ANALYSIS OF EXTREME RAINFALL SCENARIOS AND LANDSLIDE SUSCEPTIBILITY IN THE MOUNTAINOUS REGION OF PHU THO PROVINCE UNDER THE IMPACTS OF CLIMATE CHANGE

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Abstract: *This study assesses the impacts of climate change on rainfall patterns and landslide risk in Cao Phong District, Phu Tho Province, with a particular focus on Bac Phong commune - a high-risk area. Climate data were bias-corrected from three regional climate models (PRECIS, CCAM, clWRF) under two emission scenarios (RCP4.5 and RCP8.5), using quantile mapping for statistical adjustment. Analyses for the periods 2016-2035, 2046-2065, and 2080-2099, relative to the baseline (1986-2005), reveal a pronounced increase in annual precipitation. Under RCP4.5, rainfall is projected to increase by +2.3% to +11.7%, while under RCP8.5, increases reach up to +12.5% by the end of the century. Rainfall during the wet season also rises substantially, by approximately +10.6-10.7%.*

Extreme rainfall analysis indicates that about 82.5% of the district's area is exposed to daily precipitation exceeding 270 mm - a threshold that triggers landslides in steep terrain with limited vegetation cover. Three rainfall-landslide hazard scenarios were developed: Low (P20), mean, and high (P80). Integrating these scenarios with topographic, geological, and land-use factors shows that areas of high and very high landslide susceptibility may account for more than 50% of the total area, concentrated mainly in the Southeastern part of the commune. The resulting landslide hazard zoning map provides an essential tool for early warning, climate-adapted planning, and disaster risk management in the context of climate change.

Keywords: *Climate change, extreme rainfall, landslide susceptibility, RCP scenarios, Cao Phong District.*

1. Introduction

Landslides are among the most common natural hazards in mountainous regions of Viet Nam, causing severe losses of life and property over recent decades. Numerous national studies have indicated that the primary driver is extreme rainfall, compounded by steep topographic conditions and declining vegetation cover. According to Nguyen Huy Cuong et al. (2020) [1], predictions of soil mass displacement based on geotechnical monitoring data at Hai Van Pass revealed that rainfall with an intensity of 27.5 mm/hour over 5 hours, or 5.68 mm/hour sustained for 22 hours, can trigger ground movement.

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In recent studies, rainfall thresholds for landslide occurrence have been more clearly defined. The work Geologic controls and rainfall thresholds for landslide occurrence in Northern Viet Nam (Nguyen H. Thang et al., 2024) [2] analyzed the relationship between seasonal rainfall and landslide events, providing critical data on rainfall thresholds to support early warning systems.

In Viet Nam, Nguyen Thanh Long & De Smedt (2019) [3], in their study Analysis and Mapping of Rainfall-Induced Landslide Susceptibility in A Luoi District, Thua Thien Hue, employed factors such as soil cover, topography, land use, and rainfall to develop a landslide susceptibility map. The model demonstrated a relatively high AUC value (>0.8), reflecting strong predictive performance.

The Analytic Hierarchy Process (AHP) combined with GIS has also been widely applied in domestic studies. For instance, the study Landslide susceptibility and zoning in the Son La hydroelectricity area (Tran Anh Tuan & Nguyen Tu Dan, Institute of Geology and Geophysics, 2023) [4] applied AHP to evaluate and zone landslide hazards using influencing factors such as slope, elevation, rainfall, and soil cover.

The AHP method (Analytic Hierarchy Process) proposed by Saaty (1980, 1990) [5, 6] is a multi-criteria decision-making tool frequently used to determine factor weights in GIS-based spatial analysis. AHP enables pairwise comparisons of factors on a 1-9 scale, constructing a comparison matrix to derive weights. Its strength lies in the ability to integrate both qualitative and quantitative criteria while ensuring consistency checks, making it widely applicable in natural hazard studies, particularly in the development of landslide hazard maps.

Natural disasters in former Hoa Binh Province (now part of Phu Tho) (Figure 1) have become increasingly complex, causing substantial damage to human lives, property, and the living and production environment of local communities, with estimated losses of 1.0-1.5% of GDP annually. In 2017 and 2020, several extreme flood and landslide events were recorded, such as the landslide threatening 24 households in Rong Vong village, which required the urgent evacuation of 106 people. However, disaster prevention remains limited due to ineffective forecasting, lack of specialized personnel, and insufficient integration of disaster risks into spatial planning. Climate change further exacerbates the irregularity of natural hazards. Between 2006 and 2018, numerous adverse events were reported in Hoa Binh Province, driving the implementation of several local research initiatives [7]. Despite the availability of provincial- and district-scale landslide hazard zoning maps, limitations remain in integrating future climate scenarios, extreme rainfall thresholds, and spatio-temporal uncertainties into hazard prediction models.

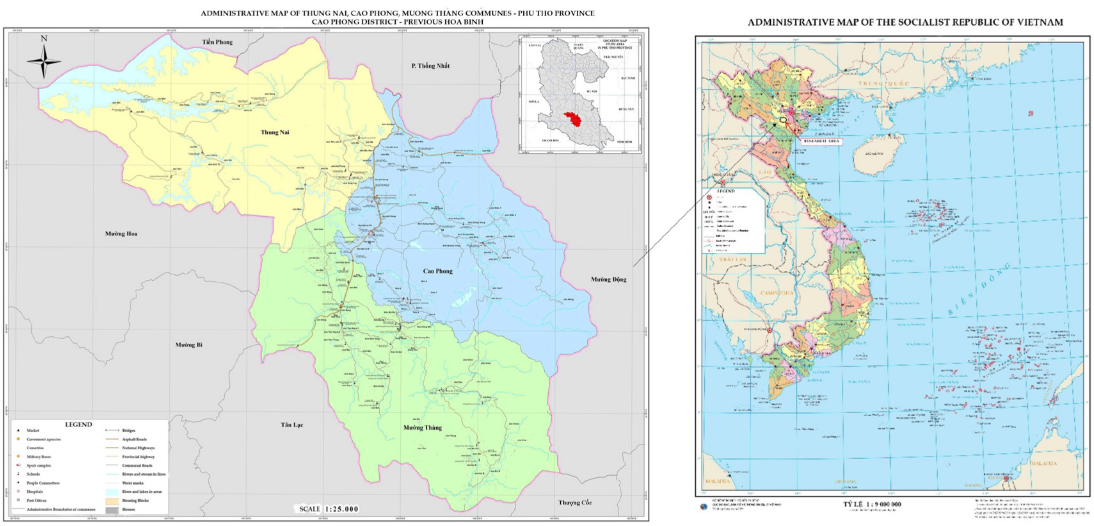

Figure 1. Location of the study area: Cao Phong Commune - Phu Tho Province - Viet Nam

Therefore, this study focuses on Bac Phong commune, Cao Phong District, Phu Tho Province with the following objectives: (i) To analyze the variability of extreme rainfall under future climate scenarios; (ii) To develop a GIS-AHP-based landslide hazard zoning map by assigning weights to influencing factors; and (iii) To assess uncertainty in rainfall scenarios and expand the warning model across low, medium, and high hazard levels.

The findings will provide scientific evidence to support spatial planning, resource management, and the development of climate-adaptive livelihood models at the local level.

2. Methodology

2.1. Climate data and climate change scenarios

Climate datasets were generated from three high-resolution regional climate models: PRECIS (UK), CCAM (Australia), and clWRF (USA), using boundary conditions from global circulation models (GCMs) within the CMIP5 project under two emission scenarios, RCP4.5 and RCP8.5. Climate projections for Hoa Binh province were analyzed for three future time slices: 2016-2035, 2046-2065, and 2080-2099, relative to the baseline period 1986-2005, consistent with AR5 (IPCC, 2013) [8] and the updated national climate scenarios of Viet Nam (MONRE, 2020) [9].

2.2. Rainfall bias correction using the Quantile Mapping (QM) method

To address systematic biases in dynamical climate simulations, the Quantile Mapping (QM) approach was applied to correct daily rainfall series. Observational data from five meteorological stations (Chi Ne, Hoa Binh, Kim Boi, Lac Son, and Mai Chau) were used as references.

Tools: The QM method was implemented in R, using the qmap and climdex.pcic packages to adjust the simulated rainfall distribution.

Evaluation of correction performance: Statistical indicators were calculated for each model and station, both before and after bias correction, including:

• ME (Mean Error): Representing systematic deviations.

• MAE (Mean Absolute Error) and RMSE (Root Mean Square Error): Reflecting overall discrepancies.

• Correlation coefficient (R): Measuring linear dependence between simulations and observations.

• Taylor diagram: Providing a visual assessment of the relationships among standard deviation, correlation, and RMSE.

These results demonstrate the effectiveness of the QM method and serve as the basis for selecting models in subsequent analyses (Figure 2).

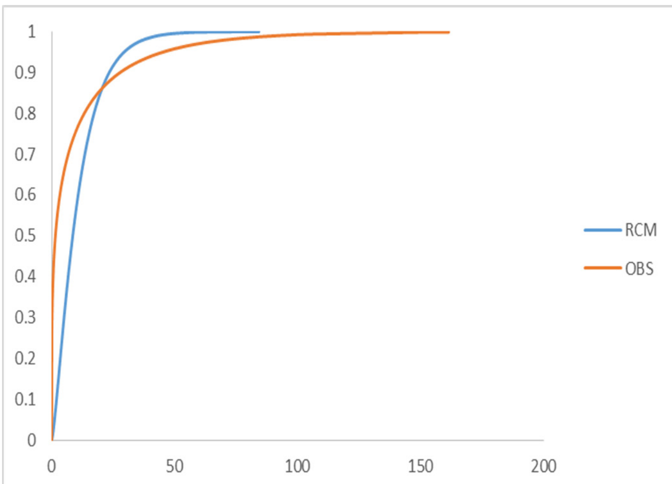

Figure 2. Illustration of cumulative rainfall distribution (red: observation, blue: model)

2.3. Treatment of uncertainty in climate scenarios

This study incorporates uncertainty ranges through a multi-model ensemble approach, consistent with the guidelines for developing national climate scenarios (MONRE, 2020). Specifically:

The ensemble mean is considered the most probable projection.

The uncertainty range is defined using the 20th-80th percentiles for rainfall, reflecting the variability among climate models.

This approach ensures consistency with the national scenarios while providing a robust scientific basis for landslide risk assessment.

2.4. Extreme rainfall analysis and rainfall intensity mapping

After bias correction, the daily rainfall series was used for extreme value analysis following the Extreme Value Theory (EVT). The main steps included:

Homogeneity testing: The Discordancy test was applied to detect and remove anomalous data series.

Probability distribution fitting: Commonly used distributions (Gumbel, GEV, GLO) were examined, and the optimal distribution was selected based on statistical criteria (K-S, AIC, BIC).

Trend analysis: The Mann-Kendall and Spearman's Rho tests at a 5% significance level (α = 0.05) were applied to assess temporal trends in extreme rainfall.

From the EVT results, rainfall thresholds for landslide initiation were determined using the P20-P80 percentile range to account for uncertainty. Based on this, three families of extreme rainfall scenarios were constructed: low (P20), medium (Mean), and high (P80). These scenarios were then integrated with topographic (slope), geological, and land-use data to develop landslide hazard zoning maps.

Spatial interpolation: Extreme rainfall parameters were interpolated using Kriging to generate extreme rainfall intensity maps for recurrence intervals (T = 5, 10, 50, 100 years).

Cross-validation of spatial interpolation:

Kriging produced the lowest errors (BIAS ≈ ±3%, RMSE ≈ 12-18 mm/day).

IDW and Spline methods showed higher errors (RMSE > 20 mm/day).

Accordingly, Kriging was selected as the optimal method for constructing extreme rainfall intensity maps.

2.5. Landslide hazard mapping using GIS-AHP

The bias-corrected extreme rainfall data were integrated with topographic, pedological, lithological, and land-use factors within a GIS environment. The weights of these factors were determined using the Analytic Hierarchy Process (AHP) following Saaty's (1980) priority scale, in which pairwise comparisons were performed to assess relative importance and to verify the consistency ratio (CR) of the matrix. After normalization, the information layers were integrated in GIS to produce the landslide hazard zoning map [10].

In this study, eight major factors were considered: Elevation, slope, aspect, curvature, drainage density, land use, lithology, and soil type. Input datasets were obtained from DEM, base maps, thematic maps, and field surveys; they were then processed in ArcGIS and overlaid using the Raster Calculator tool to generate the landslide susceptibility map.

Factor weights were derived from expert-based pairwise comparisons using the AHP method, ensuring a consistency ratio of less than 0.1. Each factor was classified into sub-classes and assigned influence weights on a scale from 1 to 9. The overlay results produced a spatially explicit landslide susceptibility zoning map [11], [12]. The accuracy of the model was validated using the Receiver Operating Characteristic (ROC) curve based on actual landslide inventory data.

2.6. Research framework for landslide hazard zoning

Step 1. Climate and climate change scenarios

Regional climate models PRECIS, CCAM, and clWRF → RCP4.5/8.5 (2016-2035, 2046-2065, 2080-2099).

Step 2. Rainfall bias correction (QM)

Observations from 5 meteorological stations → implemented in R (qmap package) → evaluation using ME, RMSE, and correlation (R).

Step 3. Extreme rainfall and scenario construction

Probability distributions (GEV, Gumbel, GLO) → P20-P80 (three scenarios) → spatial interpolation using Kriging.

Step 4. GIS-AHP integration

Factors: Slope, elevation, aspect, curvature, drainage density, lithology, soil, and land use → weighting (CR < 0.1) → spatial overlay in ArcGIS.

Step 5. Validation and application

ROC-AUC validation → landslide hazard zoning maps → application for early warning and spatial planning.

3. Results and Discussion

3.1. Annual rainfall variability under climate change impacts according to the RCP4.5 scenario

The percentage change in annual average rainfall at meteorological stations and in 10 communes of old Hoa Binh Province (now Phu Tho Province) across three future periods (2016-2035, 2046-2065, and 2080-2099), compared with the baseline period, under the RCP4.5 climate change scenario. Among them, Bac Phong Commune of Cao Phong District is a representative location, with detailed data presented in the following Table 1.

Table 1. Change in annual average rainfall (%) at Bắc Phong - Cao Phong under the RCP4.5 scenario (Values in parentheses represent the variation around the mean, with the lower bound at the 20th percentile and the upper bound at the 80th percentile

Period	Mean change	Uncertainty range (P20-P80)
2016-2035	+2.3%	(-4.3% → +9.0%)
2046-2065	+5.1%	(+1.0% → +9.6%)
2080-2099	+11.7%	(+5.4% → +18.6%)

Note: The "+" sign indicates an increase compared with the baseline period

Findings from Table 1:

Trend of increasing rainfall:

2016-2035: Mean change: +2.3% compared with the present → a slight increase, nearly stable. Range (P20-P80): From -4.3% to +9.0% → rainfall may decrease in some years/scenarios (negative values), but the overall trend remains upward. This is a period of small, unclear fluctuations, reflecting high uncertainty.

2046-2065: Mean change: +5.1% → rainfall is expected to increase more noticeably. Range: From +1.0% to +9.6% → the entire forecast range indicates an increase, with no scenario showing a decrease. This demonstrates a more certain trend of rainfall increase, though the growth rate is not very large.

2080-2099: Mean change: +11.7% → a strong increase, nearly double that of the mid-century period. Range: From +5.4% to +18.6% → a relatively wide increase margin, but all scenarios predict growth. The late-century period is projected to experience a significant rise in rainfall, leading to risks of waterlogging, flooding, and soil erosion, while also potentially enhancing water resources for production.

Overall, annual rainfall at Bắc Phong shows a gradual upward trend over time. The early period (2016-2035) remains highly uncertain, but from mid-century onwards, the trend of increase becomes more certain and pronounced. This is consistent with the RCP4.5 scenario (medium emission reduction), in which the climate system continues to warm, leading to more water vapor in the atmosphere.

The increase in rainfall, especially during the rainy season, is a key factor driving higher surface runoff in mountainous areas such as Cao Phong. When prolonged heavy rainfall or more frequent extreme rain events occur, rapid surface water flow intensifies, destabilizing soil structure and weakening slopes - creating favorable conditions for landslides.

3.2. Annual rainfall variability (%) at Bắc Phong - Cao Phong under the RCP8.5 scenario

In addition to the RCP4.5 scenario, the future trend of increasing rainfall in the study area is also clearly evident under the RCP8.5 scenario - a high-emission scenario that reflects more severe climate change impacts on rainfall patterns at Bắc Phong - Cao Phong, as shown in Table 2.

Findings from Table 2:

2016-2035: Mean change: +0.6% → almost negligible, indicating a very slight upward trend. Uncertainty range (P20-P80): -5.2% to +6.9% → high uncertainty, rainfall could either decrease or increase depending on the scenario. This period shows no clear evidence of an increasing trend.

Table 2. Change in annual average rainfall (%) at Bắc Phong - Cao Phong under the RCP8.5 scenario (Values in parentheses represent the variation around the mean, with the lower bound at the 20th percentile and the upper bound at the 80th percentile)

Period	Mean change	Uncertainty range (P20–P80)
2016-2035	+0.6%	(-5.2% → +6.9%)
2046-2065	+5.8%	(+0.5% → +10.7%)
2080-2099	+12.5%	(+4.1% → +20.5%)

Note: The "+" sign indicates an increase compared with the baseline period

2046-2065: Mean change: +5.8% → a more pronounced increase, similar to the RCP4.5 scenario. Range: +0.5% to +10.7% → most scenarios predict an increase, with the lower bound just above zero. The upward trend in rainfall begins to become more certain, though some variability remains.

2080-2099: Mean change: +12.5% → the strongest increase, exceeding that of RCP4.5 (+11.7%). Range: +4.1% to +20.5% → indicating a high certainty of increased rainfall but with a relatively wide uncertainty range. By the end of the century, rainfall at Bắc Phong is projected to increase significantly, potentially leading to severe flooding, waterlogging, and soil erosion.

Overall trend: Similar to RCP4.5, annual rainfall shows a gradual increase toward the end of the century; however, under RCP8.5, the magnitude of increase is higher and more extreme.

3.3. Rainy season rainfall variability (%) at Bắc Phong - Cao Phong under the RCP4.5 scenario

In addition to monitoring annual rainfall changes, assessing variations in rainy season precipitation (%) is particularly crucial, as this period contributes the majority of surface runoff and represents the most sensitive window for landslide hazards induced by prolonged heavy rainfall under climate change, as illustrated in Table 3.

The data in Table 3 illustrate projected changes in rainy season precipitation at Bắc Phong - Cao Phong under the RCP4.5 scenario, reflecting rainfall variability during the period most critical for surface runoff and disaster risk:

2016-2035: Mean change: 0.0% → almost no difference compared with the baseline. Uncertainty range (P20-P80): -6.0% to +6.3% → high uncertainty, indicating potential minor increases or decreases. The trend is unclear, reflecting relative short-term stability.

2046-2065: Mean change: +2.7% → a slight upward trend begins to emerge. Range: -0.2% to +5.7% → most scenarios indicate an increase, although minor decreases remain possible (close to zero). This period shows initial signs of increasing rainfall, though the signal is not yet strong.

2080-2099: Mean change: +10.6% → a pronounced increase, substantially higher than the previous periods. Range: +6.6% to +14.7% → all scenarios project an increase, with a relatively narrow uncertainty range. This period confirms a significant upward trend in rainy season precipitation with high confidence.

Table 3. Projected changes in rainy season precipitation (%) at Bắc Phong - Cao Phong under the RCP4.5 scenario (Values in parentheses represent the variation around the mean, with the lower bound at the 20th percentile and the upper bound at the 80th percentile)

Period	Mean change	Uncertainty range (P20-P80)
2016-2035	0.0%	(–6.0% → +6.3%)
2046-2065	+2.7%	(–0.2% → +5.7%)
2080-2099	+10.6%	(+6.6% → +14.7%)

The "+" sign indicates an increase relative to the baseline period

Overall trend: In the short term (2016-2035), rainy season rainfall shows no significant change. From mid-century (2046-2065), an increasing trend emerges, and by the end of the century (2080-2099), rainfall is projected to rise markedly and with high certainty. This implies that both the intensity and frequency of heavy rainfall during the rainy season may increase, leading to higher risks of flooding, waterlogging, and landslides.

3.4. Increasing Trend of Rainy Season Precipitation at Bắc Phong - Cao Phong under the RCP8.5 Scenario

Monitoring rainfall during the rainy season is essential for accurately tracking and assessing increases in precipitation driven by climate change. Such analysis is critical for forecasting surface runoff and issuing timely warnings of landslide risks, thereby enabling local authorities to proactively implement disaster prevention and mitigation measures, Table 4 presents the projected changes in rainy-season precipitation (%) at Bắc Phong-Cao Phong under the RCP8.5 scenario, highlighting the potential increase in rainfall intensity toward the end of the 21st century.

The results in Table 4 illustrate the projected changes in rainy season precipitation at Bắc Phong - Cao Phong under the high-emission RCP8.5 scenario as follows:

2016-2035: Mean change: +2.3% → the rainy season shows a slight upward trend. Uncertainty range (P20-P80): -2.0% to +6.7% → small decreases remain possible, but the overall trend leans toward an increase. This period exhibits relatively high variability, and confidence in the trend is still limited.

2046-2065: Mean change: +4.5% → a more pronounced increase compared with the previous period. Range: -1.0% to +9.3% → most scenarios indicate increasing precipitation, although minor decreases cannot be entirely ruled out. The upward trend becomes clearer, yet some uncertainty persists.

2080-2099: Mean change: +10.7% → a substantial increase, comparable to the RCP4.5 scenario for the same period (+10.6%). Range: +5.8% to +15.6% → all scenarios project an increase with higher confidence. This period confirms a strong and significant upward trend in rainy season precipitation.

Overall trend: In the short term (2016-2035), rainy season rainfall increases only slightly and remains variable. By mid-century (2046-2065), the upward trend becomes more pronounced but not yet fully certain. By the end of the century (2080-2099), rainy season precipitation is projected to increase substantially and with high confidence, indicating a heightened risk of flash floods, waterlogging, and landslides in the local area.

Table 4. Projected changes in rainy season precipitation (%) at Bắc Phong-Cao Phong under the RCP8.5 scenario (Values in parentheses represent the uncertainty range, with the lower bound at the 20th percentile and the upper bound at the 80th percentile)

Period	Mean change	Uncertainty range (P20-P80)
2016-2035	+2.3%	(-2.0% → +6.7%)
2046-2065	+4.5%	(-1.0% → +9.3%)
2080-2099	+10.7%	(+5.8% → +15.6%)

The "+" sign indicates an increase relative to the baseline period

3.5. Rainfall Intensity and Landslide Risk

Rainfall intensity plays a critical role in triggering landslide events, particularly in areas with steep topography such as Cao Phong District. Analysis of the data indicates that most of the district falls within the threshold for extreme daily rainfall, exceeding 270 mm/day. The classification of areas by rainfall intensity in Cao Phong District, Phu Tho Province is presented in Table 5.

Analysis of the area statistics by rainfall intensity class (Table 5) and the spatial distribution map of maximum daily rainfall (Figure 3) indicates that a majority of Cao

Phong District is affected by very high-intensity rainfall events. Specifically, approximately 82.52% of the district experiences extreme daily rainfall between 270-295 mm/day, primarily concentrated in the Northern and Northwestern areas, as indicated by darker green shades on the map. In contrast, areas with rainfall below 270 mm/day account for only 17.48%, scattered in the Southern and Southeastern parts of the district, represented by lighter green shades.

Extreme rainfall intensity is a key meteorological factor that triggers landslides and flash floods on steep, poorly vegetated terrain. When rainfall exceeds the threshold within a short period, the soil rapidly reaches saturation, reducing cohesion and increasing the likelihood of slope instability.

The 270-295 mm/day threshold was determined based on case studies in Northern mountainous regions of Viet Nam, particularly referencing the Ministry of Natural Resources and Environment (MONRE, 2020), which identified that daily rainfall >250 mm in steep, weak-soil areas is a strong landslide trigger. International studies, such as Glade et al. (2000), similarly report that daily rainfall exceeding 200-300 mm represents a critical threshold in many hilly regions with slopes >15° and poor vegetation cover.

Table 5. Area by rainfall intensity classification in Cao Phong District, Phu Tho Province

No	Classification Level	Area (ha)	Percentage
1	<270 mm/ngày	4,491.047	17.48%
2	270 - 295 mm/ngày	21,205.883	82.52%
	Total	25,696.930	100.00%

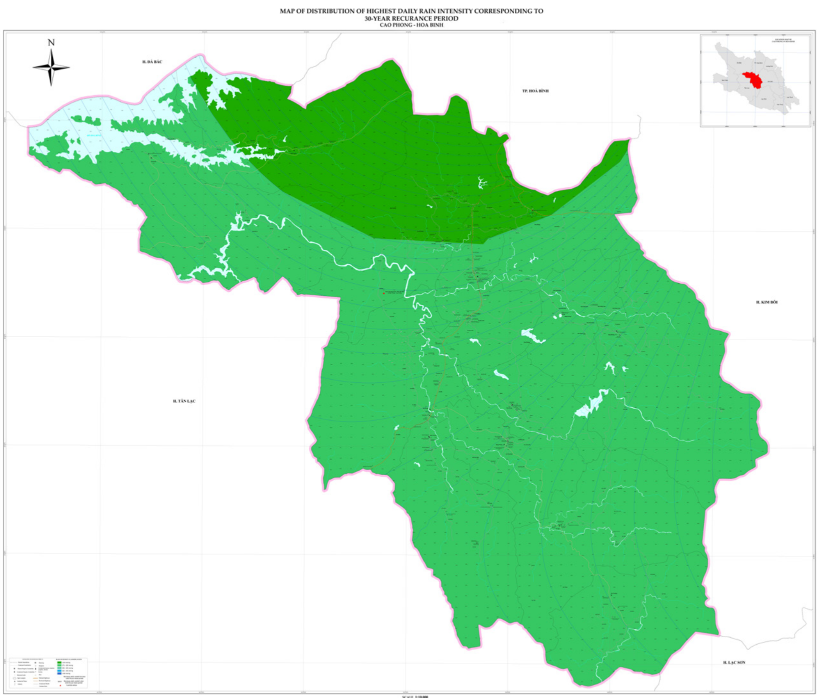

Figure 3. Maximum daily rainfall intensity distribution map in Cao Phong District, Phu Tho Province. CRS: VN-2000, central meridian 105°E, projection UTM Zone 48N. Scale: 1:10,000. Legend: light green - <270 mm/day; dark green - 270-295 mm/day

The analysis shows that approximately 82.52% of Cao Phong District experiences very high rainfall within the 270-295 mm/day range. This threshold was not arbitrarily chosen but determined through Extreme Value Analysis of the annual maximum series at Bắc Phong station. The Generalized Extreme Value (GEV) distribution was selected based on the Akaike Information Criterion (AIC), and the resulting 270-295 mm/day value falls within the 20th-80th percentile confidence interval (P20-P80) for a 50-year return period, reflecting the uncertainty of climate model simulations. This threshold aligns with historical heavy rainfall events that have caused local flooding and landslides. According to MONRE (2020), daily rainfall >250 mm on steep, weak-soil slopes is sufficient to trigger significant landslides. Internationally, critical thresholds of 200-300 mm/day have been reported [13]. Therefore, the 270-295 mm/day threshold used in this study is both statistically robust and consistent with observed local conditions. In Viet Nam, Nguyen Huy Cuong et al. (2020) demonstrated that 27.5 mm/hour for 5 hours or 5.68 mm/hour for 22 hours is sufficient to trigger ground displacement in the Hai Van Pass area.

These findings provide a critical scientific basis for identifying priority areas for monitoring and early warning, as well as for planning effective disaster risk management and water resource strategies at the local level.

3.6. Development of Three Rainfall Scenario Families and Landslide Risk

To reflect the degree of uncertainty, three families of scenarios were constructed based on percentiles of the extreme rainfall series: To reflect the degree of uncertainty, three families of scenarios were constructed based on percentiles of the extreme rainfall series: The summary of extreme rainfall scenario families and high landslide risk areas in Cao Phong District is presented in Table 6.

Table 6. Summary of extreme rainfall scenario families and high landslide risk areas in Cao Phong District

Scenario	Extreme Rainfall Threshold (mm/day)	High-Risk Area (%)
Low(P20)	~250	< 20%
Medium(Mean)	~270	30-40%
High (P80)	295-300	> 50%

The three extreme rainfall scenario families (P20 - Mean - P80) illustrate a clear increase in landslide risk with rising extreme rainfall intensity:

+ Low scenario (P20, ~250 mm/day):

High-risk areas account for less than 20% of the total district area.

The risk is scattered, mainly on steep slopes and weak soil locations.

This represents a relatively optimistic scenario, corresponding to rare extreme rainfall events.

+ Medium scenario (Mean, ~270 mm/day):

The proportion of high-risk areas increases to approximately 30-40%.

Areas along slopes, narrow valleys, and transitional terrain begin to experience significant impact.

This scenario is the most likely to occur, reflecting the existing risk under current and near-future climatic conditions.

+ High scenario (P80, 295-300 mm/day):

High and very high-risk areas exceed 50% of the total district area, with concentrations primarily in the Southeastern part of the district.

This represents the most pessimistic scenario, indicating that extreme rainfall could destabilize more than half of the district.

If realized, simultaneous measures such as early warning, population relocation, and spatial planning are necessary to mitigate potential losses.

The results demonstrate that as rainfall becomes more extreme, the area at risk of landslides increases, confirming that extreme rainfall is the key triggering factor for landslides in Cao Phong. The large differences among the three scenarios (from <20% to >50%) reflect the high uncertainty associated with climate change. These findings underscore the importance of constructing multiple scenario families to prepare for different response strategies: Managing current conditions (low scenario), enhancing early warning systems (medium scenario), and land-use planning and resettlement (high scenario).

3.7. Landslide Risk Zonation Integrating Extreme Rainfall, Topography, Geology, and Land Use

Landslide risk zonation integrating extreme rainfall, slope, and land-use data is essential for identifying sensitive and vulnerable areas. This approach supports spatial planning, early warning, and mitigation of disaster impacts.

The landslide risk map for Cao Phong District was developed by integrating extreme rainfall, topography, soil, lithology, and land-use data within a GIS framework. The weights of each factor were determined using the Analytic Hierarchy Process (AHP) based on Saaty's (1980) priority scale. Pairwise comparison results indicate that slope exerts the greatest influence (0.35), followed by elevation (0.20), land use (0.11), topographic curvature (0.10), soil type (0.07), lithology (0.06), and aspect (0.03). The consistency ratio (CR) was 0.05 (<0.1), ensuring the reliability of the comparison matrix.

The inherent classes of each factor were normalized according to risk levels, for example: Slopes of 10-20° were classified as Very High with a weight of 0.444; Cambisols soil, 0.450 (Very High); Anthrosols, 0.192 (High); and eolian lithology, 0.478 (Very High). This normalization reflects the sensitivity of each spatial unit to landslides accurately. Subsequently, all layers were overlaid to produce the integrated landslide risk zonation map.

As shown in Figure 4, the spatial distribution of landslide-prone areas in Cao Phong District, Hoa Binh province, developed by integrating topography, geology, land use, and, in particular, the influence of extreme rainfall. The map is classified into four risk levels: Low (light green), medium (yellow), high (orange), and very high (red).

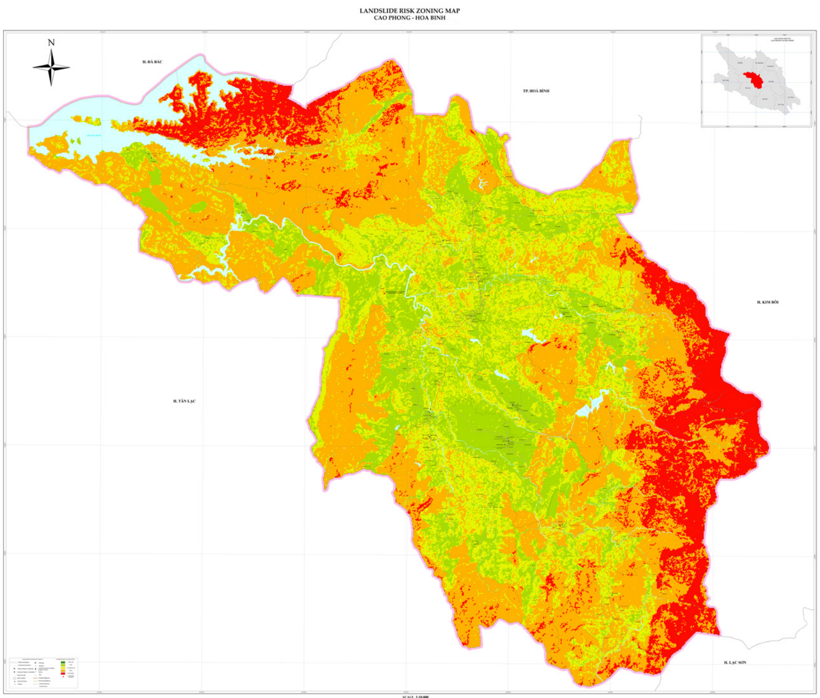

Figure 4. Landslide susceptibility zoning map of Cao Phong District, Phu Tho Province. CRS: VN-2000, central meridian 105°E, UTM Zone 48N. Scale: 1:10,000. Legend: green - low susceptibility; yellow - moderate susceptibility; orange - high susceptibility; red - very high susceptibility

The results indicate that:

Very high-risk areas (red) occupy a large portion of the eastern and Southeastern parts of the district, where slopes are steep, river and stream densities are high, and extreme rainfall exceeds the average. These zones also coincide with densely populated settlements and hillside cultivation, thereby increasing disaster risk.

High-risk areas (orange) are mainly distributed along mountain edges and transitional slopes, where rainwater tends to accumulate, compromising slope stability.

Medium- and low-risk areas (yellow and light green) are concentrated in the central part of the district, characterized by flatter terrain and better natural drainage systems.

The model's reliability was validated using the ROC curve based on local landslide occurrence data. An AUC value of 0.82 demonstrates good predictive accuracy, indicating the model's potential applicability in early warning and spatial planning. This confirms that the landslide risk zonation map serves as a vital visual tool to support effective disaster risk management and sustainable development planning in Cao Phong District.

The map provides a crucial visual basis for developing climate change adaptation scenarios and safe land-use planning. Integrating extreme rainfall simulations with natural factors offers clearer guidance for early warning of landslide hazards at the local level, especially in the context of increasingly extreme climate events.

Developing three families of rainfall and landslide scenarios further clarifies the uncertainty associated with climate change impacts, while supporting local authorities in formulating differentiated response strategies: Maintaining current management practices (low scenario), enhancing early warning systems (medium scenario), and integrating land-use planning and resettlement measures (high scenario).

4. Conclusions

The climate change scenarios RCP4.5 and RCP8.5 project an overall increasing trend in both annual and rainy-season precipitation at Bac Phong commune, Cao Phong District, with the most pronounced changes expected toward the end of the 21st century. The broad range of variability among climate models indicates a high degree of uncertainty. Mean annual precipitation is projected to increase by up to 11.7% under RCP4.5 and 12.5% under RCP8.5, while rainy-season precipitation may rise by approximately 10.6-10.7%. These changes are expected to intensify surface runoff and increase the frequency of slope failures. Consequently, the projected rise in rainfall intensity and duration is likely to substantially enhance landslide susceptibility, particularly across steep and sparsely vegetated terrains.

The projected datasets were developed using historical rainfall observations from Bac Phong station, coupled with outputs from regional climate models. Extreme value analysis (GEV) was applied to determine rainfall thresholds associated with landslide initiation, identified within the P20-P80 percentile range. These thresholds were subsequently integrated with topographic, geological, and land-use datasets to generate a spatial assessment of landslide susceptibility.

Analysis of extreme rainfall intensity indicates that approximately 82.5% of the district's area is exposed to daily precipitation exceeding 270 mm - a critical threshold for landslide occurrence on steep slopes with limited vegetation cover. To address model uncertainty, three rainfall-landslide scenario families were constructed: Low (P20), medium (Mean), and high (P80). These scenario frameworks support the identification of high-risk zones and facilitate the design of targeted risk management strategies, ranging from the maintenance of existing slope management practices and the enhancement of early warning systems to the integration of adaptive land-use planning and resettlement measures.

The resulting landslide risk zonation map, integrating extreme rainfall, topography, geology, and land use, serves as a critical decision-support tool for early warning, adaptive spatial planning, and the mitigation of disaster-related losses.

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References

1. Cuong, N. H., and Pham, H. G. (2020), *"A New Rainfall Threshold Model for Predicting Ground Movement Occurrences Based on Geotechnical Monitoring Data at the Hai Van Pass", In Geotechnics for Sustainable Infrastructure Development* (pp. 1209-1216). Springer. https://doi.org/10.1007/978-981-15-2184-3_159.
2. Thang, N. H. et al. (2024), *"Geologic controls and rainfall thresholds for landslide occurrence in Northern Viet Nam", Journal of the Japan Landslide Society*, 61(5), 175-185. https://doi.org/10.3313/jls.61.175
3. Nguyen Thanh Long and Florimond De Smedt (2019), *"Analysis and Mapping of Rainfall-Induced Landslide Susceptibility in A Luoi District, Thua Thien Hue Province, Viet Nam", Water,* 11(1), 51. https://doi.org/10.3390/w11010051.
4. Tran Anh Tuan and Nguyen Tu Dan (2012), *"Research the landslide susceptibility and zoning in the Son La hydroelectricity area by the Saaty's Analytical Hiearchy Process (AHP)", Viet Nam Journal of Earth Sciences*, 34(3), 223-232. (in Vietnamese).
5. Saaty, T. L. (1980), *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*. McGraw-Hill, New York.
6. Saaty, T. L. (1990), *Multicriteria Decision Making: The Analytic Hierarchy Process*. RWS Publications, Pittsburgh.
7. Ministry of Agriculture and Rural Development (2022), *"Research on establishing a real-time monitoring system for landslide early warning". Synthesis report on Science and Technology Tasks under the Protocol,* Thuy Loi University (in Vietnamese).
8. IPCC. (2013), *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
9. Ministry of Natural Resources and Environment (2020), *Climate change scenarios.* Viet Nam Publishing House of Natural Resources - Environment and Cartography (in Vietnamese).
10. Liu, X., Shao, S., and Shao, S. (2024), *"Landslide susceptibility zonation using the analytical hierarchy process (AHP) in the Great Xi'an Region, China", Scientific Report*s, 14, 2941. https://doi.org/10.1038/s41598-024-53630-y.
11. Ministry of Natural Resources and Environment (2020), *Circular No. 15/2020/TT-BTNMT providing technical regulations on the structure model and content of the national geographic database at a scale of 1:10,000 and 1:25,000.* Hanoi, Viet Nam (in Vietnamese).
12. Doan, H. P., et al. (2022), *Research on zoning natural disaster risks, mapping flash floods, inundation, landslides and land subsidence under the impact of climate change in Hoa Binh province and proposing solutions to prevent and minimize damage: Summary report on the implementation results of the project.* Institute of Meteorology, Hydrology and Climate Change, Hanoi.
13. Glade, T. et al. (2000), *"Rainfall-triggered landslides: A review of concepts, models and case studies", Progress in Physical Geography,* 24(3), 451-503.