FLASH FLOOD HAZARD MAPPING USING SATELLITE IMAGES AND GIS INTEGRATION METHOD: A CASE STUDY OF LAI CHAU PROVINCE, VIETNAM

Quoc Lap KIEU[1]

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ABSTRACT:

Lai Chau is a typical mountainous province of Vietnam, with a natural area of 9068.78 km^2, this is a province that frequently occurs flash floods. This paper presents the results of the application of Satellite images, combining the GIS - AHP - MCA integration method to create a zoning map and warn of flash floods in Lai Chau province. The results of this study indicate the analyses and appraisals over 6 primary factors that incite flash flood, including the characteristics of geomorphology, the properties of soils, the types of forests and fractional vegetation cover, the slope of local drainage basins, average annual rainfall and the river/stream density of the region. The zoning map showing flash flood potentials has determined that 33.55% (3042.5 km^2) of the area had an extremely high risk of flash flood occurrences, 44.42% of the area had a medium risk and 22.03% had a risk of flash flood at the low or very low level. Zoning map and flash flood warnings have great significance in preventing flash floods and minimizing damage in the study area.

Key-words: *Spatial analysis, Satellite images, GIS, flash flood, Vietnam*

1. INTRODUCTION

Flash flood calculation is an essential component of flash flood hazard mapping. However, the formation of flash floods is complicated. Flash floods also often occur in ungauged catchments, posing an even greater challenge to flash flood simulations. Many scholars have conducted studies on flash flood simulations. For example, developed a spatially distributed hydrological model on the basis of physical process representation (Roux et al., 2011); Proposed the physically based, space-time distributed hydrological model MARINE (model of anticipation of runoff and inundations for extreme events) and the geomorphological instantaneous unit hydrograph (GIUH) has been derived from the geomorphological characteristics of a catchment and used in simulation of the surface runoff hydrographs for ten rainfall events in the Ajay Catchment in eastern India (Estupina-Borrell et al., 2006; Kumar et al., 2007). Growing knowledge of flash flood mechanisms shows that the morphometric variables of a catchment control its hydrological response (Moussa, 2003; Angillieri, 2008). Based on this understanding, the geomorphological unit hydrograph (GUH) has become one of the most popular methods for estimating hydrological processes when data are inadequate (Du et al., 2009; Diakakis, 2011). Several studies concerning the risk of flash floods have described the initial versions and the evolution of a hydrological model adapted for very small watersheds (Domnița, 2012, Haidu et al., 2019). The model is based on the SCS-CN method for the rainfall excess (Haidu et al., 2017).

Nowadays, application of GIS in research and flash flood warning is a fairly popular and highly effective method. Studies regarding based on remote sensing and GIS mainly use the FFPI model to create flash flood warning maps (Gregory, 2010; Zogg, 2016; Ballesteros et al., 2017; Costache et al, 2019). Studies used the data of slopes, soil types, soil utilization types and vegetation cover to build a potential map, which provided excellent support for flash flood forecasting activities (Bajabaa, 2014; Roxana, 2018). 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 (Elkhrachy et al., 2015; Tehrany et al., 2015; Park et al., 2018; Khosravi et al., 2019). Studies regarding flash floods

[1]*Thai Nguyen University of Sciences, Thai Nguyen City, Vietnam, lapkq@tnus.edu.vn*

susceptibility mapping by integrating frequency ratio and index of entropy with multilayer perceptron and classification and regression tree (Cao, 2016; Popa, 2019; Yi, 2021).

In Vietnam, studies regarding forecasting and warning flash floods are much limited. Nevertheless, some recently have been implemented with the primary focus on the construction of zoning maps for flash flood warnings. Remarkably, there are the study building a zoning map of flash flood risks, serving disaster control activities in Yen Bai province (La et al., 2009); the study building a map for early flash flood warnings in Thuan Chau district, Son La province (Lai et al., 2018); studing status and building flash flood zoning maps for some mountainous regions in Vietnam (Nong et al., 2020). That most of the studies employed the approach of hydrology – hydraulics, applying the FFPI, HEC-RAS, SWAT, and other models to construct flash flood warning maps. Besides, some warning maps were built based on approaching flash floods at mountain ridges, which results in zoned areas according to only the ridges. Consequently, this approach lacks calculations in detail and limited applicability. Moreover, the aforementioned studies often focused on only statistical data, ultimately leading to a lack of online warning abilities. Flash floods in mountainous regions often occur suddenly without any fixed rules, intensity and damage. Flash flood in Lai Chau province of Vietnam occurs rapidly, generally within a few hoursof rainfall and sometimes accompanied by landslides, mudflows, bridge collapse, damage to buildings and fatalities (Duong et al., 2020). Lai Chau province is the primary neighborhoods of populations from minor ethnic groups. As a result, the capability of coping with flash floods is limited. There has been no scientific study serving weather forecasts, warnings, techniques against natural disasters and flash floods. Therefore, studying the application of satellite images and GIS integrated models to create a map of flash flood hazard in Lai Chau province has scientific and practical significance. The research results will contribute to warning and mitigating damage caused by flash floods.

2. STUDY AREA

Lai Chau is a province in the Northwest Vietnam, located about 400 km far from Ha Noi to the southeast, between 21°51' - 22°49' North latitude and 102°19' - 103°59' East longitude (**Fig. 1**). Lai Chau terrain is formed by mountain ranges running Northwest - Southeast direction, with many high peaks as Pu Ta Leng - 3096 m high. The province owns high and steep mountains, alternated with deep and narrow valleys. Hoang Lien Son Mountain range in the east, Song Ma Mountain in the west. Between two mountains above is the lowland belonging to Da river area with many limestone plateaus running from Phong Tho (Lai Chau province) to Quan Son (Thanh Hoa province). With 265.095km of border line sharing with China, the province has an important position in geography and national security. Lai Chau features the sub-tropical climate. The average temperature is about 21°C-23°C divided into 2 seasons following the humidity, rainy season and dry season.

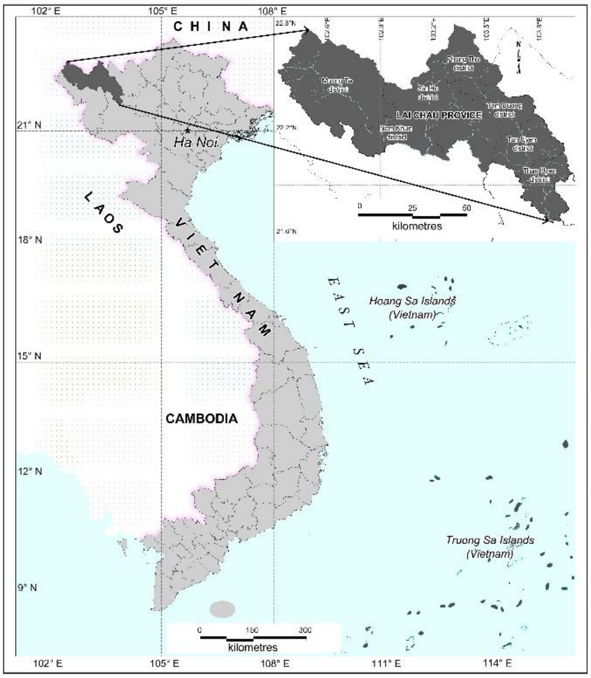


Fig. 1. Location of the Lai Chau province on a map of Vietnam.

Lai Chau province has 9068.78 square kilometers, 8 administrative units including Lai Chau City and 8 districts of Muong Te, Sin Ho, Nam Nhun, Tam Duong, Phong Tho, Tan Uyen, and Than Uyen. The province has more than 400 thousand of people of 20 ethnic groups living together, in which Thai ethnic people cover the majority of population in Lai Chau with 131.822 people, accounting for 34% of the total population. The other ethnic groups consist of H'Mong people 86.467 people (22.30%), Kinh ethnic group 54.027 people (13.94%), Dao ethnic people 51.995 people (13.41%), Ha Nhi ethnic people 14.658 people (3.78%) and other ethnic minorities (Statistical Office of Lai Chau Province, 2020). Local people mainly plant corn, cassava, upland rice, herbs, and etc on hills and wetland rice in valleys, while they also do exploitations in forests. These forms of agricultural cultivation are completely free and much dependent on natural conditions, leading to an incline in terms of flash flood potential and subsequently increasing damage. According to statistical data obtained in 20 years (from 2000 to 2020) in Lai Chau province there have been 42 flash floods, leading to the deaths of 68 people, 112 injured, 1479 houses devastated and total economic damage that is estimated up to 35 million USD (Vietnam Disaster Prevention and Control Office, 2020). Through investigations and surveys, flash flood forming factors in the research location are relatively typical with the characteristics of basins, partitioned terrains, high slopes, and flows that tend to aggregate. Moreover, in recent times the forest vegetation cover of Lai Chau tends to decrease; combined with the unsustainable form of agricultural cultivation of the people, the impact of climate change, erratic heavy rain, increases the intensity and impact of flash floods.

3. DATA AND METHODS

3.1. Study data

Flash flood hazard map in Lai Chau province employed the data from various sources, including field surveys and investigations data, statistical data, observative data, satellite images, paper maps, and data from relevant publications. The data of terrains were inherited, cited from terrain maps of Lai Chau province with a map scale of 1:500,000. Data regarding slopes were built on Digital Elevation Models (Data center, Vietnamese Ministry of Natural Resources and Environment, 2021). 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, andmechanical composition were from surveys, and the inheritance of analyses over 50 soil horizons, which represent 10 types of soils covering the research location (Soils and Fertilizers Research Institute, 2020). Data regarding forests and vegetation cover were obtained from Sentinel 2 satellite images with a resolution of 10×10m, includes four satellite imagery, was downloaded free from the U.S Geological Survey website (https://earthexplorer.usgs.gov/), date January 18, 2021. Rainfalls were collected from the rainfall database of the Institute of Hydrology and Meteorology Science and Climate Change covering a range of 60 years (1960 – 2020), combined with observative data regarding rainfalls from 9 IMETOS weather stations located in the research area. Finally, data relating to flash flood status (location, intensity, effect range, time) in 20 years (2000 – 2020) were achieved from statistic documents in combination with field investigations and interviews with local people in the research area.

3.2. Study methods

This study used the method of processing remote sensing images, with the Envi software, images with a resolution of 10x10m from Sentinel 2 satellites were processed to form maps of forests and vegetation cover in the research location. More specifically, there were 2 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 $\varepsilon = 1.0094 + 0.047 \ln (NDVI)$ (Pu et al., 2008). Additionally, the method of processing remote sensing images also provided data and supplemented the updates of terrain maps and geomorphologic maps for the research area (Asadzadeh, 2016). GIS was the primary technique used in analyses and the formation of a zoning map that evaluated the risks of flash floods. There were 2 algorithms in GIS spatial analysis, including the spatial stacking algorithmand the categorization algorithm (Goodchild, 2003;

Jia, 2017; Shirowzhan, 2019). Spatial data were processed with the ArcGIS software, subsequently forming maps with the QGIS software. In addition, this study also utilized the Digital Elevation Models (DEM) in the analysis of factors including terrain and geomorphology (Wessel et al., 2018). The spatial interpolation algorithm of GIS was also used to analyze and forecast rainfalls (Comber et al., 2019).

In this study, GIS is integrated with Analytic Hierarchy Process (AHP) and Multi-Criteria Analysis (MCA) to determine the weights and evaluate the factors that generate flash floods in Lai Chau province. 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).

MCA method combining hydrologic models and local geomorphology with the support of GIS (Triantaphyllou, 2000; Thoma, 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 the hierarchy of the capability to cause flash floods of information layers. 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:

$$F(m) = \sum_{i=1}^{n} Wi \, . \, Xi \quad (2)$$

In the equation: F(m) 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 (this study, n = 6).

Moreover, 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 flash flood hazard mapping in Lai Chau province (**Fig. 2**).

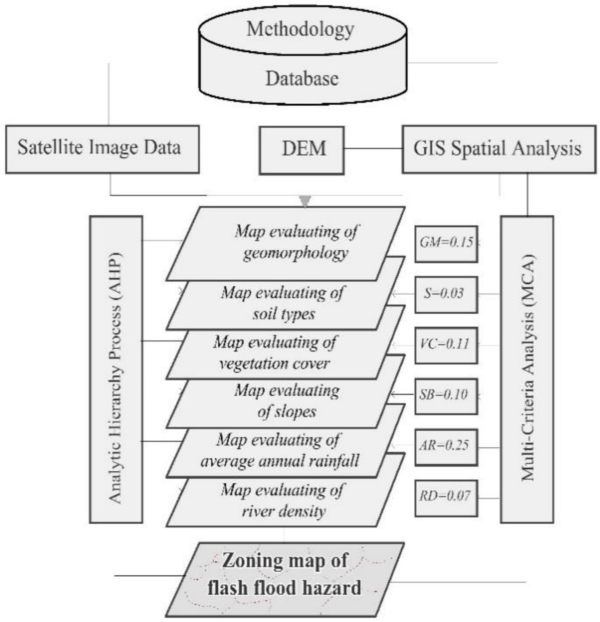


Fig. 2. Model of applying Satellite images and GIS integration method in flash flood warnings in Lai Chau province, Vietnam

4. RESULTS AND DISCUSSIONS

4.1. Evaluation of factors forming flash floods in Lai Chau province

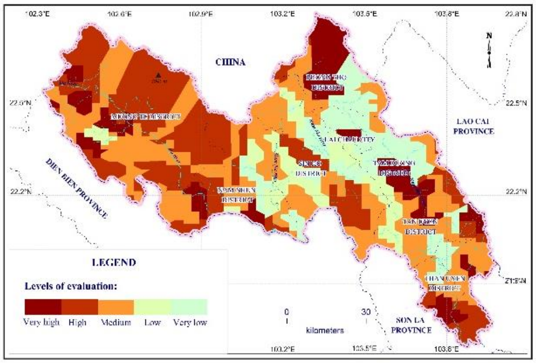
The study at Lai Chau province shows that the occurrence of flash floods primarily involves local drainage basins. According to statistical data, the slope of basins is great at the locations of flash flood occurrences, coming with thin vegetation cover of below 10%, maximum rainfalls over 150 mm/day, 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 6 fundamental factors that potentially form flash floods in mountainous regions, including: the characteristics of geomorphology, the properties of soil, vegetation cover, the slopes of drainage basins, average annual rainfall, and river density (Lai et al., 2018; Nong et al., 2020). Simultaneously, most of those studies have agreed on categorizing the potential of flash flood forming into 5 levels of intensity: "very low" risk of flash floods, "low" risk of flash floods, "medium" risk of flash floods, "high" risk of flash floods, and "very high" risk of flash floods. Referencing relevant studies in combination with statistical data, factors that potentially formed flash floods at Lai Chau province and the levels of intensity were determined and shown in **Table 1**.

Table 1.

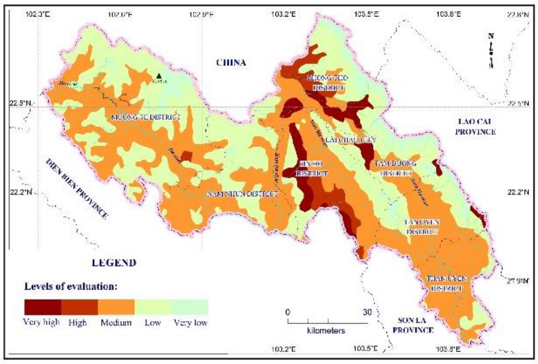
Criteria of assessing flash flood risks at Lai Chau Province.

Level	Characteristics of geomorphology	Soil properties	Vegetation cover (%)	Slopes (degree)	Average annual rainfall (mm)	River density (km/km^2)
Very low	Flat surfaces, arches with low slopes, no water aggregating, top surfaces higher than 1000 m, wave-like, weak erosions acting	Alisol or limestone mountains	>55	<10	<1000	<0.5
Low	Abrasively erosive ridges, intermediately slippery ridges, sunken and severely weathered	Dark soil or mountainous humus	40-55	10-20	1000-1500	0.5-1.5
Medium	Slippery ridges, sunken and winding, erosive ridges on different stones	Oxisols on sandstone, ferralsols on limestone	25-40	20-30	1500-2000	1.5-2.5
High	Erosive drains erosive ditches capable of aggregating water while raining, aggregated and abrasive surfaces	Oxisols degraded due to rice cultivation, oxisols and humus	10-25	30-40	2000-2500	2.5-3.5
Very high	Cavitated troughs, V-shaped water aggregating troughs, cavitated and water aggregating grounds	Strongly erosive soils, tones, aggregating sloped soils	<10%	>40	>2500	>3.5

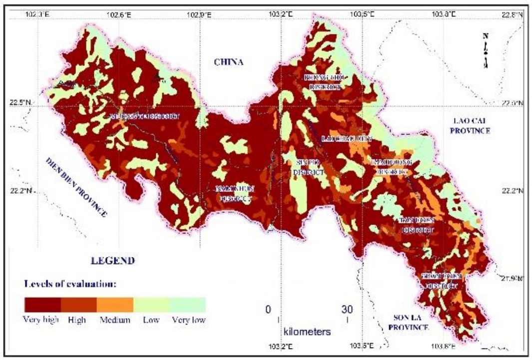
Based on the table of criteria that assessed flash flood forming factors at Lai Chau province, the employment of collected data and analytical functions of GIS resulted in a map that assessed flash flood forming factors on the surfaces of buffer zones in drainage basins. There were 6 information layers, including the characteristics of geomorphology (GM), soil types (S), vegetation cover (VC), slopes of drainage basins (SB), average annual rainfall (AR), and the river/stream density (RD). The map system that assessed the intensity of those layers was divided into 5 levels, corresponding to the risks of flash floods ranging in very low, low, medium, high and very high. The results of assessing information layers are demonstrated in **Fig. 3** and **Table 2**.



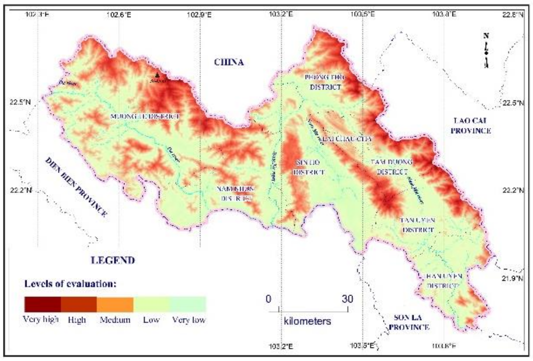
(a) Map evaluating of geomorphology



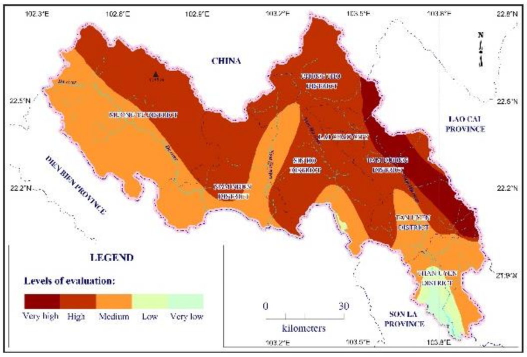
(b) Map evaluating of soil types



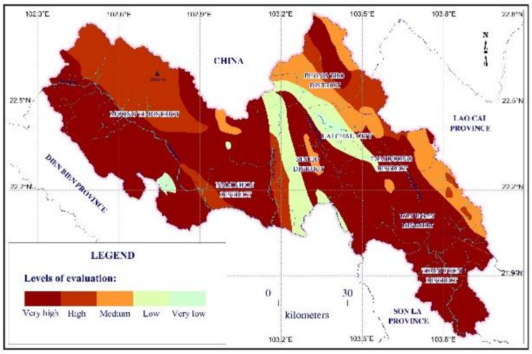
(c) Map evaluating of vegetation cover



(d) Map evaluating of slopes



(e) Map evaluating of average annual rainfall



(f) Map evaluating of the river density

Fig. 3. Maps system evaluating the risk of factors that cause flash floods in Lai Chau province.

Table 2.

Results of assessment of factors causing flash floods in Lai Chau province (km^2).

Level	GM	S	VC	AR	SB	RD
Very low	737.09	1207.05	798.85	1320.41	107.32	220.72
Low	1292.94	2603.65	1542.01	2263.57	162.00	677.35
Medium	3164.00	3577.63	1017.54	3097.90	3654.04	1643.25
High	2710.41	808.94	1634.14	1633.29	4195.72	1608.83
Very high	1164.35	871.51	4076.24	753.62	949.71	4918.63

4.2. Mapping of flash flood hazard in Lai Chau province

The AHP was utilized in calculating the weights of information layers that evaluate flash flood risks at Lai Chau Province. Results are shown in **Table 3**. Specifically, the results include: A Consistency Index CI of 0.069; A Random Consistency Index determined according to 6 factors forming flash flood RI of 1.25; and A Consistency Ratio CR = CI/RI = 0.069/1.25 = 0.055. Therefore, as the CR index is less than 0.1, the reliability of this study is assured.

Table 3.

Matrix of weights for information layers that evaluate flash flood risks in Lai Chau province.

Information layer	GM	S	VC	SB	AR	RD	Total	Weight
GM	0.14	0.12	0.16	0.17	0.18	0.11	0.88	**0.15**
S	0.02	0.03	0.02	0.04	0.04	0.02	0.17	**0.03**
VC	0.08	0.13	0.08	0.18	0.08	0.13	0.68	**0.11**
SB	0.06	0.15	0.09	0.12	0.08	0.12	0.62	**0.10**
AR	0.36	0.18	0.19	0.26	0.28	0.25	1.52	**0.25**
RD	0.06	0.13	0.04	0.05	0.07	0.04	0.39	**0.07**

With the weights shown in **Table 3**, the F(m) function was clarified with the application of Formula 2 as follows:

$$F(m) = 0.15*GM + 0.03*S + 0.11*VC + 0.10*SB + 0.25*AM + 0.07*RD \quad (3)$$

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 Lai Chau province (**Fig. 4**). Areas of flash flood risk levels by district administrative unit of Lai Chau province are shown in **Table 4**.

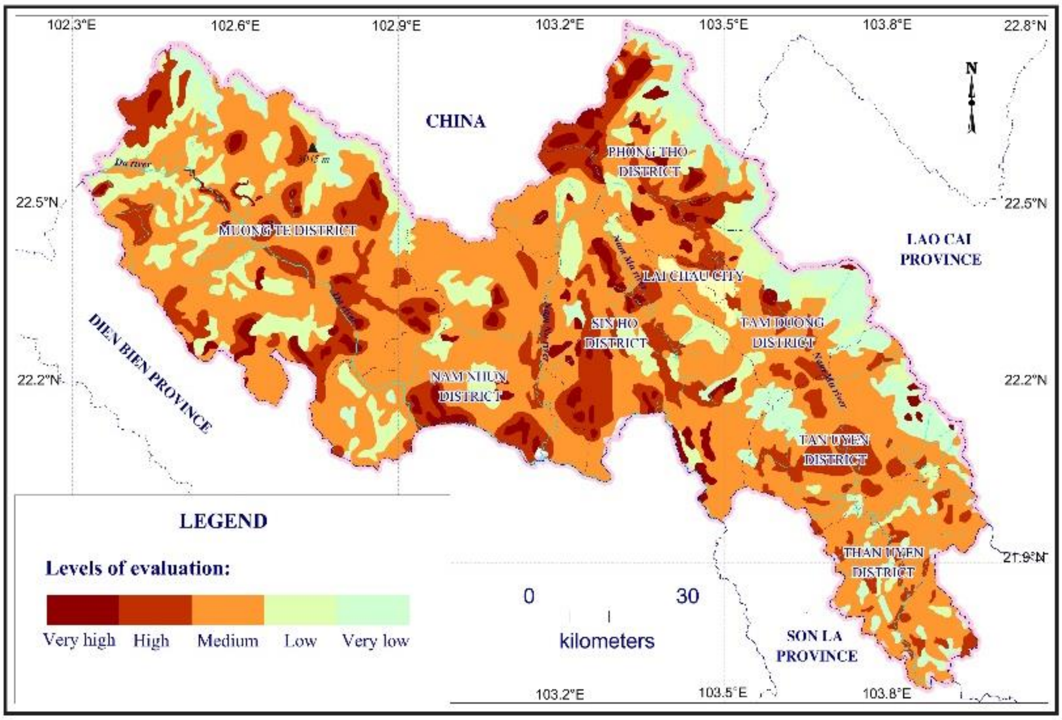


Fig. 4. Mapping of flash flood hazard in Lai Chau province.

Table 4.
Area of flash flood risk levels by administrative unit of Lai Chau province (km2).

No	District/city	Very low	Low	Medium	High	Very high
1	Lai Chau city	1.38	15.90	6.98	5.11	0.00
2	Tam Duong district	122.64	191.78	303.09	45.41	20.68
3	Tan Uyen district	98.20	154.21	551.20	105.66	85.38
4	Than Uyen district	61.44	94.11	565.85	75.46	20.08
5	Phong Tho district	188.32	282.70	384.56	200.04	108.52
6	Sin Ho district	200.46	246.44	789.00	312.07	127.71
7	Nam Nhun district	120.40	179.42	837.51	261.09	130.47
8	Muong Te district	494.18	657.75	1025.45	490.98	225.48
	Total	**1103,60**	**1938.90**	**4028.66**	**1469.11**	**528.51**

4.3. Discussion

The analysis results show that the area with a high and very high potential for flash floods accounts for 33.55% of the province's natural area, mainly concentrated in areas with steep slopes, the terrain tends to accumulate water, vegetation is mainly shrub or bare ground, typical sloping soil. The largest area belongs to Phong Tho and Sin Ho districts. This result completely coincides with the statistical documents on the locations of flash floods in the past in Lai Chau province from 2000 to the present (Statistical Office of Lai Chau Province, 2020). Especially in the area of Tua Sin Chai commune, Can Co commune of Sin Ho district; Mu Sang commune, Dao San commune, Vang Ma Chai commune in Phong Tho district. Statistics show that in the past 20 years, there have been 1-2 flash floods per year. Some small areas have a high level of potential risk assessment for flash floods, but in fact no flash floods have been recorded. These areas are often due to the hydrological network that does not tend to converge, the geomorphology is quite stable, and the terrain types are difficult to generate floods.

The study also shows that the factors that cause flash floods in Lai Chau province, including topography, geomorphology, slope, soil type, vegetation, and hydrological characteristics, are all less volatile. They can be analyzed and evaluated accurately. The factor of annual average rainfall has great variation, is the main factor causing flash floods. However, the average value of rainfall in the year doesn't accurately reflect the cause of flash floods. The factor of daily rainfall is the decisive factor for the formation of flash floods in the basin.

Studies on flash floods in mountainous areas of Vietnam also show that in areas with high risk of flash floods, as long as the amount of rain per day reaches above 200 mm, it is almost certain that flash floods will occur (La, 2009; Nong et al., 2020, Kieu et al., 2021). The factor of maximum rainfall during the day must be selected as the main factor for forecasting and early warning of flash floods. The biggest difficulty in the mountainous areas of Vietnam is the very sparse rainfall monitoring system, the lack of daily rainfall forecast data. Therefore, the study proposes to strengthen the system of automatic rainfall monitoring stations in the warning area with high risk of flash floods. Rainfall monitoring stations need to improve their accuracy, it must be able to connect to the national weather forecasting system. The reality shows that flash floods in Lai Chau province are very complicated. In many cases, flash floods occurred due to sudden causes such as landslides, flow blockage causing sudden accumulation of water in the basin (Duong et al., 2020). In this case, a satellite image system, online radar connected to the flash flood warning system is required.

The novelty of this study is flash floods were approached through drainage basins, which is considered a relatively closed system including 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). Lai Chau province possess high slopes, when rain exceeds limits, the flows aggregate to form a flash flood. Additionally, each drainage basin has a particular mechanism of flash flood occurrences.

The map of zoning and flash flood warning in Lai Chau province is built based on remote sensing and GIS integrated model. Remote sensing technology provided satellite image for the analyses of factors that formed flash floods, such as terrains, geomorphology, pedologic factors, flows, vegetation, etc. The GIS integrated model was responsible for processing spaces, forming maps of forecasts, and flash flood warnings. The results have been applied in Lai Chau province, initially offering great effectiveness in flash flood forecasting and warning. The model from this study is applicable in flash flood drainage areas at localities in mountainous regions of Vietnam.

5. CONCLUSIONS

Flash floods are extremely dangerous and unpredictable natural disasters. Flash flood hazard mapping using satellite images and GIS integration method is of great significance in early warning of flash floods, contributing to mitigating damage caused by flash floods. Research in Lai Chau province has analyzed the factors that cause flash floods and established a map of flash flood risk zoning.

Research results have identified 6 main factors that cause flash floods including geomorphological characteristics, soil properties, forest types and vegetation cover, basin slope, average annual rainfall, and the river density. The flash flood risk zoning map has identified 33.55% of Lai Chau province's area at high and very high risk of flash floods, 44.42% of the area at medium level, 22.03% of the area at low risk. low and very low. Thus, Lai Chau province is assessed as one of the provinces with the highest risk of flash floods in Vietnam.

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