A Comparative Evaluation of Bias Correction Techniques for Improving GPM-IMERG Precipitation Data in the Welang Watershed, Indonesia

Ery Suhartanto
Department of Water Resources Engineering, Universitas Brawijaya, Malang City, Indonesia
erysuhartanto@ub.ac.id (corresponding author)

Ussy Andawayanti
Department of Water Resources Engineering, Universitas Brawijaya, Malang City, Indonesia
uandawayanti@ub.ac.id

Muhammad Nurjati Hidayat
Department of Water Resources Engineering, Universitas Brawijaya, Malang City, Indonesia
muhammadhidayat@ub.ac.id

Rahmah Dara Lufira
Doctor Program of Water Resources Engineering, Universitas Brawijaya, Malang City, Indonesia
rahmahdara@ub.ac.id

Rizki Tri Utami
Master Program of Water Resources Engineering, Universitas Brawijaya, Malang City, Indonesia
rizkiutami1653@gmail.com

Received: 1 August 2025 | Revised: 11 September 2025 | Accepted: 21 September 2025

Licensed under a CC-BY 4.0 license | Copyright (c) by the authors | DOI: https://doi.org/10.48084/etasr.13762

ABSTRACT

Precise precipitation information underpins hydrological modeling, water resource planning, and hazard mitigation; yet, gauge coverage in many Indonesian catchments is sparse. The GPM-IMERG product provides 0.1°/30-min rainfall estimates, however, systematic biases limit its operational value. Five benchmark correction techniques were evaluated: Linear Scaling (LS), Linear Regression (LR), Genetic-Algorithm-based Correction Factor (GA-CF), Local Intensity Scaling (LOCI), and Power Transformation (PT) against daily observations from seven gauges in the Welang Watershed (2001-2020). LS delivered the most consistent improvement (NSE = 0.87, R = 0.92, RSR = 0.36), reducing the residual error by 30% relative to the next-best method. LR, GA-CF, and LOCI enhanced seasonal patterns (NSE ≈ 0.85), while PT provided complementary gains for moderate events but remained sub-optimal for extremes. The refined IMERG series met the accuracy thresholds proposed for reservoir operations, providing a readily deployable rainfall input for data-scarce, topographically complex tropical watersheds.

Keywords-satellite precipitation; bias correction; GPM IMERG; hydrological modeling; Welang watershed

I. INTRODUCTION

Reliable precipitation information underpins hydrological simulations, guides water resource planning, and strengthens disaster risk mitigation efforts. However, in many Indonesian watersheds, ground-based rainfall observations are often sparse, inconsistent, or incomplete due to limited monitoring networks, inadequate maintenance, and technical failures. These challenges are particularly critical in tropical catchments, where high spatiotemporal rainfall variability renders conventional observations insufficient, thereby compromising discharge estimation, flood prediction, and the development of climate resilience strategies. The Welang Watershed in East Java, Indonesia, exemplifies these conditions. As a crucial water source for irrigation, domestic supply, and agriculture, this basin is highly susceptible to hydrometeorological extremes. Yet, it continues to suffer from substantial gaps in rainfall and discharge monitoring.

The Global Precipitation Measurement (GPM) Integrated Multi-satellite Retrievals for GPM (IMERG) product provides rainfall estimates with a 0.1° spatial resolution and 30 min temporal resolution [1, 2]. It has been shown that incorporating GPM-IMERG data can improve hydrologic modeling and flood prediction, particularly in catchments with limited gauge coverage [3-5]. However, its accuracy is reduced in complex terrains and tropical convective environments due to algorithm limitations, spatial averaging, and orographic effects, which often lead to the overestimation of light rainfall and underestimation of extreme events [6, 7]. In Indonesia, earlier research using Tropical Rainfall Measuring Mission (TRMM) data demonstrated that satellite-based products can effectively capture rainfall patterns, making them useful for hydrological analysis in regions with sparse observation networks [8-11]. To increase the reliability of satellite-derived precipitation data, bias correction has become an essential preprocessing step. Simple methods, such as LS and LR, correct systematic errors, while more advanced approaches, such as LOCI, PT, and optimization-based techniques, like the GA-CF, aim to address distributional mismatches and improve performance across different rainfall intensities. Despite their growing use, comprehensive evaluations of these techniques in topographically complex tropical basins are still limited, creating uncertainty about their relative effectiveness for operational hydrological modeling. This study addresses the specific gap by systematically comparing five bias correction methods (LS, LR, GA-CF, LOCI, and PT) applied to GPM-IMERG precipitation data in the Welang Watershed, East Java, Indonesia. The analysis quantifies the performance of each method, identifies the most suitable approach for operational hydrological modeling in data-scarce tropical regions, and evaluates the influence of topographic and climatic variability on correction outcomes. Ultimately, the findings provide practical guidance for improving the application of satellite-based precipitation data in hydrology and disaster risk management.

II. MATERIALS AND METHODS

A. *Study Area and Data Collection*

This study was conducted in the Welang Watershed, as shown in Figure 1, a 522.89 km^2 catchment located in East Java, Indonesia, spanning Pasuruan Regency, Pasuruan City, and Malang Regency (7°34′–7°57′ S; 112°35′–112°56′ E). The watershed exhibits diverse physiographic characteristics, with volcanic highlands in the upstream region transitioning to low-lying alluvial plains downstream, contributing to pronounced spatial variability in hydrological responses [12]. It lies within a tropical monsoonal climate zone characterized by distinct wet and dry seasons and is frequently affected by hydrometeorological extremes, such as seasonal floods and recurrent droughts [13]. Despite its critical role in supporting domestic water supply, irrigation, and agriculture, the watershed is monitored by a sparse and inconsistently maintained hydrometeorological network, necessitating the integration of satellite-based precipitation products to enhance hydrological analyses. The precipitation dataset used in this study was the GPM-IMERG, which provides 0.1° spatial and 30-min temporal resolution estimates. Ground-based daily rainfall data from seven gauges (Telebuk, Wonorejo, Sengon Pager, Purwosari/Tejosari, Selowongko, Lawang, and Tutur) were obtained from the Water Resources Public Works Agency of East Java Province. The analysis spanned the period from 2001 to 2020.

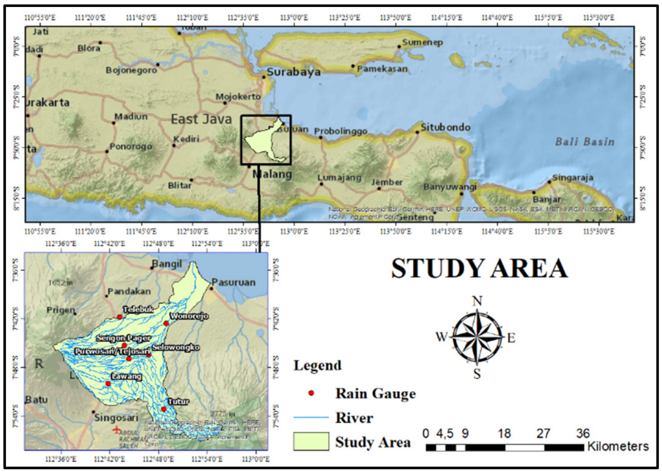

Fig. 1. The study area in the Welang watershed.

B. *Linear Scaling*

LS is a widely used bias-correction method for satellite precipitation because it is efficient and straightforward. It assumes a systematic, temporally consistent bias between satellite estimates and gauges, allowing proportional adjustment to the observed climatology. During calibration, the long-term means of the satellite $(\overline{P_{sat}})$ and observed $(\overline{P_{obs}})$ precipitation is computed, the scaling factor (α) is derived, and applied to the whole series. On a monthly m basis, the correction is expressed as:

$$P_{cor,m} = \alpha_m \times P_{sat,m}, \text{ where } \alpha_m = \frac{\overline{P_{obs}}}{\overline{P_{sat}}} \qquad (1)$$

LS maintains the temporal variability of satellite rainfall while adjusting magnitudes to match ground observations, making it useful for hydrological modeling in data-scarce basins. Its performance is typically assessed using the Pearson correlation coefficient (R), Nash-Sutcliffe Efficiency (NSE), and the RMSE-to-Standard-Deviation Ratio (RSR) [14]. However, the method assumes a constant bias, which may not hold under non-stationary conditions, thereby motivating the adoption of adaptive or hybrid correction approaches [15].

C. *Linear Regression*

LR is a parametric technique commonly used for bias correction in satellite-derived precipitation, establishing a direct linear relationship between satellite estimates (P_{sat}) and ground-based observations (P_{obs}) [16]. For each month m, the model is expressed as:

$$P_{obs,m} = a_m + \left(b_m \times P_{sat,m}\right) \qquad (2)$$

LR adjusts satellite precipitation estimates using additive (a_m) and multiplicative (b_m) terms derived through ordinary least squares, minimizing residual errors. This method corrects systematic biases, improving consistency with ground observations across rainfall intensities. Its performance is evaluated using R, NSE, and RSR, making LR a reliable tool for hydrological modeling and satellite rainfall validation in complex regions.

D. Genetic Algorithm-Based Correction Factor (GA-CF)

The GA-CF is an evolutionary optimization technique designed to identify optimal bias adjustment parameters for satellite-derived precipitation [17]. GA-CF refines a pool of candidate bias correction factors via repeated cycles of selection, crossover, and mutation, aiming to reduce the RMSE between the adjusted IMERG rainfall (P_{cor}) and gauge-measured precipitation (P_{obs}). For each month, the correction is expressed as:

$$P_{cor,m} = \theta \times P_{sat,m} \qquad (3)$$

GA-CF uses an optimized correction factor (θ) to search for large solution spaces, avoid local minima, and capture nonlinear relationships. Optimization stops at convergence. Corrected data are validated with R, NSE, and RSR. GA-CF outperforms static methods in complex, nonstationary tropical watersheds [18].

E. Local Intensity Scaling

LOCI corrects rainfall occurrence and intensity, addressing satellite biases, such as excessive light-rain days and underestimated heavy storms [19]. For each month m, LOCI sets a wet-day threshold $(P_{thres,m})$ to match wet-day frequencies, then applies a scaling factor S_m on wet days $> (P_{thres,m})$. The adjusted precipitation is computed monthly and expressed as:

$$P_{cor,m} = \begin{cases} 0, \; if \; P_{sat,m} < P_{thres,m} \\ S_m \times P_{sat,m}, \; if \; P_{sat,m} \geq P_{thres,m} \end{cases} \qquad (4)$$

where $P_{sat,m}$ is the original satellite precipitation in month (m). This localised adjustment enhances temporal coherence and rainfall magnitude estimates, making LOCI suitable for bias correction in flood-prone, topographically complex catchments.

F. Power Transformation

PT is a nonlinear bias correction method, often applied after LOCI, to adjust both the mean and variance of satellite precipitation and enhance its distributional accuracy [19]. It estimates a monthly exponent parameter (b_m) that minimizes the difference between the coefficient of variation of the transformed satellite data and ground observations. The corrected precipitation is then expressed as:

$$P_{cor,m} = S_m \times P_{LOCI,m}^{bm} \qquad (5)$$

Applying LOCI followed by PT, with S_m aligning the transformed mean to observations, reduces systematic biases, better captures extremes, and improves satellite precipitation statistics, enhancing suitability for hydrological modeling and climate-impact analyses [20]. Yet, a uniform PT exponent may underperform in highly nonstationary settings, motivating the use of adaptive integration.

III. RESULTS AND DISCUSSION

A. Linear Scaling

LS significantly improved the agreement between GPM-IMERG and ground observations in the Welang Watershed. The bias-adjusted series achieved R = 0.92, NSE = 0.87, and RSR = 0.36, with points clustering near the 1:1 line, and only minor high-intensity deviations, supporting hydrological modeling, flood forecasting, and climate assessments. While advanced methods, such as Quantile Mapping, can achieve marginally higher accuracy under specific conditions [21], LS offers a practical balance between computational simplicity and reliability, making it well-suited for operational applications. Time series analysis further confirmed LS's ability to preserve the temporal distribution of rainfall, effectively capturing wet and dry seasonal cycles with improved fidelity. This observation aligns with [22], where similar improvements in temporal coherence were reported following bias correction. Collectively, these results affirm LS as a reliable and computationally efficient method for enhancing the hydrological applicability of GPM-IMERG precipitation data in tropical and topographically complex regions.

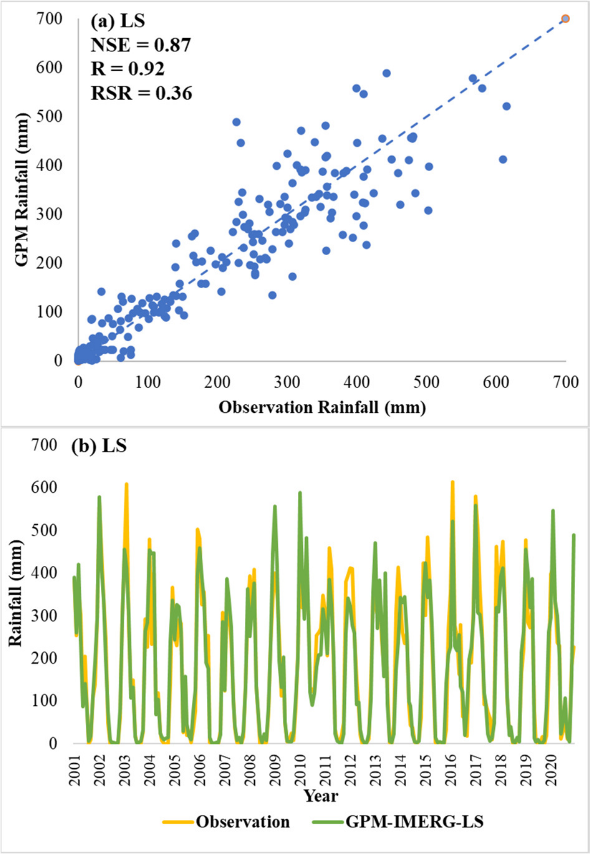

Fig. 2. Comparison of GPM-IMERG rainfall estimates and ground-based observations using LS: (a) scatterplot, (b) time series.

B. Linear Regression

LR significantly improved the agreement between GPM-IMERG estimates and gauge observations in the Welang Watershed, producing a bias-corrected series that closely matched ground data (R = 0.92, NSE = 0.85, RSR = 0.38). Data points clustered near the 1:1 line, reflecting reduced systematic bias and improved monthly rainfall estimates, though slight underestimation remained for high-intensity events. LR successfully preserved seasonal patterns and temporal coherence, offering a balance between computational efficiency and correction accuracy. This makes it well-suited for large-scale, long-term hydrological applications, while modeling extreme events may still require hybrid or complementary techniques.

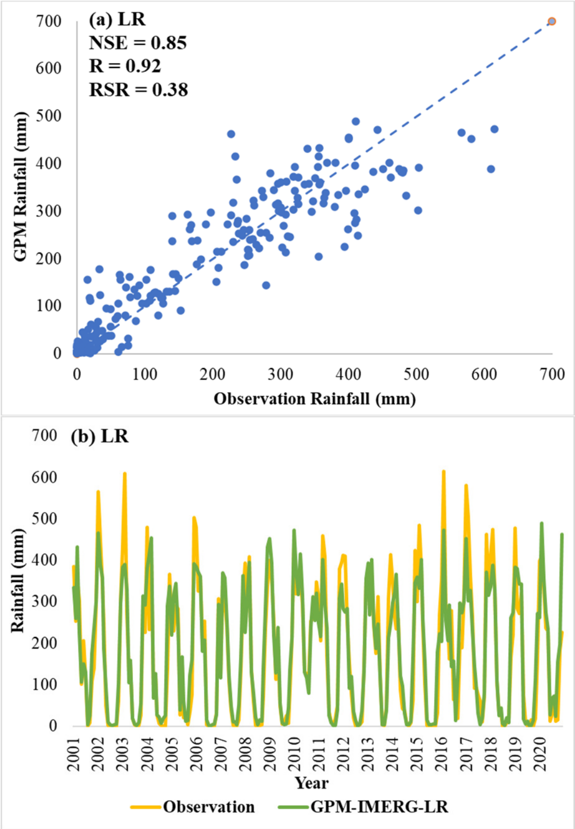

Fig. 3. Comparison of GPM-IMERG rainfall estimates and ground-based observations using LR: (a) scatterplot, (b) time series.

C. Correction Factor (Genetic Algorithm-Based)

GA-CF optimized correction factors strengthened the agreement between GPM-IMERG and gauges in the Welang Watershed. The corrected series achieved NSE = 0.85, R = 0.90, and RSR = 0.39, indicating high predictive skill and reduced bias, with only minor dispersion at high rainfall. GA-CF's adaptive selection–crossover–mutation process outperforms static methods, yielding dependable inputs for hydrological modeling, flood forecasting, and water management in data-sparse tropical regions [23]. The time series analysis confirmed GA-CF's ability to preserve seasonal and interannual rainfall variability while improving overall alignment with ground-based observations. The correction factors varied from 0.39 for 0 mm–50 mm, 0.42 for 50 mm–100 mm, 0.53 for 100 mm–150 mm, 0.62 for 150 mm–200 mm, 0.75 for 200 mm–250 mm, 0.82 for 250 mm–300 mm, and 0.98 for extreme events >300 mm, illustrating GA's sensitivity to satellite overestimation under heavy precipitation and its adaptive correction capability across diverse hydrological conditions. These findings are consistent with previous research validating GA-CF for enhancing satellite rainfall estimation in complex terrains [24]. However, residual underestimations of peak events suggest the need for further refinement or integration with distribution-based techniques to improve extreme-event modeling. Collectively, GA-CF demonstrates strong potential as a flexible, high-performing tool for bias correction in satellite-derived precipitation within hydrologically dynamic tropical watersheds.

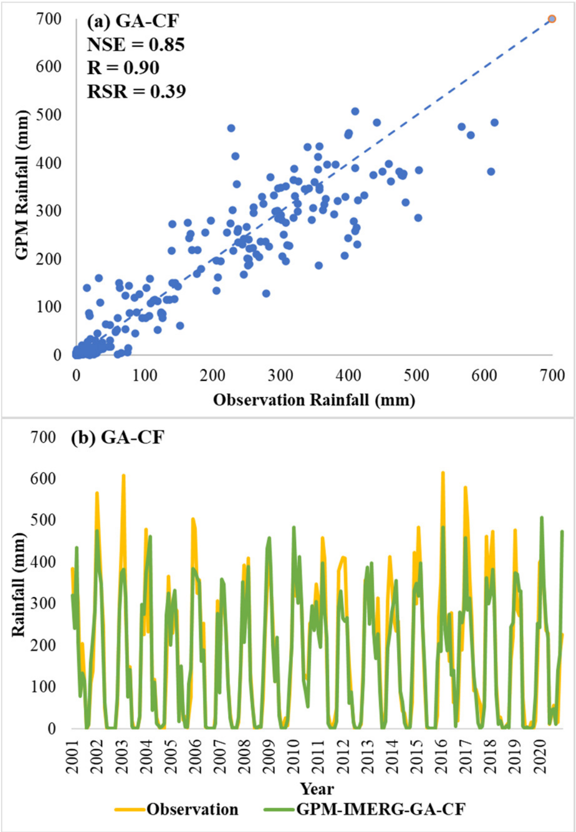

Fig. 4. Comparison of GPM-IMERG rainfall estimates and ground-based observations using GA-CF: (a) scatterplot, (b) time series.

D. Local Intensity Capacity

LOCI improved the alignment between GPM-IMERG estimates and gauge observations in the Welang Watershed (R = 0.92, NSE = 0.83, RSR = 0.41), showing consistent performance across rainfall intensities. It preserved seasonal patterns and improved estimates for moderate rainfall, making it useful for long-term hydrological assessments, water resource planning, and climate studies. However, its persistent underestimation of high-intensity events reduces its suitability for flood forecasting. Compared to LR, which is less effective for nonlinear rainfall behavior, LOCI enhances temporal fidelity by locally adjusting rainfall intensities. While more advanced methods, like Quantile Mapping and GA, can better capture extremes, their higher computational demands and reliance on dense observational data limit their practicality for operational use.

E. Power Transformation

PT provided moderate bias correction for GPM-IMERG precipitation in the Welang Watershed. While the adjusted series showed strong correlation with gauges (R = 0.92), its overall performance was limited and only marginally acceptable (NSE = 0.75; RSR = 0.50), with higher dispersion at intense rainfall levels. PT effectively corrected low-to-moderate intensity events but failed to adequately represent extremes, reflecting limited flexibility in handling nonlinear rainfall dynamics. Its main advantages are simplicity and low computational cost, making it suitable for baseline hydrological analyses, preliminary studies, and applications in data-scarce areas. Consistent with prior findings, an NSE ≥ 0.75 marks the lower threshold of acceptability. Accordingly, PT is best used as a complementary or preliminary adjustment method, ideally within hybrid frameworks that improve the representation of extreme events and expand its role in regional water balance and climate assessments.

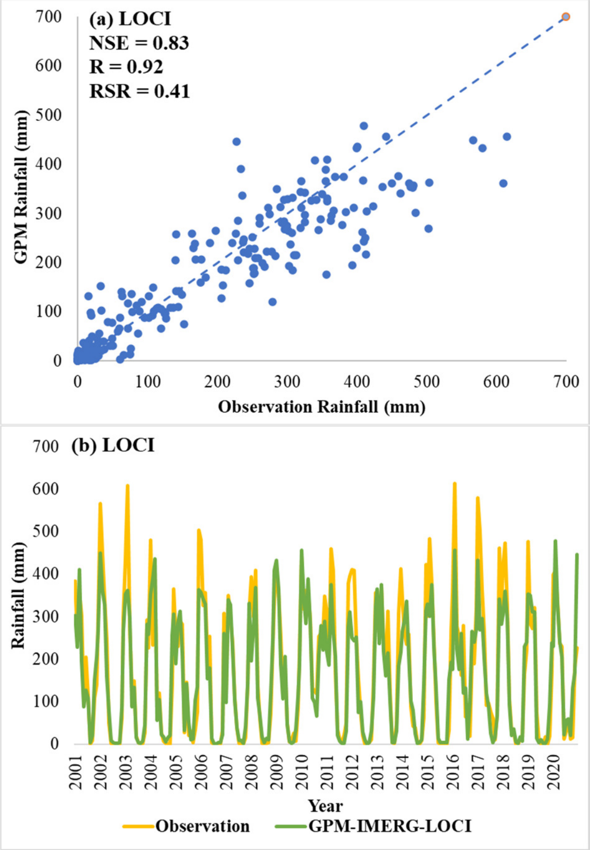

Fig. 5. Comparison of GPM-IMERG rainfall estimates and ground-based observations using LOCI: (a) scatterplot, (b) time series.

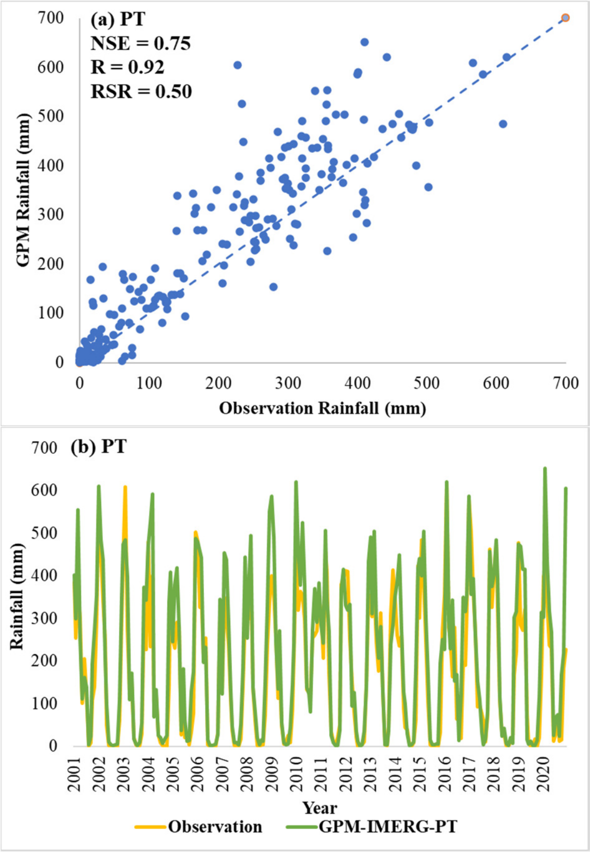

Fig. 6. Comparison of GPM-IMERG rainfall estimates and ground-based observations using PT: (a) scatterplot, (b) time series.

Across the five evaluated correction techniques, LS demonstrated the best overall performance, achieving the highest accuracy (NSE = 0.87), strongest correlation (R = 0.92), and lowest residual error (RSR = 0.36), as shown in Table I. This reinforces earlier studies that highlighted the reliability of linear approaches for satellite rainfall correction in tropical basins [25]. Both LR and GA-CF performed well (NSE = 0.85 each) but remained less effective in capturing extreme rainfall. In contrast, LOCI and PT were more responsive to topographic and seasonal variability but showed higher residual errors. Overall, the findings suggest that while adaptive methods, such as GA-CF and LOCI, offer greater contextual flexibility, simpler techniques, like LS, remain more robust and computationally efficient. This underscores the importance of selecting correction methods according to watershed conditions, climatic variability, and modeling objectives.

TABLE I. ACCURACY COMPARISON OF BIAS CORRECTION METHODS DURING THE VALIDATION PERIODS (2001–2020)

No.	Method	NSE	R	RSR
1	LS	0.87	0.92	0.36
2	LR	0.85	0.92	0.38
3	GA-CF	0.85	0.90	0.39
4	LOCI	0.83	0.92	0.41
5	PT	0.75	0.92	0.50

Beyond its statistical performance (NSE = 0.87, R = 0.92, RSR = 0.36), LS also demonstrates clear operational advantages. In real-time hydrological forecasting for data-scarce tropical watersheds, such as the Welang Watershed, approaches that are both computationally simple and consistently reliable are particularly valuable. Unlike optimization-based or distribution-focused correction methods, LS can be implemented rapidly with minimal data and processing requirements. This efficiency makes LS more feasible for near-real-time rainfall adjustment to support flood forecasting and reservoir operation. Its stable performance across rainfall intensities further ensures that hydrological models are supplied with dependable input data, thereby strengthening the timeliness and reliability of operational water resource management.

IV. CONCLUSIONS

This study evaluated GPM-IMERG rainfall estimates using five bias correction techniques, LS, LR, GA-CF, LOCI, and PT, in the topographically complex Welang Watershed. Among these, LS proved the most effective, achieving the highest accuracy (NSE = 0.87, R = 0.92, RSR = 0.36) and delivering consistent improvements across rainfall intensities and time scales. LR and GA-CF also improved data reliability but were less effective in representing extreme events. LOCI and PT preserved seasonal patterns but showed higher residual errors, limiting their usefulness for applications requiring high precision, such as flood forecasting. The findings highlight the importance of bias correction for enhancing the operational value of satellite-derived precipitation in tropical watersheds prone to flooding and characterized by sparse observational data. At the same time, they emphasize the limitations of static correction models in capturing nonlinear and high-intensity rainfall, underscoring the need for adaptive and hybrid approaches that integrate machine learning, evolutionary optimization, and multisource data fusion. Advancing such techniques will further improve accuracy and broaden the applicability of satellite-based rainfall products for real-time hydrologic forecasting and climate-resilient water resource planning. Based on the results, the choice of bias correction method should be guided by both climatic and topographic conditions. For data-scarce tropical watersheds with high rainfall variability, LS offers a robust and computationally efficient solution for operational hydrological modeling. In areas where extreme events are a priority, optimization-based methods, like GA-CF, or distribution-focused techniques, such as LOCI and PT, may provide additional value despite their higher computational requirements. Conversely, in regions with moderate rainfall regimes and sufficient observational support, simpler approaches, such as LR, remain effective and easy to implement. These recommendations reinforce the need to tailor bias correction strategies to data availability, computational resources, and the specific requirements of hydrological applications.

ACKNOWLEDGMENT

The authors express their sincere gratitude to the National Aeronautics and Space Administration (NASA) of the United States and the Water Resources Public Works Agency (*Dinas Pekerjaan Umum Sumber Daya Air*) of East Java Province for providing essential data and technical support. They also extend their appreciation to all collaborators for their valuable contributions to this research.

REFERENCES

[1] M. L. Tan and Z. Duan, "Assessment of GPM and TRMM Precipitation Products over Singapore," *Remote Sensing*, vol. 9, no. 7, July 2017, Art. no. 720, https://doi.org/10.3390/rs9070720.

[2] Z. E. Asong, S. Razavi, H. S. Wheater, and J. S. Wong, "Evaluation of Integrated Multisatellite Retrievals for GPM (IMERG) over Southern Canada against Ground Precipitation Observations: A Preliminary Assessment," pp. 1033–1050, Apr. 2017, https://doi.org/10.1175/JHM-D-16-0187.1.

[3] W. Sun *et al.*, "Evaluation and Correction of GPM IMERG Precipitation Products over the Capital Circle in Northeast China at Multiple Spatiotemporal Scales," *Advances in Meteorology*, vol. 2018, no. 1, 2018, Art. no. 4714173, https://doi.org/10.1155/2018/4714173.

[4] A. Lombardi *et al.*, "On the combined use of rain gauges and GPM IMERG satellite rainfall products for hydrological modelling: impact assessment of the cellular-automata-based methodology in the Tanaro River basin in Italy," *Hydrology and Earth System Sciences*, vol. 28, no. 16, pp. 3777–3797, Aug. 2024, https://doi.org/10.5194/hess-28-3777-2024.

[5] M. Jawad, B. Bhattacharya, A. Young, and S. J. van Andel, "Evaluation of Near Real-Time Global Precipitation Measurement (GPM) Precipitation Products for Hydrological Modelling and Flood Inundation Mapping of Sparsely Gauged Large Transboundary Basins—A Case Study of the Brahmaputra Basin," *Remote Sensing*, vol. 16, no. 10, Jan. 2024, Art. no. 1756, https://doi.org/10.3390/rs16101756.

[6] X. Pan *et al.*, "Evaluation and Applicability Analysis of GPM Satellite Precipitation over Mainland China," *Remote Sensing*, vol. 15, no. 11, Jan. 2023, Art. no. 2866, https://doi.org/10.3390/rs15112866.

[7] D. R. Tama, Limantara, Lily M., E. Suhartanto, and Y. P. Devia, "The important of Global Precipitation Measurement in ungauged catchment," *ARPN Journal of Engineering and Applied Sciences*, pp. 2043–2050, Nov. 2023, https://doi.org/10.59018/0923250.

[8] H. Kuswanto, D. Setiawan, and A. Sopaheluwakan, "Clustering of Precipitation Pattern in Indonesia Using TRMM Satellite Data," *Engineering, Technology & Applied Science Research*, vol. 9, no. 4, pp. 4484–4489, Aug. 2019, https://doi.org/10.48084/etasr.2950.

[9] Abd. R. As-syakur, T. Tanaka, T. Osawa, and M. S. Mahendra, "Indonesian rainfall variability observation using TRMM multi-satellite data," *International Journal of Remote Sensing*, vol. 34, no. 21, pp. 7723–7738, Nov. 2013, https://doi.org/10.1080/01431161.2013.826837.

[10] S. Suroso, P. B. Santoso, S. Birkinshaw, C. Kilsby, A. Bardossy, and E. Aldrian, "Assessment of TRMM rainfall data for flood modelling in three contrasting catchments in Java, Indonesia," *Journal of Hydroinformatics*, vol. 25, no. 3, pp. 797–814, Apr. 2023, https://doi.org/10.2166/hydro.2023.132.

[11] 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," *Journal of Ecological Engineering*, vol. 22, no. 11, 2021, https://doi.org/10.12911/22998993/142843.

[12] S. Purnama, "Evaluation of Groundwater and Springs Potency in East Java Province," *E3S Web of Conferences*, vol. 468, 2023, Art. no. 08003, https://doi.org/10.1051/e3sconf/202346808003.

[13] H. Mulyanti, I. Istadi, and R. Gernowo, "Historical, Recent, and Future Threat of Drought on Agriculture in East Java, Indonesia: A Review," *E3S Web of Conferences*, vol. 448, 2023, Art. no. 03016, https://doi.org/10.1051/e3sconf/202344803016.

[14] N. Rahmawati, K. Rahayu, and S. T. Yuliasari, "Performance of daily satellite-based rainfall in groundwater basin of Merapi Aquifer System, Yogyakarta," *Theoretical and Applied Climatology*, vol. 146, no. 1, pp. 173–190, Oct. 2021, https://doi.org/10.1007/s00704-021-03731-9.

[15] A. W. Worako, A. T. Haile, T. Rientjes, and T. A. Woldesenbet, "Error propagation of climate model rainfall to streamflow simulation in the Gidabo sub-basin, Ethiopian Rift Valley Lakes Basin," *Hydrological*

Sciences Journal, pp. 1185–1198, June 2022, https://doi.org/10.1080/02626667.2022.2072220.

[16] D. Y. Faidah, H. Kuswanto, and S. Sutikno, "Improving the Accuracy of Rainfall Prediction Using Bias-Corrected NMME Outputs: A Case Study of Surabaya City, Indonesia," *The Scientific World Journal*, vol. 2022, no. 1, 2022, Art. no. 9779829, https://doi.org/10.1155/2022/9779829.

[17] Z. Iqbal, S. Shahid, K. Ahmed, X. Wang, T. Ismail, and H. F. Gabriel, "Bias correction method of high-resolution satellite-based precipitation product for Peninsular Malaysia," *Theoretical and Applied Climatology*, vol. 148, no. 3, pp. 1429–1446, May 2022, https://doi.org/10.1007/s00704-022-04007-6.

[18] R. Nosratpour and M. Rahimzadegan, "Clustering and assessment of precipitation climates using satellite precipitation products and improved machine learning precipitation models," *International Journal of Climatology*, vol. 43, no. 16, pp. 7819–7850, 2023, https://doi.org/10.1002/joc.8294.

[19] G. H. Fang, J. Yang, Y. N. Chen, and C. Zammit, "Comparing bias correction methods in downscaling meteorological variables for a hydrologic impact study in an arid area in China," *Hydrology and Earth System Sciences*, vol. 19, no. 6, pp. 2547–2559, June 2015, https://doi.org/10.5194/hess-19-2547-2015.

[20] E. Soriano, L. Mediero, and C. Garijo, "Selection of Bias Correction Methods to Assess the Impact of Climate Change on Flood Frequency Curves," *Water*, vol. 11, no. 11, Nov. 2019, Art. no. 2266, https://doi.org/10.3390/w11112266.

[21] D. S. Londhe, Y. B. Katpatal, and N. D. Bokde, "Performance Assessment of Bias Correction Methods for Precipitation and Temperature from CMIP5 Model Simulation," *Applied Sciences*, vol. 13, no. 16, Jan. 2023, Art. no. 9142, https://doi.org/10.3390/app13169142.

[22] L. Tu and L. Duan, "Spatial downscaling analysis of GPM IMERG precipitation dataset based on multiscale geographically weighted regression model: a case study of the Inner Mongolia Reach of the Yellow River basin," *Frontiers in Environmental Science*, vol. 12, Apr. 2024, https://doi.org/10.3389/fenvs.2024.1389587.

[23] H. Yang *et al.*, "An Efficient Method for Wavefront Aberration Correction Based on the RUN Optimizer," *Photonics*, vol. 11, no. 1, Jan. 2024, Art. no. 29, https://doi.org/10.3390/photonics11010029.

[24] N. Turini *et al.*, "Assessment of Satellite-Based Rainfall Products Using a X-Band Rain Radar Network in the Complex Terrain of the Ecuadorian Andes," *Atmosphere*, vol. 12, no. 12, Dec. 2021, Art. no. 1678, https://doi.org/10.3390/atmos12121678.

[25] W. Gumindoga, T. H. M. Rientjes, A. T. Haile, H. Makurira, and P. Reggiani, "Performance of bias-correction schemes for CMORPH rainfall estimates in the Zambezi River basin," *Hydrology and Earth System Sciences*, vol. 23, no. 7, pp. 2915–2938, July 2019, https://doi.org/10.5194/hess-23-2915-2019.