CSVTU Research Journal

Vol. 9(1), 62-74, 2020 ISSN: 0974-8725

A Review on Gridded Rainfall Data for Hydrological Modelling

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Received July 03, 2020; received in revised form July 17, 2020; Accepted July 17, 2020

Research Article

Abstract

In the domain of hydrological modelling precipitation is one of the essential parameter as an input variable. Precipitation input as point gauge based rainfall data is commonly to use in hydrological modelling. Point gauge based rainfall data measurement has a very big limitation of spatial coverage of rainfall data over the area. Most of the countries in the world has very poor density of rain gauge network including India. Thus, it is very important to use rainfall record which has a good spatial as well as temporal resolutions. Precipitation measurement has been significantly evolved after introduction of remote sensing technologies. There are very few method/model of satellite driven rainfall, which has very good spatio-temporal gridded resolution of rainfall records. This paper presents a review of such multi-satellite precipitation estimates of gridded rainfall data set over the World. The data sets which we have selected has more than three decades of various precipitation data, i.e., Moderate Resolution Imaging Spectroradiometer (MODIS), PERSIANN-Cloud Classification System (PERSIANN-CCS), Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE's), Climate Prediction Center (CPC), Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Climatology Project (GPCP). The application of satellite based rainfall measurement and its application in hydrological modelling also discussed in this paper, briefly.

Keywords: *APHRODITE's, CPC, GPCP,* PERSIANN-CCS, *MODIS, Rain gauge, Satellite rainfall, TRMM*

1. Introduction

Precipitation is the most important and active variable in hydro-climatological circulation [1] and a critical component of the water cycle. Exact and reliable data is not only critical for climate trends and variability studies but also for hydrological, climatic and water resources and weather forecasting. Rainfall from satellite-based information could be extremely useful in improving water resource management, especially in ungauged catchments. Many rainfall products based on satellite have become available in recent years [2].It is useful to note that rainfall characteristics are well understood to have a significant effect on hydrological modelling, especially the spatial distribution of the precipitation and its severity, and a large portions of the precipitation runoff modelling are clarified by uncertainties in precipitation forecasts. Satellite-based precipitation (SPPs), through continuous precipitation monitoring with increased spatial coverage, offers a viable alternative to land-based information. In the past 20 years, several studies have compared the use of satellite-based precipitation as the source in hydrological modelling and on-site observations [3]. It is well understood that precipitation intensity, frequency and duration have a significant and direct impact on the magnitude of runoff and on streamflow. Satellite precipitation products (SPPs) can track and monitor heavy precipitation systems based on one or more remote sensor cloud features such as reflectiveness, visible cloud top (VIS), infrared (IR) imaging - or raindrop emissions/scatter effects or ice particles, such as passive microwave radiation (PMW)[2]. It should be noted that there are different time ranges for all satellite-based precipitation products (SPPs). The present papers address and deliver the critical review on characterization and availability of various satellite based rainfall, its application as well.

1.1 Research gap in precipitation measurement

- **Station Based precipitation measurement**

Higher spatial and temporal variation is apparent in precipitation. Climate change and variability analysis is often dependent on observations of surface gauges. Rain gauge is the most common tool for calculating the rainfall intensity as it accumulates over time to specifically determine the level rainfall at the soil. Several forms of rain scale exist, such as collection gauges, bucket gauges, measuring gauges, and optical gauges; all of these gauges have power and drawbacks [4]. However, gauges have environmental problems and other error causes, including climate, evaporations, weathering, sprinkling, position, instrument errors and spatiotemporal shifts in the distribution of drop level, and frozen versus precipitation of liquid fluids[5][6]. In many climate and related applications, data grids are needed because of uneven distribution of observation stations. Figure 1 shows the girdded and gauge measured rainfall for same area. Many gridded data sets were developed and are commonly used, based exclusively on measurement details.

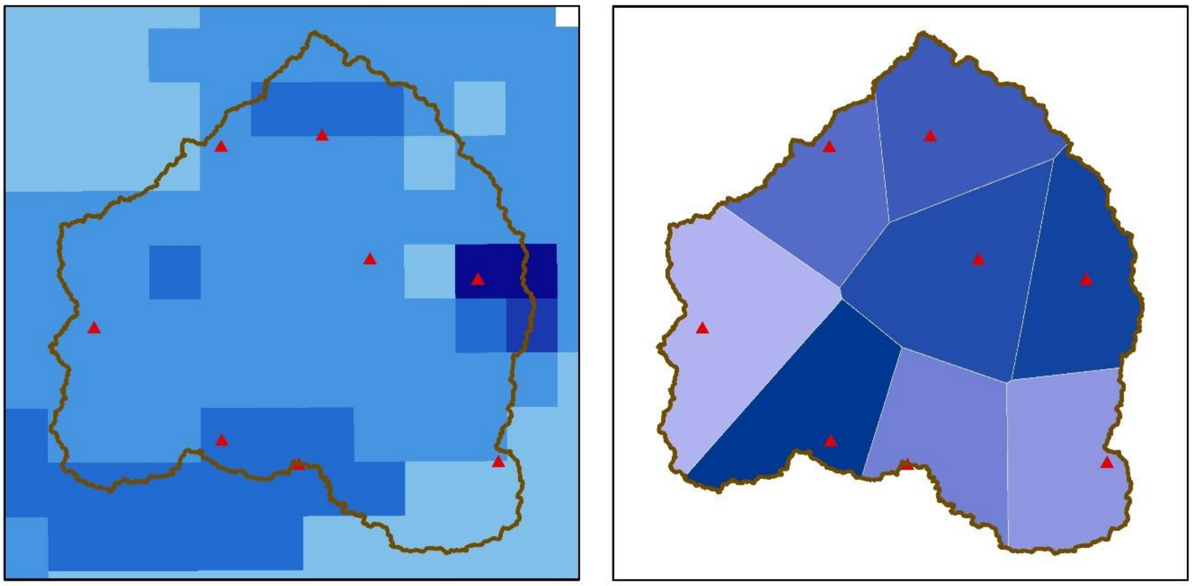

Fig. 1: measured rainfall data; left image shows gridded rainfall and right image shows gauge station based interpolated rainfall using Thiessen polygon

- **Satellite based measurement**

Satellite systems are essential devices for calculating at regular intervals the regional atmospheric parameters. Figure 2 shows the framework of satellite based rainfall. The first TV and IR Observatory

Satellite (TIROS) launched in April 1960 and created pictures of clouds equivalent to synchronized weather observations [7]. Since then, there has been a major increase in the number of ambient satellite sensors. The only instruments that can provide worldwide, standardized precipitation calculation are currently the on board satellite sensors. The sensors may be categorized in three categories: Geo-stationary (géo) visible / IR (VIS / IR) and low Earth orbit (LEO) (VIS / IR) sensors, LEO (Passive MW) sensors, and active MW sensors on LEO satellites. Appropriate precipitation methods including VIS / IR methods, active and passive MW technology and merged VIS / IR and MW approaches have been developed [2].

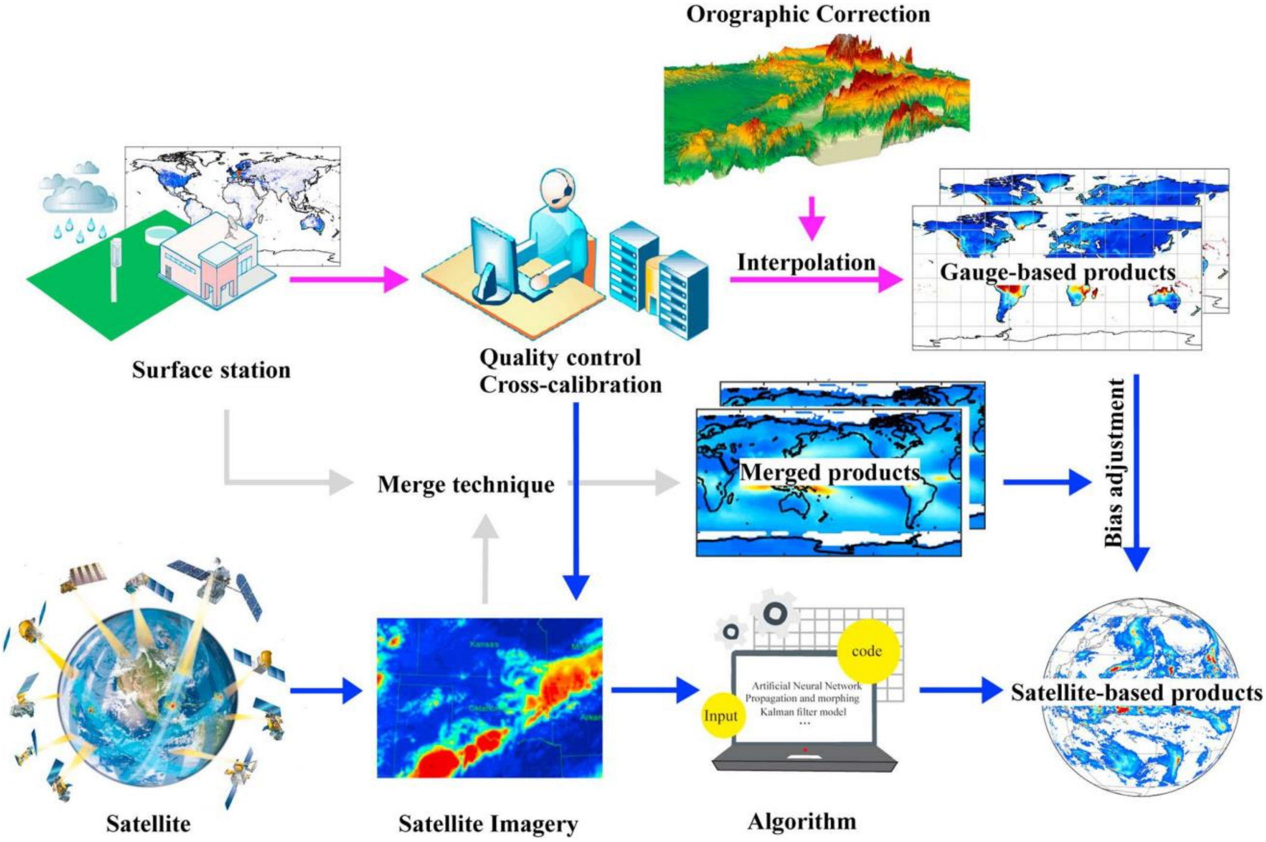

Fig. 2: Satellite based rainfall data acquisition framework [8]**.**

2. Characterising various satellite-based rainfall outputs

- ***TRMM (Tropical Rainfall Measuring Mission)***

Table 1 show various gridded rainfall product with multiple spatio-temporal resolution. The TRMM is a joint space mission of the NASA-Japan Aerospace Exploration Agency (JAXA) to map and analyze tropical and subtropical rainfall and energy discharge (Madiment et al., 2014). TRMM was a research satellite designed to improve our understanding of the distribution and variability of rainfall within Tropics as part of the water cycle in current climate system. In the tropically and sub-tropically located regions of the world, TRMM has provided a much-needed insight into the precipitation of the rains and its associated heat emission [10].

The most widely used outputs are TMPA 3 hours (TRMM 3B42), collected daily and monthly TRMM 3B43 products [9]. The satellite mission of TRMM started in 1997, and ended in 2015. TRMM-based products were then spread over tropics and subtropics between 50 ° N and 50 ° S [11]. In particular, the TMPA algorithm incorporates infrared and microwave sensor data in both real-time and latent, optimized versions (3B42-RT and 3B42-V7 respectively) to generate precipitation products with a spatial resolution of 0.25 ° and a temporal resolution of 3h.

Table 1: Spatio-temporal resolution of various gridded rainfall products and its availability

TRMM (Temporal resolution)	0.04°	0.25°	0.5°	1°	2.5°	5°	from	to
6min								
1hr								
3hr		•					12-1997	Present
6hr								
12hr								
1day		•					01-1998	Present
8day								
1month		•					01-1998	Present

GPCP (Temporal resolution)	0.04°	0.25°	0.5°	1°	2.5°	5°	from	to
6min								
1hr								
3hr								
6hr								
12hr								
1day								
8day								
1month			•		•	•	01-1983 01-1986 07-1987	01-2017 01-1996 01-1996

MODIS (Temporal resolution)	0.04°	0.25°	0.5°	1°	2.5°	5°	from	to
6min			•				08-2002	12-2019
1hr								
3hr								
6hr								
12hr				•			08-2002	12-2019
1day								
8day				•			09-2002	10-2016
1month				•			09-2002	12-2019

CHIRPS/ CMORPH (Temporal resolution)	0.05°	0.25°	0.5°	1°	2.5°	5°	from	to
6min								
1hr								
3hr								
6hr								
12hr								
1day	•	•					01-1981 12-2002	07-2019 10-2017
8day								
1month	•						01-1981	07-2019

PERCIANN (Temporal resolution)	0.04°	0.25°	0.5°	1°	2.5°	5°	from	to
6min								
1hr	•	•					01-2003 03-2000	Present
3hr	•	•						
6hr	•	•						
12hr								
1day	•	•					01-2003 03-2000	Present
8day								
1month		•					01-1983	Present

APHRODITE (Temporal resolution)	0.04°	0.25°	0.5°	1°	2.5°	5°	from	to
6min								
1hr								
3hr								
6hr								
12hr								
1day		•	•				01-1998 01-1948	10-2017 06-2018
8day								
1month					•		01-1979	11-2019

- ***PERSIANN-CSS***

In order to provide a real-time worldwide high resolution (0,04 x 0.04 or 4 km x 4 km) satellite precipitation tool, the PERSIANN-Cloud Classification System (PERSIANN-

CCS) has been developed at the Centre of Hydrometeorology and Remote Sensing (CEM) at the University of California, Irvine (UCI). [12] PERSIANN-CCS, first released in 2003, is an algorithm that extracts cloud information of a variety of multi-agency geostationary satellites between 60 ° N and 60 ° S[13][14]. Precipitation predictions vary from segmented cloud characteristics to brightness-temperature threats with infrared cloud images, such as figures, textures and geometry. This knowledge is used to relate the brightness temperature to the amount of precipitation. These classifications lead towards a specific rainfall to a pixel ratio in each cloud centering on a common curve [12]

- ***GPCP (Global Precipitation Climatology Center)***

The Global Precipitation Climatology Project provides 1 ° [15] for both the monthly (GPCP-V2.1), and daily (GPCP1DD) product. The monthly estimates for GPCP-V2.1 consist of a mixture of geostationary TIRs, polar orbiting satellite PMW imagery and rain-gauge data, which are commonly used in analyzing climate model simulations, such as(Allan et al.,2010)[17]. The GPCP 1DD product as its name suggests, is generated in a normal process at 1 ° spatial resolution. The GPCP-1DD is conceptually similar to the GPI for each 1 degree square, but the temperature threshold is calculated as compared to the precipitation images provided by the GPROF algorithm [18]from PMW data. The total monthly precipitation will match the GPCP-V2.1 monthly total. Each rainy TRI pixel is then assigned a rain rate.

- ***CMORPH***

CMORPH refers to the National Centers for Environmental Prediction (NCEP), Climate Prediction Center (CPC) MORPHing technique [19]. With a time, resolution of 0.5 h and a spatial resolution of 8 km, CMORPH can provide data on precipitation. The CMORPH data grid is evenly distributed throughout the field to compensate for interpolation errors of weather stations. Therefore, CMORPH precipitation products may be used to monitor and quantify regional droughts even in areas that are scattered and erratic and lack of data or no data for spatial distributions of meteorological stations[20]. CMORPH also supports future hydrological and disaster monitoring national predictions by providing expert assistance.

- ***MODIS***

On board the U.S. Terra and Aqua satellites, the two MODIS (Moderate Resolution Imaging Spectro radiometer) sensors are almost ideal tool for national flood monitoring and surface water measurement [21]. MODIS is a spatial band with a resolution of five hundred meters and one kilometer (nadir) from early 2001 on, but it also includes two spectral bands with a resolution of 250 meters (visible and close to IR). Both provide good water / land discrimination with acceptable spatial resolution for many applications in many settings. MODIS data provide frequent coverage (more than daily) and are made available to the international public free of charge by NASA. The recent Environment Versions, including commercial remote sensing software, are able to read, correct and re-project MODIS data without further modification. Additionally, Environmentsupported unsupervised classification algorithms can consistently classify water image pixels, and groups of water pixels can be transformed into GIS vectors or outlines by vectorization algorithms. The MODIS-observed water can be exported in mapping layers and integrated into a variety of other map display systems. Because all the data obtained since the launch is openly available, processed and used, and because MODIS data is routinely, smoothly and spatially sound to map various small and large rivers, there are substantial operational applications opportunities for hydrological applications.

- ***CHIRPS DATA***

The CHIRPS data set was developed by the U.S. Geological Survey (USGS) and Climate Hazards Group at the University of California, Santa Barbara (UCSB). The data generated by CHIRPS were: (1) Climate Hazard Precipitation Climatology (CHPClim); (2) practically global TIR geostationary observer data from the two NOAA sources, the CPC and the National Data Center for Climate Change (NDC), (3) the NOAA Climate Forecast System atmosphoric model rainfall fields, version 2 (CFSv2); (4) the NASA product TRMM 3B42; and (5) precipitate on-site input data[22].

- ***APHRODITE***

The only continental daily product (1951 onwards), which comprises an extensive network of frequent rain gage data for Asia, including the Himalayans, South and Southeast Asia and mountainous areas in the Middle East, is the irregular gridded precipitation of APHRODITE (Asian Precipitation-Highly Resolved Observational Data integration for Evaluation). The number of eligible stations ranged between 5,000 and 12,000 which reflects 2.3 to 4.5 time the data available via the global network used in most daily grid rainfall items.[23] These products are regionally available. Using the Asian Precipitation data collection and analysis of rain gage observation data in Asia, a regular gridded precipitation dataset spanning more than 50 years was created. Highly resolute incorporation of observational data. For Water Resources Assessment (APHRODITE) program. The daily grid precipitation of APHRODITE is actually the only high-resolution daily commodity in a long-term continental scale.

3. Reviews on various gridded rainfall

Table 2 shows Application of various gridded rainfall product based on previous studies.[14] There is an increasing need to improve the spatial and temporal resolution and accuracy of global precipitation estimates in order to study the weather, hydrology, and diverse environmental processes. The review of existing rainfall items indicates that the development of high-quality TRMM data significantly increases our ability to satisfy these demands. While the minimal evaluations recorded in this analysis indicate that further changes have to be made, the new PERSIANN-GT algorithm provides enhanced tropical rainfall products with a comparatively high spatial and temporal resolution. The PERSIANN-GT and TRMM 3B43 seem to be the most accurate devices.

In the [20] analysis, the two long-term satellite SAREs, the PERSIANN-CDR and CHIRPS, have explored the potential for SSI-monitoring hydrological droughts in the Beijiang River basin, a medium-sized basin in southern China's humid zone. The hydro-logical model provided by GXAJ was used for hydrological simulations to measure the SSI. The PERSIANN-CDR as well as the CHIRPS show high coherence with CGDPA-based basin-averages, in which the output of CHIRPS is slightly superior to that of PERSIANN-CDR. PERSIANN-CDR showed clear understatement for low rainfall, with CHIRPS typically precision-balanced CGDPA.

Requirements include flood warning and alertness, flood quick response and flood risk evaluation (by assembling a MODIS flood over time) [21]. The operational application on the NASA / NOAA Visibles / Infrarot Imagers / Radiometers Suites, VIIRS on NPTS is ongoing for the purposes of hydrology. The operational application of MODIS and its expected follow up sensors is under way. The ability was nevertheless clearly seen. It can take place globally as long as the public wants to obtain these data and Internet data storage services are funded.

TRMM precipitation analyzed and compared with soil-based measurement of Radar and Gage [24], using two recently developed high resolution precipitation data sets, TRMM 3B42 and CMORPH. In particular, in the CMORPH data, U.S. FAR shows particularly high values over the spread land patcher. These features are also available in 3B42, but less pronounced and more spatially limited. But they are more confined to space and less pronounced. Further analysis has shown that the bulk of these FAR irregularities occur on pixels representing tiny bodies of water.

The study [25] describes a new daily record of Indian rainfall during 14 seasons. The TRMM TMPA precipitation is merged with IMD measuring system information. The new NMSG daily data has more detail than GPCP regular rainfall statistics, as local estimated values are included. The system is equivalent to other routine databases in terms of prejudice and expertise. This data set is beneficial for work into the creation of monsoon intra-seasonals and monsoon models. A composite data set may be useful for displaying large-scale regular rainfall patterns. The only details to plan and check these data is rain-field data in India.

The research [26] aims to estimate satellite precipitation for a sample catchment in Morocco (North Africa) in order to support water resource management operations in this region. Compared with different spatial interpolation techniques, the generation of a soil reference is initially comparable with the different satellite precipitation products. The climate period and precipitation levels are measured at different stages. In five different satellite weather products there were great differences in their ability to reproduce observed precipitation patterns. The precipitation observed in the catchment of interest (monthly and annual total), followed by the precursor TRMM-3B42 v6, and also RFE 2.0, was reproduced in TRMM-3B42 v7. When the hydrological model input is the TRMM-3B42 v7 data, the monthly results of flush simulations can be obtained. While TRMM-3B42 v7 can be used as a good alternative to land-based precipitation data for developing models for water resources management at the minimum monthly level.

This result is of particular relevance in the Maghreb region, where most catchments and in particular several dam catchments were ungauged. The main objective of the analysis [27] was to calculate the precision and the effects for the limited use in the operational EWS of remotely sensed precipitation items in a semi-Aryan region of West Africa.

Table 2: Applications of various gridded rainfall products

Rainfall Product	Applications	
	Drought monitoring and modelling	**Flood monitoring and modelling**
TRMM	(Tropical et al. 2019); (Anderson 2006); (Tian and Peters-lidard 2007); (Levina et al. 2016)	(C. Kidd and Levizzani 2011); (Nijssen and Lettenmaier 2004); (Tropical et al. 2019); (Kummerow et al. 2001); (Mitra et al. 2013); (Tramblay et al. 2016); (Dembélé and Zwart 2016); (Maggioni and Massari 2018); (Maggioni, Meyers, and Robinson 2016); (Habib, Elsaadani, and Haile 2012); (Thiemig et al. 2013); (Satgé et al. 2016); (Tang et al. 2016)
GPCP	(Sun et al. 2018); (Adler et al. 2003); (Mitra et al. 2013); (Sohn et al. 2012); (Prakash, Mahesh, and Gairola 2011)	(Adler et al. 2003); (Sohn et al. 2012); (Prakash, Mahesh, and Gairola 2011); (Hong et al. 2007); (Reager and Famiglietti 2009)
MODIS	(C. Kidd and Levizzani 2011); (Anderson 2006); (Yang et al. 2011); (Parida and Oinam 2008); (Ghaleb, Mario, and Sandra 2015)	(Anderson 2006); (Funk et al. 2014); (Yang et al. 2011); (Try et al. 2018)
CHRIPS/ CMORPH	(Guo et al. 2017); (Zhong et al. 2019); (Toté et al. 2015); (Katsanos et al. 2016)	(Joyce et al. 2004); (Tian and Peters-lidard 2007); (Tramblay et al. 2016); (Habib, Elsaadani, and Haile 2012); (Thiemig et al. 2013); (Satgé et al. 2016); (Tang et al. 2016)
PERCIANN	(Anderson 2006); (Guo et al. 2017); (Zhong et al. 2019); (Zhao and Ma 2019)	(Sun et al. 2018); (Hsu et al. 1997); (Sorooshian et al. 2000); (Dembélé and Zwart 2016); (Thiemig et al. 2013); (Satgé et al. 2016); (Tang et al. 2016)
APHRODITE'S	(Levina et al. 2016); (Pramudya et al. 2019); (Homdee, Pongput, and Kanae 2016); (Vu et al. 2015); (Wen et al. 2019)	(Sohn et al. 2012); (Try et al. 2018); (Sohaila et al. 2011); (Qian, Hsu, and Kazuyoshi 2019)

We have assessed seven satellite rainfall products by comparing their estimates with ground observations from nine weather stations spread over Burkina Faso. We used 7 statistical metrics, both categorical and continuous statistics, to compare four period accumulations, that is, daily, decadal, monthly and annual precipitation values. For all daily rainfall estimates based on saturated sites, the rain-scale data was compared with a spot-based station scale – i.e. The data concerning ARC, CHIRPS, PERSIANN, RFE and TRMM 3B42. The data and rain gage data for each regular satellite commodity are weakly linked. CHIRPS data were used for best performance, but the connection with rain gauge data was low. It is possible to lose more placed convective precipitation in addition to the kind of contrast. Differences between rain-guess and satellite data can therefore be predicted. The paper [28] analyses the data quality of the TRMM and APHRODITE in relation of their Standardized Precipitation Index (SPI) and Standardized Runoff Index (SRI) hydro sensitivity index with the estimation results of ground station data by contrasting their SPI meteorological drought and the SRI hydrological drought index. Both data accuracy parameters are measured using a correlation coefficient and RMSE. The discharges derived from TRMM data generally give better results than APHRODITE in the case of hydrological drought index SRIs. The monthly rainfall satellite data of both TRMM and APHRODITE have value close to data from the ground station, except for high rainfall. TRMM satellite data for meteorological drought index SPI 3 months to 12 months gives better results than APHRODITE, whereas for SPI 1 month is the opposite. In the case of hydrological drought index SRIs, the discharges produced from TRMM data generally give better results than APHRODITE.

4. Discussion and Conclusions

After through survey of literatures and critical reviews on available satellite-based rainfall data. We came to conclusion that the gridded rainfall from satellite data are more reliable than gauge-based rainfall records. The network density of such station-based rainfall measurement is very poor in India and all over in the world due to lack of common standards and economic perspective. Rain gages have the ability to measure rainfall records where they installed so as they need interpolation if one needs rainfall variation in between. This is a biggest limitation of rainfall recording with station-based rainfall measurement. Due to the sparse of the rain gauges or even the absence of any ground station, since more rain gauge cannot be installed into a catchment due to its cost. Remote sensing with precipitation data has become a viable tool for recording network variation of weather in the vast majority of the globe. The small-scale intermittency of the rainfall could influence the distinction between rain gage measurements and rainfall estimates based on remote sensing. As some rules apply in flat areas, mountainous areas, and arid and polar regions to place rain gages. As a consequence, we can't get reliable runoff results in a gauge-based runoff due to a gap between the two gauges that are at some distance from each other. The satellite uses its temporal resolution in the grids to cover the entire globe, so that we can get more precipitation data compared to the gauge. In review, we have shown 4 X 4 KM of gridded rainfall with gauge based rainfall & conclude that gridded will yield better results than rainfall based on gauge. While measuring rainfall data between two stations, it is important to use gridded rainfall which will provide better expected outcome than taking difference of two gauge based rainfall. Because to get rainfall data between two station at any location than we will interpolate rainfall data of two near station. While in gridded we have rainfall data of a particular location which help to get better result than putting difference value in between station for hydrological cycle. In comparison to the rain gage, satellite was used to collect rainfall data from any particular area and, when compared with station-based gage rainfall, it found that it did not rain on that area, this sometimes indicates that the satellite has produced the wrong result. This means that rainfall based on satellite also has some limitations in comparison with gauge. But it's essential to use gridded rainfall for measuring rainfall where we don't have a gauge. The spatio-temporal gridded runoff resulting may change the entire runoff measurement models, which now a days simulated using gauge-based rainfall measurement. Hence, we can say that the computation of such gridded runoff will further improve the accuracy in hydrological modelling domain.

Conflict of interest

The author declares no conflict of interest.

References

[1] C. Kidd and G. Huffman, "Global precipitation measurement," *Meteorol. Appl.*, vol. 18, no. 3, pp. 334–353, 2011.

[2] C. Kidd and V. Levizzani, "Status of satellite precipitation retrievals," *Hydrol. Earth Syst. Sci.*, vol. 15, no. 4, pp. 1109–1116, 2011.

[3] B. Nijssen and D. P. Lettenmaier, "Effect of precipitation sampling error on simulated hydrological fluxes and states: Anticipating the Global Precipitation Measurement satellites," *J. Geophys. Res. D Atmos.*, vol. 109, no. 2, pp. 1–15, 2004.

[4] F. J. Tapiador *et al.*, "Global precipitation measurement: Methods, datasets and applications," *Atmos. Res.*, vol. 104–105, pp. 70–97, 2012.

[5] D. B. Michelson, "Systematic correction of precipitation gauge observations using analyzed meteorological variables," *J. Hydrol.*, vol. 290, no. 3–4, pp. 161–177, 2004.

[6] T. C. Peterson *et al.*, "Homogeneity adjustments of in situ atmospheric climate data: A review," *Int. J. Climatol.*, vol. 18, no. 13, pp. 1493–1517, 1998.

[7] C. Kidd, "Satellite rainfall climatology: A review," *Int. J. Climatol.*, vol. 21, no. 9, pp. 1041–1066, 2001.

[8] Q. Sun, C. Miao, Q. Duan, H. Ashouri, S. Sorooshian, and K. L. Hsu, "A Review of Global Precipitation Data Sets: Data Sources, Estimation, and Intercomparisons," *Rev. Geophys.*, vol. 56, no. 1, pp. 79–107, 2018.

[9] E. Tarnavsky *et al.*, "Journal of Geophysical Research: Atmospheres And Time series (TARCAT) data set," *J. Geophys. Res. Atmos.*, vol. 119, pp. 10619–10644, 2014.

[10] T. Tropical, R. Measuring, T. Trmm, and T. Trmm, "+ NASA Homepage The TRMM mission ended in 2015 and final TRMM multi-satellite precipitation analyses (TMPA , product 3B42 / 3B43) data processing will end December 31st , 2019 . As a result , this TRMM webpage is in the process of being retired and some," pp. 1–4, 2019.

[11] G. J. Huffman *et al.*, "The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-global, multiyear,

combined-sensor precipitation estimates at fine scales," *J. Hydrometeorol.*, vol. 8, no. 1, pp. 38–55, 2007.

[12] "PERSIANN PERSIANN-CCS PERSIANN-CDR," p. 2020, 2020.

[13] K. L. Hsu, X. Gao, S. Sorooshian, and H. V. Gupta, "Precipitation estimation from remotely sensed information using artificial neural networks," *J. Appl. Meteorol.*, vol. 36, no. 9, pp. 1176–1190, 1997.

[14] S. Sorooshian, K. L. Hsu, X. Gao, H. V. Gupta, B. Imam, and D. Braithwaite, "Evaluation of PERSIANN system satellite-based estimates of tropical rainfall," *Bull. Am. Meteorol. Soc.*, vol. 81, no. 9, pp. 2035–2046, 2000.

[15] G. J. Huffman *et al.*, "Global precipitation at one-degree daily resolution from multisatellite observations," *J. Hydrometeorol.*, vol. 2, no. 1, pp. 36–50, 2001.

[16] R. P. Allan, A. Slingo, S. F. Milton, and M. E. Brooks, "Evaluation of the Met Office global forecast model using Geostationary Earth Radiation Budget (GERB) data," *Q. J. R. Meteorol. Soc.*, vol. 133, no. 629 B, pp. 1993–2010, 2007.

[17] R. F. Adler *et al.*, "The version-2 global precipitation climatology project (GPCP) monthly precipitation analysis (1979-present)," *J. Hydrometeorol.*, vol. 4, no. 6, pp. 1147–1167, 2003.

[18] C. Kummerow *et al.*, "The evolution of the Goddard profiling algorithm (GPROF) for rainfall estimation from passive microwave sensors," *J. Appl. Meteorol.*, vol. 40, no. 11, pp. 1801–1820, 2001.

[19] R. J. Joyce, J. E. Janowiak, P. A. Arkin, and P. Xie, "CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution," *J. Hydrometeorol.*, vol. 5, no. 3, pp. 487–503, 2004.

[20] C. Lai *et al.*, "Monitoring hydrological drought using long-term satellite-based precipitation data," *Sci. Total Environ.*, vol. 649, pp. 1198–1208, 2019.

[21] E. Anderson, "Transboundary Floods: Reducing Risks Through Flood Management," *Transbound. Floods Reducing Risks Through Flood Manag.*, pp. 1–12, 2006.

[22] C. C. Funk *et al.*, "A Quasi-Global Precipitation Time Series for Drought Monitoring," *U.S. Geol. Surv. Data Ser.*, vol. 832, p. 4, 2014.

[23] C. Data, "Cite this page," pp. 1–2, 2020.

[24] Y. Tian and C. D. Peters-lidard, "Systematic anomalies over inland water bodies in satellite-based precipitation estimates," vol. 34, no. June, pp. 1–5, 2007.

[25] A. K. Mitra, I. M. Momin, E. N. Rajagopal, S. Basu, M. N. Rajeevan, and T. N. Krishnamurti, "Gridded daily Indian monsoon rainfall for 14 seasons: Merged TRMM and IMD gauge analyzed values," *J. Earth Syst. Sci.*, vol. 122, no. 5, pp. 1173–1182, 2013.

[26] Y. Tramblay, V. Thiemig, A. Dezetter, and L. Hanich, "Evaluation of satellite-based rainfall products for hydrological modelling in Morocco," *Hydrol. Sci. J.*, vol. 61, no. 14, pp. 2509–2519, 2016.

[27] M. Dembélé and S. J. Zwart, "Evaluation and comparison of satellite-based rainfall products in Burkina Faso, West Africa," *Int. J. Remote Sens.*, vol. 37, no. 17, pp. 3995–4014, 2016.

[28] Levina, W. Hatmoko, W. Seizarwati, and R. Vernimmen, "Comparison of

TRMM Satellite Rainfall and APHRODITE for Drought Analysis in the Pemali-comal River Basin," *Procedia Environ. Sci.*, vol. 33, pp. 187–195, 2016.

[29] V. Maggioni and C. Massari, "On the performance of satellite precipitation products in riverine flood modeling: A review," *J. Hydrol.*, vol. 558, pp. 214–224, 2018.

[30] V. Maggioni, P. C. Meyers, and M. D. Robinson, "A review of merged high-resolution satellite precipitation product accuracy during the Tropical Rainfall Measuring Mission (TRMM) era," *J. Hydrometeorol.*, vol. 17, no. 4, pp. 1101–1117, 2016.

[31] E. Habib, M. Elsaadani, and A. T. Haile, "Climatology-Focused evaluation of CMORPH and TMPA satellite rainfall products over the Nile Basin," *J. Appl. Meteorol. Climatol.*, vol. 51, no. 12, pp. 2105–2121, 2012.

[32] V. Thiemig, R. Rojas, M. Zambrano-bigiarini, and A. De Roo, "Hydrological evaluation of satellite-based rainfall estimates over the Volta and Baro-Akobo Basin," *J. Hydrol.*, vol. 499, pp. 324–338, 2013.

[33] F. Satgé *et al.*, "Assessment of satellite rainfall products over the Andean plateau," *Atmos. Res.*, vol. 167, pp. 1–14, 2016.

[34] G. Tang, Y. Ma, D. Long, L. Zhong, and Y. Hong, "Evaluation of GPM Day-1 IMERG and TMPA Version-7 legacy products over Mainland China at multiple spatiotemporal scales," *J. Hydrol.*, vol. 533, pp. 152–167, 2016.

[35] S. J. Sohn, C. Y. Tam, K. Ashok, and J. B. Ahn, "Quantifying the reliability of precipitation datasets for monitoring large-scale East Asian precipitation variations," *Int. J. Climatol.*, vol. 32, no. 10, pp. 1520–1526, 2012.

[36] S. Prakash, C. Mahesh, and R. M. Gairola, "Large-scale precipitation estimation using Kalpana-1 IR measurements and its validation using GPCP and GPCC data," *Theor. Appl. Climatol.*, vol. 106, no. 3–4, pp. 283–293, 2011.

[37] Y. Hong, R. F. Adler, A. Negri, and G. J. Huffman, "Flood and landslide applications of near real-time satellite rainfall products," *Nat. Hazards*, vol. 43, no. 2, pp. 285–294, 2007.

[38] J. T. Reager and J. S. Famiglietti, "Global terrestrial water storage capacity and flood potential using GRACE," *Geophys. Res. Lett.*, vol. 36, no. 23, pp. 2–7, 2009.

[39] Z. Yang, L. Di, G. Yu, and Z. Chen, "Vegetation condition indices for crop vegetation condition monitoring," *Int. Geosci. Remote Sens. Symp.*, pp. 3534–3537, 2011.

[40] B. Parida and B. Oinam, "Drought monitoring in India and the Philippines with satellite remote sensing measurements," *EARSeL eProceedings*, vol. 7, no. 1, pp. 81–91, 2008.

[41] F. Ghaleb, M. Mario, and A. N. Sandra, "Regional landsat-based drought monitoring from 1982 to 2014," *Climate*, vol. 3, no. 3, pp. 563–577, 2015.

[42] S. Try, G. Lee, W. Yu, C. Oeurng, and C. Jang, "Large-scale flood-inundation modeling in the Mekong River Basin," *J. Hydrol. Eng.*, vol. 23, no. 7, pp. 1–10, 2018.

[43] H. Guo *et al.*, "Meteorological drought analysis in the Lower Mekong Basin using satellite-based long-term CHIRPS product," *Sustain.*, vol. 9, no. 6, 2017.

[44] R. Zhong *et al.*, "Drought monitoring utility of satellite-based precipitation products across mainland

China," *J. Hydrol.*, vol. 568, no. June 2018, pp. 343–359, 2019.

[45] C. Toté, D. Patricio, H. Boogaard, R. van der Wijngaart, E. Tarnavsky, and C. Funk, "Evaluation of satellite rainfall estimates for drought and flood monitoring in Mozambique," *Remote Sens.*, vol. 7, no. 2, pp. 1758–1776, 2015.

[46] D. Katsanos, A. Retalis, F. Tymvios, and S. Michaelides, "Analysis of precipitation extremes based on satellite (CHIRPS) and in situ dataset over Cyprus," *Nat. Hazards*, vol. 83, pp. 53–63, 2016.

[47] H. Zhao and Y. Ma, "Evaluating the drought-monitoring utility of four satellite-based quantitative precipitation estimation products at global scale," *Remote Sens.*, vol. 11, no. 17, 2019.

[48] Y. Pramudya, T. Onishi, M. Senge, K. Hiramatsu, and P. M. R. Nur, "Evaluation of recent drought conditions by standardized precipitation index and potential evapotranspiration over Indonesia," *Paddy Water Environ.*, vol. 17, no. 3, pp. 331–338, 2019.

[49] T. Homdee, K. Pongput, and S. Kanae, "A comparative performance analysis of three standardized climatic drought indices in the Chi River basin, Thailand," *Agric. Nat. Resour.*, vol. 50, no. 3, pp. 211–219, 2016.

[50] M. T. Vu, S. V. Raghavan, D. M. Pham, and S. Y. Liong, "Investigating drought over the Central Highland, Vietnam, using regional climate models," *J. Hydrol.*, vol. 526, pp. 265–273, 2015.

[51] S. Wen *et al.*, "Population exposed to drought under the 1.5 °C and 2.0 °C warming in the Indus River Basin," *Atmos. Res.*, vol. 218, pp. 296–305, 2019.

[52] J. Sohaila, J. Jamali, A. Yatagai, and E. Mahdavi, "Spatial and Temporal Analysis of Precipitation over Iran Using Gridded Precipitation Data of APHRODITE," *Glob. Environ. Res.*, vol. 15, no. 2, pp. 157–164, 2011.

[53] Y. Qian, P. C. Hsu, and K. Kazuyoshi, "New real-time indices for the quasi-biweekly oscillation over the Asian summer monsoon region," *Clim. Dyn.*, vol. 53, no. 5–6, pp. 2603–2624, 2019.