A GIS-based Spatial Multi-criteria Approach for Flash Flood Risk Assessment in the Ngan Sau-Ngan Pho Mountainous River Basin, North Central of Vietnam

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ABSTRACT

Flash flood risks in the Ngan Sau-Ngan Pho mountainous river basin (north central of Vietnam) were examined based on GIS and a spatial multi-criteria approach. A set of indicators were firstly proposed for the assessment of hazard, exposure and vulnerability. Analytic hierarchy process (AHP) technique and Iyengar and Sudarshan's method were then applied for calculating weights of hazard and vulnerability indicators, respectively. Flash flood risks were assessed by means of the "risk triangle" approach and were finally validated using past flood records. It was found that flash flood hazard was mainly at medium and low levels, with a very high hazard area of 178.6 ha accounting for 0.1% of the total river basin. Exposure at high and very high levels was mainly detected in the economic center of the basin. The high and very high vulnerability areas accounting for 98.2% of the total area were mainly concentrated in mountainous areas. The largest area was low risk totaling 219,083.1 ha (accounting for 68.6% of the basin area), followed by 67,148.6 ha (very low risk: 21%), 27,181 ha (medium risk: 9%), 5,909.7 ha (high and very high risks: 1.8%). These results demonstrate the proposed set of indicators, GIS and spatial multi-criteria analysis allow for effective flash flood risk assessment in mountains.

1. INTRODUCTION

Floods and/or flash floods are among the most common of all environmental hazards in the world causing the largest amount of deaths and property damage (CEOS, 2003). The main factors contributing to flooding problems are topography, geomorphology, drainage, engineering structures, and climate (Youssef et al., 2011). Most floods are caused by convective or frontal storms combined with the intensity and duration of the rain. In addition, there are other interrelated factors influencing flash flood severity including rainfall characteristics, water loss (evaporation and infiltration), drainage networks, drainage orders, drainage characteristics, and environmental and human processes (Saleh, 1989). Heavy rains, land-use change in basin areas and various engineering applications also contribute to the magnitude and frequency of flood events (Youssef et al., 2011). Floods can influence many aspects of human life due to their destructive effects and create significant expenses on mitigation efforts (Youssef et al., 2011). Smith (2003) indicated flooding regularly claims over 20,000 lives per year and adversely affects around 75 million people world-wide. Situated in the tropical monsoon zone close to the typhoon centre of the western pacific, Vietnam is one of the most disaster prone countries in the Mekong region and aproximately 70% of the people in Vietnam live in disaster-prone areas, with the majority of the people in the Central region (Shaw, 2006), especially in the Ngan Pho-Ngan Sau river basin (see section 2.1 for a more detailed discussion). Therefore, flash flood risk assessment

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plays a vital role in reducing flood inundation risk in this area.

During the past few years, many models have been proposed to assess flood hazard and risk. Prediction of flood hazard has been conventionally achieved by applying hydrologic and hydraulic models (Booij, 2005; Myronidis et al., 2009). However, the main limitation of these models is the unavailability of large-scale data. By setting up a framework by means of which the different processes of flood management can be classified, Plate (2002) defined a procedure for handling risks due to natural, environmental or man-made hazards, of which floods are representative. Based on this framework, many studies have employed remote sensing and GIS to map flood hazard and risk. Typically, using probabilistic methods, radar remote sensing data have been extensively used for flood monitoring in many basins such as Johor river (Malaysia) (Kia et al., 2012), Severn river (UK) (Matgen et al., 2011), Basilicata region (Southern Italy) (Refice et al., 2014), Europe (Sanders et al., 2005) and Dee River in Wales (UK) (Schumann and Di Baldassarre, 2010). Flood susceptibility mapping using hydrological, hydrodynamic and stochastic rainfall models has been successfully employed in the Upper Tiber River (central Italy) (Brocca et al., 2011), three mesoscale catchments in northern Germany (Haberlandt and Radtke, 2014), three raingauge sites (Ghana) (Unami et al., 2010) and along Malaysia's east coast (Pradhan, 2010; Unami et al., 2010). In addition, flood susceptibility mapping has been applied in various case studies with the help of GIS (Kia et al., 2012; Lee et al., 2012; Pradhan, 2010), neural network methods (Kia et al., 2012) and support vector machine models (Tehrany et al., 2014; Tehrany et al., 2015). Alternatively, several studies have successfully unitilzed multicriteria analysis methods to assess flood hazard in Tucumán Province (Argentina) (Fernández and Lutz, 2010), Dongting Lake region, Hunan, Central China (Wang et al., 2011) and Yasooj region (Iran) (Rahmati et al., 2016). Recently, many studies have used AHP with the help of GIS to assess flood hazard (Kazakis et al., 2015; Rahmati et al., 2016) and risk (Chen et al., 2011; Meyer et al., 2009). Furthermore, recent studies by Schumann and Di Baldassarre (2010) and Wang et al. (2011) have successfully combined AHP with fuzzy logic and genetic algorithms to incorporate the possible changes (climate change, land use change) over years into the assessment of flood hazard and management of water resources. Although all the above-discussed methods have proven successful in flood risk assessment in terms of their effectiveness and also in terms of their efficiency in many studies, they fail to take into account the indicators associated with the social-economic factors in mountains when assessing flood risks in a mountainous river basin. It is therefore, with the main objective of assessing flash flood risks by considering a wide range of climatic, natural and social-economic conditions, this study provides new insights into these factors with the help of GIS and spatial multi-criteria approach in assessing flash flood risks in a mountainous river basin.

2. METHODOLOGY

2.1 Description of study area

Ngan Sau-Ngan Pho river basin is located in Ha Tinh province (north central of Vietnam), consisting of Huong Son, Duc Tho, Vu Quang and Huong Khe Districts (Figure 1). It's geographic location extends latitudinally from 17°50′00″N to 18°37′58″N and longitudinally from 105°07′00″E to 106°56′00′E. Ngan Pho River originates from small streams in the Giang Man mountainous area, in the areas of Son Hong, Son Kim 1 and Son Kim communes of Huong Son District at an altitude of about 700 m above the mean sea level. Its maximum length, average height and slope range from 71 km to 72 km, 331 m, 25.2%, relatively. The area of Ngan Pho basin is 1,060 km^2 with river and stream density of 0.91 km/km^2. Its total volume of water is 1.40 km^3 corresponding to the average flow of 45.6 m^3/s. Whereas, Ngan Sau river system is the second largest tributary of Ca river extending 135 km and covering a basin area of 3,214 km^2.

Situated in the north central Vietnam, Ha Tinh province is often hardest hit by floods (Anh et al., 2014; Luu et al., 2019; Nguyen and Ha, 2017; Schad et al., 2012; Thao et al., 2014), especially in the Ngan Sau-Ngan Pho river basin (Kha et al., 2018; Long and Dung, 2009; Nguyen and Ha, 2017; Nguyen et al., 2017b; Trung, 2015). A flash flood in upstream Ngan Pho River occurred in September 1989 caused 10 deaths, 96 injuries, 16,200 households flooded, 177 houses washed away, and 5,026 ha of winter-spring rice damaged. Another historic flood in September 18-22nd 2002 in the upstream area of Ngan Pho and in the Central Region and Central Highlands of Vietnam river caused 77 deaths, hundreds of injuries, and 70,694 houses flooded (Figure 2(a)). The floodwaters of Ngan Sau in October 15-18nd 2010 overtook the 2002 historical flood causing all communes of Vu Quang District to be flooded and isolated (Figure 2(b)). Especially, floodwaters swept away and caused landslides of 1,520 households in 6 communes in the downstream of the Ngan Sau River. Most recently, a flood in October 2017 (Figure 2(c)-(d)) broke 28 km of the dam at the Co Chau Reservoir in Ha Tinh damaging 145 ha of rice, 2 ha of orchards and over 11,600 ha of other crops (NDO, 2017).

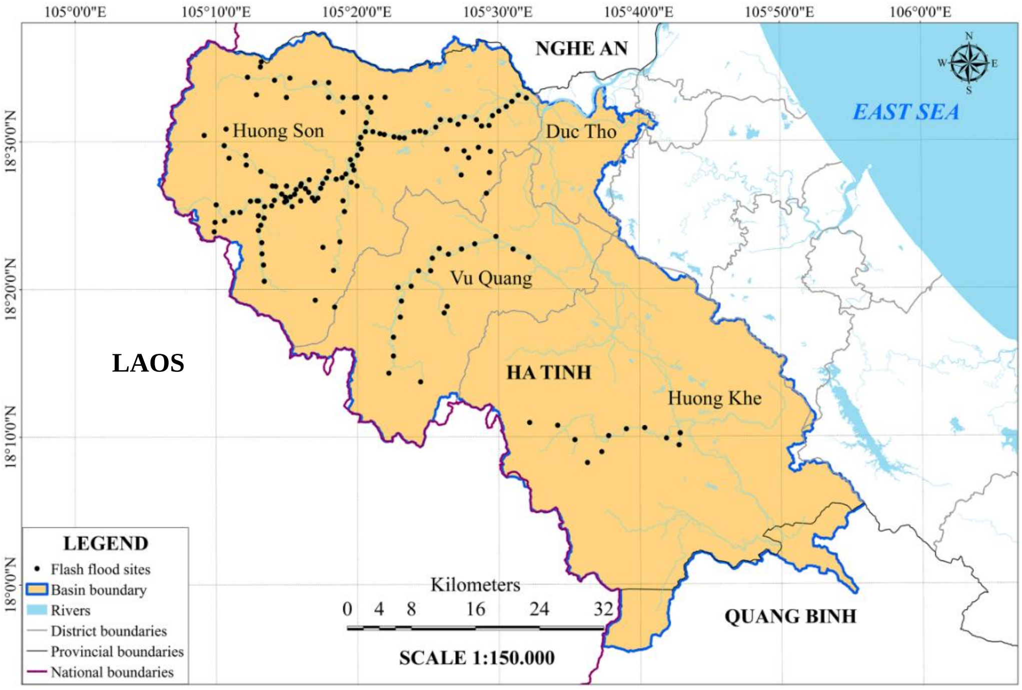

Figure 1. Study area of Ngan Pho-Ngan Sau river basin, North Central of Vietnam.

2.2 Data used

In this study, reports of flash flood status in Ngan Sau and Ngan Pho rivers were collected. Data used for risk assessment include hydro-meteorological data, land use map, topographic map, data from the statistical yearbook of the General Statistics Office in 2016, annual reports of Department of Agriculture and Rural Development, Department of Natural Resources and Environment, Steering Committee for Disaster Prevention and Search and rescue of Ha Tinh (Vietnam). In addition, field survey data collected in Ngan Pho, Ngan Sau river basin including 3,860 questionnaires from the people, district and commune officials was used as input data for flash flood risk assessment, whereas a total of 350 flash flood sites recorded in the past were used for the validation of flash flood risks in the study area.

2.3 GIS and spatial multi-criteria approach based flash flood assessment

A region's flood risk can be calculated by the "risk triangle" approach proposed by Crichton (1999) whose sides are represented by the amplitude of hazard (H), exposure (E) and vulnerability (V) as given in equation (1). If any of the sides increases, the area of the triangle, i.e., the amount of risk, increases also. Hence, risk is the result of the interaction of these three elements (Barredo and Engelen, 2010). The workflow of flood assessment is shown in Figure 3.

Hazard assessment: recent studies have indicated the cause of flash flood formation is divided into two groups of fast- (H_1) and low- (H_2) changing factors. Flood hazard is assessed as shown in Figure 4 using the following equation:

$$H = f(H_1, H_2)$$

Where, H_1 takes into account rainfall and flow surface, whereas H_2 is related to soil types, slope, density of rivers and streams, distance to rivers and land-use types.

$$R = f(H, E, V) \quad (1)$$

Figure 2. Flash floods in the study area: (a) a historic flood in September 2002 in the Ngan Pho basin; (b) in Huong Khe in October 2017, and (c and d) in Huong Khe in October 2017.

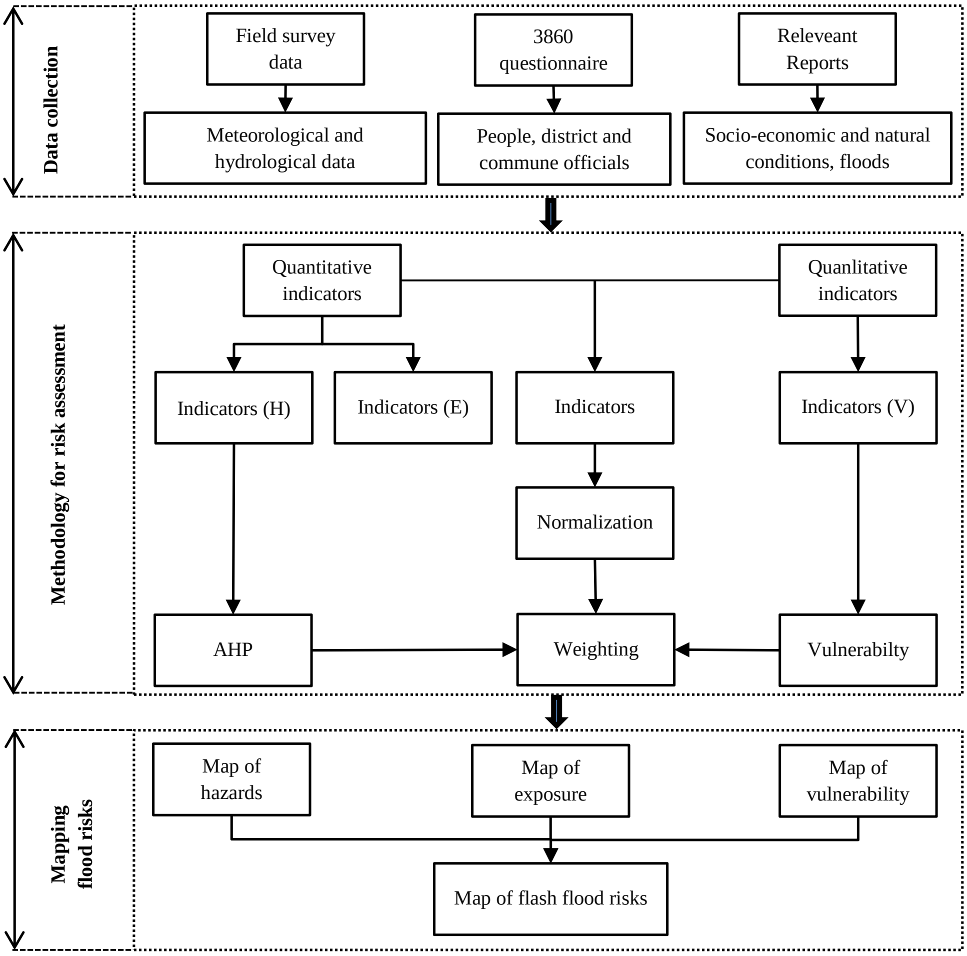

Figure 3. The workflow of flash flood assessment based on GIS and multi-criteria analysis.

Exposure assessment: exposure (E) is employed to refer to the presence (location) of people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected by physical events and which, thereby, are subject to potential future harm, loss, or damage (Field et al., 2012). Exposure indicators used in this study is land-use types. Based on the importance of land-use types and to the level of flash flood disaster risk, five types of land use will be assigned a value determined from 1 to 5: traffic housing (5); agricultural land (4); forestry land and bamboo (3); evergreen broadleaf forest (2); and bare land and rocky mountains (1).

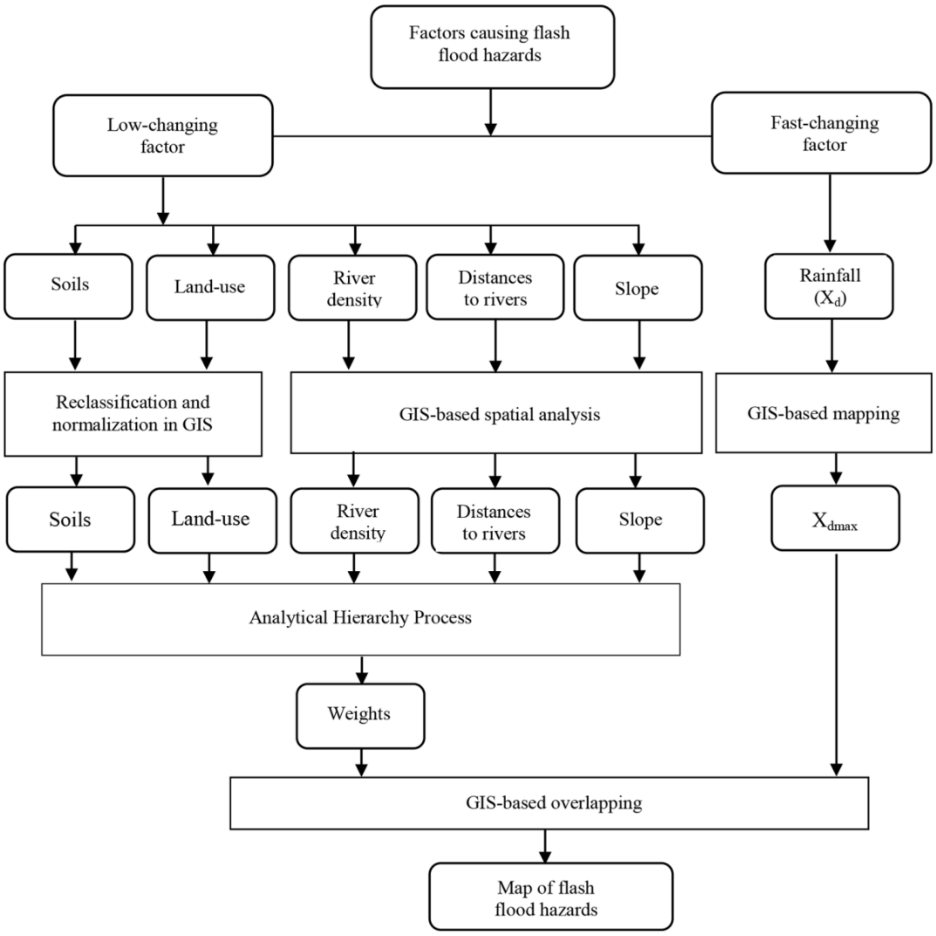

Figure 4. Flood hazard assessment using GIS and AHP.

Vulnerability assessment: according to the IPCC definition of vulnerability, vulnerability to climate change and variability is represented by three elements: exposure, sensitivity, and adaptive capacity (Bernstein et al., 2008). In this study, the social factors are clearly emphasized. Vulnerability assessment focuses on human capacity to resist, deal with flash floods and promptly recover damages and losses, so socio-economic factors were reviewed and analysed. Vulnerability indicators are identified based on a combination of two main indicators: sensitivity (S) and adaptive capacity (AC). Indicators of sensitivity (S) include people, jobs, health and education, infrastructure, agriculture (cultivation-livestock), forestry, seafood (30 sub-indicators), whereas indicators of adaptive capacity include self-recovery ability, social policies, infrastructure, awareness and communication (23 sub-indicators). These (sub-) indicators are summarised in Table 1. The vulnerability index is calculated using equation (2):

$$V = \sum_{j=1}^{n} S_i \times W_S + \sum_{j=1}^{m} AC_i \times W_{AC} \qquad (2)$$

Where, V is vulnerability index; S_i is sensitivity indicators; AC_i is adaptive capacity indicators; and W_s and W_{ac} are weights of sensitivity and adaptive capacity indicators, respectively; n and m are number of sub-indicators; and V is the vulnerability index which lies between 0 and 1, with 1 indicating maximum vulnerability and 0 indicating no vulnerability at all.

2.3.1 Normalization of indicators

Each indicator is measured in different scales and units. Therefore, they need to be normalized to values between 0 and 1 to ensure that they are comparable. Where, 1 being the highest value and 0 with being the least vulnerable area for the indicators with positive relationship with vulnerability to climate changes. This was important to identify the two possible types of functional relationship between the indicators and vulnerability. In addition, it is ensured that the index values are always in positive correlation with vulnerability and that higher value means higher vulnerability and vice versa (Žurovec et al., 2017). If vulnerability increases with an increase in the value of the indicator (positive correlation), and therefore has a positive functional relationship with vulnerability. Normalization of indicators was carried out by using the the methodology developed for the calculation of the Human Development Index (UNDP, 2006) as shown in equation (3),

$$x_{ij} = \frac{X_{ij} - Min(X_{ij})}{Max(X_{ij}) - Min(X_{ij})} \quad (3)$$

Where, X is the separated value in the distribution, $Min(X_{ij})$ is the minimum value in the distribution; $Max(X_{ij})$ is the maximum value of the mean of the distribution i is the sub-city; and j is number of indicators. If the indicators are assumed to have a negative relationship with vulnerability, the above formula will be changed to the following as described in equation (4):

$$y_{ij} = \frac{Max(X_{ij}) - X_{ij}}{Max(X_{ij}) - Min(X_{ij})} \quad (4)$$

2.3.2 Weighting methods

The next step after normalization of indicators was to summarize indicators into composite indices and assign weights based on their degree of influence on hazard and vulnerability. In this study, the weights of hazard and vulnerability components were calculated using AHP and weighting method proposed by Iyengar and Sudarshan (1982), respectively.

The weights of hazard components were obtained using the AHP technique which was proposed by Saaty (1977) and Saaty (1990). Using this method, the relative weight of each factor was estimated. The comparative scale consists of integer numbers from 1 to 9, where 1 means that the factors are equally important and 9, that a factor is extremely more important than another (Saaty, 1977; Saaty, 1990; Saaty and Vargas, 1984). The discordances between the pairwise comparisons and the reliability of the obtained weights were checked using the consistency ratio (CR) in equation (5). The consistency is used to build a matrix and is expressed by a consistency ratio, which must be less than 0.1 so as to be accepted. Otherwise, it is necessary to recalculate the weights (Saaty and Vargas, 2012).

$$CR = \frac{CI}{RI} \quad (5)$$

Where, RI is the random index and CI represents the consistency index computing according:

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (6)$$

Where, λ_{max} represents the sum of the products between the sum of each column of the comparison matrix and the relative weights and n represents the size of the matrix.

The weights of land-use types were 0.33 (traffic housing), 0.27 (agricultural land), 0.2 (forestry land and bamboo), 0.13 (evergreen broadleaf forest) and 0.07 (bare land and rocky mountains) with the derived consistency ratio (CR) value of 0.08 (less than 0.1). The obtained weights of sub-indicators and indicators of hazard component, and their corresponding CR values are shown in Table 1. Data in Table 1 illustrates that the value of of CR was smaller than 0.1, therefore, these derived weights are considered reliable.

The weights of vulnerability component were obtained using method of Iyengar and Sudarshan (1982). This method was introduced to work-out a composite index from multivariate data and to rank the districts in terms of their economic performance. It is statistically sound and well suited for the development of composite index of vulnerability to climate change also (Hiremath and Shiyani, 2012). In this method, it is assumed that there are M regions/districts, *K* indicators of vulnerability and X_{ij} (i=1,2…, M; j=1,2,..., K) is the normalized score. The level of risk of i^{th} zone R_i, is assumed to be a linear sum of x_{ij} as:

$$R_i = \sum_{j=1}^{K} w_i x_{ij} \;\; (0 < x_{ij} < 1 \text{ and } \sum_{j=1}^{K} w_i = 1) \quad (7)$$

Table 1. Summary table of weights of hazard and vulnerability indicators

(a) – Weights of hazard indicators

Indicators	Weight	Sub-indicators	Weight
Fast-changing factor	0.25	Maximum daily rainfall	1
Low-changing factor	0.75	Types of soils	0.306
		Slope	0.295
		Density of rivers and streams	0.194
		Distance to rivers	0.148
		Types of land-use	0.057
CR = 0.03 (< 0.1)		CR = 0.07 (< 0.1)	

(b) – Weights of sensitivity indicators

Indicators	Weight	Sub-indicators	Weight
People	0.094	Rate of population growth (5 years of population)	0.027
		Percentage of elderly >60 years old	0.038
		Percentage of children <15 years	0.034
		Percentage of Women	0.033
		Percentage of poor people	0.032
		Percentage of ethnic minorities	0.060
Job	0.114	Average income per capita	0.027
		Main occupations of households (civil servants, service, industry, agriculture)	0.040
		Number of poor households	0.034
Medical	0.155	Number of patients attending hospital and commune health stations	0.043
		Average distance from commune health station/Commune People's Committee to the hospital, health center, nearest polyclinic	0.031
		Disease phenomenon after flash flood	0.033
Education	0.234	Number of pupils (preschool, primary, secondary, high school)	0.030
Infrastructure	0.136	Type of local roads	0.022
		Damage to social infrastructure facilities (schools, hospitals, clinics, cultural houses)	0.024
		Number of water wells for domestic use	0.029
		Number of households using water from dug wells and ponds for domestic use	0.024
Agriculture (cultivation-livestock)	0.076	Area of agricultural land	0.034
		Agricultural labor force	0.029
		Number of agricultural households	0.027
		Agricultural production and crop losses after flash floods	0.024

(b) – Weights of sensitivity indicators (cont.)

Indicators	Weight	Sub-indicators	Weight
Forestry	0.103	Area of forestry land	0.039
		Number of forestry households	0.053
		Forestry labor force	0.029
Seafood	0.088	Area of aquaculture	0.053
		Aquaculture water surface area affected by flash flood	0.019
		Damage to aquatic products of all kinds	0.025
		Number of aquaculture households	0.054
		Fisheries workforce	0.053

(c) – Weights of adaptive capacity indicators

Indicators	Weight	Sub-indicators	Weight
Self-recovery ability	0.436	Number of people in working age	0.044
		Life stabilization time after flash flood	0.043
Social policies	0.247	Households supported to build and repair houses	0.053
		Reserve of essentials for flash flood prevention	0.041
		Temporary relocation plans	0.028
Infrastructure	0.153	Number of local health facilities (stations, hospitals)	0.074
		Number of medical doctors	0.085
		Percentage of rural residents participating in health insurance (%)	0.032
		Type of housing	0.037
		Number of water pumping stations serving production and aquaculture in the commune	0.028
		Length of irrigation canals in the commune (km)	0.051
		Number of households using water from concentrated domestic water supply works	0.035
		Current status of local flood prevention works	0.055
Awareness and communication	0.164	Number of teachers	0.052
		Number of schools (preschool, primary, secondary, high school)	0.041
		Number of loudspeakers	0.047
		Percentage of households with radio and television	0.022
		Phone subscription number	0.048
		Number of computers with internet connection	0.054
		Ability to access to flash flood warning information	0.025
		Understanding of flash flood and prevention approaches	0.025
		Propaganda and training on natural disaster prevention and mitigation	0.033
		Early monitoring/warning system	0.047

In the method of Iyengar and Sudarshan (1982), the weights are assumed to vary inversely with the variance over the regions in the respective indicators of vulnerability. The weight w_i can be determined as:

$$w_i = \frac{c}{\sqrt{var(x_{ij})}} \quad (8)$$

Where, c is a normalizing constant and can be obtained as below:

$$c = \left[\sum_{j=1}^{j=K} \frac{1}{var(x_{ij})}\right]^{-1} \quad (9)$$

2.3.3 Identification of flood risk levels

A meaningful characterization of the vulnerability profiles should be in terms of a fractile classification based on an assumed distribution of R_i (Iyengar and Sudarshan, 1982). It is assumed that R_i follows a Beta distribution in the range (0, 1) which is skewed and relevant to characterize positive valued random variables (Bucaram et al., 2016). This distribution has the probability density as follows:

$$f(z) = \frac{z^{a-1}(1-z)^{b-1}dx}{B(a,b)}, 0 < z < 1 \text{ and } a, b > 0 \quad (10)$$

Where:

$$B(a, b) = \int_0^1 x^{a-1}(1-z)^{b-1}dx \quad (11)$$

The parameters a and b can be estimated by solving the following two simultaneous equations:

$$(1-y)a - yb = 0 \quad (12)$$
$$(y-m)a - mb = m - y$$

Where, y is the overall mean of the localities indicators and m is defined as:

$$m = s_y^2 + y^2 \quad (13)$$

Where, s_y^2 is the variance of the indicator by locality. Let $(0, z_1)$, (z_1, z_2), (z_2, z_3), (z_3, z_4), (z_4, z_5) be the linear intervals such that each one has the same probability weight of 20%. Five classes of risks are obtained and districts were ranked accordingly: (i) less risk, if $0<y_i< z_1$; (ii) moderately risk, if $z_1<y_i< z_2$; (iii) risk, if $z_2<y_i< z_3$ (iv) highly risk, if $z_3<y_i< z_4$ and (v) very high risk, if $z_4<y_i< 1$.

3. RESULTS AND DISCUSSION

3.1 Assessment of hazard

From data in Table 2 we can see that flash flood hazards in the Ngan Pho-Ngan Sau basin were mainly low and medium, covering areas of 81,636.7 ha and 220,246.5 ha, accounting for 25.5% and 68.8% of total area, respectively. A very low hazard area of 4,643.8 ha accounting for 1.5% was measured in northeast of the basin, whereas, high and very high hazard areas of 13,274.2 ha and 178.6 ha accounting for 4.1% and 0.1% were also detected near rivers and streams (Figure 5) with high slopes and poor structures such as Son Kim 1, Tay Son, Son Hong and Su Diem communes of Huong Son District; Huong Tho, Duc Bong and Duc Giang communes of Vu Quang District; Duc Lang and Duc Dong communes of Duc Tho District (Thao et al. 2014); Phu Gia, Hoa Hai, Huong Lam and Huong Lien communes of Huong Khe District (Nguyen and Ha, 2017; Nguyen et al., 2017b).

Table 2. Summary table of areas of hazard, exposure, vulnerability and flash flood risks.

Levels	Hazard		Exposure		Vulnerability		Flash flood risks	
	Area (ha)	Percent (%)	Area (ha)	Percent (%)	Area (ha)	Percent (%)	Area (ha)	Percent (%)
Very low	4643.8	1.5	393.5	0.1	1102.4	0.3	67148.6	21.0
Low	81636.7	25.6	172769.0	54.1	336.6	0.1	219083.1	68.6
Medium	219589.3	68.8	72854.4	22.8	4310.0	1.3	27181.1	8.5
High	13274.2	4.2	52487.3	16.4	96060.4	30.1	5809.5	1.8
Very high	178.6	0.1	20818.4	6.5	217513.1	68.1	100.2	0.0
Total	319322.5	100.0	319322.5	100.0	319322.5	100.0	319322.5	100.0

3.2 Assessment of exposure

The exposure to flash flood risk in Ngan Pho-Ngan Sau river basin in Table 2 shows that areas with high and very high exposures were mainly concentrated in the economic center of the basin where densely populated areas, agricultural and non-agricultural economic activities are located. The high and very high exposure covered an area of about 73,305.7 ha, accounting for 22.9% of the basin area and were mainly concentrated in northeast and north of the basin (Figure 6). The exposure was at medium level with an area of 72,854.4 ha, accounting for 22.8%, whereas, the level of exposure was at low and very low levels corresponding to areas of 173,047.9 ha and 393.5 ha, accounting for 54.1% and only 0.1% of the total area, respectively.

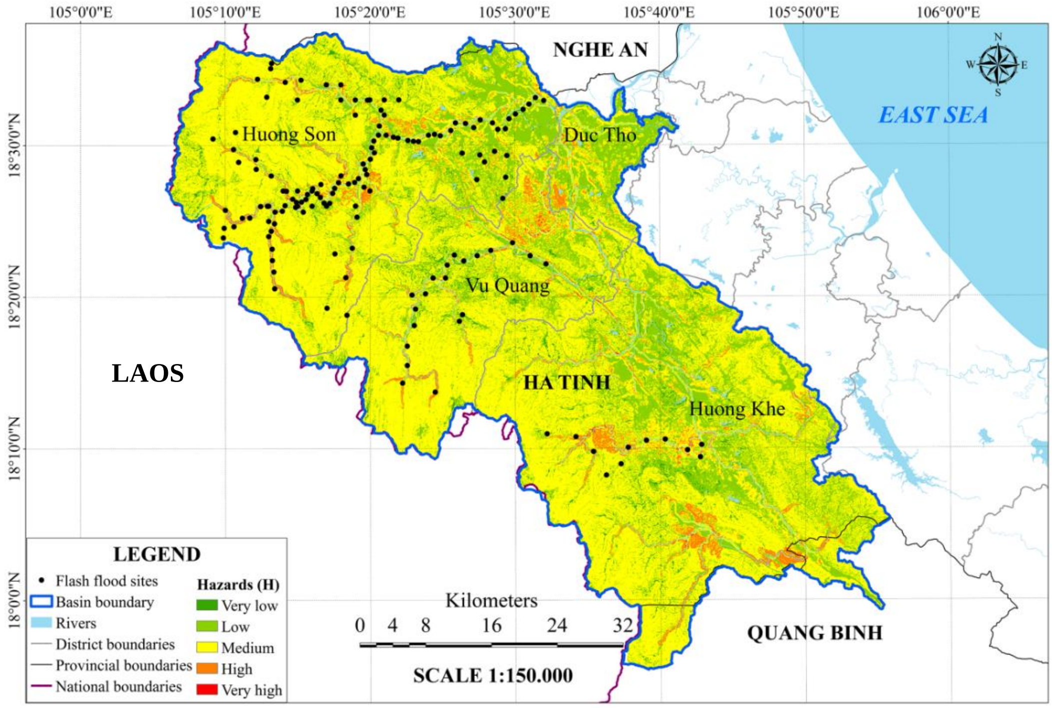

Figure 5. Map of flash flood hazard of the Ngan Pho-Ngan Sau river basin.

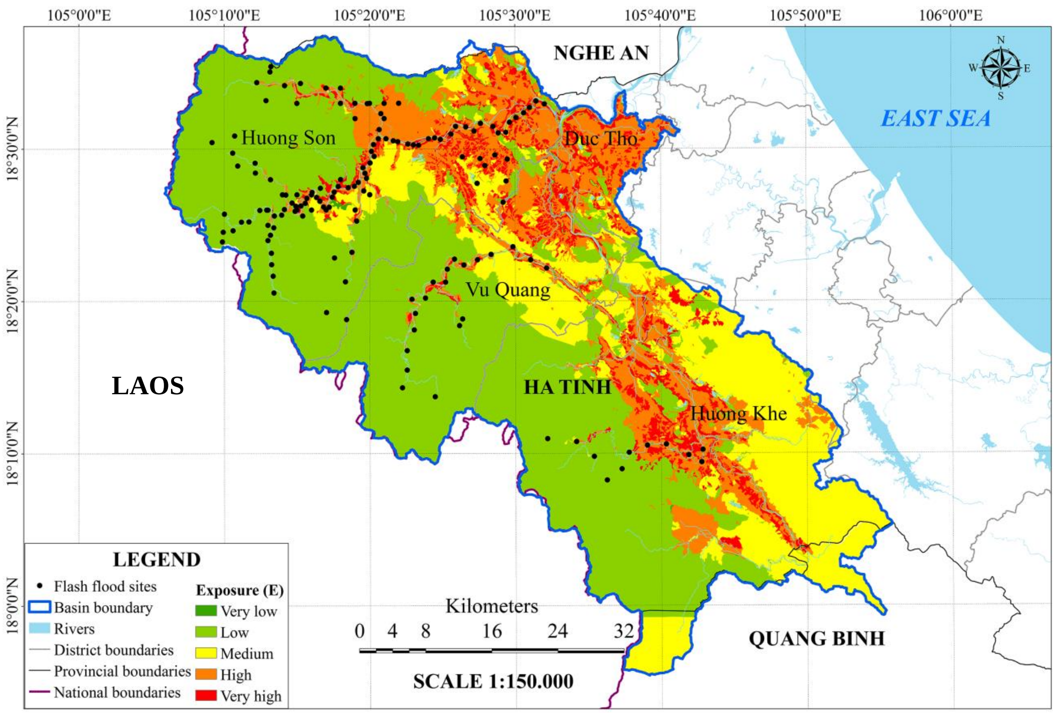

Figure 6. Map of flash flood exposure of the Ngan Pho-Ngan Sau river basin.

3.3 Asesment of vulnerability

Data in Table 2 demonstrated that the flash flood vulnerability of the Ngan Pho-Ngan Sau river basin the vulnerability was mainly at high and very high levels. In particular, the vulnerability at a very high level had an area of 219,000.1 ha (accounting for

68.3% of the basin area), followed by 96,060.4 ha of high level (accounting for 29.9%), 4,310.0 ha of medium level (accounting for 1.3%), and a relatively small area of low and very low levels with an area of 1,439.0 ha (accounting for only 0.4%). It is shown in Figure 7 that the areas of high and very high vulnerability were concentrated mainly in mountainous areas which were affected by flash floods annually, such as in the Son Kim 1, Son Kim 2, Son Hong, Son Linh communes of Huong Son District; Huong Quang, Huong Minh and Huong Tho communes of Vu Quang District; and Phu Gia, Huong Lam and Huong Lien communes of Huong Khe District (Nguyen and Ha, 2017; Nguyen et al., 2017b).

3.4 Assessment of flash flood risks

A total of 350 past-recorded flood sites were used as verification sites to validate the generated flash flood risks. Data from Figure 8 shows that most of verification sites were strongly correlated with flood risks at high and very high levels, especially in Huong Son, Duc Tho and Vu Quang Districts. A total of 303 generated risk sites at high and very high levels were detected at verification sites presenting an occupancy rate of 86.6%. This result suggests that the proposed method is very useful for accurate and reliable flash flood risk mapping. Data in Figure 8 also shows that the largest area was at low risk level covering an area of 219,083.1 ha (accounting for 68.6% of the basin area), followed by 67,148.6 ha of very low risk (21%), 27,181.1 ha of medium risk (8.5%), 5,809.5 ha of high risk and 100.2 ha of very high risk. The risks of flash floods at high and very high levels were concentrated in areas of high densities of rivers and streams (Figure 8). Specifically, high and very high flash flood risk areas were detected which accounts for 42%, 26.5%, 22.9% and 8.6% of Huong Khe, Huong Son, Duc Tho, and Vu Quang Districts, respectively. This finding is similar to flash flood records ussually reported annually in Huong Khe (Nguyen and Ha, 2017; Nguyen et al., 2011; Nguyen et al., 2017b; Thuy and Mui, 2018), Huong Son (Nguyen et al., 2017a), Duc Tho (Thao et al., 2014) and Vu Quang (Nguyen et al., 2011). Most of these areas were located in Son Hong, Son Tay, Son Ha, Son Kim 1 and Son Kim 2 communes of Huong Son District; Duc Dong and Duc Lang communes of Duc Tho District; Duc Giang, Duc Linh and Duc Bong communes of Vu Quang District; and Hoa Hai, Loc An, Phu Gia and Huong Lam communes of Huong Khe District.

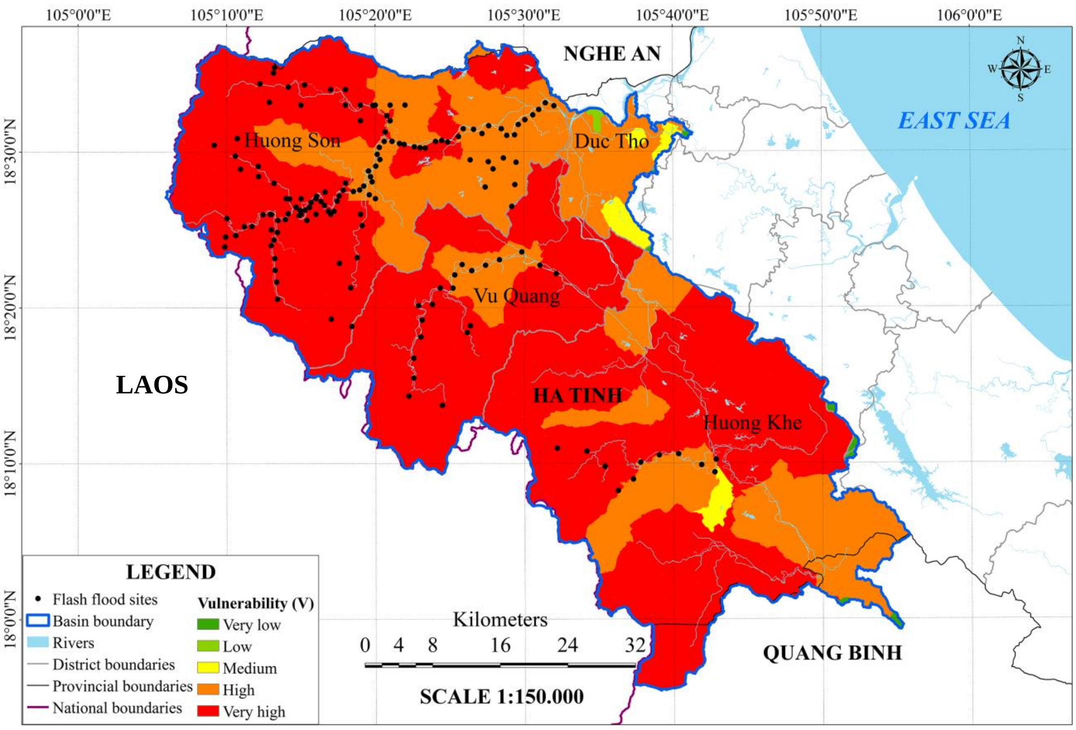

Figure 7. Map of flash flood vulnerability of Ngan Pho-Ngan Sau river basin.

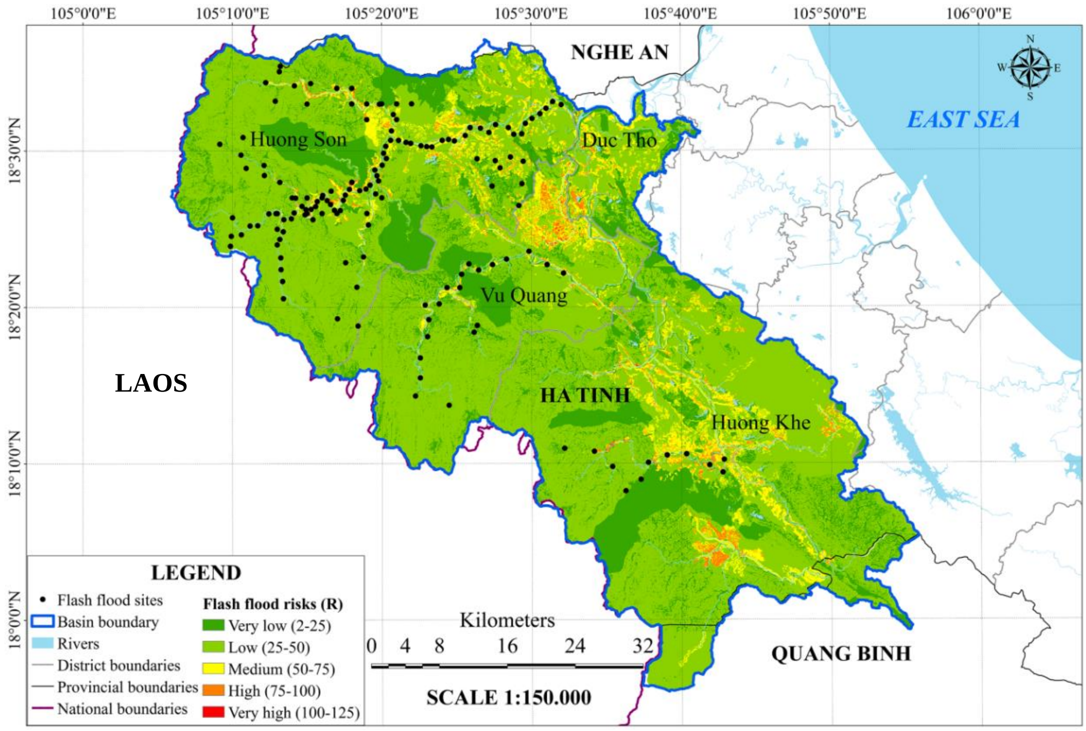

Figure 8. Map of flash flood risks of Ngan Pho-Ngan Sau river basin.

Huong Khe District: the total area of low risk was 90,928 ha accounting for 68.1.8% of the district area, followed by 21.1% (very low risk), 8.9% (medium risk), and 1.9% (high and very high risk). The total area of high and very high risk was 2,540 ha and was mainly concentrated in Huong Lam commune (741 ha), followed by Loc Yen, Phu Gia and Hoa Hai and other communes (from 14.04 ha to 97 ha). Whereas, very high risk areas were 23.9 ha and occured in seven communes of Phu Gia, Hoa Hai, Loc Yen, Huong Lien, Gia Pho, Huong Do and Phuc Dong. This result shows a good conformity with those reported by Nguyen and Ha (2017). In addition, a study of Nguyen et al. (2017b) indicated that rainfall duration and intensity in the period of 1990-2012 caused floods in 2002, 2007 and 2010 in this area. The high risk area was 2,516 ha and was mainly detected in Huong Lam commune (740.94 ha), several areas of Phuc Trach commune (14 ha) Floods were also reported in these districts in 2017 (Nguyen, 2017) and 2016 (PSN, 2016), respectively. The medium risk area was 11,904 ha and was evenly distributed in the communes. Low risk area of 90,928 ha was mainly detected in Hoa Hai commune (12,673 ha), and some of Huong Khe town, whereas a very low risk area of 28,182 ha was mainly found in Huong Vinh commune (5,538 ha and Huong Khe town (8.6 ha).

Huong Son District: the largest area of risk was at low level detected in Huong Son District with an area of 23,899.3 ha accounting for 69% of the district area, followed by 23,899 ha of very low risk, 8,361 ha of medium risk, 1,474 ha of high risk and 128 ha of very high risk. The total area of flash flood risks at high and very high levels was 1,602 ha, accounting for only 1.5% of study area and occured mainly in four communes of Son Hong, Son Kim 1, Son Kim 2 and Son Tay. Particularly, very high risks were found in Son Giang, Son Hong, Tay Son, Son Ha, Son Giang, Son Kim 1, Son Kim 2, Son Diem communes. A serious flood in Son Kim 1 and Son Kim 2 in October 2013 was also reported by Hong (2014). The flood destroyed hundreds of houses and civil works in the areas of Son Kim 1 and Son Kim 2 communes. In addition, about 300 households had all assets swept away, 57,100 houses flooded, 366 houses roofed in Huong Son. The areas of medium risks at medium level were mainly detected in Son Linh commune with an area of 1,015 ha and in Son An commune (34 ha). Low risk areas of 20,788 ha and 136 ha were found in Son Kim 1 commune and Pho Chau town, respectively. The risk area at the very low level occured mostly in Son Tay commune (9,363 ha) and some areas of Son An commune (2.6 ha).

Duc Tho District: the total area of flash flood risk at low level accounts for 55.4% of the district area, followed by 24.7% (very low level), 16.4% (medium level), 3.6% (high level). No risk at very high level was detected. The total area of high risk was 519 ha mainly concentrated in Duc Dong (146 ha) and Duc Lang (123 ha) communes. This result is similar to a flood reported in Duc Dong in 2017 (Thien, 2017) and in Duc Lang in 2016 (Group, 2016). The medimum risk areas were mainly detected in Duc Bong, Tung Anh, Duc An, Duc Lang and Duc Lac communes and some areas of Thai Yen and Duc Thanh communes (only 0.3 ha). Low risks were unevenly distributed across the district, and mostly occured in Duc Bong, Tan Huong, Duc Long, Duc Lang and Duc Hoa and in some areas of Duc Thanh commune with an area of 71 ha. A very low risk area of 3,541 ha was identified, mainly in communes of Tan Huong (907 ha), Duc Lang (602 ha).

Vu Quang District: the total low risk area accounts for 72.8% of the district area, followed by 17.3% (very low level), 7.7% (medium level), 2.2% (1,387 ha of high and very high risk area). The high risk area was mainly identified in Duc Bong commune with an area of 20.34 ha, followed by Duc Linh, Huong Tho, Duc Giang, Huong Quang, Huong Minh communes and Vu Quang town (only 0.09 ha). Four of six communes including Duc Bong, Duc Linh, Duc Giang and Huong Minh were devastated by a flood in 2011 (Minh Thu and Chau, 2011). In adition, about 300 households in Duc Bong were also isolated in a flood in 2017 (Tien, 2017). Medium risk was mostly concentrated in Duc Linh commune with an area of 1,104 ha, followed by Duc Giang, Duc Huong, Duc Bong, Huong Quang Huong Dien commune (84.7 ha). Low risk was detected in Huong Quang commune (26,632 ha) and Duc Giang commune (277.47 ha). The very low risk area was 10,767 ha, of which the largest area was found in Huong Dien commune (2,432 ha) whereas the smallest area was detected in Duc Giang commune (12 ha).

4. CONCLUSION

In this study, flash flood risk was assessed based on GIS and spatial multi-criteria approach. A set of indicators were firstly proposed for hazard, exposure and vulnerability components in mountains. An AHP technique and weighting method proposed by Iyengar and Sudarshan were then applied for calculating weights of hazard and vulnerability indicators, respectively. Flash flood risks were finally assessed using the “risk triangle” approach. The results showed that: (i) Flash flood hazard was mainly at medium and low levels. The very high hazard area was 178.6 ha, accounting for 0.1% of the total river basin; (ii) High and very high exposure was detected and mainly concentrated in the economic center of the basin; (iii) The areas of high and very high vulnerability were dominant in the basin, accounting for 98.2% of total area and were concentrated mainly in mountainous areas; (iv) The largest area of low risk was 219,083.1 ha (accounting for 68.6% of the basin area), followed by 67,148.6 ha (very low risk: 21%), 27,181.1 ha (medium risk: 9%), and 5,909.7 ha (high and very high risks: 1.8%). These results demonstrated the proposed GIS-based spatial multi-criteria approach is effective for flash flood risk assessment in mountainous river basin.

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