Assessing Flash Flood Risks based on Analytic Hierarchy Process (AHP) and Geographic Information System (GIS): A Case Study of Hieu Catchment (Nghe An, Vietnam)

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Abstract: Flash flood hazards from heavy rainstorms are common in Hieu catchment (Nghe An province). This study presents a flash flood hazard assessment for Hieu catchment using the combination of Analytic Hierarchy Process (AHP) and Geographic Information System (GIS). A total of seven parameters to control flash flood occurrence were calculated using AHP and overlaid in GIS. Flash flood risk hazard map of Hieu catchment is divided into 5 risk levels: very high (2.01%), high (20.32%), medium (43.78%), low (30.59%), very low (3.3%). A hazard map was produced to help local authorities implement land use planning that reflects the hazards, and prepare to increase disaster response capacity human and environmental resilience to flash floods.

Keywords: Flash food; hazard analysis; Analytic Hierarchy Process (AHP); Geographic Information System (GIS); Hieu catchment; Nghe An; Vietnam.

1. Introduction

Flash flood is a dangerous phenomenon occurring in many river basins in the world, typically associated with hot, summers and heavy convective rainfall (Taha et al. 2017). Flash flood incidence is perceived by residents of the subject province to be increased. An accurate and credible assessment is needed to minimize flood impacts and inform land-use planning (Youssef et al., 2011).

The factors that form flash floods include topography, rainfall, vegetation cover and human changes to watershed function. Saleh (1989) described a set of influencing factors, including rainfall characteristics, evaporation infiltration, drainage networks shape, drainage orders, hillslope drainage characteristics, and environmental and human changes. Minea (2013) identified factors that lead to flash floods in terms of physiographic characteristics from the catchment, including terrain, slope, profile curvature, land use and soil texture.

Smith (2003), in order to identify areas that promote flooding, suggests an indicator, called Flash Flood Potential Index (FFPI). Its estimation is realized using GIS techniques and is based on four grids overlapping the physiographic features of the hydrologic catchment (terrain slope, land use, forest density, and soil texture); these four are considered to have a major hydrologic influence on surface runoff processes and flood occurrence.

Remote sensing tools combined with hydrological, geomorphologic data can be combined in GIS to provide a flash flooding hazard based on our best current understanding of the influencing factors.

Seven parameters were selected as being the primary determinants of the hazard. The selected parameters were: soil properties, geology, drainage density, flow direction, land use, and density of vegetation. The study identifies high flash flood hazard areas using GIS and an analytic hierarchy process (AHP) method. The AHP is used for multi-criteria decision, based on expert weighting of the importance of influencing factors. The AHP gives comparison of design criteria and elements in a pair-wise technique of comparison of various parameters, decreasing the complexity of decision-making process and increasing its transparency to users. Hieu is a headwater catchment of the Ca River basin in Nghe An Province of Vietnam, and was selected as study area where flash floods are known to occur frequently, causing large losses of life and property.

2. Methodology

2.1. Study area

Hieu is a headwater catchment of the Ca basin. Hieu catchment covers an area of approximately 4.935km^2, forming a basin with a rounded shape. It can be divided into three sub-basin: Upper Hieu basin, Song Con basin and Ban Mong - Cay Chanh. Local conditions (e.g. lithology, relief and climate) along with the anthropic influence (land use) constitute conditional and control factors for runoff. Through northwest to southeast, it comprises a diversity of terrains, including Bu Khang formation (Proterozoi age), and Dong Trau formation rocks and deposites of Quaternary of Song Ca formation. The geology is primarily composed of granitic rocks, migmatites, gneisses, synorogenic granitoids, and gabbrodiorite intrusions that are further intruded by post-orogenic granites. Hieu River has a subtropical monsoon climate characterized by hot summers and warm winters,with average rainfall of 1630 mm, and a mild climate, with an annual average temperature of 16.3^{0}C. The highest is 2421m at Pu Hoat mountain. Heavy rainfall can produce flash flooding in Hieu River and its tributaries, primariliy during the summer months, from June to August. For the period 1990-2015 the average rainfall was 1593 mm in Upper Hieu basin, 1619 mm in Song Con basin, and 1587 mm Ban Mong - Cay Chanh, in which, Upper Hieu catchment account for the largest proportion of the area (North Central Vietnam Hydro-meteorological Center, Vietnam).

2.2. Data processing

The hierarchical analysis method supports expert group determination and weight of factors considered to be most important to the generation of flash flooding. After calculating the weight of the factors, integration in GIS will give us a flash flood index. Using the overlap tool in ArcGIS for re-edited maps, new maps were created and weighted to form a flash flood potential map. After being divided according to the appropriate influence levels will create a flash flood potential map. The whole process of developing a flash flood risk map for the river basin is shown in Figure 1.

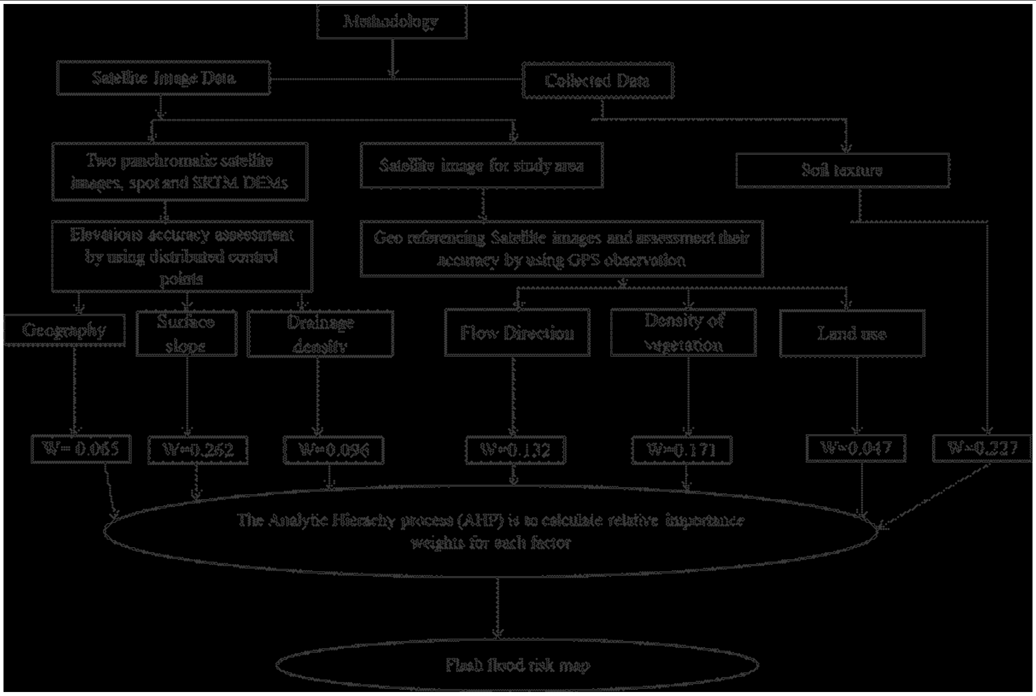

Figure 1. Methodology for flood hazard mapping (w = the weight of each flood causative factor)

AHP method was used to determine the important coefficient of parameters which were evaluated by designing a hierarchy of main criteria and sub-criteria. Multi-criteria decision problems were solved by establishing the pair wise comparison matrix, which reflect the relationship between the components of a level with properties of a higher level. This technique was implemented in a comparison matrix with two criteria at a time. The comparison of the selected parameters was determined for calculating weight of multicriteria in Hieu catchment. The matrix classification is based on 1-9 scale relative importance of pairwise criteria, where level 1 represents an equally important and level 9 shows extreme importance. Then Saaty method was applied to calculate weights and Eigenvalues. The efficiency criteria of AHP was evaluated by consistency relationship (CR) which is measured by equation CR = CI/RI where CI represents consistency index and RI represents random index.

An Analytical Hierarchy Process (AHP) is used to set-weight for factors causing flash floods: Geology, surface slope, drainage density, flow direction, land use, density of vegetation, soil influences (texture). Satty (1980) developed AHP to standardize as a support method decision making when there are many factors affecting flash flood. AHP provides a structure hierarchy by reducing the choice between many factors into pairwise comparison and priorities in each pair based on users' opinions. In AHP, factors are compared with other factors to determine the importance of each element in the general purpose. The value calculated for each pair of principle uses is published in Satty's standard measure. Details of the AHP method include a sequence of steps in order.

3. Results

3.1.Drivers of flash floods risks

3.1.1. Soil Influences: The process of hillslope runoff and flooding is dominated by soil surface conditions. Surface conditions affect the amount of slow runoff that do not contribute to flash flooding. Slow runoff influences include infiltration, surface depressions, vegetation cover, and evaporation. Soil type and structures are important factors in determining water retention and permeability characteristics of an area affecting the susceptibility to flash floods. Runoff from intense rainfall is likely to be more rapid and greater with clay soils than with sandy soils. In the study area, soil structure is mainly fine loamy to coarse loamy with relatively good permeability.

3.1.2. Geology: Geological factors determine the nature and characteristics of the catchments, including the soils, the risk of landslides, and the morphology of the river network.

3.1.3. Surface slope: the slope of a basin is considered to be of hydrological significance. Steep slopes have high surface runoff during rainfall that exceeds infiltration capacity, accelerating runoff delivery to channels and soil erosion. Sediment loads tend to be highest in dryer watersheds, where slopes are overgrazed and barren.

3.1.4. Drainage density

Drainage density (Dd) is the ratio of total length of streams of all orders to the basin area. Dd value refers to the proximity of the channel spacing; therefore, it is a quantitative measure for relief analysis, runoff potential and thus, in turn the drainage efficiency of the river basin (Yahya and Atef, 2017). A low drainage density indicates poor drainage basin with a slow hydrological response while a high drainage density shows a highly separated basin with a relatively rapid hydrologic reaction to rainfall (Melton. M.A., 1957). Drainage density is the one of the factors controlling the surface flow and consequently affecting sediment and water production from the basin (Chorley, 1969). High Dd values denote high flow and low penetration rates due to the presence of waterproof base materials, spare vegetation and hilly relief. Conversely, low drainage density implies low runoff, high infiltration and groundwater recharge (Yahya and Atef, 2017). Dd value for Hieu watershed range from 0.035 to 0.35.

3.1.6. *Flow direction:* The higher the slope of the flow, the faster the ability to concentrate water, causing a high risk of flood formation.

3.1.5. Land use: Surface is a factor that is also quite important for flash floods where soil is the main component of the surface. Rain is a necessary condition, while the surface is sufficient. Surface conditions dominate the process of flood formation. Surface affects the amount of flood runoff loss. Land use is a continuous, wide and varied process. It not only changes the physical properties of the soil, but also changes the cover, even the surface terrain. For instance, the smooth surface makes the runoff concentration time and runoff rate increase after construction. Consequently, land use will affect the process of forming flash floods. For urbanized, construction and traffic land, the surface is usually poured with concrete, the soil is tightened to prevent water permeability and increase the flow concentration. It is easy to generate flash floods. However, natural and plantation forest will not only prevent water but also absorb water well because of the humus upper layer, reducing the risk of flood formation. Natural forest land which occupies the largest area (55.81% of the area) can limit the flow, reduce the potential of flash floods.

3.1.6. Density of vegetation: Vegetation plays a role in stabilizing the surface thanks to the mechanical effects of the roots associated on soil components and regulating the sudden change in soil moisture. The coverage ratio protects the soil from erosion, helps regulate the flow, and transforms part of surface water into groundwater. When it rains, not all of the rain water falls to the forest ground and it is partially retained. The amount of water retained in the forest canopy depends on the factors: forest type, age, species composition, meteorological conditions, precipitation and rainfall intensity, vegetation cover, moisture, air temperature, weather and season. Generally, the amount of water retained in the canopy is about 30-50% of the total rainfall. The surface runoff depends on the length the slope, the intensity and duration of the rain, soil texture, and terrain. In the forest which creates favorable conditions to convert surface flow into seepage, the surface flow account for about 2% of the total rainfall. While in the area of compacted soil where humus, litter is destroyed, the surface flow is very large.

Low forest density will increase flood peaks, shorten the time of flood concentration. It helps to affirm that heavily exploited forests make bare surfaces one of the causes of flash flood formation. Deforested forests will enhance erosion and landslides, causing mud and flash floods. The protection of forest rehabilitation, afforestation and rational exploitation of forests on the surface of the basin in general and the watershed in particular is one of the measures to prevent and limit the destruction of flash floods. Most of the area has an average cover of 30-40%, which is relatively sensitive to flash floods.

3.2. Weight of parameters in the model

Based on the AHP principle the priority order of the elements will be compared one by one. The comparison results are shown in Table 1. The weight of the factors is determined by the average value in Table 2. Moreover, in order for the matrix to be reliable, the AHP has also calculated consistency ratio (CR) that is the ratio between consistency index (CI) and random index (RI).

Table 1. Comparing the priority of the elements

No	Criteria	Surface slope	Soil Influences	Density of vegetation	Direct Drainage	Drainage density	Geography	Land use
1	Surface slope	1	1.3	1.4	2.4	3.1	3.9	4.3
2	Soil Influences		1	1.5	1.9	2.9	3.4	3.8

3	Density of vegetation			1	1.8	1.8	2.4	3.0
4	Flow Direction				1	1.6	2.5	3.6
5	Drainage density					1	2.0	2.5
6	Geography						1	1.9
7	Land use							1

Table 2 Weight values of the elements

No	Criteria	Surface slope	Soil Influences	Density of vegetation	Direct Drainage	Drainage density	Geography	Land use	Weight
1	Surface slope	1							0.262
2	Soil Influences		1						0.227
3	Density of vegetation			1					0.171
4	Flow Direction				1				0.132
5	Drainage density					1			0.096
6	Geography						1		0.065
7	Land use							1	0.047

Table 3 RI index with n = 10

N	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	0.52	0.94	1.14	1.19	1.27	1.46	1.63	1.86

3.3. Generation of component maps

All parameters are were rated on a scale of 1-10, divided into 10 different categories for mapping. The sub-criteria are divided into different scales in which, score 1 for the lowest values and score 10 for point is the highest values (Table 4).

Table 4 Statistics results area of decentralized criteria and sub-criteria

Criteria	Sub-criteria	Acreage (ha)	Portion (%)	Score
Surface slope (°)	0-3	20702.54	8.68	1
	3-8	90108.5	19.74	3
	8-15	28509.8	3.46	5
	15-20	18509.12	1.14	7
	20-25	73503.3	2.29	9
	25-87	7285.39	0.11	10
Geography	- Quaterary formation (Aq)	1143.079	0.47	10
	-Limestone rock of La Khe formation (C1lk)	3049.531	1.26	2
	- Limestone rock of Muong Long formation (Cpml)	13127.38	5.42	4
	- Sedimentary rock of Nam Tan formation (d12nt1)	551.765	0.23	3
	- Sedimentary rock of Nam Can formation (d1frnc)	315.894	0.13	4
	- Sedimentry and metamorphic rock of Huoi Loi formation (d2hl)	76612.86	31.66	1
	- Granit rock of Dai Loc complex (gad1dt1)	28523.47	11.79	7
	- Granit rock of Dai Loc complex (gad1dt2)	567.6453	0.23	7
	- Eruptions rock of Song Ma complex (G/t2-3sm1)	728.625	0.30	1
	- Eruptions rock of Muong Hinh complex (jmh)	14119.7	5.83	6
	- Sedimentary and metamorphic rock of Song Ca formation (o3s1sc2)	33956.48	14.03	8
	- Sedimentary and metamorphic rock of Song Ca formation (o3s1sc3)	3300.699	1.36	8
	- Metamorphic and sedimentary rock of Bu Khang formation (pr3e1bk)	10299.82	4.26	5
	- Metamorphic and sedimentary rock of Bu Khang formation (pr3e1bk2)	6440.4	2.66	5
	- Quaterary formation (Q)	153.162	0.06	10
	- Eruptions rock of Huoi Nhi complex (s2d1hn)	862.664	0.36	3
	- Sedimentary rock of Dong Trau formation (T2adt1)	39734.66	16.42	7
	- Sedimentary rock of Dong Trau formation (t2adt2)	1945.665	0.80	7

	- Sedimentary rock of Dong Trau formation (t3nrdd1)	6575.73	2.72	9
Soil Influences	-Rock mountain	3712.409	1.56	1
	- River	708.5092	0.30	10
	- Fine loamy to Coarse loamy	163324.9	68.65	7
	-Gravelly loamy	48038.73	20.19	3
	- Coarse loamy	22114.3	9.30	5
Drainage density	0 - 0.035	8048.214	3.37	10
	0.035 - 0.07	18418.29	7.72	9
	0.07 - 0.105	28133.7	11.79	8
	0.105 - 0.14	38372.14	16.09	7
	0.14 - 0.175	34270.52	14.37	6
	0.175 - 0.21	32041.98	13.43	5
	0.21 - 0.245	31806.66	13.33	4
	0.245 - 0.28	23153.04	9.71	3
	0.28 - 0.315	13619.73	5.71	2
	0.315 - 0.35	10682.1	4.48	1
Flow Direction	1	18593.99	7.79	2
	2	41143.95	17.24	3
	4	22534.11	9.44	4
	8	30449.83	12.76	5
	16	28997.43	12.15	6
	32	18340.61	7.69	7
	64	40655.74	17.04	8
	128	37899.15	15.88	9
Land use	- Natural forest land	131716.6	55.81	1
	- Planted forest land	36339.71	15.40	3
	-Forest restoration land	26549.49	11.25	7
	-Agriculture land	15902.39	6.74	9
	-Settlement land	25514.13	10.81	10
Density of vegetation	0% - 10%	9855.491	4.13	1
	10% - 20%	13570.4	5.69	2
	20% - 30%	15131.92	6.34	3
	30% - 40%	165323.1	69.26	4
	40% - 50%	10271.68	4.30	5
	50% - 60%	11456.98	4.80	6
	60% - 70%	10639.12	4.46	7
	70% - 80%	1856.934	0.78	8
	80% - 90%	464.7491	0.19	9
	90% - 100%	120.1987	0.05	10

3.4. Flash flood risk map

Study results indicate that: very high risk of flash flood is 4796.23 (2.01%), high risk of flash flood is 48487.31 (20.32%), 104467.24 ha medium risk flash flood (43.78%), low (30.59%), very low (3.3%).

Very high risk area: About 4796.23 ha (2.01%) land falls in this category. This area has high slope (20-87^0), dry soil, rocky terrain, high drainage density, residential land, poor vegetation layer. Thus, it is necessary to take measures to warn people and not allow construction.

High risk area: About 48487.31 ha (20.32%) land falls in this category. Characteristics of this area are high slope, dry soil, barren land, rocky soil. These areas have a high risk of flash flooding. If they are residential areas, immigration is required.

Medium risk area: About 104467.24 ha land (43.78%) falls in this category. Characteristics of this area are gentle to moderate slopes (15°-20^0), forest restoration land, ferralitic soil and moderate coverage density. This area have an average flash flood potential. It can be arrange construction works and residential areas but there should be warning measures especially during rainy season.

Low risk area: Land in this category falls on gentle to stiff slopes (8°-15°), medium soil, moderate coverage density, at relatively low elevation. The area has low flash flood potential, reliable for human socio-economic activities.

Very low area: About 7874.42 ha land (3.30%) falls on this category. Characteristics of this area are gentle slopes (0°-8°), loamy sand, low drainage density, natural forest land, high coverage density. This area has a very low flash flood potential.

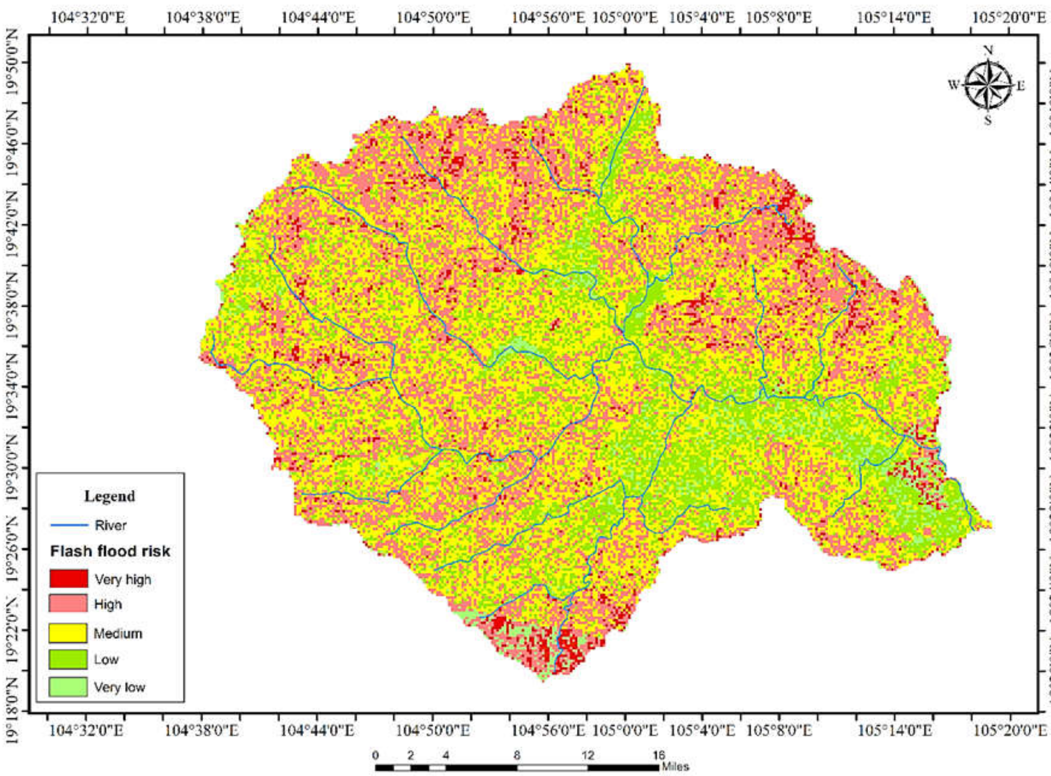

Figure 2. Map of flash flood risk in Hieu catchment

4. Conclusions and discussion

That integrating hierarchical analysis results into determinative factors in GIS method to develop yielded flash flood potential hazard maps that can be used in land-use and disaster response planning to reduce loss of life and property in Nghe An Province is an effective approach in researching natural hazards. The calculation process for mapping, risk partitioning and risk level of flash flood in Hieu catchment is carried out according to a logical and scientific assessment system based on GIS technology. Weighting for each element with quantitative values has removed quantified our subjective in the assessment of risk of flash flood hazard.

Using the AHP method has assessed the influence of seven factors were included, using the AHP method: geology, surface slope, drainage density, flow direction, land use, density of vegetation, soil influences (texture) on flash flood in Hieu catchment river with corresponding weight: 0.065; 0.262; 0.096; 0.132; 0.047; 0.171; 0.227. Flash flood risk hazard map of Hieu river basin is divided into 5 risk levels: very high (2.01%), high (20.32%), medium (43.78%), low (30.59%), very low (3.3%).

The present approach of AHP-GIS applied in this study area can help in the environmental protection management of other areas. However, this study has some limitations of suitability of selection of criteria for flash flood risk mapping depending on the local condition and variation in climatic condition.

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