NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ

Bulletin of Geography. Physical Geography Series, No. 28 (2025): 17–31
http://doi.org/10.12775/bgeo-2025-0002

Research on the factors contributing to flash floods in the Northern mountainous region of Vietnam: criteria, weights, and evaluation indexes

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Abstract. Flash floods are one of the most severe natural disasters, particularly in the northern mountainous regions of Vietnam, where steep terrain and dense river and stream networks are prevalent. These flash floods cause significant loss of life and property, threatening the sustainable development of these areas. However, assessing and forecasting flash flood risks remains challenging due to the lack of specific scientific analysis methods. This study aims to systematically analyze both natural and anthropogenic factors contributing to flash flood risks and to develop a comprehensive, multi-criterion index system for assessing flash flood risk levels in the mountainous river basins of Northern Vietnam. By employing multi-criterion evaluation (MCE) and the Analytic Hierarchy Process (AHP), the study seeks to construct a scientifically robust framework for flash flood risk assessment tailored to the unique geographic and climatic conditions of the region. The study also developed a risk classification map for flash floods in five representative river basins, with areas of very high risk accounting for 20.06% of the study area. The research outcomes, including a risk classification map for representative river basins, are intended to enhance disaster risk management and sustainable development practices in the area.

Key words:
Flash floods,
factors,
weights,
mountainous,
basin

Introduction

Flash floods are natural disasters that occur when a large amount of rainfall within a short period overwhelms the land's ability to absorb water or the capacity of river systems to channel the excess water, causing overflow and generating powerful water currents (Sadkou et al. 2024). These currents can carry soil, rocks, branches, debris and other materials, resulting in severe destruction to both life and property (Sapan et al. 2023; Masoud et al. 2024). Flash floods typically occur in areas with steep terrain, where river systems or drainage channels cannot accommodate the large volume of water generated by heavy rainfall over a short period. Flash floods can develop rapidly and are highly dangerous, causing significant loss of life and damage to infrastructure. Mountainous regions, especially those with steep slopes, dense river networks and low forest cover, are particularly vulnerable to flash floods (Sadkou et al. 2024).

Research on flash floods reveals that the typical contributing factors include rainfall, watershed morphology characteristics, geological factors, watershed cover conditions and human activities (Yadav et al. 2023; Ebro et al. 2024; Sadkou et al. 2024). Among these, rainfall is the primary cause (Sadkou et al. 2024). Depending on the characteristics of the watershed and flow mechanisms, the causes of flash floods vary between watersheds. In mountainous watersheds in tropical regions, where slope flash floods occur, topography plays a crucial role (Yadav et al. 2023; Nagamani et al. 2024). Mixed flash floods, which involve mechanisms such as debris flow and landslide processes, form a combined flow. Channel-blocking flash floods are primarily formed due to human impacts, with the main causes including activities directly affecting the flow, such as the construction of transportation infrastructure, irrigation works, mineral extraction and the construction of hydroelectric dams (Špitalar et al. 2014; Zhong et al. 2020; Wardhani et al. 2022).

In recent years, the application of technology and artificial intelligence in flash flood research has become widespread. Notably, machine learning algorithms are used to predict flash floods based on real-time and historical data (Zhao et al. 2022; Chen et al. 2023; Habibi et al. 2023; Basumatary et al. 2024; Li et al. 2024). Internet of Things devices are employed to monitor and collect data on weather conditions and streamflow in areas at risk of flash floods (Lai et al. 2019; Prakash et al. 2023; Rahardjo et al. 2023). Common methods for determining flash flood potential indices involve hierarchical analysis and multi-criterion analysis algorithms (Shawky et al. 2023). Research on susceptibility and the creation of flash flood warning maps utilizes logistic regression (El-Rawy et al. 2022), decision trees (Cao et al. 2020; Handini et al. 2021), artificial neural networks (Dinu et al. 2017; Sapan et al. 2023), support vector machines (Handini et al. 2021; Rahardjo et al. 2023), frequency ratio (Tariq et al. 2022; Brázdil et al. 2024; Li et al. 2024), weight of evidence (El-Rawy et al. 2022; Saleh et al. 2022), statistical index (Hidayah et al. 2023; Kotecha et al. 2023; Saha et al. 2024), certainty factor (Cao et al. 2020; Costache et al. 2023; Chowdhury 2024; Zhao et al. 2024) and entropy index (Meyer et al. 2022; Chen et al. 2023; Masoud et al. 2024). These methods approach and evaluate the factors contributing to flash floods by analyzing individual components, determining weights and assessing weight variability. However, no single method is universally applicable to all watershed systems. Additionally, due to limitations in identifying indices and the impact levels of flash floods, the accuracy of results in flash flood studies remains low. Furthermore, the assessment of flash flood risks in the context of climate change and the integrated use of both natural and social indices have not been fully implemented.

In Vietnam, research on flash floods is still very limited. Most studies focus on proposing solutions such as creating flash flood zoning maps, developing early warning systems and raising public awareness in high-risk areas (Ba et al. 2022). Some studies evaluate damage and analyze causes for typical flash flood events, building a scientific basis for zoning warnings and forecasting flash floods, and developing early warning models (Nguyen et al. 2015; Tuc et al. 2015; Van Hoang et al. 2019; Ngo et al. 2020; Chau et al. 2021; Nguyen et al. 2021; Vu et al. 2023). The major gap in flash flood research in Vietnam lies in the lack of a comprehensive and detailed risk assessment and classification system, particularly for river basins in mountainous regions (Ba et al. 2022). The application of advanced technologies such as GIS and remote sensing for flash flood risk assessment remains limited and has not been widely adopted. Furthermore, the criteria and standards for evaluating the factors contributing to flash floods in Vietnam have not been standardized or systematically studied across different river basins (Nguyen et al. 2015; Chau et al. 2021; Bui 2023).

This study seeks to address the critical research gap in flash flood risk assessment in Vietnam by developing a standardized and systematic index system for evaluating the natural and anthropogenic factors contributing to flash flood risks. Using Multi-Criterion Evaluation (MCE) and the Analytic Hierarchy Process (AHP), the research integrates geographic and environmental data to propose a tailored and reliable framework for assessing flash flood risks across five representative river basins in Northern Vietnam. The study aims to provide actionable insights for improving disaster management, forecasting systems and early warning strategies, while promoting sustainable development in vulnerable regions.

Materials and methods

Study location

The northern mountainous region of Vietnam is one of the most diverse and complex geographical areas in the country, covering a total area of 100,965 km^2. This region features diverse natural conditions, high mountainous terrain, a complex climate and abundant mineral resources (Thao et al. 2022). It plays a crucial role in economic and social development as well as environmental protection. The area includes the provinces of Ha Giang, Lao Cai, Yen Bai, Lai Chau, Sơn La, Dien Bien, Hoa Binh, Bac Kan, Cao Bang, Lang Son, Thai Nguyen, Phu Tho and Tuyen Quang (Fig. 1). Within the scope of the research project, experimental studies were conducted in five river basins, namely the Cao Bo river basin (Ha Giang Province), the Leng river basin (Bac Kan Province), the Chat river basin (Son La Province), the Ngoi Dum river basin (Lao Cai Province) and the Nam Kim river basin (Yen Bai Province). These are representative basins in the northern mountainous region of Vietnam, characterized by distinct factors that contribute to flash floods.

The topography of the northern mountainous region of Vietnam is predominantly composed of hills and mountains, with a dense network of rivers and streams creating significant fragmentation and forming numerous valleys and river basins (Vu 2022). This area experiences hot, humid summers and cold, dry winters. Extreme weather events such as heavy rainfall, flooding and frost occur frequently, particularly during the rainy season. The primary agricultural products in the region include rice, maize, tea, orchard fruits and medicinal plants. Natural forests play a crucial role, providing valuable timber and forest products such as bamboo, rattan, bamboo shoots and pine resin. As of 2024, the total population of the northern mountainous region is ~14.2 million people and home to various ethnic minority groups, each with its own distinct cultural identity, customs and languages. The population distribution is uneven, with concentrations in valleys, along rivers and in towns. This region often faces natural disasters such as flash floods, landslides, droughts and frost (Thanh Thi Pham et al. 2020).

In the five studied basins, the characteristics conducive to flash flood formation are quite typical. The basin topography features an average elevation ranging from 600 to 1,400 meters, with the Ngoi Dum basin having an average elevation nearing 1,500 meters above sea level. The average slope gradient ranges from 18 to 30 degrees, with annual rainfall averaging between 1,800 and 2,500 mm, and forest cover at ~36.7% (Vu 2022). According to statistical data from 2000 to 2023, these basins experience an average of two to five flash flood events per year, with the Chat Stream and Nam Kim basins having the highest frequency of flash flood occurrences (Vietnam 2023).

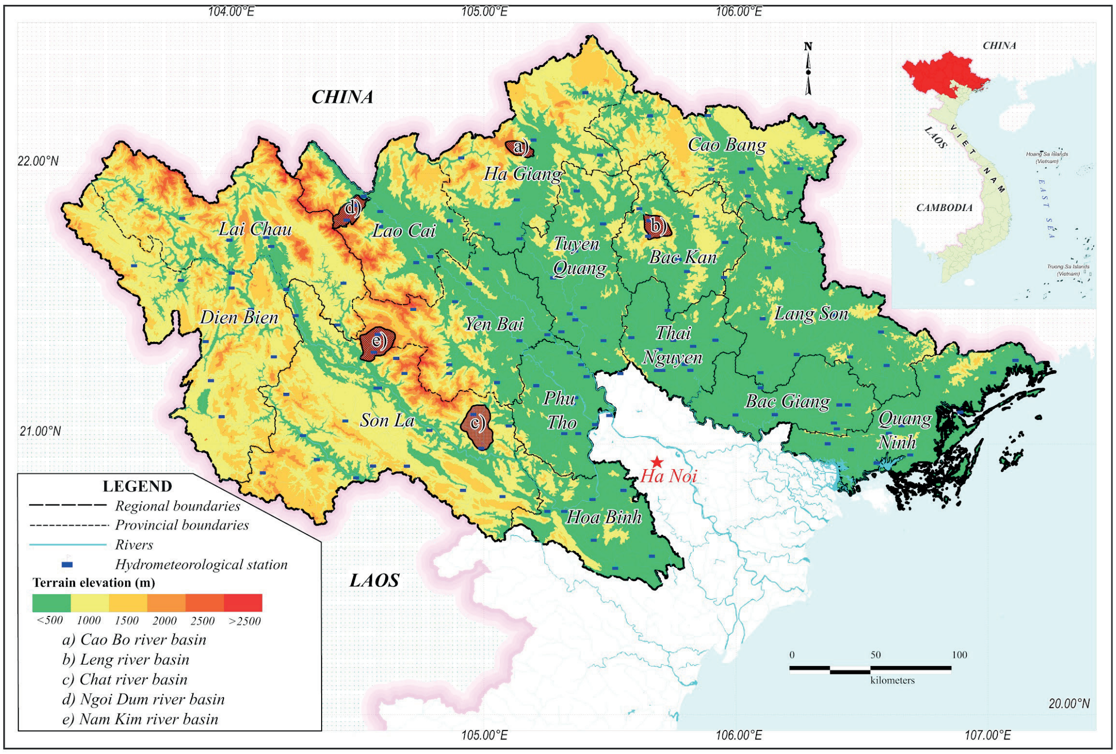

Fig. 1. Study area

Study data

This study utilizes data from various sources, including preliminary survey data, statistical data, survey data, satellite imagery, expert opinion workshops and data from related studies. The specific data types, data sources and technical parameters of the data used are described in detail in Table 1.

Methods

Survey and data collection methods

The study surveyed five river basins in the northern mountainous region of Vietnam to conduct a preliminary assessment, collect data and verify research results. At each surveyed basin, the research team conducted on-site observations and measurements, recording parameters related to watershed morphology and flow traces, and identifying factors contributing to flash floods. The survey method was combined with field data collection using questionnaires, household surveys and interviews with local officials. Directly collected data included information on the current status of flash floods, their frequency and contributing factors. Field survey data were crucial for providing research data and for comparison and validation with statistical results and spatial analysis from remote-sensing and satellite imagery data.

Table 1. Summary of study data

Data name	Data type	Data source	Technical parameters
Flash floods	Statistical data	Northern mountainous Region disaster prevention Center of Vietnam (2000–2023)	Flash flood statistics over the period 2000–2023
Watershed morphology	Spatial Data	Topographic maps, Digital Elevation Models (DEM)	1:10,000 scale topographic maps; DEM data for terrain analysis, resolution is 10 m
Rainfall data	Meteorological data	Automatic rain gauge stations, 211 observational stations	Automatic and manual rainfall data from 211 stations
Vegetation cover	Remote Sensing data	Landsat satellite imagery (https://earthexplorer.usgs.gov/)	Resolution is 30 m for vegetation classification
Current land use	Remote Sensing data	Landsat satellite imagery https://earthexplorer.usgs.gov/)	Resolution is 30 m for land use/ cover classification
River density	Remote Sensing data	Landsat satellite imagery (https://earthexplorer.usgs.gov/)	Resolution is 30 m for river network density
Farming practices	Survey data	Satellite imagery, surveys, interviews	Data on farming types, distribution, and practices collected from satellite images, surveys, and interviews with local stakeholders
Infrastructure density	Survey data	Landsat satellite imagery, surveys, interviews	Density of infrastructure (roads, buildings, etc.) from satellite imagery and field surveys
Flash flood event details	Survey/Statistical data	Statistical documents, surveys, Expert opinion workshops	Location, extent, scope, influencing factors, and timing of flash flood events from surveys, expert opinions and local records

Multi-Criterion Evaluation (MCE) and Analytic Hierarchy Process (AHP)

MCE and AHP are powerful tools for assessing factors contributing to flash floods. MCE facilitates decision-making based on aggregated criteria and evaluates flash flood risks through GIS tools (Shawky et al. 2023). In AHP, elements are compared in pairs to determine the relative importance of each element to the others. Each value in the pairwise comparison matrix is divided by the sum of the values in the corresponding column to normalize the matrix. The weights of the elements are calculated by averaging the values in each row of the normalized matrix. The Consistency Index (CI) is calculated as $CI = (\lambda_{max} - n) / (n - 1)$, where λ_{max} is the largest eigenvalue of the matrix, and n is the number of elements. The Consistency Ratio (CR) is then determined by dividing the Consistency Index by the Random Index. If $CR<0.1$, the matrix is considered consistent and the weights are accepted. If $CR\geq0.1$, the matrix needs to be adjusted for higher consistency (Saaty 1987; Majeed et al. 2023).

The integration of MCE and AHP improves the accuracy and reliability of the research by providing a structured and scientific framework for assessing flash flood risks. This study analyzed the factors contributing to flash floods in river basins across the northern mountainous region of Vietnam through a<[multi-phase methodology, including:

1. ***Factor identification and hierarchy development:*** Relevant factors influencing flash flood risks were identified, and a hierarchical structure was established to reflect their relationships and levels of importance.
2. ***Factor ranking and pairwise comparison:*** The identified factors were systematically compared in pairs to evaluate their relative importance in contributing to flash flood risks.
3. ***Weight calculation:*** The weight of each factor was derived from the pairwise comparison matrix, quantifying each factor's proportional contribution to flash flood risk.
4. ***Consistency assessment:*** The consistency of the pairwise comparisons was evaluated using the Consistency Index (CI) and Consistency Ratio (CR) to ensure the reliability and validity of the calculated weights.

The matrix coefficients were calculated on a scale of 1 to 10 points, depending on the importance of the flash flood contributing factors. Based on the analytical hierarchy process combined with expert opinions, a comparison matrix of the flash flood factors was established. The Ministry of Natural Resources and Environment of Vietnam classifies flash flood risk into five levels: Level 1 (very low risk), Level 2 (low risk), Level 3 (moderate risk), Level 4 (high risk), and Level 5 (very high risk) (Ba et al. 2022).

Application of remote-sensing and Geographic Information Systems (GIS) methods

Remote sensing and GIS play a crucial role in studying factors contributing to flash floods (Wang 2017; Xiong et al. 2019; Yang 2024). Remote-sensing imagery provides data for analyzing surface structures and contributing factors within watersheds (Thapa et al. 2023). Landsat remote-sensing data, including spectral bands from Landsat 8 OLI sensors with a resolution of 30 meters, were collected from USGS Earth Explorer. The Normalized Difference Vegetation Index (NDVI) was calculated based on the near-infrared and red bands. NDVI values from the period 2000–23 were compared to investigate changes in vegetation cover across the study watersheds. The K-means algorithm, combined with sample data, was used to classify land-use status in these watersheds. DEM from USGS Earth Explorer was employed to analyze the watershed's morphological characteristics, such as topography, geomorphology and basin structure. DEM data allows for the calculation of terrain slope, a critical factor in assessing the flow movement contributing to flash floods. DEM was also utilized to identify landforms, cliffs, fractures, watershed shape structures, drainage networks, and water accumulation and dispersion points that influence flash flood development. This study used GIS spatial analysis tools within QGIS software to analyze the contributing factors and generate hazard maps assessing flash flood risk.

The systematization of the content and research methods for studying factors contributing to flash floods in the northern mountainous region of Vietnam is illustrated in Figure 2. The research framework comprises four steps: (1) Data collection and establishment of scientific and practical foundations for studying flash flood contributing factors in the northern mountainous region of Vietnam; (2) Identification of contributing factors for the study area;

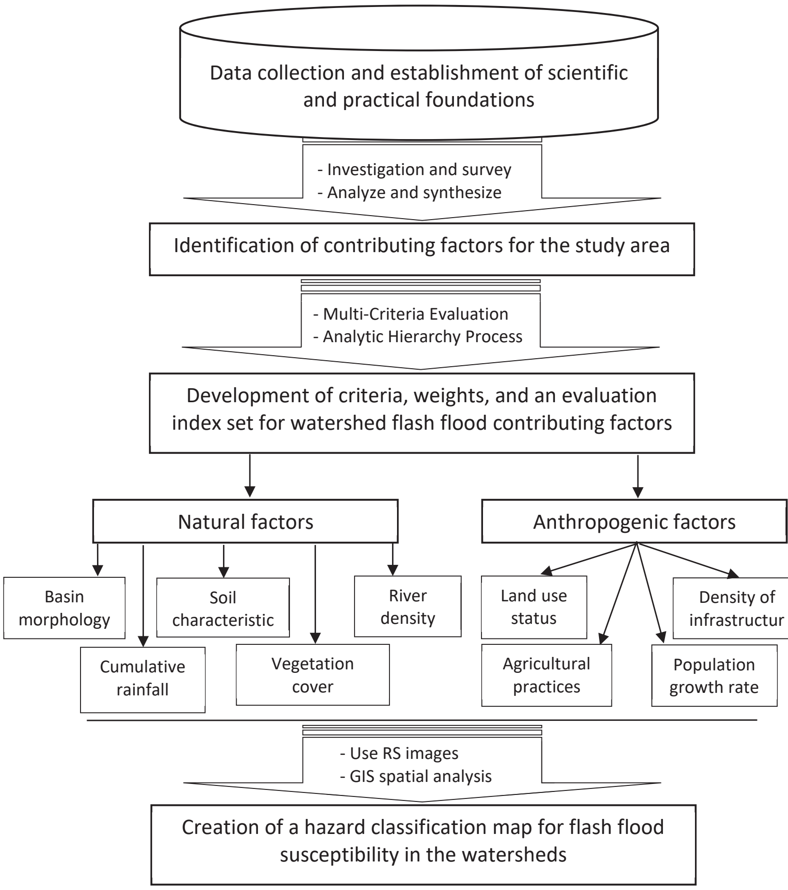

Fig. 2. The research framework

(3) Development of criteria, weights, and an evaluation index set for watershed flash flood contributing factors; (4) Creation of a hazard classification map for flash flood susceptibility in the watersheds (experimental study in five watersheds). Each step involves specific research methods, with the primary methods being MCE, AHP and GIS spatial analysis.

Results

Factors contributing to flash floods

Statistical data from 320 frequently affected flash flood sites reveal that these areas typically exhibit basin slopes greater than 15%, vegetation cover below 10%, maximum daily rainfall exceeding 200 mm, moderate to poor soil permeability, and V-shaped valley landforms (Ngo et al. 2020, 2023b; Thanh Thi Pham et al. 2020; Kieu et al. 2021; Thao et al. 2022; Vu et al. 2023). While flash floods in this region are primarily driven by natural factors, human activities also contribute to the phenomenon. Deforestation and slash-and-burn agriculture reduce vegetation cover, thereby increasing flood risks. Additionally, changes in land use alter soil properties, further enhancing the likelihood of flash floods.

This study employed the MCE and AHP methods to develop a set of criteria for evaluating factors contributing to flash flood occurrences in the mountainous regions of Vietnam, detailed indicators are shown in Table 2.

Table 2 provides a quantifiable and graded assessment of factors contributing to flash flood risk, offering a clear reference framework for evaluating these influences. Several representative indicators were used, including basin morphology coefficient and slope, which reflect the basin's morphological characteristics. Maximum daily accumulated rainfall serves as an indicator for rainfall-related flash flood events. Soil type characterizes terrain properties, while

Table 2. Criteria for evaluating flash flood risk factors in the northern mountainous region of Vietnam

No.	Factor	Level 1	Level 2	Level 3	Level 4	Level 5
1	Basin morphology coefficient (Bm)	<0.2	0.21–0.4	0.41–0.6	0.61–0.8	>0.8
2	Basin slope (Bs) (%)	<10	10.1–15	15.1–20	20.1–25	>25
3	Cumulative rainfall (Rf) (mm)	<50	50.1–100	100.1–150	150.1–200	>200
4	Soil type (St)	Humus soil	Abiotic humus soil, black soil	Feralitic soil, red brown soil on limestone	Red yellow soil, yellow brown soil, alluvial soil	Eroded soil, alluvial soil
5	Vegetation cover (Vc) (%)	>50	40.1–50	30.1–40	20.1–30	<20
6	River density (Rd) (km/km²)	<1.0	1.1–2.0	2.1–3.0	3.1–4.0	>4.0
7	Land use type (Lu)	Natural forest land	Planted forest land	Rice land, perennial crops land	Grassland, shrub land	Bare land, residential land, rocky mountains
8	Cultivation method (Cm)	Very sustainable	Sustainable	Relatively sustainable	Less sustainable	Unsustainable
9	Infrastructure density (Id) (structures/km²)	<5	5.1–10	10.1–15	15.1–20	>20
10	Population growth rate (Pg) (%)	<1.0	1.1–1.5	1.51–2.0	2.1–2.5	>2.5

the sustainability of agricultural practices represents the impact of land use. Other factors were categorized based on their varying levels of influence on flash flood occurrences.

The basin morphology coefficient is a key indicator reflecting the area and perimeter of a basin, which determines its shape, ranging from elongated to nearly circular forms. A larger coefficient is associated with a higher flash flood risk. As basin slope increases, water flow accelerates, heightening the potential for flash floods. Slopes ranging from below 10% to above 25% show an increased flood risk with steeper gradients. Cumulative rainfall is directly correlated with flash flood risk. Soil type affects water infiltration and surface runoff, with humic and feralitic soils offering better absorption compared to eroded and colluvial soils, which are associated with higher flood risks. Vegetation cover reduces surface runoff, and lower coverage correlates with higher flash flood risk. Higher river density enhances water concentration, with densities exceeding 2.0 km/km² indicating a very high flood risk.

Land-use type influences flood risk, with natural forest land presenting a lower risk compared to bare land, residential areas and rocky mountains, due to its superior water retention. Agricultural sustainability, which preserves soil integrity, reduces flood risk. Higher infrastructure density obstructs natural water drainage, thereby increasing flash flood risk. Additionally, rapid population growth can lead to unsustainable land use practices, further elevating flood risk.

Weight evaluation of flash flood risk factors

The hierarchical analysis method was used to calculate the weights of flash flood risk factors in the mountainous regions of Vietnam. The results are presented in Table 3.

Table 3 shows that cumulative rainfall has the highest weight, highlighting its primary role in flash flood occurrence. Basin slope and vegetation cover also exhibit relatively high weights, underscoring their significant influence. The remaining factors, while

Table 3. Weight matrix for flash flood risk factors in the northern mountainous region of Vietnam

Factors	Bm	Bs	Rf	St	Vc	Rd	Lu	Cm	Id	Pg	Total	Weight
Bm	0.02	0.16	0.23	0.05	0.08	0.09	0.05	0.09	0.07	0.05	0.89	**0.09**
Bs	0.16	0.32	0.32	0.16	0.11	0.11	0.08	0.09	0.06	0.04	1.45	**0.15**
Rf	0.23	0.32	0.21	0.16	0.28	0.25	0.28	0.17	0.14	0.15	2.19	**0.22**
St	0.05	0.16	0.16	0.05	0.04	0.06	0.07	0.04	0.02	0.02	0.67	**0.07**
Vc	0.08	0.11	0.28	0.04	0.31	0.12	0.15	0.09	0.11	0.08	1.37	**0.14**
Rd	0.09	0.11	0.25	0.06	0.12	0.13	0.03	0.15	0.14	0.06	1.14	**0.11**
Lu	0.05	0.08	0.28	0.07	0.15	0.03	0.09	0.08	0.09	0.04	0.96	**0.10**
Cm	0.09	0.09	0.17	0.04	0.09	0.15	0.08	0.11	0.08	0.02	0.92	**0.09**
Id	0.07	0.06	0.14	0.02	0.11	0.14	0.09	0.08	0.07	0.03	0.81	**0.08**
Pg	0.05	0.04	0.15	0.02	0.08	0.06	0.04	0.02	0.03	0.04	0.53	**0.05**

having lower weights, still contribute to the overall flash flood risk.

The Analytic Hierarchy Process (Saaty 1987) was applied to calculate the indices for flash flood risk factors in the northern mountainous regions of Vietnam. The resulting consistency index, random index and consistency ratio are presented in Table 4.

Table 4. Consistency Index, Random Index and Consistency Ratio values for flash flood risk factors in the northern mountainous region of Vietnam

No	Index	Values
1	Consistency Index (CI)	0.099
2	Random Index (RI)	1.49
3	Consistency Ratio (CR)	0.066

Table 4 shows that the consistency ratio (CR) is less than 0.1, indicating the reliability of the study. Using the weights from Table 3, the flash flood risk function (Fm) for the northern mountainous regions of Vietnam was calculated in Eq. 1:

$$Fm=0.09*Bm+0.15*Bs+0.22*Rf+0.07*St+0.14*Vc+$$
$$+0.11*Rd+0.10*Lu+0.09*Cm+0.08*Id+0.05*Pg$$

Research results in five typical river basins

Using the established criteria and weights, the study conducted empirical assessments in five representative river basins in the northern mountainous region of Vietnam: the Cao Bo, Leng, Chat, Ngoi Dum and Nam Kim basins. The evaluation results are presented in Table 5 and Figure 3.

The experimental results from five river basins in the northern mountainous regions of Vietnam reveal a relatively high flash flood risk, with variations across the basins. The Chat river basin exhibits the highest risk, with 14.58% of its area at a very high risk level and 30.27% at a high risk level. The Nam Kim river basin follows, with 10.71% at a very high risk level and 21.54% at a high risk level. The Cao Bo river basin shows a very high flash flood risk in 8.25% of its area and a high risk in 15.48%. The Ngoi Dum and Leng river basins present lower risks, with the Ngoi Dum basin having about 10% of its area at high and very high risk levels, and the rest at medium, low or very low risk levels. The Leng river basin is predominantly classified at a medium risk level (42.1%), with only 12.1% of its area at high or very high risk levels.

Table 5. Area and proportion of flash flood risk levels in the experimental river basins

No	Name of river basin	Area, proportion	Level 1	Level 2	Level 3	Level 4	Level 5	Total
1	Cao Bo river basin	Area (ha)	95.23	133.34	117.94	70.33	37.48	454.32
		Proportion (%)	20.96	29.35	25.96	15.48	8.25	100.00
2	Leng river basin	Area (ha)	173.78	153.34	300.83	80.10	6.50	714.56
		Proportion (%)	24.32	21.46	42.1	11.21	0.91	100.00
3	Chat river basin	Area (ha)	178.83	231.80	374.60	430.99	207.59	1423.81
		Proportion (%)	12.56	16.28	26.31	30.27	14.58	100.00
4	Ngoi Dum river basin	Area (ha)	254.62	337.93	187.10	58.06	30.11	867.83
		Proportion (%)	29.34	38.94	21.56	6.69	3.47	100.00
5	Nam Kim river basin	Area (ha)	188.59	151.31	485.49	262.42	130.48	1218.29
		Proportion (%)	15.48	12.42	39.85	21.54	10.71	100.00

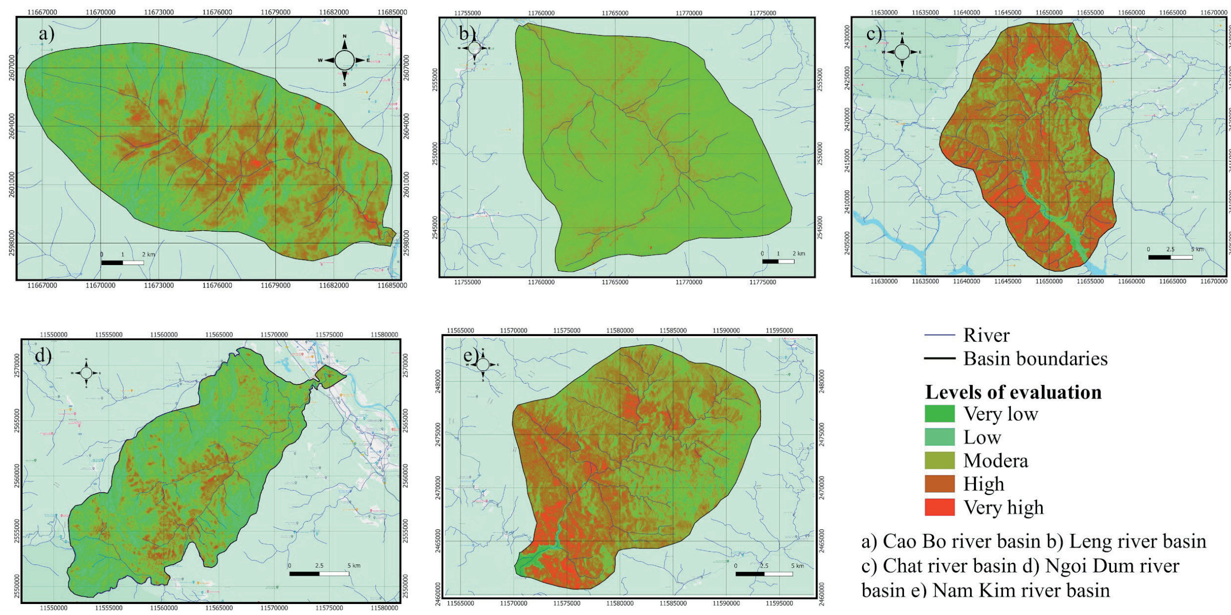

Fig. 3. Map evaluating flash flood risk levels in the experimental river basins

Discussion

This study investigates the factors influencing flash flood risks in the northern mountainous regions of Vietnam, highlighting the complex interaction between natural and anthropogenic variables. Our findings underscore the role of basin morphology, rainfall intensity, soil properties, vegetation cover, river density and land-use practices in determining flash flood risks. These results largely corroborate existing studies (Ngo et al. 2020; Thao et al. 2022; Vu et al. 2023), while also contributing new insights into the specific regional characteristics of flash flood susceptibility.

The study confirms that basin morphology is a critical factor in flash flood risk, with larger, elongated basins increasing the capacity for water accumulation and accelerating runoff (Ba et al. 2022; Suwannachai et al. 2024). Basins with steep slopes, particularly those above 25%, significantly heighten the likelihood of flash floods due to rapid runoff, a finding consistent with Qie et al. (2021). V-shaped valleys further exacerbate this risk by concentrating water flow, as also observed by Ba et al. (2022).

Rainfall intensity, especially cumulative rainfall exceeding 200 mm, was found to be strongly associated with higher flood risks, in line with the literature (Ámon et al. 2023). Flash floods in the study area tend to occur during intense, short-duration rainfall events that saturate the soil, leading to rapid surface runoff (Chau et al. 2021; Kieu et al. 2021). Soil properties, particularly permeability and stability, play a significant role in controlling water infiltration and runoff. Eroded and clay-rich soils, which reduce water absorption, were found to exacerbate flood risks (Van Hoang et al. 2019; Nagamani et al. 2024), a finding echoed by Zhao et al. (2024).

Vegetation cover also plays a crucial role in mitigating flood risks. Dense vegetation, especially in riparian zones, helps slow water movement and stabilizes the soil, thus reducing runoff (Ba et al. 2022; Ebro et al. 2024). Our study found that areas with less than 20% vegetation cover are at the highest risk of flash floods. This highlights the importance of maintaining natural vegetation to reduce flood risks in vulnerable areas.

River density is another important factor, with high river density correlating with greater flood risk. Our study showed that river densities greater than 2.0 km/km^2 are associated with increased flood risks, consistent with previous research (Van Hoang et al., 2019; Hidayah et al. 2023). The dense network of rivers and streams facilitates faster water flow, especially in steep, mountainous terrains, thereby intensifying flood events (Luu et al. 2023).

Human activities such as deforestation, unsustainable farming practices and urban expansion exacerbate flash flood risks by altering land use and disrupting natural hydrological processes. Deforestation reduces soil retention, increasing surface runoff (Ngo et al. 2020). The conversion of forested areas into agricultural or residential zones in mountainous regions significantly alters water flow patterns, leading to higher flood risks (Zhong et al. 2020; Akter et al. 2022). Unsustainable farming practices, such as shifting cultivation, further contribute to soil degradation and flood vulnerability (Špitalar et al. 2014).

The risk assessment across five river basins in the study area reveals significant variability in flood risk levels. The Chat river basin, characterized by steep slopes, poor vegetation cover and eroded soils, exhibited the highest risk, with 14.58% of its area at very high risk and 30.27% at high risk. In contrast, the Leng and Ngoi Dum basins showed more varied results, with the latter having lower flood risks despite high cumulative rainfall. These findings emphasize the need for tailored flood risk management strategies that account for local environmental and anthropogenic conditions.

The findings of this study align with several key studies on flash flood risk, while offering new insights into the role of specific regional factors. The relationship between basin morphology and flood risk is well established, with previous studies confirming that larger, steeper basins are more prone to flash floods (Ba et al. 2022; Suwannachai et al. 2024). Our study builds on these findings by highlighting the critical role of V-shaped valleys in concentrating water flow.

The impact of rainfall intensity on flash flood occurrence has been well documented, and our results support these findings, emphasizing the importance of intense, short-duration rainfall events in triggering flash floods (Kieu et al. 2021; Ámon et al. 2023). Similarly, the role of soil properties in runoff and water infiltration has been confirmed in prior research (Van Hoang et al. 2019; Nagamani et al. 2024). Our study further underscores the vulnerability of eroded and clay-rich soils to flash floods, aligning with the findings of Zhao et al. (2024).

The mitigating role of vegetation cover in flash flood risk has also been observed in previous studies (Ba et al. 2022; Ebro et al. 2024). Our research reinforces this by showing that areas with sparse vegetation are at significantly higher risk. Furthermore, the relationship between river density and flood risk, particularly in mountainous regions, is supported by earlier research (Hidayah et al. 2023; Luu et al. 2023), confirming that higher river density leads to more concentrated water flow and increased flood potential.

While this study provides valuable insights, there are several limitations that should be addressed in future research. First, the assessment was based on data from five river basins, which may not fully represent the variability of flash flood risks across the entire northern mountainous region. Expanding the study to include more diverse geographical areas would provide a more comprehensive understanding of regional flash flood dynamics.

Second, while the study employed MCE and AHP methods, the subjectivity involved in weighting factors may introduce variability in the results. Future studies could refine the assessment process by incorporating more local data and advanced hydrological models to improve the accuracy of flood risk predictions.

Third, the study's reliance on static spatial data limits its ability to capture the dynamic nature of flash floods, which are influenced by real-time meteorological and hydrological changes. Incorporating dynamic modeling tools, such as real-time weather data and flood simulation models, could enhance future assessments.

Future research should focus on enhancing the understanding of flash flood dynamics in complex mountainous terrains, particularly in regions with limited data. Investigating the effects of climate change on rainfall patterns and flood frequencies will be critical in understanding how flash flood risks evolve over time. Additionally, research into the effectiveness of land-use interventions, such as reforestation and sustainable agriculture, in mitigating flash flood risks will provide important insights for developing adaptive management strategies.

Further studies should also explore the role of local knowledge and community-based flood risk management in improving resilience to flash floods. Involving local communities in the planning and implementation of flood mitigation strategies can lead to more contextually appropriate and effective solutions.

The findings of this study are directly relevant to flood risk management practices in mountainous regions. By highlighting the key factors contributing to flash flood risk, this research provides valuable guidance for policymakers and disaster management authorities. It underscores the need for region-specific flood risk management strategies that consider local environmental, social and economic conditions. The study also emphasizes the importance of maintaining natural vegetation, implementing sustainable land-use practices and preserving soil integrity to reduce flood risks.

In practice, the research can inform land-use planning, especially in flood-prone areas, helping to guide decisions about urban development, agricultural practices and infrastructure development. By incorporating these findings into flood risk management plans, communities in the northern mountainous regions of Vietnam and similar areas worldwide can better prepare for and mitigate the impacts of flash floods.

Conclusion

This study aimed to develop a comprehensive framework for assessing flash flood risks in Northern Vietnam by systematically analyzing the interplay between natural factors, such as basin morphology, rainfall intensity and vegetation cover, and anthropogenic influences, including land use and agricultural practices. Through the application of MCE and AHP, the study established a Multi-Criterion index system and created a risk classification map for five representative river basins. The findings underscore the need for a standardized and scientifically rigorous approach to flash flood risk management and highlight the potential for this framework to guide disaster mitigation efforts, early warning systems and sustainable development initiatives in the region. Future research should expand the methodology to include more localized data and dynamic modeling techniques to refine predictions and enhance practical applicability.

Disclosure statement

No potential conflict of interest was reported by the authors.

Author contributions

Study design: HP; data collection: HP; statistical analysis: HP; result interpretation: QK; manuscript preparation: QK; literature review: QK.

Acknowledgements

This research is funded by Thai Nguyen University of Education under grant number TNUE-2024-12

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Received 24 July 2024
Accepted 10 January 2025