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ORIGINAL ARTICLE

Multi-geospatial flood hazard modelling for a large and complex river basin with data sparsity: a case study of the Lam River Basin, Vietnam

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Abstract
Mapping flood hazard becomes a basic and crucial requirement to cope with and to mitigate flood risks. However, it is a big challenge to accurately construct a flood hazard map in the large and sparsity data basin. Here, we present a new approach to make a flood hazard map in a large and complex river basin with data sparsity based on a comprehensive analysis of the relationship between previous flood records and hydrometeorological and geographical features coupled with holistic knowledge. The results show that the AHP-GIS approach (an integrated GIS-based Analytic Hierarchy Process method) can produce more accurate and reliable flood hazard map in basins with complex geological and hydrometeorological features such as the Lam River Basin (LRB). The LRB was a high vulnerability to flooding with approximately more than 90% of the total area in this river basin was classified into moderate, high, and very high hazard of flooding. More specifically, high, and very high flood hazard area occupied nearly 30% of the total area and affected nearly 45% of households living in the basin. More noticeable, these high flood hazard areas were in small valleys along the rivers and streams running from high mountains in the southwest to the coastal region. Moreover, the study indicated that rainfall and slope were the main factors that influence mapping flood hazard and assessing flood risk in the steep slope areas.

Keywords Model selection · Flood hazard map · Flood risk zoning · Lam river basin · Vietnam

1 Introduction

Flooding is one of the most destructive natural hazards which has severe impacts on human lives and socio-economic development in many countries across the world (Al-Awadhi et al. 2018; Gissing et al. 2019; Shadmehri Toosi et al. 2020; Thapa et al. 2020; Tombrink 2017; Wei et al. 2018; Yonehara and Kawasaki 2020). Likewise, flooding is the most popular calamities in Vietnam causing many people dead, destroying thousands of houses as well as many infrastructure systems, and threatening sustainable socio-economic development (Luu et al. 2018; Vachaud et al. 2019). It was reported that floods have caused nearly 15,000 people dead and missing between 1989 and 2014. It also damages 1% of the nation's gross domestic product (GDP) annually (Luu et al. 2015).

Although flooding is a natural phenomenon and unavoidable event, its destructive losses and damages can be reduced by taking appropriate measures. It means that it is necessary to find out sustainable solutions for flood risk management. Therefore, great efforts have been made to mitigate flood damages worldwide. For example, many countries have conducted many "hard solutions" by constructing many hydraulic systems to protect residents, agricultural and industrial activities (Kieu 2011). Additionally, non-construction solutions so-called "soft solutions" have been applied widely to minimize the negative impacts of flooding. However, these

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solutions result in the efficiency of flood prevention and mitigation if we could provide a simple and straightforward understanding of flood hazards in a specific watershed.

Moreover, flood hazard information should be accurate, understandable, user friendly, and as accessible as possible to local authorities and residents. Therefore, the flood hazard map is widely used for these purposes (Dash and Sar 2020; Eini et al. 2020) since it provides visual and understandable information on the potentiality of flood occurrences and its damages. Flood hazard information can help decision-makers and natural disaster manager immediately taking appropriate solutions for reducing flood risks. For the last several decades, several methods have been widely used for establishing flood hazard maps including deterministic, heuristic, and statistical models (Cabrera and Lee 2020a; Di Baldassarre et al. 2010a; Eini et al. 2020; Gilany and Iqbal 2020; Guerriero et al. 2020; Ogato et al. 2020; Robinson and Botzen 2020; Skilodimou et al. 2019). These methods are mainly based on analyzing the relationship between flood events and the capability of flood occurrences in a certain watershed in considering flood controlling factors such as hydrometeorology, geology, geography, and human activities based expert knowledge, physical-based models, and geospatial analysis.

The abovementioned models successfully provided flood hazard assessment, but they also have some limitations. The deterministic models have the advantage of sticking to the basic physical laws, such as conservation laws; hence they are widely applied to predict hydrological processes related to rainfall-runoff generation and flood occurrences (Teng et al. 2017a). The deterministic models have a capability of simulating rainfall-runoff in a watershed and flow processes in the river and canal systems (Di Baldassarre et al. 2010b; Erena et al. 2018; Teng et al. 2017a). For the last several decades, many hydrological and hydraulic models have been developed and widely applied in flood modelling such as VRSAP (Hoanh et al. 2012), HEC-RAS (Ben Khalfallah and Saidi 2018; Mai and De Smedt 2017), Flo-2D (Erena et al. 2018), DHI MIKE (Meng et al. 2016; Zăinescu et al. 2019), ISIS (U.K.), TELEMAC (He et al. 2020; Li et al. 2019; Richet and Bacchi 2019), SRH-2D (Sakhaee 2020), Delft3D Flexible Mesh (Vo Quoc Thanh 2020) and CaMa-Flood (Shin et al. 2020). The outputs of these models are flood depth and inundation areas with a certain period. These results, coupled with geographical data, could help to provide the flood susceptibility, hazard and risk zonation mapping (Oubennaceur et al. 2019; Thapa et al. 2020). However, these models often require sufficient input data and time-consuming computation (Chau et al. 2005; Fenicia et al. 2014; Refsgaard 1997). Additionally, predictive results from deterministic models are often high uncertainties which may lead to misunderstanding on flood mapping (Teng et al. 2017b).

Heuristic models have been widely used to establish flood susceptibility, hazard and risk maps (De Brito and Evers 2016; Souissi et al. 2020), in which AHP (Analytic Hierarchy Process) has been widely used as it yields high accuracy especially in decision making with several criteria because of the hierarchy system and taking into account the complex interactions among the elements (Das 2018; Ghosh and Kar 2018; Skilodimou et al. 2019). In general, the heuristic model can provide an acceptable accuracy of mapping flood hazard with relatively low cost, simple data manipulation, easy understanding, rapid updating of data, and consistency in judgment (Kaur et al. 2017; Ouma and Tateishi 2014; Rahmati et al. 2016; Tehrany et al. 2014). Moreover, the method does not limit the number of input parameters (Feizizadeh et al. 2020; Institute of Transport Science and Technology 2012; Ouma and Tateishi 2014). Therefore, all factors contributing to flood creation can be used in the model calculation if there are enough data. A significant advantage of this method is highly flexible in which the flood hazard models can be easily adjusted both the number of parameters and their role. These good points create favorable conditions for changing and redefining the model when the incorrect results of the model are detected (Minh 2019). However, this approach has some limitations. Firstly, this model is based on expert opinions and thus may be subjected to cognitive restrictions with uncertainty and subjectivity (Cabrera and Lee 2019; Pourghasemi et al. 2016; Rahmati et al. 2016). Secondly, criteria weighting is mainly based on experts, which can cause a significant bias in mapping flood hazard if experts were chosen inappropriately. Finally, it was worth noting that data used in heuristic models are often derived from various sources with different formats, periods and resolutions. Therefore, it can be difficult to standardize the data for assessing the flood hazard and risks. Fortunately, these limitations may not cause a significant influence on the quality of ranking the flood causative criteria because these factors are weighted differently (Ouma and Tateishi 2014). For all the above reasons, the heuristic model should only be applied in large areas with less detailed input and output information while using this approach for small study area may cause a high error (Minh 2019).

Statistical models enable to quantitatively correlate between geo-environmental factors and past flood occurrences which are often prepared from field investigations and historical flood areas reports for the study area (Pradhan 2010). In other words, these models are often used to find a relationship between a dependent variable (flood hazard) and independent variables (influencing factors). For the last several decades, the statistical models have become a popular approach in mapping flood-prone areas. Many previous studies illustrated the efficiency of this approach for flood susceptibility, hazard, and risk assessment (Griffiths et al. 2020; Neri et al. 2020; Razavi

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Termeh et al. 2018; Tehrany et al. 2013; Wang et al. 2019). However, this method requires sufficient influencing factors and previous flood records which are not always available in many developing countries, including Vietnam. In addition, the statistical model considers the flood as a probabilistic phenomenon under certain conditions which does not provide any physically-based processes of flood occurrences in a certain watershed (Nguyen et al. 2020). Thus, the threshold values can be ignored, and the accuracy of the model also will be reduced (Minh 2019). The judgments of the benefit of each model and its weakness are shown in Table S1; this helps us to make a proper choice for each application.

With the advantages and disadvantages of the abovementioned models, the model used in the flood hazard zoning can be evaluated based on four criteria: easy to implement on GIS, easy to adjust (openness), area of research region, and data collection capability. As such, all three models are easily implemented on GIS due to data used in the form of vector or raster. However, in terms of openness and flexibility, the heuristic model is most appreciated because the number of parameters is unlimited, and it is easy for adjustment. However, the model scale is also an important factor in considering an appropriate approach for flood hazard mapping. For instance, the deterministic model is often applied for the small regions to accurate prediction of flood processes. In contrast, heuristics and statistical models can be used for a large river basin. Besides, data acquisition is also considerable in modelling methodology. Additionally, deterministic and statistical models often require sufficient data of geo-environmental factors and historical flood records which are not always available.

As flooding is a complex phenomenon, the accuracy of mapping flood hazards in a certain watershed depend not only on influencing factors but selecting methods, especially for data-sparse areas. In addition to the flooding, there are many studies on other environmental problems in data-sparse regions using readily available maps and remote sensing datasets. For example, in hyper-arid deserts, the in-situ datasets that are essential to characterize and mitigate different environmental problems are lacking and thus great efforts have been made to deal with these problems such as using hybrid geostatistical models and satellite data to map algal blooms (Elkadiri et al. 2016), integrating geophysical and topographic maps to assess flashflood hazards, groundwater elevation (Abotalib et al. 2019; El-saadawy et al. 2020) and landslide hazard prediction (Weidner et al. 2018). This study aims to provide a flood hazard mapping method in a large river basin with sparsity data to assess flood risks in a large river basin. The specific objectives of this study were to (i) select the appropriate approach for mapping flood hazard areas; (ii) establish flood hazard maps based on the proposed AHP-GIS method, and (iii) evaluate the flood vulnerability levels on the number of households in the study area.

2 Research Area

The present study is conducted in Lam river basin (LRB), lying at 103°14′E to 106°10′E and 17°50′N to 20°50′N in the North-Central coast of Vietnam (Fig. 1). It covers an area of 27,200 km^2 and 3.8 million people, accounting for approximately 8% and 2.3% of the total national area and population, respectively (Kieu 2015). Morphometrically, LRB has a complex terrain, consisting of mountainous, hills, valleys, rivers, streams, and plains. Topography shows a heterogeneously spatial distribution with steep mountainous areas in the upstream and middle parts of the basin and relatively flat areas along Land river system extending to the coast. Land-cover in the LRB is dominated by natural forest (689,077 hectares) which accounts for about 42% of the total area. The Lam river is quite narrow and highly steep in the upstream area, then widens in the middle LRB (from Con Cuong to Anh Son), and finally combines the Hieu River on its left side. In the downstream area, the Lam river flows through the plain and finally joins the La River on the right side (Hung et al. 2014). Climate condition in the basin is typically classified into subtropical monsoonal with two seasons, rainy (from April to September) and a dry (from October to March) (Tien Bui and Hoang 2017). The average yearly total rainfall ranges between 200 and 2400 mm with more than 85% occurring in the rainy season. The extreme rain often occurs in September with maximum daily precipitation reached to 800 mm/day in 2010 (Hung et al. 2014).

From the viewpoint of hydrology, the study area has a complex river network consisting mainly of Lam River and its tributaries (e.g., La River, Hieu River, Ngan Sau River, Ngan Pho River). Lam river system is one of the nine major river systems in Vietnam having a total annual flow of 23.1 km^3 with 18.6 km^3 from Vietnam and 4.45 km^3 from Lao PDR. However, yearly river flow distributes unevenly in the basin ranging from below 20 $l/s.km^2$ to above 80 $l/s.km^2$ on the Eastern side of the North Truong Son mountain range. As most of the rivers in this basin originate from Truong Son mountain ranges running throughout different terrains from steep areas in the Northwest to lowland areas in the Southeast regions leading to the high potentiality of flood occurrences (ADB 2005).

The flood events usually start in early July to late November on Lam River and its tributaries in the upstream and middle regions with total flood volume accounting for around 55–75% of the annual discharge. The maximum flow is usually taken place in July, August, and September while the lowest flow typically occurs from February to May. The maximum flood discharge can peak at 10 $m^3/s.km^2$ on the

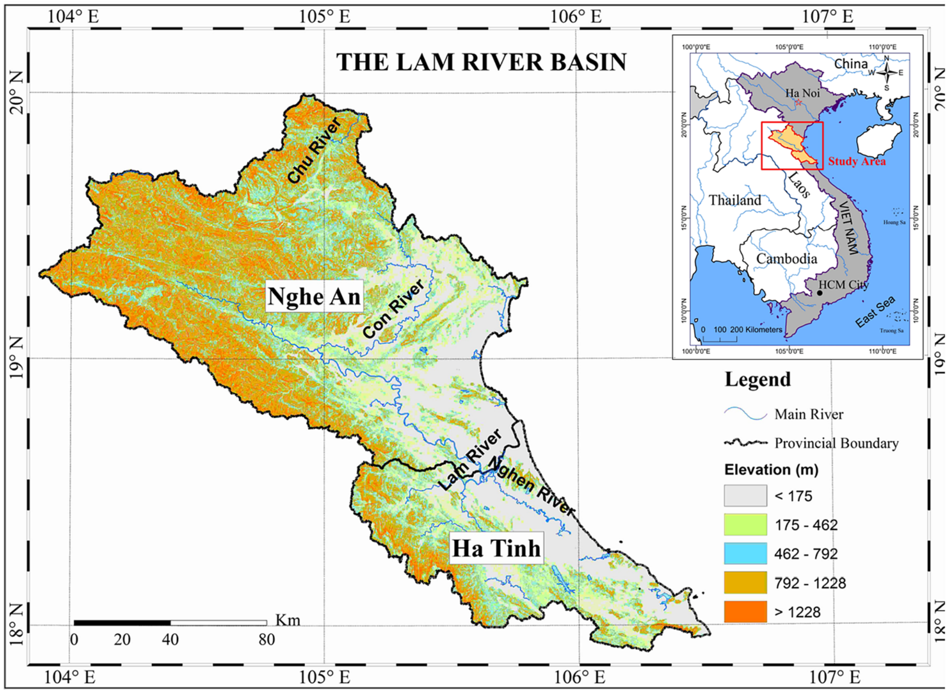

Fig. 1 The Lam River Basin, Vietnam

upstream and 0.6–6.6 $m^3/s.km^2$ in the central areas while the downstream areas are below 0.5 $m^3/s.km^2$. Historical flood event was observed at Dua station in September 1978 with a maximum flood discharge of 10,200 m^3/s. With complex geographical conditions coupled with heavy rainfall occurring in the short period of the rainy season, flooding in this basin has severely affected local livelihood and social-economic development in the basin annually (Kieu 2015). Therefore, mapping flood hazard is essential to prevent and mitigate flood damages servicing to sustainable socio-economic development in this important region of Vietnam.

3 Methodology and Data

3.1 Modeling Approaches

Flood hazard model is a function that represents the role, the degree of influence of the factors on flood hazard. In terms of mathematical, the flood hazard zoning is expressed in the following form:

$$Hz = f(Ft) \tag{1}$$

In which:

Hz: Flood Hazard

Ft: Factors affecting flood hazard

f: Function indicates the impact level of the factors affecting flood risk

For mapping flood hazard, it is necessary to set the requirements as (Minh 2019): (1) Easy to implement on GIS that requires a model with an f(Ft) function defined, in which the factors (Ft) are determined and can be presented in the form of a map; (2) Openness should consider as a crucial criterion due to the complexity of the flood risk zoning problem, parameters with their different levels of influence may or may not be considered so that the models (or the function f(Ft)) must be open for adding or removing parameters when necessary; (3) Scale of the study area is an important criterion, especially when assessing flood hazards in large basins, which is directly related to the scale of the research area, and (4) The capability of data acquisition is also an important requirement because flood data is dynamic and various, thereby it is not easy and simple to collect this data completely, accurately, and cyclically. So, the model should consider this possibility, especially for study areas having difficulties with collecting data.

3.2 Appropriate Model Selection for Zoning Flood Hazard

Delphi technique is widely used to select an appropriate flood hazard model. This method was conducted based on intensive interviews with expert groups in the fields of hydraulics, hydrogeology, geology, meteorological, water resources, environment, geodesy, soil, remote sensing, and GIS. Several rounds of questionnaires are sent out to the experts with a request to appreciate the model's ability in zoning flood hazards based on four requisitions, and the maximum score for each criterion is 5. Moreover, the performance capability will be assessed by dividing the degrees and the corresponding scores as follows:

Not implemented	0
Very difficult to implement/Very small area	1
Difficult to implement/Small area	2
Implemented on average/Average area	3
Easily implement/Large area	4
Very easy to implement/Very large area	5

After multiple rounds of information feedback, we took the median of their scores as the final score for each index and based on the above index and expert scores; the score quantifies the criteria as Table 1. These results help to make a worthy decision for assessing and choosing the proper method. The score calculated for the heuristic model is consistent with the advantages: easy to understand and highly accurate in determining the weight, unlimit the number of input parameters, performance capability on GIS, and easy to adjust. Therefore, the heuristic model in zoning flood hazard is the appropriate method that can be applied in the large river basins, small scale, and insufficient data collected. The quantification is made to compare criteria together easily but is not aimed at greater than or less than comparisons of the methods. Therefore, comparative benchmarks are also subjective (Minh 2019).

It is necessary to determine some parameters when the heuristic approaches use in the flood risk zoning such as the influencing factors (the causes of the flood), the weight (level of influence) of such factors, and the value of the influencing factors. Each parameter has a different determination method; Table 2 is the method for identifying those parameters.

Table 1 Criteria for evaluating models and respective scores

Models	Easy to implement in GIS	Openness	Area of study region	Data acquisition
Maximum score	*5*	*5*	*5*	*5*
Detreministic model	5	1	2	2
Heuristic model	5	5	5	5
Statistic model	5	4	5	2

In general, the application process of the heuristic model in the flood hazard-assessment consists of three steps as follows (1) Define the input parameters (influencing factors). The input parameters identified are relatively different due to the abundance of factors affecting the flood risk and the diversity of geographical areas; (2) Assess the importance of factors affecting the flood risk. The level of impact on the flood risk often depends on the research area, expert opinion as well as an assessment method; and (3) Calculate (or assign) the weight of the factors. The technique often used by scientists to calculate weights for the factors affecting flood risk is the Saaty's AHP method.

In the current study, the zonation of flood hazard in Lam river bain is carried out by the AHP (Analytic Hierarchy Process) method and GIS software. The flowchart of this process is presented in Fig. 2, which includes the selection of appropriate methods, the preparation of the flood causative factors, the determination of the importance degree of criteria, the creation of the maps of factors affecting flood hazard and the flood hazard zoning map.

3.3 The AHP method for mapping the flood hazard zone

The AHP is one of the suggestions for solutions involving the construction and application of multicriteria evaluation systems. It originated in the 1970s in the United States and was initially developed by Saaty in 1980s (Saaty 1988). The AHP can be defined as a process of hierarchizing a system to perform a wide-ranging assessment and final option of one of the alternative solutions to a problem. The method can also be deduced more broadly as a theory of measurement using quantitative and qualitative data (Pawel 2010). The purpose of AHP is to judge the given preferences for a specific aim by developing priorities for these alternatives and the preferred factors. The analytic hierarchy process is a structured technique for dealing with complex decisions, was applied in structuring the flood causative factors (Ouma and Tateishi 2014). An attribute hierarchy has at least three levels: (1) the overall goal of the problem on the top level; (2) multiple criteria that define alternatives in the middle level; (3) and competing alternatives in the bottom level.

Table 2 Methods for determining the parameters in the heuristic model applied in the flood hazard zoning

Criteria	Methods for determining
Factors affecting the floods	Experts, analyzing flood situation in the area
Weight (levels of influence of factors affecting floods)	Experts, experience, other studies, and analyzing flood situation in the area (pairwise comparison)
Value of factors affecting floods	Input maps

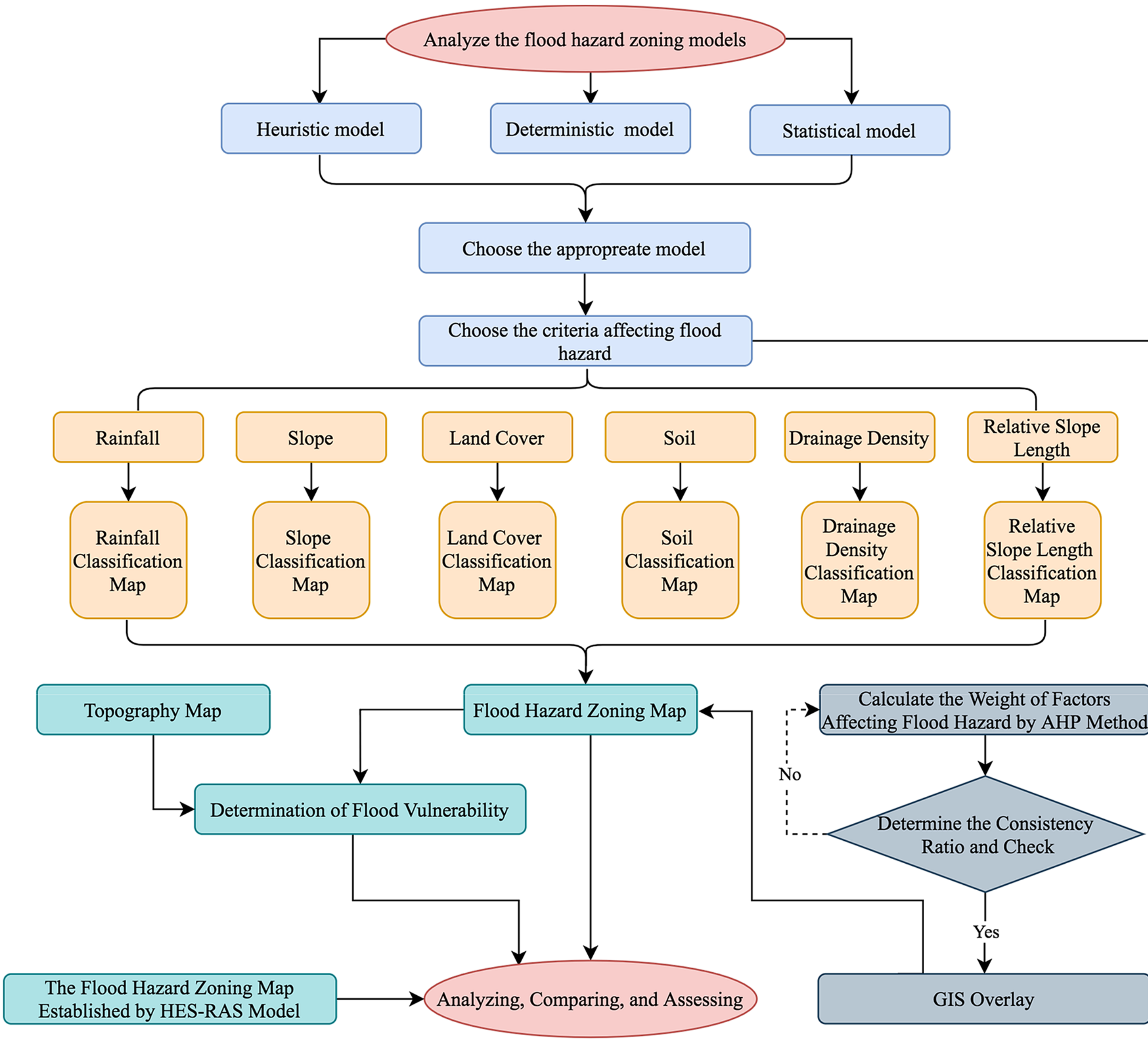

Fig. 2 Flowchart of research

In this research, level 1 shows the target of flood risk zone, level 2 represents the main criteria including rainfall, land use, slope, relative slope length, soil, and drainage density, and the final level shows the risk value (Dung et al 2020b).

The quality of the output of the AHP is strictly related to the consistency of the pairwise comparison judgments. The consistency index CI is given by Eq. (2):

$$CI = \left(\lambda_{\max -n}\right)/(n-1) \tag{2}$$

where λ_{max} is the largest eigenvalue derived from the paired comparison matrix, n is the number of criteria or sub-criteria.

The consistency of judgments is checked by the ratio of the CI and the random index (R.I.) (C.R.—consistency ratio), as expressed in Eq. (3). Saaty (1988) suggested that C.R. should be less than 0.1, although greater consistency does not mean greater accuracy (Saaty 1988).

$$CR = CI/RI \tag{3}$$

R.I. is the random index representing the consistency of a randomly generated pairwise comparison matrix. It is derived as an average random consistency index, computed by Saaty (1988) from a sample of 500 matrices that are generated randomly (Harker 1989; Jaiswal et al. 2014) as Table 3.

There are several studies on creating flood hazard maps in Lam river basin, Vietnam, such as (Anh et al. 2011; Duyen and Hai 2017; Hung et al. 2014; Kieu 2015). However, these

Table 3 Random Index (RI) used to compute consistency ratios (CR)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

studies focused only on the flash flood; the study area was a part of Lam river basin or only used hydrological data. This study implemented a flood hazard assessment through six criteria, including rainfall, slope, land use, drainage density, soil, relative slope length by integrated GIS-based AHP method. These elements then are made into the thematic maps which associated with the weights computed by AHP to establish the flood hazard zone map. The following Equation calculated the flood hazard potential index (FHI) based on factors' index:

$$FHI = R_W R_R + S_W S_R + RSL_W RSL_R + LU_W LU_R + DD_W DD_R + S_W S_R \tag{4}$$

where: R = rainfall, S = slope, RSL = relative slope length, $L.U.$ = land use, $D.D.$ = drainage density, S = soil, and the subscripts 'W' indicate normalized weights of each flood causative factor and the subscripts' R' are score ratings of the flood causative factor in each point.

3.4 Data used

To accurately map flood risk zones, the study uses primary data from different sources such as surveys, interviews, previous studies, authority reports, other documents, and the Internet. Also, we obtained available data from local and national authorities and agencies, including topography, land cover, administrative boundary, stream networks, hydrological stations, and the average annual rainfall data (Table 4).

All six criteria used in calculating the model contribute significantly to flood formation. Rainfall is a triggering factor in flood generation, and in the absence of this factor, no flooding will be generated. This means that floods are associated with extremes in rainfall**,** an overflow occurs after heavy rain when natural watercourses cannot carry excess water (Ouma and Tateishi 2014), so that rainfall is one of the primary causes of creating flood hazard. At any location, the higher rainfall amount usually increases a chance of flood-prone area (Cabrera and Lee 2019; Seejata et al. 2018).

Moreover, the slope plays an important role in recognizing the areas susceptible to flood occurrence; thus this factor is one of the crucial indicators of surface zones, which are highly prone to flooding. Steeper slopes make rapid flows, that means when the slope increases, then the flow velocity will also increase, the time of concentration decreases and, therefore, the danger of flooding decrease (Cabrera and Lee 2019). On the flatter surface, water is moving more slowly, collects longer and accumulates, so these areas are riskier concerning the occurrence of floods to the steeper surfaces (Gigović et al. 2017).

Besides, the drainage density, a fundamental concept in hydrologic analysis, is also a key parameter, which actively contributes to flooding occurrence. This indicator is defined as the ratio of the length of all channels within the basin and the area of the LRB (Elkhrachy 2015). A dense drainage system is a credible index of flow accumulation pathways and of regions with a high potential of creating flood hazard (Islam and Sado 2000). Drainage density is managed by permeability, erodibility of surface materials, vegetation, slope and time. This criterion is an inverse function of infiltration. Greater drainage density shows high runoff for basin area along with erodible materials, and less prone to flood (Wondim 2016).

Table 4 Geospatial data sources used for the flood hazard zone mapping in this Research

Factor	Source	Flood hazard relation	Reference
Rainfall	Annual average rainfall data Period 1961–2017	One of the most important factors contributes to flooding	(Minh 2019) (Fig. 3a)
Slope	Topographic map 1: 50,000 scale of Lam river basin	It affects the speed and flow of water	(Minh 2019) (Fig. 3b)
Drainage density	Topographic map 1: 50.000 scale of Lam river basin Map of river and stream system 1: 50.000 scale of Lam river basin	Floods can cause the presence of rivers in any area	(Minh and Dung 2018) (Fig. 3e)
Soil	Current land use map 1: 50.000 scale of Lam river basin	Soil type has a significant influence on water infiltration	(Minh 2017b) (Fig. 3c)
Land cover	Current land use map 1: 50.000 scale of Lam river basin	Each type of land cover has a different role in the flood event	(Minh 2017a) (Fig. 3d)
Relative slope length	Topographic map 1: 50,000 scale of Lam river basin	Relative slope length influences the time of water concentration	(Minh 2019) (Fig. 3g) (Dung et al. 2020a)

Furthermore, according to Dung et al. (2020a, b), water concentrates gradually in the process of moving along the slope from high to low and flood mostly only appear in the lower area so that the slope length factor will affect both floods as well as the possibility of flooding (Dung et al. 2020a). The further the slope length, the greater the volume of water, flow speed, and inertia force. That is, the longer the distance from the watershed line, the greater the kinetic energy of the runoff, the higher the speed of the flow leading to an enhancement in flood risk. It was noted that when the slope length increases, the tilted area will extend as well; hence the further the distance from the watershed divide is, the more the volume of water accumulated on the surface will be (Yongmei et al. 2011).

Also, soil type and texture remarkably affect the infiltration rate and the inter-relationship between surface and infiltration rate and eventually impact on flood susceptibility (Ahmed et al. 2020). According to Nyarko (2002), the type of soil is an essential element in determining the water holding capacity and infiltration properties of a region, which in turn influence the flood occurrence potential (Nyarko 2002). The probability of the occurrence of flood hazard increases with reduction in infiltration capacity of the soil, which causes an increase in surface flow. When the infiltration capacity of the soil or the rate of infiltration has been surpassed by the amount of water supplied such as rainfall, irrigation, etc., water will move downslope as runoff on sloping land and can lead to flooding (Ouma and Tateishi 2014).

In addition to the abovementioned factors, land cover is also one of the main factors that contribute to the occurrence of floods, influencing on runoff as well as the soil water storage capacity (Gigović et al. 2017). Because of the positive relationship between infiltration capability and vegetation density so as per susceptibility ranking, vegetated areas are less prone to flooding (Ahmed et al. 2020). Besides, there exists an inverse correlation between flood occurrence and vegetation density. Because rainfalls on the bare lands flow rapidly compared to the farmlands and forest zones; hence the urban areas with imperviable surfaces yield more violence runoff compared to the same regions overlayed by mass vegetation and forestry.

In this study, the drainage density map (Fig. 3e) (Minh and Dung 2018), relative slope length map (Fig. 3g), and slope map (Fig. 3b) (Minh 2019) were prepared using topographic map and river system map which derived from the Vietnam National Space Center. The land cover map (Fig. 3d) and soil map (Fig. 3c) were created based on the current land use map done by the Department of Natural Resources and Environment (DONRE) of Ha Tinh, Nghe An, and Thanh Hoa provinces and validated with field samples (Minh 2017a, b). Spatial distribution of rainfall was created using the inverse distance weight method (IDW) based on an average annual rainfall data obtaining from the National Centre for Hydrometeorological Forecasting (Minh 2019). All maps were prepared in a resolution of 100 m × 100 m using ArcGIS 10.2.

4 Results and Discussion

4.1 Flood conditioning factors assessment

In this study, the AHP method was employed to select the flood hazard potential criterion. For this purpose, the questionnaire surveys on comparison ratings on a scale of 1–9 were prepared and distributed to 50 knowledgeable people who are the national and international experts on the fields of geomatics, surveying, soil, geology, meteorology, hydrology, and water resources management. Basing on this scale, a pairwise comparison matrix of the criteria for the AHP process was established and shown in Table 5 (Dung et al. 2020b).

In the AHP method, while the pairwise comparisons of all the factors were considered as the inputs, the weights of these parameters were the outputs. Furthermore, the final weightings for the elements are the normalized values of the eigenvectors that are connected to the maximum eigenvalues of the ratio (reciprocal) matrix (Razandi et al. 2015).

A summary showing the various flood causative factors, their respective weights (Dung et al. 2020b), and how they are ranked according to their influence on flood events in the study area is presented in Table 6 (Minh 2019).

The consistency of pairwise comparisons, one of the limitations of the AHP method, were investigated. Also, the parameters of the comparison matrix are calculated in Table 7. The significant findings showed a C.R. value of 0.016, which fell much below the threshold value of 0.1, and it indicated a high level of consistency in the pairwise comparisons. Therefore, the normalized weights of factors are considered credible in this study.

The weights generated reveal that rainfall and slope, weighted 45.8 and 25.3, have the greatest influence on flood hazard in the study area. Relative slope length, drainage density, land use, and soil, on the other hand, contribute to the flood incidence in that order. This implies that the rainfall factor has the greatest impact on flood hazard, and the soil is considered as the factor formed the flood hazard at least. This result consistent with those of (Kieu 2015) who used the main factor analysis method in mapping flood hazard zone in Lam river. The author also admitted that rainfall and slope are two more important factors in generating flood hazard in the study area. Moreover, there are studies with various physical characteristics found that precipitation and slope also are the key factors leading to the formation of floods (Cabrera and Lee 2019; Seejata et al. 2018; Umar et al. 2019).

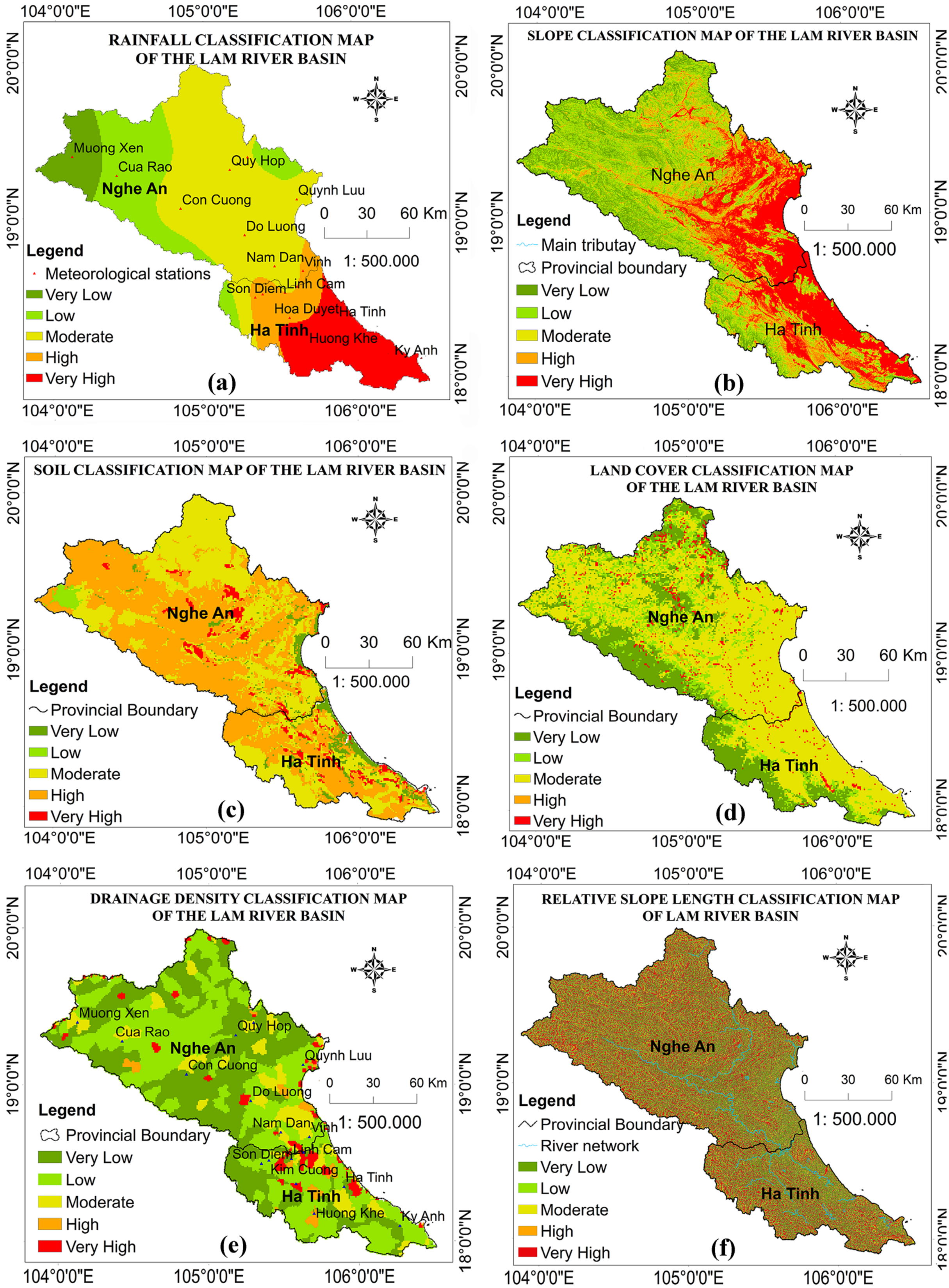

Fig. 3 Flood-influencing factors' hierarchy map of the Lam River Basin: (**a**) Rainfall, (**b**) Slope, (**c**) Soil, (**d**) Land cover, (**e**) Drainage density, (**g**) Relative slope length

Table 5 Pairwise comparison matrix

Criteria	Rainfall	Soil	Slope	Land cover	Drainage density	Relative slope length
Rainfall	1	7	3	5	5	5
Soil	1/7	1	1/5	1	1	1
Slope	1/3	5	1	5	3	3
Land cover	1/5	1	1/5	1	1	1
Drainage density	1/5	1	1/3	1	1	1
Relative slope length	1/5	1	1/3	1	1	1

Table 6 Decision hierarchy model for flood exposure indicators

Criteria	Weight (%)	Classes	Level of risk
Rainfall	45.8	< 1200 mm	Very low
		1201–1600 mm	Low
		1601–2000 mm	Moderate
		2001–2400 mm	High
		> 2400 mm	Very high
Slope	25.3	< 25°	Very low
		15.1–25°	Low
		8.1–15°	Moderate
		3.1–8°	High
		< 3°	Very high
Relative slope length	7.6	< 20%	Very low
		20.1–40%	Low
		40.1–60%	Moderate
		60.1–80%	High
		80.1–100%	Very high
Drainage density	7.6	D < 0.5	Very low
		D = 0.51–1.0	Low
		D = 1.01–1.5	Moderate
		D = 1.51–2.0	High
		D > 2.01	Very high
Land cover	7.1	Broadleaf Evergreen forest (high, medium, low reserve)	Very low
		Renew Forest, Mixed Bamboo Forest	Low
		Residential Land, Other Land	Moderate
		Shrubs, Agricultural Land, Bare Lands	High
		Cultivated Aquatic Land	Very high
Soil	6.6	C, Cc	Very low
		A, Ha, Hq, Hs	Low
		Fk, Fp,Fv, Nt, B, Ba, Bq, Fa, Fj, Fq, P, Pb, Pf, Py, R, Rdv, Rk	Moderate
		D, Fl, Fs, SM, Sj1Mi, Sj2Mi, M, Mi, Mm, Mn, Pg, Pj	High
		E, Nu	Very high

4.2 Flood hazard zoning map

The overlay was made for flood hazard zoning map from all thematic maps by incorporating the weight factor of the AHP analysis. The score for flood risk was estimated for this study using Eq. (4) and prepared in the form of GIS data. Finally, the scores were classified into four categories as low (1.28–3), medium (3.1–5), high (5.1–7), and very high (7.1–8.53) (Fig. 4) (Minh 2019).

Table 7 Parameters of AHP

Parameters	Value
Eigen value of a matrix (λ_{max})	6.11
The number of criterion (n)	6
Consistency index (CI)	0.02
Random index (RI)	1.24
Consistency ratio (CR)	0.016

It was found that the LRB is highly vulnerable to flooding because approximately 90% of the total area was classified from moderate level to very high flood hazard level (Fig. 4). More specifically, high to very high flood hazard areas account for more than 35% of toral river basin area which is located in the southwestern region with high rainfall, dense river density, long relative slope length and low permeability soil. Moderate flood hazard areas are in the North and East of the LRB where have low elevation and plains area, while low hazard areas were found in the Northwest of the river basin where has low rainfall and high terrain. These results were agreed with previous studies using the deterministic model such as HES-GeoRAS (Kieu 2015) in which low flood hazard belongs in upstream of Ca and Hieu rivers, whilst the high level of flood hazard is in the upstream of the Ngan Pho, La and Ca rivers. Especially, the highest flood risk was found in the Nam Dan station of Ca river branch, Son Diem station of Ngan Pho river tributary, and Hoa Duyet station of Ngan Sau effluent. Hence, the study results show that the high flood hazard areas are mainly concentrated locally in the western region of Ha Tinh province, while the other sites are not much. This region is not the highest hierarchy area for all factors. However, in this zone, in addition to the element with the greatest weight (45%), rainfall, the relative slope length factor is assigned the highest level of flood risk. Although the weight of the relative slope length is not much (7.6%), including this criterion will make the flood hazard map more accurate. This has been proven in the Research of (Dung et al. 2020a) when making the comparison of the outcomes of zoning the flood hazard in two cases: using five factors and using six parameters (adding the relative slope length alternative) to calculate the model.

The judgment upon the acceptability of the model could be made using external information from ground-truth data, namely data of typical flood events obtained in hydrological stations in the Lam river basin. In this study, data of three floods provided by government authorities concerning neighbourhoods influenced by floods in the output map indicating a significant coincidence, especially very high hazard areas (Table 8). Also, the results of comparing the risk level at some hydrographical stations on the map established by two methods indicate that the risk level is almost the same, namely, low and medium risk levels for the Do Luong and Nam Dan hydrological stations, very high and high-risk levels for Son Diem, Chu Le, and Hoa Duyet stations.

However, there are some differences in mapping flood hazard areas between our study and previous ones. In this study, for instance, Do Luong, Linh Cam, and Chu Le hydrological stations were classified into very high hazard

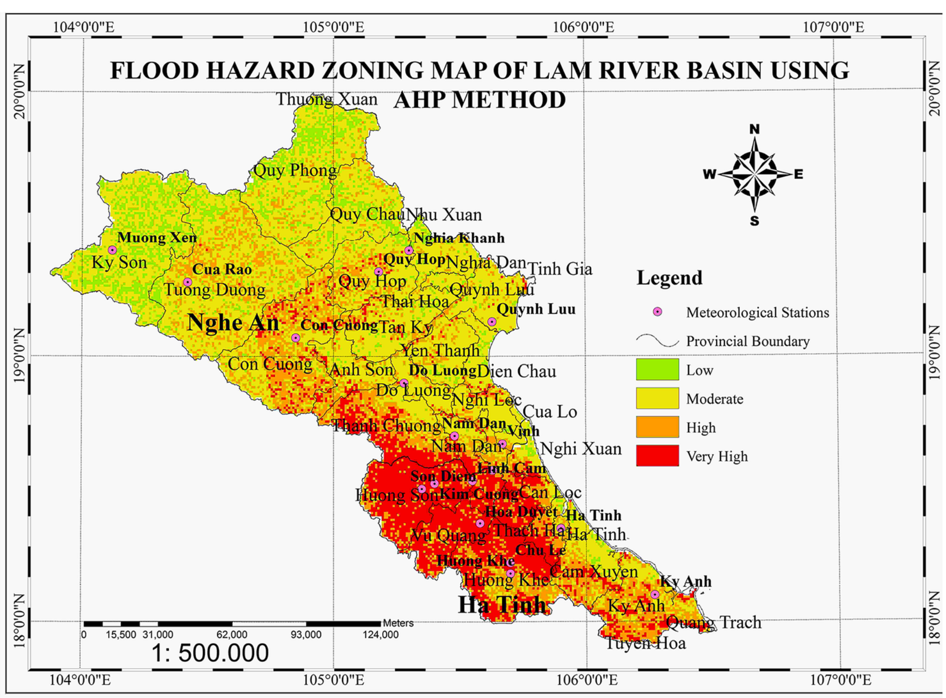

Fig. 4 The flood hazard zoning map of Lam river basin using AHP method

Table 8 The flood hazard levels in some hydrological stations in both methods

Hydro-logical stations	Flood event	The water level in reality (m)	Alarm level	Hazard level in reality	Risk level on a map using the AHP method	Risk level on a map using the HEC-RAS model
Son Diem	October 16–18, 2010	13.00	Over alarm level 3 (0.78 m)	Very high	Very high	Very high
	October 15–16, 2013	14.62	Over alarm level 3 (1.62 m)	Very high	Very high	Very high
	October 15–16, 2013	12.8	Over alarm level 3 (0.2 m)	Very high	Very high	Very high
Hoa Duyet	October 16–18, 2010	12,37	Over alarm level 3 (1.87 m)	Very high	Very high	Very high
	October 15–16, 2013	11.26	Over alarm level 3 (0.76 m)	Very high	Very high	Very high
	October 15–16, 2016	10.91	Over alarm level 3 (0.41 m)	Very high	Very high	Very high
Linh Cam	October 16–18, 2010	7.28	Over alarm level 3 (0.78 m)	Very high	Very high	***Moderate***
	October 15–16, 2013	5.74	Over alarm level 2 (0.24 m)	High	Very high	***Moderate***
	October 15–16, 2016	5.5	Alarm level 2	High	Very high	***Moderate***
Nam Đan	October 16–18, 2010	6.2	Over alarm level 1 (0.8 m)	Medium	Medium	Medium
	October 15–16, 2013	6.5	Under alarm level 2 (0.4 m)	Medium	Medium	Medium
	October 15–16, 2016	5.66	Over alarm level 1 (0.26 m)	Medium	Medium	Medium
Chu Le	October 16–18, 2010	16.56	Over alarm level 3 (3.06 m)	Very high	Very high	High
	October 15–16, 2013	14.42	Over alarm level 3 (0.92 m)	Very high	Very high	High
	October 15–16, 2016	15.64	Over alarm level 3 (2.14 m)	Very high	Very high	High
Do Lương	October 15–16, 2013	13.19	Under alarm level 1 (1.31 m)	Low	Low	Moderate
	October 15–16, 2016	13.00	Under alarm level 1 (1.12 m)	Low	Low	Moderate

compared to a moderate level in the previous study (Table 8) as our research integrated different input data with more detailed subbasin classification as well as using holistic knowledge to establish the flood hazard map. Moreover, in term of hydrological processes, the degree of flood concentration and the likelihood of occurrence of a flood in the study region do not always happen at the same time which may cause a reduction of flood risk when using the HES-GeoRAS model. It was also noted that water level at Linh Cam station depends not only Ngan Pho and Ngan Sau river, but also Ca river. In other words, when the Lam river mainstream flood appears in synchronization with the river floods of the Lam river system, the flood water level in the Linh Cam is very high and vice versa. Overall, the analysis reveals that AHP was much more accurate and reliable for flood risk analysis in this study.

4.3 Assessment of flood vulnerability

Flood vulnerability is the most important component of flood risk because susceptibility will be determined if exposure to a hazard constitutes a threat (Cabrera and Lee 2020b). Thus, assessment of flood vulnerability is important for decision-makers for planning and management activities.

Traditionally, deterministic models such as hydrologic/hydraulic models are commonly used to assess the potential areas of flood damage for given reappearance intervals (Ouma and Tateishi 2014). However, the acquisition of adequate data used for these models is not easy in the field. Also, according to (Ouma and Tateishi 2014), the AHP approach may be more pragmatic than the hydraulic-only models. Therefore, the AHP method is utilized to assess the flood vulnerability in this study. This method consists of two basic periods: firstly, the parameters causing floods are determined; secondly, the GIS-based AHP technique is applied, and these approaches are evaluated in identifying the flood hazard areas in various extents. From that, vulnerability levels will be assessed. There are several factors related to susceptibility and exposure, such as the land use, age and health of the population, the socio-economic activities, the quality of buildings and their location, etc. concerning flooding. In the case of socio-economic data sparsity, the number of households living in the Lam river basin is used as an indicator of the vulnerability assessment. Table 9 shows the number of households was affected by flood hazard in four different levels, including very high, high, moderate, and low in the whole of the districts in the Lam river basin.

It was estimated that approximately 94% of total households (132,732) fell into moderate to a very high-risk level of flooding. In comparison, just only 6% of families may not affect by flooding, indicating that the majority population in the LRB could frequently face flood events (Fig. 5). Specifically, high, and very high flood risk areas were found mainly in the mountainous and semi-hilly regions such as Huong Son, Thanh Chuong, Nam Dan, Thach Ha, and Do Luong (Fig. 5, Table 9). In contrast, low flood risk areas located not only in high mountainous regions such as Tuong Duong, Ky Son and Nghia Dan but in lowland regions such as Dien Chau and Quynh Luu. Lower flood risk was found in high mountainous areas may attribute to low population density while that of lowland areas maybe because of flood-control constructions preventing residents from flooding. However,

Table 9 The number of households affected by flood hazard at different levels

District	Hazard level				District	Hazard level			
	Low	Mode-rate	High	Very high		Low	Moderate	High	Very high
Cam Xuyen	397	3147	761	30	Do Luong	78	3116	842	333
Can Loc	30	487	642	1771	Hung Nguyen	0	1764	1919	101
Duc Tho	0	18	312	1241	Ky Son	805	1146	6	128
Ha Tinh	2	940	592	0	Nam Dan	14	3423	1821	1483
Hong Linh	0	0	497	116	Nghi Loc	279	9826	416	46
Huong Khe	0	635	2972	1791	Nghi Dan	520	4848	196	0
Huong Son	22	16	980	5158	Que Phong	857	2553	205	107
Ky Anh	62	1138	444	128	Quy Chau	546	843	28	0
Nghi Xuan	494	2236	286	94	Quy Hop	542	6430	1211	203
Thach Ha	495	3059	2506	1161	Quynh luu	601	9588	945	280
Vu Quang	0	15	103	871	Thai Hoa	59	1134	13	4
Anh Son	279	5746	802	114	Thanh Chuong	76	7150	6496	1781
Con Cuong	112	2361	943	158	Tuong Duong	283	2003	429	6
Cua Lo	140	842	2	0	Vinh	181	3391	1351	16
Dien Chau	705	5725	117	22	Yen Thanh	131	3969	188	15

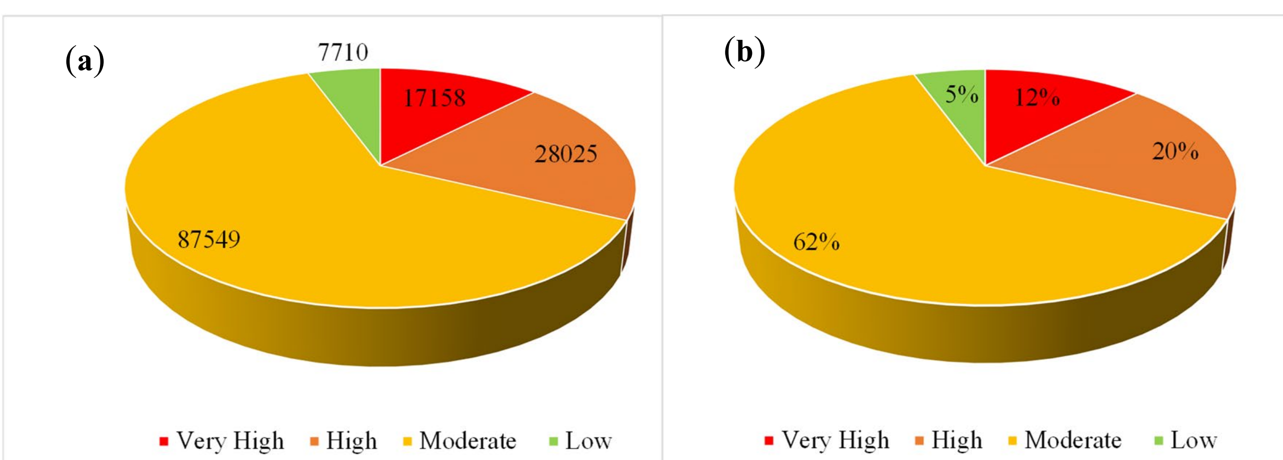

Fig. 5 The number (**a**) and percentage (**b**) of households affected by different levels of flood hazard

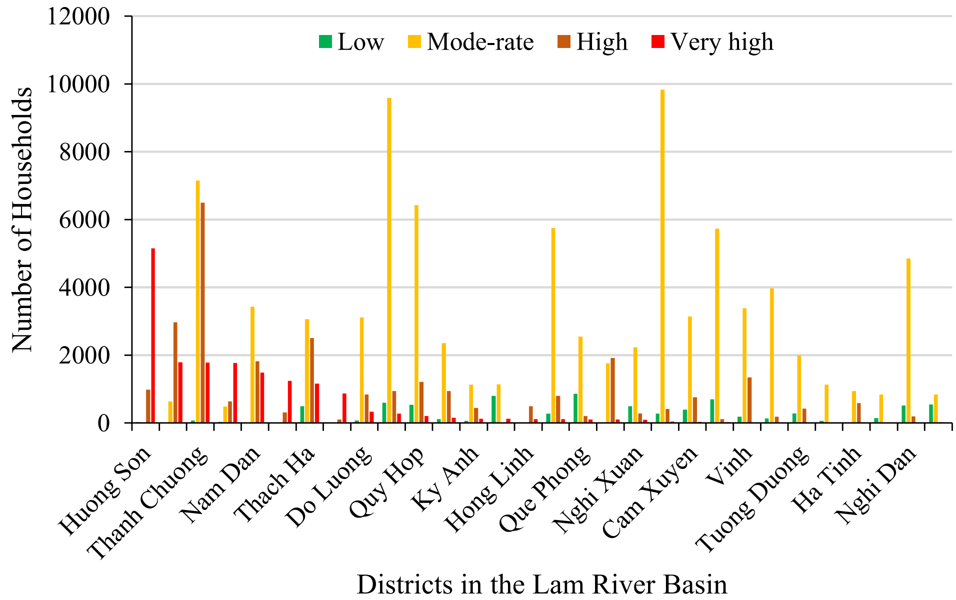

Fig. 6 The number of the household of each district is affected by flood hazard

it was worth noting that moderate flood risk intends taking place in the majority population (62%) living in plains such as Quynh Luu and Nghi Loc districts while having high drain density and dense population density with 9588 and 9826 family units, respectively. These results indicated high flood risks depend not only on geo-hydrometeorological conditions but population density and flood management strategies. The results of this research will contribute to flooding forecasting and early warning, and minimize flood disasters, reduce the overall impact of severe flood events and save lives and their properties (Fig. 6).

5 Conclusion

The main purpose of this study is to establish a flood hazard map in the large and complex river basin with data sparsity. In this respect, we developed a new approach to select a suitable method for mapping flood hazard in a large river basin with sparsity data. Six physical parameters were chosen to determine a weight of the relative importance using a pairwise matrix comparison of the AHP algorithm in which rainfall and slope are the main drivers of mapping flood hazard. Our major findings are summarized as follows.

- To create an accurate and reliable flood hazard map, the suitable methodology and integrate analysis of hydrogeological features coupled with holistic knowledge are crucial.
- High to very high flood hazard areas are often occurred in valleys along the rivers and streams in the transition areas from mountainous to lowland regions.
- High flood hazard and increased flood risk level are not always in the same areas because flood risk depends not only on geo-hydrometeorological conditions in a certain area but the population density and flood risk management strategies.
- Heuristic model, namely the AHP method coupled with GIS technique (AHP-GIS) is promising of making rather a reliable forecasting for flood extent and may be recommended for assessment of the flood hazard potential, specifically in data-lacking regions.

Future work to test AHP-GIS method based on analyzing the relationship between flood processes and physical conditions coupled with human activities is highly recommended.

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Declarations

Conflict of interest On behalf of all the authors, the corresponding author states that there is no conflict of interest.

References

Abotalib AZ, Heggy E, Scabbia G, Mazzoni A (2019) Groundwater dynamics in fossil fractured carbonate aquifers in Eastern Arabian Peninsula: a preliminary investigation. J Hydrol 571:460–470

ADB (2005) Irrigation and flood protection rehabilitation project (Loan 1259-VIE[SF]) in viet nam. Operations evaluation department Asian development Bank

Ahmed I, Maund K, Gajendran T (2020). Disaster Resilience in South Asia: Tackling the Odds in the Sub-Continental Fringes. Routledge,

Al-Awadhi T, Charabi Y, Choudri BS, Bani Oraba Y (2018) Flooding risk analysis: a case study of Muscat Governorate, Sultanate of Oman Human and ecological risk assessment. Int J 24:667–678. https://doi.org/10.1080/10807039.2017.1396441

Anh LH, Tuan TP, Thanh NN (2011). Flash flood hazard zoning in nghe an's mountain area The 4-th National Scientific Conference on Ecology and Biological Resources 5:1377-1381

Ben Khalfallah C, Saidi S (2018) Spatiotemporal floodplain mapping and prediction using HEC-RAS - GIS tools: case of the Mejerda river Tunisia. J Afr Earth Sci 142:44–51. https://doi.org/10.1016/j.jafrearsci.2018.03.004

Cabrera JS, Lee HS (2019) Flood-prone area assessment using GIS-based multi-criteria analysis: a case study in Davao Oriental. Philippines Water 11:2203

Cabrera JS, Lee HS (2020a) Flood risk assessment for Davao Oriental in the Philippines using geographic information system-based multi-criteria analysis and the maximum entropy model. J Flood Risk Manag 13:e12607. https://doi.org/10.1111/jfr3.12607

Cabrera JS, Lee HS (2020b) Flood risk assessment for Davao Oriental in the Philippines using geographic information system-based multi-criteria analysis and the maximum entropy model. J Flood Risk Manage 5:e12607

Chau K, Wu C, Li Y (2005) Comparison of several flood forecasting models in Yangtze River. J Hydrol Eng 10:485–491

Das S (2018) Geographic information system and AHP-based flood hazard zonation of Vaitarna basin, Maharashtra India Arabian. J Geosci 11:576. https://doi.org/10.1007/s12517-018-3933-4

Dash P, Sar J (2020) Identification and validation of potential flood hazard area using GIS-based multi-criteria analysis and satellite data-derived water index. J Flood Risk Manag. https://doi.org/10.1111/jfr3.12620

De Brito MM, Evers M (2016) Multi-criteria decision-making for flood risk management: a survey of the current state of the art Nat Hazards Earth. Syst Sci 16:1019–1033. https://doi.org/10.5194/nhess-16-1019-2016

Di Baldassarre G, Schumann G, Bates PD, Freer JE, Beven KJ (2010a) Flood-plain mapping: a critical discussion of deterministic and probabilistic approaches. Hydrol Sci J 55:364–376. https://doi.org/10.1080/02626661003683389

Dung NB, Minh DT, Ahmad A, Long NQ (2020a) The role of relative slope length in flood hazard mapping using Ahp And Gis (Case Study: Lam River Basin, Vietnam) GEOGRAPHY. Environ Sustain 13:115–123

Dung NB, Minh DT, Long NQ, Ha LTT (2020b) Weights of factors contributing to flood formation in the Lam River Basin Vietnam. J Southwest Jiaotong Univ 2:19–34

Duyen NTM, Hai HQ (2017) Hai H.Q. J Sci Technol Dev 2(20):249–254

Eini M, Kaboli HS, Rashidian M, Hedayat H (2020) Hazard and vulnerability in urban flood risk mapping: Machine learning techniques and considering the role of urban districts. Internat J Disast Risk Red 50:101687. https://doi.org/10.1016/j.ijdrr.2020.101687

Elkadiri R, Manche C, Sultan M, Al-Dousari A, Uddin S, Chouinard K, Abotalib AZ (2016) Development of a coupled spatiotemporal algal bloom model for coastal areas: a remote sensing and data mining-based approach. IEEE J Select Top Appl Earth Observ Remote Sens 9(11):5159–5171

Elkhrachy I (2015) Flash flood hazard mapping using satellite images and GIS tools: a case study of Najran City, Kingdom of Saudi Arabia (KSA) The Egyptian. J Remote Sens Space Sci 18:261–278

El-Saadawy O, Gaber A, Othman A, Abotalib AZ, El Bastawesy M, Attwa M (2020) Modeling flash floods and induced recharge into Alluvial Aquifers using multi-temporal remote sensing and electrical resistivity imaging. Sustainability 12(23):10204

Erena SH, Worku H, De Paola F (2018) Flood hazard mapping using FLO-2D and local management strategies of Dire Dawa city Ethiopia. J Hydrol Reg Stud 19:224–239. https://doi.org/10.1016/j.ejrh.2018.09.005

Feizizadeh B, Gheshlaghi HA, Bui DT (2020) An integrated approach of GIS and hybrid intelligence techniques applied for flood risk modeling. J Environ Plan Manage 4:1–32. https://doi.org/10.1080/09640568.2020.1775561

Fenicia F, Kavetski D, Savenije HH, Clark MP, Schoups G, Pfister L, Freer J (2014) Catchment properties, function, and conceptual model representation: is there a correspondence? Hydrol Process 28:2451–2467

Ghosh A, Kar SK (2018) Application of analytical hierarchy process (AHP) for flood risk assessment: a case study in Malda district of West Bengal. India Natural Hazards 94:349–368. https://doi.org/10.1007/s11069-018-3392-y

Gigović L, Pamučar D, Bajić Z, Drobnjak S (2017) Application of GIS-interval rough AHP methodology for flood hazard mapping in urban areas. Water 9:360

Gilany N, Iqbal J (2020) Geospatial analysis and simulation of glacial lake outburst flood hazard in Shyok Basin of Pakistan. Environ Earth Sci 79:139. https://doi.org/10.1007/s12665-020-8867-y

Gissing A, Opper S, Tofa M, Coates L, McAneney J (2019) Influence of road characteristics on flood fatalities in Australia. Environ Hazards 18:434–445. https://doi.org/10.1080/17477891.2019.1609407

Griffiths GA, Singh SK, McKerchar AI (2020) Flood frequency estimation in New Zealand using a region of influence approach and statistical depth functions. J Hydrol 589:125187. https://doi.org/10.1016/j.jhydrol.2020.125187

Guerriero L, Ruzza G, Guadagno FM, Revellino P (2020) Flood hazard mapping incorporating multiple probability models. J Hydrol 587:125020. https://doi.org/10.1016/j.jhydrol.2020.125020

Harker B (1989). The analytic hierarchy process: applications and studies

He Z, Jia L, Jia Y, He J (2020) Effects of flood events on sediment transport and deposition in the waterways of Lingding Bay, Pearl River Delta. China Ocean Coastal Manag 185:105062. https://doi.org/10.1016/j.ocecoaman.2019.105062

Hoanh CT, Phong ND, Trung NH, Dung LC, Hien NX, Ngoc NV, Tuong TP (2012) Modelling to support land and water management: experiences from the Mekong River Delta. Viet Water Internat 37:408–426. https://doi.org/10.1080/02508060.2012.706797

Hung NQ, Son NT, Anh TN, Kha DD (2014). Development and application of Flood Vulnerability Indies for commune level – A case study in Lam river basin, Nghe An province, Vietnam International Young Researchers Workshop River Basin Environment and Management Asian Institute of Technology, Thailand

Institute of Transport Science and Technology (2012). Research on the basis of applying GIS technology in the risk assessment of landslide for transport works in the northwest mountainous areas. Ministry level scientific research project

Islam M, Sado K (2000) Flood hazard assessment for the construction of flood hazard map and land development priority map using NOAA/AVHRR data and GIS–a case study in Bangladesh. Hydrol Sci J 45:337–357

Jaiswal R, Thomas T, Galkate R, Ghosh N, Singh S (2014) Watershed prioritization using Saaty's AHP based decision support for soil conservation measures. Water Res Manag 28:475–494
Kaur H, Gupta S, Parkash S, Thapa R, Mandal R (2017) Geospatial modelling of flood susceptibility pattern in a subtropical area of West Bengal. India Environ Earth Sci 76:339. https://doi.org/10.1007/s12665-017-6667-9
Kieu TD (2011). Research on large flood management in the Lam River basin PhD Thesis
Kieu TD (2015) Identifying a big flood, zoning big flood and preparing flood map fo warning big flood of Lam river basin. Ministry-level scientific research project
Li Z, Liu J, Mei C, Shao W, Wang H, Yan D (2019) Comparative analysis of building representations in TELEMAC-2D for flood inundation in idealized Urban Districts. Water 1:11. https://doi.org/10.3390/w11091840
Luu C, Von Meding J, Kanjanabootra S, Pham D (2015) A proposed flood risk assessment method for Central Vietnam. In: 5th International Conference on Building Resilience.
Luu C, Von Meding J, Kanjanabootra S (2018) Flood risk management activities in Vietnam: a study of local practice in Quang Nam province. Internat J Disaster Risk Red 28:776–787. https://doi.org/10.1016/j.ijdrr.2018.02.006
Mai DT, De Smedt F (2017). A combined hydrological and hydraulic model for flood prediction in Vietnam applied to the Huong river basin as a test case study water 9 doi:https://doi.org/10.3390/w9110879
Meng X-l, Liang X-J, Yan B-Z, Li W, Guo L-H, Feng B (2016) Optimizing schemes on dynamic control of reservoir normal elevation in flood season. Nat Hazards 81:1161–1175. https://doi.org/10.1007/s11069-015-2125-8
Minh DT (2017a) The application of GIS technology in establishing a land cover hierarchy map for zoning flood hazard in Lam river basin. Mining Industry J 5:37–40
Minh DT (2017b) The application of GIS technology to build a soil classification map following level of flood risk in Lam river basin. J Sci Nat Res Environ 16:68–74
Minh DT (2019). Research on the application of special modeling in zoning flood hazard in flood warning in Lam river basin. PhD Thesis Hanoi University of Mining and Geology
Minh DT, Dung NB (2018) Application of GIS technology to establish a drainage density hierarchical map for flood hazard zoning in Lam river basin. J Mining Earth Sci 59(6):32–42
Neri A, Villarini G, Napolitano F (2020) Statistically-based projected changes in the frequency of flood events across the US Midwest. J Hydrol 584:124314. https://doi.org/10.1016/j.jhydrol.2019.124314
Nguyen V-N et al (2020) A new modeling approach for spatial prediction of flash flood with biogeography optimized CHAID tree ensemble and remote sensing. Data Remote Sens 12:78. https://doi.org/10.3390/rs12091373
Nyarko BK (2002) Application of a rational model in GIS for flood risk assessment in Accra Ghana. J Spatial Hydrol 2:123–134
Ogato GS, Bantider A, Abebe K, Geneletti D (2020) Geographic information system (GIS)-Based multicriteria analysis of flooding hazard and risk in Ambo Town and its watershed, West shoa zone, oromia regional State. Ethiopia J Hydrol Reg Studies 27:100659. https://doi.org/10.1016/j.ejrh.2019.100659
Oubennaceur K, Chokmani K, Nastev M, Lhissou R, El Alem A (2019) Flood risk mapping for direct damage to residential buildings in Quebec Canada. Internat J Disaster Risk Red 33:44–54. https://doi.org/10.1016/j.ijdrr.2018.09.007
Ouma YO, Tateishi R (2014) Urban flood vulnerability and risk mapping using integrated multi-parametric AHP and GIS: methodological overview and case study assessment. Water 6:1515–1545
Pawel C (2010) Using the analytic hierarchy process in evaluating decision alternatives. Operat Res Decision 1:12–34
Pourghasemi HR, Beheshtirad M, Pradhan B (2016) A comparative assessment of prediction capabilities of modified analytical hierarchy process (M-AHP) and Mamdani fuzzy logic models using Netcad-GIS for forest fire susceptibility mapping Geomatics. Nat Haz Risk 7:861–885
Pradhan B (2010) Flood susceptible mapping and risk area delineation using logistic regression, GIS and remote sensing. J Spatial Hydrol 9:120–133
Rahmati O, Zeinivand H, Besharat M (2016) Flood hazard zoning in Yasooj region, Iran, using GIS and multi-criteria decision analysis. Geomat Nat Haz Risk 7:1000–1017. https://doi.org/10.1080/19475705.2015.1045043
Razandi Y, Pourghasemi HR, Neisani NS, Rahmati O (2015) Application of analytical hierarchy process, frequency ratio, and certainty factor models for groundwater potential mapping using GIS Earth. Sci Inform 8:867–883
Razavi Termeh SV, Kornejady A, Pourghasemi HR, Keesstra S (2018) Flood susceptibility mapping using novel ensembles of adaptive neuro fuzzy inference system and metaheuristic algorithms. Sci Total Environ 615:438–451. https://doi.org/10.1016/j.scitotenv.2017.09.262
Refsgaard JC (1997) Parameterisation, calibration and validation of distributed hydrological models. J Hydrol 198:69–97
Richet Y, Bacchi V (2019) Inversion algorithm for civil flood defense optimization: application to two-dimensional numerical model of the Garonne River in France. Front Environ Sci 7:120–143. https://doi.org/10.3389/fenvs.2019.00160
Robinson PJ, Botzen WJW (2020) Flood insurance demand and probability weighting: The influences of regret, worry, locus of control and the threshold of concern heuristic. Water Res Econ 30:100144. https://doi.org/10.1016/j.wre.2019.100144
Saaty TL (1988) What is the analytic hierarchy process? In: Mathematical models for decision support. Springer, pp 109–121
Sakhaee F (2020) Steady and unsteady flow simulation with SRH-2D. J Ocean Eng Sci. https://doi.org/10.1016/j.joes.2020.01.002
Seejata K, Yodying A, Wongthadam T, Mahavik N, Tantanee S (2018) Assessment of flood hazard areas using analytical hierarchy process over the lower Yom Basin Sukhothai Province. Proc Eng 212:340–347. https://doi.org/10.1016/j.proeng.2018.01.044
Shadmehri Toosi A, Doulabian S, Ghasemi Tousi E, Calbimonte GH, Alaghmand S (2020) Large-scale flood hazard assessment under climate change: a case study. Ecol Eng 147:105765. https://doi.org/10.1016/j.ecoleng.2020.105765
Shin S et al (2020) High resolution modeling of river-floodplain-reservoir inundation dynamics in the Mekong River Basin. Water Res Res 56:e2019WR026449. https://doi.org/10.1029/2019WR026449
Skilodimou HD, Bathrellos GD, Chousianitis K, Youssef AM, Pradhan B (2019) Multi-hazard assessment modeling via multi-criteria analysis and GIS: a case study. Environ Earth Sci 78:47. https://doi.org/10.1007/s12665-018-8003-4
Souissi D, Zouhri L, Hammami S, Msaddek MH, Zghibi A, Dlala M (2020) GIS-based MCDM – AHP modeling for flood susceptibility mapping of arid areas, southeastern. Tunisia Geocarto Internat 35:991–1017. https://doi.org/10.1080/10106049.2019.1566405
Tehrany MS, Pradhan B, Jebur MN (2013) Spatial prediction of flood susceptible areas using rule based decision tree (DT) and a novel ensemble bivariate and multivariate statistical models in GIS. J Hydrol 504:69–79. https://doi.org/10.1016/j.jhydrol.2013.09.034
Tehrany MS, Pradhan B, Jebur MN (2014) Flood susceptibility mapping using a novel ensemble weights-of-evidence and support vector machine models in GIS. J Hydrol 512:332–343

Teng J, Jakeman AJ, Vaze J, Croke BF, Dutta D, Kim S (2017a) Flood inundation modelling: a review of methods, recent advances and uncertainty analysis. Environ Model Softw 90:201–216

Teng J, Jakeman AJ, Vaze J, Croke BFW, Dutta D, Kim S (2017b) Flood inundation modelling: a review of methods, recent advances and uncertainty analysis. Environ Model Soft 90:201–216. https://doi.org/10.1016/j.envsoft.2017.01.006

Thapa S, Shrestha A, Lamichhane S, Adhikari R, Gautam D (2020) Catchment-scale flood hazard mapping and flood vulnerability analysis of residential buildings: the case of Khando River in eastern Nepal Journal of Hydrology. Reg Stud 30:100704. https://doi.org/10.1016/j.ejrh.2020.100704

Tien Bui D, Hoang ND (2017) A Bayesian framework based on a Gaussian mixture model and radial-basis-function Fisher discriminant analysis (BayGmmKda V11) for spatial prediction of floods. Geosci Model Dev 10:3391–3409. https://doi.org/10.5194/gmd-10-3391-2017

Tombrink G (2017) Flood events and their effects in a Himalayan mountain river: geomorphological examples from the Buri Gandaki Valley. Nepal J Mount Sci 14:1303–1316. https://doi.org/10.1007/s11629-016-4154-5

Umar NK, Abdullahi HS, Usman AK (2019) A multi-criteria decision support system in the analysis of flood risk and vulnerability mapping in Suleja, Niger state, Nigeria. In: Proceedings of the ICA. Copernicus GmbH, pp NA-NA

Vachaud G et al (2019) Flood-related risks in Ho Chi Minh City and ways of mitigation. J Hydrol 573:1021–1027. https://doi.org/10.1016/j.jhydrol.2018.02.044

Vo Quoc Thanh DR, van der Wegen M, Reyns J, Kernkamp H, Van Vinh G, Linh VTP (2020) Flooding in the Mekong Delta: the impact of dyke systems on downstream hydrodynamics. Hydrol Earth Syst Sci 1:189–212. https://doi.org/10.5194/hess-24-189-2020

Wang Y et al (2019) Flood susceptibility mapping in Dingnan County (China) using adaptive neuro-fuzzy inference system with biogeography based optimization and imperialistic competitive algorithm. J Environ Manag 247:712–729. https://doi.org/10.1016/j.jenvman.2019.06.102

Wei L, Hu K-h, Hu X-d (2018) Rainfall occurrence and its relation to flood damage in China from 2000 to 2015. J Mount Sci 15:2492–2504. https://doi.org/10.1007/s11629-018-4931-4

Weidner L, Oommen T, Escobar-Wolf R, Sajinkumar KS, Samuel RA (2018) Regional-scale back-analysis using TRIGRS: an approach to advance landslide hazard modeling and prediction in sparse data regions. Landslides 15(12):2343–2356

Wondim YK (2016) Flood hazard and risk assessment using GIS and remote sensing in lower Awash sub-basin. Ethiopia J Environ Earth Sci 6:69–85

Yonehara S, Kawasaki A (2020) Assessment of the tidal effect on flood inundation in a low-lying river basin under composite future scenarios. J Flood Risk Manag 1:e312606. https://doi.org/10.1111/jfr3.12606

Yongmei D, Xihuan S, Xianghong G, Shijun N, Juanjuan M (2011) Analysis of slope length on water soil erosion. In: 2011 International conference on consumer electronics, communications and networks (CECNet). IEEE, pp 2943–2946

Zăinescu F, Vespremeanu-Stroe A, Anthony E, Tătui F, Preoteasa L, Mateescu R (2019) Flood deposition and storm removal of sediments in front of a deltaic wave-influenced river mouth. Mar Geol 417:106015. https://doi.org/10.1016/j.margeo.2019.106015