

Article

Long-Term Evaluation of Satellite Precipitation Products for Extreme Rainfall and Water-Related Hazard Assessment Along a Mountainous Corridor in Northern Vietnam

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Abstract

Accurate rainfall information is essential for water-related hazard assessment in mountainous regions, where complex terrain and sparse gauge networks limit monitoring reliability. This study evaluated long-term rainfall characteristics and the performance of three satellite precipitation products—CHIRPS, GPM IMERG, and GSMaP—along the National Highway 6 corridor in northern Vietnam. Daily gauge observations from 11 meteorological stations with station-dependent records between 1961 and 2024 were used to characterize rainfall variability and heavy-rainfall frequency. Matched gauge–satellite records from 2001 to 2024 were evaluated using continuous statistical indicators, contingency-table metrics, empirical cumulative distribution functions, and percentile-based analysis. Data from 2025 were additionally examined as an extreme-rainfall case study, supplemented by visual gauge–satellite comparisons; however, these data were not used as an independent satellite-validation period. The long-term gauge records showed marked spatial variability in rainfall magnitude and threshold-exceedance frequency. In 2025, all 11 stations recorded daily rainfall exceeding 50 mm, while eight stations recorded events exceeding 100 mm. Satellite-product performance varied substantially among stations, rainfall thresholds, and evaluation metrics, and no product was uniformly superior. At the 100 mm/day threshold, the probability of detection ranged from 0.024 to 0.276, whereas the false alarm ratio ranged from 0.781 to 0.916. Upper-tail analysis showed contrasting product-specific behavior: at the 99th percentile, CHIRPS and GPM IMERG underestimated gauge rainfall by 20.95 and 8.95 mm, respectively, whereas GSMaP overestimated it by 35.57 mm. These findings demonstrate that local validation, uncertainty assessment, and application-specific adjustment are necessary before satellite precipitation products are used for flash-flood, rainfall-induced landslide, drainage-risk, and transportation-infrastructure assessments in mountainous regions.



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Keywords: satellite precipitation; extreme rainfall; upper-tail uncertainty; mountainous transportation corridor; Northern Vietnam

1. Introduction

Accurate precipitation information is fundamental for hydrological analysis, climate-risk assessment, water-resource planning, and disaster-risk management. However, the

spatial distribution of rain-gauge networks remains highly uneven, particularly in mountainous and data-scarce regions, where rainfall variability is strongly controlled by local topography and atmospheric circulation. In such regions, satellite precipitation products provide an important alternative source of spatially continuous rainfall information, supporting applications where ground observations are sparse or incomplete [1–3]. Over the past two decades, several global and quasi-global precipitation datasets have been widely used in hydrological and environmental studies, including CHIRPS, GPM IMERG, and GSMaP, all of which provide rainfall estimates at relatively high spatial and temporal resolutions [4–8].

Despite substantial improvements in satellite-based precipitation retrieval, the accuracy of satellite rainfall products remains uncertain under complex terrain and extreme rainfall conditions. Mountainous regions pose particular challenges because precipitation is influenced by orographic lifting, localized convective systems, strong spatial gradients, and rapid changes in rainfall intensity over short distances. These factors may reduce the ability of satellite sensors and retrieval algorithms to accurately capture both rainfall occurrence and magnitude. Previous studies have shown that satellite precipitation products often perform reasonably well for light to moderate rainfall but may exhibit larger errors and systematic biases during heavy rainfall and extreme events [9–12]. This limitation is especially important because extreme precipitation events are expected to intensify in a warming climate, with increasing implications for floods, landslides, and infrastructure disruption [13–16].

In tropical and monsoon-dominated regions, the evaluation of satellite rainfall products is particularly important because high-intensity rainfall events often occur during short periods and may be strongly affected by seasonal circulation and terrain-induced enhancement. In Vietnam, previous studies have assessed the applicability of satellite-derived precipitation products for hydrological modeling and rainfall estimation at basin and regional scales [17]. Le et al. [18] examined the adequacy of satellite-derived precipitation estimates for hydrological modeling in Vietnamese basins, while Tran et al. [19] evaluated the robustness of gridded precipitation products across Vietnam using a comprehensive rainfall-assessment framework. For northern Vietnam, Nguyen and Do [20] assessed the accuracy of GPM IMERG rainfall products, and Nguyen [21] also investigated GPM products over North Vietnam. More recently, Nguyen et al. [22] analyzed meteorological trends and variabilities in major river basins of northern Vietnam using global datasets. These studies provide important evidence on the potential and limitations of gridded and satellite rainfall products in Vietnam; however, further assessment is still needed for mountainous transportation corridors, where extreme rainfall directly affects slope stability, flash-flood generation, and road safety.

Northern Vietnam is characterized by complex mountainous terrain, steep slopes, and strong seasonal rainfall variability. National Highway 6, which crosses Hoa Binh and Son La provinces, is one of the most important transportation corridors in the northwestern mountainous region. This corridor is frequently exposed to rainfall-induced hazards, including landslides, slope failures, flash floods, and road disruption. Heavy rainfall is widely recognized as a major triggering factor for landslides and slope instability, particularly where steep terrain and vulnerable geological conditions coincide [23,24]. In addition, satellite precipitation products have been increasingly explored for detecting extreme rainfall events and supporting disaster-risk applications, but their reliability remains highly dependent on local terrain and rainfall characteristics [25,26]. Therefore, evaluating the performance of satellite rainfall products under heavy-rainfall conditions along mountainous transportation corridors is essential for improving water-related hazard assessment and infrastructure-resilience planning.

Although previous studies have provided valuable evidence on the performance of satellite precipitation products in Vietnam and other monsoon-dominated regions, several important gaps remain for water-related hazard assessment in mountainous transportation corridors. First, many satellite rainfall evaluations have focused on basin-scale hydrological applications or regional precipitation assessment, whereas fewer studies have explicitly examined how satellite rainfall uncertainty may affect hazard interpretation along linear infrastructure systems in complex terrain. Second, the performance of satellite precipitation products under heavy-rainfall thresholds relevant to flash floods, rainfall-induced landslides, drainage overload, and slope instability remains insufficiently quantified for the National Highway 6 corridor in northern Vietnam. Third, long-term rain-gauge observations are rarely combined with long-term gauge–satellite comparisons to provide both climatological context and application-oriented insight into the reliability of satellite rainfall estimates for early warning and infrastructure-resilience planning.

These gaps are important because heavy rainfall is a primary hydrological trigger of water-related hazards in mountainous regions. In steep terrain, intense rainfall can generate rapid surface runoff, increase pore-water pressure in slopes, overload drainage systems, and accelerate localized erosion, thereby increasing the likelihood of flash floods, landslides, slope failures, and transport disruption. If satellite precipitation products underestimate heavy rainfall or fail to reproduce upper-tail rainfall behavior, rainfall-threshold-based warning systems and hazard assessments may underestimate risk levels and delay emergency responses. Therefore, local validation of satellite rainfall products under heavy-rainfall conditions is essential before these products are applied to water-related hazard monitoring and risk management in mountainous corridors.

Most existing evaluations of satellite precipitation products have been conducted at basin, regional, or national scales. Such large-scale assessments are valuable for understanding general product performance, but they may not fully represent the requirements of hazard assessment along linear infrastructure corridors, where rainfall-related impacts are spatially localized and directly linked to vulnerable road sections, drainage systems, slopes, and river crossings. A corridor-based evaluation is therefore useful for examining how satellite rainfall uncertainty may affect practical water-related hazard applications along mountainous transportation routes. In this study, the National Highway 6 corridor is used as a representative mountainous transportation corridor to investigate the strengths and limitations of satellite precipitation products for rainfall monitoring, heavy-rainfall characterization, and hazard-informed infrastructure planning.

This study aims to evaluate long-term extreme rainfall characteristics and satellite precipitation uncertainty for water-related hazard assessment along the National Highway 6 mountainous transportation corridor in northern Vietnam. The specific objectives are to (i) characterize long-term rainfall variability and extreme-rainfall frequency using daily observations from 11 meteorological stations along and around the corridor; (ii) assess the performance of CHIRPS, GPM IMERG, and GSMaP against gauge observations under all-day, rainy-day, heavy-rainfall, and extreme-rainfall conditions; (iii) examine upper-tail rainfall uncertainty using empirical CDF comparison, percentile-based differences, and correction factors; and (iv) discuss the implications of satellite rainfall uncertainty for flash-flood monitoring, rainfall-induced landslide warning, drainage-risk assessment, early warning, and infrastructure-resilience planning in mountainous regions. By integrating long-term gauge-based rainfall characterization with long-term gauge–satellite evaluation during 2001–2024, this study provides a practical basis for improving the use of satellite precipitation products in water-related hazard assessment and risk-informed infrastructure planning in complex terrain environments.

2. Materials and Methods

2.1. Study Area and Gauge Rainfall Data

This study focuses on the mountainous corridor along National Highway 6 in northern Vietnam, covering Hoa Binh and Son La provinces. The region is characterized by complex terrain, steep slopes, strong orographic effects, and pronounced seasonal rainfall variability. These physical conditions make the corridor highly susceptible to water-related hazards, including flash floods, rainfall-induced landslides, slope failures, drainage overload, erosion, and road disruption.

Daily gauge rainfall observations were collected from 11 meteorological stations distributed along and around the corridor, including Hoa Binh, Kim Boi, Lac Son, Mai Chau, Chi Ne, Yen Chau, Moc Chau, Son La, Song Ma, Co Noi, and Quynh Nhai. The gauge rainfall dataset includes station-dependent long-term records from 1961 to 2024, as well as an additional 2025 gauge-based case-study year. Because the starting years differ among stations, the long-term gauge dataset was used primarily to characterize rainfall climatology, spatial rainfall variability, and the frequency of heavy and extreme rainfall events at each station. The locations of the 11 meteorological stations and the National Highway 6 corridor are shown in Figure 1.

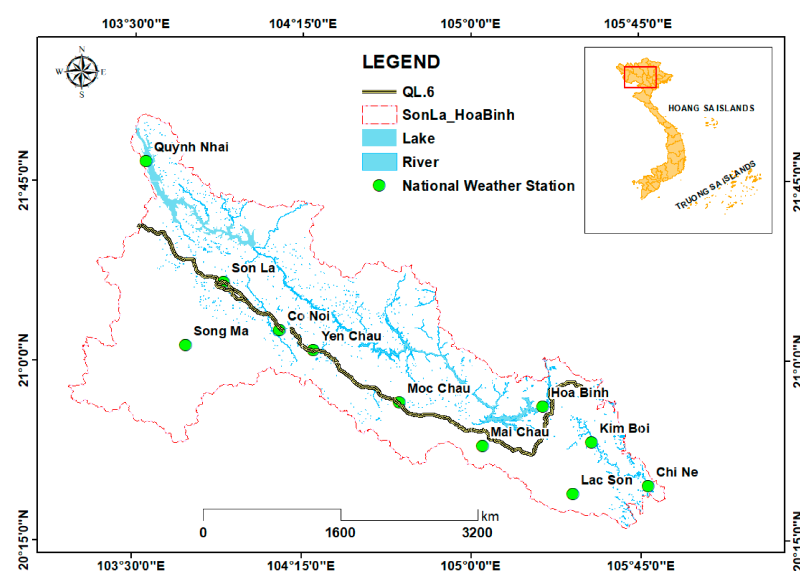


Figure 1. Location of the study area and meteorological stations along National Highway 6 in northern Vietnam.

The long-term gauge rainfall analysis provides a climatological background for identifying rainfall-prone areas along the mountainous corridor. This information is important for water-related hazard assessment because areas with frequent heavy rainfall may experience higher exposure to flash floods, rainfall-induced landslides, slope instability, and drainage-related infrastructure problems.

2.2. Satellite Precipitation Products

Three satellite precipitation products were selected for long-term evaluation: CHIRPS, GPM IMERG, and GSMaP. These products were chosen because they are widely used in hydrological, climatological, and disaster-risk studies and provide spatially continuous rainfall information that can support rainfall assessment in regions where ground-based observations are sparse or unevenly distributed.

CHIRPS is a quasi-global precipitation dataset that combines satellite infrared observations, climatological information, and station data. Its relatively long temporal coverage

and station-blended structure make it useful for rainfall monitoring and retrospective rainfall assessment in data-scarce regions.

GPM IMERG is a global precipitation product developed under the Global Precipitation Measurement mission. It integrates multiple satellite-based precipitation estimates and provides rainfall information at fine spatial and temporal resolutions. The gauge-adjusted final product is particularly useful for retrospective evaluation and hydrological applications.

GSMaP, developed by the Japan Aerospace Exploration Agency, provides global precipitation estimates based on passive microwave and infrared observations. It has been widely used for rainfall monitoring in Asia and other monsoon-dominated regions. However, its performance may vary depending on the rainfall regime, terrain complexity, and local gauge-adjustment conditions.

For the satellite–gauge evaluation, daily satellite precipitation estimates from CHIRPS, GPM IMERG, and GSMaP were extracted at the locations of the 11 meteorological stations. The evaluation used available matched daily records within the 2001–2024 period. Most stations covered 2001–2024, whereas Quynh Nhai covered 2005–2024. Records with missing gauge or satellite values were excluded on a pairwise basis.

2.3. Data Preprocessing and Gauge–Satellite Matching

All datasets were processed on a daily time scale. Gauge rainfall observations were used as the reference data for evaluating satellite precipitation products. For each station, satellite rainfall values were matched with the corresponding daily gauge rainfall observations to establish paired gauge–satellite datasets.

Before analysis, missing and non-numeric rainfall values were checked. Valid zero-rainfall records were retained, while records with missing gauge or satellite values were excluded from the paired comparison. This ensured that all statistical indicators were calculated using matched daily observations.

The matched dataset contains daily rainfall records for 11 stations over the 2001–2024 evaluation period. For each station and each satellite product, paired daily rainfall values were used to evaluate the ability of satellite products to reproduce observed rainfall variability, rainfall magnitude, and heavy-rainfall behavior in complex mountainous terrain.

2.4. Rainfall-Threshold Classification for Water-Related Hazard Assessment

Rainfall events were classified using threshold-based categories relevant to water-related hazard assessment in mountainous regions. Four rainfall conditions were considered: all days, rainy days, heavy-rainfall days, and extreme-rainfall days. Rainy days were defined as days with gauge-observed rainfall greater than 1 mm/day. The 1 mm/day threshold was selected to exclude trace precipitation and potential measurement or retrieval noise while retaining light-rainfall events for satellite-product evaluation. Heavy and extreme rainfall conditions were evaluated using daily rainfall thresholds of 25, 50, and 100 mm/day. These fixed thresholds were used as comparative screening levels and should not be interpreted as universal triggering thresholds for floods or rainfall-induced landslides.

These thresholds were selected to represent rainfall conditions that may contribute to water-related hazards along the mountainous corridor. In steep terrain, intense rainfall can generate rapid surface runoff, increase infiltration into slope materials, raise pore-water pressure, reduce slope stability, overload drainage systems, and accelerate erosion. These processes can contribute to flash floods, rainfall-induced landslides, slope failures, debris movement, and infrastructure disruption.

For the long-term gauge dataset, the number of days exceeding 25, 50, and 100 mm/day was calculated at each meteorological station to identify spatial differences in heavy and extreme rainfall frequency. For the gauge–satellite matched dataset, the same thresholds were

applied to the observed rainfall data to evaluate satellite product performance under different rainfall-intensity conditions.

2.5. Statistical Performance Metrics

The performance of CHIRPS, GPM IMERG, and GSMaP was evaluated by comparing satellite-derived rainfall estimates with gauge observations at the 11 stations. Four statistical indicators were used: coefficient of determination, root mean square error, mean absolute error, and bias.

The coefficient of determination, R^2 , was used to measure the degree of agreement between daily satellite rainfall estimates and gauge observations. Higher R^2 values indicate a better reproduction of observed rainfall variability.

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

The root mean square error, RMSE, was used to quantify the overall magnitude of rainfall error. Because RMSE gives greater weight to large errors, it is particularly useful for evaluating satellite rainfall performance under heavy-rainfall conditions.

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

The mean absolute error, MAE, was calculated as a complementary measure of average error magnitude. Compared with RMSE, MAE is less sensitive to extreme outliers and provides an additional indication of overall error.

$$MAE = \frac{1}{n} \sum_{i=1}^n |S_i - G_i| \quad (3)$$

Bias was used to assess the systematic tendency of satellite products to overestimate or underestimate observed rainfall. A positive bias indicates overestimation, whereas a negative bias indicates underestimation.

$$Bias = \frac{1}{n} \sum_{i=1}^n (S_i - G_i) \quad (4)$$

These metrics were calculated for all days, rainy days, and rainfall events exceeding 25, 50, and 100 mm/day. This multi-threshold evaluation was adopted because satellite precipitation products may perform differently under general rainfall and heavy-rainfall conditions. Such a distinction is important for water-related hazard applications because hazardous processes in mountainous regions are often triggered by high-intensity rainfall events rather than by average rainfall conditions.

2.6. CDF and Percentile-Based Assessment of Upper-Tail Rainfall Uncertainty

In addition to conventional statistical metrics, empirical cumulative distribution function and percentile-based analyses were conducted to evaluate the ability of satellite precipitation products to reproduce the distribution of observed daily rainfall. For each product, paired daily gauge–satellite rainfall values from the 2001–2024 dataset were pooled across the 11 meteorological stations and sorted in ascending order to construct empirical cumulative distribution functions.

The CDF comparison was used to examine whether CHIRPS, GPM IMERG, and GSMaP systematically overestimate or underestimate observed rainfall across different

rainfall-intensity ranges. Particular attention was given to the upper tail of the rainfall distribution because high-percentile rainfall events are more relevant to flash floods, rainfall-induced landslides, drainage overload, and slope instability.

Percentile differences were calculated at selected percentiles: the 50th, 75th, 90th, 95th, and 99th percentiles. The percentile difference was defined as:

$$PD_p = S_p - G_p \quad (5)$$

where S_p and G_p denote the satellite-derived rainfall and gauge-observed rainfall at percentile p , respectively. Negative percentile differences indicate underestimation by the satellite product, while positive values indicate overestimation.

To provide a practical adjustment indicator for high-rainfall conditions, an empirical correction factor was calculated at the 95th percentile:

$$CF_p = \frac{G_p}{S_p} \quad (6)$$

where CF_{95} is the empirical correction factor at the 95th percentile. A value greater than 1 indicates that the satellite product underestimates high-percentile rainfall and may require upward adjustment before being applied to rainfall-threshold-based hazard assessment. A value less than 1 indicates overestimation at the 95th percentile.

To further evaluate the capability of satellite precipitation products to detect heavy rainfall events, five categorical verification metrics, namely the probability of detection (POD), false alarm ratio (FAR), critical success index (CSI), equitable threat score (ETS), and Heidke skill score (HSS), were calculated from contingency tables at rainfall thresholds of 25, 50, and 100 mm day⁻¹.

$$POD = \frac{H}{H + M} \quad (7)$$

$$FAR = \frac{F}{H + F} \quad (8)$$

$$CSI = \frac{H}{H + M + F} \quad (9)$$

$$ETS = \frac{H - H_r}{H + M + F - H_r} \quad (10)$$

$$H_r = \frac{(H + M)(H + F)}{N}$$

$$HSS = \frac{2(H \times CN - M \times F)}{(H + M)(M + CN) + (H + F)(F + CN)} \quad (11)$$

where H = Hit; M = Miss; F = False alarm; CN = Correct negative; N = Total number of paired observations.

Higher POD , CSI , ETS , and HSS indicate better detection performance, whereas a lower FAR indicates fewer false alarms.

2.7. Methodological Framework

The methodological framework integrates long-term gauge-based rainfall characterization with long-term satellite precipitation evaluation. First, daily gauge rainfall observations from 11 meteorological stations were used to analyze spatial rainfall variability and the frequency of heavy and extreme rainfall events along the mountainous corridor. Second, daily satellite precipitation estimates from CHIRPS, GPM IMERG, and GSMaP were matched with gauge observations for the 2001–2024 evaluation period. Third, the matched gauge–satellite datasets were evaluated using statistical metrics under multiple rainfall-threshold conditions. Fourth,

empirical CDFs, percentile differences, and correction factors were used to assess upper-tail rainfall uncertainty. Finally, the results were interpreted in relation to water-related hazard assessment, including flash floods, rainfall-induced landslides, drainage overload, early warning, and infrastructure-resilience planning in mountainous terrain.

Figure 2 illustrates the methodological framework used to evaluate long-term extreme rainfall characteristics and satellite precipitation performance. Figure 2 was generated with the assistance of a generative AI tool solely to illustrate the methodological workflow of this study. The tool was not used to generate, modify, analyze, or interpret any research data, model outputs, or scientific results.

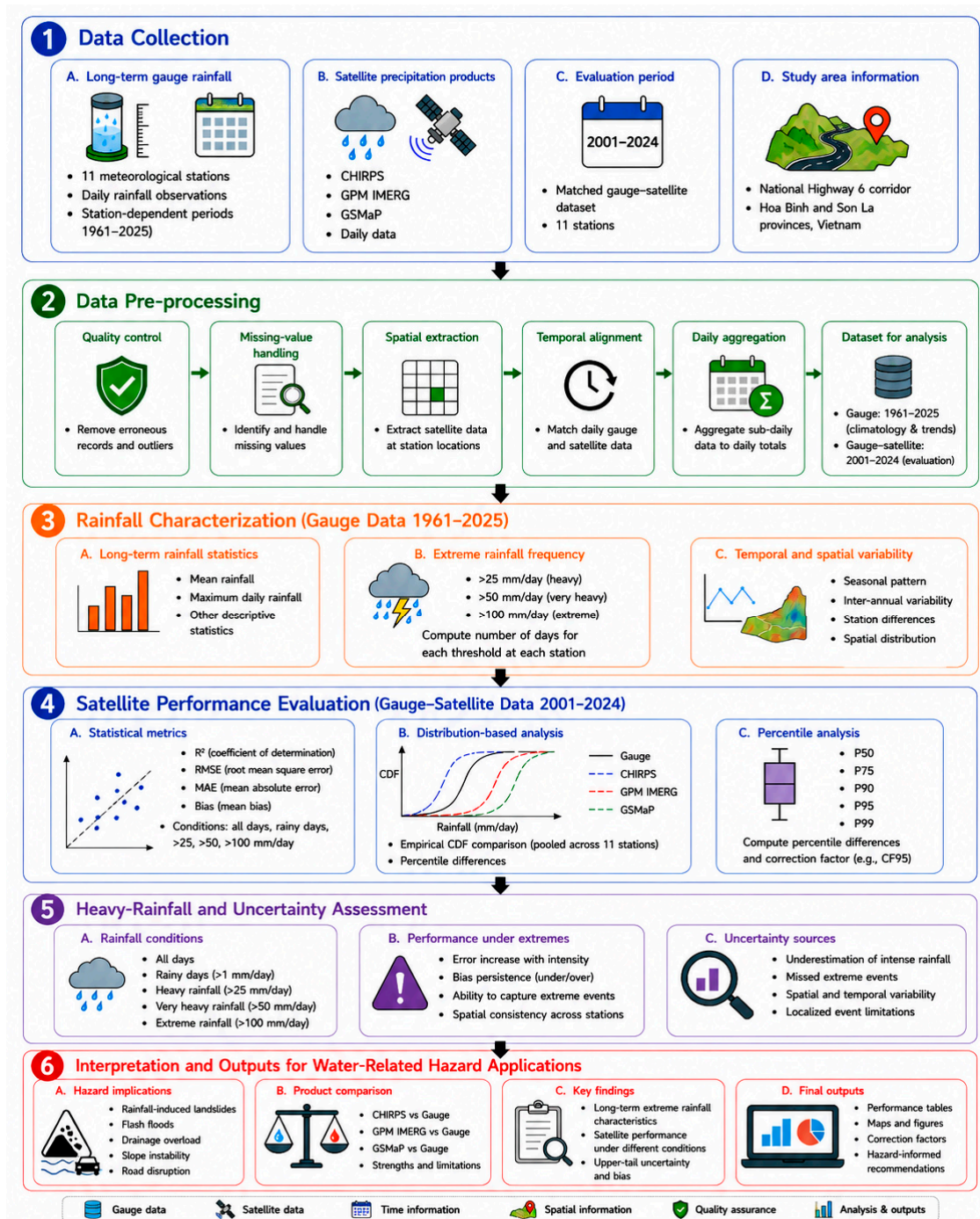


Figure 2. Methodological framework for evaluating long-term extreme rainfall characteristics and satellite precipitation performance along the National Highway 6 mountainous transportation corridor.

3. Results

3.1. Long-Term Rainfall Characteristics

The long-term rainfall statistics presented in Table 1 indicate substantial spatial variability in rainfall characteristics across the 11 meteorological stations along and around the National Highway 6 corridor. Stations located in the eastern and central parts of the corridor, such as Hoa Binh, Kim Boi, Lac Son, Mai Chau, and Chi Ne, have recorded relatively high mean rainfall and frequent heavy-rainfall events. These results reflect the influence of complex terrain and orographic enhancement on rainfall formation in the mountainous region of northern Vietnam. In contrast, stations such as Song Ma, Co Noi, and Quynh Nhai showed lower rainfall intensity and fewer days exceeding the selected heavy-rainfall thresholds.

Table 1. Long-term rainfall characteristics and extreme rainfall frequency at 11 meteorological stations along National Highway 6 during the available observation periods up to 2024.

Station	Mean Rainfall (mm/Day)	Maximum Daily Rainfall (mm/Day)	Valid Daily Observations, N	Days > 25 mm/Day (Day), n (%)	Days > 50 mm/Day (Day), n (%)	Days > 100 mm/Day (Day), n (%)
Chi Ne	5.32	393.7	18,993	1182 (6.22)	480 (2.53)	144 (0.76)
Co Noi	3.67	313.5	7300	314 (4.30)	86 (1.18)	8 (0.11)
Hoa Binh	5.16	340.6	25,203	1631 (6.47)	602 (2.39)	120 (0.48)
Kim Boi	5.11	360.5	22,646	1418 (6.26)	548 (2.42)	119 (0.53)
Lac Son	5.47	530	23,376	1566 (6.70)	610 (2.61)	108 (0.46)
Mai Chau	4.87	350	23,376	1376 (5.89)	498 (2.13)	125 (0.53)
Moc Chau	7.58	230.3	11,364	1031 (9.07)	290 (2.55)	49 (0.43)
Quynh Nhai	4.38	170.8	7297	403 (5.52)	116 (1.59)	11 (0.15)
Song Ma	3.19	219	20,089	708 (3.52)	147 (0.73)	11 (0.05)
Son La	3.88	368.4	21,915	972 (4.44)	268 (1.22)	27 (0.12)
Yen Chau	8.49	286.7	7589	717 (9.45)	193 (2.54)	26 (0.34)

The long-term threshold analysis further shows that heavy and extreme rainfall are not uniformly distributed across the study area. The number of days exceeding 25, 50, and 100 mm/day varies markedly among stations, indicating that rainfall-related hazard potential differs considerably along the corridor. This spatial heterogeneity is important for transportation-infrastructure risk assessment because road sections located near stations with frequent heavy rainfall may be more susceptible to rainfall-induced landslides, slope instability, and flash floods.

Table 1 presents the rainfall characteristics across the study area. Stations such as Moc Chau and Mai Chau exhibited relatively high rainfall intensity and/or frequent heavy-rainfall events, reflecting the influence of orographic conditions in mountainous terrain.

Percentages were calculated relative to the number of valid daily observations (N) available at each station.

3.2. The 2025 Gauge-Based Case Study

The year 2025 was selected as an extreme-rainfall case-study year because several stations along the NH6 corridor had recorded exceptionally high daily rainfall and frequent threshold exceedances. The analysis presented here focuses on gauge-observed rainfall along the NH6 corridor and is intended to illustrate the timing, spatial variability, and frequency of recent heavy-rainfall events rather than to provide an independent satellite-validation period.

To distinguish long-term rainfall climatology from recent rainfall conditions, the rainfall characteristics for the 2025 case-study year were summarized separately. As shown in Table 2, all stations recorded heavy rainfall days exceeding 50 mm/day, while extreme rainfall events above 100 mm/day were observed at several stations, particularly Kim Boi, Mai Chau, Moc Chau, Lac Son, Chi Ne, Hoa Binh, Yen Chau, and Song Ma. These results indicate that 2025 provides a relevant recent case-study year for examining heavy rainfall conditions and their implications for transportation-related hazards along National Highway 6.

Table 2. Rainfall characteristics at 11 meteorological stations in 2025.

Station	Mean Rainfall (mm/Day)	Annual Rainfall (mm)	Maximum Daily Rainfall (mm/Day)	Days > 25 mm/Day, n (%)	Days > 50 mm/Day, n (%)	Days > 100 mm/Day, n (%)
Yen Chau	3.61	1319.3	101.3	15 (4.11)	5 (1.37)	1 (0.27)
Song Ma	5.42	1980.0	145.1	30 (8.22)	10 (2.74)	1 (0.27)
Son La	4.58	1670.5	93.3	23 (6.3)	5 (1.37)	0 (0.00)
Quynh Nhai	5.10	1862.3	85.4	26 (7.12)	9 (2.47)	0 (0.00)
Moc Chau	6.55	2391.0	238.4	29 (7.95)	11 (3.01)	3 (0.82)
Mai Chau	6.69	2442.6	274.2	29 (7.95)	11 (3.01)	4 (1.10)
Lac Son	7.88	2877.0	261.7	35 (9.59)	11 (3.01)	3 (0.82)
Kim Boi	7.53	2748.1	215.2	28 (7.67)	9 (2.47)	5 (1.37)
Hoa Binh	6.62	2415.6	273.9	25 (6.85)	13 (3.56)	2 (0.55)
Co Noi	3.28	1197.6	67.6	14 (3.84)	3 (0.82)	0 (0.00)
Chi Ne	6.76	2466.1	158.3	32 (8.77)	12 (3.29)	3 (0.82)

The 2025 case-study year provides a recent illustration of heavy-rainfall conditions along the corridor. As shown in Table 2, all stations recorded rainfall events exceeding 50 mm/day, while rainfall greater than 100 mm/day occurred at several stations, including Kim Boi, Mai Chau, Moc Chau, Lac Son, Chi Ne, Hoa Binh, Yen Chau, and Song Ma. The highest annual rainfall totals in 2025 were observed at Lac Son, Kim Boi, Chi Ne, Mai Chau, Hoa Binh, and Moc Chau, confirming that the eastern and mountainous parts of the corridor experienced more intense rainfall conditions during the case-study year.

The spatial distribution of heavy-rainfall frequency in 2025 is shown in Figure 3. Areas with higher frequencies of rainfall exceeding 50 mm/day are concentrated along the mountainous sections of National Highway 6, particularly in the Hoa Binh–Mai Chau–Moc Chau corridor.

This pattern suggests that heavy rainfall is strongly influenced by local terrain conditions and may contribute to localized hazard hotspots along the transportation route.

Figure 4 further illustrates the distribution of daily rainfall across the 11 stations in 2025. The box plot shows that most daily rainfall values are concentrated in the low-rainfall range, whereas several stations exhibit high outliers associated with intense rainfall events. Stations such as Lac Son, Mai Chau, Moc Chau, Kim Boi, Hoa Binh, and Chi Ne show more pronounced extreme values, indicating greater temporal rainfall variability. This finding is consistent with the threshold-based statistics in Table 2 and highlights the need to evaluate satellite rainfall products not only under general rainfall conditions but also under heavy-rainfall events.

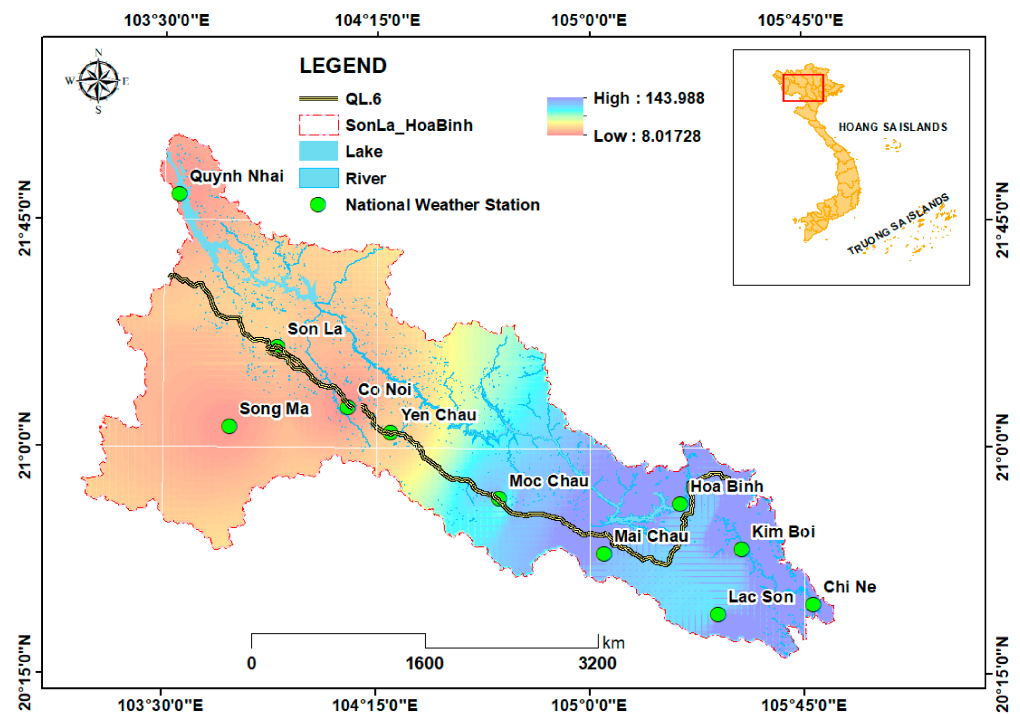


Figure 3. Spatial distribution of heavy rainfall frequency (>50 mm/day) in 2025 along National Highway 6.

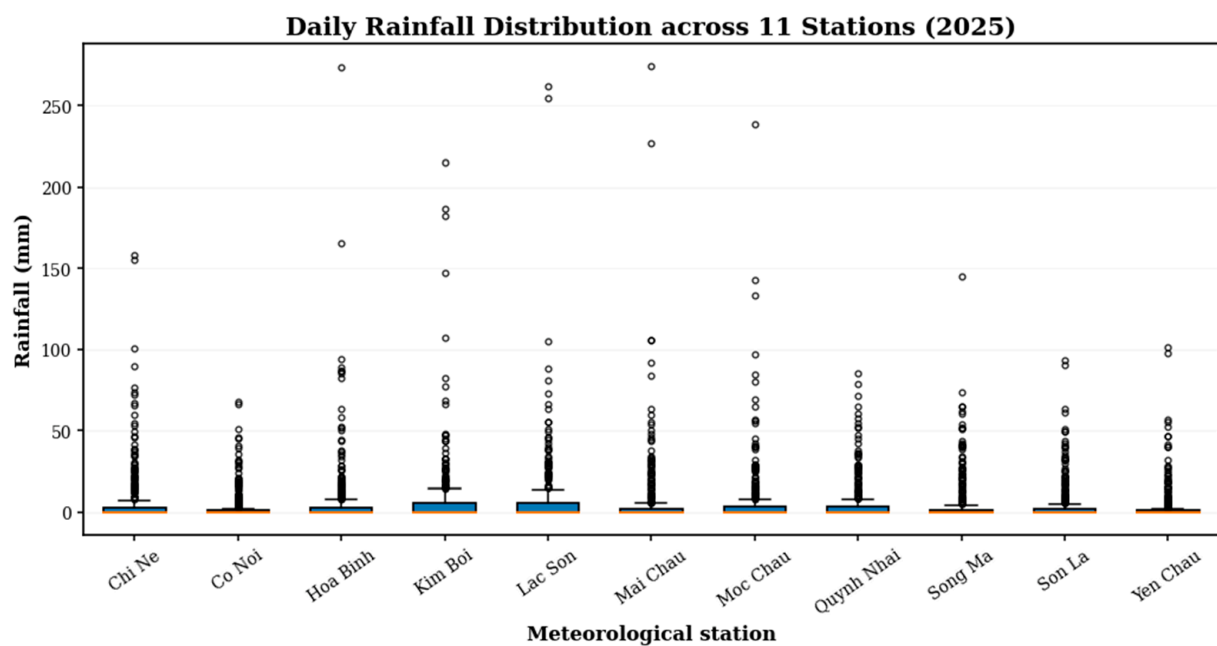


Figure 4. Box plot of daily rainfall distribution across 11 meteorological stations in 2025. Blue boxes represent the interquartile range, orange horizontal lines indicate the median, and black circles denote outliers.

The temporal distribution of daily rainfall in 2025 is presented in Figure 5. Rainfall was concentrated mainly during the wet season, from May to October, with several high-intensity events occurring between July and September. This seasonal concentration is typical of monsoon-dominated mountainous regions and is particularly important for hazard assessment because intense rainfall during the wet season may trigger slope failures, flash floods, drainage overload, and road disruption along mountainous transportation corridors.

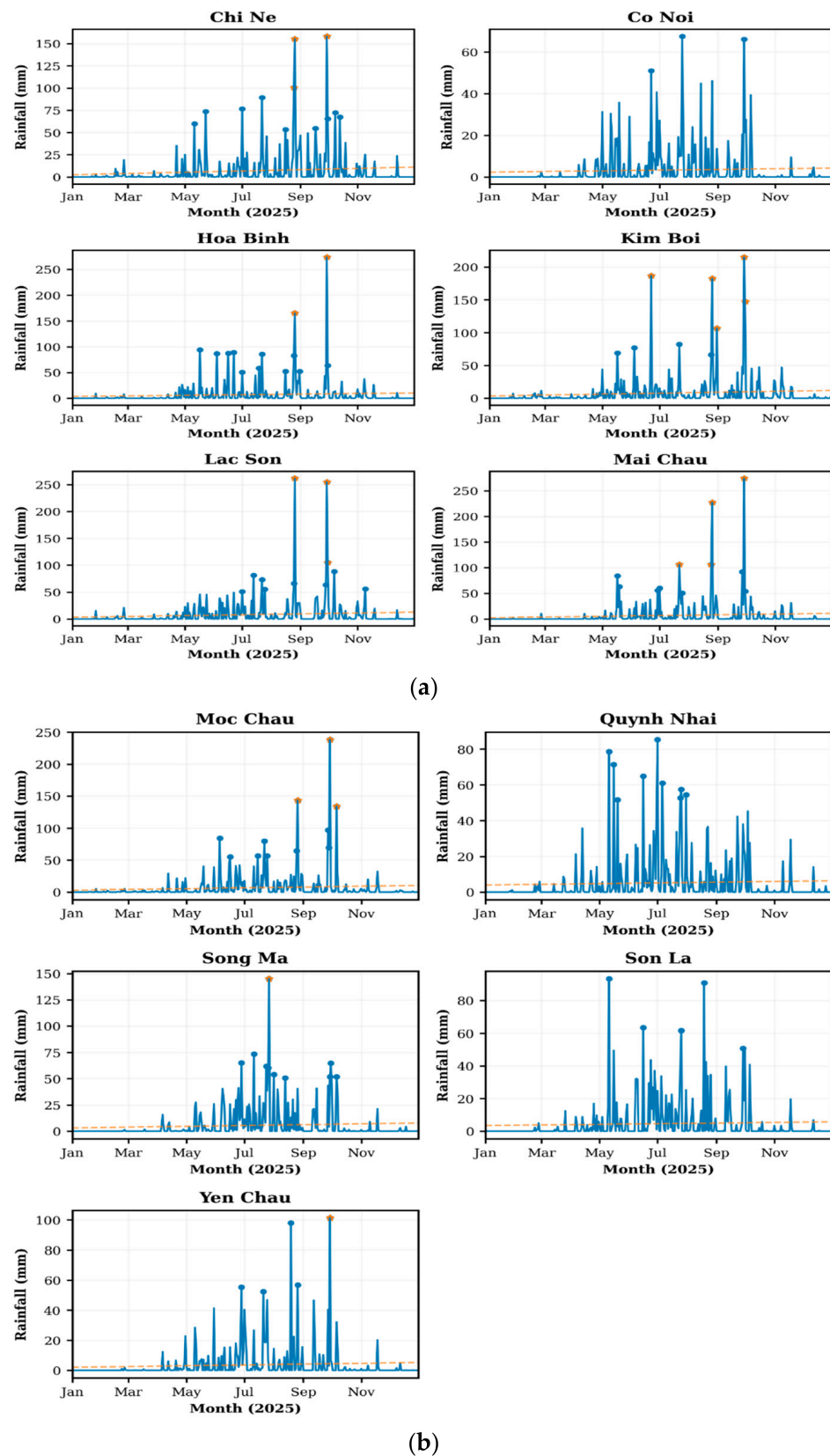


Figure 5. Daily rainfall time series at 11 meteorological stations in 2025: (a) Chi Ne, Co Noi, Hoa Binh, Kim Boi, Lac Son, and Mai Chau; (b) Moc Chau, Quynh Nhai, Song Ma, Son La, and Yen Chau. The blue line with circular markers represents daily rainfall, the orange triangular markers indicate extreme-rainfall events exceeding 100 mm/day, and the orange dashed horizontal line represents the mean daily rainfall at each station.

To further illustrate the behavior of satellite rainfall estimates during a recent extreme rainfall year, scatter plot comparisons were also constructed for the 2025 case-study dataset, as shown in Figure 6.

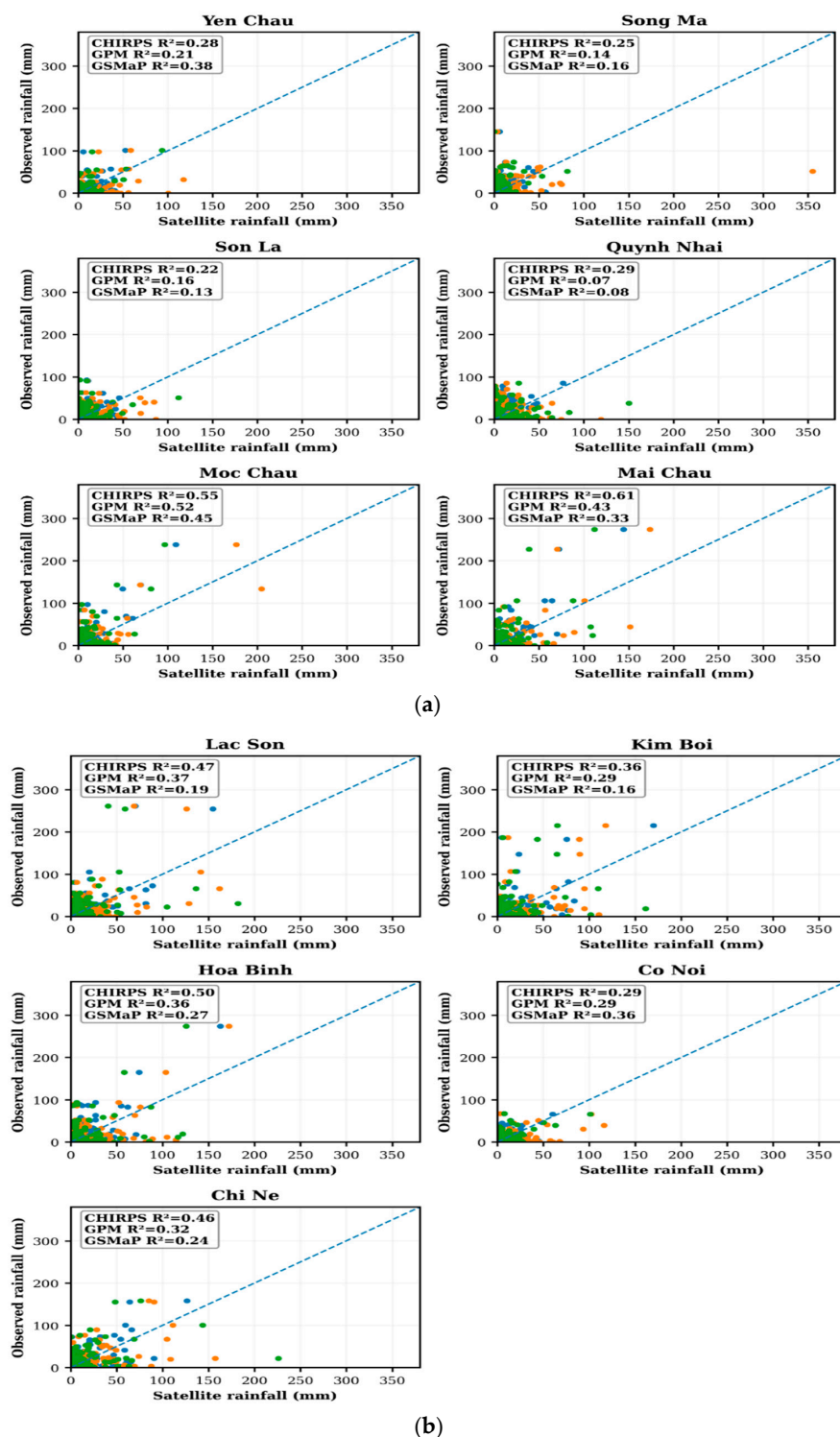


Figure 6. Scatter plot comparison between gauge-observed rainfall and satellite-derived rainfall from CHIRPS, GPM IMERG, and GSMap at 11 meteorological stations in 2025: (a) first group of stations; (b) second group of stations. Blue, orange, and green markers represent CHIRPS, GPM IMERG, and GSMap, respectively. The blue dashed diagonal line represents the 1:1 reference line between satellite-derived and gauge-observed rainfall.

3.3. Long-Term Satellite Performance Under Rainy-Day Conditions

The rainy-day performance of the three satellite precipitation products was first evaluated at the station scale using matched daily gauge–satellite rainfall records during 2001–2024. This station-based assessment provides a clearer view of the spatial variability in product performance along the NH6 corridor, rather than relying solely on overall averaged statistics.

Figure 7 provides a station-based view of long-term rainy-day performance during 2001–2024. The results show clear spatial variability in the correlation between gauge-observed rainfall and satellite-derived estimates across the 11 stations. GPM IMERG achieved the highest R^2 at several stations, particularly at Chi Ne, Hoa Binh, Kim Boi, Lac Son, and Mai Chau, whereas CHIRPS also showed relatively consistent performance at many stations. In contrast, lower R^2 values were observed at stations such as Co Noi, Moc Chau, Son La, and Song Ma, indicating that satellite products had greater difficulty reproducing rainy-day variability in areas with more heterogeneous rainfall processes and complex terrain influences. GSMaP showed comparatively weaker performance at many stations, although it performed relatively better at selected locations such as Yen Chau. These results highlight that satellite rainfall performance along the NH6 corridor is strongly location-dependent and should be interpreted with local terrain and rainfall regime in mind.

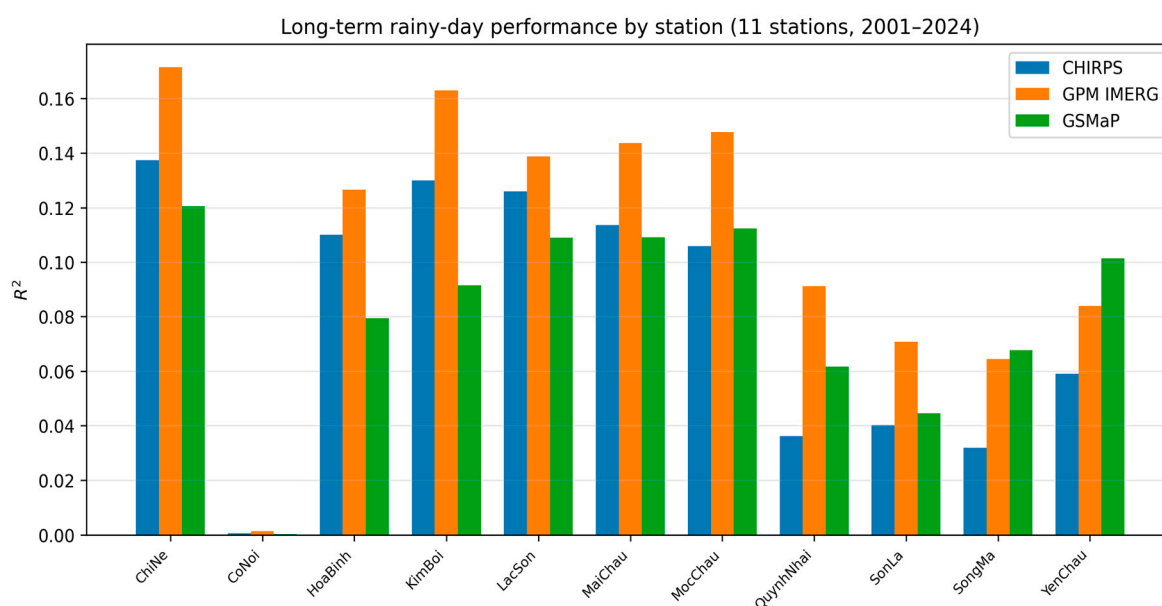


Figure 7. Long-term rainy-day performance (R^2) of CHIRPS, GPM IMERG, and GSMaP across 11 meteorological stations along the National Highway 6 corridor during 2001–2024.

The scatter plots in Figure 6 provide further evidence of the relationship between observed and satellite-derived rainfall. Although satellite estimates generally capture low to moderate rainfall values, the scatter points deviate substantially from the 1:1 reference line during higher rainfall events. This indicates that all three satellite products have limitations in reproducing rainfall magnitude during intense events, even when they can capture general rainfall variability at some stations.

Rainfall-induced hazards along the NH6 corridor are mainly triggered by high-intensity rainfall events. Therefore, a separate assessment under heavy-rainfall conditions was conducted to examine how satellite precipitation products perform during events that are more relevant to flash floods, rainfall-induced landslides, drainage overload, and slope instability. The results are presented in Section 3.4.

In addition, correlation-based metrics alone cannot fully explain how satellite products represent high-intensity rainfall. To further evaluate their behavior in the upper tail of the rainfall distribution, a pooled empirical CDF analysis was conducted, which is presented in the next section.

3.4. Event Detection Performance Under Heavy-Rainfall Thresholds

To complement the continuous-value statistics, contingency-table metrics were calculated for daily rainfall thresholds of 25, 50, and 100 mm/day using all valid paired gauge–satellite observations during 2001–2024. Probability of detection (POD), false alarm ratio (FAR), critical success index (CSI), equitable threat score (ETS), and Heidke skill score (HSS) were used to evaluate whether each satellite product correctly identified the occurrence of heavy and extreme rainfall events.

The pooled event-detection performance of CHIRPS, GPM IMERG, and GSMaP at the selected rainfall thresholds is summarized in Table 3.

Table 3. Pooled contingency table performance of CHIRPS, GPM IMERG, and GSMaP for daily rainfall thresholds of 25, 50, and 100 mm/day during 2001–2024.

Threshold (mm/Day)	Product	POD	FAR	CSI	ETS	HSS
25	CHIRPS	0.254	0.727	0.152	0.124	0.221
25	GPM IMERG	0.291	0.692	0.176	0.149	0.259
25	GSMaP	0.369	0.727	0.186	0.154	0.267
50	CHIRPS	0.110	0.737	0.084	0.079	0.146
50	GPM IMERG	0.171	0.773	0.108	0.100	0.181
50	GSMaP	0.289	0.844	0.113	0.100	0.182
100	CHIRPS	0.024	0.781	0.022	0.021	0.042
100	GPM IMERG	0.138	0.793	0.090	0.089	0.163
100	GSMaP	0.276	0.916	0.069	0.066	0.125

Valid paired observations were $N = 92,021$ for CHIRPS and GSMaP, and $N = 92,029$ for GPM IMERG.

The event-detection results show that product ranking depends on the selected threshold and metric. Higher POD values do not necessarily indicate better overall performance when accompanied by high FAR values. Therefore, no single satellite product can be considered uniformly superior for all heavy-rainfall detection applications.

3.5. Upper-Tail and Percentile Performance

The performance of satellite precipitation products under high-rainfall conditions was further examined because rainfall-induced hazards along the NH6 corridor are mainly associated with intense rainfall events. Compared with general rainy-day conditions, satellite rainfall uncertainty becomes more critical at higher rainfall intensities, where errors in rainfall magnitude may directly affect flash-flood, landslide, drainage-overload, and slope-instability assessment. Therefore, an upper-tail distribution analysis was conducted to evaluate how the three satellite products represent high daily rainfall during the 2001–2024 period.

The upper-tail CDF comparison in Figure 8 provides additional insight into how the satellite products represent high daily rainfall across the study area. CHIRPS and GPM IMERG generally track the gauge distribution reasonably well over the moderate rainfall range, but noticeable deviations emerge toward the upper tail, indicating increasing difficulty in reproducing intense rainfall magnitudes. GSMaP shows a more distinct divergence from the gauge-based distribution in the high-rainfall range, suggesting different behavior

in representing extreme rainfall. This pooled distribution-based analysis complements the station-based performance metrics by showing that even when rainy-day variability is partially captured, uncertainties remain substantial for the upper end of the rainfall distribution. Such uncertainty is particularly important for flash-flood, landslide, and drainage-risk assessment, where hazard levels are often controlled by high-intensity rainfall rather than by average rainfall conditions.

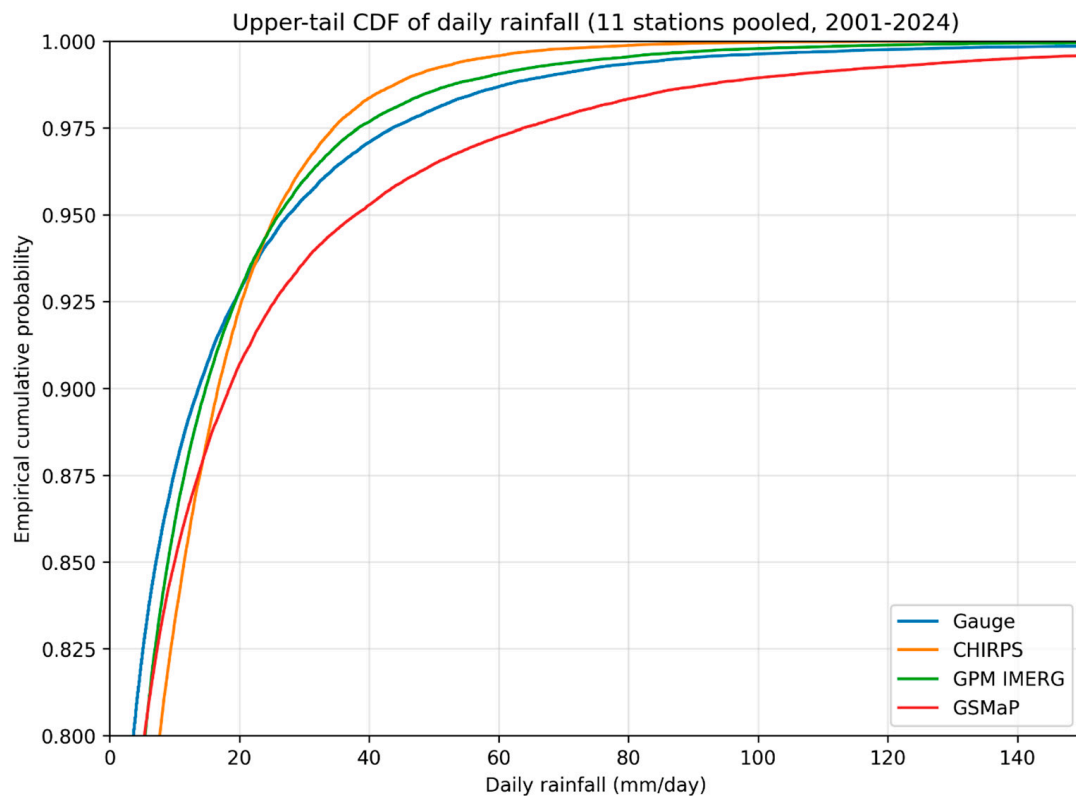


Figure 8. Empirical cumulative distribution functions (CDFs) of pooled daily rainfall from gauge observations and three satellite precipitation products for the upper tail of the rainfall distribution across 11 meteorological stations during 2001–2024.

Table 4 summarizes the percentile differences and empirical correction factors of the satellite precipitation products in the upper tail of the rainfall distribution.

Table 4. Percentile differences and empirical correction factors for satellite rainfall products based on pooled paired daily gauge–satellite rainfall records from 11 meteorological stations during 2001–2024.

Product	P90 Difference (mm)	P95 Difference (mm)	P99 Difference (mm)	Correction Factor at P95
CHIRPS	3.00	−2.08	−20.95	1.08
GPM IMERG	1.10	−1.50	−8.95	1.06
GSMaP	4.76	10.27	35.57	0.73

The percentile-based comparison further confirms that satellite precipitation uncertainty becomes more pronounced toward the upper tail of the rainfall distribution. At P90, all three products slightly overestimated gauge rainfall, with differences of 3.00 mm for CHIRPS, 1.10 mm for GPM IMERG, and 4.76 mm for GSMaP. At P95, CHIRPS and GPM IMERG underestimated gauge rainfall by 2.08 and 1.50 mm, respectively, whereas GSMaP overestimated it by 10.27 mm. The largest product differences occurred at P99: CHIRPS

and GPM IMERG underestimated gauge rainfall by 20.95 and 8.95 mm, respectively, while GSMaP overestimated it by 35.57 mm.

The empirical correction factors at P95 were 1.08 for CHIRPS, 1.06 for GPM IMERG, and 0.73 for GSMaP. Correction factors greater than 1 indicate that CHIRPS and GPM IMERG may require modest upward adjustment around P95, whereas the value below 1 for GSMaP indicates the need for downward adjustment. These contrasting upper-tail behaviors demonstrate that a uniform correction direction is not appropriate for all satellite precipitation products.

The contrast between rainy-day and heavy-rainfall performance provides important insight into the applicability of satellite precipitation products for hazard-oriented assessment. Satellite-product reliability generally decreased at higher rainfall thresholds, as indicated by the low POD and skill-score values and the high FAR values at the 100 mm/day threshold. The upper-tail results further revealed product-specific magnitude biases: CHIRPS and GPM IMERG underestimated gauge rainfall at P99, whereas GSMaP overestimated it. Therefore, the principal limitation involves not only event detection but also inconsistent representation of extreme-rainfall magnitude among products.

These product-specific biases may affect hazard interpretation in different ways. Underestimation may lead to underestimated risk levels or delayed warnings, whereas overestimation may increase false alarms. Therefore, satellite precipitation products should be locally validated and adjusted using product-specific procedures before being applied to rainfall-threshold-based warning, landslide assessment, or transportation-infrastructure risk analysis.

4. Discussion

4.1. Influence of Terrain and Product Characteristics

The results indicate that satellite rainfall performance is influenced by both terrain complexity and product characteristics. Stations located in complex mountainous areas, such as Mai Chau, Moc Chau, Hoa Binh, Kim Boi, and Lac Son, show high rainfall variability and frequent heavy-rainfall events. These conditions can improve the detectability of rainfall occurrence but may also increase errors in rainfall magnitude because satellite algorithms may not fully capture localized orographic enhancement.

The relatively consistent station-scale performance of CHIRPS may be related to its incorporation of station data and climatological information, which can improve rainfall representation in regions where gauge information contributes to bias adjustment. This is consistent with the design of CHIRPS as a satellite–station blended product intended for monitoring rainfall variability and extremes [5]. GPM IMERG, particularly the Final product, incorporates multi-satellite estimates and gauge adjustment, making it suitable for retrospective precipitation evaluation [6]. Scale-dependent variations in IMERG performance have also been reported over mainland China [27]. GSMaP relies on passive microwave and infrared observations and is widely used for rainfall monitoring in Asia, but its performance can vary depending on rainfall regime, terrain complexity, and gauge-adjustment procedures [8,28].

The present findings are generally consistent with previous evaluations in East Asia, including studies conducted in China, which also reported substantial spatial heterogeneity in satellite precipitation performance over complex terrain [29]. Together, these studies highlight the importance of regional validation before satellite precipitation products are applied to hazard-related analyses in mountainous environments.

The comparison among products suggests that no single satellite rainfall product can be used without caution in mountainous regions. Performance ranking varied according to the metric and rainfall threshold. GPM IMERG achieved the highest rainy-day R^2 at

several stations, whereas GSMaP attained higher POD values but also substantially higher FAR values at heavy-rainfall thresholds. CHIRPS showed relatively consistent station-scale performance but underestimated gauge rainfall at P95 and P99. Therefore, no single product was uniformly superior across all evaluation criteria. These findings suggest that product selection should consider both the intended application and the rainfall regime. For general rainfall monitoring, product selection should depend on the station, rainfall regime, and intended application.

4.2. Implications, Limitations, and Practical Applications

The hazard-related interpretation presented here is based on rainfall characteristics and satellite-product uncertainty rather than on a quantitative hazard-outcome model. No landslide inventory, flood-damage database, road-closure record, or drainage-failure dataset was used to establish causal rainfall–impact relationships. Accordingly, the results should be interpreted as hazard-relevant rainfall evidence and methodological guidance for future risk assessment, rather than as a direct validation of hazard occurrence.

The results have important implications for transportation-infrastructure risk management along National Highway 6. Heavy rainfall is a major triggering factor for landslides, flash floods, slope instability, and road disruption in mountainous terrain. The spatial concentration of heavy-rainfall frequency along parts of the corridor, together with the high rainfall variability observed at several stations, indicate that certain road sections may be more exposed to rainfall-induced hazards.

Figure 9 illustrates the overlap between heavy-rainfall frequency and the National Highway 6 corridor, together with field evidence of landslide and road damage. This figure highlights the practical relevance of integrating rainfall analysis with transportation-risk interpretation. Areas with frequent heavy rainfall should be prioritized for slope monitoring, drainage maintenance, landslide-risk inspection, and early-warning preparation during the wet season.

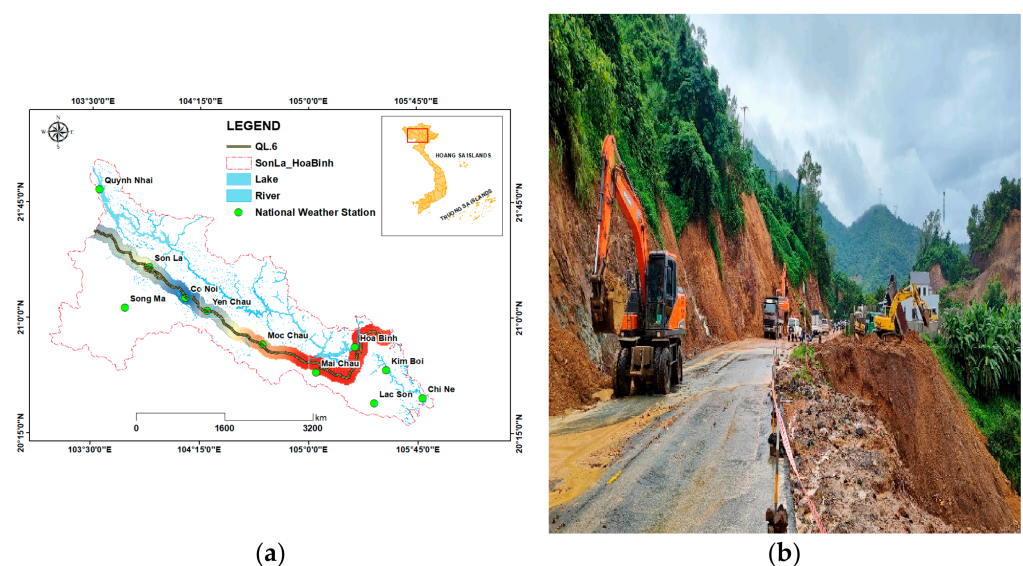


Figure 9. Transportation risk induced by heavy rainfall along National Highway 6 (Field photograph of a rainfall-induced landslide near National Highway 6, Hoa Binh Province, September 2025. Photograph by the authors). (a) Spatial distribution of heavy rainfall frequency (>50 mm/day) and its overlap with National Highway 6. (b) Field evidence of landslide and road damage in a mountainous section of Hoa Binh Province, showing slope failure and traffic disruption following heavy rainfall events.

The reduced reliability of satellite rainfall products under heavy-rainfall conditions is particularly important for infrastructure applications. If satellite products underestimate intense rainfall, hazard levels may also be underestimated. This can affect the reliability of early-warning systems, susceptibility mapping, emergency response, and infrastructure-resilience planning. Therefore, satellite precipitation products should not be used as direct substitutes for gauge observations without local validation and bias assessment.

For mountainous transportation corridors such as National Highway 6, a combined approach is recommended. Long-term gauge observations should be used to identify climatological rainfall patterns and extreme-rainfall hotspots, while satellite precipitation products can provide spatially continuous information for areas without dense gauge coverage. However, satellite estimates should be evaluated and adjusted using available ground observations before being applied to landslide, flash-flood, or transportation-risk assessment. This integrated approach can improve the reliability of rainfall-based hazard assessment and support more resilient transportation-infrastructure planning in northern Vietnam.

This study has several limitations. First, gauge-record lengths differed among stations; therefore, comparisons of absolute maximum rainfall should be interpreted cautiously because longer records have a greater probability of capturing rare extreme events. Second, the analysis relied on fixed daily rainfall thresholds and did not explicitly account for rainfall duration or antecedent rainfall conditions. Third, no independently validated landslide inventory, flood-damage database, road-closure record, or drainage-failure dataset was available to quantify rainfall–impact relationships. Fourth, the present study did not evaluate temporal rainfall trends or attribute the observed extreme events to climate change. Future studies should integrate event inventories, antecedent- and duration-based rainfall indicators, terrain and geological variables, and station-specific trend analyses to support more robust quantitative hazard assessment and operational early-warning applications.

5. Conclusions

This study evaluated long-term extreme rainfall characteristics and the performance of three satellite precipitation products—CHIRPS, GPM IMERG, and GSMaP—along the National Highway 6 mountainous transportation corridor in northern Vietnam. By combining long-term gauge observations for 1961–2024, matched gauge–satellite rainfall records for 2001–2024, and a recent gauge-based case study for 2025, the study provides both a climatological understanding of rainfall extremes and an application-oriented assessment of satellite rainfall reliability under complex mountainous terrain conditions.

The long-term gauge analysis revealed strong spatial variability in rainfall characteristics across the 11 meteorological stations. Stations located in the eastern and central mountainous parts of the corridor, including Hoa Binh, Kim Boi, Lac Son, Mai Chau, Moc Chau, and Chi Ne, showed relatively high rainfall intensity and more frequent heavy-rainfall events. The 2025 case-study year further illustrated that all stations experienced rainfall events exceeding 50 mm/day, while several stations recorded extreme rainfall above 100 mm/day. These findings indicate that heavy rainfall is spatially uneven and strongly influenced by terrain conditions, leading to localized hazard-prone areas along the National Highway 6 corridor.

The satellite–gauge comparison during 2001–2024 showed that satellite precipitation performance varied considerably by station and product. CHIRPS generally showed relatively consistent performance in reproducing rainy-day rainfall variability, while GPM IMERG also performed well at several stations. GSMaP showed weaker overall agreement and greater divergence in the upper tail of the rainfall distribution. However, all three satellite products showed limitations in representing high-rainfall conditions, indicating

that rainfall magnitude errors become more important when satellite estimates are used for hazard-oriented applications.

The upper-tail CDF and percentile-based analyses further confirmed that satellite rainfall uncertainty increases toward high daily rainfall values. This finding is particularly important for mountainous transportation corridors, where landslides, flash floods, slope failures, drainage overload, and road disruption are often triggered by intense rainfall rather than average rainfall conditions. Therefore, correlation-based metrics alone are insufficient for evaluating satellite precipitation products in hazard assessment, and distribution-based indicators and high-percentile rainfall behavior should also be considered.

The findings have important implications for water-related hazard and transportation-infrastructure risk management in mountainous regions. Satellite precipitation products can provide valuable, spatially continuous rainfall information, especially where rain-gauge networks are sparse. However, they should not be used as direct substitutes for ground observations without local validation, bias assessment, and application-specific adjustment. For the National Highway 6 corridor, long-term gauge observations remain essential for identifying extreme-rainfall hotspots, while satellite products can support broader spatial assessment when combined with gauge-based correction and uncertainty evaluation.

Overall, this study highlights the need for an integrated rainfall-assessment framework that combines long-term ground observations, locally evaluated satellite precipitation products, rainfall-threshold analysis, upper-tail distribution assessment, and transportation-hazard interpretation. Future research should further develop bias-correction and machine-learning-based adjustment methods, evaluate seasonal and event-based performance, and incorporate additional hydrological and geomorphological factors to improve the reliability of satellite rainfall estimates for flash-flood, landslide, drainage-risk, and infrastructure-resilience applications in the mountainous regions of northern Vietnam.

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Data Availability Statement: The rain-gauge data used in this study are available from the corresponding author upon reasonable request. These data are not publicly available because they were obtained from the relevant meteorological data providers and are subject to data-use restrictions. The satellite precipitation datasets are publicly available from their respective data providers.

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