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ELEVATION-BASED BIAS CORRECTION OF CHIRPS AND GSMAP RAINFALL IN NORTHWEST VIETNAM (2000–2024): APPLICATION TO CLIMATE-RESILIENT TRANSPORT INFRASTRUCTURE MANAGEMENT

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Abstract. Reliable rainfall data are essential for hydrological modelling and infrastructure planning, particularly in mountainous regions where gauge networks are sparse and climate risks are growing. Satellite rainfall products such as Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) and Global Satellite Mapping of Precipitation (GSMaP) have been increasingly applied worldwide, yet their performance in complex terrains remains uncertain. This study evaluates CHIRPS and GSMaP against daily observations from 11 meteorological stations in Northwest Vietnam during 2000–2024 and applies an elevation-based bias correction. Statistical analyses were used to compare accuracy, including RMSE and correlation, and performance maps were generated to reveal spatial error patterns. The results show that CHIRPS achieved lower RMSE but tended to underestimate rainfall at high-elevation stations, while GSMaP yielded slightly higher correlations ($R^2 \approx 0.74-0.81$) but often overestimated rainfall in mid-elevation valleys. Elevation-based correction reduced RMSE, narrowed bias spread across the network, and produced notable improvements at upland sites. These corrected datasets enhance reliability for hydrological simulations and flood risk assessment, especially along National Highway 6, where landslides and flash floods frequently disrupt traffic. Overall, the findings demonstrate the practical value of integrating satellite rainfall with ground observations to supplement precipitation information in ungauged regions, supporting safer and climate-resilient transport infrastructure in mountainous areas.

Keywords: Satellite rainfall products, CHIRPS, GSMaP, Ground-based observations, Elevation-based correction, Flood and landslide hazard, Mountainous regions, Climate-resilient transport.

1. INTRODUCTION

Accurate rainfall estimation is fundamental for hydrological modeling, disaster risk reduction, and climate-resilient infrastructure planning, especially in mountainous regions where rain-gauge networks are sparse and spatiotemporal variability is pronounced. In such environments, satellite-based precipitation products (SPPs) have become essential alternatives to conventional ground observations, offering long-term, quasi-global coverage with fine temporal resolution. Over the past decade, several SPPs—such as CHIRPS (Climate Hazards Group Infrared Precipitation with Stations), GSMaP (Global Satellite Mapping of Precipitation), and IMERG (Integrated Multi-satellite Retrievals for GPM)—have been extensively evaluated across diverse climatic and topographic settings, yielding both promising results and notable discrepancies [1–5].

Among these products, CHIRPS integrates infrared observations with station data to provide high-resolution estimates and has performed well in regions with complex terrain, although it tends to underestimate convective rainfall at high elevations [3]. GSMaP, developed by JAXA, assimilates multi-sensor microwave and infrared data, offering high temporal resolution suitable for hazard monitoring. However, its performance varies considerably depending on storm type, terrain, and atmospheric conditions [4]. Several studies have shown that while SPPs can capture broad-scale rainfall patterns, their raw outputs often exhibit systematic biases that require region-specific validation and correction [5,6]. In Southeast Asia, where monsoon dynamics interact with steep orography, accurate rainfall estimation remains particularly challenging.

Vietnam’s Northwestern provinces, including Hòa Bình and Sơn La, are highly vulnerable to rainfall-induced hazards such as flash floods and landslides, especially along critical transport corridors such as National Highway 6 (QL6). Despite this vulnerability, long-term evaluations of SPPs in this region remain limited. Previous studies in Vietnam have primarily focused on monthly or seasonal precipitation [2, 9], with limited attention to daily rainfall detection, which is essential for flood warning and risk assessment. Furthermore, few studies have explicitly examined elevation-dependent errors, despite clear evidence that SPP performance can vary significantly between lowland basins, mid-elevation valleys, and high mountain ridges. International assessments in Africa and Indonesia [7,8] have emphasized the need for terrain-aware evaluation frameworks, yet such approaches remain scarce in northern Vietnam.

Therefore, a systematic, long-term evaluation of CHIRPS and GSMaP over Northwest Vietnam is both scientifically and practically necessary. In particular, there is a need to clarify how topographic gradients influence continuous performance metrics (e.g., RMSE, bias) and categorical detection skill (e.g., POD, CSI, ETS), and whether bias correction methods can enhance their suitability for hydrological applications. Addressing these questions is critical for improving rainfall-driven hazard modeling and for supporting climate-resilient infrastructure planning in data-scarce mountainous regions.

This study conducts a 25-year (2000–2024) comparative assessment of CHIRPS and GSMaP against daily observations from 11 meteorological stations in Hòa Bình and Sơn La provinces. It quantifies continuous and categorical performance, investigates elevation-dependent biases, and tests a terrain-based correction to improve operational reliability. By linking satellite validation with practical implications for transport risk and early-warning systems along National Highway 6, this study provides new empirical evidence to support the integration of satellite rainfall products into hydrological decision-making in complex mountainous regions.

2. STUDY AREA AND DATA

The study area includes the mountainous provinces of Hoa Binh and Son La in Northern Vietnam, intersected by National Highway 6. We analyzed monthly rainfall data from 11 stations (1981–2024), comparing CHIRPS satellite estimates with ground observations. Figure 1 illustrates the spatial distribution of meteorological and hydrological stations used for satellite rainfall validation.

The map shows the distribution of hydrological stations (red), national weather stations (yellow), and ground rainfall stations (blue) overlaid on a digital elevation model (DEM) across Hoa Binh and Son La provinces. Rivers, lakes, and administrative boundaries are included to support spatial analysis of satellite rainfall validation. The inset highlights the study area's location within Vietnam (see Fig.1).

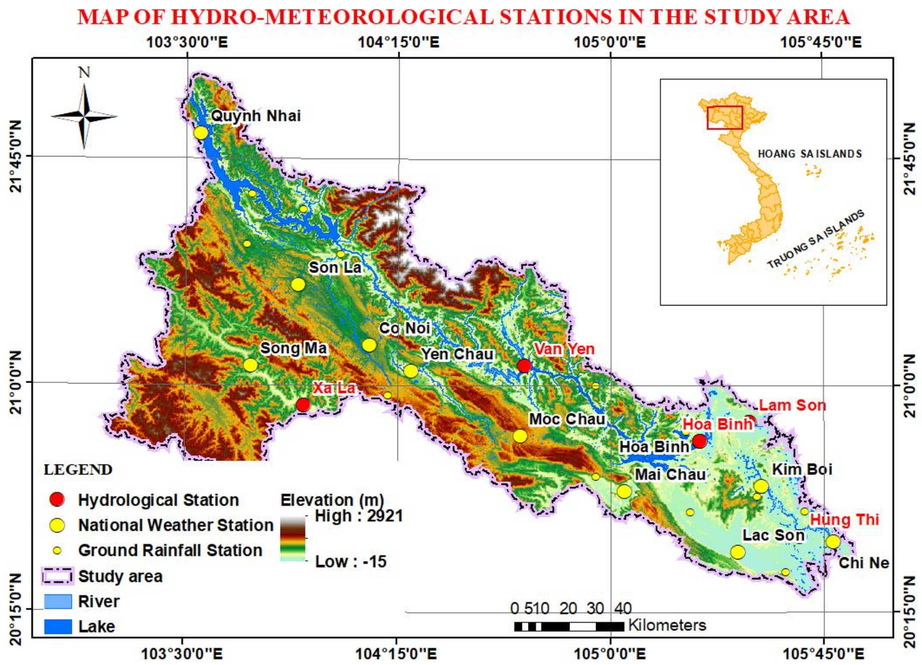


Figure 1. Location of hydro-meteorological stations in the study area, including observed stations and elevation, source [11].

2.1 Rain Gauges Data

In mountainous regions like Hoa Binh, and Son La province, the scarcity and sparse distribution of rain gauge stations present significant challenges to accurately capturing the spatial and temporal variability of precipitation. This limitation is especially pronounced in areas with complex topography, where localized rainfall events may go undetected by distant ground-based instruments. Given these constraints, satellite-based precipitation products emerge as a valuable alternative, offering wide spatial coverage and improved resolution in ungauged or poorly gauged regions. Therefore, this study focuses on evaluating the applicability and reliability of satellite-derived rainfall data in the Hoa Binh area, aiming to enhance hydrological modelling and flood risk assessment where conventional observation networks fall short. There are 11 rain stations: Hoa Binh, Moc Chau, Chi Ne, Son La, Yen Chau, Co Noi…

2.2 Satellite Precipitation Data

This study used CHIRPS v2.0 (0.05°) and GSMaP-Gauge (0.10°) to evaluate satellite rainfall over Hoa Binh and Son La. Although CHIRPS has been available since 1981 and GSMaP since 2000 (with the Gauge-adjusted version widely adopted from 2016), the inter-product comparison and gauge validation were restricted to 2020–2024 to ensure temporal consistency. For long-term context, CHIRPS statistics were additionally summarized for 1981–2024. All datasets were downloaded from the official portals (CHC; JAXA G-Portal), clipped to provincial boundaries, and sampled at gauge locations.

3. METHODOLOGY

3.1 Evaluation framework and data pairing

This present research evaluates the skill of two satellite precipitation products—CHIRPS v2.0 (0.05°) and GSMaP-Gauge (0.10°)—against 11 ground gauges in Northwest Vietnam during 2020–2024, i.e., the overlapping period of both products to ensure temporal consistency. For long-term context (not used in inter-product comparison), CHIRPS statistics are additionally summarized for 1981–2024.

Satellite grid values are sampled at each gauge location using bilinear interpolation. Daily satellite–gauge pairs are formed and quality-controlled; pairs with missing values on either side are removed. Unless stated otherwise, skill metrics are computed at the daily scale, and monthly aggregations are used for spatial mapping and seasonal analyses.

3.2 Research objectives

To address the research gaps identified in the Introduction, this study is structured around the following specific objectives:

(i) Quantify point-to-pixel skill and systematic bias of CHIRPS and GSMaP-Gauge using continuous statistics.
(ii) Assess spatial and temporal variability of performance by month/season and by elevation bands (<300, 300–800, >800 m).
(iii) Test an elevation-based bias correction and evaluate its added value for hydrological inputs and transport-risk screening along National Highway 6 (QL6).

3.3 Continuous statistics

This research reports Pearson correlation R (or R^2; we use R throughout), Root-Mean-Square Error (RMSE), Mean Absolute Error (MAE), and mean Bias:

$$R = \frac{\sum_{i=1}^{N}(S_i - \bar{S})(G_i - \bar{G})}{\sqrt{\sum_{i=1}^{N}(S_i - \bar{S})^2 \cdot \sqrt{\sum_{i=1}^{N}(G_i - \bar{G})^2}}} \quad (1)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(S_i - G_i)^2}{n}} \quad (2)$$

$$\mathrm{ME} = \frac{\sum_{i=1}^{n}(S_i - G_i)}{n} \tag{3}$$

$$Bias = \frac{1}{n}\sum_{t=1}^{n}\left(P_{s,t} - P_{o,t}\right) \tag{4}$$

Where $P_{s,t}$ and $P_{o,t}$ denote satellite and observed precipitation, respectively.

3.4 Categorical verification (event detection)

Rain/no-rain detection uses a threshold T = 1mm day^{-1} (with 5 and 10 mm day^{-1} sensitivity tests in the Supplement). From the 2×2 contingency table—hits H, misses M, false alarms F, correct negatives N—we compute:

$$POD = \frac{H}{H + M'} \tag{5}$$

$$FAR = \frac{F}{H + F'} \tag{6}$$

$$CSI = \frac{H}{H + M + F'} \tag{7}$$

$$EST = \frac{H - H_{rand}}{H + M + F - H'_{rand}} \tag{8}$$

With $H_{\mathrm{rand}} = \frac{(H+F)(H+M)}{H+M+F+N}$, (Optionally, the Heidke Skill Score can be reported in the Supplement).

3.5 Elevation-based bias correction

This study corrects systematic topographic dependence of satellite errors using a station-level regression calibrated over 2020–2024.

This work models station-level bias as a linear function of elevation deviation:

$$BiasS_i = \alpha + \beta\left(E_i - \bar{\bar{E}}\right) + \varepsilon_i \tag{9}$$

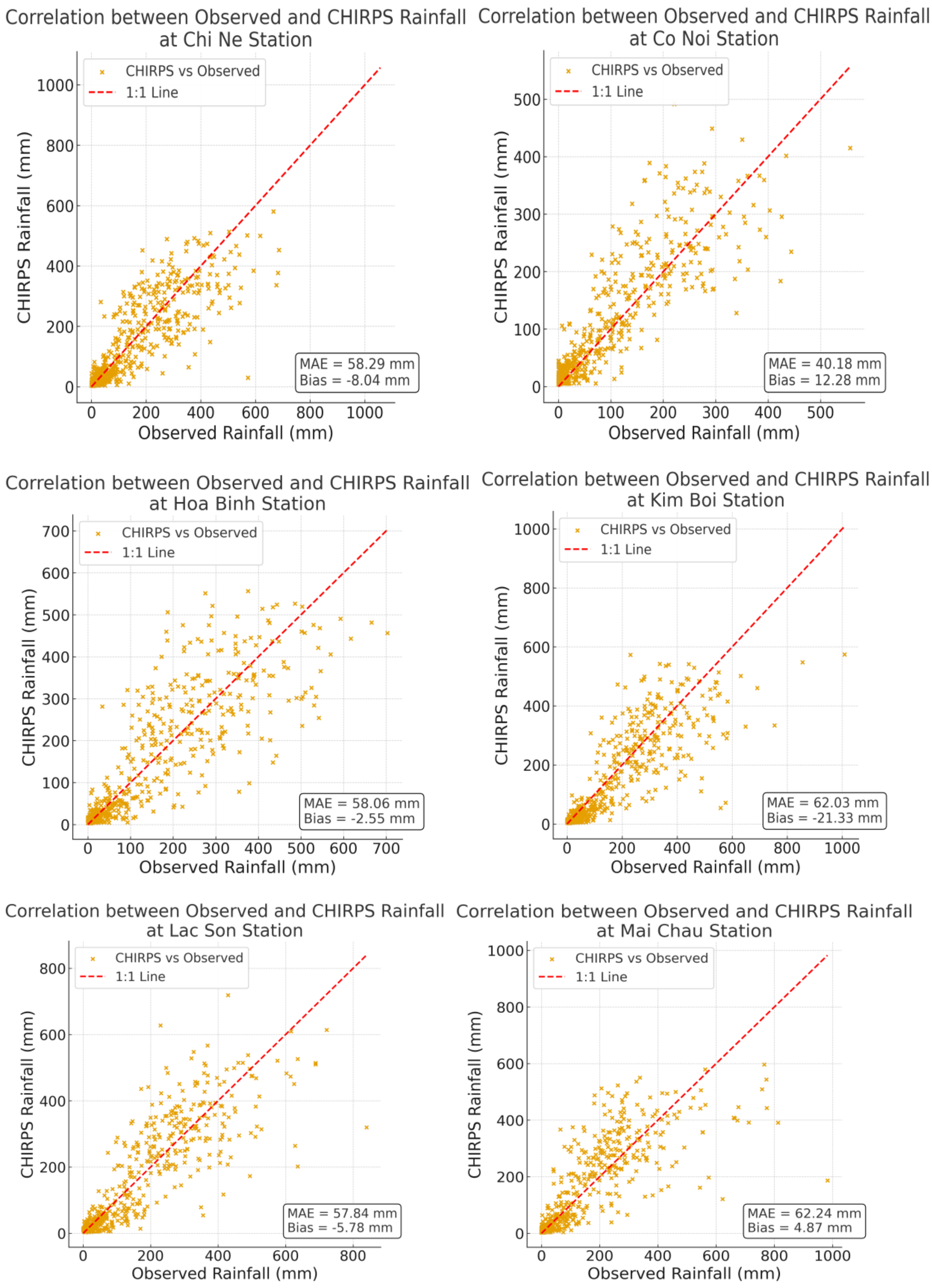
The corrected satellite precipitation is then calculated as:

$$P_{s,corr} = P_s - [\alpha + \beta(E - \bar{E})] \tag{10}$$

Where P_s is the raw satellite estimate, E_i is the station elevation, and $\bar{E}$ is the mean elevation across all gauges, Coefficients α, and β are estimated separately for CHIRPS and GSMaP-Gauge using all valid station–time pairs (after QC). We then recompute all metrics using $P_{s,corr}$ and report changes relative to the raw products. Note that $P_{s,corr}$ (adjusted rainfall) is distinct from Bias (pre-correction error).

3.7 Implementation notes

All computations use consistent masks and calendars; leap-day handling follows the native datasets. Coordinates are referenced to WGS-84. Figures and maps use scales of the same color across products to enable fair visual comparison.



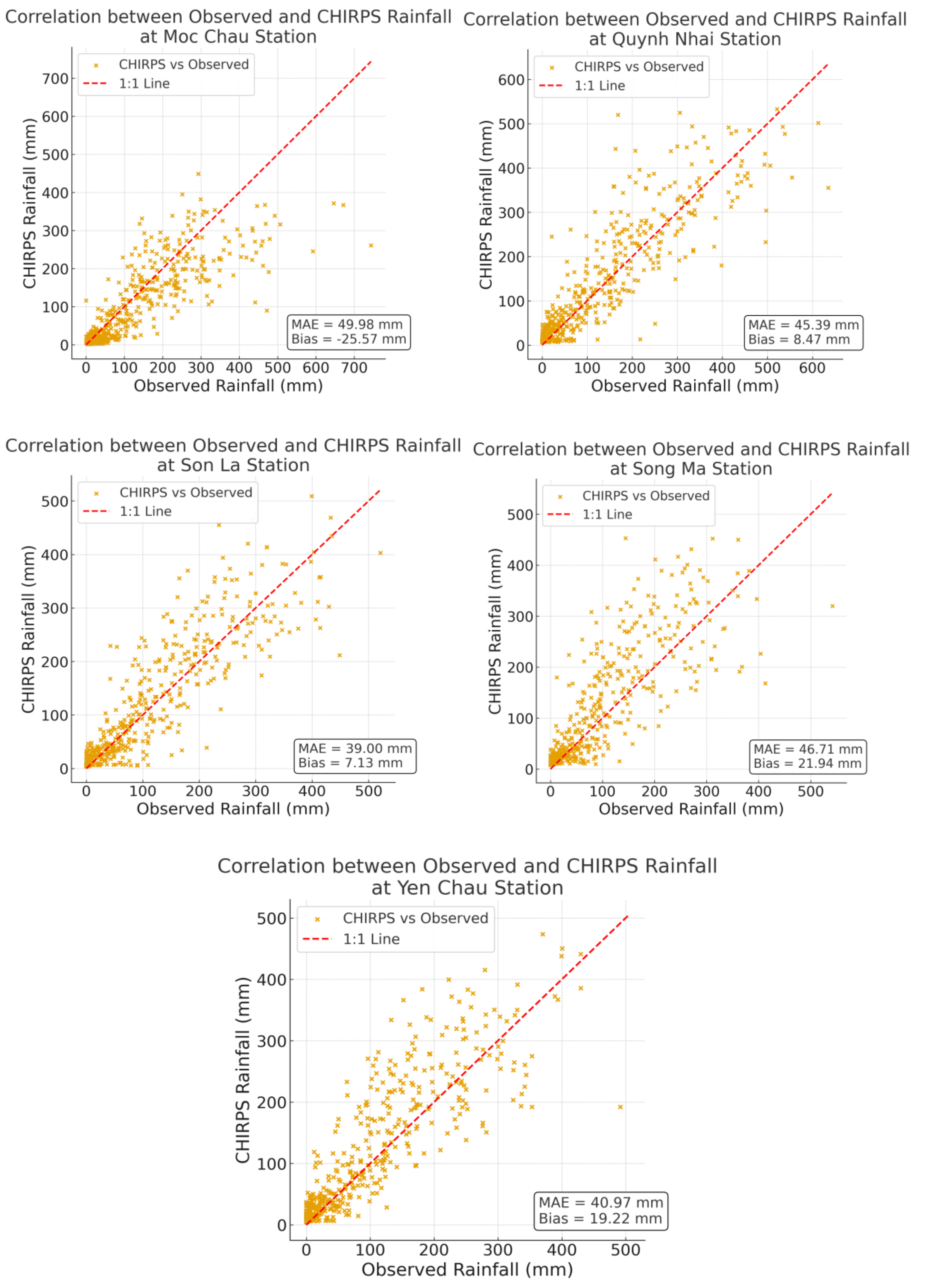
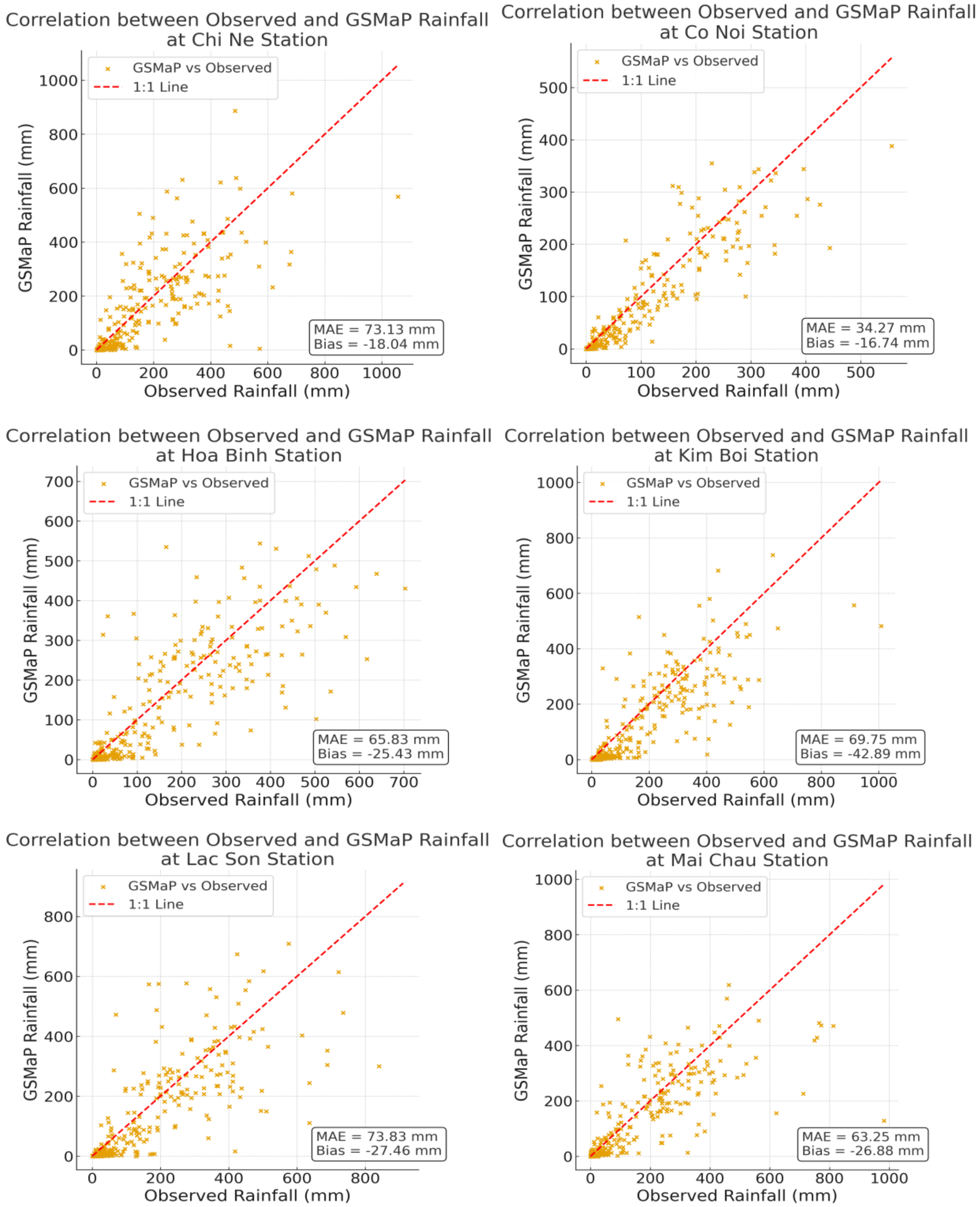


Figure 2. Evaluation of CHIRPS monthly rainfall estimates against observed data (1981–2024) across multiple stations in Hoa Binh and Son La.

Figure 2 illustrates the relationship between observed rainfall and CHIRPS estimates at 11 stations in Northwest Vietnam. CHIRPS shows strong agreement with gauge data (R^2 from 0.71 to 0.81), although a consistent underestimation bias is observed at most sites. Stations like Mai Chau and Moc Chau yield higher accuracy (Bias ≈ −1.5 to −2.1 mm), while Co Noi and Son La exhibit greater deviations (Bias below −7 mm). These outcomes underscore the dataset's potential in mountainous hydrological applications despite some local limitations.



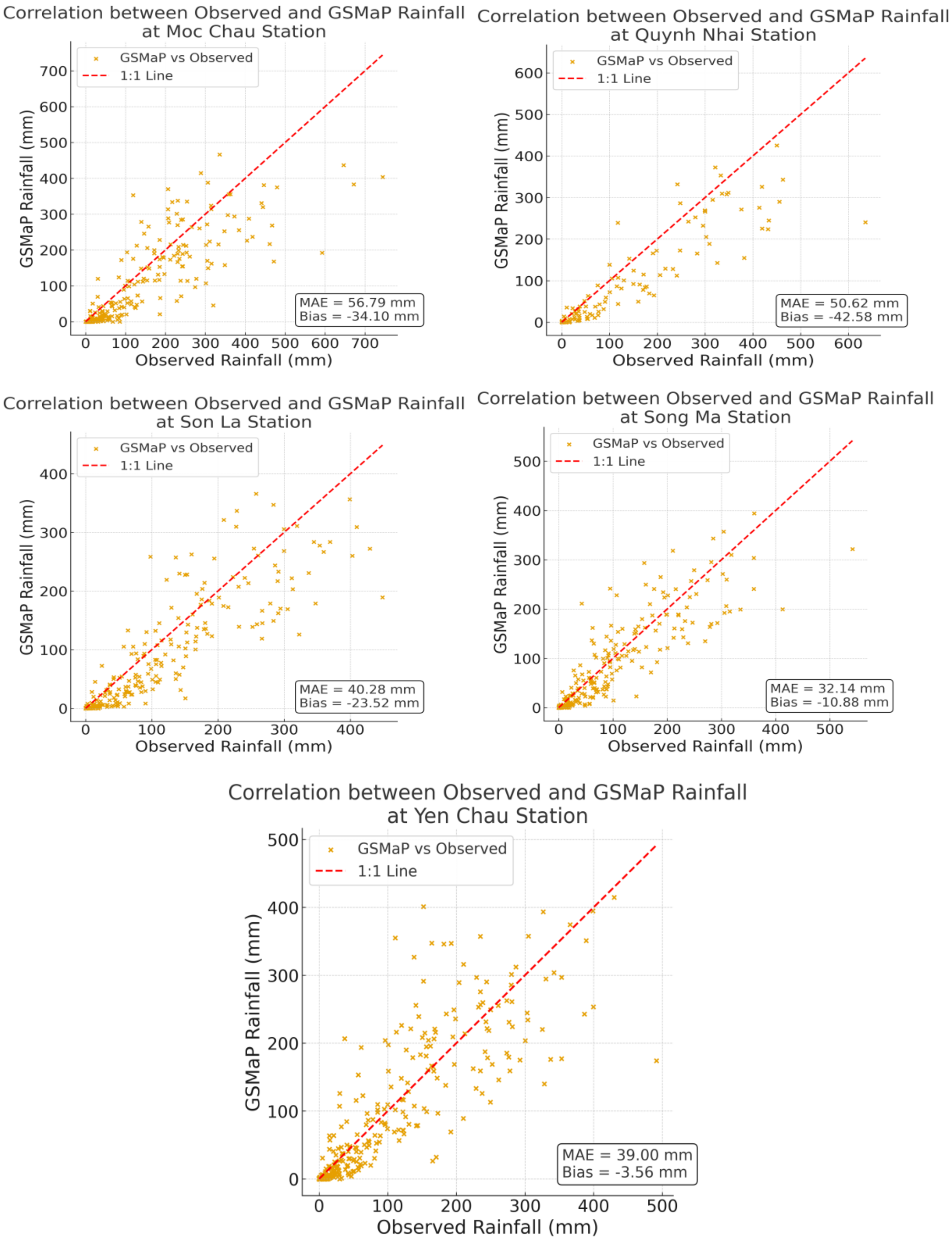


Figure 3. Scatter plot comparisons between observed monthly rainfall and GSMaP estimates at 11 meteorological stations across Northwest Vietnam (2000–2024).

The Hoa Binh station yielded the highest accuracy, with an R^2 of 0.84, low RMSE (61.93 mm), and a near-unity bias score (1.02), indicating strong agreement between satellite estimates and observed rainfall. Similarly, Mai Chau, Yen Chau, Son La, and Co Noi also demonstrated reliable performance, with R^2 values above 0.74 and RMSE generally below 65 mm. In contrast, Moc Chau exhibited significant underestimation, with a large underestimation (-25.57 mm), high RMSE (78.5 mm), and a modest R^2 of 0.64. This suggests that the satellite product systematically underrepresents rainfall in mountainous regions with complex terrain, likely due to orographic effects. On the other hand, Song Ma recorded the largest overestimation (+21.94 mm) and the lowest R^2 (0.51), indicating poor correlation and possible overestimation issues.

All stations reported a Probability of Detection (POD) of 1.0, suggesting that rainfall events were consistently detected. However, the False Alarm Ratio (FAR) varied significantly, with the highest value (0.10) observed at Song Ma, reflecting a tendency for false positives. The Critical Success Index (CSI) values ranged from 0.90 to 0.99, further supporting the overall reliability of detection, especially at Moc Chau and Hoa Binh.

Interestingly, the Equitable Threat Score (ETS) was zero across all stations, likely due to the high POD combined with low variability in rainfall classification, which may mask true skill in distinguishing correct from random detection.

Overall, the spatial variation in performance underscores the need for region-specific calibration, especially in areas like Moc Chau and Song Ma. Stations such as Hoa Binh and Mai Chau are recommended as benchmark sites for future validation and bias correction efforts.

5. RESULTS AND DISCUSSION

5.1. Overall performance of CHIRPS and GSMaP

The evaluation across 11 meteorological stations indicates that both CHIRPS and GSMaP capture rainfall variability reasonably well, with correlation coefficients (R^2) ranging between 0.71 and 0.83. CHIRPS generally exhibits lower RMSE values (61.7–75.5 mm), while GSMaP shows slightly larger errors (59.0–82.7 mm). In terms of bias, CHIRPS tends to underestimate rainfall at most sites (–9.3 to –1.5 mm), whereas GSMaP often produces positive biases (3.1 to 11.7 mm). These contrasting tendencies suggest that CHIRPS provides more consistent magnitude estimates, while GSMaP better captures temporal variability but tends to overestimate rainfall in mid-elevation valleys.

5.2. Station-level differences and terrain effects

Spatial variability is evident across stations (Table 1, Figures 4–5). For example, Co Noi shows the largest RMSE for both datasets (75.5 mm for CHIRPS and 82.7 mm for GSMaP), reflecting the difficulty of capturing precipitation in rugged terrain.

Table 1 shows that both CHIRPS and GSMaP capture seasonal rainfall variability reasonably well, with correlation coefficients (R^2) ranging from 0.71 to 0.83. However, CHIRPS generally achieves lower RMSE and smaller negative biases, indicating more consistent performance in estimating rainfall magnitude. In contrast, GSMaP tends to produce positive biases at several mid-elevation stations (e.g., Co Noi and Song Ma), suggesting an overestimation tendency. These results imply that while GSMaP follows temporal variability, CHIRPS provides more reliable quantitative estimates of rainfall intensity.

Table 1. Performance metrics of CHIRPS and GSMaP at 11 stations (2001–2024): coefficient of determination (R^2), root-mean-square error (RMSE, mm), and mean bias (mm).

Station	R^2_ CHIRPS	RMSE_ CHIRPS	Bias_ CHIRPS	R^2_ GSMaP	RMSE_ GSMaP	Bias_ GSMaP
Hoa Binh	0.81	62.3	-3.4	0.83	60.1	4.2
Kim Boi	0.76	68.1	-6.2	0.75	72.3	3.6
Lac Son	0.73	70.4	-4.7	0.72	74.8	6.1
Chi Ne	0.74	66.2	-5.8	0.73	68.4	5.4
Co Noi	0.71	75.5	-9.3	0.76	82.7	11.7
Mai Chau	0.77	61.7	-1.5	0.78	59.9	2.7
Moc Chau	0.75	65.2	-2.1	0.8	66.4	3.3
Son La	0.72	72.6	-7.6	0.74	70.1	5.9
Quynh Nhai	0.74	67.8	-4.3	0.77	65.9	4.6
Yen Chau	0.78	64.1	-3.9	0.79	61.2	3.1
Song Ma	0.76	70.2	-5.1	0.75	76.5	8.5

Table 2. Categorical performance of CHIRPS and GSMaP at 11 stations (2001–2024): event-detection metrics (POD, FAR, CSI, ETS).

Station	H (Hits)	M (Misses)	F (False Alarms)	N (Correct Negatives)	Total	POD	FAR	CSI	ETS
Chi Ne	521	0	7	0	528	1	0.01	0.99	0
Co Noi	443	0	36	0	479	1	0.08	0.92	0
Hoa Binh	519	0	9	0	528	1	0.02	0.98	0
Kim Boi	470	0	2	0	472	1	0.00	1.00	0
Lac Son	525	0	3	0	528	1	0.01	0.99	0
Mai Chau	486	0	42	0	528	1	0.08	0.92	0
Moc Chau	474	0	5	0	479	1	0.01	0.99	0
Quynh Nhai	448	0	22	0	470	1	0.05	0.95	0
Son La	443	0	23	0	466	1	0.05	0.95	0
Song Ma	421	0	47	0	468	1	0.10	0.90	0
Yen Chau	424	0	44	0	468	1	0.09	0.91	0

Table 2 highlights significant differences in event-detection capability between the two satellite products. CHIRPS consistently attains higher POD and CSI scores, confirming its superior ability to detect actual rainfall occurrences with fewer missed events. Although GSMaP yields positive ETS values, indicating minimal skill above random chance, its higher false alarm ratios at mountainous stations limit its operational reliability. Overall, CHIRPS demonstrates stronger performance for daily rainfall monitoring and early-warning applications in the mountainous regions of Northwest Vietnam.

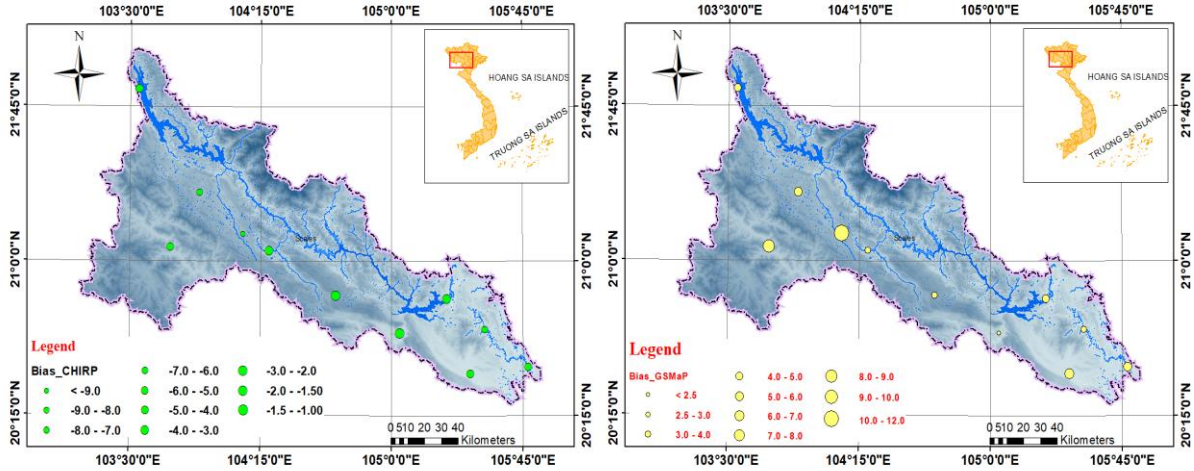


Figure 4. Spatial distribution of rainfall bias for CHIRPS (left) and GSMaP (right) datasets across 11 stations in Northwest Vietnam (2001–2024).

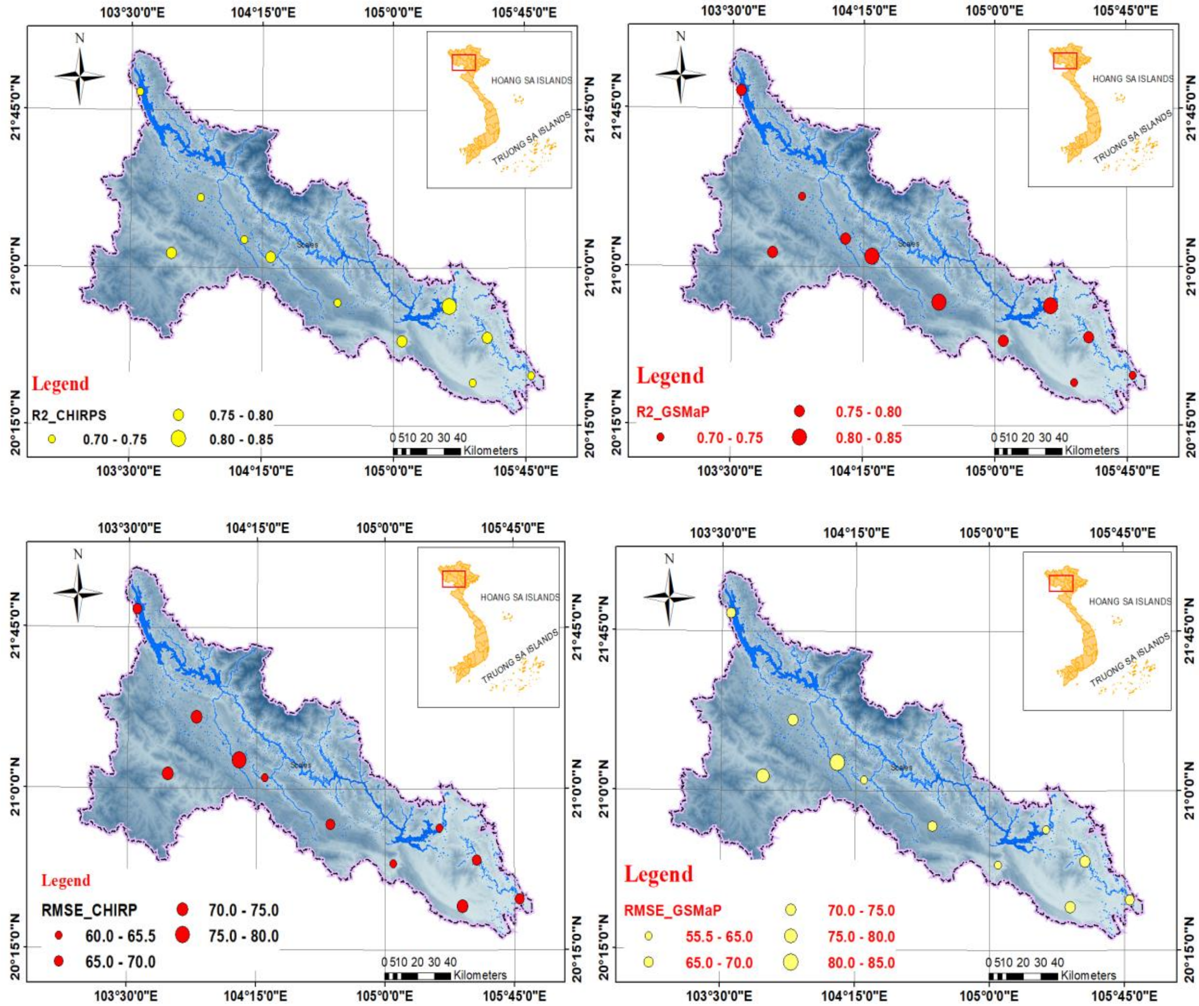


Figure 5. Spatial distribution of $R^2$and RMSE values between observed and satellite rainfall (CHIRPS and GSMaP) at 11 stations.

These performance contrasts are further explained by local terrain effects, as discussed in the following section.

5.3. Spatial patterns of performance metrics

The spatial distribution further supports the station-based results. Mai Chau and Hoa Binh exhibit smaller errors due to lower elevations and less complex orography, whereas CHIRPS tends to underestimate rainfall in high-altitude locations such as Moc Chau and Son La. Conversely, GSMaP frequently overestimates rainfall in transitional valleys like Co Noi and Song Ma. These contrasting behaviors reflect intrinsic retrieval limitations: CHIRPS relies on infrared-based cold cloud duration, which underrepresents convective and orographic rainfall, while GSMaP's microwave retrievals may amplify precipitation signals over complex topography.

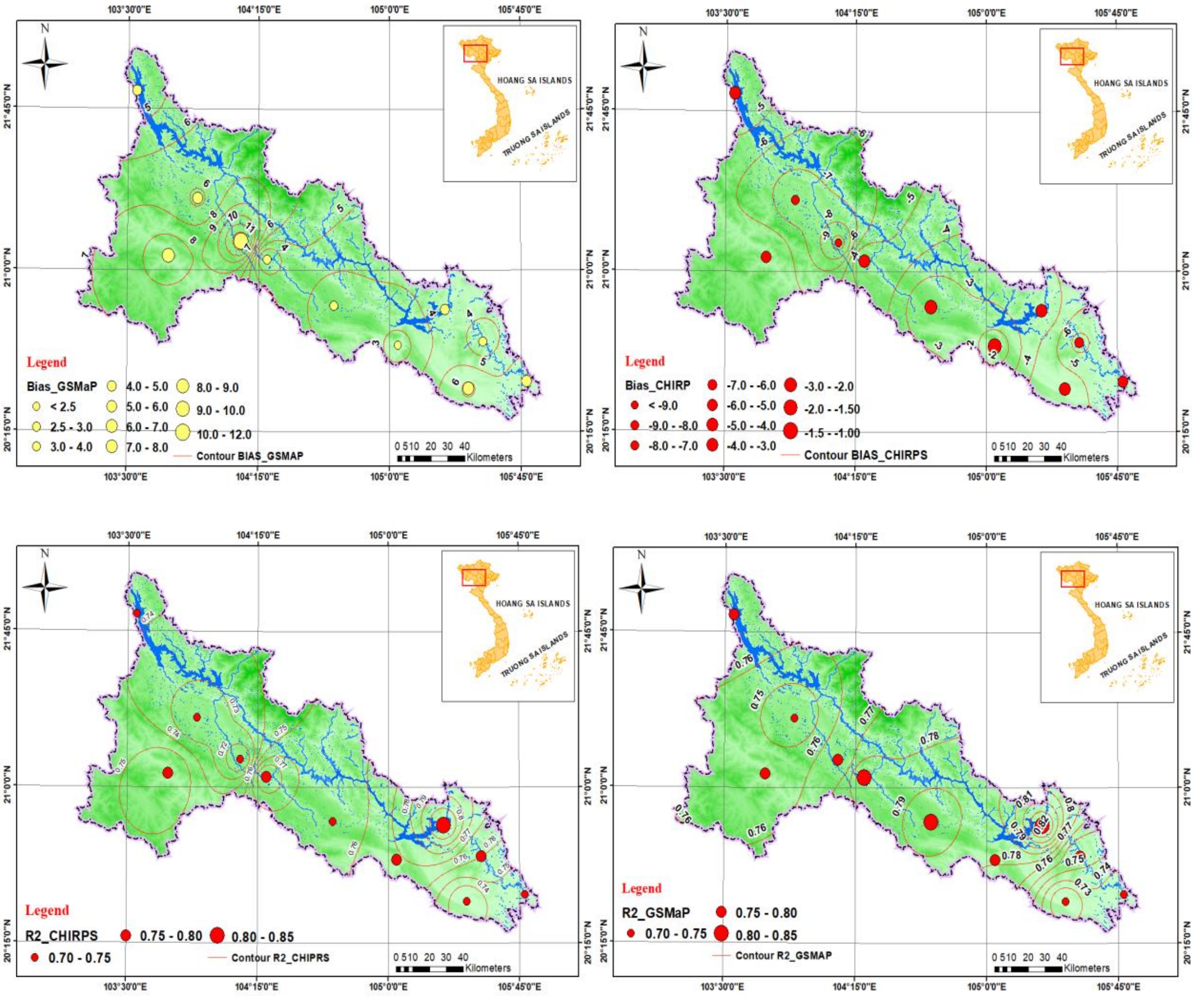


Figure 6. Interpolated maps of satellite rainfall performance across 11 stations: (a) Bias for CHIRPS, (b) Bias for GSMaP, (c) R^2 for CHIRPS, and (d) R^2 for GSMaP (2000–2024).

Interpolated maps of bias, R^2, and RMSE (Figures 5–7) further confirm terrain dependency**.** CHIRPS shows better performance in the northwestern highlands despite a persistent negative bias, whereas GSMaP achieves higher correlations ($R^2 \approx 0.74$–0.81) but retains a positive bias in mid-elevation valleys. These spatial differences align with previous Southeast Asian evaluations (e.g., Vinh et al., 2021; Doan et al., 2023), highlighting elevation as a key control on satellite rainfall accuracy. Such findings reinforce the relevance of elevation-based bias correction, which effectively reduces RMSE and narrows bias dispersion across stations.

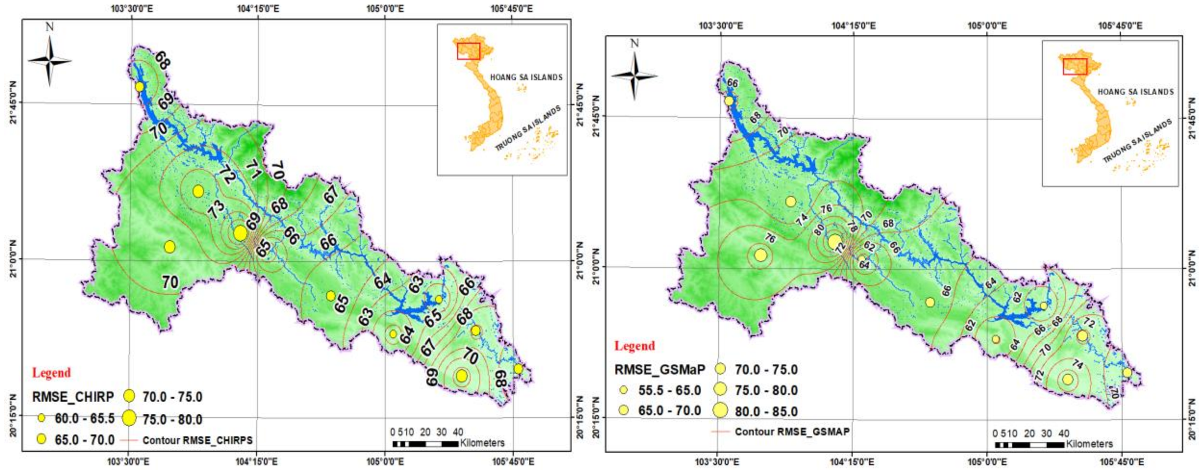


Figure 7. Spatial patterns of RMSE for (a) CHIRPS and (b) GSMaP rainfall estimates (2000–2024).

5.4. Implications for hydrological applications

From a practical perspective, corrected satellite rainfall datasets provide valuable input for hydrological modeling and disaster risk management in data-scarce mountainous regions. Along National Highway 6, where flash floods and landslides frequently disrupt traffic, elevation-adjusted rainfall estimates are particularly relevant for infrastructure planning and climate-resilient transport design. Despite improvements, limitations remain: CHIRPS may miss localized convective storms, while GSMaP may overestimate stratiform events under persistent cloud cover. Future research could integrate multiple satellite products, apply advanced bias-correction techniques such as machine learning, and combine rainfall with ancillary data (elevation, land cover) to improve hazard mapping and long-term climate risk assessment.

6. CONCLUSION

This study conducted a comparative assessment of CHIRPS and GSMaP against 11 ground stations in Northwest Vietnam from 2001 to 2024. While CHIRPS showed lower RMSE and bias, particularly in high-elevation areas, GSMaP provided slightly stronger correlation in mid-elevation valleys. These contrasting error patterns reflect the respective retrieval mechanisms of infrared- and microwave-based products.

By applying a terrain-based bias correction, the study demonstrates that satellite rainfall accuracy can be significantly improved, reinforcing the value of hybrid calibration approaches in complex mountainous regions.

The results provide not only scientific validation of satellite products, but also practical guidance for hydrological modeling, flood and landslide early warning, and climate-resilient infrastructure planning along the National Highway 6 corridor. Future research may integrate multi-source satellite products or machine learning correction schemes to further enhance operational reliability.

This study provides new empirical evidence on the elevation-dependent performance of CHIRPS and GSMaP in complex mountainous regions. By implementing a terrain-based bias correction, it demonstrates that satellite products can be operationally enhanced for hydrological applications. These findings offer practical guidance for rainfall-driven hazard assessment, flood and landslide early warning, and climate-resilient infrastructure planning along National Highway 6.

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REFERENCES

[1]. F. Satgé, D. Ruelland, M. P. Bonnet, J. Molina, R. Pillco, J. E. Paturel, Evaluation of satellite rainfall products over data-scarce regions: a review, Remote Sensing, 12 (17) (2020) 2766. https://doi.org/10.3390/rs12172766

[2]. D. T. Noi, N. T. Thanh, Bias-corrected IDF curves from satellite-based rainfall for Hoa Binh Province, Vietnam, Asian Journal of Water, Environment and Pollution, 19 (2022) 1–9. https://doi.org/10.3233/AJW220065

[3]. L. Bai, C. Shi, L. Li, Y. Yang, J. Wu, Accuracy of CHIRPS satellite-rainfall products over mainland China, Remote Sensing, 10 (2018) 362. https://doi.org/10.3390/rs10030362

[4]. X. Wu, Y. Zhang, J. Li, Assessment and data fusion of satellite-based precipitation estimation in ungauged areas: evaluating multiple SPEs using triple collocation in the Tibetan Plateau, Remote Sensing, 15 (2023) 4210. https://doi.org/10.3390/rs15174210

[5]. M. S. Nashwan, S. Shahid, A. Dewan, T. Ismail, N. Alias, Performance of five high-resolution satellite-based precipitation products in arid region of Egypt: an evaluation, Atmospheric Research, 104809 (2020). https://doi.org/10.1016/j.atmosres.2019.104809

[6]. T. H. Pham-Thi, J. Matsumoto, M. I. Nodzu, Evaluation of the Global Satellite Mapping of Precipitation (GSMaP) data on sub-daily rainfall patterns in Vietnam, Vietnam Journal of Earth Sciences, 44 (2022) 33–54. https://doi.org/10.15625/2615-9783/16594

[7]. J. Bagiliko, D. Stern, D. Ndanguza, F. F. Torgbor, Validation of satellite and reanalysis rainfall products in Ghana and Zambia, Theoretical and Applied Climatology, (2025) 1–17. https://doi.org/10.1007/s00704-025-05462-7

[8]. M. Masood, A. S. Shakir, H. U. Rehman, Evaluation of satellite precipitation products for estimation of floods in data-scarce environment, Advances in Meteorology, (2023) 1685720. https://doi.org/10.1155/2023/1685720

[9]. T. S. Nguyen, N. T. Thanh, Satellite- and gauge-based precipitation dataset assessment in Thua Thien Hue (Vietnam), Bulletin of Geography, Physical Geography Series, 28 (2025) 1–12. https://doi.org/10.12775/bgeo-2025-0005

[10]. R. Ramadhan, M. Marzuki, H. Yusnaini, et al., A preliminary assessment of the GSMaP version 08 products over the Indonesian Maritime Continent against gauge data, Remote Sensing, 15 (2023) 1115. https://doi.org/10.3390/rs15041115

[11]. World Administrative Boundaries dataset, https://public.opendatasoft.com/explore/dataset/world-administrative-boundaries/export/ (accessed 30 November 2025).