Bulletin of Geography. Physical Geography Series, No. 20 (2021): 31–43
http://dx.doi.org/10.2478/bgeo-2021-0003

Application of geospatial technologies in constructing a flash flood warning model in northern mountainous regions of Vietnam: a case study at TrinhTuong commune, Bat Xat district, LaoCai province

ISSN 2080-7686

Quoc Lap Kieu [1,a], Duc Van Tran[2]

[1] Faculty of Natural Resources and Environment,TNU – University of Sciences, Tan Thinh ward, Thai Nguyen city, Vietnam, E-mail: lapkq@tnus.edu.com (corresponding author).

[2] Faculty of Geography, TNU – University of Education, Quang Trungward, Thai Nguyen city, Vietnam.

[a] https://orcid.org/0000-0002-1496-9950

Abstract. The model was constructed based on GIS spatial analyses, combined with Analytic Hierarchy Process (AHP) and Multi-Criterion Analysis method (MCA). The data gathered for the study were mainly from remote-sensing images, statistical data and surveys. Field experiments were conducted in Trinh Tuong Commune, Bat Xat District, Lao Cai province. This is a typical remote mountainous region of Vietnam in which flash floods often occur. The study analyzes and evaluates six primary factors that incite flash flood, namely: geomorphological characteristics, soil properties, forest and fractional vegetation cover types, local drainage basin slopes, maximum average rainfall of various years, and the river/stream density of the region. The zoning map showing flash flood potentials has determined that 19.91% of the area had an extremely high risk of flash flood occurrence, 64.92% of the area had a medium risk, and 15.17% had a low or very low risk. Based on the employment of daily maximum rainfalls as the primary factor, an online flash flood warning model was constructed for areas with a "high" or "very high" risk of flash flood occurrence.

Key words:
Geospatial technologies,
flash flood,
warning model,
natural disaster,
mountainous region

Introduction

Flash floods are among the world's deadliest natural disasters, with more than 5,000 lives lost annually, and result in significant social, economic and environmental impacts. Accounting for approximately 85% of flooding cases, flash floods also have the highest mortality rate among different classes of flooding. A flash flood is flooding with a rapid speed on sloped terrains, ultimately leading to huge destruction, which makes forecasting of flash floods quite a different challenge as compared to traditional flood forecasting approaches (World Meteorological Organization 2017). Particularly dangerous are multi-cell storms, consisting of many storm clouds, which sometimes organise into a mesocyclone. In the mesocyclone the derecho phenomenon can be created – violent storms accompanied by strong winds, especially on the squall line. Its appearance is visible on meteorological radars as a "bow echo" (Trapp and Weismann 2003; Taszarek 2019).

Mountainous regions in Northerm Vietnam have a total area of 100,965 km^2, with diverse natural conditions, high mountains, complicated weather differentiation, and plentiful mineral resources. However, these regions often suffer from many risks regarding natural disasters, especially flash floods. According to statistical data obtained for 20 years (2000–2020), in mountainous provinces of Northern Vietnam, there have been 590 flash floods, leading to the deaths of 748 people, 1,912 injured, 58,544 houses devastated, and total

© Author(s) 2021. This work is distributed under the Creative Commons Attribution 4.0 License (http://creativecommons.org/licenses/by-nc-nd/4.0/).

economic damage that is estimated up to USD 800 million (Vietnam Disaster Prevention and Control Office 2020). In addition, mountainous regions of Northern Vietnam are the primary neighbourhoods for populations from minority ethnic groups. As a result, the capacity to cope with flash floods is limited. There has been no scientific study serving weather forecasts, warnings and techniques against natural disasters and flash floods.

Geospatial technologies are the combination of Remote Sensing (RS), a Geographic Information System (GIS), and a Global Positioning System (GPS) in order to locate and analyze spatial data. In recent years, the application of spatial geography in researching, forecasting and warnings of flash flood risks has gradually grown in popularity. Studies regarding flash floods based on GIS and RS and in accordance with the FFPI model have been conducted with success, such as the studies of Smith (2010), Zogg and Deitsch (2016), Ballesteros et al. (2018), Costache et al. (2020) and Tincu et al. (2018); these articles used the data of slopes, soil types, land use types, and vegetation cover to build a potential map, which provided excellent support for flash flood forecasting activities. There were also studies on the index of flash flood occurrences, serving flash flood warnings based on indexes of the relationship between vegetation and ridge slopes as well as indexes of flash flood occurrences through remote-sensing data and GIS (Sivakumar et al. 2004; Elkhrachy 2015; Tehrany et al. 2015; Khosravi et al. 2018; Park et al. 2018). Some studies relate to mapping flash flood susceptibility by integrating frequency ratio and index of entropy with multilayer perceptron and classification and regression trees (Cao et al. 2016; Popa et al. 2019).

In Vietnam, studies regarding forecasting and warning of flash floods are greatly limited. Nevertheless, some have recently been implemented with a primary focus on constructing zoning maps for flash flood warnings. Remarkably, there is the study by Ha (2009) on building a zoning map of flash flood risks, serving disaster control activities in Yen Bai Province; the study by Lai et al. (2018) on building a map for early flash flood warnings in Thuan Chau district, Son La province; and the study by Tran (2020) on the status and flash flood zoning maps for some mountainous regions in Vietnam. Overall, most studies regarding flash floods in mountainous regions employed the approach of hydrology and/or hydraulics, applying FFPI, HEC-RAS, SWAT and other models to construct flash flood warning maps (Smith 2010; Cao et al. 2016). Furthermore, some warning maps were built based on approaching flash floods at mountain ridges (Ha 2009; Smith 2010; Cao et al. 2016; Park et al. 2018; Lai et al. 2018; Tran 2020), which results in areas being zoned according to ridges alone. Consequently, this approach lacks detailed calculations and has limited applicability. Moreover, the aforementioned studies often focused on statistical data alone, ultimately leading to a lack of online warning abilities. On the other hand, flash floods in mountainous regions often occur suddenly without any fixed rules, intensity or damage. The power of flash floods also depends greatly on factors that can arise instantaneously, such as a huge rainfall in a single day, the congestion of flows, and changes in flood draining in drainage basins.

In this study, flash floods were approached by considering drainage basins, which are considered relatively closed systems and include small tributaries. Furthermore, when there is rain, the indexes of buffer surfaces would be used to determine the mode of transportation and aggregation of flows within the area of drainage basins (Oliveira et al. 2019). Mountainous regions often possess high slopes. Therefore, when rain exceeds limits, the flows aggregate to form a flash flood. Additionally, each drainage basin has a particular mechanism of flash flood occurrences. In this study, the model of flash flood warnings in accordance with drainage basins was constructed based on geospatial technologies. More specifically, the remote-sensing technology provided satellite images for the analyses of factors that formed flash floods, such as terrains, geomorphology, and factors relating to pedology, flows, vegetation, etc. The GIS technique was responsible for processing spaces, forming maps of forecasts, and issuing alerts in terms of flash flood risks and intensity. Finally, GPS identified locations, enabling online warnings to be issued. The study experimentally applied the technologies at Trinh Tuong commune, Bat Xat district, Lao Cai province. This is a typical commune in a mountainous region of Vietnam that consists of high mountains, partitions according to drainage basins, and a frequent occurrence of flash floods leading to huge damages in terms of population and properties. The results have been applied in fields, initially offering great effectiveness in flash flood forecasting and warning. The model from this study is applicable in flash flood drainage areas in mountainous localities in Vietnam.

Location, data and methodology

Study location

Trinh Tuong is a remote commune located in the border region of Northerm Vietnam. It has a total area of 7,976.27 hectares and a population of 6,871 people, mainly composed of H'mong, Dao and Ha Nhi ethnic groups, totalling 91.8% of the population (Lao Cai province People's Committee 2020). The primary terrains of Trinh Tuong are high mountains with an average height of 1,458 m above sea level. The highest area is mount Lao Than, which is 2,860 m high, while the lowest area is Na Lac valley, having an average height of only 120 m. The terrain of this commune is severely partitioned in an upward direction from north-east to south-west, with relatively high slopes. Through drainage basins, the average slope is above 15° and the most common terrain is alluvial deposit (Lap et al. 2019).

The river/stream system of this place is relatively dense, with an average density of 1.36 km/km^2. Hong river and Tung Chin river are the primary hydrologic systems. However, the Hong river passes the territory of Trinh Tuong. Thus it is less significant in terms of hydrological geography. With a total basin area of 4,261 hectares, the Tung Chin river basin runs through every village of the commune and plays an important role in the hydrological regulation and the formation of terrains in small basins. Trinh Tuong also has the tropical monsoon climate conditions of mountainous regions with an annual average temperature ranging from 15 to 21°C and an annual average rainfall of 1,800 mm (Lap et al. 2019). Due to the high mountains, the differences among seasons are notable. Weathers at the communes are also clearly differentiated. Extreme weather phenomena such as extreme cold or heavy rain even appear in some particular areas. Vegetation cover reaches 45.19%, distributed unevenly, with planted forests predominating. The total area of natural forests and protection forests only accounts for 4.8% of the total area. On the other hand, empty grounds and bare hills are increasing in terms of their area. The analyses of satellite images in December 2020 showed that these two terrains occupied a total of 26.3% of the commune's area (Nguyen et al. 2020). In terms of pedology, the conditions of Trinh Tuong commune are rich, with ten primary types of soils, including humus, greysols, dark soils, oxisols, ferralsols, mountainous humus, raw mountainous humus, oxisols degraded due to rice cultivation, strongly erosive soils, and aggregating sloped soils.

Trinh Tuong is one of the communes that suffer from flash floods most in Lao Cai province. According to statistical data, in the term from 2000 to 2020, the locality witnessed 28 flash floods, leading to 47 dead or missing and economic damage totalling USD 1.2 million (Vietnam Disaster Prevention and Control Office 2020). The areas with the most flash flood occurrences are along the basin of Tung Chin River, belonging to the territories of Phin Ngan, Ban San and Tung Chinh villages. Through investigations and surveys, flash-flood-forming factors in the research location are relatively typical

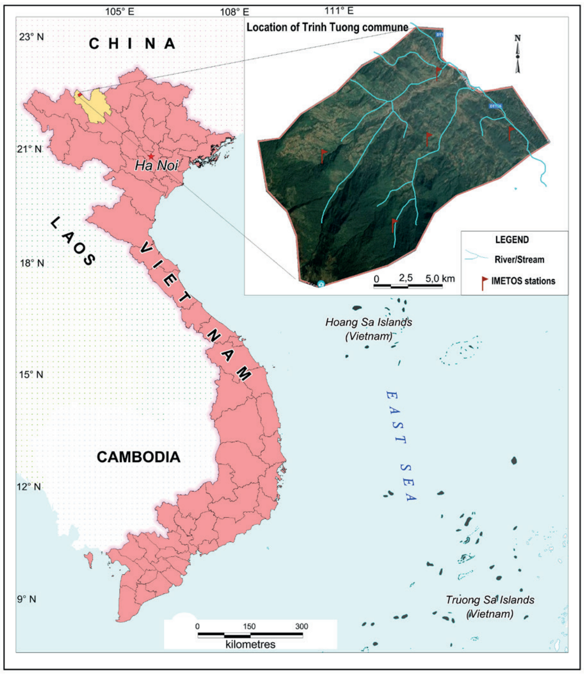


Fig. 1. Study area

with the characteristics of basins, partitioned terrains, high slopes and flows that tend to aggregate. In addition, Trinh Tuong is a purely agricultural commune, with 96.8% of households working in agriculture. Local people mainly plant corn, cassava, upland rice, herbs, etc. on hills, and wetland rice in valleys, while they also engage in forestry (Trinh Tuong People's committee 2021). These forms of agricultural cultivation are completely free and much dependent on natural conditions, leading to an increase in flash flood potential and thereby to increased damage.

Study data

This study employed data from various sources, including field surveys and investigations, statistical data, observative data, satellite images, paper maps, and data from relevant publications. The data of terrains were inherited, cited from terrain maps of Bat Xat district with a scale of 1:10,000. Data regarding slopes were built on Digital Elevation Models (DEM) and satellite images. Geomorphologic maps were constructed based on original morphology, combined with GIS analyses from terrain maps, geologic maps, satellite images and field data. Pedologic data – the characteristics of samples, types of soils, soil horizons and mechanical composition – were obtained from surveys, and the inheritance of analyses of over 36 soil horizons, which represent ten types of soils covering the research location. Data regarding forests and vegetation cover were obtained from Sentinel 2 satellite images and field investigation data. Rainfall was collected from the rainfall database of the Institute of Hydrology and Meteorology Science and Climate Change for a period of 60 years (1960–2020), combined with observative data regarding rainfalls from five IMETOS weather stations located in the research area. Finally, data relating to flash flood status (location, intensity, effect range, time) over 20 years (2000–2020) were achieved from statistical documents in combination with field investigations and interviews with local people in the research area.

Methods

This study employed the Analytic Hierarchy Process (AHP), Multi-Criterion Analysis (MCA), the GIS spatial analysis method, satellite image processing, field surveys, data collection and statistics.

Analytic Hierarchy Process (AHP): This method was studied and developed by Saaty in the 1980s. So

Table 1. Data sources used in the study

No	Type of data	Characteristic	Source
1	Terrain map	Scale of 1:10,000	Cited from the terrain map of Bat Xat District (from Data center, Vietnamese Ministry of Natural Resources and Environment)
2	Geomorphologic map	Scale of 1:5,000	Built based on the regulation of original morphology and GIS analysis data.
3	Slope map	Scale of 1:5,000	DEM models and terrain maps (from Data center, Vietnamese Ministry of Natural Resources and Environment)
4	Pedologic map	Scale of 1:5.000	Maps of soil classification in Lao Cai District with a scale of 1:10,000 (from the Publisher of maps, 2018); Statistical data; Analysis data of 36 soil horizons (from Soils and Fertilizers Research Institute, 2020)
5	Forest and vegetation map	Scale of 1:5.000	Analyzed from SPOT satellites images and Sentinel 2B satellites images with a resolution of 10×10 m
6	Rainfall data	Data: mean, max., min.	From Institute of Hydrology and Meteorology Science and Climate change, IMETOS weather station
7	Historical data from 2000–2020	Location and intensity of damage	Statistics, investigations, and surveys.

far, it is still widely utilised to calculate the weights of multi-criterion maths (especially: Saaty 1987; González-Prida et al. 2012). This method also provides an order of decisions, based on which the final decision is derived and made. In this study, the AHP method was used to confirm the reliability of a matrix determined from the Consistency Ratio (CR) among flash-flood-forming factors. The Consistency Ratio is calculated through the Consistency Index (CI) and the Random Consistency Index (RI). The formula of calculation is as follows:

$$CR=CI/RI \quad (1)$$

In the equation: CI = λmax-n/n-1; λmax is the average value of the consistency vector; n is the number of criteria; RI is random. Therefore, it depends on the number criteria brought in comparisons; in this case, n=6. From the appendix of AHP, RI=1.25. If the value of CR is less than or equal to 0.1, the consistency among factors in the matrix is assured (Saaty 1987).

Multi-Criterion Analysis (MCA): This is a method combining hydrologic models and local geomorphology with the support of GIS (Saaty 1987; Triantaphyllou 2000; Saaty 2008). Employing this technique, this study focused on the determination of factors that formed flash floods in the research area and simultaneously combined the goal with statistical data for comparisons, ultimately leading to a hierarchy of information layers in terms of their capacity to cause flash floods. With the application of GIS in determining weights, the spatial integration of factors and weights in order to build a map of flash flood potentials at the research area was executed in accordance with the following function:

$$Fm=\sum_{i=1}^{n} Wi\,.Xi \qquad (2)$$

In the equation: Fm is the map of flash flood potentials, *Wi* is the weight of factor (*i*), *Xi* is factor (*i*), and n represents the number of flash-flood-forming factors (n=6 in this study).

Geographic Information System (GIS): GIS was the primary technique used in the analyses and the formation of a zoning map that evaluated the risks of flash floods. There were two algorithms in GIS spatial analysis, including the spatial stacking algorithm and the categorisation algorithm (Goodchild et al. 2004; Jia et al. 2017; Shirowzhan et al. 2019). Spatial data were processed with the ArcGIS software, subsequently forming maps with the QGIS software. In addition, this study also utilised Digital Elevation Models in the analysis of factors including terrain and geomorphology (Wessel et al. 2018). The spatial interpolation algorithm of GIS was also used to analyse and forecast rainfalls (Comber et al. 2019).

The method of processing remote-sensing images: with the Envi software, images with a resolution of 10×10 m from SPOT satellites (1 scene from October 15, 2019) and Sentinel 2B satellites (2 scenes from November 22, 2019 and January 14, 2020) were processed to form maps of forests and vegetation cover in the research location. More specifically, there were two options to process the images, including the NDVI differencing method and the Post Classification method, in which the radiation of vegetation cover in the research location was calculated through the formula of ε = 1.0094 + 0.047 ln(NDVI) (Pu et al. 2008; Asadzadeh et al. 2016). Additionally, the method of processing RS images also provided data and supplemented the updates of terrain maps and geomorphologic maps for the research area.

Field survey and statistical data collection: during the execution of this study, many field surveys were conducted to comprehensively evaluate the research area, collect relevant documents and data, and verify the study results. More remarkably, the data of flash floods occurring throughout history and the locations of occurrences in 20 years (2000–2020) were investigated and confirmed by interviewing local people. The study also combined the collection of statistical data regarding natural conditions, social and economic status, and the status of flash floods in the research area.

The system of those aforementioned methods was employed to construct a model applying geospatial technologies in flash flood warnings in mountainous regions of Northern Vietnam (Fig. 2). The model consisted of three steps: Step 1: Evaluating flash-flood-forming factors at drainage basins, Step 2: Zoning the areas with potentials for flash floods, and Step 3: Online warning information.

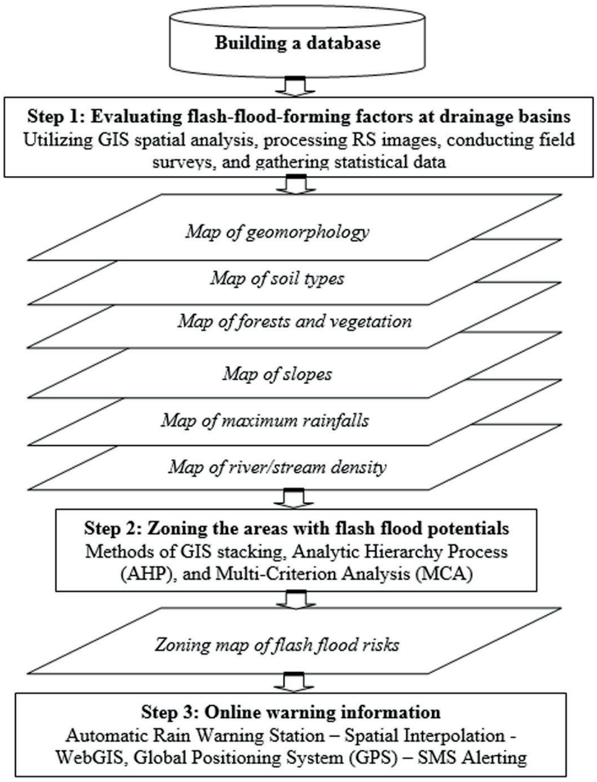


Fig. 2. Model of applying geospatial technologies in flash flood warnings in mountainous regions of Northern Vietnam

Results and discussion

The evaluation of factors forming flash floods at the research location

The overall information of studies regarding flash floods in mountainous regions indicates that flash floods occur due to rainfalls, terrain, geomorphology, slopes, the characteristic of soils, vegetation, river/stream density, aggregating flows, etc (Smith 2010; Tran 2020). Depending on each region's different characteristics, the mechanisms and the factors of flash flood occurrences change. The determination of control limits above which flash floods occur is a crucial mission. Nevertheless, it is also difficult, as the limits of flash floods in mountainous regions vary greatly in accordance with complicated conditions in the buffer surfaces of drainage basins.

The study at Trinh Tuong commune shows that the occurrence of flash floods primarily involves local drainage basins. According to statistical data, the slope of basins is great at the locations of flash flood occurrences, and is accompanied by a thin vegetation cover of below 10%, maximum rainfalls of over 200 mm/day, soil types with medium/low permeability, and geomorphology that is V-shaped or resembles water-aggregating valleys. Many publications regarding flash floods in Vietnam have identified six fundamental factors that potentially form flash floods in mountainous regions, including: geomorphological characteristics, soil properties (soil types), vegetation cover (forests), drainage basin slopes, maximum rainfalls, and river/stream density (Ha 2009; Tran 2020). Simultaneously, most of those studies have agreed on categorising the potential of flash flood forming into five levels of risk intensity: 1 – "Very low", 2 – "Low", 3 – "Medium", 4 – "High", and 5 – "Very high".

Referencing relevant studies (Ha 2009; Lap et al. 2019; Nguyen et al. 2020; Tran 2020) in combination with statistical data, factors that potentially formed flash floods at Trinh Tuong commune and the levels of intensity were determined and shown in Table 2.

Based on the table of criteria that assessed flash-flood-forming factors at Trinh Tuong commune (Table 2), the employment of collected data and analytical functions of GIS resulted in a map that assessed flash-flood-forming factors on the surfaces of buffer zones in drainage basins. There were six information layers, including geomorphological characteristics (GM), soil types (S), forests and vegetation cover (FV), drainage basin slopes (SB), maximum rainfalls in days (RM), and river/stream density (RD). The map system that assessed the intensity of those layers was divided into five levels, corresponding to the risks of flash floods evaluated as "very low", "low", "medium", "high" and "very high". The results of assessing information layers are demonstrated in Figure 3.

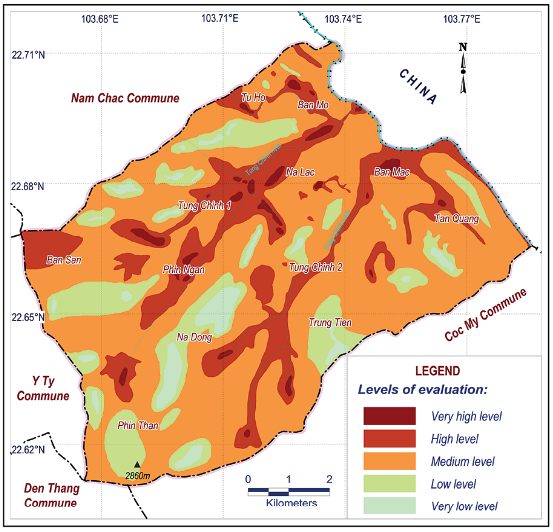
Table 2. Criteria of assessing flash flood risks in Trinh Tuong commune

Level	Factor					
	Geomorphology	Soil properties	Forests and vegetation cover	Slopes of drainage basins (degree)	Max. rainfall (mm/day)	River/ stream density (km/km^2)
1	Top surfaces higher than 1000 m, wave-like, weak erosions acting; Flat surfaces, arches with low slopes, no water aggregating	Limestone mountains; Alisol (soil), good permeability	Primeval forests andmixed forests, covering over 55%	Below 10	Below 50	0.0–0.5
2	Abrasively erosive ridges; Intermediately slippery ridges, sunken and severely weathered	Mountainous humus; Dark soil at medium horizons, good permeability	Broadleaf forests and bamboo forests, covering 40–55%	10–20	50–100	0.5–1.5
3	Slippery ridges, sunken and winding; Erosive ridges on different stones	Oxisols on sandstone; Ferralsols on limestone	Forests on limestones andplanted forests, covering 25–40%	20–30	100–150	1.5–2.5
4	Aggregated and abrasive surfaces; Erosive drains, erosive ditches capable of aggregating water while raining	Oxisols degraded due to rice cultivation; Oxisols and humus	Housing zones, agricultural crops, bushes, covering 10–25%	30–40	150–200	2.5–3.5
5	Cavitated troughs, V-shaped water-aggregating troughs; Cavitated and water-aggregating grounds	Strongly erosive soils, stones; Aggregating sloped soils	Empty ground and water, covering less than 10%	>40	>200	>3.5

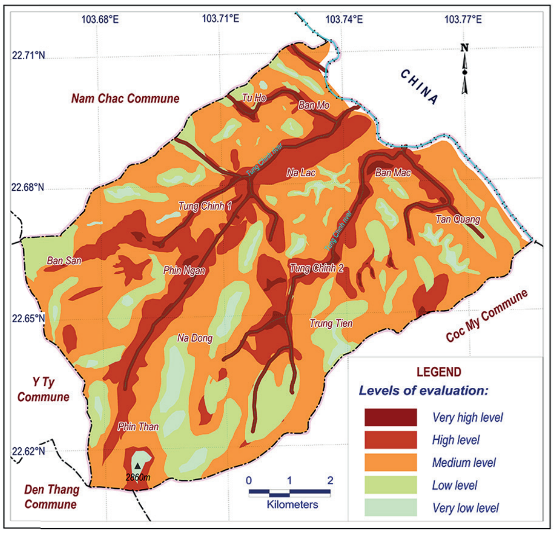
Zoning the areas with flash flood potentials at the research location

The Analytic Hierarchy Process (AHP) was utilised in calculating the weights of information layers that evaluate flash flood risks at Trinh Tuong commune. The results are shown in Table 3.

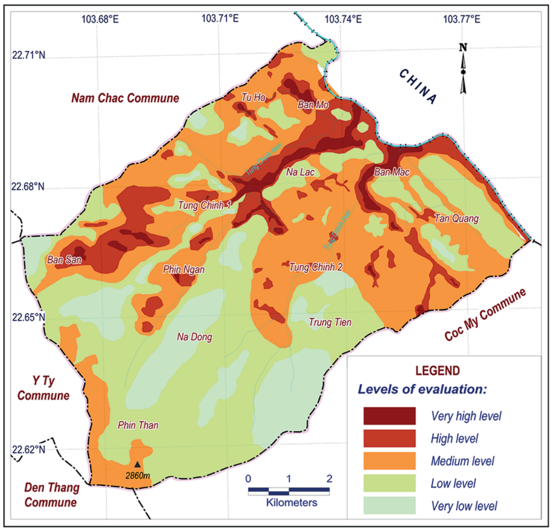
Specifically, the results include: a Consistency Index CI of 0.068; a Random Consistency Index determined according to six factors forming flash flood RI of 1.25; and a Consistency Ratio CR=CI/RI=0.068/1.25=0.054 (Formula 1). Therefore, as the CR index is less than 0.1, the reliability of this study is assured.



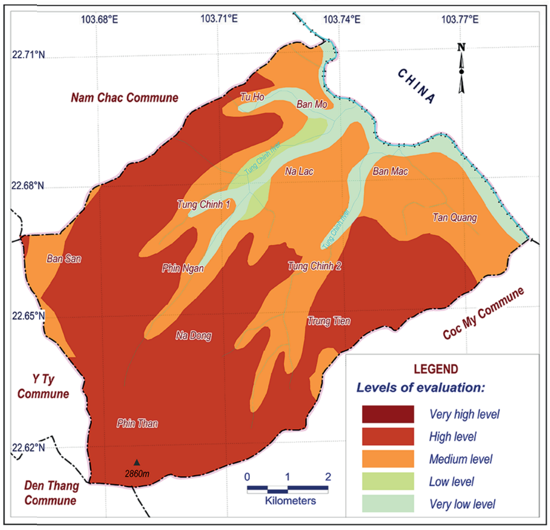
a. Map evaluating geomorphology



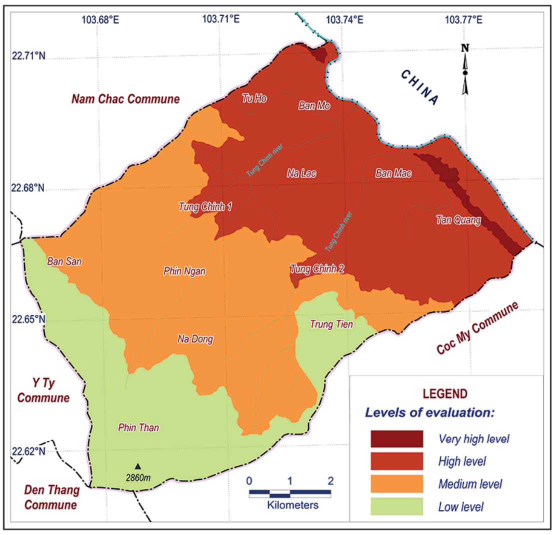
b. Map evaluating soil types



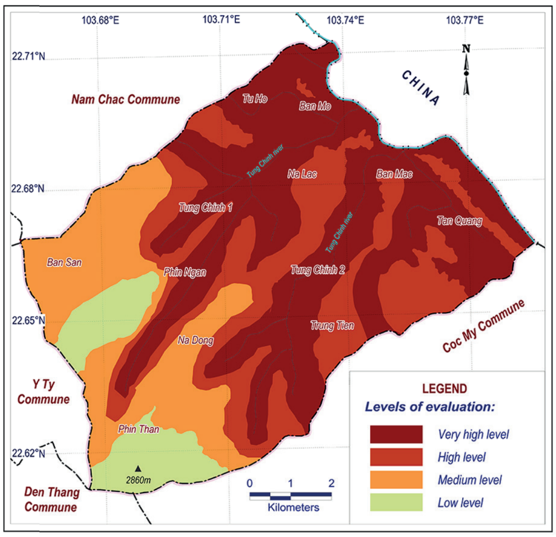
c. Map evaluating forestand vegetation cover



d. Map evaluating drainage basin slopes



e. Map evaluating maximum rainfalls



f. Map evaluating river/stream density

Fig. 3. Map system evaluating the risk of factors that cause flash floods at Trinh Tuong communes

With the weights shown in Table 3, the Fm function was clarified with the application of Formula 3 as follows:

$$Fm = 0.14*GM + 0.02*S + 0.11*FV + 0.10*SB + 0.25*RM + 0.06*RD \quad (3)$$

Employing the analysis spatial model GIS, the stack of information layers regarding factors that formed flash floods resulted in a zoning map identifying the areas with potential risks of flash floods in Trinh Tuong commune (Fig. 4).

The analyses also show that the areas with a “high” and “very high” potential of flash floods account for 19.91% of the commune’s total area, which mainly concentrates at the valley of Tung Chin stream throughout Phin Ngan, Ban San, Tung Chinh and Na Lac villages. This result completely fits documents relating to the locations of flash flood occurrences in 20 years beginning in 2000. Especially, in the areas of Phin Ngan and Ban San villages, statistical data for the 20 years all indicate that there have been 1–2 flash floods per year (Vietnam Disaster Prevention and Control Office 2020). Some small areas were also evaluated as possessing a “high” flash flood risk. However, in fact, there was no occurrence in those places where hydrologic networks do not tend to aggregate. Moreover, the geomorphology is relatively stable, and it is hard for flash floods to occur.

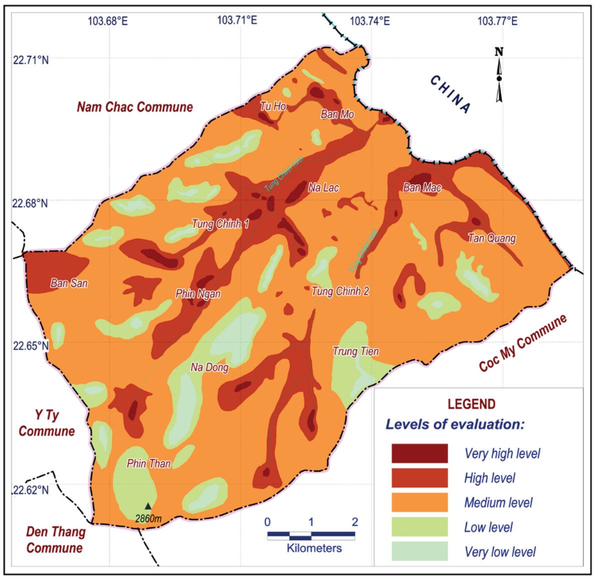


Fig. 4. Zoning map of flash flood risks at Trinh Tuong commune

The areas with a “very high” flash flood risk account for only 1.58% of the total area (approximately 126.23 hectares). Nevertheless, these are essential regions concentrated in the drainage basin of Tung Chin River, where there are housing zones. The surveys at locations with a “very high” flash flood risk all detected typical flash-flood-forming factors, such as a high density of flows, trough-like terrains or diluvium, strong activities of abrasive erosion, thin vegetation with bushes, and empty ground.

The areas with a “high” flash flood risk occupy 18.33% of the commune’s area, concentrating in the abrasive aggregated areas, sides of waterbody systems, oxisols degraded due to rice cultivation, and thin vegetation cover. These areas are also inhabited. Therefore, the possible damage of a flash flood would be considerable. According to statistical data, in 2004, there was a historic flash flood at Phin Ngan village, causing the deaths of 11 people, the loss of 25 houses, and extreme damage to plants and agriculture (Vietnam Disaster Prevention and Control Office 2020).

The areas with a “medium” flash flood risk occupy nearly 65% of the total area. These are the places of cultivated forests and limestone forests on erosive ridges and different types of stones. The flash-flood-forming factors appear at a medium level. However, some particular locations have the characteristics of elongated valleys that are advantageous for the aggregation of water and thus the formation of flash floods. In fact, there have been some small flash floods in these areas.

The areas with “low” and “very low” flash flood risks comprise 15.17% of the total area. These places have the factors that form floods at a very low intensity or no factors of water aggregation, such as mountain tops, flat zones, and ridges with low slopes. The total area of regions within natural forests and protection forests is relatively large, with vegetation cover over 50%, primarily at the sources of rivers. It is therefore necessary to protect these areas in order to reduce potential flash-flood-forming factors for depressions.

Tablez 3. Matrix of weights for information layers that evaluate flash flood risks at Trinh Tuong commune

Information layer	GM	S	FV	SB	RM	RD	Total	Weight
GM	0.12	0.10	0.18	0.16	0.17	0.13	**0.86**	**0.14**
S	0.03	0.03	0.01	0.02	0.02	0.01	**0.12**	**0.02**
FV	0.06	0.15	0.08	0.19	0.07	0.12	**0.67**	**0.11**
SB	0.07	0.14	0.05	0.10	0.09	0.14	**0.59**	**0.10**
RM	0.35	0.16	0.21	0.28	0.25	0.23	**1.48**	**0.25**
RD	0.05	0.12	0.03	0.04	0.06	0.03	**0.33**	**0.06**

Table 4. Table of hierarchy and levels of flash flood risks in Trinh Tuong commune

Hierarchy	Intensity	Fm score	Area (ha)	Proportion (%)
Level 1	Very low	≤1.0	278.05	3.49
Level 2	Low	1.0–2.0	931.53	11.68
Level 3	Medium	2.0–3.0	5,178.20	64.92
Level 4	High	3.0–4.0	1,462.25	18.33
Level 5	Very high	≥4.0	126.23	1.58

Source: GIS analysis results

Constructing an online flash flood warning model at the research location

The factors that potentially form flash floods include terrain, geomorphology, slopes, soil types, vegetation and hydrologic characteristics, and these are virtually non-changing factors that can be analyzed and assessed pre-emptively with high accuracy. Rainfall is the only factor of considerable unpredictability. More importantly, it is also the decisive factor for forming flash floods. According to data regarding flash floods in mountainous regions of Vietnam (Vietnam Disaster Prevention and Control Office 2020), the identification of regions with a high risk of flash floods only requires a daily rainfall exceeding 250 mm, which guarantees a flash flood with certainty. Therefore, in this study, rainfalls were selected as the primary factor for early flash flood forecasting and warning.

In the experimental model tested at Trinh Truong commune, a system of five rain alerting stations was installed at regions with “high” or “very high” risks of flash floods forming. These systems are automatically connected to regional and national centres of hydro-meteorological forecasting. Information regarding forecasted and actual rainfalls according to the coordinates of the stations was integrated with the map of potential flash flood risks through the WebGIS system. A flash flood warning software was constructed based on the programming language Python with an open source code and the PostGIS database (Anselin et al. 2014). The main function of this software is to manage the input database, and to process and interpolate rainfall data according to spaces. If the forecasted or actual rainfall exceeds limits, potentially creating flash floods, the system would provide alerting information to users by SMS on mobile devices.

Within the research location, the early flash flood warning model at Trinh Tuong commune has only been experimental. During the execution of experimental studies from April 2020 to December

2020, the warning system operated well. Data were received and processed in a timely manner. There were two times when the system enacted a high-level risk alert (daily forecasted rainfall exceeded 150 mm). Initially, the model demonstrated significant effectiveness in forecasting flash floods in mountainous regions with quick processing capability and high accuracy. However, in order to practically apply this model in reality, there are two proposed issues:

1. It is required to promote the observation station system's scale of operation. This means not only an increase in quantity and density of stations but also an improvement in quality, accuracy, and connectivity with national and international weather forecasts. Moreover, the design of the station system needs to employ sustainable solar energy and fortify the stations to avoid the damage caused by rain and floods. The current global economic environment is significantly different from that in which the first SEZs began to work. In order to attract investors to modern economic zones, significantly better regimes should be offered, in terms of costs and experience.

2. It is required to combine the system of satellite images and online radars to forecast unanticipated flood-forming-factors. In fact, flash floods occur in a complicated way that varies between regions. In many cases, flash floods were caused by unexpected factors such as landslides or flow congestion, which leads to sudden water aggregation in drainage basins. In such cases, the connection of both satellite images and online radars to the flash flood forecasting system is essential.

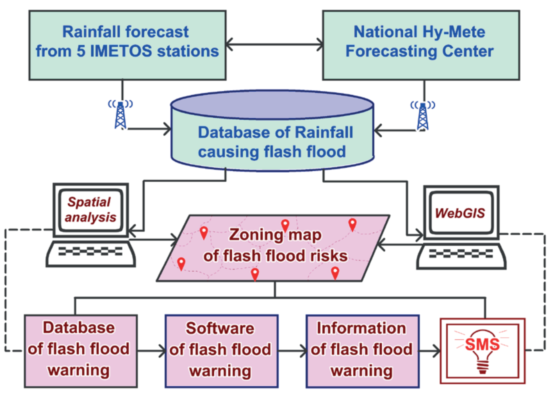


Fig. 5. Simulation of an early flash flood warning model at Trinh Tuong commune

Conclusion

In the mountainous regions of Vietnam, flash floods are an extremely dangerous and apparently unpredictable natural disaster. The study on applying geospatial technologies in building a flash flood warning model proved crucial in early flash flood alerting, thus contributing to reducing the damage caused by natural disasters. The case of Trinh Tuong commune has clearly analyzed factors that potentially formed flash floods. There are six identified factors, including geomorphological characteristics, soil properties, forest and vegetation cover types, drainage basin slopes, and average maximum rainfall through the years. As one of the results, the zoning map showing flash flood potentials according to areas indicated an area of 19.91% with a "high" or "very high" flash flood risk, 64.92% with a "medium" risk, and 15.17% with a "low" or "very low" risk. Based on determining the maximum rainfall per day as the primary factor, an online model of early flash flood forecasting was constructed. The model has been successfully tested in the field, and thus offers several solutions for addressing flash floods in mountainous regions issue and proving the large-scale applicability of this model in mountainous regions for flash flood forecasting and warning.

Disclosure statement

No potential conflict of interest was reported by the authors.

Author contributions

Study design: QLK; data collection DVT; statistical analysis: QLK; result interpretation QLK; manuscript preparation QLK; literature review: DVT.

Acknowledgements

The authors gratefully acknowledge the Ministry of Natural Resources and Environment in Vietnam, the Soils and Fertilizers Research Institute in Vietnam, the People's Committee of Lao Cai Province, and Thai Nguyen University of Sciencesin Vietnam for providing data and other necessary facilities for this study.

References

ANSELIN L and REY S, 2014, *Modern Spatial Econometrics in Practice: A Guide to GeoDa, GeoDaSpace and PySAL*. GeoDa Press.

ASADZADEH S and DE SOUZA FILHO CR, 2016, A review on spectral processing methods for geological remote sensing. *International Journal of Applied Earth Observation and Geoinformation* 47: 69–90.

BALLESTEROS C, JIMÉNEZ JA and VIAVATTENE C, 2018, A multi-component flood risk assessment in the Maresme coast (NW Mediterranean). *Natural Hazards* 90: 265–292.

CAO C, XU P, WANG Y, CHEN J, ZHENG L and NIU C, 2016, Flash Flood Hazard Susceptibility Mapping Using Frequency Ratio and Statistical Index Methods in Coalmine Subsidence Areas. *Sustainability* 8(9): 948 .

COMBER A and ZENG W, 2019, Spatial interpolation using areal features: A review of methods and opportunities using new forms of data with coded illustrations. *Geography Compass* 13(10): 1–23.

COSTACHE R, PHAM QB, SHARIFI E, LINH NTT, ABBA SI, VOJTEK M, VOJTEKOVÁ J, NHI PTT and KHOI DN, 2020, Flash-flood susceptibility assessment using multi-criteria decision making and machine learning supported by remote sensing and GIS techniques. *Remote Sensing* 12(1): 106.

ELKHRACHY I, 2015, Flash Flood Hazard Mapping Using Satellite Images and GIS Tools: A case study of Najran City, Kingdom of Saudi Arabia (KSA). *Egyptian Journal of Remote Sensing and Space Science* 18(2): 261–278, DOI: https://doi.org/10.1016/j.ejrs.2015.06.007.

GONZÁLEZ-PRIDA V, BARBERÁ L, VIVEROS P, and CRESPO A, 2012, Dynamic Analytic Hierarchy Process: AHP method adapted to a changing environment. *IFAC Proceedings Volumes* 45(31): 25–29, DOI: https://doi.org/10.3182/20121122-2-ES-4026.00005.

GOODCHILD MF and HAINING RP, 2004, GIS and spatial data analysis: Converging perspectives. *Papers in Regional Science* 83(1): 363–385, DOI: https://doi.org/10.1007/s10110-003-0190-y.

HA LTT, 2009, Research and develop flash flood risk zoning maps to serve the prevention of flash floods for Yen Bai province. *Journal of Meteorology and Hydrology* 211: 11–15.

JIA P, CHENG X, XUE H and WANG Y, 2017, Applications of geographic information systems (GIS) data and methods in obesity-related research. *Obesity reviews: an official journal of the International Association for the Study of Obesity* 18(4): 400–411, DOI: https://doi.org/10.1111/obr.12495.

KHOSRAVI K, PHAM BT, CHAPI K, SHIRZADI A, SHAHABI H, REVHAUG I, PRAKASH I and TIEN BUI D, 2018, A comparative assessment of decision trees algorithms for flash flood susceptibility modeling at Haraz watershed, northern Iran. *Science of the Total Environment* 627: 744–755

LAI TA, NGUYEN TN, PHAM XC and LE NN, 2018, Building an early warning system for flash floods in mountainous areas, testing it in Thuan Chau district, Son La province. *Journal of Science and Technology of Vietnam* 60: 28–35.

LAO CAI PROVINCE PEOPLE'S COMMITTEE, 2020, Statistical Yearbook.

LAP KQ, HA HT, 2019, Natural characteristics and natural resources of Trinh Tuong commune, Bat Xat district, Lao Cai province. *Journal of Science and Technology of Thai Nguyen University* 219: 21–32.

NGUYEN QH, V.T D, B.N H, 2020, Study on the change of vegetation cover in Trinh Tuong commune, Bat Xat district, Lao Cai province in the period 2010-2020. *Journal of Ecology* 112: 114–126.

OLIVEIRA EA, PIRES RS, OLIVEIRA RS, FURTADO V, HERRMANN HJ and ANDRADE JS, 2019, A universal approach for drainage basins. *Scientific Reports* 9: 1–10.

PARK S, LEE CW, LEE S and LEE MJ, 2018, Landslide Susceptibility Mapping and Comparison Using Decision Tree Models: A Case Study of Jumunjin Area, Korea. *Remote Sensing* 10(10): 1545, DOI: https://doi.org/10.3390/rs10101545.

POPA MC and DIACONU DC, 2019, Flood and Flash Flood Hazard Mapping Using the Frequency Ratio, Multilayer Perceptron and Their Hybrid Ensemble. *Proceedings* 48: 6.

PU R, GONG P, TIAN Y, MIAO X, CARRUTHERS RI and ANDERSON GL, 2008, Using classification and NDVI differencing methods for monitoring sparse vegetation coverage: A case study of saltcedar in Nevada, USA. *International Journal of Remote Sensing* 29(14): 3987–4011, DOI: https://doi.org/10.1080/01431160801908095.

SAATY RW, 1987, The analytic hierarchy process – what it is and how it is used. *Mathematical Modelling* 9(3-5): 161–176, DOI: https://doi.org/10.1016/0270-0255(87)90473-8.

SAATY TL, 2008, Decision making with the analytic hierarchy process. *International Journal of Services Sciences* 1(1): 83–98.

SHIROWZHAN S and SEPASGOZAR SME, 2019, Spatial Analysis Using Temporal Point Clouds in Advanced GIS: Methods for Ground Elevation Extraction in Slant Areas and Building Classifications. *ISPRS International Journal of Geo-Information* 8(3): 120.

SIVAKUMAR MVK, ROY PS, HARMSEN K and SAHA SK (eds), 2004, Satellite Remote Sensing and GIS Applications in Agricultural Meteorology. *Proceedings of the Training Workshop 7-11 July, 2003, Dehra Dun, India.* World Meteorological Organisation. Switzerland.

SMITH G, 2010, Development of a flash flood potential index using physiographic data sets within a geographic information system. In thesis, retrieved from https://collections.lib.utah.edu/dl_files/59/0d/590d31179c399e040a6b171fa2feb1ca7d27f0fc.pdf .

TEHRANY MS, PRADHAN B and JEBUR MN, 2015, Flood susceptibility analysis and its verification using a novel ensemble support vector machine and frequency ratio method. *Stochastic Environmental Research and Risk Assessment* 29: 1149–1165.

TINCU R, LAZAR G and LAZAR I, 2018, Modified flash flood potential index in order to estimate areas with predisposition to water accumulation. *Open Geosciences* 10: 593–606.

TRAN VK, 2020, Studying the current situation and establishing flash flood zoning maps for some mountainous areas of Vietnam. *Journal of Science and Technology of Thai Nguyen University* 225: 38–47.

TRIANTAPHYLLOU E, 2000, *Multi-Criteria Decision Making Methods: A Comparative Study.* Kluwer Academic Publishers, Dordrecht, The Netherlands.

TRINH TUONG PEOPLE'S COMMITTEE, 2021, Report on socio-economic situation of Trinh Tuong commune in 2020, Lao Cai 2021.

VIETNAM DISASTER PREVENTION AND CONTROL OFFICE, 2020, Report on flash floods and landslides in mountainous areas in the period 2000-2020.

WESSEL B, HUBER M, WOHLFART C, MARSCHALK U, KOSMANN D and ROTH A, 2018, Accuracy assessment of the global TanDEM-X Digital Elevation Model with GPS data. ISPRS. *Journal of Photogrammetry and Remote Sensing* 139: 171–182.

WORLD METEOROLOGICAL ORGANIZATION, 2017, Flash Flood Guidance System with Global Coverage.

ZOGG J, DEITSCH K, 2016, The Flash Flood Potential Index at WFO Des Moines, IA. NWS Technical Report, National Weather Service. Retrieved June 2016.

Received 22 May 2021
Accepted 25 June 2021