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Research Article

Potential risks of landslides in the context of increasing extreme rainfall events in mountainous regions of Nghe An province

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Abstract

This study investigates the potential risks of landslides in mountainous regions of Nghe An province, Vietnam under the impacts of increasing extreme rainfall events. Using nonparametric statistical methods including Mann-Kendall test and Sen's slope estimator, the study analyzed rainfall trends from 1998-2020 across four observation stations. The analysis focused on rainfall in September, October and maximum rainfall intensity, which historically correlate with landslide occurrences in the region. Results reveal statistically significant upward trends in rainfall intensity across all stations, with particularly strong signals in September (Zs=6.50, p=0.05) and October (Zs=5.42, p=0.09) at Dua station. The Sen's slope estimates indicate substantial increasing trends, ranging from 4.90 to 6.48 for September and 4.00 to 8.60 for October. The significant upward trends in extreme rainfall events (β=5.96-9.90) further amplify these risks. This research underscores the urgent need for enhanced landslide risk management strategies in Nghe An's mountainous regions, particularly during the typhoon season when rainfall intensities are projected to continue increasing.

Keywords: *Landslides, extreme rainfall, trend, Mann-Kendall test, mountainous regions.*

1. Introduction

Landslides in mountainous regions can have devastating impacts on society, causing property losses, affecting poor people and ethnic minorities in rural and mountainous regions [3, 4]. The Intergovernmental Panel on Climate Change (IPCC) has highlighted that hydro-geomorphological events, such as landslides, have increased throughout the last century and are expected to further rise as a direct consequence of climate change [6, 7]. Global warming is projected to increase the frequency and intensity of severe rainfall events, a primary trigger of rapid-moving landslides that cause many landslide fatalities [1, 2].

Rainfall is considered as the main factor for landslides in mountainous regions around the world, and extreme rainfall is the most important physical process for landslide triggering [9, 10]. Anthropogenic factors, such as increasing population, urbanization in hazardous areas, deforestation, and land use change, amplify the negative consequences and increase the exposure of people and infrastructures to disaster risk [8, 11]. Climate change is expected to cause an increase in the frequency of intense rainfall events in some regions, leading to an increase in the occurrence of hydro-geomorphological disasters [12, 13]. Studies have shown that climate change has a significant impact on landslides, with studies emphasizing the importance of analyzing changing trends in rainfall and updating regional rainfall thresholds to be considered for triggering landslides. Araújo et al. (2022) [4] stressed the importance of analyzing the changing trends in rainfall and consequently the regular updating of regional rainfall thresholds to be considered for the triggering of landslides. According to Vijith and Dodge (2017), the most important physical process for landslide triggering is extreme rainfall. Besides, meteorological factors that trigger landslide events, anthropogenic factors, like increasing urbanization in hazardous areas, deforestation, and land use conversion, leading to the negative consequences of the disaster risks [14, 16]. Furthermore, based on projected variations in rainfall conditions at regional scale, Alvioli et al. (2018) [3] highlighted that rainfall is mainly factor for landslides in the mountainous region around the world. Recent works, also, analyzed future rainfall conditions based on climate scenarios to evaluate landslide susceptibility [16, 18].

Nghe An Province of Vietnam, including the mountainous regions have suffered increasingly from landslides due to heavy rainfall events, as part of the impact of climate change and anthropogenic activities. Climate change is expected to increase extreme climate and weather events, such as heavy rainfall, flash floods, typhoons, and wildfires, which are recorded as unusual and rare events in mountainous regions in Nghe An Province. Anthropogenic activities, such as expanding agriculture, burning forests for farming, and harvesting uncontrollably timber, have contributed to increasing soil degradation and further lead to landslides and soil erosion. The main objective of this study is to investigate the changed trends of heavy rainfall events across the mountainous regions of Nghe An Province for predicting the potential risks of landslides in the context of increased extreme rainfall events.

2. Materials and methods

2.1. Description of the study area

This study was carried out at mountainous regions located in Nghe An Province, Vietnam [8]. The study area is characterized by diverse topographic conditions, ranging from flat plains to steep terrain, with elevations from 1 mm to 1500 mm above mean sea level (Figure 1).

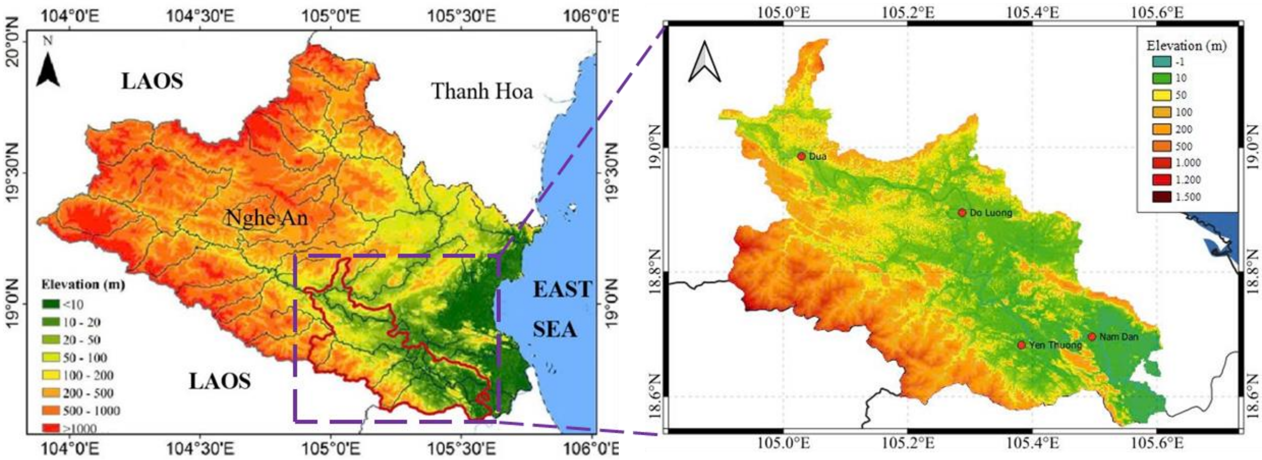

Figure 1: Illustration of topographic map of the study area

The terrain is gradually tilted from north to south and from west to east [8]. Nghe An Province is located in the tropical monsoon climate zone, with two distinct seasons summer and winter with average annual rainfall ranges from 1,200 mm to 2,000 mm (Figure 2) and average annual temperature is from 23°C to 24°C [8]. In winter, it is commonly affected by the cold and humid northeast monsoon [8]. The study area is facing landslides and soil erosion due to anthropogenic activities and climate change. Mountainous regions are threatened by high rates of soil loss by landslides and erosion (Figure 3).

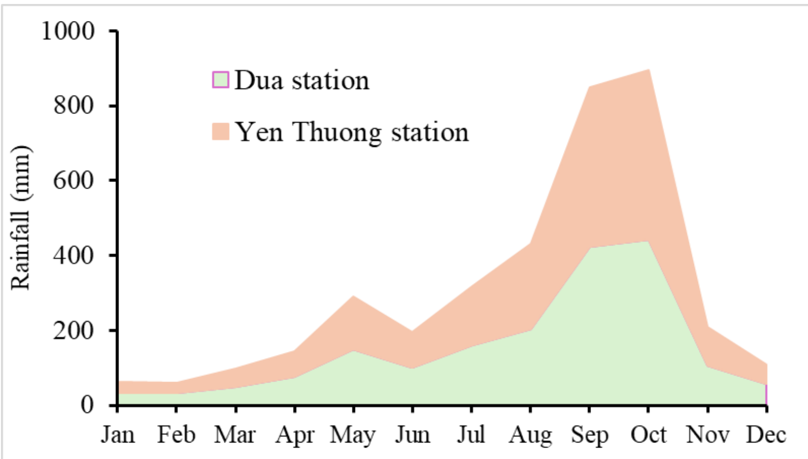

Figure 2: Distribution of monthly rainfall at gauge stations across the study area

Anthropogenic activities have contributed to exposing bare soil areas without forest cover, causing the potential risks for landslides and soil erosion [3, 4, 6] while heavy rainfall events, cyclones, and tropical storms have appeared frequently in the rainy season period from May to November, and especially heavy rainfall occurred after storms usually concentrated in September and October every year (Figure 2), causing flash floods result in landslides and soil erosion [3, 5].

Figure 3: Heavy rainfall event caused a) flash floods in Nghe An province (source: Health and Life newspaper published on 02 October 2022) and b) serious landslides at National Highway 46 through Ru Nguoc (source: Anh sang and Cuoc Song newspaper published on 30 October 2020)

2.2 Data analysis approach methods

2.2.1 Coefficient of variation

This investigation employs a comprehensive statistical framework to analyze rainfall patterns, incorporating both variability metrics and trend detection methodologies. The analytical approach encompasses four primary statistical tools: standard deviation (SD), coefficient of variation (CV), Mann-Kendall test, and Sen's slope estimator.

The September, October and extreme rainfall variability was analyzed using Equation 1 to define SD.

$$SD = \sqrt{(R_I - \bar{R})^2} \qquad (1)$$

where: SD is the standard deviation, R is mean monthly rainfall; N: the total number of years

To quantify rainfall variability, the CV is applied to provide a dimensionless measure of dispersion. The CV framework categorizes rainfall variability into three distinct classifications: minimal variation (CV < 20), intermediate variation (20 < CV < 30), and pronounced variation (CV > 30). This classification system enables the identification of temporal rainfall stability and potential extreme events within the dataset.

$$CV = \frac{\sqrt{(R_I - \bar{R})^2}}{\bar{R}} \qquad (2)$$

2.2.2 Mann-Kendall test

For trend detection, the study utilized the Mann-Kendall test, a robust non-parametric statistical approach particularly suited for hydrometeorological time series analysis. This methodology offers several advantages over parametric alternatives, including distribution-independent analysis, resilience to outlier influence, capability to handle missing values and effectiveness in detecting monotonic trends. The Mann-Kendall test operates by evaluating the correlation between data points and their temporal rankings, facilitating trend detection even in the presence of serial correlation. This approach proves particularly valuable when analyzing non-normally distributed hydroclimatic data series. The test statistic is calculated as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{Sign}\,(X_j - X_i) \qquad (3)$$

Where Sign $(X_j - X_i)$ is defined based on formula (4)

$$\mathrm{Sign}\,(X_j - X_i) = \begin{cases} +1 & \text{if } x_j - x_i > 0 \\ 0 & \text{if } x_j - x_i = 0 \\ -1 & \text{if } x_j - x_i < 0 \end{cases} \qquad (4)$$

With X_j, X_i are the annual data series and j, i with the condition is j > i.

and variance (Var) is defined by formula (5).

$$\mathrm{Var(S)} = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{j=1}^{m} t_j(t_j-1)(2t_j+5)\right] \quad (5)$$

In the formula (5), m and t_j are the number of the tied groups and the number of ties to extent j in the data series.
For the sample size n > 10, the values of S and Var(S) are defined by the statistics of standard test (Z_s) and, Z_s is given follow as:

$$Z_S = \begin{cases} \frac{S-1}{\sqrt{\mathrm{Var(S)}}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S-1}{\sqrt{\mathrm{Var(S)}}} & \text{if } S < 0 \end{cases} \quad (6)$$

And S in the formula (6) is calculated by formula (7)

$$\tau = \frac{S}{D} \quad (7)$$

D in Formula (7) is defined by formula (8)

$$D = \left[\frac{1}{2}n(n-1) - \frac{1}{2}\sum_{j=1}^{m} t_j(t_j-1)\right]^{\frac{1}{2}}\left[\frac{1}{2}n(n-1)\right]^{\frac{1}{2}} \quad (8)$$

The statistic Z_s test is applied to detect the monotonous tendencies. Where Z_s in formula (6) will present an upward trend if Z_S is positive, otherwise Z_S will describe a downward trend (Attogouinon et al. 2017).

2.2.3 Sen's slope estimator

To complement the trend detection analysis, the study also employed Sen's slope estimator, a non-parametric technique that quantifies the magnitude of identified trends. This method calculates the median slope among all possible pairs of observations in the time series, providing a robust measure of trend intensity that remains unaffected by outliers or data gaps.
The Sen's slope is defined as follow:

$$Q_i = \frac{x_j - x_k}{j-k} \quad \text{with } j \neq k \quad (9)$$

Where x_j and x_k are the data values at times j and k (j > k), correspondingly.

The statistical significance of identified trends was evaluated using a 95% confidence interval framework. Under this approach, trends were considered statistically significant when the absolute value of the standardized test statistic (|Zs|) exceeded 1.96, corresponding to the critical threshold for rejecting the null hypothesis of no trend. This rigorous statistical framework ensures reliable identification of meaningful temporal changes in precipitation patterns while minimizing the likelihood of false positive results.

3. Results and discussion

3.1 Basic characteristics of rainfall

The analysis of basic characteristics of rainfall features at Yen Thuong, Dua, Do Luong and Nam Dan in September are presented in Table 1. The mean rainfall values for these months are 424.4 mm, 332.2 mm, 369.2 mm and 424.2 mm, respectively. The minimum rainfall values at these stations in September are 65.6 mm, 82.6 mm, 82.6 mm and 127.5 mm, respectively while the maximum rainfall values are 826.8 mm, 662.9 mm, 646.5 mm and 824.2 mm. In terms of SD, the values for September are 192.2 mm, 185.0 mm, 173.5 mm and 189.7 mm, respectively. These values indicate that the rainfall data for these months exhibit relatively high variability. The CV for rainfall in September is 0.45, 0.55, 0.47 and 0.44, respectively. The basic characteristics of rainfall features at these stations in October are also presented in Table 2. The mean rainfall values for these months are 443.2 mm, 303.5 mm, 368.3 mm and 451.3 mm, respectively. The corresponding values of minimum rainfall in October are 73.4 mm, 29.0 mm, 15.1 mm and 77.5 mm, respectively while the maximum rainfall values are 1106.6 mm, 932.6 mm, 1108.9 mm and 1177.1 mm. In terms of SD, these values for October are 315.0 mm, 233.3 mm, 295.3 mm and 327.6 mm, respectively. These values indicate that the rainfall data for October exhibit relatively high variability. The CV for rainfall in October is 0.71, 0.76, 0.80 and 0.72, respectively.

Table 1: Basic rainfall features across the study area during the period 1989-2020

Station	Min (mm)	Max (mm)	Mean (mm)	SD (mm)	CV (%)	Skewness	Kurtosis
Yen Thuong station							
September	65.6	826.8	424.4	192.2	0.45	0.32	-0.45
October	73.4	1106.6	443.2	315.0	0.71	0.55	-0.75
Dua							

September	82.6	662.9	332.2	185.0	0.55	0.48	-1.34
October	29.0	932.6	303.5	233.3	0.76	1.08	0.86
Do Luong station							
September	82.6	646.5	369.2	173.5	0.47	0.13	-1.26
October	15.1	1108.9	368.3	295.3	0.80	1.10	0.79
Nam Dan station							
September	127.5	824.2	424.2	189.7	0.44	0.44	-0.46
October	77.5	1177.1	451.3	327.6	0.72	0.69	-0.51

Based on the data in Table 1, the analysis shows that skewness and kurtosis values at Yen Thuong, Dua, Do Luong and Nam Dan stations are 0.32 and -0.45, 0.48 and -1.34, 0.13 and -1.26, and 0.44 and -0.46 for rainfall in September. These indicates that the distribution of rainfall data in September across the study area is not symmetrical, with some high rainfall values significantly higher than the average. For rainfall in October, the analysis reveals that the analysis shows that skewness and kurtosis values at Yen Thuong, Dua, Do Luong and Nam Dan stations are 0.55 and -0.75, 1.08 and 0.86, 1.10 and 0.79, and 0.69 and -0.51. These results imply that that the distribution of rainfall data in October in the study area is not symmetrical, with some high rainfall values significantly higher than the average.

3.2 Change trends of rainfall features

Analysis of rainfall trends in September and October across four stations (Yen Thuong, Dua, Do Luong and Nam Dan) during the period 1989-2020 are presented in Table 2, Figure 4 and Figure 5. At Dua station, the most significant trend is observed with a Mann-Kendall test statistic (Zs) of 6.50 and a p-value of 0.05, indicating a statistically significant upward trend at the 95% confidence level. The Sen's slope (β) of 5.69 shows a substantial increase trend of rainfall in September. Yen Thuong station shows a moderate upward trend (Zs = 5.12, p = 0.10) with a Sen's slope of 4.90. Do Luong station exhibits similar characteristics with Zs = 5.0 (p = 0.11) and the highest Sen's slope among all stations at 6.48. Nam Dan station shows a significant upward trend at the 95% confidence level (Zs = 4.15, p = 0.16) but maintains a considerable Sen's slope of 6.20.

Table 2: Trend of rainfall variables across the study area during the period 1989-2020

Rainfall	Yen Thuong			Dua			Do Luong			Nam Dan		
	MKz	p	β	MKz	p	β	MKz	p	β	MKz	p	β
Sep.	5.12	0.10	4.90	6.50	0.05	5.69	5.0	0.11	6.48	4.15	0.16	6.20
Oct.	2.70	0.31	6.63	5.42	0.09	8.60	1.97	0.35	4.00	2.51	0.36	5.57
Rmax	5.21	0.10	5.96	2.84	0.025	6.37	6.11	0.06	8.35	4.37	0.14	9.90

MKz- Kendall's tau; p-Critical value; β-Sen's slope

For October rainfall Patterns, the trends in rainfall are generally less pronounced compared to September (Figure 4). Dua station again shows the strongest trend with Zs = 5.42, p = 0.09 and the highest Sen's slope of 8.60, indicating a substantial increase in rainfall intensity. Yen Thuong station demonstrates a moderate trend (Zs = 2.70, p = 0.31) with a Sen's slope of 6.63. Do Luong and Nam Dan stations show a statistically significant upward with Zs values of 1.97 and 2.51 respectively, and p-values exceeding 0.35, suggesting a significant increase trend in September rainfall patterns.

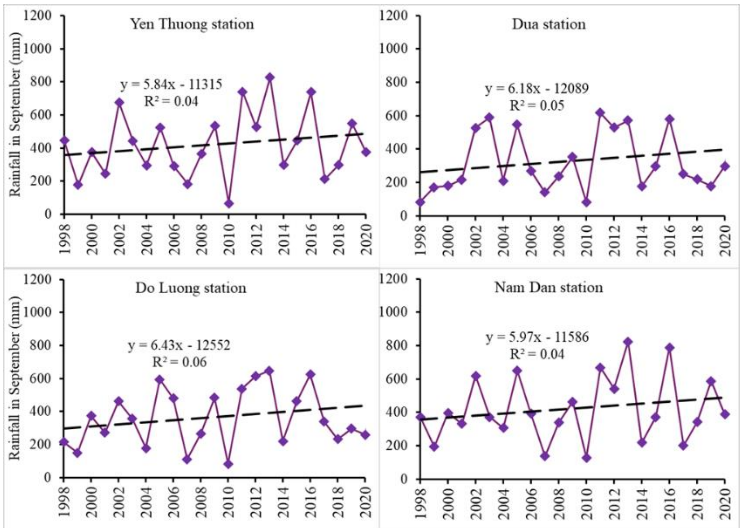

Figure 4: Rainfall trends in September across the study area during the period 1998-2020

All stations consistently show positive Zs values across both months, indicating an overall upward trend in rainfall amounts. The trends exceed the critical value of |Zs| > 1.96 required for statistical significance at the 95% confidence level. The strongest signals are observed in September, particularly at Dua station, which approaches statistical significance with its lowest p-value of 0.05. The Sen's slope estimates reveal substantial trends of change, with October generally showing higher trends of increase compared to September, despite having lower statistical values. This suggests that while October rainfall is increasing more rapidly in absolute terms, the rainfall in October is more variable and less consistent than the September trends (Figure 5).

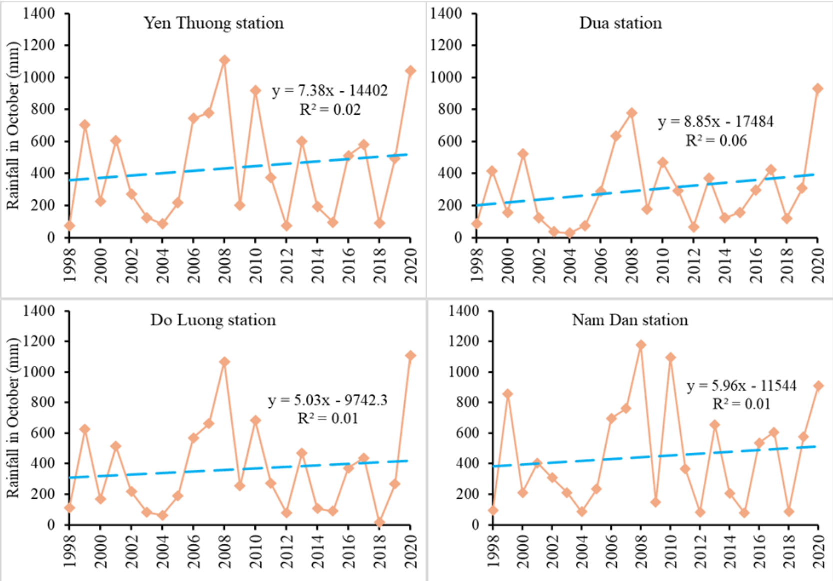

Figure 5: Rainfall trends in September across the study area during the period 1998-2020

In overall, while all stations exhibit positive trends in rainfall during both months, the changes are more pronounced and consistent in October. Dua station consistently shows the strongest trends, while Nam Dan generally exhibits the weakest statistical signals. These findings suggest a general intensification of rainfall patterns across the study area, particularly during the early autumn period with most trends of statistical significance at the 95% confidence level.

The analysis of maximum rainfall intensity (Rmax) across Yen Thuong, Dua, Do Luong, and Nam Dan stations during the period 1998-2020 are presented in Table 2 and Figure 6. The results reveal positive trends, indicating a general increase in maximum rainfall intensity throughout the study period. Do Luong station demonstrates the most pronounced trend with an MKz value of 6.11 and a p-value of 0.06, approaching statistical significance at the 95% confidence level. The Sen's slope of 8.35 indicates a substantial rate of increase in maximum rainfall intensity, suggesting a notable intensification of extreme rainfall events at this location. For Yen Thuong Station, the analysis reveals a strong positive trend with an MKz value of 5.21 (p = 0.10).

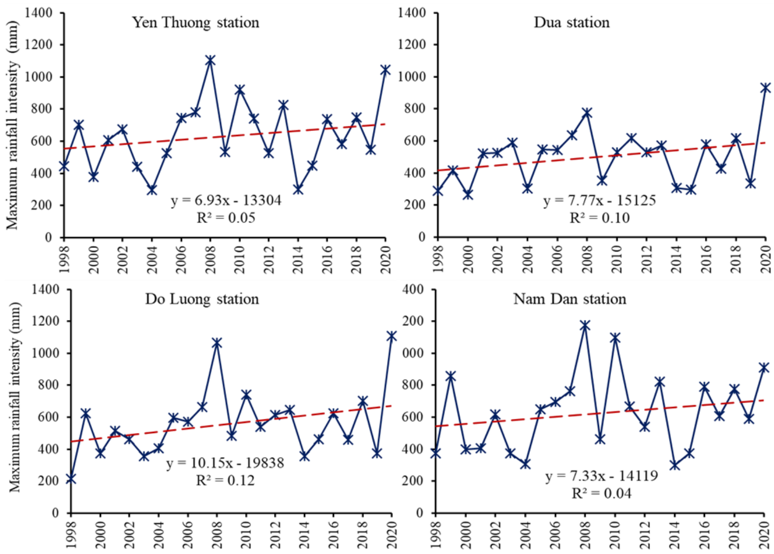

Figure 6: Trends of the intensity of maximum rainfall across the study area during the period 1998-2020

The Sen's slope estimator indicates an increase of 5.96, suggesting a consistent strengthening of maximum rainfall events. For Dua station, the results show the most statistically significant trend with the lowest p-value (0.025) among all stations, though with a relatively lower MKz value of 2.84. The Sen's slope of 6.37 indicates a steady increase in Rmax, providing strong evidence of changing rainfall patterns. For Nam Dan station, the results show the Sen's slope value up to 9.90, exhibiting a moderate MKz value of 4.37 with a p-value of 0.14. This suggests that despite having the highest rate of change, the trend shows more variability compared to other stations

4. Conclusion

This study presents a comprehensive analysis of rainfall patterns in September, October and maximum rainfall intensity and their potential implications for landslide risks in the mountainous regions of Nghe An province. The analysis revealed significant upward trends in rainfall intensity during September and October from 1998 to 2020 across the study area. The Mann-Kendall test results showed particularly strong positive trends at Dua station ($Zs = 6.50$, $p = 0.05$) for September rainfall, with substantial Sen's slope values ranging from 4.90 to 6.48 across stations. October rainfall exhibited even higher increasing rates, with Sen's slope values reaching up to 8.60 at Dua station.

These findings indicate a concerning intensification of rainfall patterns in the region, particularly during the most critical months for landslide occurrence. The combination of increasing rainfall trends with the area's steep topography and anthropogenic factors significantly elevates the risk of landslides and flash floods. The results suggest a high probability of more frequent and severe hydro geomorphological risks in the future. This heightened risk requires immediate attention from local authorities to develop and implement appropriate disaster risk reduction strategies, including early warning systems, land-use planning reforms, and enhanced forest management practices to protect vulnerable communities in these mountainous regions.

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