Spatial variation of RMSE in the Brahmaputra basin for mean daily statistics.

Figure 7 and Figure 8 illustrates the overall situation of the co-efficient of determination (R^2) for the entire Brahmaputra river basin in sub-basin scale. It is obvious from the maps that R^2 is better for the monthly statistics than daily statistics. And re-analysis-based data sets of WFDEI and MSWEP shows better performance rather satellite estimation datasets of GSMaP, CMORPH and TRMM rainfall. The R^2 values for WFDEI and MSWEP datasets ranges from 0.12 to 0.36 and 0.10 to 0.44 respectively for the daily mean statistics. Again mean monthly R^2 values varies from 0.48 to 0.92 and 0.60 to 0.95 for the reanalysis-based rainfall datasets of WFDEI and MSWEP respectively. Figure 9 and Figure 10shows the overall bias and RMSE spatial illustration for the entire Brahmaputra river basin. GSMaP and CMORPH rainfall datasets show the underestimation as the bias value ranges from -0.90 to 0.45. And the TRMM, WFDEI and MSWEP datasets show the overestimation. TRMM shows the bias ranging from -0.45 to -0.60. The bias value varies from -0.58 to 1.71 and from -0.733 to 1.59 for the reanalysis-based datasets WFDEI and MSWEP respectively. For RMSE analysis the satellite estimation GSMaP, CMORPH and TRMM shows more RMSE values than reanalysis-based rainfall datasets of WFDEI and MSWEP where the RMSE for mean daily statistics values ranges from 2.734 to 15.94 and 2.22 to 17.68 for WGDEI and MSWEP datasets respectively.

4.3 Estimation of runoff from satellite-based and reanalysis-based rainfall

After evaluation of the satellite and reanalysis-based rainfall data sets over observed rainfall, runoff has been computed from all of the datasets using the calibrated local level hydrological model for the period of 2002 to 2012. The estimated monthly mean runoff has been compared with rated discharge at Bahadurabad station which is shown in Figure 10.

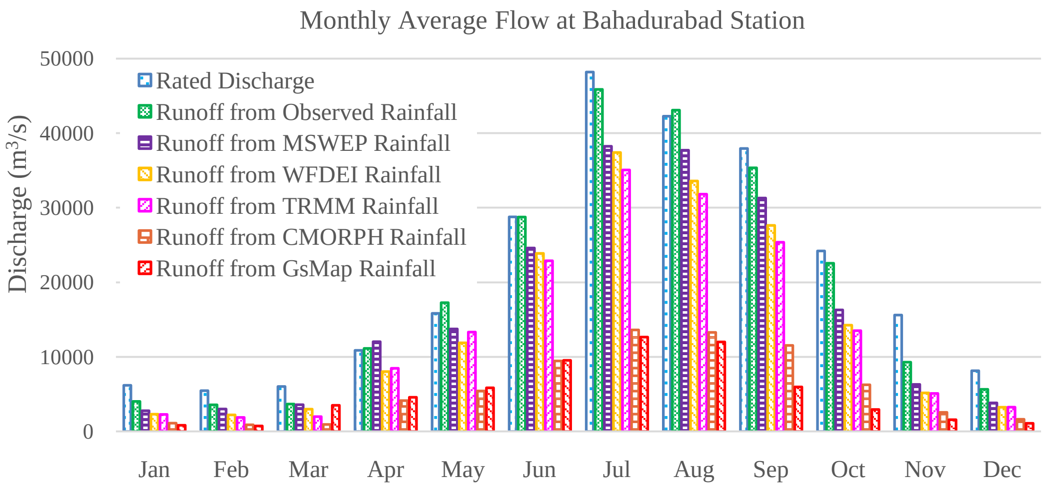

Fig. 11. Comparison of estimated runoff at Bahadurabad location of Bangladesh.

Runoff computed from the observed rainfall shows the best performance in water availability assessment. However, from the comparison plotting, it clear that runoff estimated from the reanalysis-based rainfall for WFDEI and MSWEP datasets show better observation than satellite based rainfall datasets such as TRMM, CMORPH and GSMaP. Especially, GSMaP and CMORPH shows very poor estimation of runoff in compare to the rated discharge at mentioned location.

5. Conclusion

The major objective of this study was to evaluate and subsequently assess the applicability of the satellite-based (TRMM, CMORPH and GsMap) and reanalysis-based (WFDEI and

MSWEP) rainfall product over observed gauge rainfall for the estimation of basin water resources of the Brahmaputra river basin. The evaluation of rainfall products has been carried out in at daily & monthly in temporal scale where sub-basin in geo-spatial scale. Different statistics such as POD, FAR, R^2, bias, RMSE, etc. has been analysed to address the evaluation of the rainfall products for the duration from 2002 to 2012. Local level hydrological model has been developed and calibrated for the Brahmaputra river basin using DHI developed modelling software MIKE Basin and MIKE 11 NAM. Finally, the calibrated model has been applied to estimate runoff using different satellite and re-analysis-based rainfall and compared at Bahadurabad location of Bangladesh. From the outcome of the study, it has been found that reanalysis-based rainfall products such as WFDEI and MSWEP datasets show better correlation than satellite-based rainfall products such as TRMM, CMORPH and GsMap datasets. Again TRMM product show better performance even than GSMaP and CMORPH datasets. In temporal scale, monthly accumulated statistics gives better correlation rather daily accumulated statistics as rainfall is a meteorological variable which is random and heterogeneous in nature. From the analysis of the storm capturing, it has been found that both satellite and reanalysis-based rainfall products show better detection during monsoon than dry season. Probability of Detection (POD) shows better for lower sub-catchment as compared to upper sub-catchments. Overall, the rainfall products evaluated in this study are rationally good in detecting the rainfall events rather poor in quantitative estimation of daily rainfall. However, the same results should not be expected from the satellite estimation over observed rain gauge data due to the variability of measurements both in temporal and spatial samplings even observed gauge data accuracy is also questionable due to discontinuity in series and subject to various probable error sources (Liechti et al., 2012).

The Brahmaputra basin model has been simulated with input rainfall data available from TRMM, GSMaP, CMORPH, WFDEI and MSWEP for the period 2002 to 20012. GSMaP and CMORPH gives underestimated flow whereas TRMM results are closer to the reality. And reanalysis-based product WFDEI and the successor MSWEP data gives much better monthly flow values compared to other EO products. In conclusion, the reanalysis-based rainfall products such as WFDEI and MSWEP provides better rainfall estimation than satellite-based rainfall products over the Brahmaputra basin. Thus, global earth observation products open a new horizon of hydrological data generation which would supplement the existing monitoring system specially for remote hilly areas. Reanalysis-based EO products evaluated under this study are very promising in assessing the basin level resources.

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References

Aonashi, K. and Liu, G. (2000).“Passive microwave precipitation retrievals using TMI during the Baiu period of 1998. Part I: Algorithm description and validation”, Journal of Applied Meteorology, Volume 39, 2024-2037.

Bajracharya, S. R., Palash, W., Shrestha, M. S., Khadgi, V. R., Duo, C., Das, P. J. and Dorji, C. (2015).“Systematic Evaluation of Satellite-Based Rainfall Products over the Brahmaputra Basin for Hydrological Applications”, Advances in Meteorology, doi:10.1155/2015/398687.

Beck, H. E., Van Dijk, A. I., Levizzani, V., Schellekens, J., Miralles, D. G., Martens, B., and De Roo, A. (2017).“MSWEP: 3-hourly 0.25 global gridded precipitation (1979-2015) by merging gauge, satellite, and reanalysis data”, Hydrology and Earth System Sciences, Volume 21(1), 589.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., and Bechtold, P. (2011).“The ERA-Interim reanalysis: Configuration and performance of the data assimilation system”, Quarterly Journal of the royal meteorological society, Volume 137(656), 553-597.

Dey, N. C., Alam, M. S., Sajjan, A. K., Bhuiyan, M. A., Ghose, L., Ibaraki, Y., and Karim, F. (2011).“Assessing Environmental and Health Impact of Drought in the Northwest Bangladesh”, Journal of Environmental Science & Natural Resources, Volume 4(2), 89-97.

DHI. (2007). MIKE BASIN User Guide, Danish Hydraulic Institute (DHI Water & Environment).

Dinku, T., Ruiz, F., Connor, S. J., and Ceccato, P. (2009).“Validation and Intercomparison of Satellite Rainfall Estimates over Colombia”, Journal of Applied Meteorology and Climatology, Volume 49, 1004-1014, doi:10.1175/2009JAMC2260.1.

Gao, Y. C. and Liu, M. F. (2013).“Evaluation of High-Resolution Satellite Precipitation Products using Rain Gauge Observations over the Tibetan Plateau”, Hydrology and Earth System Sciences, Volume 17, 837-849, doi:10.5194/hess-17-837-2013.

Goswami, D. C. (2008).“Managing the wealth and woes of the river Brahmaputra”. Ishani, 2(4).

Huffman, G. J., Adler, R. F., Bolvin, D. T., Gu, G., Nelkin, E. J., Bowman, K. P., Hong, Y., Stocker, E. F. and Wolff, D. B. (2006).“The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-Global, Multiyear, Combined-Sensor Precipitation Estimates at Fine Scales”, Journal of Hydrometeorology, Volume 8, 38-55.

Joyce, R. J., Janowiak, J. E., Arkin, P. A. and Xie, P. (2004).“CMORPH: A Method that Produces Global Precipitation Estimates from Passive Microwave and Infrared Data at High Spatial and Temporal Resolution”, Journal of Hydrometeorology, Volume 5.

Liechti, T. C., Matos, J. P., Boillat, J. L. and Schleiss, A. J. (2012).“Comparison and Evaluation of Satellite Derived Precipitation Products for Hydrological Modeling of the Zambezi River Basin”, Hydrology and Earth System Sciences, Volume 16, 489-500, doi:10.5194/hess-16-489-2012.

Liu, J., Duan, Z., Jiang, J. and Zhu, A. X. (2015).“Evaluation of Three Satellite Precipitation Products TRMM 3B42, CMORPH, and PERSIANN over a Subtropical Watershed in China”, Advances in Meteorology, doi:10.1155/2015/151239.

Mirza, M. M. Q. (2003).“Three Recent Extreme Floods in Bangladesh: A Hydro-Meteorological Analysis”, Natural Hazards, Volume 28, 35-64.

Mirza, M. M. Q. (2011).“Climate change, flooding in South Asia and implications”, Regional Environmental Change, Volume 11(1), S95-S107, doi:10.1007/s10113-010-0184-7.

Nielsen, S. A. and Hansen, E. (1973).“Numerical simulation of the rainfall runoff process on a daily basis”, Nordic Hydrol, Volume 4, 171–190.

Weedon, G. P., Balsamo, G., Bellouin, N., Gomes, S., Best, M. J. and Viterbo, P. (2014).“The WFDEI meteorological forcing data set: WATCH Forcing Data methodology applied to ERA-Interim reanalysis data”, Water Resources Research, Volume 50(9), 7505-7514.