

**RAINFALL VARIABILITY AND EXTREME PRECIPITATION EVENTS
UNDER CLIMATE CHANGE: A CASE STUDY
IN PHU THO PROVINCE, VIETNAM**

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Abstract. This study investigates rainfall variability in Phu Tho province, Vietnam, focusing on total annual rainfall, the frequency of heavy rainfall days (≥ 50 mm/day), and very heavy rainfall days (≥ 100 mm/day), alongside rainy season characteristics using daily rainfall data from 1995 to 2024. Trends and variability in rainfall were analyzed using statistical methods, including the Mann–Kendall test and Sen’s slope estimator. The results indicate that trends in total annual rainfall are generally weak and spatio-temporal heterogeneity. In contrast, distinct climate change signals are evident in the intensification of rainfall and extreme weather patterns. Heavy and very heavy rainfall events contribute a disproportionately large share of total annual rainfall, particularly in mountainous terrain, despite their relatively low frequency. Furthermore, changes in rainy season duration remain limited, suggesting that recent climate impacts are primarily manifested through increased rainfall intensity rather than shifts in seasonality. These findings underscore the escalating significance of extreme rainfall events for disaster risk management and climate change adaptation in Phu Tho province.

Keywords: rainfall variability, climate change, extreme precipitation, disaster risk reduction, Phu Tho province.

1. Introduction

Rainfall is a fundamental climatic variable that plays a pivotal role in hydrological processes, water resources, agricultural productivity, and the manifestation of natural hazards. In tropical monsoon regions like Vietnam, rainfall variability and extreme

precipitation events are among the primary catalysts for floods, flash floods, landslides, and urban inundation [1], [2]. In recent decades, anthropogenic climate change has intensified concerns regarding shifts in rainfall characteristics and the escalation of associated disaster risks.

According to the Intergovernmental Panel on Climate Change (IPCC), climate change does not uniformly result in consistent increases or decreases in total annual rainfall; instead, it is more pronouncedly reflected in shifts in rainfall intensity, variability, and extreme precipitation events [3], [4]. Numerous global studies have reported a marked increase in short-duration, high-intensity rainfall episodes, even in regions where long-term trends in annual rainfall remain muted or statistically insignificant [5], [6]. Such climatological shifts significantly exacerbate disaster risks and undermine existing disaster risk reduction (DRR) and mitigation strategies.

In Southeast Asia, rainfall regimes are dynamically driven by the Asian monsoon system, tropical cyclogenesis, and complex topographic features [7]. Previous studies have demonstrated that rainfall variability in this region is pronounced, with discernible upwards trends in heavy and extreme precipitation events observed in recent decades [8], [9]. These changes in hydro-meteorological shifts have intensified the frequency and severity of rainfall-induced disasters across the region. In Vietnam, rainfall characteristics exhibit pronounced spatial and temporal variability due to the synergistic effects of monsoon circulation, tropical disturbances, and local orographic conditions [10]. While trends in total annual rainfall are often spatially heterogeneous and statistically inconclusive, several studies have reported a notable escalation in heavy and very heavy rainfall events, particularly in Northern and Central Vietnam [11]-[13]. These climatological shifts have been intrinsically linked to heightened risks of floods, flash floods, landslides, and urban inundation. Phu Tho province is situated in the Northern Midland region of Vietnam, characterized by transitional topography that shifts from rugged mountainous areas to low-lying plains. This geographical configuration renders the province highly susceptible to rainfall-induced hazards. In recent years, Phu Tho has been struck by several extreme precipitation events leading to significant socio-economics losses from inundation, flash floods, and landslides. However, most existing research on rainfall variability and climate change impacts in Vietnam has focused on national or basin-wide scales, whereas granular, provincial-scale analyses utilizing long-term daily rainfall records remain critically sparse [14]-[16].

Moreover, previous studies have frequently analyzed rainfall extremes or seasonal characteristics in isolation, whereas integrated assessments that combine rainfall variability, extreme precipitation indices, and rainy season dynamics are essential for a comprehensive understanding of climate change impacts and disaster risks. Such multidimensional analyses are especially critical for supporting evidence-based disaster risk reduction (DRR) and climate change adaptation strategies at the provincial level. Therefore, this study aims to investigate rainfall variability and climate change signals in Phu Tho province using high-resolution daily rainfall records from 1995 to 2024. The specific objectives are to: (i) characterize and analyze trends in total annual precipitation and its inter-annual variability; (ii) quantify shifts in extreme precipitation indices, specifically focusing on heavy rainfall (≥ 50 mm/day) and very heavy rainfall (≥ 100 mm/day),

and (iii) examine temporal variations in the duration and dynamics of the rainy season. These findings are expected to provide robust scientific evidence for understanding localized climate change impacts and for bolstering disaster risk reduction (DRR) and climate change adaptation frameworks in Phu Tho province [17].

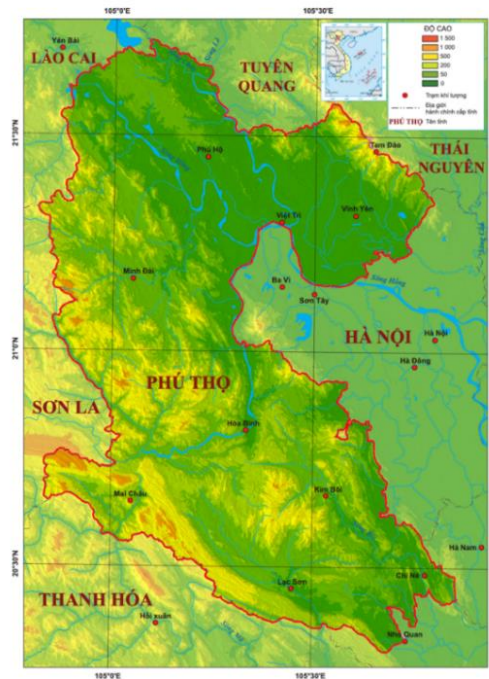


Figure 1. Location of the study area and meteorological station network in Phu Tho province, Vietnam

2. Content

2.1. Data and methods

2.1.1. Study area

The study area is Phu Tho province, situated in the northern midland region of Vietnam. Serving as a transitional zone between the Northwestern mountainous highlands and the Red River Delta, Phu Tho is characterized by complex topography and an intricate fluvial network [18], with the Red, Lo, and Da Rivers constituting the primary hydrological backbone of the province. Elevation exhibits a pronounced gradient, ranging from below 20 m in the alluvial plains to over 1,300 m within the Tam Dao mountain range. This results in a highly dissected terrain categorized into three distinct morphological zones: mountainous, midland, and lowland.

The province is influenced by a humid tropical monsoon climate [19], with approximately 80–85% of annual precipitation concentrated during the wet season. Rainfall patterns are primarily modulated by the Asian monsoon circulation, encompassing the southwest summer monsoon and tropical disturbances originating from the Western Pacific. The synergistic interaction between moist-laden monsoonal air

masses and the complex orography, particularly the Tam Dao range, facilitates orographic lifting, thereby intensifying precipitation in high-elevation areas. Furthermore, anthropogenic pressures, including deforestation and logging, coupled with steep slopes and soil degradation, have significantly diminished the natural hydrological regulation capacity of the landscape, exacerbating the province’s vulnerability to flash floods and landslides.

The synergistic effects of atmospheric circulation and topographic forcing contribute significantly to the spatial heterogeneity of rainfall and extreme precipitation events across the province. These factors collectively reinforce the region’s vulnerability to rainfall-induced hazards, including flash floods and landslides.

2.1.2. Data sources

This study utilizes long-term daily rainfall records spanning the 30 years from 1995 to 2024. The dataset was sourced from the Vietnam Center of Hydro-Meteorological Data, the authoritative national agency mandated for meteorological and hydrological observations in Vietnam [20].

The monitoring network comprises 10 meteorological stations, strategically distributed to capture the physiographic diversity of Phu Tho province. These stations encompass mountainous, midland, and lowland zones, thereby providing a spatially representative framework for a comprehensive assessment of spatio-temporal rainfall variability and extreme precipitation patterns across the region.

Prior to formal analysis, the rainfall datasets underwent rigorous quality control (QC) procedures, including comprehensive checks for missing values, statistical outliers, and temporal inconsistencies. To ensure the robustness of the trend analysis, three stations were excluded from the final selection due to insufficient data continuity and significant gaps in their records. Only the 10 stations possessing long-term, high-fidelity daily records (1995-2024) were retained for further investigation.

The geographic metadata and locational characteristics of these 10 prioritized meteorological stations are systematically summarized in Table 1.

Table 1. Geographic characteristics of meteorological stations in Phu Tho province

No.	Station name	Latitude (°N)	Longitude (°E)	Elevation (m)
1	Mai Chau	20.65	105.05	165.48
2	Kim Boi	20.67	105.53	61.10
3	Chi Ne	20.48	105.78	11.32
4	Lac Son	20.45	105.45	41.17
5	Hoa Binh	20.82	105.33	22.69
6	Minh Dai	21.17	105.05	100.00
7	Phu Ho	21.45	105.23	54.06
8	Viet Tri	21.30	105.42	30.48
9	Tam Dao	21.47	105.65	933.77
10	Vinh Yen	21.32	105.60	9.94

2.1.3. Methods

To rigorously evaluate rainfall variability, extreme precipitation characteristics, and rainy season dynamics in Phu Tho province, a multifaceted analytical framework was employed. This approach integrates standardized climatological indices with robust non-parametric statistical methods to detect long-term trends and shifts in rainfall patterns.

**** Rainfall characteristics and variability***

Total annual rainfall was derived by aggregating daily precipitation records for each meteorological station. To evaluate interannual rainfall variability, the coefficient of variation (CV) was employed, defined as the ratio of the standard deviation to the mean annual rainfall [21]. This dimensionless indicator serves as a robust metric to quantify the degree of rainfall instability and climatological uncertainty over the study period.

**** Analysis of heavy and very heavy rainfall***

In this study, extreme rainfall is defined based on high-intensity daily precipitation thresholds. Following the standards of the World Meteorological Organization (WMO), heavy rainfall and very heavy rainfall are identified as daily totals ≥ 50 mm and ≥ 100 mm, respectively [22]. It should be noted that very heavy rainfall events constitute a subset of heavy rainfall events; thus, the number of heavy rainfall days includes those classified as very heavy. For each meteorological station, the annual frequency of these events was computed to assess the occurrence of extreme weather. Furthermore, the term “extreme rainfall” in this study refers to high-intensity daily precipitation. This category encompasses heavy rainfall events (≥ 50 mm/day), within which very heavy rainfall events (≥ 100 mm/day) represent the highest intensity threshold. Additionally, extreme rainfall includes the annual maximum 1-day precipitation index (Rx1 day), which records the highest daily total each year and is widely utilized in flood and landslide susceptibility assessments [23].

**** Rainy season characteristics***

Rainy season length was determined based on monthly precipitation totals. A rainy season was identified by the occurrence of at least three consecutive months with monthly rainfall of ≥ 100 mm of rainfall. For each station and year, the longest continuous period meeting the criterion was defined as the annual rainy season length [24].

**** Trend analysis***

Long-term trends in annual rainfall and extreme precipitation indices were analyzed using the Mann–Kendall (MK) non-parametric test [25], [26]. The magnitude of these trends was quantified using Sen’s slope estimator [27], which provides a robust estimate of the rate of change over time. Statistical significance was rigorously evaluated at the 95% confidence level ($\alpha = 0.05$), ensuring that the identified climate signals are statistically meaningful and not due to random fluctuations.

2.2. Results

2.2.1. Characteristics and variability of annual rainfall

The spatial distribution of mean annual rainfall in Phu Tho province exhibits marked heterogeneity across the monitoring network, with values ranging from approximately 1,500 to over 2,000 mm. Higher precipitation totals are concentrated in the mountainous

interior, whereas lower values are observed in the midland and lowland sectors. The interannual variability (CV) spans a range of 18 - 23% (Table 2), indicating moderate fluctuations. Notably, higher variability is recorded at lowland and urban-influenced stations, suggesting a more erratic rainfall regime in these areas.

Trend analysis utilizing the Mann–Kendall test reveals spatially inconsistent and statistically weak shifts in annual rainfall. Although Sen’s slope estimator indicates slight upward trajectories at several locations (Table 2), these trends lack robust significance. As illustrated in Figure 2, most stations exhibit positive slopes, signifying a subtle increasing trend, while a downward trend is exclusively observed at the Chi Ne station.

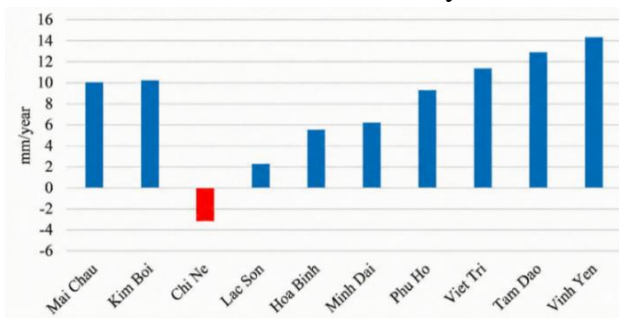


Figure 2. Sen’s slope of total annual rainfall at the 10 meteorological stations in Phu Tho province during 1995 - 2024

Table 2. Characteristics and trends of total annual rainfall in Phu Tho province (1995 - 2024)

No.	Station name	Mean annual rainfall (mm)	Coefficient of variation (%)	Sen’s slope (mm/year)
1	Mai Chau	1804.4	20.87	10.01
2	Kim Boi	2156.3	18.73	10.28
3	Chi Ne	1857.1	19.29	-3.18
4	Lac Son	2029.9	18.64	2.34
5	Hoa Binh	1894.6	20.30	5.50
6	Minh Dai	1692.5	19.92	6.19
7	Phu Ho	1533.5	21.41	9.31
8	Viet Tri	1517.4	22.57	11.38
9	Tam Dao	2327.9	18.61	12.93
10	Vinh Yen	1537.4	23.00	14.35

2.2.2. Changes in heavy rainfall events

Heavy rainfall events (≥ 50 mm/day) exhibit pronounced spatial variability across the study area during 1995 - 2024 (Table 3). The mean annual frequency ranges from 6.5 to 11.2 days, with higher occurrences concentrated at mountainous stations, including (Tam Dao, Kim Boi, Lac Son).

Trend analysis reveals statistically significant increases at Phu Ho, Tam Dao, and Vinh Yen, where Sen’s slopes range from 0.17 to 0.22 days/year, indicating a consistent escalation in the frequency of events. In contrast, trends at other stations remain weak and statistically negligible.

In contrast, the findings indicate intensifying heavy rainfall at specific mountainous and transitional sites, while the majority of the monitoring network shows no definite long-term shift.

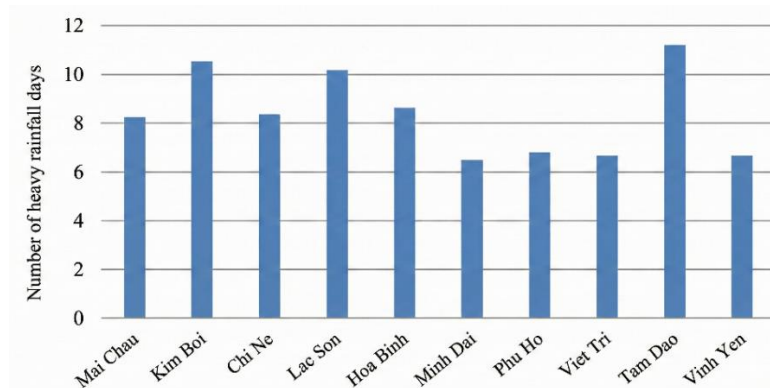


Figure 3. Variation in the annual number of heavy rainfall days (≥ 50 mm/day) at selected stations

Table 3. Frequency and trends of heavy rainfall days (≥ 50 mm/day) in Phu Tho province

No.	Station	Mean number of heavy rainfall days (days/year)	Sen’s slope (days/year)
1	Mai Chau	8.27	0.10
2	Kim Boi	10.53	0.08
3	Chi Ne	8.40	0.00
4	Lac Son	10.17	0.13
5	Hoa Binh	8.60	0.00
6	Minh Dai	6.53	-0.07
7	Phu Ho	6.80	0.17
8	Viet Tri	6.73	0.00
9	Tam Dao	11.20	0.22
10	Vinh Yen	6.70	0.18

2.2.3. Very heavy rainfall events

Very heavy rainfall events (≥ 100 mm/day) occur with significantly lower frequency compared to heavy rainfall events across the study area. For the period 1995 - 2024, the mean annual frequency ranges from approximately 1.0 to 3.3 (Figure 4). Spatially, higher frequencies are predominantly concentrated at stations situated in mountainous and high-

elevation terrain, most notably at Tam Dao, Kim Boi, and Chi Ne. These localized hotspots underscore the critical role of topographic forcing in generating high-intensity precipitation within the province.

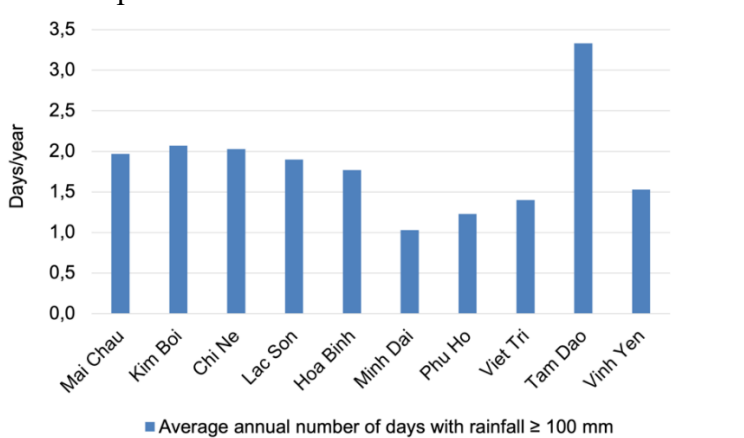


Figure 4. Frequency of very heavy rainfall events (≥ 100 mm/day) at the meteorological stations in Phu Tho province during 1995 - 2024

2.2.4. Changes in rainy season length

The mean duration of the rainy season across the study area typically spans 6 to 7 months during the period 1995 - 2024 (Figure 5). Prolonged rainy seasons are generally characteristic of stations situated in mountainous and high-altitude regions, most notably at Kim Boi and Tam Dao. In contrast, shorter seasonal durations are observed at the majority of remaining stations, particularly within the lowland and midland sectors, including Viet Tri, Vinh Yen, and Phu Ho.

Month	Mai Châu	Kim Bôi	Chi Nê	Lạc Sơn	Hòa Bình	Minh Đài	Phú Hộ	Việt Trì	Vĩnh Yên	Tam Đảo
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0
4	0	1	0	0	0	0	0	0	0	1
5	1	1	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	1
11	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0
1	Rainy season month									

Figure 5. Rainy season length in Phu Tho province

2.2.5. Contribution of heavy rainfall to total annual rainfall

The proportional contribution of heavy rainfall (≥ 50 mm/day) to total annual precipitation exhibits considerable spatial variability across the study area during the period 1995 - 2024 (Table 6). These high-intensity events account for approximately 31 - 44% of the annual rainfall, with the specific magnitude contingent upon station location and

topography. Within this category, very heavy rainfall events (≥ 100 mm/day) - representing the highest-intensity subset - contribute about 8 - 21% of the annual total.

Higher proportional contributions of both heavy and very heavy rainfall are generally observed at mountainous and high-elevation stations, most notably at Tam Dao, Chi Ne, and Mai Chau. At these stations, precipitation from very heavy rainfall events (≥ 100 mm/day) alone contributes more than 15% of the annual total. This underscores the dominant role of high-intensity precipitation in shaping the annual precipitation regimes of the province's highland areas.

In contrast, lower proportional contributions are observed at midland and lowland stations such as Minh Dai, Vinh Yen, Viet Tri, and Phu Ho. However, even in these regions, heavy rainfall still accounts for a substantial fraction of the total annual precipitation. Overall, these findings indicate that a relatively small number of high-intensity rainfall events contribute disproportionately to the annual totals. This phenomenon underscores the critical hydrological significance of extreme precipitation in the study area, particularly regarding its role in runoff generation and flood risk.

The concentration of annual precipitation into a limited number of intense events significantly increases the risk of fluvial floods, flash floods, urban inundation, and landslides. This suggests that hydrological hazards can be severely exacerbated even in years without marked shifts in total annual rainfall. Such a disproportionate rainfall distribution underscores the need for adaptive water management and early warning systems tailored to extreme weather pulses rather than just seasonal averages.

Figure 6 illustrates the relative contribution of heavy rainfall (≥ 50 mm/day), disaggregated into distinct intensity categories: rainfall between 50–100 mm/day and very heavy rainfall (≥ 100 mm/day). At several mountainous stations, the very heavy rainfall component alone accounts for more than 15 - 20% of the total annual precipitation. These findings underscore the disproportionate influence of a few high-intensity precipitation events in determining the annual hydrological budget of the province's highland regions.

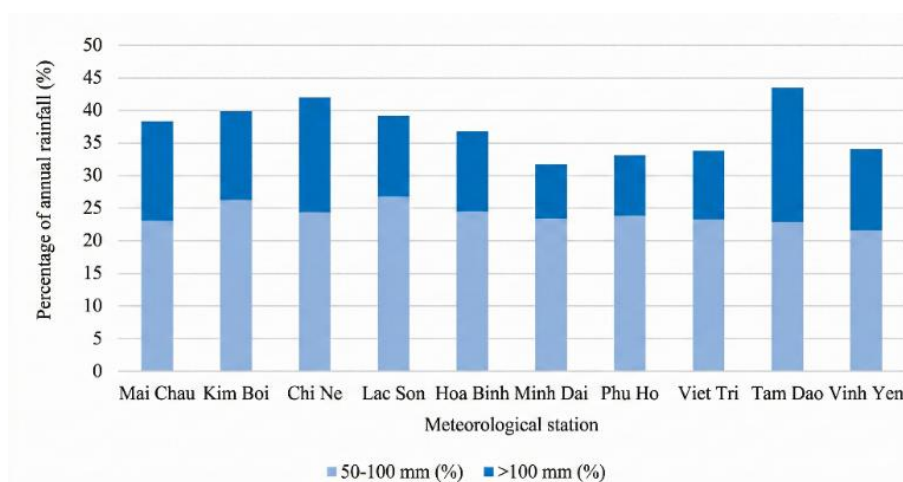


Figure 6. Contribution of heavy rainfall (≥ 50 mm/day) to total annual rainfall at meteorological stations in Phu Tho province during 1995–2024

In Figure 6, the lower segments of the bars represent rainfall intensities between 50 and 100 mm/day, while the upper segment denotes very heavy rainfall (≥ 100 mm/day). Collectively, these two components constitute the aggregate contribution of heavy rainfall (≥ 50 mm/day). This visualization highlights the internal composition of extreme precipitation, allowing for a clear distinction between moderately heavy and catastrophic rainfall levels.

Table 6. Contribution of heavy and very heavy rainfall to total annual rainfall in Phu Tho province (1995 - 2024)

No.	Station	Contribution of heavy rainfall (≥ 50 mm/day) (%)	Contribution of very heavy rainfall (≥ 100 mm/day) (%)
1	Mai Chau	38.37	15.25
2	Kim Boi	39.85	13.58
3	Chi Ne	42.03	17.56
4	Lac Son	39.25	12.41
5	Hoa Binh	36.87	12.33
6	Minh Dai	31.75	8.32
7	Phu Ho	33.22	9.27
8	Viet Tri	33.87	10.55
9	Tam Dao	43.55	20.61
10	Vinh Yen	34.13	12.50

Note. Contributions represent the percentage of total annual rainfall from heavy rainfall days (≥ 50 mm/day), within which very heavy rainfall days (≥ 100 mm/day) represent the highest intensity subset.

2.3. Discussion

The results indicate that precipitation characteristics in Phu Tho province exhibit pronounced spatial variability and notable climate change signals. Although long-term trends in total annual rainfall remain generally weak and statistically insignificant across the majority of stations, the prevalence of positive Sen’s slope values suggests an underlying upward trajectory in annual precipitation. This observed pattern aligns with regional climatological studies in northern Vietnam, which have similarly reported heterogeneous and non-uniform trends in total rainfall under the influence of global climate change [28], [29].

In contrast, shifts in rainfall extremes are significantly more pronounced. The increasing frequency of heavy rainfall events (≥ 50 mm/day) recorded at several stations - particularly within mountainous and transitional areas - is consistent with broader findings across Vietnam and Southeast Asia. In these regions, climate change impacts are primarily manifested through heightened rainfall intensity and the concentration of precipitation, rather than substantial changes in cumulative annual totals [8], [9].

Although very heavy rainfall events (≥ 100 mm/day) do not exhibit statistically significant trends, the elevated values of the Rx1day index underscore pronounced rainfall intensity extremes, particularly in high-elevation terrains. This observation is consistent with climatological literature, which emphasizes that extreme precipitation intensity can pose serious natural disaster risks even in the absence of detectable long-term monotonic trends [2], [5].

The relative stability of rainy season length across most stations suggests that recent climate change has had a limited influence on rainfall seasonality within the study area. This finding aligns with previous climatological research, which indicates that in monsoon-dominated regions, the signals of climate change are more conspicuous in rainfall intensity and extreme indices rather than in the temporal timing or duration of the seasonal cycle [30]. Consequently, while the "window" of the rainy season remains predictable, the internal volatility of precipitation within that window has significantly intensified.

Notably, heavy and very heavy rainfall events contribute a disproportionately large share of the total annual precipitation in the study area. The concentration of rainfall into a limited number of intense events is widely recognized as a primary driver of fluvial floods, flash floods, landslides, and urban inundation within rugged mountainous terrains [31], [32]. Consequently, these findings underscore the imperative of integrating extreme rainfall indicators – rather than just mean values – into disaster risk reduction (DRR) frameworks and climate change adaptation strategies. Such an approach is essential for enhancing the resilience of infrastructure and developing early warning systems tailored to high-intensity precipitation pulses.

3. Conclusions

This study provides a comprehensive assessment of rainfall variability, precipitation extremes, and rainy season characteristics in Phu Tho province over the 1995–2024 period. The findings demonstrate that while long-term trends in total annual rainfall remain generally weak and spatially heterogeneous, definite climate change signals are evident through the intensification of rainfall and the shifting nature of extreme precipitation indices. These localized shifts underscore a transition toward a more volatile hydrological regime, particularly in the province's mountainous and transitional zones.

Heavy and very heavy rainfall events contribute a disproportionately large share of the total annual precipitation, particularly within mountainous and transitional sectors. Although these very heavy rainfall episodes occur with low annual frequency, their extreme intensity and substantial volumetric contribution to annual totals significantly amplify the risks of fluvial floods, flash floods, landslides, and urban inundation. In contrast, shifts in rainy season duration are limited, indicating that contemporary climate change impacts in the study area are primarily manifested through intensified rainfall magnitude rather than alterations in rainfall seasonality.

These findings underscore the imperative of integrating extreme rainfall indicators and intensity-based thresholds into disaster risk reduction (DRR) and climate change adaptation (CCA) strategies within Phu Tho province, with a primary focus on vulnerable

mountainous regions. The results provide a robust scientific foundation for enhancing early warning systems (EWS), optimizing land-use planning, and informing climate-resilient infrastructure. Such measurements are critical for mitigating the escalating hydrological threats posed by intensified precipitation patterns under a shifting climatic regime.

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