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THE TYPICAL MECHANISMS AND FACTORS LEADING TO FLASH FLOODS IN SMALL WATERSHEDS IN THE MOUNTAINOUS REGION OF VIETNAM. A CASE STUDY IN THE CHU VA STREAM WATERSHED

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ABSTRACT

Flash floods are a major natural hazard in mountainous areas, particularly within small river watershed. The Chu Va stream, located in the mountainous region of Vietnam, serves as a representative example where flash floods frequently occur, leading to substantial losses in both human life and property. This study employs spatial analysis and multi-criteria analysis techniques, utilizing survey data, expert assessments, and satellite imagery, to investigate the underlying mechanisms of flash flood events over the past two decades. The findings indicate that 95% of flash floods occur during the rainy season (June to August), with an average event rainfall of 274.8 mm and an average rainfall intensity of 19.05 mm/h. The primary mechanisms identified in the formation of flash floods in this watershed include heavy rainfall, material movement, flow obstruction, and sediment deposition. Additionally, the basin’s morphological features, such as steep slopes and flow convergence, are found to significantly contribute to the increased frequency of flash floods. These results are critical for advancing the understanding of flash flood dynamics in small river basins, and can inform the development of more effective flash flood forecasting and mitigation strategies in Vietnam's mountainous regions.

Keywords: Flash floods, Watershed, Mechanisms, Chu Va stream, Mountainous region

INTRODUCTION

Flash floods, or even floods, are a critical natural hazard characterized by a rapid and sudden rise in water levels, typically resulting from the swift movement of large volumes of water from high to low-lying terrain, accompanied by fast-moving currents (Benkhaled et al., 2013; Hafnaoui et al., 2023; Remini, 2023; Wang et al., 2023; Abd Rahman et al., 2023). These events, often carrying trees, rocks, mud, and debris, cause substantial damage to property, lead to loss of life, and disrupt the livelihoods of affected populations (Nezzal et al., 2015; Kouadio et al., 2018; Bakr et al., 2022). In rare cases, flooding is sometimes beneficial (Remini, 2020a, 2020b, 2020c; Remini, 2022). Globally, floods or flash floods occur in various regions and are caused by diverse factors such as heavy rainfall (Gassi and Saoudi, 2023), snowmelt, storms, or the formation resulting from the breach of water reservoirs or the release of large volumes of water (Zhai and Zhang, 2021; Yang et al., 2021; Hafnaoui et al., 2022; Yadav and Kumar, 2023; Wang et al., 2023; Sathyaraj et al., 2023; Measures and Study, 2023).

A considerable number of nations worldwide contend with the profound consequences of flooding and flash floods, with their intensity varying across regions, further aggravated by the effects of climate change and drought on water resources and hydrological systems, especially in arid and semi-arid regions (Derdour et al., 2017; Boubakeur, 2018; Doumounia et al., 2020; Remini, 2020d; Nassa et al., 2021; Assemian et al., 2021; Nakou et al., 2023; Chadee et al., 2023; Benali Khodja and Ferdjouni, 2024).

Floods and flash floods pose significant challenges to water management systems by overwhelming drainage infrastructure, contaminating water supplies, and disrupting water distribution networks. Effective water supply management must incorporate flood resilience strategies to ensure the availability of clean water during and after extreme weather events. Decision support systems (DSS) play a crucial role in managing water distribution networks by integrating real-time hydrological data, predictive models, and emergency response measures to mitigate flood impacts. A comprehensive water strategy should include adaptive flood control mechanisms such as reservoir operation and flood forecasting, flood risk mapping, flood management, sustainable watershed management, and climate-resilient infrastructure to safeguard water resources and ensure long-term water security. Extensive research has been carried out on all the aforementioned key aspects, and readers are encouraged to refer to the following most pertinent studies (Ayari et al., 2016; Bouguerra and Benslimane, 2017; Bouly et al., 2019; Hountondji et al., 2019; Bekhira et al., 2019; Cherki 2019; Benslimane et al., 2020; Aroua, 2020; Aroua, 2022; Pandey et al., 2022; Long et al., 2023; Mehta et al., 2023; Zegait and Pizzo, 2023; Bentalha, 2023; Baudhanwala et al., 2023; Trivedi and Suryanarayana, 2023; Verma et al., 2023; Kouloughli and Telli, 2023; Berrezel et al., 2023; Ben Said et al., 2024; Mah et al., 2024; Shaikh et al., 2024)

In Vietnam, flash floods are particularly frequent in the northern mountainous regions, where complex terrain and steep slopes create conditions conducive to these extreme events. Recent trends show an increase in both the frequency and intensity of flash floods in these areas, leading to increasingly severe impacts on both people and property

(Vietnam, 2022). Consequently, understanding the mechanisms behind flash floods and identifying key contributing factors is vital for developing effective flood management solutions in Vietnam's mountainous areas.

The mechanisms and causes of flash floods are complex and vary significantly between regions, depending on factors such as rainfall intensity, watershed characteristics, and local terrain conditions (Malik et al., 2023; Remini, 2023; Wang et al., 2023b; Yadav and Kumar, 2023). A review of over 300 studies indicates that typical triggering factors include rainfall quantity, geomorphological characteristics of the watershed, geological factors, conditions of the watershed cover, and human activities (Saleh et al., 2020). Among these, rainfall quantity is the leading cause, accounting for up to 60% of the group of causes and the weight of flash flood occurrences (Akter et al., 2023). Geomorphological characteristics of the watershed account for approximately 25% of the group of causes of flash floods, while other factors make up 15% of the causes of flash floods (Asri and Mahmud, 2023; Chen et al., 2022; Sapan et al., 2023). In tropical mountainous regions, terrain characteristics, such as steep slopes, are particularly influential in determining flash flood occurrence (Bakr et al., 2022; Chen et al., 2019). Additionally, human activities such as deforestation and infrastructure development exacerbate flash flood risks by altering natural water flow patterns (Liu et al., 2021).

Rainfall is a primary and direct contributor to the occurrence of flash floods. As rainwater accumulates, it saturates the soil and flows over the surface, resulting in erosion, washouts, landslides, and mudslides (Amon and Bene, 2023). Therefore, most countries worldwide use rainfall as the most crucial input data for flash flood warnings. In-depth studies on the relationship between rainfall and flash floods often conclude that prolonged heavy rainfall is the determining factor for flash flood formation. However, the rainfall threshold for flash flood occurrence depends on watershed characteristics. Currently, two widely adopted methods for rainfall-based flash flood warning systems are the Japan Critical Limited Line method (Matsumoto et al., 2022) and the United States flash flood guidance method.. These are advanced and highly applicable methods, but they require a sufficiently large historical rainfall dataset, a long observation period for rainfall, and an appropriate density of rain gauge stations to enhance accuracy in warnings. Some studies on flash floods in Chinese river basins have identified that cumulative rainfall exceeding 200-300mm per event increases the risk of flash flood occurrence by over 50-60% (Ma et al., 2022; Wang et al., 2017; Yang et al., 2021; Zhai et al., 2021). Additionally, investigations in small watersheds in East Java reveal that continuous rainfall exceeding 250 mm over five hours elevates the likelihood of flash floods by 61% (Putra et al., 2022). Similarly, studies in the Himalayan river basins have also determined rainfall thresholds and flash flood occurrence levels for each watershed (Yadav and Kumar, 2023).

Recent advances in flash flood research have leveraged modern technologies, including remote sensing, geographic information systems (GIS), artificial intelligence (AI), and machine learning algorithms, to improve flood prediction and management (Abdel-Fattah et al., 2016; González-Prida et al., 2012). These methodologies have enabled the development of models like the Flash Flood Potential Index (FFPI) and various machine learning techniques (Saaty, 1987; Saaty, 2015; Yassin et al., 2023); Sensitivity studies and the establishment of flash flood warning maps utilize logistic regression (Cao et al., 2020; El-Rawy et al., 2022; López and Rodriguez, 2020; Pham et al., 2020), decision trees (Abedi et al., 2022; Costache et al., 2021), artificial neural networks (Dinu et al., 2017), support vector machines (Xiong et al., 2019), frequency ratio (Tariq et al., 2022; Waqas et al., 2021), weight of evidence (Pham et al., 2020; Saleh et al., 2022), statistical index (Lee and Kim, 2019), certainty factor (Cao et al., 2020; Sapan et al., 2023) and entropy index. In general, these methods integrate and analyze various factors contributing to flash floods by examining individual components, assigning weights, and evaluating the variability of these weights. However, their effectiveness is heavily dependent on the accuracy and reliability of the input data, particularly rainfall data. This reliance presents a significant limitation, especially in regions with insufficient data collection, sparse networks of monitoring stations, and incomplete historical records of flash flood events. Such data deficiencies can undermine the precision and reliability of research outcomes, potentially leading to less accurate assessments and predictions.

This study focuses on understanding the mechanisms behind flash floods in the northern mountainous region of Vietnam, with a case study conducted in the Chu Va watershed in Lai Chau province. The research adopts a watershed-centric approach, specifically focusing on small, steeply sloped watersheds that are typical of flash flood-prone areas in Vietnam's mountains. This method is scientifically robust, as small watersheds are relatively closed systems where rainfall patterns and geomorphological characteristics dictate the formation and flow direction of flash floods (Qie, 2021). Each watershed will have its distinct flash flood formation mechanism. Several studies have also indicated that flash floods often occur in small watersheds with significant slopes (Chen et al., 2019; Laudan et al., 2020; Remini, 2023; Asri and Mahmud, 2023; Chowdhury, 2024). In Europe, 80% of flash events occur in watersheds smaller than 100 km^2 (Marchi et al., 2010). In the United States, flash floods predominantly occur in very small watersheds ranging from 0.125 to 0.312 km^2; the smaller the watershed, the quicker the formation of the flood wave (Papagiannaki et al., 2015). Research has also revealed that for watersheds of approximately 0.65 km^2, the time for flood wave formation is 40 minutes, while for a watershed of 165 km^2, the formation time extends to 5 hours. In the context of existing research, which has largely focused on large-scale analyses and flood zoning (Chau et al., 2021; Kieu and Tran, 2021; Ngo et al., 2023; Nguyen et al., 2015; Vu and Bui, 2023). Some studies assess damages and analyze the causes of typical flash flood events (Le et al., 2022), establish a scientific basis for zoning warnings and forecasting flash floods (Nguyen et al., 2015; Nguyen and Kieu, 2021), develop early warning models for flash floods (Hoang et al., 2019; Ngo et al., 2020; Chau et al., 2021), create flash flood warning maps for the Central Highlands region (Nguyen et al., 2015).

Flash flood research in Vietnam has primarily focused on large-scale studies with a high degree of generalization, often overlooking small watersheds that are critical for understanding the specific causes and mechanisms of typical flash floods (Chau et al., 2021; Ngo et al., 2023). Existing methodologies, such as the Japan Critical Limited Line and U.S. Flash Flood Guidance, are widely applied but rely heavily on the availability of dense rain gauge networks and long-term data, which are often unavailable in remote, data-sparse regions. In contrast, the proposed watershed-centric approach, which concentrates on small, steeply sloped watersheds like the Chu Va watershed, offers a more localized and context-specific methodology. This approach has the potential to provide a more detailed understanding of flash flood dynamics in mountainous areas, enhancing predictive accuracy and improving flood management strategies tailored to the unique characteristics of these regions. This research seeks to address this gap by providing a more granular analysis of flash flood mechanisms in mountainous watersheds, with the aim of contributing to the scientific understanding of flash flood formation and supporting the development of more effective flood management strategies, which could be applied to similar regions across Vietnam.

STUDY AREA

The Chu Va stream watershed is entirely located within the administrative boundaries of Tam Duong District, Lai Chau Province, in the northern mountainous region of Vietnam. The watershed lies between geographical coordinates 22.322° – 22.406° North latitude and 103.623° – 103.751° East longitude (Fig. 1). It covers a total area of 137.27 km^2, which is subdivided into six smaller sub-watersheds: Chu Va stream 1 (CV1), Chu Va stream 2 (CV2), Chu Va stream 3 (CV3), Chu Va stream 4 (CV4), Chu Va stream 5 (CV5), and Chu Va stream 6 (CV6). The CV2 sub-watershed has the largest area (38.36 km^2), while the CV3 sub-watershed is the smallest (12.46 km^2). The perimeter of the watershed is 53.32 kilometers, and its shape factor is 0.91. Detaling the watershed and sub-watershed areas is important as it enables a more precise understanding of the hydrological and ecological characteristics of each section, allowing for better management and conservation practices.

The Chu Va stream watershed is one of the highest elevation watersheds in Vietnam, characterized by significant topographic relief. The average elevation is 1,968 meters above sea level, with the highest point at 3,036 meters and the lowest point at 629 meters, resulting in a total vertical relief of 2,407 meters. This substantial relief contributes to an average slope of over 35 degrees across the watershed, with certain sub-watersheds, such as CV1 and CV2, exhibiting slopes exceeding 40 degrees. The total length of the Chu Va stream is 92.89 kilometers, with an elevation difference of nearly 2,000 meters along its course (Table 1).

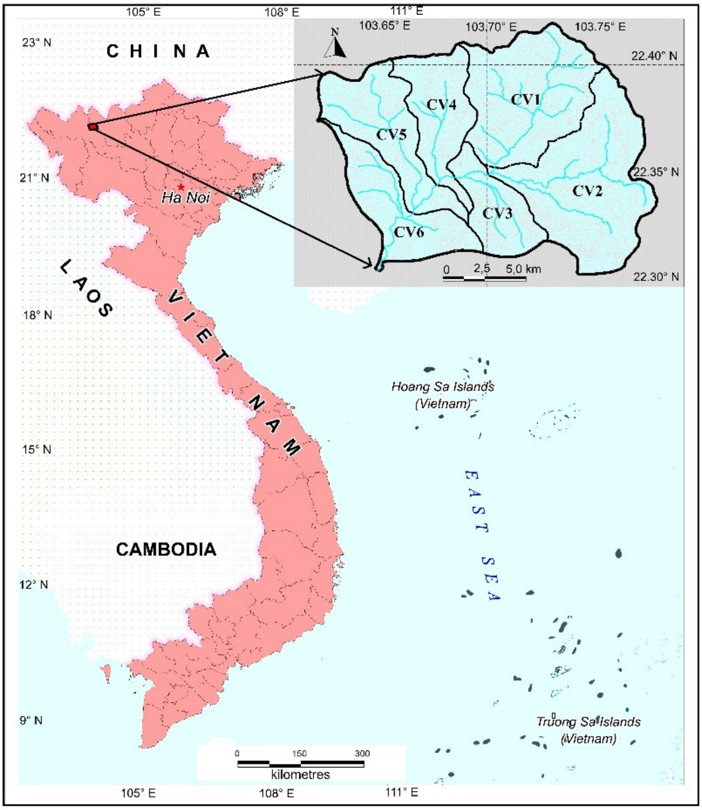


Figure 1: Location map of the study area

Table 1: The basic physiographic of the Chu Va stream watershed

No	Watershed parameters	CV1	CV2	CV3	CV4	CV5	CV6	CV
1	Area (km^2)	31.82	38.36	12.46	16.40	20.55	17.68	137.27
2	Perimeter (km)	25.88	32.22	16.52	23.34	26.61	25.81	53.32
3	Shape factor	1.23	1.19	0.75	0.70	0.77	0.69	0.91
4	Highest point (m)	2805	3036	2485	2675	2618	2525	3036
5	Lowest point (m)	1035	1015	902	880	748	629	629
6	Topo relief (m)	1770	2021	1583	1795	1870	1896	2407
7	Average slope (%)	41.6	46.9	26.8	32.6	35.8	39.7	37.2
8	Stream length (km)	21.72	23.17	10.36	9.65	15.2	12.79	92.89
9	Elevation difference within the stream channel (m)	1515	1056	1187	1030	1482	1122	1921

MATERIAL AND METHODS

Data and material

The research employs multiple data sources. Data on flash floods are derived from statistical records maintained by the Provincial Center for Natural Disaster Prevention and Control in Lai Chau province, covering the period from 2000 to 2023. Rainfall data were collected from automatic rain gauge stations and meteorological stations, with relevant data specifically recorded at the Binh Lu station of the Northern Vietnam Meteorological and Hydrological Agency. Information on topography, morphology, watershed slope, and vegetation cover was obtained from Digital Elevation Models (DEM) resolution is 10 m, and Landsat satellite imagery (2010, 2023), sourced from the USGS Earth Explorer (https://earthexplorer.usgs.gov/). During the course of the research, the research team conducted surveys and interviews with local residents and authorities at sites where flash floods frequently occur. These surveys aimed to gather data on the current flash flood situation, factors contributing to flash floods, and the extent of damage caused. Flash flood images and real-time data were collected, analyzed, and used to validate the research findings. Additionally, the study incorporated data from previous research on flash floods in the northern mountainous region of Vietnam, including information on the state of flash floods, contributing conditions, and factors specific to the Chu Va stream watershed (Kieu and Nguyen, 2021; Ngo, 2020; Thuy et al., 2021).

Methods

Survey and data collection for the research

The survey method was employed to conduct preliminary assessments, gather data, and validate research findings (Du et al., 2023). Based on statistical data on flash floods, the study focused on five areas within the Chu Va stream watershed that are regularly prone to flash flooding. At each survey site, the research team performed on-site observations and analyses, measuring parameters related to flow morphology, watershed topography, and identifying factors contributing to flash floods. In addition, the survey method was supplemented by field data collection through questionnaires and interviews with local households. The data collected directly from these sources included information on the current state of flash floods, their frequency, the impact of floods on local communities, and public perceptions of flash flood events. These field survey data provided an essential foundation for the study, offering comparative data for validating statistical results and supporting spatial analyses derived from remote sensing data and satellite imagery.

Multi-Criteria Analysis (MCA) and Analytic Hierarchy Process (AHP)

The MCA method enables decision-making based on criteria from individuals or organizations (Triantaphyllou, 2000). AHP is a weighting calculation method used in decision-making problems to rank selected criteria (Saaty, 2002). The study identified flash flood-triggering factors in the Chu Va stream watershed based on the analysis of 15 input factors and the opinions of 30 experts in the research field. The MCA-AHP analysis model, combined with a watershed topography analysis using GIS, determined the typical flash flood-triggering factors in small watersheds in mountainous regions of Vietnam (Nguyen et al., 2015; Hoang et al., 2019; Pham et al., 2020; Chau et al., 2021; Ngo et al., 2023). From these identified flash flood-triggering factors, the study established pairwise comparison matrices for each factor, assigned standard ranks, calculated weight values, and assessed the consistency of the factors. Based on the AHP calculation steps combined with expert opinions, the study selected four factors, including cumulative rainfall, watershed morphology characteristics, vegetation cover reduction, and human impacts, for analyzing and explaining the causes of flash floods in the Chu Va stream watershed. This method is particularly relevant to the study as it enables a structured decision-making process that incorporates both qualitative and quantitative inputs, which is crucial for understanding complex, multi-dimensional environmental issues like flash flood risks in mountainous watersheds.

Calculation of cumulative rainfall triggering flash floods

The calculation method for determining cumulative rainfall triggering flash floods is based on rainfall data recorded during each continuous rainfall event preceding a flash flood occurrence. A continuous rainfall event is defined as the rainfall calculated from the onset of continuous rainfall until its cessation, with no interruption in rainfall duration (Papagiannaki et al., 2015). In this study, the concept of cumulative rainfall triggering flash floods is employed and calculated using the following formula:

$$Rfi = \sum_{j=1}^{i} Rj \qquad (1)$$

Where, Rfi is the cumulative rainfall triggering flash floods at time i, Rj is the rainfall measured at time j, and j is calculated from the first moment of rainfall until the last moment of rainfall before time i. Consequently, the cumulative rainfall triggering flash floods in this study is derived from hourly rainfall measurements, specifically as the total accumulated rainfall during the continuous rainfall event leading up to the flash flood occurrence.

Utilizing satellite imagery and GIS spatial analysis

Satellite imagery provides essential data for analyzing surface structures and factors contributing to flash floods in a watershed. In this study, a Digital Elevation Model (DEM) resolution is 10 m is used to examine the geomorphic features of the watershed, including terrain elevation, slope, aspect, landform features, and watershed structure. Landsat imagery from the period 2010–2023 is employed to assess surface cover characteristics, calculate variations in vegetation indices, and evaluate land use changes within the watershed. The primary methods applied in this analysis include attribute classification (Shirowzhan and Sepasgozar, 2019) and spatial analysis (Goodchild and Haining, 2004). Spatial analysis tools in QGIS software are used to investigate the mechanisms and factors contributing to flash floods, as well as to create simulation maps that illustrate the occurrence process of flash floods and the associated factors within the watershed.

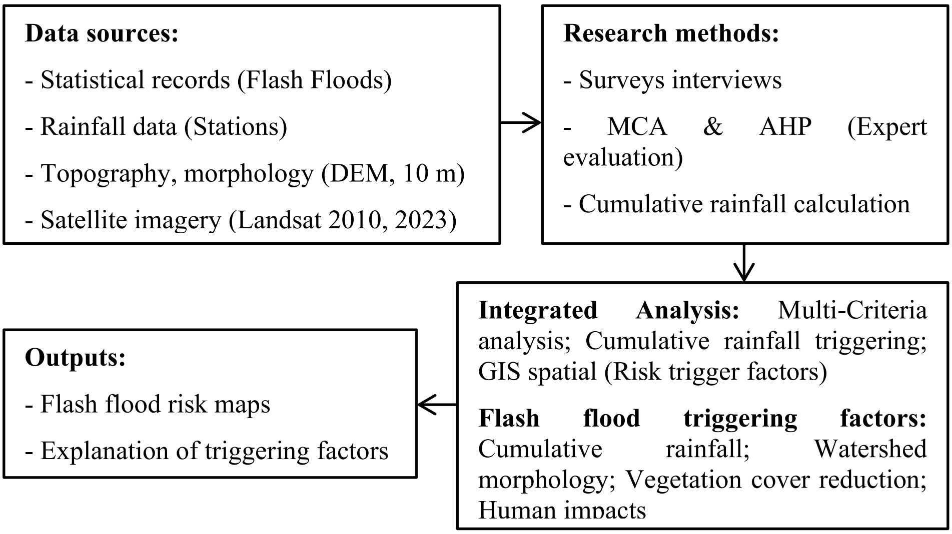


Figure 2: The framework for investigating the mechanisms and factors triggering flash floods in the Chu Va stream watershed

The framework for investigating the mechanisms and factors triggering flash floods in the Chu Va stream watershed can be summarized in Fig. 2.The research framework begins by collecting diverse data from statistical records, rainfall measurements, satellite imagery, field surveys, and previous studies on flash floods in the Chu Va stream watershed. It then applies MCA-AHP to prioritize flash flood triggering factors, followed by cumulative rainfall calculation and GIS-based spatial analysis to assess the influence of terrain, vegetation, and human impacts. The integrated analysis leads to identifying key flash flood triggers and creating risk maps, which are validated through field data and expert opinions, ultimately providing insights for policy recommendations and disaster prevention strategies.

RESULTS

Overview of flash flood events in the Chu Va stream watershed

The Chu Va stream watershed is characterized by complex flash flood dynamics, with the highest frequency and intensity of flash floods observed among small river basins in the Northern mountainous region of Vietnam (Kieu and Nguyen, 2021). According to data from the Provincial Center for Disaster Prevention in Lai Chau, between 2000 and 2023, the watershed experienced 48 flash flood events of varying intensities. Of these, 10 flash floods resulted in significant damage to both human life and property. Detailed records of the major flash floods include information on the time of occurrence, intensity, affected areas, and the extent of casualties and property damage (Table 2). These significant events will be further analyzed to investigate the underlying mechanisms and factors contributing to their occurrence.

Table 2: Occurrence time, intensity, affected area, and extent of casualties and property damage caused by major flash floods in the Chu Va stream watershed during the period 2000-2023

No.	Date	Rainfall intensity and range	Impacts
1	July 30, 2002	Heavy rain over 9 hours, rainfall over 180.25mm	3 fatalities, 2 injuries, 8 houses swept away, 120ha of flowers submerged, 5 irrigation projects destroyed
2	July 11, 2008	Prolonged heavy rain for 22 hours, total rainfall 283.58mm	6 missing persons, 12 houses swept away, 5 fish farms destroyed
3	July 30, 2009	Heavy rain with total rainfall exceeding 230mm	8 houses swept away, 90ha of rice and flowers submerged, 6 irrigation projects destroyed, estimated damage over 100,000 USD
4	August 2, 2010	10-hour rainfall of 180.27mm, flooding in Chu Va main stream	2 injuries, 2 irrigation projects destroyed, estimated damage over 150,000 USD
5	June 29-30, 2011	Prolonged rain for 19 hours, total rainfall 339mm	7 houses destroyed, landslides affecting roads and stream embankments, 20ha of flowers damaged
6	July 26, 2013	14-hour rainfall of 321.35mm, flooding in main stream and tributaries	5 injuries, 8 houses swept away, 100ha of flowers submerged, 3 irrigation projects destroyed
7	August 12, 2014	12-hour rainfall of 265.05mm, flow rate at the main stream reaches 6500m^3/s	4 injuries, 90ha of flowers submerged, 2 irrigation projects and transportation infrastructure destroyed, estimated damage over 180,000 USD
8	June 24, 2018	20-hour rainfall of 420.25mm, flow rate at the main stream reaches 6700m^3/s	3 fatalities, 3 missing persons, 30 houses affected, 4 fish farms swept away, estimated damage over 350,000 USD
9	July 16, 2021	8-hour rainfall of 160.87mm, flow rate at the main stream reaches 5200m^3/s	2 missing persons, 24 houses affected, 2 fish farms swept away, extensive damage to flowers and crops, estimated damage over 250,000 USD
10	June 13, 2023	13-hour rainfall of 367.16mm, flow rate at the main stream reaches 6300m^3/s	4 missing persons, 26 houses affected, 5 sturgeon and catfish farms swept away, 6 irrigation projects and transportation infrastructure destroyed, estimated damage over 300,000 USD

The statistical data of flash flood events in the Chu Va stream watershed, presented in Table 2, shows that these incidents predominantly occur during the months of June, July, and August. The flood intensity, as indicated by the flow rate and accumulated rainfall, exhibits an increasing trend over time. The most severe flash flood event was recorded on June 24, 2018, with a total accumulated rainfall of 420mm over 20 hours, resulting in a stream flow rate of 6700 m^3/s. This event caused significant casualties, including 6 fatalities, 3 individuals reported missing, and damage to 30 houses. Another notable flash flood occurred on June 13, 2023, with an accumulated rainfall of 367 mm over 13 hours, and a stream flow rate of 6300m^3/s. This event impacted the entire Chu Va stream watershed, causing 4 fatalities, affecting 26 houses, sweeping away 5 sturgeon and catfish farms, and destroying 6 irrigation projects and transportation infrastructure (Table 2). Over the past 20 years, flash floods in the Chu Va stream watershed have claimed 42 lives, affected more than 100 houses, and caused the destruction of 60 transportation and irrigation projects. The total estimated property damage from these events exceeds 3 million USD.

The mechanisms of flash flood generation in the Chu Va stream watershed

Survey results and investigations into flash flood events in the Chu Va stream watershed identify two primary types of flash floods: slope-induced flash floods and channel-obstructed flash floods. Slope-induced flash floods occur in areas with high slopes, steep terrain, and topographic features that amplify the effects of sudden, intense rainfall, leading to rapid but short-duration floods (Wang et al., 2023; Vu, 2022). These floods are triggered when heavy rainfall overwhelms the capacity of steep slopes to absorb water, resulting in quick runoff and flash flooding. Channel-obstructed flash floods, on the other hand, occur when objects such as trees, mud, sand, or man-made structures block the natural flow of water in the stream channels. During heavy rainfall, floodwaters and sediment accumulate in these obstructed channels, and when the obstruction is eventually breached or overwhelmed, it triggers a flash flood (Malik et al., 2023; Remini, 2023; Kieu and Tran, 2021). Of the 48 recorded flash flood events in the Chu Va stream watershed, 21 were slope-induced, while 27 were channel-obstructed. Both types of flash floods share common mechanisms, including heavy rainfall that initiates water flow, material displacement, channel blockage, erosion, and sediment deposition (Fig. 3).

Flash floods in the Chu Va stream watershed typically initiate and form in its upper reaches, which are characterized by steep slopes, high terrain, and pronounced topographical features. The streambed in these areas is relatively narrow, facilitating the convergence of flow (Kieu and Tran, 2021). These morphological characteristics create conditions that are conducive to the initiation and formation of flash floods. Images from the CV1 and CV4 stream sections reveal the influence of human activities, such as road construction, hydraulic infrastructure, and stream channelization for fish farming. Under prolonged heavy rainfall, these altered areas become particularly vulnerable to landslides, which mobilize soil and rock materials. This process results in the downstream transport of mud and debris, further exacerbating the flood risk within the watershed.

Figure 3: Simulated mechanisms of flash flood generation in the Chu Va stream watershed (flash flood event on June 13, 2023)

Channel blockages and flow obstructions typically occur when the flow rate and material accumulation during flash floods are substantial. In the absence of such blockages, the flash flood takes the form of slope-driven floods, as observed in the CV4 and CV5 stream sections. However, more commonly, flash floods encounter obstacles in their flow, such as vegetation, mud, sand, or man-made structures. These obstructions can lead to the formation of damming flash floods, where the flow is temporarily blocked or redirected before the obstruction is eventually breached.

The flash flood event on June 13, 2023, provides a clear example of a damming flash flood. Prolonged heavy rainfall generated significant flow in the CV1 and CV2 stream sections, transporting materials downstream to the intersection near Chu Va 2 village, where construction activities had created an obstruction in the flow. This blockage caused the accumulation of a large volume of floodwater. Eventually, the water pressure surpassed the capacity of the obstruction, breaching it and releasing a massive surge of water downstream. The resulting flood caused extensive damage and carried away all materials in its path.

The area of destruction and sediment deposition is located in the middle and downstream of the watershed. The results of the survey on the three most recent flash floods indicate that the area of destruction and sediment deposition tends to expand downstream. The extent of destruction depends on the intensity and flow rate of the stream (Vu and Bui, 2023). In the Chu Va watershed, 37 out of 48 (77%) flash flood events occurred at night, resulting in greater damage. Slope-driven flash floods generally cause less damage and sediment deposition than damming flash floods (Le et al., 2022). The flash flood on June 24, 2018, affected an area exceeding 12.0 km^2, depositing materials including large rocks, concrete blocks from the Chu Va 1 bridge, and remnants of large trees still visible in the main stream downstream of the Chu Va watershed.

Flood-triggering factors in the Chu Va stream watershed

Studies on flash floods in the mountainous regions of Vietnam consistently identify two main groups of factors contributing to their occurrence: natural factors and anthropogenic factors. Natural factors include rainfall, topography, geology, river density, vegetation cover, and soil characteristics, while anthropogenic factors encompass economic and social activities, transportation infrastructure development, hydraulic engineering, deforestation, and mineral exploitation, among others (Hoang et al., 2019; Kieu and Tran, 2021; Vu, 2022; Ngo et al., 2023; Vu and Bui, 2023). Results from the MCA-AHP analysis, based on expert evaluation, have identified the key factors and their respective weights that contribute to flash flood events in the Chu Va stream watershed. Four primary factors were identified as the most significant for flash flood occurrences: cumulative rainfall (0.28), watershed morphological characteristics (0.21), reduction in vegetation cover (0.19), and human activities (0.12). These findings align with the flash flood generation mechanisms observed in the Chu Va stream watershed, as detailed in the previous analysis.

In addition to the four primary factors that determine flash flood occurrences mentioned above, studies also highlight the significant role of geological conditions, soil characteristics, and land types in the flash flood processes in the mountainous regions of Vietnam (Ngo et al., 2023; Vu and Bui, 2023). However, the Chu Va stream watershed is characterized by relatively stable geological conditions, consisting mainly of metamorphic and magmatic rocks that were formed during the Paleozoic and Mesozoic eras. The soil types in this area are influenced by both climate and topography, with the most common types being red-yellow feralit soils, mountain peat soils, and Nitisols. This study specifically focuses on analyzing the factors that contribute to flash flood occurrences in the Chu Va stream watershed, including cumulative rainfall as a trigger, watershed morphological characteristics, the reduction of vegetation cover, and human impact.

The rainfall-activated flash flood factor

Statistical data on rainfall at the Binh Lu station within the Chu Va stream watershed indicates an average annual rainfall of 2,294.4 mm for the period from 2000 to 2023. The distribution of rainfall throughout the year is uneven, with 89.6% of the total annual rainfall occurring between April and October. Notably, the months of June, July, and August account for 60.5% of the total annual rainfall (Fig. 4).

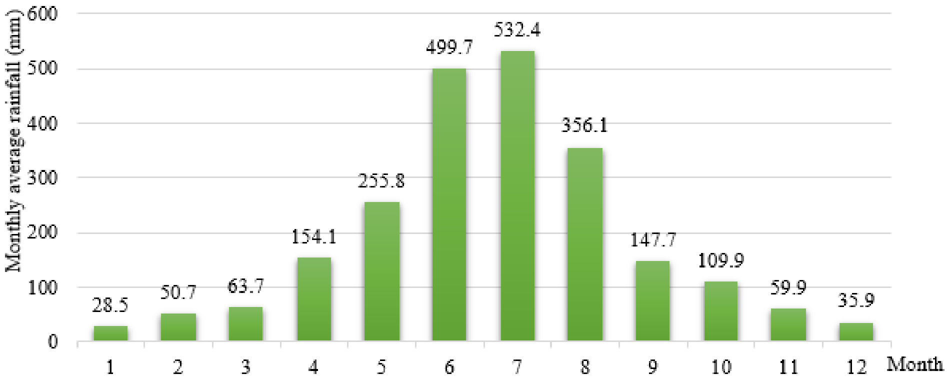


Figure 4: Monthly average rainfall chart in the Chu Va stream watershed for the period 2000-2023

Using hourly rainfall data, the study calculated the duration of rainfall events, cumulative rainfall, and average rainfall intensity during the 10 major flash flood events recorded in Table 2. Cumulative rainfall, which directly triggered the flash floods, was calculated up to the moment of their occurrence (Vu and Nguyen, 2023). The average values from these 10 flash flood events indicate a cumulative rainfall of 274.8 mm up to the point of flood occurrence, with an average hourly rainfall intensity of 19.05 mm/h. The continuous duration of rainfall events leading to the flash floods averaged 14.8 hours (Fig. 5).

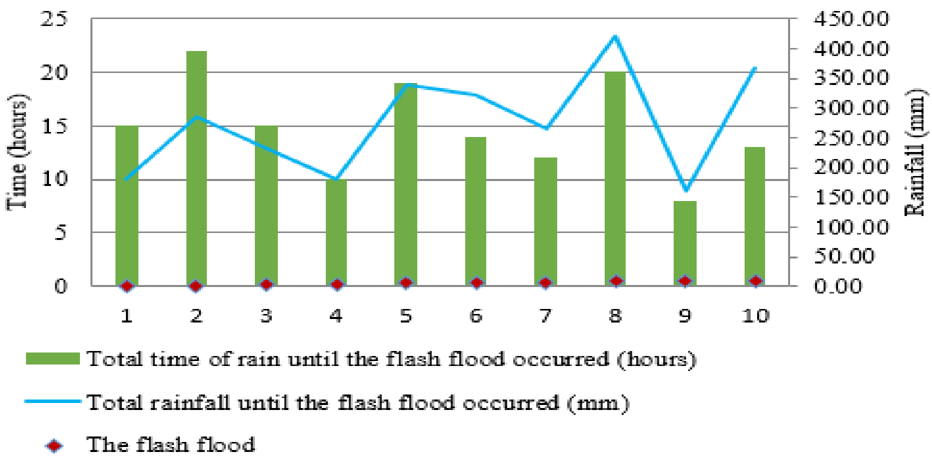
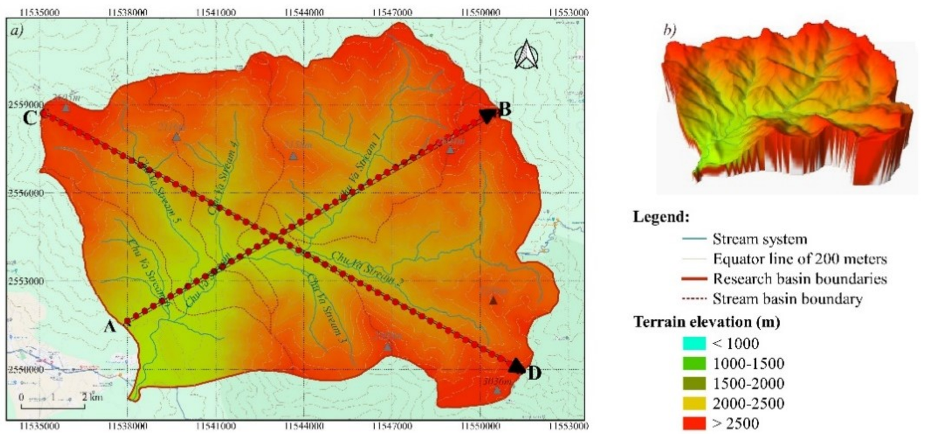


Figure 5: Total rainfall, and total time of rainfall until the flash flood occurred in 10 flash flood events in the Chu Va stream watershed

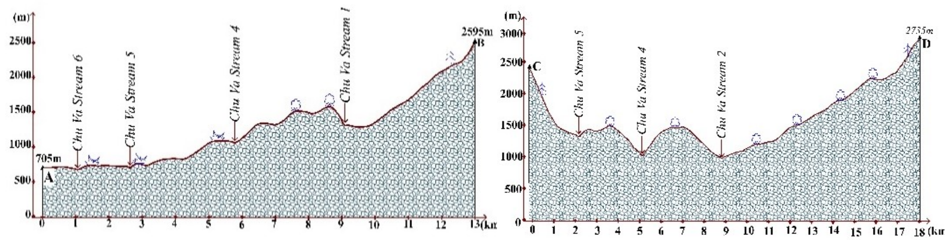
The chart in Fig. 5 shows the duration of continuous rainfall leading up to the occurrence of flash floods in the Chu Va stream watershed, ranging from 8 to 22 hours. Among these events, four occurred on the first day of continuous rainfall, while six took place on the second day. Flash flood event number 6, which occurred on July 26, 2013, had the shortest duration, with the flash flood occurring after just 2.5 hours of continuous rainfall. The cumulative rainfall prior to the flash flood consistently exceeded 180 mm, with the highest recorded rainfall event occurring on June 24, 2018, at 420.25 mm. The average hourly rainfall intensity showed an increasing trend over time, with the highest observed intensity of 28.24 mm/h occurring on June 13, 2023. Of the 10 events, 8 exhibited an average hourly intensity that surpassed the 24-hour average rainfall intensity threshold used for flash flood forecasting in Vietnam.

Morphological characteristics of the Chu Va stream watershed

The analysis of watershed parameters in the Chu Va stream, as presented in Table 1, reveals a complex and rugged terrain characterized by significant elevation, steep slopes, and extensive topographic dissection. The Chu Va stream watershed generally slopes southwestward, with an elevation difference of 2,407 meters, leading to steep gradients and a high potential for hydrological concentration due to its expansive basin morphology. This topographic configuration is the primary factor contributing to the occurrence of flash floods in the Chu Va stream watershed.



a- Contour map of terrain elevation b- 3D model depicting watershed morphology



c- Cross-sectional profile AB d- Cross-sectional profile CD

Figure 6: Morphological characteristics of the Chu Va stream watershed

The topographical map (Fig. 6a) shows that the Chu Va stream watershed is primarily composed of high mountains, which can be classified into five elevation bands.

- Band 1 (below 1,000 m, constituting 15.8% of the basin area) consists mainly of valleys and lower basin floors, serving as deposition zones for materials during flood events.
- Band 2 (1,000–1,500 m, constituting 21.3% of the basin area) includes terraces and sloping hillsides, where overflow occurs during floods. This band includes parts of the lower reaches of CV4, CV5, and CV6.
- Band 3 (1,500–2,000 m, constituting 26.7% of the basin area) is characterized by areas prone to material displacement and the formation of flow impediments during heavy rainfall. Certain hillsides in the CV1, CV2, and CV6 basins are particularly susceptible to slope-driven flash floods due to the convergence of surface runoff.
- Band 4 (2,000–2,500 m, constituting 28.4% of the basin area) is the largest and is the region where flash floods originate and develop. This band is concentrated in the upper reaches of stream tributaries, with slopes exceeding 40 degrees and significant terrain dissection.
- Band 5 (above 2,500 m, constituting 7.8% of the basin area) consists mainly of mountain peaks on the eastern, northeastern, and northwestern edges of the basin. It is characterized by considerable terrain dissection and slopes often exceeding 50 degrees.

These elevation bands play a critical role in the hydrological dynamics and flash flood occurrence in the Chu Va stream watershed.

Fig. 6b presents a clear 3D model that illustrates the morphological characteristics of the Chu Va stream watershed. Overall, the watershed exhibits a southwestward slope, with small tributaries originating from the high, extensively dissected mountainous regions. Notably, six distinct breaks correspond to the convergence of six streams in the southwestern part of the basin. The CV1 and CV2 watersheds, in particular, feature V-shaped terrain that converges into a funnel-shaped central area, creating conditions highly conducive to flash flood occurrences. This region experiences the highest frequency of flash floods, accounting for over 60% of the total flash flood events within the watershed.

To further elucidate the morphological characteristics of the Chu Va stream watershed, two cross-sectional profiles were generated-profile AB along the main stream (Fig. 6c) and profile CD intersecting small tributaries (Fig. 6d). Profile AB depicts an elevation increase from the southwest to the northeast, following the main stream and intersecting CV6, CV5, CV4, and CV1. The lowest point is at 705m, the highest point at 2595m, with an average slope of 38.6%. The morphological features of profile AB highlight a significant potential for flow convergence and kinetic energy within the Chu Va stream. This explains why the Chu Va watershed experiences a much higher frequency of large-scale flash floods compared to other mountainous regions, given equivalent rainfall and rainfall intensity. Profile CD, running from the northwest to the southeast across CV5, CV4, CV3, and CV2, reflects the U-shaped morphology of the main watershed, illustrating a substantial east-to-west terrain dissection, with decreasing elevations from over 2500m on the periphery to 1000m at the central region. This morphological characteristic further clarifies the factor contributing to increased flow convergence from small tributaries to the main stream during rainfall, creating the necessary conditions for flash flood occurrences within the watershed.

Reduction of vegetative cover

Vegetative cover plays a crucial role in influencing the occurrence of flash floods within a watershed. In mountainous areas, vegetative cover acts as a barrier, inhibiting the initiation and reducing the intensity of flash floods (Le et al., 2022). Human activities have altered vegetative cover, disrupting the stability of the main slopes and serving as an exogenous factor leading to flash floods in the Chu Va stream watershed. This study utilized the Normalized Difference Vegetation Index (NDVI) (Shah et al., 2022; Xu et al., 2023) to analyze the extent of vegetative cover reduction in the study area. The results of the NDVI analysis for the period 2010-2023 reveal a significant decline in vegetative cover in the Chu Va stream watershed (Fig. 7). Regions with NDVI values above 0.3 experienced substantial reduction, while areas with NDVI values below 0.1 exhibited an increasing trend. Fig. 6c illustrates the degree of vegetative decline in the Chu Va stream watershed during the 2010-2023 period, indicating that 86.2% of the basin area experienced a reduction in vegetative cover, with the remaining 13.8% showing an upward trend in vegetative cover.

The variation in vegetation cover within the Chu Va stream watershed exhibits significant differences across its sub-basins during the period from 2010 to 2023 (Fig. 7c). Notably, the CV2, CV3, and CV6 sub-basins have experienced the most substantial decline in vegetation. This reduction in cover is particularly pronounced in the lower reaches of the main stream and along the banks of major tributaries, which are also the areas most heavily impacted during flash floods. Field surveys further reveal notable changes in land use within the watershed in recent years, which have significantly impacted the factors contributing to flash flood occurrences. Areas of bare land, denuded hills, residential areas, and land designated for tourism are increasing, while the extent of natural forest cover and rich forests is decreasing. The loss of forest vegetation increases the risk of soil erosion during heavy rainfall (Lap et al., 2021). When combined with flash floods, this heightened risk of erosion can lead to the formation of debris flows, causing substantial damage.

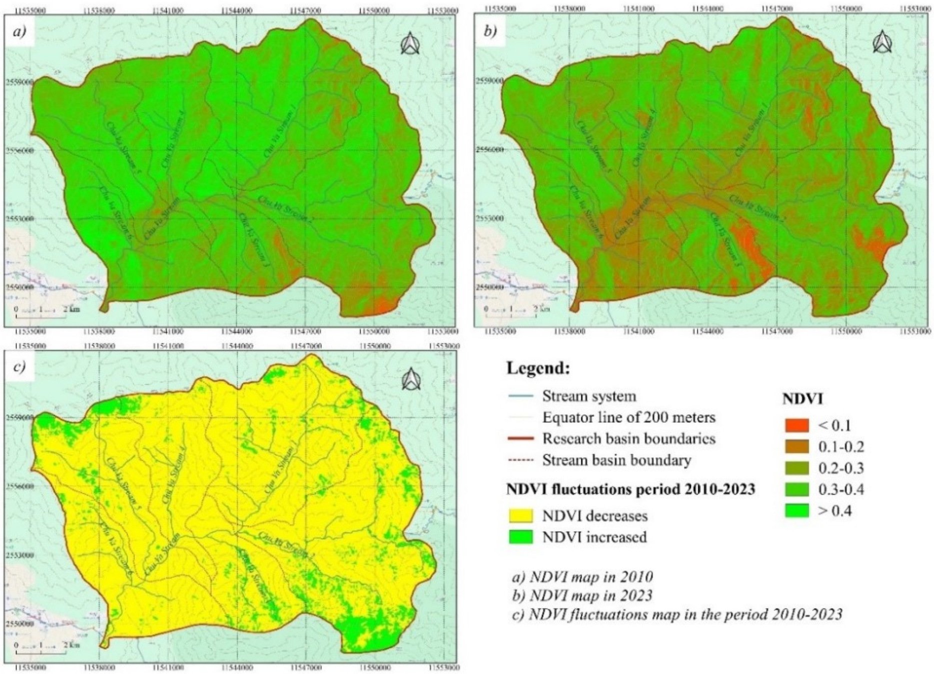


Figure 7: Dynamics of vegetation index in the Chu Va stream watershed during the 2010-2023 period

Impacts of human activities

Human activities have a significant impact on the formation of flash floods, particularly river-blocking flash floods. Survey results within the Chu Va stream watershed indicate a growing human influence on the natural environment. Notably, activities such as deforestation, reduction of vegetative cover, and the depletion of natural forests contribute to an increased risk of flash flood occurrences. Along National Highway 4D, which follows the Chu Va stream, the effects of human activities on the stream are readily observable. These activities include the construction of transportation infrastructure, hydroelectric projects, irrigation works, embankments, channel straightening for fish farming, mineral extraction, and tourism development, among others. All human activities, whether direct or indirect, affect the formation of flash floods. In fact, recent flash flood events have demonstrated that human activities influence not only the mechanisms behind flash floods but also their intensity and extent. Studies on river-blocking flash floods have shown that over 70% of flash flood causes are attributed to human activities, with the most significant contributions stemming from the construction of transportation infrastructure and hydropower projects, which directly obstruct the flow of the river (Nguyen et al., 2015; Chau et al., 2021); or the materials used in construction indirectly obstructing the flow (Vu and Bui, 2023).

DISCUSSION

Existing research on flash floods highlights a notable increase in both the frequency and intensity of such events in the mountainous regions of Vietnam (Vietnam, 2022). However, the challenge remains in fully elucidating the mechanisms and factors contributing to flash flood occurrences, particularly in small basins within these mountainous areas. Flash flood studies are diverse and, as a result, often lack complete consensus on the mechanisms that lead to such events (Saleh et al., 2020; Le et al., 2022; Wang et al., 2023). This variability is understandable, given that floods are multifaceted phenomena influenced by various regional characteristics and differences in research perspectives. Nevertheless, recent studies tend to focus on flash floods in small basins, as this approach provides valuable insight into localized conditions. While studies utilizing administrative spatial units at the provincial level may be convenient for management purposes, they often fail to address the complexities of flash floods, as these events do not conform to administrative boundaries (Kieu and Nguyen, 2021; Malik et al., 2023).

The mechanisms and characteristics of flash floods in the Chu Va stream watershed are representative of flash flood dynamics in small stream watersheds in Vietnam's mountainous regions. Studies of mountain flash floods consistently identify three typical types: slope washout, channel-blocking flash floods, and mixed flash floods (Le et al., 2022). The occurrence of these flood types is generally the result of the simultaneous presence of several contributing factors, such as intense rainfall, steep terrain prone to torrential flow, geological characteristics, and ground cover conducive to flood formation. The formation of flash floods is marked by three distinct zones: the formation zone, the displacement zone, and the deposition zone (Vu and Bui, 2023). In the case of the Chu Va stream watershed, slope washout and channel-blocking flash floods are the most common. During heavy rainfall, water sources trigger floods that move materials, block channels, and cause damage while depositing materials downstream (Pham et al., 2020). The key factor contributing to the higher frequency of flash floods in the Chu Va stream watershed is its morphological characteristics. A comparison of small basins highlights significant differences in elevation, slope, and channel convergence, all of which play a critical role in flash flood dynamics. Several studies have established correlations between watershed morphology and the occurrence of flash floods (Vu and Nguyen, 2023).

This study offers a novel approach by analyzing the factors contributing to flash flood occurrences based on the specific conditions of small river basins, particularly the Chu Va stream watershed. This focus on small basins is a relatively new approach in Vietnam, where most flash flood studies tend to concentrate on larger river basins. As a result, the typical mechanisms of flash floods in smaller watersheds often remain underexplored (Le et al., 2022). The methodology and approach used in this study have contributed to reliable and visually insightful results, enhancing the understanding of flash flood dynamics in small basins. However, some limitations must be acknowledged, which also present avenues for future research.

One of the primary limitations of this study is the lack of direct data on flow and water discharge during flash floods. The study relies heavily on statistical data, which can be incomplete, and there is a notable scarcity of real-time data on flow rates, water discharge, and rainfall measurements across the entire Chu Va stream watershed. The absence of such data limits the precision of flood simulations and flow dynamics analysis. In future research, the collection of more comprehensive data on these parameters, including the installation of additional rainfall measurement devices and hydrological monitoring stations across the watershed, would significantly improve the accuracy of flood modeling (Le et al., 2022).

Finally, a promising avenue for future research is the integration of the findings from this study into hydraulic modeling efforts. Specifically, insights into flash flood mechanisms in the Chu Va watershed could help improve flood simulations, including more accurate representations of flow dynamics, channel geometry, and sediment transport during flash floods (Pham et al., 2020). Establishing better rainfall-runoff relationships would further enhance hydrological modeling efforts, providing more reliable predictions and guiding mitigation strategies for flash flood-prone areas in Vietnam and similar regions.

CONCLUSIONS

Chu Va is a typical mountain stream watershed in Vietnam, frequently experiencing flash floods that cause significant damage to both life and property. The flash flood mechanism in the Chu Va watershed is driven by heavy rainfall, which generates runoff, triggers material movement, causes flow obstruction, overflows, and sediment deposition. The study identifies four key factors that determine flash flood occurrence in the watershed: accumulated rainfall triggering floods, watershed morphology contributing to flood formation, vegetation cover degradation, and human activities. Each of these factors plays a crucial role in the formation and escalation of flood risks. Accumulated rainfall is the primary factor directly responsible for triggering flash floods, while the steep terrain and highly fragmented topography of the watershed provide favorable conditions for flood generation. The findings indicate that 95% of flash floods occur during the rainy season, with an average event rainfall of 274.8 mm and an average rainfall intensity of 19.05 mm/h. Vegetation cover is vital in stabilizing the soil and reducing erosion, and human activities such as logging, infrastructure development, hydropower projects, and mining have significant impacts on flood mechanisms. This research not only enhances understanding of the factors influencing flash flood occurrences in the Chu Va area but also has broader implications for using spatial analysis methods and real-world data to predict and mitigate flash flood risks in other mountainous regions of Vietnam and similar areas worldwide.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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