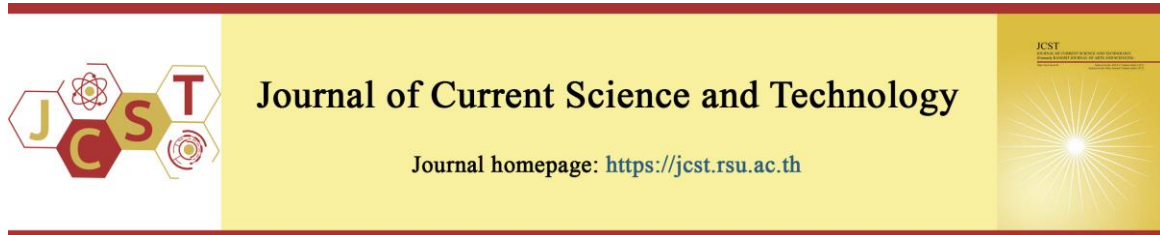


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Rainfall Variability Analysis Using Rolling Statistics in Chiang Rai Province

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Abstract

This study analyzed long-term rainfall variability in Chiang Rai Province (1981–2024) using rolling statistics and the non-parametric Mann–Kendall test to detect temporal changes in both the mean and variability of annual rainfall. Annual rainfall data from five meteorological locations were examined using 3-, 5-, 7-, and 12-year moving windows to characterize short-, medium-, and decadal-scale fluctuations. Although previous studies in northern Thailand have examined trends in total or extreme rainfall, multi-scale variability has not been systematically assessed, leaving uncertainty about how rainfall behavior is changing across different temporal windows. Results indicate that mean annual rainfall remains statistically stable ($p > 0.05$) at most locations, except for Wiang Pa Pao, which shows a significant upward trend ($Z = 3.79–5.35$). In contrast, the rolling standard deviation increased consistently across all locations, suggesting intensifying interannual variability. These findings indicate that rainfall in northern Thailand has become more unpredictable, with larger departures from the mean despite relatively stable long-term averages. The results point to practical needs for updating design-rainfall criteria and integrating variability-based assessments into regional water-resource and climate-adaptation planning.

Keywords: Chiang Rai; rainfall variability; rolling statistics; Mann–Kendall test; climate change

1. Introduction

Rainfall variability is a fundamental driver of hydrological processes and water resource availability. Increasing evidence indicates that climate change has intensified the irregularity and non-stationarity of rainfall patterns, posing systemic risks to water security, agriculture, and infrastructure resilience across tropical regions (Nassor et al., 2025; Praveen & Roy, 2022; UNDP, 2024). Thailand, located within

the Southeast Asian monsoon domain, has exhibited distinct temporal and spatial changes in rainfall characteristics, including shifts in seasonal intensity and the frequency of extreme events (Supharatid et al., 2022; Chaithong, 2023; Chaiwino et al., 2025). Spatial analyses further reveal that the increased occurrence of extreme precipitation is strongly associated with soil erosion, slope instability, and flash flooding in

mountainous catchments (Chaithong, 2023; Rojpratak & Supharatid, 2023).

The Coupled Model Intercomparison Project Phase 6 (CMIP6) has been widely employed as an inferential tool to assess potential climate change through intensive statistical analyses. The findings suggest that the mean precipitation in Southeast Asia is projected to increase by approximately 7–20% by the end of the century (Supharatid et al., 2022; Narudeesri-utai et al., 2025). In southern Thailand, research indicates that the probability distribution of severe daily rainfall is expected to have thicker tails under conditions of increased greenhouse gas emissions (Thapthai & Prathumchai, 2025).

Previous research on rainfall behavior in Thailand and surrounding regions has applied a variety of statistical approaches, each highlighting different aspects of hydro-climatic variability (Chitwatulsiri et al. 2025). Standardized indices such as SPI and SPEI have been widely used to classify drought and wetness conditions, while extreme-value models including the Generalized Extreme Value (GEV) and Generalized Pareto (GP) distributions have supported the estimation of high-intensity rainfall probabilities relevant to flood risk (de Oliveira-Júnior et al., 2025; Chaito & Khamkong, 2020). Trend detection in long-term hydrological series has frequently relied on the non-parametric Mann–Kendall test, which is effective for identifying monotonic changes in annual or seasonal rainfall totals (Gocic & Trajkovic, 2013; Chaisompran & Chaipimonplin, 2017). However, several studies have shown that stable long-term totals can mask substantial fluctuations at shorter time scales; for example, Calma & Fajardo (2025) found that annual rainfall in Central Luzon exhibited no significant trend using the MK test, even though monthly extremes intensified. ENSO-related anomalies further compound these fluctuations, with strong El Niño phases consistently associated with regional drought intensification (Srivichai, 2025). Collectively, these studies suggest that conventional trend and extreme-value analyses alone are insufficient for understanding how rainfall evolves across multiple temporal scales particularly in regions where interannual variability plays a dominant hydrological role (Jeeranant & Kampanart, 2021; Chanthon et al., 2021). This limitation is especially relevant in mountainous catchments, where short-term and

decadal fluctuations strongly influence runoff generation and water-resource vulnerability (Drake & Hogan, 2013; UNDP, 2013).

Chiang Rai Province, located in the headwater region of the Kok–Mekong River system, contains steep mountainous catchments where small shifts in seasonal rainfall can rapidly translate into water scarcity, elevated runoff, or flash-flood occurrences. These characteristics make the province particularly sensitive to changes in monsoon behavior and interannual variability. Although several studies in northern Thailand have assessed rainfall trends, extreme indices, or flood-generating events, multi-scale rainfall variability in Chiang Rai has not yet been examined systematically, leaving limited understanding of how short-term, medium-term, and decadal fluctuations shape hydrological conditions in this headwater environment. Addressing this knowledge gap is essential for improving interpretations of rainfall behavior and anticipating hydro-climatic risks in the province (UNDP, 2018; Hidayat et al., 2022).

2. Objectives

This study aims to quantify long-term, medium-term, and short-term rainfall variability in Chiang Rai Province by analyzing annual rainfall trends using the non-parametric Mann–Kendall test and evaluating multi-scale fluctuations through rolling statistical windows of 3-, 5-, 7-, and 12-years. By identifying the temporal dynamics of rainfall variability in this hydrologically sensitive region, the study provides empirical evidence to improve design rainfall estimation, strengthen water resources planning, and support climate-adaptation strategies under increasing hydro-climatic extremes.

3. Materials and Methods

This research was conducted to examine the monotonic trend and variability of annual rainfall in Chiang Rai Province using the CHIRPS satellite-based rainfall product, covering five main districts Chiang Rai, Phan, Wiang Pa Pao, Chiang Khong, and Mae Sai whose locations are shown in Figure 1. The data span the period from 1981 to 2024. Prior to analysis, data completeness and potential gaps were assessed and addressed to ensure the quality and continuity of the time series used in the statistical analysis with R.

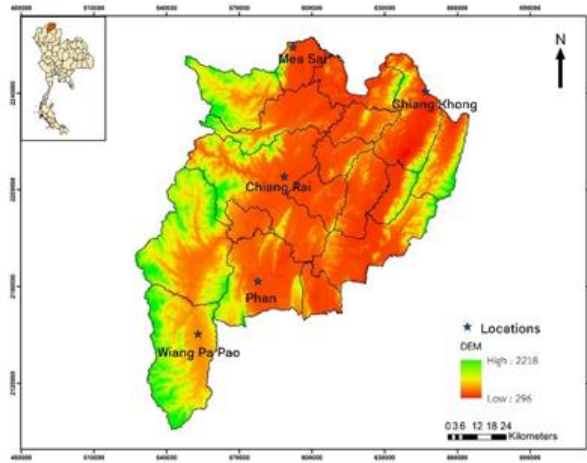


Figure 1 Locations of the five study districts in Chiang Rai Province.

The identification of statistically significant rainfall trends was performed using the Mann–Kendall test, which is a non-parametric statistical test suitable for hydrological time-series analysis without requiring any assumption of a normal distribution. It is widely applied for detecting trends in hydrological data series $X(x_1, x_2, \dots, x_n)$. The Mann–Kendall statistic (S) can be obtained from the following formula:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i)$$

$$\text{where } \text{sgn}(x_j - x_i) = \begin{cases} +1 & ; (x_j - x_i) > 0 \\ 0 & ; (x_j - x_i) = 0 \\ -1 & ; (x_j - x_i) < 0 \end{cases}$$

Where x_i and x_j are the data values at time i and j and $j > i$. The variable n represents the number of data points. For $n \geq 8$, the statistic S is approximately normally distributed, allowing the mean and variance to be expressed as follows:

$$V(S) = \frac{1}{18} [n(n-1)(2n-5) - \sum_{i=1}^n t_i i(i-1)(2i+5)]$$

where t_i is the number of tied groups of extent i

The test statistic Z is calculated as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{V(S)}} & ; S > 0 \\ 0 & ; S = 0 \\ \frac{S+1}{\sqrt{V(S)}} & ; S < 0 \end{cases}$$

The null hypothesis (H_0) of the test states that there is no statistically significant trend in the rainfall time series. The calculation uses the test statistic Z , which is derived from the S value (Mann–Kendall sum) and adjusted for tied values (tie correction) to determine the direction of the trend (increasing or decreasing) and the confidence level of the detected change.

Rolling window analysis was also applied in conjunction with the Mann–Kendall test. The test was performed on annual cumulative rainfall calculated as a moving average with time windows of 3-, 5-, 7-, and 12-years. These selected time intervals represent short-, medium-, and decadal-scale trends, respectively, allowing the distinction between natural variability and long-term climate change trends with greater clarity and depth.

4. Results

Figure 2 illustrates the descriptive statistical analysis of annual rainfall from five locations in Chiang Rai Province for the period 1981–2024. The data show that substantial year-to-year variation. For example, 1994 was noted as an extremely wet year, while other years such as 2006, 2017, 2022, and 2024 also had higher rainfall than the norm for the study period. In addition, among the locations, Wiang Pa Pao consistently had the lowest annual mean rainfall compared to the other locations. This could be due to local topography.

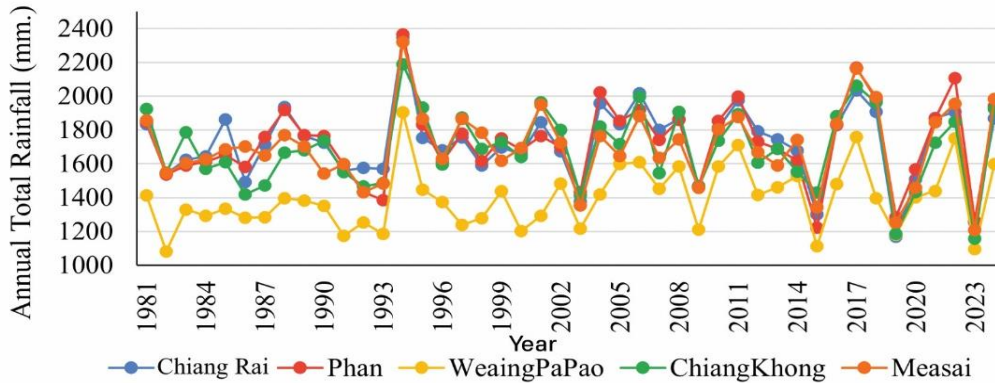


Figure 2 Annual total rainfall observed at five locations in Chiang Rai Province from 1981 to 2024

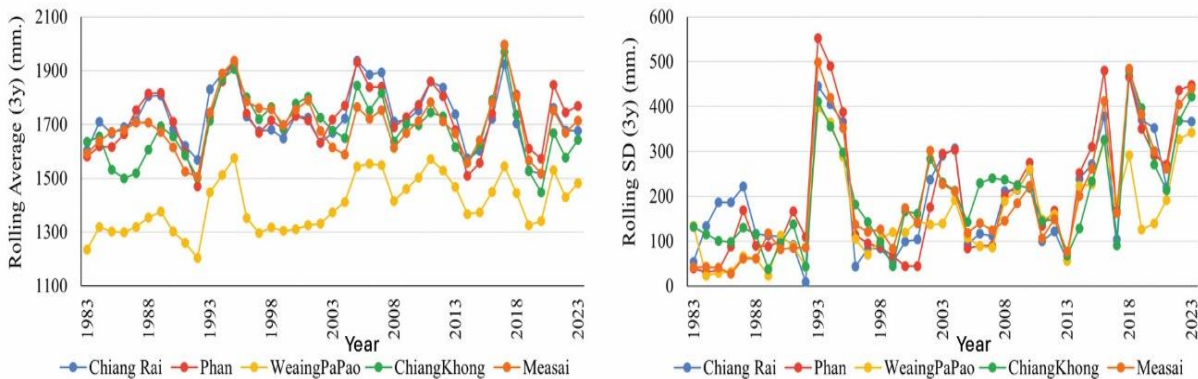


Figure 3 Three-year rolling of (a) mean of annual rainfall (b) standard deviation of annual rainfall

Figure 3a shows the 3-year rolling mean of rainfall across all locations in Chiang Rai Province. The overall mean rainfall remained consistent and showed no statistically significant trend. In contrast, Figure 3b shows the 3-year rolling standard deviation, indicating that rainfall variability at all locations increased over time. These results suggest that the likelihood of very high or very low rainfall years has increased over short, three-year periods. This indicates that rainfall variability is increasing even as mean values remain relatively consistent. As a result, the area is experiencing more frequent years with both excessive and insufficient rainfall. The increased uncertainty has significant implications on water resources engineering, particularly in the design of flood protection systems, reservoir management, and the planning of drainage systems for urban and agricultural areas, all of which must adapt to the growing risk of extreme rainfall events.

Figures 4a and 5a show the 5-year and 7-year rolling means, respectively. The average rainfall remained roughly the same, similar to the 3-year analysis. In contrast, Wiang Pa Pao showed a continuous increase, whereas the other locations changed only slightly at certain times. Figures 4b and 5b illustrate the 5-year and 7-year rolling standard deviations, respectively. These show larger changes in rainfall variability over time than the 3-year period, notably after 2000. The results indicate that medium-term rainfall variability (5–7 years) has intensified and become more persistent than short-term changes. Departures from the mean have increased over the past five years compared with the beginning of the study period. This higher level of uncertainty has important implications for engineering planning and design. For instance, it affects the selection of design-rainfall parameters for hydrological and drainage systems that must accommodate increasingly intense and frequent extreme rainfall events in the future.

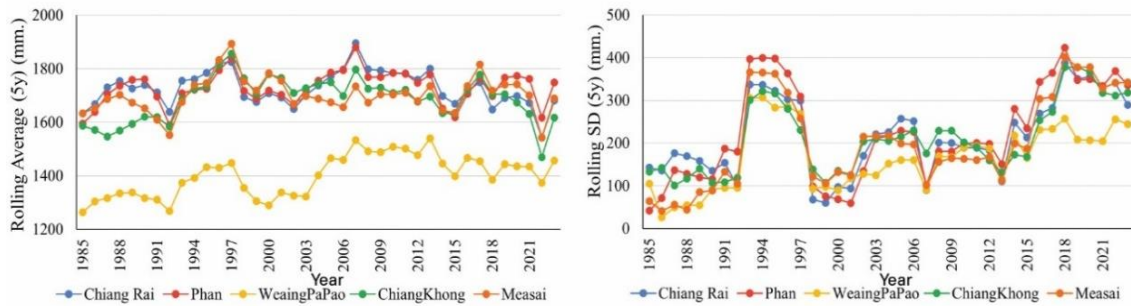


Figure 4 Five-year rolling of (a) mean of annual rainfall (b) standard deviation of annual rainfall

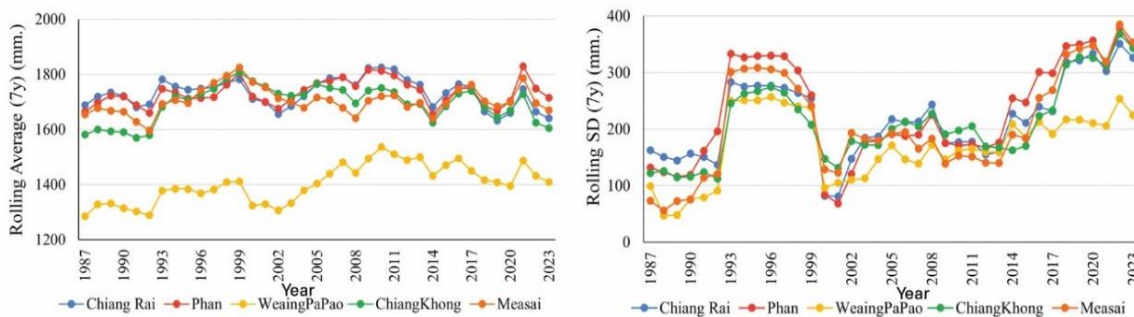


Figure 5 Seven year rolling of (a) mean of annual rainfall (b) standard deviation of annual rainfall

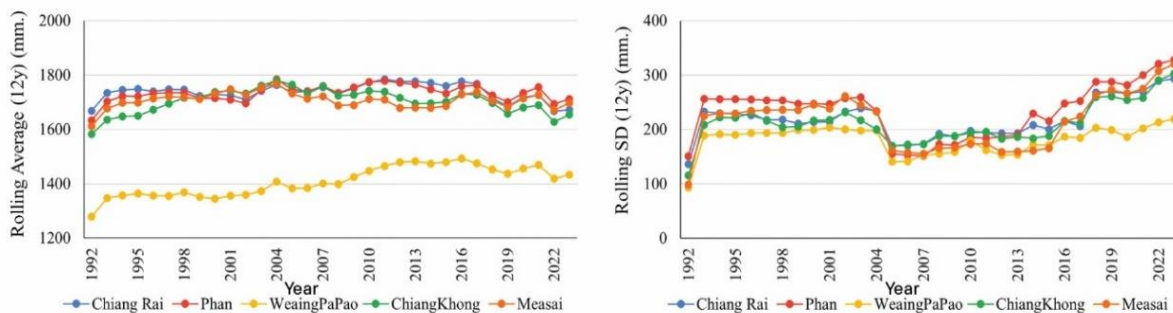


Figure 6 Twelve -year rolling of (a) mean of annual rainfall (b) standard deviation of annual rainfall

Figures 6a and 6b show the 12-year rolling mean and rolling standard deviation (SD). The results suggest that the long-term average rainfall did not change substantially at any location, except for Wiang Pa Pao, which exhibited a clear upward trend. The mean and SD curves are smoother when a longer averaging window is used than when 3–7 years are used because year-to-year changes become less pronounced. The SD still shows a rising trend, indicating that, from an engineering perspective, long-term uncertainty persists. This suggests that engineers designing hydraulic structures such as dams, reservoirs, and drainage systems should consider changes in rainfall variability even when the mean

remains stable. This will help ensure that these structures can withstand more intense and more frequent rainstorms in the future.

The analysis of the rolling standard deviation (SD) of annual cumulative rainfall revealed trend changes that depended on the averaging window employed. Over the three-year period, precipitation levels exhibited significant annual fluctuations; however, the signal remained relatively stable. Conversely, analyses with 5–7-year intervals obscured short-term fluctuations, resulting in smoother trend lines that indicated a more consistent increase. This enhances our understanding of the declining predictability of rainfall over a decade.

Table 1 Mann–Kendall test results of rolling statistics (3-, 5-, 7-, and 12-year periods)

| Location | Period (year) | Rolling Mean (Z, p) | Trend of Mean | Rolling SD (Z, p) | Trend of SD |
|--------------|---------------|---------------------|---------------|-------------------|-------------|
| Chiang Rai | 3 | 0.24 (0.812) | ↑ | 2.47 (0.013)* | ↑ |
| Chiang Rai | 5 | −0.36 (0.718) | ↓ | 2.95 (0.003)* | ↑ |
| Chiang Rai | 7 | −0.03 (0.980) | ↓ | 3.02 (0.003)* | ↑ |
| Chiang Rai | 12 | 0.60 (0.546) | ↑ | 1.91 (0.057) | ↑ |
| Phan | 3 | 1.56 (0.119) | ↑ | 3.42 (0.001)* | ↑ |
| Phan | 5 | 1.53 (0.127) | ↑ | 3.51 (0.000)* | ↑ |
| Phan | 7 | 1.79 (0.074) | ↑ | 3.14 (0.002)* | ↑ |
| Phan | 12 | 1.78 (0.075) | ↑ | 1.84 (0.065) | ↑ |
| Wiang Pa Pao | 3 | 3.79 (0.000)* | ↑ | 3.94 (0.000)* | ↑ |
| Wiang Pa Pao | 5 | 3.95 (0.000)* | ↑ | 3.88 (0.000)* | ↑ |
| Wiang Pa Pao | 7 | 4.55 (0.000)* | ↑ | 3.19 (0.001)* | ↑ |
| Wiang Pa Pao | 12 | 5.35 (0.000)* | ↑ | 1.78 (0.075) | ↑ |
| Chiang Khong | 3 | 0.13 (0.897) | ↑ | 2.99 (0.003)* | ↑ |
| Chiang Khong | 5 | 0.29 (0.771) | ↑ | 3.46 (0.001)* | ↑ |
| Chiang Khong | 7 | 0.30 (0.763) | ↑ | 3.22 (0.001)* | ↑ |
| Chiang Khong | 12 | 0.11 (0.914) | ↑ | 2.22 (0.027)* | ↑ |
| Mae Sai | 3 | 0.52 (0.603) | ↑ | 4.49 (0.000)* | ↑ |
| Mae Sai | 5 | 1.11 (0.268) | ↑ | 4.00 (0.000)* | ↑ |
| Mae Sai | 7 | 1.21 (0.227) | ↑ | 3.47 (0.001)* | ↑ |
| Mae Sai | 12 | −0.08 (0.938) | ↓ | 1.91 (0.057) | ↑ |

Note: * $p < 0.05$ indicates statistical significance.

↑ increasing trend, ↓ decreasing trend.

The 12-year analysis still indicated an upward trend. However, the change was less discernible because the longer averaging period reduced signal clarity. Although the standard deviation trend is less evident in short- and medium-term evaluations, the overall evidence indicates that precipitation variability warrants long-term consideration.

Table 1 summarizes the Mann–Kendall test results applied to rolling statistics using 3-, 5-, 7-, and 12-year windows. The rolling mean rainfall does not exhibit statistically significant monotonic trends at most locations across all window sizes. Wiang Pa Pao is the only location showing consistently high positive Z-values and statistically significant p-values ($p < \alpha$) for all rolling windows, indicating a persistent increasing tendency in mean annual rainfall at this site.

In contrast, the rolling standard deviation (SD) shows predominantly positive Z-values at all locations, with statistically significant trends observed mainly for the 3–7 year windows. This pattern indicates a systematic increase in rainfall variability over time. These results suggest that while long-term mean rainfall has remained relatively stable at most locations, the dispersion of rainfall values has

increased, reflecting growing interannual variability and statistical uncertainty in annual rainfall behavior.

5. Discussion

This study examined annual rainfall patterns in Chiang Rai Province using rolling windows of 3-, 5-, 7-, and 12-years, together with the Mann–Kendall test, to assess temporal changes. The results indicate that long-term mean rainfall shows no statistically significant trend at most locations, with Wiang Pa Pao being the only site exhibiting a persistent upward trend. In contrast, the rolling standard deviation increased significantly across all locations, implying greater year-to-year variability despite stable annual totals. This pattern is consistent with previous national-scale findings by Limsakul & Singhruck (2016), who reported that although total annual rainfall in Thailand has remained broadly stable, indices reflecting rainfall intensity and variability have increased markedly. Similar conclusions were reached by Chueasa et al. (2024), who showed that ENSO phases and changes in large-scale circulation, such as the Walker circulation strongly influence rainfall variability in Thailand. In northern Thailand, the southwest monsoon remains a major moisture source, shaping much of the seasonal rainfall regime.

Recent increases in rainfall variability in northern Thailand may also reflect the influence of evolving atmospheric processes under a warming climate. Three mechanisms are particularly relevant: (1) Atmospheric rivers (ARs), which transport concentrated corridors of moisture and can produce prolonged, high-accumulation rainfall; (2) rain bombs or microbursts, which generate short-lived but intense convective downpours over limited areas; and (3) the seasonal monsoon circulation, which forms the background moisture environment over mainland Southeast Asia. When AR events or strong convective storms interact with the monsoon flow, rainfall can become unusually prolonged or abruptly intense. These interacting processes offer a physical explanation for the significant increases in rolling standard deviation identified in this study and are consistent with CMIP6 projections indicating that extreme rainfall events are likely to intensify even if annual totals remain relatively unchanged (Supharatid & Nafung, 2021).

The distinctive behavior observed at Wiang Pa Pao, where both mean rainfall and variability increased, may be partly linked to its transitional topographic position between mountainous terrain and lowland valleys. Such settings can enhance convective development and orographic lifting, making them more sensitive to monsoon surges, AR-related moisture plumes, and localized convective bursts. As rainfall variability continues to rise, water-resource planning in Chiang Rai will benefit from placing greater emphasis on changing rainfall patterns rather than relying solely on long-term means. In practical terms, design rainfall criteria, safety margins for reservoirs, drainage capacity, and early-warning thresholds should be revisited to incorporate the increasing unpredictability of rainfall patterns. Proactive and adaptive measures will be necessary to reduce flood and drought risks under a changing climate.

These interpretations should be considered in light of several study limitations. The analysis relies on satellite-based rainfall data and a limited number of representative locations, which may not fully capture microscale variability in complex mountainous terrain. In addition, the focus on annual rainfall aggregates does not explicitly resolve sub-seasonal extremes. Future studies should therefore integrate denser gauge networks, higher temporal resolution data, and impact-based metrics to further refine assessments of rainfall variability and associated risks.

6. Conclusion

The analysis of annual rainfall in Chiang Rai Province during 1981–2024 using rolling statistics and the Mann–Kendall test showed that annual mean rainfall was generally stable at most locations, except for Wiang Pa Pao, which exhibited a clear increasing trend with statistical significance. Rainfall variability, however, has increased continuously at all locations, especially for the short- to medium-term windows (3–7 years). This indicates higher rainfall uncertainty even though mean rainfall has not changed much. These results suggest that future water resources management should place greater emphasis on rainfall variability and uncertainty rather than focusing only on mean values. This will help improve design rainfall criteria and increase the flexibility of drainage systems, dams, and reservoirs to cope with more frequent and intense extreme rainfall events under changing climate conditions.

Future studies could extend this work by examining rainfall variability using higher-frequency datasets to capture short-duration extremes relevant to flash-flood early warning and urban drainage design. In addition, coupling rainfall variability with hydrological or land–atmosphere models would help clarify how fluctuations translate into runoff responses across different catchments in Chiang Rai Province. Advanced analytical techniques such as machine-learning or Bayesian approaches may further improve the prediction of rainfall anomalies, particularly during ENSO or monsoon transition periods. Finally, future research may incorporate bias-adjusted CMIP6 projections to assess how rainfall variability could evolve under different climate-warming scenarios, supporting long-term adaptation planning.

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8. Abbreviations

| Abbreviation | Full Term |
|--------------|--|
| ARs | Atmospheric Rivers |
| CHIRPS | Climate Hazards Group InfraRed Precipitation with Station data |
| CMIP6 | Coupled Model Intercomparison Project Phase 6 |
| ENSO | El Niño–Southern Oscillation |
| GEV | Generalized Extreme Value |
| GP | Generalized Pareto |
| MK test | Mann–Kendall test |
| SD | Standard Deviation |
| SPEI | Standardized Precipitation Evapotranspiration Index |
| SPI | Standardized Precipitation Index |

9. CRediT Statement

Noppharat Techaphanrattanakul:

Conceptualization, Methodology, Data Curation, Formal Analysis, Software, Writing – Review & Editing.

Kanoktip Anorat: Validation.

Suruswadee Nanglae: Methodology.

Pongpan Kanjanakaron: Conceptualization, Data Curation.

Mongkorn Srivichai: Conceptualization, Methodology, Resources, Writing – Original Draft, Project Administration, Writing – Review & Editing.

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