

Validation of TRMM and GPM Satellite Data Using Daily Precipitation Observations

Rafika Andari^{a,c}, Nurhamidah^{a,*}, Darwizal Daoed^a, Marzuki^b

^a Department of Civil Engineering, Faculty of Engineering, Andalas University, Padang 25163, Indonesia

^b Department of Physics, Faculty of Mathematical and Natural Sciences, Andalas University, Padang, 25163, Indonesia

^c Department of Electrical Engineering, Faculty of Engineering, Institute of Technology Padang, Padang, 25173, Indonesia

Corresponding author: *nurhamidah@eng.unand.ac.id

Abstract—Accurate precipitation data holds immense significance in hydrological analysis. A common challenge in this field often stems from the lack of comprehensive data availability. High-resolution satellite-based precipitation measurements covering large areas offer a potential solution. However, disparities in the resolution of observed rainfall data can impact data accuracy. The main goal of this study is to evaluate the accuracy of rainfall data obtained from the TRMM and GPM satellites in the Kuranji watershed. The evaluation was conducted on the performance of the GPM IMERG-F from the Integrated Multi-satellite Retrievals for the GPM mission and the TRMM 3B42RT on a daily scale spanning from 2015 to 2019 over the Kuranji watershed. The daily precipitation measurements were validated using three widely used statistical metrics (R, RMSE, and RB). The precipitation detection capability (POD, FAR, and CSI) was also considered in this assessment. The findings demonstrate that both satellite estimations exhibit a substantial correlation coefficient (0.68 for GPM, 0.62 for TRMM) with the measurements obtained from gauges, along with an inclination to overestimate precipitation. GPM IMERG-F and TRMM 3B42RT manifest a consistent spatial pattern in daily precipitation distribution, effectively representing the observed precipitation distribution. The greater probability of detection (POD), critical success index (CSI), and lower false alarm ratio (FAR) exhibited by GPM IMERG-F at varying rainfall intensities suggests its superior performance in accurately identifying observed precipitations. This finding supports the preference for GPM IMERG-F data over TRMM 3B42RT data across various applications, hydrology, and related disciplines in the future.

Keywords— GPM; precipitation; TRMM; validation.

Manuscript received 10 May 2023; revised 28 Aug. 2023; accepted 17 Mar. 2024. Date of publication 30 Apr. 2024.
IJASEIT is licensed under a Creative Commons Attribution-Share Alike 4.0 International License.



I. INTRODUCTION

In the global water cycle, precipitation is crucial [1]. It plays a crucial role in the interplay between the hydrosphere, atmosphere, and biosphere and offers vital information for a wide range of uses, including managing water resources and conducting research on the climate [2]. Therefore, the availability of precipitation data is essential for such applications. Some of the restrictions and issues are the scarcity of in situ precipitation measurements, the lack of spatially and temporally accessible precipitation observation data, the inadequacy and incompleteness of the precipitation time series data, the uneven distribution of the precipitation stations, and the lack of sufficient observers [3]. The limitation and problem is the difficulty of obtaining real-time surface precipitation observation data, which requires an initial check of the data before it can be used directly [4]. For

this reason, data accuracy and long-term precipitation are needed [5]. The most recent technology, satellite-based remote sensing, can now fill the data gap left by the absence of historical precipitation data. Precipitation information can be obtained through satellite at any time and location. In general, satellites provide several advantages over ground-based rain gauges, including higher spatial and temporal resolution, more comprehensive coverage, continuous data recording in close to real-time, quick access, different regimes, and less field variability. [6], [7].

Several products that measure rainfall using satellites exist, and they have different levels of precision. Some examples are the CPC Morphing algorithm (CMORPH) [8], Global Satellite Mapping of Precipitation (GSMaP) [9], Tropical Precipitation Measuring Mission (TRMM), Multisatellite Precipitation Analysis (TMPA) [10], and others. These

datasets have been assessed for their work and their usefulness for specific regions or purposes [11].

TRMM is designed to measure precipitation in tropical and oceanic regions [12]. It was launched in 1997 with a limited mission duration. In May 2012, Version 7 (V7) of the TRMM Multi-satellite Precipitation Analysis (TMPA) replaced Version 6 (V6) [13], [14]. TRMM offers data characterized by a high spatial resolution ($0.25^\circ \times 0.25^\circ$) and temporal resolution (capturing instantaneous data every three hours), coupled with improved accuracy [12], [15].

In April 2014, NASA and JAXA initiated the Global Precipitation Measurement (GPM) Mission as a successor to TRMM. GPM aims to enhance the precision, coverage, and dynamic scope of global precipitation measurements, enabling researchers to scrutinize alterations in precipitation patterns [16], [17].

Many studies have indicated that GPM products outperform TRMM systems in terms of precipitation observation accuracy and hydrological simulation capability in several regions of Singapore [18], the USA [19], Pakistan [20], China [2], [21], [22], India [23], and Oman [24]. When it comes to projecting daily precipitation, the IMERG products outperform the TMPA products [25], with IMERG-F being the most accurate option [26], [27], [28]. However, except for two near real-time items in winter, IMERG's product suite, including the monthly scale, tends to underestimate daily precipitation across all four seasons [29]. In contrast, the 3B42RT overestimated both summer and winter precipitation. Regarding precipitation detection performance, TMPA products are more accurate in correctly identifying daily precipitation events, whereas IMERG products have fewer false detections [21], [30].

In Indonesia, IMERG rainfall product validation has been carried out in a number of places, including Surabaya [31], various stations in West Papua [32], West Nusa Tenggara Province [33], and Bali Province [34], [35]. The results of the study indicate that the IMERG rainfall product is highly effective in accurately determining the occurrence or absence of rainfall in these areas. Additionally, other studies have emphasized the satisfactory capability of IMERG in detecting daily rain on the Indonesian Maritime Continent (IMC) [36], [37]. Moreover, evaluations and validations of GPM-IMERG data have been conducted specifically for mountainous regions, and the IMERG-F product has demonstrated excellent performance in detecting rainfall for both daily and hourly data [38], [39].

Multiple studies conducted in Indonesia have focused on validating satellite precipitation products for rainfall predictions [34], [40], [41], Pratiwi et al. [42] conducted research where they evaluated TRMM 3B42, TRMM 3B42RT, GPM, and PERSIANN CCS satellite data. The study revealed that the GPM satellite provided good results for predicting observed rainfall data in the Dengkeng watershed, specifically for the daily period, with a correlation coefficient of 0.66. Similarly, Ginting et al. [43] compared GPM and PERSIANN satellite data at the Kalibawang ARR

station in the downstream area of the Progo watershed. They used the correlation coefficient method and calculated the lag time to assess accuracy. The study concluded that the GPM satellite demonstrated higher accuracy than the PERSIANN satellite data, furthermore, in the research of Marta et al. [44] evaluated the TRMM and GPM IMERG-F satellite in the Ngasinan Hulu watershed using the Root Mean Square Error (RMSE), Nash-Sutcliffe Efficiency (NSE), and Relative Bias (RB) methods. TRMM and GPM IMERG-F can be used as a substitute for hydrological data for the Sutami Reservoir area because the GPM IMERG-F satellite-based calibration and validation simulations have better accuracy and performance [45]. The GPM satellite rainfall estimation product has the most fantastic accuracy and correlation value in the Java Region, with a value of 0.68 when compared to the TRMM and GSMaP satellites [46].

Previous validation activities for TRMM and GPM-IMERG in Indonesia have been limited to small areas and short durations. Watershed validations have primarily focused on specific watersheds in Java, such as Dengkeng watershed in Solo, Central Java [42], Ngasinan Hulu watershed [44], The Sampean Baru, Bedadung and Mayang watersheds in East Java, [47], the Citarum watershed in West Java and the Sutami-Brantas watershed [48], and so on. Validation for watersheds, specifically on Sumatra Island, has not been done extensively [38]. Therefore, further validation activities are needed to assess the performance of these satellite products, especially in watersheds such as the Kuranji watershed in Sumatra Island. This study evaluated the statistical forecasts made by the TRMM 3B42RT V7 and GPM IMERG-F satellites based on ground-based precipitation monitoring in the Kuranji Watershed (Figure 1). This research compares and statistically assesses the product of daily precipitation performance from TRMM 3B42RT V7 and GPM IMERG-F, recommending the preferred satellite to be utilized at the study site. This evaluation is anticipated to discover a connection between satellite rain data and field observations, allowing the satellite data to fill in the gaps in the observed rainfall data. The study's findings are beneficial in supporting efforts for improving satellite rainfall products and water resource implications.

II. MATERIALS AND METHOD

A. Study Area

The research location is in the Kuranji watershed in Padang, West Sumatra. Geographically, the Kuranji watershed is located at $00^{\circ}48' - 00^{\circ}56'$ North Latitude and $100^{\circ}20' - 100^{\circ}34'$ East Longitude. The upper part of the Kuranji watershed is adjacent to Padang City and Solok Regency on the western coast of Sumatra. This region encompasses five sub-districts: Pauh, Kuranji, Padang Utara, Nanggalo, and Koto Tangah Subdistricts. It covers an elevation ranging up to 1858 meters above sea level and encompasses an area of approximately 215.615 km^2 [49]. The Kuranji watershed map is displayed in Figure 1.

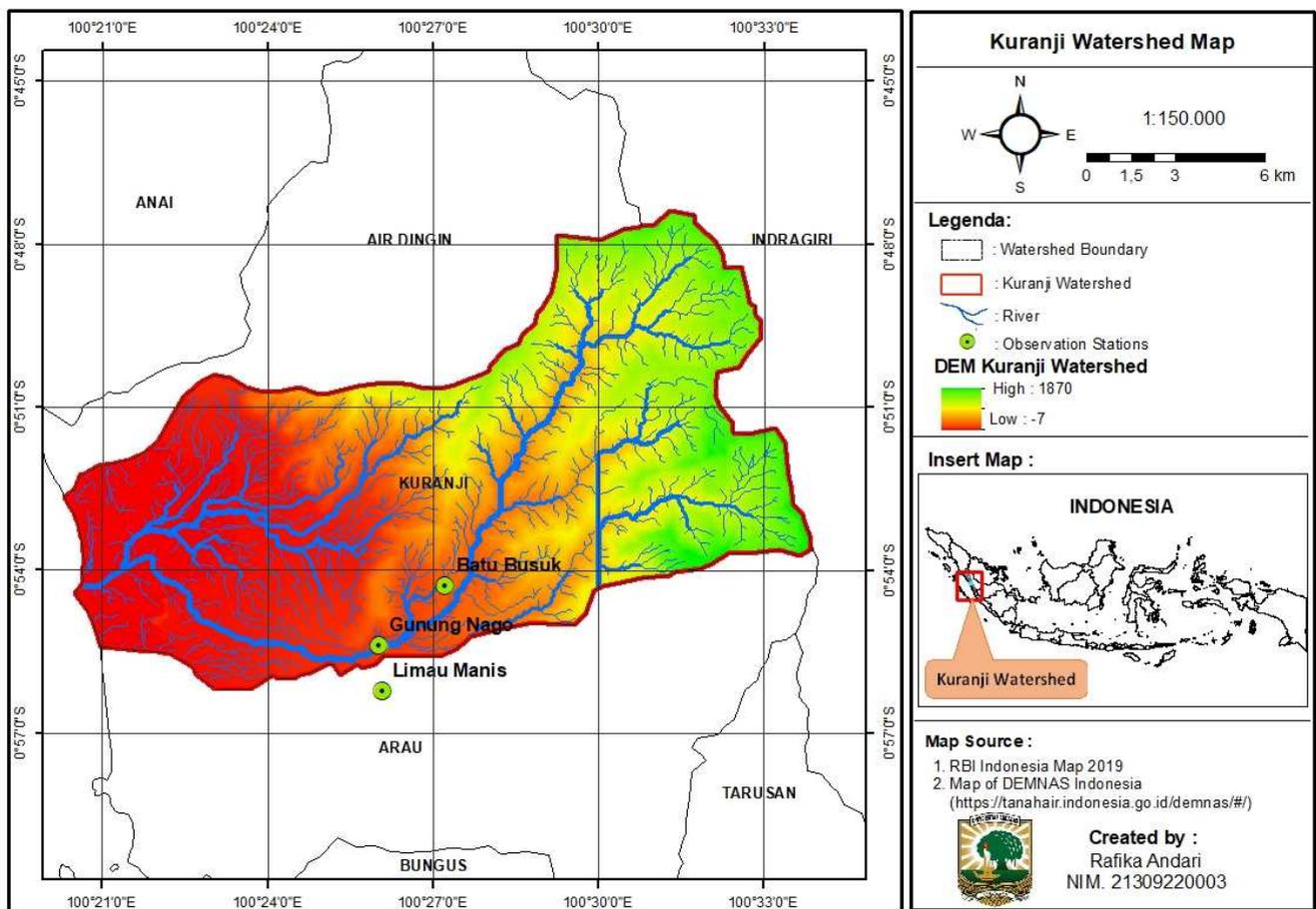


Fig.1 Topography of the Kuranji Watershed

B. Gauge Precipitation Observation

For this study, data on daily precipitation were collected from gauging stations within the Kuranji watershed. Specifically, data were collected from three observation stations: Batu Busuk, Gunung Nago, and Limau Manis. These daily precipitation records were acquired from the Dinas Pengelolaan Sumber Daya Air (PSDA)/Water Resources Management Department, West Sumatera, from 2015 to 2019. Notably, the Kuranji watershed's rain gauge station network contributed 1826 recorded instances of rainfall.

C. Satellite Precipitation Products

The TRMM 3B42RT V7 daily and GPM-IMERG final run daily precipitation products were used in this study as the two types of satellite precipitation products. The Tropical Rainfall Measuring Mission (TRMM) is a tropical precipitation measurement mission designed jointly by the Japan Aerospace Exploration Agency (JAXA) and the National Aeronautics and Space Administration (NASA). TRMM Multi-Satellite Precipitation Analysis (TMPA) is a product created by combining multi-satellite (microwave and infrared satellites) and GPCC monthly gauge precipitation, and additional information about TMPA is available [50]. TRMM-3B42V7, part of the TMPA product line, encompasses a latitude range spanning from 50°N to 50°S. This specific version offers a resolution of 0.25° for its data. [27]. Among the TMPA (TRMM Multi-satellite Precipitation Analysis) products, the version 7 daily-scale 3B42 (post-

processing) and 3B42RT (real-time) versions, introduced in May 2012, have garnered notable attention in hydro-climatic research. The real-time version, 3B42RT, employs data from the TRMM Combined Instrument (TMI) for the preceding 30 days to calibrate its measurements. This product is available around 8 hours after the satellite's data collection [21]. [18].

The IMERG-Final Version 06 (IMERG-F V06) dataset requires validation. Within the realm of IMERG data, three distinct types exist. IMERG-F is the recommended choice for research endeavors and applications such as weather forecasting, slope monitoring, and hydrological modeling [25]. This study used PrecipitationCal data because the quality is superior in quantifying surface rainfall. The IMERG has a time resolution of 30 minutes and a spatial resolution of 0.1° (equal to 11.1 km). The TRMM 3B42RT and GPM IMERG-F datasets were sourced from the NASA website, accessible at <https://giovanni.gsfc.nasa.gov/>.

D. Methodology

Comparing precipitation values between Satellite Precipitation Products (SPPs) and ground-based observations necessitates careful consideration due to the inherent disparity in spatial scales between the two datasets. This aspect holds particular significance since Satellite-Based Precipitation Products (SPPs) provide precipitation values at a grid scale (0.1° for GPM-IMERG and 0.25° for the TRMM products examined in this study), while measurements from precipitation gauges offer point-scale precipitation data [51]. One common approach involves upscaling point-based

precipitation data derived from gauges to match the grid size of SPPs. This upscaling can be achieved through spatial interpolation or simple averaging. The pixel-to-pixel evaluation method [52], [53] embodies this concept. However, it's worth noting that interpolation can introduce uncertainties due to factors like gauge density, systematic errors, and variations in interpolation techniques [18], [54]. In our research, we adopted a straightforward averaging approach to scale up point-based gauge precipitation data to align with the grid scale of both GPM-IMERG and the TRMM products. When evaluating these two Satellite-Based Precipitation Products (SPPs), our analysis specifically concentrated on grids that encompassed at least one precipitation gauge. Grids lacking coverage from any precipitation gauges were omitted from the evaluation process [37], [55].

Our analysis of the existing literature revealed that several researchers have successfully compared and validated TRMM and GPM-IMERG products with observational data. This is done using descriptive statistical indices, which are widely used in research [18], [22], [56], [57]. The assessment of TRMM 3B42RT V7 and GPM IMERG-F performance involved two distinct forecasting tests: a general evaluation using continuous statistical matrices, and an assessment of their ability to detect rainfall using categorical statistical matrices. Within these indices, the calculation of correlation coefficient (R), Root Mean Square Error (RMSE), and Relative Bias (RB) holds prominent usage in the realm of continuous statistical matrices. The following equation determines these three continuous statistical matrices' values [58] [59]:

$$R = \frac{n \sum xy - \sum x \sum y}{\sqrt{[n \sum x^2 - (\sum x)^2][n \sum y^2 - (\sum y)^2]}} \quad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (x-y)^2}{n}} \quad (2)$$

$$RB = \frac{\sum_{i=1}^n (x-y)}{\sum x} \quad (3)$$

where n denotes the number of samples, x is the amount of precipitation as determined by the satellite, and y is the data from the observed rain gauge.

The correlation coefficient (R) ranges from -1 to 1 and is used to determine the linear correlation between satellite precipitation estimates and field measurements. A correlation that is less is indicated by a number that is closer to zero. Root-mean-square error (RMSE), a measure of the error rate and general quality of satellite data, is used to determine the degree of dispersion between satellite-measured precipitation and actual precipitation [60]. A lower RMSE number denotes improved satellite data performance. The systematic bias of satellite precipitation in comparison to measuring data is measured by relative bias (RB). When the RB value was positive, it meant that the satellite had measured the

precipitation higher than the rain gauge, whereas when it was negative, it meant the opposite [36], [61].

To evaluate the SPPs' ability to detect precipitation, categorical statistical metrics were used, specifically the Probability of Detection (POD), False Alarm Ratio (FAR), and Critical Success Index (CSI) [18], [62]. The POD expresses the proportion of accurately detected precipitation events by SPPs in respect to the total number of precipitation occurrences. The FAR, on the other hand, evaluates the proportion of erroneously recognized precipitation events by SPPs out of all observed events. The CSI, which considers both POD and FAR, provides a fairer assessment. The threshold for precipitation days was established at 1 millimeter per day, in accordance with the rain classification defined by the World Meteorological Organization (WMO) [55]. These specific category statistical measurements were calculated using the following methods:

$$POD = \frac{H}{H+M} \quad (4)$$

$$FAR = \frac{F}{H+F} \quad (5)$$

$$CSI = \frac{H}{H+M+F} \quad (6)$$

where H stands for the count of actual rain events accurately identified by the satellite; M represents the count of real rain events that went unnoticed by the satellite; and F indicates the count of rain events detected by the satellite but that didn't actually happen. POD, FAR, and CSI range from 0 to 1, with ideal values being 1 for POD and CSI and 0 for FAR [31], [38], [64].

III. RESULTS AND DISCUSSION

The daily precipitation estimates of these two satellite products at the locations of three rain gauges were calculated and compared to the gauge-based precipitation to assess the quality of TRMM 3B42RT V7 and GPM IMERG-F. products. Figure 2. demonstrates that TRMM 3B42RT V7 and GPM IMERG-F may capture the temporal fluctuation patterns of daily rainfall at the three rain gauges. The graph lines show a general alignment, suggesting that the daily precipitation measurements from the three data sources maintain reasonable consistency and accuracy. Nevertheless, some instances deviate from this trend. For example, in June 2016, October 2016, January 2017, September 2017, December 2018, and December 2019. The Rain Gauge line indicates significantly higher daily precipitation values than the TRMM and GPM-IMERG lines. In particular, a significant difference can be seen in the observed rainfall value >200 mm/day on October 17, 2016, recorded at 411 mm. This difference can be caused by various factors, including errors originating from sensors, data retrieval algorithms, cloud characteristics, climate variations, seasonal effects, as well as the geographical location and topography of the observation station [54], [65].

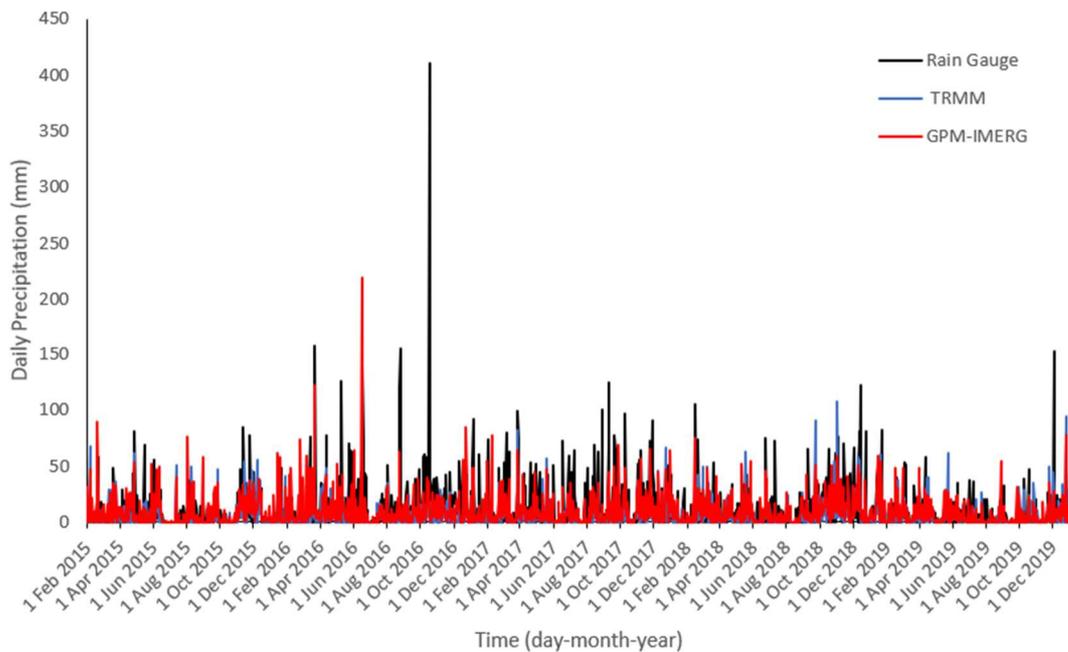


Fig. 2 Comparison of the daily precipitation estimates from the satellite products TRMM 3B42RT V7 and GPM IMERG-F with the time series of rainfall measured by rain gauges from 2015 to 2019

A. Continuous Statistical Matrices

Calculations for the correlation coefficient (R), root mean square error (RMSE), and relative bias (RB) were used to evaluate the precision and effectiveness of the satellite-derived precipitation data. Figure 3 depicts a scatterplot illustrating the daily precipitation estimates from TRMM 3B42RT and GPM IMERG-F for 2015 to 2019 across the Kuranji watershed. Notably, the GPM IMERG-F product displayed a higher correlation with the rain gauge data ($R = 0.68$), surpassing the performance of the TRMM 3B42RT product ($R = 0.62$). These correlation coefficients indicate a moderately strong correlation value (0.5-0.7) between the satellite products and the rain gauge data. Several studies show IMERG's daily data has a reasonably good accuracy ($R > 0.7$) are found in Bali [36], [37], Ngasinan Hulu Watershed [46], the Sousse Mass and the Upper Draa Basins [66], Philippines [67], and China [68], while others show a moderate ($0.5 < R < 0.7$) in Shuaishui River Basin [23], Pakistan [57], Indonesia [69], Mekong River Basin [70], and poor correlations ($R < 0.5$) in Kototabang [40], Vamsadhara River Basin (VRB) [27]. Topographical conditions and the density of the rain gauge network influence this variability. The accuracy of the validation results increases with increasing rain gauge density [69].

The overestimation of daily precipitation in both TRMM and GPM IMERG data was accompanied by Root Mean Square Error (RMSE) values, peaking at 22.63 mm/day for TRMM and 22.64 mm/day for GPM IMERG. The analysis highlighted a substantial underestimation of gauge precipitation by both satellite-derived precipitation products. The Relative Bias (RB) was -1.17 for TRMM 3B42RT and -4.43 for GPM IMERG-F. When zero rainfall gauge stations were excluded in Figure 3, the correlation coefficient (R) remained relatively low. This outcome stemmed primarily from the fact that the satellite sensors lack a complete record of the entire rainfall process due to their temporal resolutions

(30 minutes for GPM IMERG-F and 3 hours for TRMM 3B42RT), resulting in inaccurate monitoring of smaller rainfall events [71].

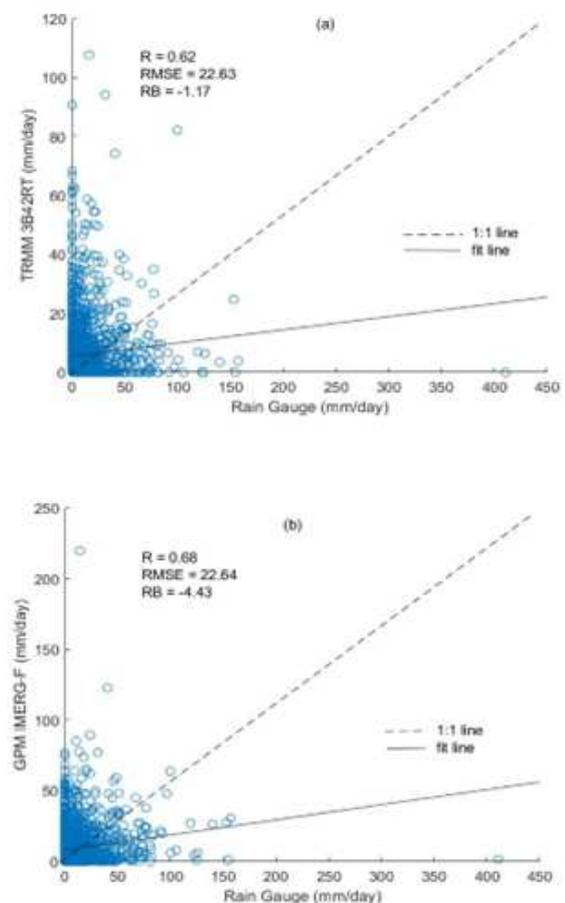


Fig. 3 Scatterplot of daily precipitation estimates from (a) TRMM 3B42RT and (b) GPM IMERG-F from 2015 to 2019

Typically, the TRMM precipitation radar (PR), which operates at longer emission wavelengths, can detect rain rates as low as 0.7 mm/h. The ability of GPM, which outperforms TRMM, to monitor lighter rain (below 0.5 mm/h), solid precipitation, and the microphysical properties of precipitation particles is a considerable improvement [18]. As a result, on a daily scale, the absolute RB of GPM IMERG-F, as shown in Figure 3, was lower than that of TRMM 3B42RT.

B. Categorical Statistical Matrices

Categorical statistical matrices were used to observe IMERG's capability to identify daily precipitation values. Table 2 displays the daily outcomes of three measures (POD, CSI, and FAR) for various precipitation levels.

TABLE II
THE CATEGORICAL STATISTICAL METRICS OF DAILY PRECIPITATION
ESTIMATES BY TRMM 3B42RT AND GPM IMERG-F

Matrices	TRMM 2B42RT	GPM IMERG-F
POD	0.61	0.82
FAR	0.36	0.38
CSI	0.46	0.55

Generally, GPM IMERG-F consistently exhibits higher matrices values than TRMM 3B42RT, implying that GPM IMERG-F is a more accurate and dependable method for daily precipitation estimation. Specifically, GPM IMERG-F, with a value of 0.82, boasts a superior POD (Probability of Detection) score compared to TRMM 3B42RT's 0.61. The daily POD values in Kuranji Waterhed were better than those found in Qujiang River Basin (0.59) [72]. This result is similar to previous studies in Singapore (0.74-0.81) [20], and in Pakistan (0.81) [57]. This indicates that GPM IMERG-F is more sensitive and proficient at identifying a more significant number of precipitation events than TRMM 3B42RT. The FAR (False Alarm Rate) values for GPM IMERG-F and TRMM 3B42RT, being close at 0.36 and 0.38, respectively, suggest that both methods have similar error rates when estimating daily precipitation. Although the FAR is lower (0.18) in Malaysia than it was in this study, the POD for daily rainfall is greater (0.89), and the CSI is also better (0.73) [56]. Additionally, GPM IMERG-F demonstrates a higher CSI (Critical Success Index) value (0.46) than TRMM 3B42RT (0.55), underscoring its superior effectiveness and efficiency in accurately estimating daily precipitation. In Malaysia, the POD for daily rainfall is higher (0.89), and the CSI is likewise better (0.73) even though the FAR there is lower (0.18) than it was in this study [56].

The GPM IMERG-F product improved performance in identifying precipitation within the Kuranji watershed, as evidenced by its comparatively elevated POD and CSI values. This improvement can be attributed primarily to the capabilities of the GPM combined Instrument (GMI) sensor, which is adept at capturing light precipitation more effectively compared to the TRMM combined Instrument (TMI) [71].

IV. CONCLUSION

Over the daily period from 2015 to 2019 within the Kuranji watershed, an extensive evaluation was carried out to assess the accuracy of rainfall data derived from TRMM and GPM IMERG, utilizing gauge-observed data. GPM IMERG-F generally exhibited noteworthy enhancements in observing

rainfall contingencies compared to TRMM products. The results showed a significant improvement in the metrics used to evaluate the GPM IMERG-F new-generation satellite-based rainfall product, which is consistent with findings reported in numerous other watersheds [46], [66], [72].

Each satellite-based precipitation product exhibited moderate correlations (with coefficients falling between 0.5 and 0.7) compared to the daily gauge-based reference precipitation data. This observation emphasizes the critical influence of local climatic and topographic variables on the efficacy of these items, which is supported by data from numerous international research. A more thorough evaluation of the effectiveness of these satellite-based precipitation products is urgently needed in light of these geographical variances. Such research would offer a more comprehensive and pertinent understanding of their efficacy worldwide. This early analysis of TRMM and GPM IMERG results is expected to serve as the basis for the creation of effective regional bias correction algorithms. In the future, these algorithms will play a critical role in boosting the dependability and usefulness of TRMM and GPM IMERG products in various applications, including hydrology, meteorology, and related sciences.

REFERENCES

- [1] T. Alsumaiti, K. Hussein, D. Ghebreyesus, and H. Sharif, "Performance of the CMORPH and GPM IMERG products over the United Arab Emirates," *Remote Sens.*, vol. 12, no. 9, 2020, doi:10.3390/RS12091426.
- [2] X. Wang, Y. Ding, C. Zhao, and J. Wang, "Similarities and improvements of GPM IMERG upon TRMM 3B42 precipitation product under complex topographic and climatic conditions over Hexi region, Northeastern Tibetan Plateau," *Atmos. Res.*, vol. 218, pp. 347–363, 2019, doi: 10.1016/j.atmosres.2018.12.011.
- [3] F. Su, Y. Hong, and D. P. Lettenmaier, "Evaluation of TRMM multisatellite precipitation analysis (TMPA) and its utility in hydrologic prediction in the La Plata Basin," *J. Hydrometeorol.*, vol. 9, no. 4, pp. 622–640, 2008, doi: 10.1175/2007JHM944.1.
- [4] M. Mamenun, H. Pawitan, and A. Sopaheluwakan, "Validasi dan Koreksi Data Satelit TRMM pada Tiga Pola Hujan di Indonesia," *Jurnal Meteorologi dan Geofisika*, vol. 15, no. 1, Apr. 2014, doi: 10.31172/jmg.v15i1.169.
- [5] D. S. Krisnayanti, D. F. B. Welkis, F. M. Hepy, and D. Legono, "Evaluasi Kesesuaian Data Tropical Rainfall Measuring Mission (TRMM) dengan Data Pos Hujan Pada Das Temef di Kabupaten Timor Tengah Selatan," *J. Sumber Daya Air*, vol. 16, no. 1, pp. 51–62, 2020, doi: 10.32679/jsda.v16i1.646.
- [6] Santos, R. M. . Neto, R. M. da Silva, and S. G. F. Costa, "Cluster analysis applied to spatiotemporal variability of monthly precipitation over Paraiba state using tropical rainfall measuring mission (TRMM) data," *Remote Sens.*, vol. 11, no. 6, 2019, doi: 10.3390/rs11060637.
- [7] T. Kubota *et al.*, "Global precipitation map using satellite-borne microwave radiometers by the GSMaP project: Production and validation," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 45, no. 7, pp. 2259–2275, 2007, doi: 10.1109/TGRS.2007.895337.
- [8] T. Ushio *et al.*, "A kalman filter approach to the global satellite mapping of precipitation (GSMaP) from combined passive microwave and infrared radiometric data," *J. Meteorol. Soc. Japan*, vol. 87 A, no. June 2008, pp. 137–151, 2009, doi: 10.2151/jmsj.87A.137.
- [9] K. Aonashi, "Gsmmap passive microwave precipitation retrieval algorithm: Algorithm description and validation," *J. Meteorol. Soc. Japan*, vol. 87, pp. 119–136, 2009, doi: 10.2151/jmsj.87A.119.
- [10] G. Huffman, "The TRMM Multi-satellite Precipitation Analysis (TMPA)," *Satellite Rainfall Applications for Surface Hydrology*, pp. 3–22, 2010, doi: 10.1007/978-90-481-2915-7_1.
- [11] A. Khan, M. Koch, and K. Chinchilla, "Evaluation of Gridded Multi-Satellite Precipitation Estimation (TRMM-3B42-V7) Performance in the Upper Indus Basin (UIB)," *Climate*, vol. 6, no. 3, p. 76, Sep. 2018, doi: 10.3390/cli6030076.
- [12] X. H. Li, "Suitability of the TRMM satellite rainfalls in driving a distributed hydrological model for water balance computations in

- Xinjiang catchment, Poyang lake basin,” *J. Hydrol.*, vol. 426, pp. 28–38, 2012, doi: 10.1016/j.jhydrol.2012.01.013.
- [13] N. Yang *et al.*, “Evaluation of the TRMM multisatellite precipitation analysis and its applicability in supporting reservoir operation and water resources management in Hanjiang basin, China,” *J. Hydrol.*, vol. 549, pp. 313–325, 2017, doi: 10.1016/j.jhydrol.2017.04.006.
- [14] 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, doi: 10.1175/JHM560.1.
- [15] Z. Liu, “Comparison of versions 6 and 7 3-hourly TRMM multi-satellite precipitation analysis (TMPA) research products,” *Atmos. Res.*, vol. 163, pp. 91–101, 2015, doi: 10.1016/j.atmosres.2014.12.015.
- [16] S. Prakash, A. K. Mitra, I. M. Momin, D. S. Pai, E. N. Rajagopal, and S. Basu, “Comparison of TMPA-3B42 versions 6 and 7 precipitation products with gauge-based data over India for the southwest monsoon period,” *J. Hydrometeorol.*, vol. 16, no. 1, pp. 346–362, 2015, doi:10.1175/JHM-D-14-0024.1.
- [17] A. K. Sahoo, J. Sheffield, M. Pan, and E. F. Wood, “Evaluation of the Tropical Rainfall Measuring Mission Multi-Satellite Precipitation Analysis (TMPA) for assessment of large-scale meteorological drought,” *Remote Sensing of Environment*, vol. 159, pp. 181–193, Mar. 2015, doi: 10.1016/j.rse.2014.11.032.
- [18] A. Y. Hou *et al.*, “The global precipitation measurement mission,” *Bull. Am. Meteorol. Soc.*, vol. 95, no. 5, pp. 701–722, 2014, doi:10.1175/BAMS-D-13-00164.1.
- [19] C. Liu and E. J. Zipser, “The global distribution of largest, deepest, and most intense precipitation systems,” *Geophys. Res. Lett.*, vol. 42, no. 9, pp. 3591–3595, 2015, doi: 10.1002/2015GL063776.
- [20] M. Tan and Z. Duan, “Assessment of GPM and TRMM precipitation products over Singapore,” *Remote Sens.*, vol. 9, no. 7, 2017, doi:10.3390/rs9070720.
- [21] J. Wang, W. Peterson, and D. Wolff, “Validation of satellite-based precipitation products from TRMM to GPM,” *Remote Sens.*, vol. 13, no. 9, 2021, doi: 10.3390/rs13091745.
- [22] M. Arshad *et al.*, “Evaluation of GPM-IMERG and TRMM-3B42 precipitation products over Pakistan,” *Atmos. Res.*, vol. 249, p. 105341, 2021, doi: 10.1016/j.atmosres.2020.105341.
- [23] X. Yang, Y. Lu, M. L. Tan, X. Li, G. Wang, and R. He, “Nine-Year Systematic Evaluation of the GPM and TRMM Precipitation Products in the Shuaishui River Basin in East-Central China,” *Remote Sensing*, vol. 12, no. 6, p. 1042, Mar. 2020, doi: 10.3390/rs12061042.
- [24] Y. Wu, Z. Zhang, Y. Huang, Q. Jin, X. Chen, and J. Chang, “Evaluation of the GPM IMERG v5 and TRMM 3B42 v7 Precipitation Products in the Yangtze River Basin, China,” *Water*, vol. 11, no. 7, p. 1459, Jul. 2019, doi: 10.3390/w11071459.
- [25] M. Kumar, O. Hodnebrog, A. Daloz, S. Sen, S. Badiger, and J. Krishnaswamy, “Measuring precipitation in Eastern Himalaya: Ground validation of eleven satellite, model and gauge interpolated gridded products,” *J. Hydrol.*, vol. 599, 2021, doi:10.1016/j.jhydrol.2021.126252.
- [26] A. Boluwade, “Spatial-temporal assessment of satellite-based rainfall estimates in different precipitation regimes in water-scarce and data-sparse regions,” *Atmosphere (Basel)*, vol. 11, no. 9, 2020, doi:10.3390/ATMOS111090901.
- [27] S. Setti, K. Yumnam, M. Rathinasamy, and A. Agarwal, “Assessment of satellite precipitation products at different time scales over a cyclone prone coastal river basin in India,” *J. Water Clim. Chang.*, vol. 14, no. 1, pp. 38–65, 2023, doi: 10.2166/wcc.2022.166.
- [28] E. Sharifi, R. Steinacker, and B. Saghafian, “Assessment of GPM-IMERG and other precipitation products against gauge data under different topographic and climatic conditions in Iran: Preliminary results,” *Remote Sens.*, vol. 8, no. 2, 2016, doi: 10.3390/rs8020135.
- [29] F. Yuan, “Applications of TRMM- and GPM-era multiple- satellite precipitation products for flood simulations at sub-daily scales in a sparsely gauged watershed in Myanmar,” *Remote Sens.*, vol. 11, no. 2, 2019, doi: 10.3390/rs11020140.
- [30] M. Benkirane, “Hydro Statistical Assessment of TRMM and GPM Precipitation Products against Ground Precipitation over a Mediterranean Mountainous Watershed (in the Moroccan High Atlas),” *Appl. Sci.*, vol. 12, no. 16, 2022, doi: 10.3390/app12168309.
- [31] Q. Ma *et al.*, “Performance evaluation and correction of precipitation data using the 20-year IMERG and TMPA precipitation products in diverse subregions of China,” *Atmos. Res.*, vol. 249, 2021, doi:10.1016/j.atmosres.2020.105304.
- [32] Z. Shirmohammadi-Aliakbarhani and A. Akbari, “Ground validation of diurnal TRMM 3B42 V7 and GPM precipitation products over the northeast of Iran,” *Theor. Appl. Climatol.*, vol. 142, no. 3, pp. 1413–1423, 2020, doi: 10.1007/s00704-020-03392-0.
- [33] M. A. Azka, P. A. Sugianto, A. K. Silitonga, and I. R. Nugraheni, “Uji Akurasi Produk Estimasi Curah Hujan Satelit Gpm Imerg Di Surabaya, Indonesia,” *J. Sains Teknol. Modif. Cuaca*, vol. 19, no. 2, p. 83, 2018, doi: 10.29122/jstmc.v19i2.3153.
- [34] A. Faisol, Budiyono, and E. Novita, “Evaluasi Data Hujan Harian Global Precipitation An Evaluation of Daily Precipitation Data from Global Precipitation Digital Repository Universitas Jember,” *Pros. Semin. Nasioanal MIPA UNIPA IV*, vol. IV, 2019.
- [35] I. Kurniawan, “Evaluasi Data GPM-IMERG (Global Precipitation Measurement - Integrated Multi-Satellite Retrieval For GPM) di Provinsi NTB,” *Megasains*, vol. 13, no. 01, pp. 6–13, 2022, doi:10.46824/megasains.v13i01.62.
- [36] C. Y. Liu, P. Aryastana, G. R. Liu, and W. R. Huang, “Assessment of satellite precipitation product estimates over Bali Island,” *Atmos. Res.*, vol. 244, no. April, p. 105032, 2020, doi:10.1016/j.atmosres.2020.105032.
- [37] I. W. A. Yuda, R. Prasetya, A. R. As-Syakur, T. Osawa, and M. Nagai, “An assessment of IMERG rainfall products over Bali at multiple time scale,” *E3S Web Conf.*, vol. 153, pp. 1–12, 2020, doi:10.1051/e3sconf/202015302001.
- [38] R. Ramadhan *et al.*, “Evaluation of GPM IMERG Performance Using Gauge Data over Indonesian Maritime Continent at Different Time Scales,” *Remote Sens.*, vol. 14, no. 5, pp. 1–24, 2022, doi:10.3390/rs14051172.
- [39] R. Ramadhan *et al.*, “Capability of GPM IMERG Products for Extreme Precipitation Analysis over the Indonesian Maritime Continent,” *Remote Sens.*, vol. 14, no. 2, 2022, doi: 10.3390/rs14020412.
- [40] H. Yusnaini *et al.*, “Statistical Comparison of IMERG Precipitation Products with Optical Rain Gauge Observations over Kototabang, Indonesia,” *J. Ilmu Fis. | Univ. Andalas*, vol. 14, no. 1, pp. 10–20, 2021, doi: 10.25077/jif.14.1.10-20.2022.
- [41] R. Ramadhan *et al.*, “Ground Validation of GPM IMERG-F Precipitation Products with the Point Rain Gauge Records on the Extreme Rainfall Over a Mountainous Area of Sumatra Island,” *J. Penelit. Pendidik. IPA*, vol. 8, no. 1, pp. 163–170, 2022, doi:10.29303/jppipa.v8i1.1155.
- [42] D. Yunita Samosir, I. Made Yuliara, and R. Prasetya, “Perbandingan dan Analisis Pola Spasial Curah Hujan Data IMERG (Integrated Multi-Satellite Retrievals for GPM) dan Data Observasi di Provinsi Bali Comparison and Analysis of Rainfall Spatial Patterns IMERG (Integrated Multi-Satellite Retrievals for GPM) Da,” *SINTA 4 Accredit. Start.*, vol. 22, no. 2, pp. 67–76, 2021, [Online]. Available: <https://disc.gsfc.nasa.gov>.
- [43] A. Faisol and B. Ollin Paga, “Komparasi Citra Satelit Hujan Resolusi Tinggi dalam Mengestimasi Curah Hujan Harian di Provinsi Papua Barat Comparison of High-Resolution Rainfall Satellite Image in Estimating Daily Rainfall in West Papua,” vol. 4, no. 1, pp. 2620–4738, 2021.
- [44] D. W. Pratiwi, J. Sujono, and A. P. Rahardjo, “Evaluasi Data Hujan Satelit untuk Prediksi Data Hujan Pengamatan Menggunakan Cross Correlation,” *Pros. Semnastek*, 2017, [Online]. Available: <https://jurnal.umj.ac.id/index.php/semnastek/article/view/1829>.
- [45] J. M. Ginting, J. Sujono, and D. R. Jayadi, “Analisis Hubungan Data Hujan Satelit dengan Hujan Terukur ARR Kalibawang,” *Pros. Konf. Pascasarj. Tek. Sipil*, no. November, pp. 89–102, 2019.
- [46] S. D. Marta, E. Suhartanto, and J. S. Fidari, “Validasi Data Curah Hujan Satelit dengan Data Stasiun Hujan di DAS Ngasihan Hulu, Kabupaten Trenggalek, Jawa Timur,” *J. Teknol. dan Rekayasa Sumber Daya Air*, vol. 3, no. 1, pp. 35–45, 2023, doi:10.21776/ub.jtresda.2023.003.01.04.
- [47] N. A. Arrokhman, S. Wahyuni, and E. Suhartanto, “Evaluasi Kesesuaian Data Satelit untuk Curah Hujan dan Evaporasi Terhadap Data Pengukuran di Kawasan Waduk Sutami,” *J. Teknol. dan Rekayasa Sumber Daya Air*, vol. 1, no. 2, pp. 904–916, 2021, doi:10.21776/ub.jtresda.2021.001.02.46.
- [48] M. Adib Azka, T. Kadar Dzikiro, U. Kusuma Wardani, and A. Fadlan Sekolah Tinggi Meteorologi Klimatologi dan Geofisika, “Uji Akurasi Data Model Estimasi Curah Hujan Satelit TRMM, GSMAP, Dan GPM Selama Periode Siklon Tropis Cempaka dan Dahlia Di Wilayah Jawa Validation of TRMM, GSMAP, and GPM Modeling Data Accuracy During Tropical Cyclone Event in Java Region,” *Semin. Nas. Penginderaan Jauh*, no. July 2018, pp. 983–991, 2018.
- [49] E. Hidayah, W. Y. Widiarti, P. P. Putra, A. A. Dewantie, M. Z. Alhamda, and H. Prastika, “Evaluation Of Hydrologic Modelling Using Satellite Product, And Mmr Rainfall In East Java, Indonesia,”

- J. Ecol. Eng.*, vol. 22, no. 11, pp. 246–260, 2021, doi:10.12911/22998993/142843.
- [50] M. D. Syaifulloh, “Validasi Data Trmm Terhadap Data Curah Hujan Aktual Di Tiga Das Di Indonesia,” *J. Meteorol. dan Geofis.*, vol. 15, no. 2, pp. 109–118, 2014, doi: 10.31172/jmg.v15i2.180.
- [51] A. I. Suryani, “Kajian Reklamasi Lahan Daerah Aliran Sungai Batang Kuranji Kota Padang,” *J. Spasial*, vol. 1, no. 1, 2017, doi:10.22202/js.v1i1.1571.
- [52] A. S. Gebregiorgis *et al.*, “To What Extent is the Day 1 GPM IMERG Satellite Precipitation Estimate Improved as Compared to TRMM TMPA-RT?,” *J. Geophys. Res. Atmos.*, vol. 123, no. 3, pp. 1694–1707, 2018, doi: 10.1002/2017JD027606.
- [53] X. Min, C. Yang, and N. Dong, “Merging satellite and gauge rainfalls for flood forecasting of two catchments under different climate conditions,” *Water (Switzerland)*, vol. 12, no. 3, pp. 1–17, 2020, doi:10.3390/w12030802.
- [54] G. Tang, M. Clark, S. Papalexioiu, Z. Ma, and Y. Hong, “Have satellite precipitation products improved over last two decades? A comprehensive comparison of GPM IMERG with nine satellite and reanalysis datasets,” *Remote Sens. Environ.*, vol. 240, 2020, doi:10.1016/j.rse.2020.111697.
- [55] M. Mahmoud, S. Mohammed, M. Hamouda, and M. Mohamed, “Impact of topography and rainfall intensity on the accuracy of imerg precipitation estimates in an arid region,” *Remote Sens.*, vol. 13, no. 1, pp. 1–17, 2021, doi: 10.3390/rs13010013.
- [56] M. L. Tan and H. Santo, “Comparison of GPM IMERG, TMPA 3B42 and PERSIANN-CDR satellite precipitation products over Malaysia,” *Atmos. Res.*, vol. 202, no. September 2017, pp. 63–76, 2018, doi:10.1016/j.atmosres.2017.11.006.
- [57] M. N. Anjum *et al.*, “Performance evaluation of latest integrated multi-satellite retrievals for Global Precipitation Measurement (IMERG) over the northern highlands of Pakistan,” *Atmos. Res.*, vol. 205, pp. 134–146, 2018, doi: 10.1016/j.atmosres.2018.02.010.
- [58] J. R. Rozante, D. A. Vila, J. B. Chiquetto, A. de A. Fernandes, and D. S. Alvim, “Evaluation of TRMM/GPM blended daily products over Brazil,” *Remote Sens.*, vol. 10, no. 6, pp. 1–17, 2018, doi:10.3390/rs10060882.
- [59] S. Wang, J. Liu, J. Wang, X. Qiao, and J. Zhang, “Evaluation of GPM IMERG V05B and TRMM 3B42V7 Precipitation products over high mountainous tributaries in Lhasa with dense rain gauges,” *Remote Sens.*, 2019, [Online]. Available: <https://www.mdpi.com/528832>.
- [60] L. A. Blacutt, D. L. Herdies, L. G. G. de Gonçalves, D. A. Vila, and M. Andrade, “Precipitation comparison for the CFSR, MERRA, TRMM3B42 and Combined Scheme datasets in Bolivia,” *Atmos. Res.*, vol. 163, pp. 117–131, 2015, doi: 10.1016/j.atmosres.2015.02.002.
- [61] B. Yong *et al.*, “First evaluation of the climatological calibration algorithm in the real-time TMPA precipitation estimates over two basins at high and low latitudes,” *Water Resour. Res.*, vol. 49, no. 5, pp. 2461–2472, 2013, doi: 10.1002/wrcr.20246.
- [62] T. Condom, P. Rau, and J. C. Espinoza, “Correction of TRMM 3B43 monthly precipitation data over the mountainous areas of Peru during the period 1998–2007,” *Hydrol. Process.*, vol. 25, no. 12, pp. 1924–1933, 2011, doi: 10.1002/hyp.7949.
- [63] E. Ebert, J. Janowiak, and C. Kidd, “Comparasion of Near-Real-Time Precipitation Estimates from Satellite Observations and Numerical Models,” *Am. Meteorol. Soc.*, pp. 47–64, 2007, doi:10.1007/978-3-540-89725-5_19.
- [64] R. Ramadhan *et al.*, “A Preliminary Assessment of the GSMP Version 08 Products over Indonesian Maritime Continent against Gauge Data,” *Remote Sens.*, vol. 15, no. 4, 2023, doi:10.3390/rs15041115.
- [65] A. Nkuzimana, S. Bi, M. A. A. Alriah, T. Zhi, and N. A. D. Kur, “Comparative Analysis of the Performance of Satellite-Based Rainfall Products Over Various Topographical Unities in Central East Africa: Case of Burundi,” *Earth Sp. Sci.*, vol. 7, no. 5, pp. 0–3, 2020, doi:10.1029/2019EA000834.
- [66] M. Rachdane, E. M. El Khalki, M. E. Saidi, M. Nehmadou, A. Ahbari, and Y. Trambly, “Comparison of High-Resolution Satellite Precipitation Products in Sub-Saharan Morocco,” *Water (Switzerland)*, vol. 14, no. 20, 2022, doi: 10.3390/w14203336.
- [67] A. Veloria, G. J. Perez, G. Tapang, and J. Comiso, “Improved rainfall data in the Philippines through concurrent use of GPM IMERG and ground-based measurements,” *Remote Sens.*, vol. 13, no. 15, pp. 1–21, 2021, doi: 10.3390/rs13152859.
- [68] F. Xu *et al.*, “Systematical Evaluation of GPM IMERG and TRMM 3B42V7 Precipitation Products in the Huang-Huai-Hai Plain, China,” *Remote Sensing*, vol. 11, no. 6, p. 697, Mar. 2019, doi:10.3390/rs11060697.
- [69] R. Ramadhan *et al.*, “Evaluation of GPM IMERG Products for Extreme Precipitation over Indonesia,” *J. Phys. Conf. Ser.*, vol. 2309, no. 1, 2022, doi: 10.1088/1742-6596/2309/1/012008.
- [70] W. Wang, H. Lu, T. Zhao, L. Jiang, and J. Shi, “Evaluation and Comparison of Daily Rainfall From Latest GPM and TRMM Products Over the Mekong River Basin,” *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 10, no. 6, pp. 2540–2549, Jun. 2017, doi: 10.1109/jstars.2017.2672786.
- [71] C. Chen *et al.*, “Multiscale Comparative Evaluation of the GPM IMERG v5 and TRMM 3B42 v7 Precipitation Products from 2015 to 2017 over a Climate Transition Area of China,” *Remote Sensing*, vol. 10, no. 6, p. 944, Jun. 2018, doi: 10.3390/rs10060944.
- [72] Y. Song, J. Zhang, X. Meng, Y. Zhou, Y. Lai, and Y. Cao, “Comparison study of multiple precipitation forcing data on hydrological modeling and projection in the qujiang river basin,” *Water (Switzerland)*, vol. 12, no. 9, 2020, doi: 10.3390/w12092626.