




Article

Framework of Spatial Flood Risk Assessment for a Case Study in Quang Binh Province, Vietnam

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Abstract: Vietnam has been extensively affected by floods, suffering heavy losses in human life and property. While the Vietnamese government has focused on structural measures of flood defence such as levees and early warning systems, the country still lacks flood risk assessment methodologies and frameworks at local and national levels. In response to this gap, this study developed a flood risk assessment framework that uses historical flood mark data and a high-resolution digital elevation model to create an inundation map, then combined this map with exposure and vulnerability data to develop a holistic flood risk assessment map. The case study is the October 2010 flood event in Quang Binh province, which caused 74 deaths, 210 injuries, 188,628 flooded properties, 9019 ha of submerged and damaged agricultural land, and widespread damages to canals, levees, and roads. The final flood risk map showed a total inundation area of 64,348 ha, in which 8.3% area of low risk, 16.3% area of medium risk, 12.0% area of high risk, 37.1% area of very high risk, and 26.2% area of extremely high risk. The holistic flood risk assessment map of Quang Binh province is a valuable tool and source for flood preparedness activities at the local scale.

Keywords: flood risk assessment; flood risk management; flood risk map; historical flood mark; Quang Binh; Vietnam

1. Introduction

Rivers have always been used as a water resource for food and hygiene needs as well as for agricultural and industrial harvesting. Land use planning around the world is often linked to hydrology and water supply [1]. Alluvial plains are ideal places for the development of urban activities as they are

generally pleasant places to live and their flat topography allows for straightforward development [2]. However, rivers are subjected to variations of flow with periods of low water and high water which are often the origin of floods.

Floods cause serious harm to people and adversely affect socio-economic development around the world, especially in urban areas where the high risks of flooding are the consequences of urbanisation and urban development [3]. According to the EM-DAT reports, Asia has the highest number of floods and storms that caused severe impacts on humans spanning the period of 1900–2016 [4]. From 1996 to 2015, Vietnam was one of the most affected countries by floods and typhoons in Asia [5]. For example, a November 2017 typhoon caused an estimated 110 deaths and a loss of \$650 million (US) in the Philippines and Vietnam [6]. Vietnam is located in the tropical zone with unique characteristics, populations settle in low-lying coastal areas such as the narrow plains along the central coast of Vietnam, the Red River Delta, and the Mekong Delta, making it particularly vulnerable to floods [7]. Moreover, it has experienced a process of rapid urbanisation in recent decades. The urbanisation rate increased from 19.6% in 2009 to 36.6% in 2016 [8], particularly in riverine and littoral areas. With an increase in the frequency of extreme weather events, rapid urbanisation will increase risk, especially in flood zones. To counter the growing threat posed by floods, a range of effective adaptation strategies are needed.

In the face of flood risks, people have three options: withdrawal, resistance, or adaptation [9]. Withdrawal is only necessary when the risk of staying in place reaches an insurmountable level [10]. People mostly prefer resistance strategies—defensive developments such as embankments that allow, in most situations, the use of the exposed areas for evacuation [11]. Finally, adaptation to flooding is often designed into the planning of the flood-prone areas [12].

A predominance of resistance strategies in Vietnam feeds on a rationalist myth of risk control [13]. The economic pressure to turn natural resources to profit is intense, as in many developing countries which are growing rapidly. However, resources are often rare [14]. The paradox of strategies of resistance to natural hydrological hazards is that they invariably result in a multiplication of issues in flood zones, ultimately exacerbating risk [15]. Frameworks for natural hazard resistance strategies meet several difficulties, such as assessing risks and addressing uncertainties [16]. Appropriate and detailed flood risk map is undoubtedly an important tool for assisting planning authorities, informing residents living in risk areas, and improving emergency plans. To be useful in practice, these maps must have been designed to include flood marks, topographic data, exposure data, and vulnerability data.

In this context, there have been many studies on flood risk analysis in Vietnam with a variety of approaches [17–20]. However, there is still a lack of studies on holistic flood risk assessments at local scales. Detailed flood risk assessment maps can serve as a basis for defining mitigation and adaptation actions [21]. The three regions of Vietnam (the North, the Central, and the South) have different flood risks because of their geographical conditions. In the North, cascaded hydropower reservoirs in the Da river basin efficiently control floods. However, the North has high landslide risk during the rainy season [22]. In the South, flooding is caused by heavy rainfalls, tide, and sea-level rise [23]. The central region is characterized by a sloping topography, very narrow lowland plain, and long coastal line [24]. Therefore, the central coastal region of Vietnam is the most vulnerable, with flooding consistently affecting people's livelihoods and socio-economic development. Quang Binh province, which is in the central region and frequently affected by floods and storms, is selected as a case study in this study. In the province, urbanisation encroaches on rivers, which means that these parts of the city are located in exposed areas of floods. Severe floods in the city, as in 1999, 2007, 2008, 2010, 2013, and 2016 caused loss of life and property damage. However, there are still no specialised tools for assessing flood risks in Quang Binh province, especially in combination with flood exposure and vulnerability data. Thus, this study was undertaken to evaluate the actual impact of flooding on Quang Binh province using an innovative approach for flood risk assessment mapping. By combining flood mark data with flood exposure and vulnerability data, a flood risk assessment map for Quang Binh province was created. First, the area of inundation from flood marks and the topography was determined. Second, a flood exposure and vulnerability assessment framework for Quang Binh province with reference to flood

risk was developed. Finally, flood risk assessment was undertaken, and mapping developed for the province. This mapping could provide necessary information that can help local authorities and policy-makers to manage the risks of floods and to mitigate material and human damage in the context of flood hazards.

2. Research Area

Quang Binh is a coastal province in the North Central Coast located in the latitude from $17^{\circ}5'02''$ to $18^{\circ}5'12''$ North and longitude $105^{\circ}36'55''$ to $106^{\circ}59'37''$ East. This province is selected as a case study since it is one of the most flood-prone areas in Vietnam [7]. Recent hazardous flood events occurred in the year 1995, 1999, 2007, 2008, 2010, and 2016. The province has an area of 800 km^2 , an average population of 887,600 in 2018, and a coastal length of 116.04 km (Figure 1). The rainy season is from September to November, accounting for 80% of the total annual rainfall, often causing large-scale floods. The average annual rainfall is 2100–2200 mm. The average number of rainy days is 152 days. Meanwhile, the dry season is from December to August, which often causes drought. The average temperature is from $24\text{--}25^{\circ}\text{C}$, gradually increasing from the North to the South and decreasing from East to West.

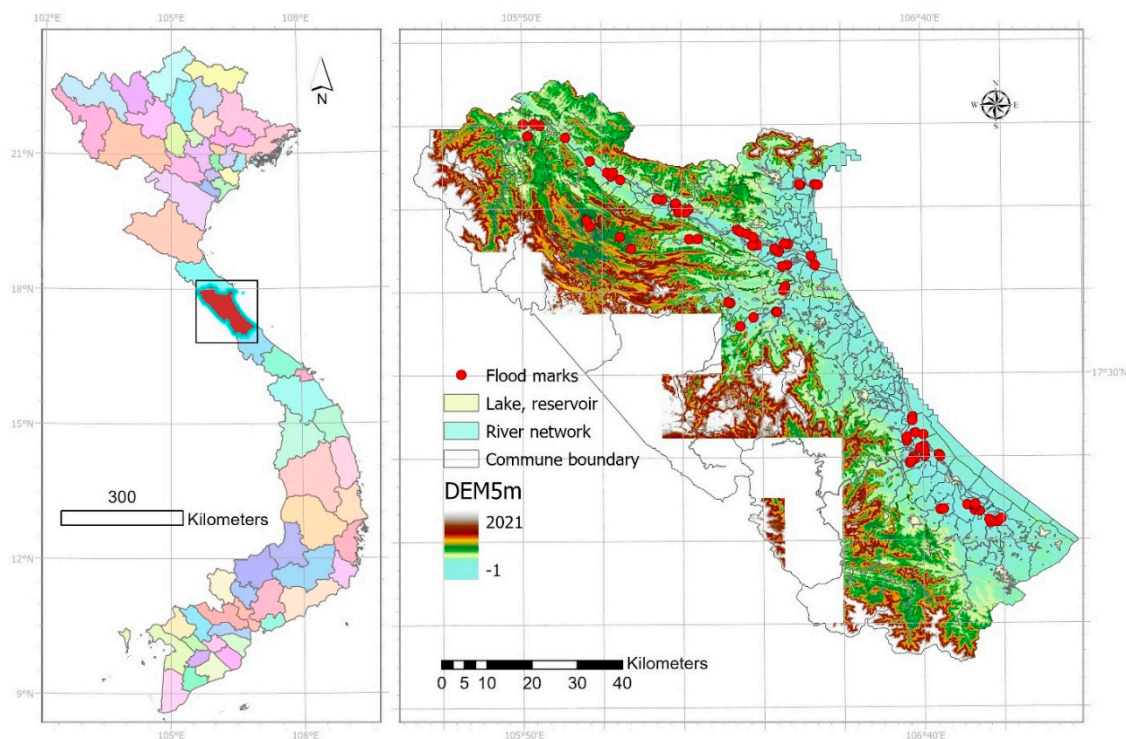


Figure 1. Location of flood marks for the October 2010 flood event in Quang collected by Quang Binh Centre for Hydrometeorological Forecasting.

Floods often occur from September to November every year. When storms and tropical low pressures occur together with heavy rains, high tides cause floods in the plains and flash floods in mountainous and hilly areas. The flood damage categories throughout the period of 1989–2015 of Quang Binh province are summarised in Figure 2. The October 2010 flood event was the largest and most damaging recorded event during the period, which caused 74 flood fatalities, 188,628 damaged houses, and many other damages. This flood event was chosen as the case study for this research.

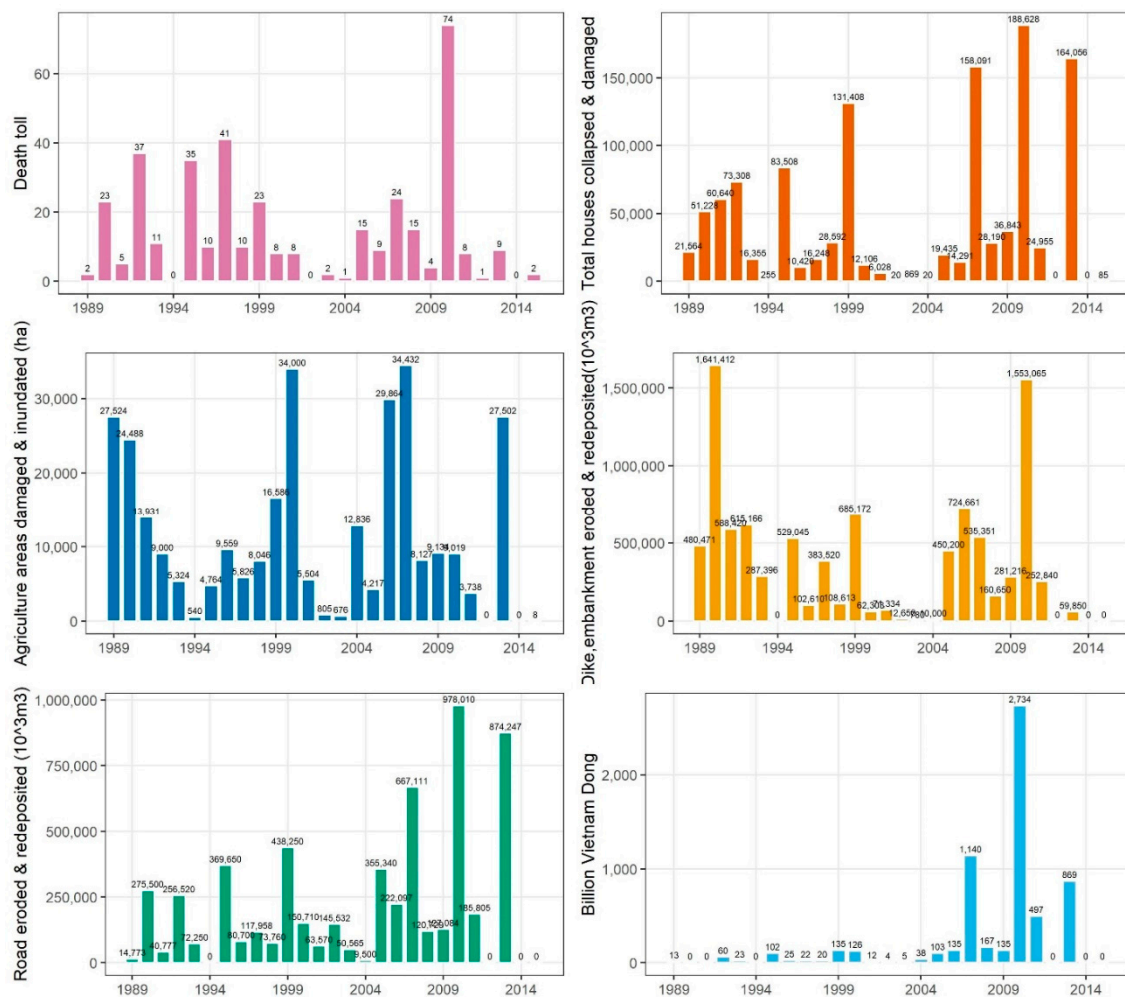


Figure 2. Flood damage data in Quang Binh province in the period of 1989 and 2015 (compiled from national disaster loss database provided by the National Steering Committee on Natural Disaster Prevention and Control).

3. Methodology

3.1. Flood Risk Assessment Framework

In response to the impact of floods around the world (including Vietnam [25]), this study proposed a unique approach to flood risk assessment. The concept of flood risk is often considered to involve the three elements of hazard, exposure, and vulnerability [26–29]. The combination is illustrated as in Equation (1). Flood exposure and flood vulnerability should be combined with flood hazard in assessing flood risk to provide a comprehensive resource reference for decision-makers in flood risk management [30]. Flood hazard can be determined as the potential for harm, loss, or damage of an event occurring at one location [28,31]. Exposure to flood hazard is defined by the potential for personal danger or property damage occurring during flood events [32,33]. Vulnerability is specified by the characteristics of a community that make it vulnerable to the damage of a flood hazard [26,34].

$$\text{Flood risk} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability} \quad (1)$$

This study aimed to assess the nature and extent of flood risk by analysing potential flood hazards and evaluating existing conditions of flood exposure and vulnerability that potentially harm people, property, and livelihoods as shown in Equation (1). The case study is the October 2010 flood event of

Quang Binh province, a hazardous flood event. The indicators or criteria of flood hazard, exposure, and vulnerability are adapted a variety of studies and based on an analysis of the existing data in Quang Binh province. The risk assessment result is integrated into a GIS framework to provide a flood risk map. The incorporation of flood risk assessment into a GIS framework has been applied at global, regional, and local scales in many recent studies [29,35–38]. Meanwhile, there have been a few applications of geospatial assessment tools, including GIS, to assess the flood risk in Vietnam [18–20,39]. The proposed flood risk assessment framework of this study is described in Figure 3. The framework presents the relevant relationships between the flood risk components, flood risk assessment, and flood risk management that is proposed for Quang Binh province. This is the first time that a holistic flood risk assessment combining hazard, exposure, and vulnerability indicators has been conducted in the study area.

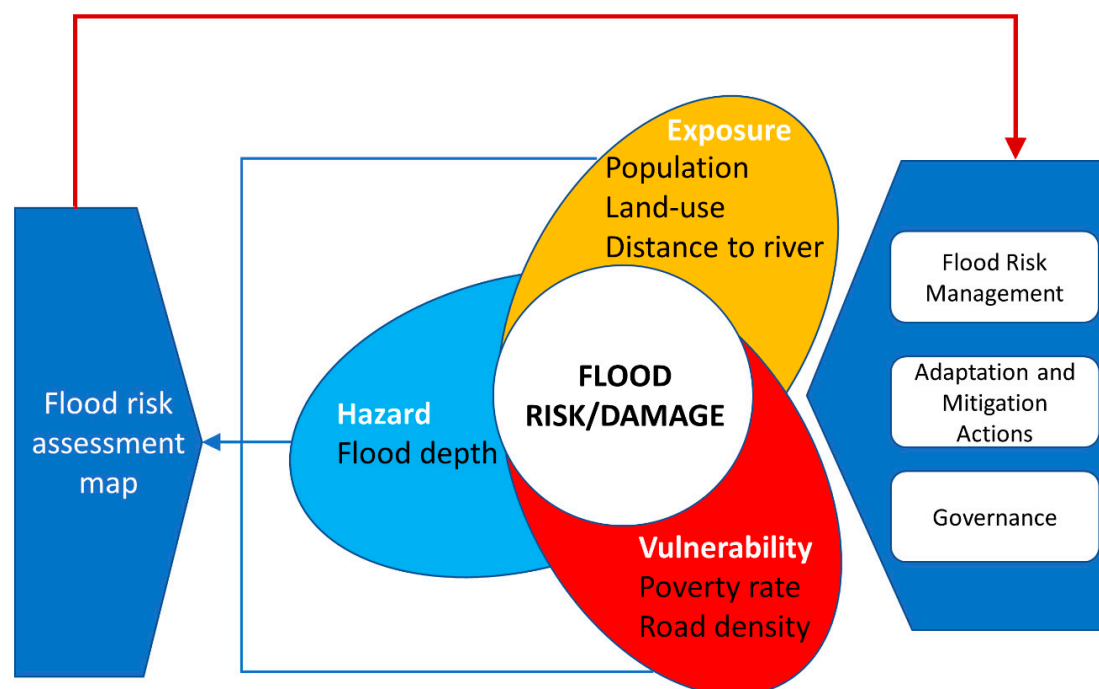


Figure 3. Flood risk assessment and management framework for Quang Binh province adapted from several studies [26,31].

In this study, based on a critical analysis of the available data in Quang Binh province, we used indicators applied to flood hazard, exposure, and vulnerability as shown in Figure 3. This framework might also assess the risk of flooding in other provinces in Vietnam. Historical flood marks, land use map, Digital Elevation Model (DEM), river network map, transportation network map, and social-economic data are used in this study for mapping flood risk assessment. Various GIS techniques are applied for analysing and overlaying data and establishing spatial relationships using distributed information. In addition, the Analytical Hierarchy Process (AHP) is applied to give spatial decisions and provides the weights to analyse the input indicators [40–43]. Flood risk assessment and flood risk mapping that include the analysis of flood hazard, exposure, and vulnerability can provide a useful resource for flood risk management, mitigation actions, and governance (Figure 3). The systematic approach and management aim to minimise potential harm and loss of flood risk.

3.2. Multi-Criteria Decision-Making Analysis Model

Multi-criteria decision analysis methods (MCDA) allow working with quantitative variables and are applied to decision-making processes. These methods have potential applications in solving flood risk management issues (e.g., formulating their preferences and measuring these priorities [44]).

Several popular MCDA are Analytical Hierarchy Process (AHP) [20], Analytic Network Process (ANP) [45], Compromise Programming (CP) [46], Multi-Attribute Utility Theory (MAUT) [47], Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) [48], Elimination et choix traduisant la re-alité (ELECTREE) [49], Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) [50], and Vlekkriterijumsko KOMPromisno Rangiranje VIKOR [51].

In this study, AHP is selected to weight criteria and subcriteria for flood risk assessment model. Several advantages of AHP include the direct opinion involvement, simple GIS integration [52], criteria and sub-criteria systematisation [53], and consistency in judgement [54]. Besides these advantages, this approach has three main limitations of subjective preference in the evaluation [55], a large number of pairwise comparisons [56], and vague criteria [57]. However, these shortcomings remain in almost MCDA methods [53,57].

AHP is a theory of tangible criteria measurement proposed by T. Saaty [58]. The weight of the criteria is evaluated through algorithms and pairwise comparison matrices. AHP basically supports the decision-making process by quantifying alternative priorities for decision-makers [56]. This is a powerful and flexible technique to support setting priorities and improving decision-making processes. This method has been widely used in many areas such as economics, planning, education, environment, transportation, resource allocation, and management [59,60]. More recently, it has been applied to flood risk assessment studies [42,45,61,62].

Figure 4 illustrates the AHP model used to assess the flood risk for Quang Binh province. The flood risk is assessed by the combination of flood hazard (flood depth indicator), flood exposure indicators of population density, land-use classification, and distance to river, and flood vulnerability indicators of road density and poverty rate. The AHP is performed by the following three main steps:

Step 1: Construct a hierarchical decision model as in Figure 4.

Step 2: Develop a paired comparison matrix for criteria or sub-criteria of the decision model as in Equation (2) based on subjective judgment and reciprocal judgement axiom.

Step 3: Obtain the relative importance or weights of criteria and sub-criteria.

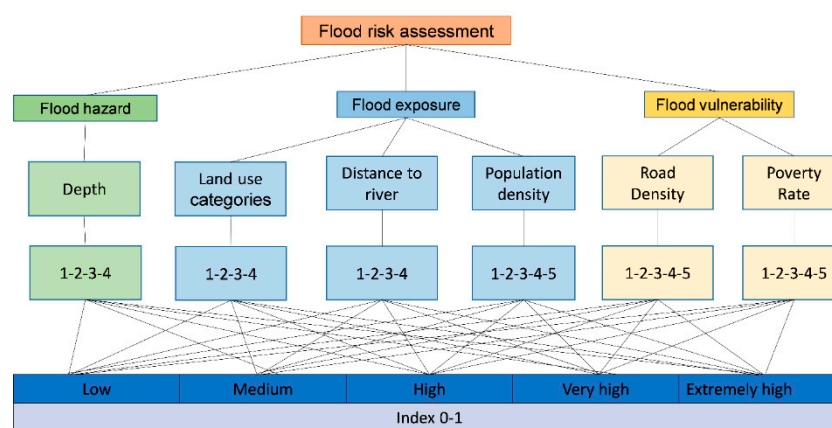


Figure 4. The hierarchy framework for flood risk assessment of Quang Binh province.

The paired comparison matrix in Step 2 is $A = [a_{ij}]$, $ij = 1, 2, \dots, n$. The entries a_{ij} is defined by reciprocal judgement rule, if $a_{ij} = a$, then $a_{ji} = 1/a$, $a > 0$ in Equation (2).

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \quad (2)$$

AHP operates by setting priorities for multi-criteria, which are judged by experts to derive the best decision [63]. The weights of criteria in AHP method rely upon the subjective judgment of several experts [64–67], or the author experience-based assessment [42,61,62]. In this study, we applied the author experience-based assessment. We also referenced the related studies which used the AHP to assess flood risk criteria [42,55,57,64–67].

3.3. Data Used

The historical flood in October 2010 in Quang Binh resulted in 74 deaths, 210 injuries, 188,628 flooded properties, 9019 ha of submerged and damaged agricultural land, and widespread damage to canals, levees, embankments, and road (see Figure 3). The flood frequency of 2010 flood event was estimated at 5% or 20 years of return period at Gianh river basin, and at 2% [68] or 50 years of return period at Nhat Le river basin [69]. Flood marks of 2010 flood event were collected by Quang Binh Centre for Hydrometeorological Forecasting. Flood marks were mainly distributed along Gianh and Nhat Le river basins, which are frequently flooded areas of Quang Binh province. The flood mark data then were integrated with a high-resolution DEM to establish flood inundation map. The DEM was collected from the Department of Surveying and Mapping, Vietnam.

Three criteria were selected to estimate flood exposure: land use categories, population density, and distance to the river. The land use map was provided by Quang Binh Environment and Natural resource Department. The land-use categories include residential areas, construction areas, transportation areas, mining areas, agricultural areas, grassland, water bodies, forest, plants in residential areas, woodland, and bare soil. In this study, the land use criterion was used to estimate flood exposure. Land use categories were reclassified into four classes: homestead and built up, agriculture land, forest and vegetation, and water bodies. The classification is often used for flood risk assessment models [42,43]. Population density is the most important criterion in flood exposure analysis since it is determined by human settlements. This data was collected in the 2019 statistical yearbooks of eight districts of Quang Binh province. More densely populated areas are at higher risk when floods occur [10]. The distance to rivers is taken from a river network map using Euclidian distance tool in ArcGIS software. People living near river systems are also at higher risk than others [42].

Two criteria were used in the present study to analyse flood vulnerability: poverty rate and road density. The poor are more vulnerable to natural hazards [14] and the poverty rate is often considered a structural cause of flood vulnerability. The poverty rate data was collected in the 2019 statistical yearbooks. Roads or transportation system play an important role in disaster response activities (e.g., evacuation) and recovery activities [70]. Many other criteria could be added to assess flood vulnerability, such as healthcare facilities, disabilities, income, gender, age, and adaptive indicators. However, such data is not currently available in the research area.

4. Results

4.1. Flood Inundation Map

This study used flood mark data from the October 2010 flood event and a 5 m resolution DEM to create a flood inundation map using spatial analyst techniques. The flood inundation map in Figure 5 is the result of the geospatial modelling techniques which was established in the study of Luu et al. [20]. The flooded areas are mostly located close to and along Gianh and Nhat Le river basins including Nhat Le, Quang Ninh, Quang Trach, Bo Trach, and Tuyen Hoa districts. The total flooded area in the 2010 flood event in Quang Binh is 68,534 ha, in which 3372 ha of ≤ 0.5 m, 6623 ha of 0.5–1.0 m, 15,334 ha of 1.0–2.0 m, and 43,205 ha of > 2.0 m. Flood hazard increases with the depth of inundation.

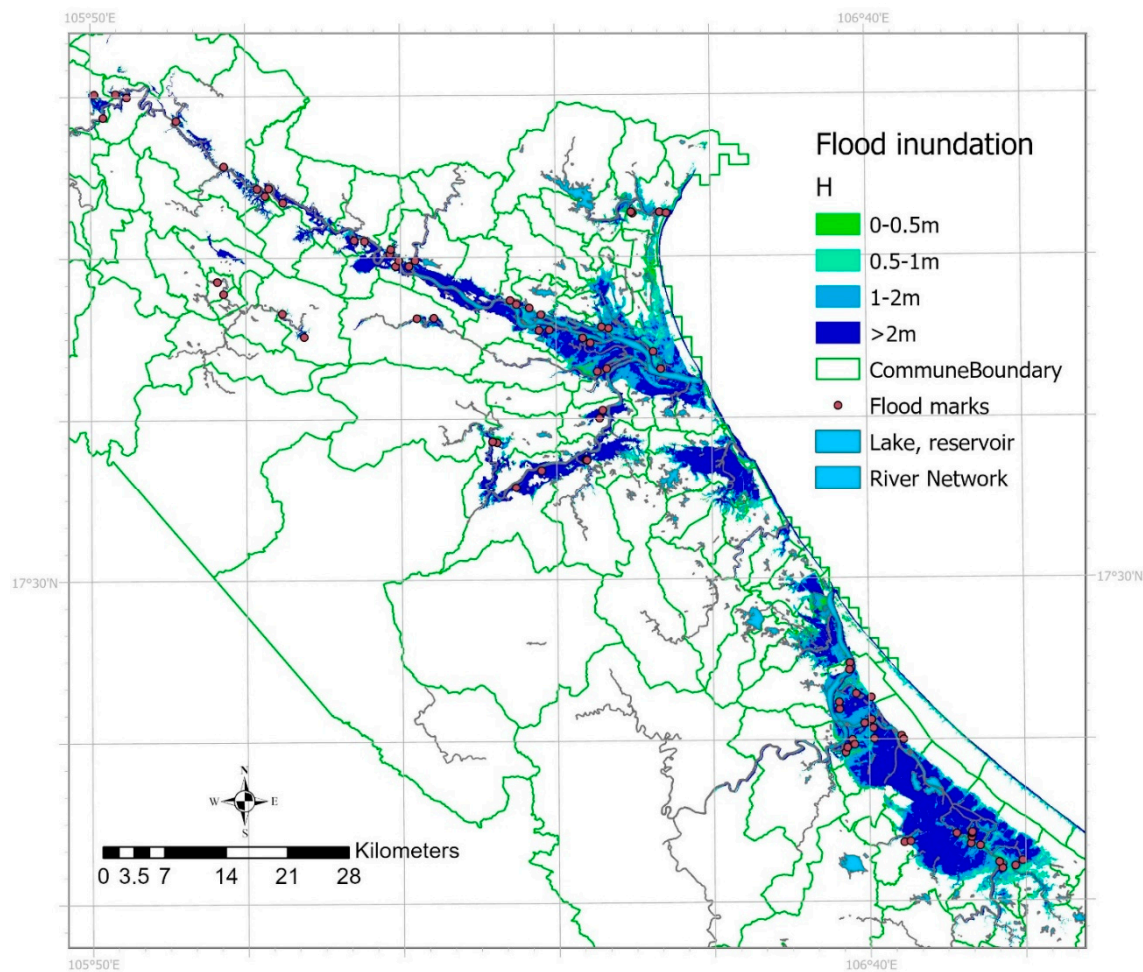


Figure 5. Inundation map of the October 2010 flood event in Quang Binh province which was built from flood marks and high-resolution DEM.

4.2. Flood Exposure Analysis

Flood exposure criteria, including land use categories, population density, and distance to rivers criteria are shown in Figure 6. The weights of criteria and sub-criteria are derived from the AHP model (Figure 4). We used Super Decision software [71] to calculate AHP algorithms based on subjective judgements. The distance to rivers is acquired from river and stream network data. It is classified into four categories: less than 1 km from river systems, 1–2 km, 2–3 km, and greater than 3 km. The closer it is to rivers, the more dangerous it is when exposed to floods. The higher score is given to closer distance to the river system. The land-use categories are reclassified into agricultural land, homestead and built-up, water bodies, and forest and vegetation. The potential impact of flooding is very high on residences and infrastructure involving people, so the relative weight is set to be the highest for the homestead and built-up category. The second highest weight is achieved for agriculture land because it is linked to the livelihood of the communities. The forest and vegetation and water bodies have the lowest weights since they do not pose a threat to people. The population density is the most crucial criterion since it is directly linked to people. The higher the population density is, the higher the weight is distributed (Table 1).

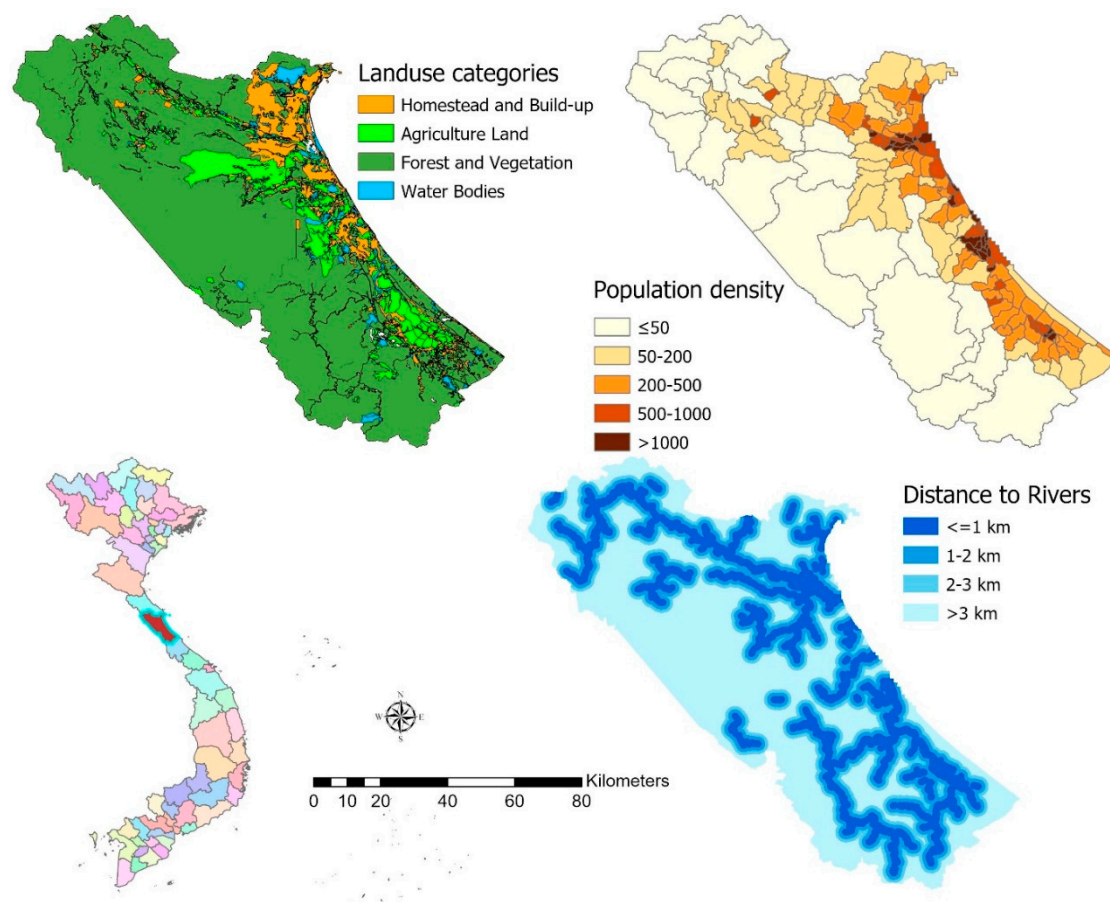


Figure 6. Flood exposure criteria distribution, including land use categories, population density, and distance to rivers.

Table 1. AHP model for flood exposure criteria.

Component	Criteria	Weight	Sub-Criteria	Weight
Flood exposure	Population density (person/km ²)	0.53961	≤50	0.07138
			50–200	0.10766
			200–500	0.16732
			500–1000	0.25904
			>1000	0.39460
	Distance to rivers (km)	0.29696	<1	0.51701
			1–2	0.32894
			2–3	0.10779
			>3	0.04626
	Land-use category	0.16342	Agricultural land	0.27365
			Homestead and built-up	0.49179
			Forest and vegetation	0.12295
			Water bodies	0.11160

4.3. Flood Vulnerability Analysis

Flood vulnerability criteria, including poverty rate and road density, are shown in Figure 7. The weights of criteria and sub-criteria are derived from the AHP model (Figure 4). We used Super Decision software [71] to calculate AHP algorithms based on subjective judgements. The poverty rate and flood vulnerability are interrelated in Vietnam [18]. A higher poverty rate receives a higher weight for flood vulnerability. The road density is derived from intersecting transportation network and commune boundary. The lower road density area has a higher vulnerability score (Table 2).

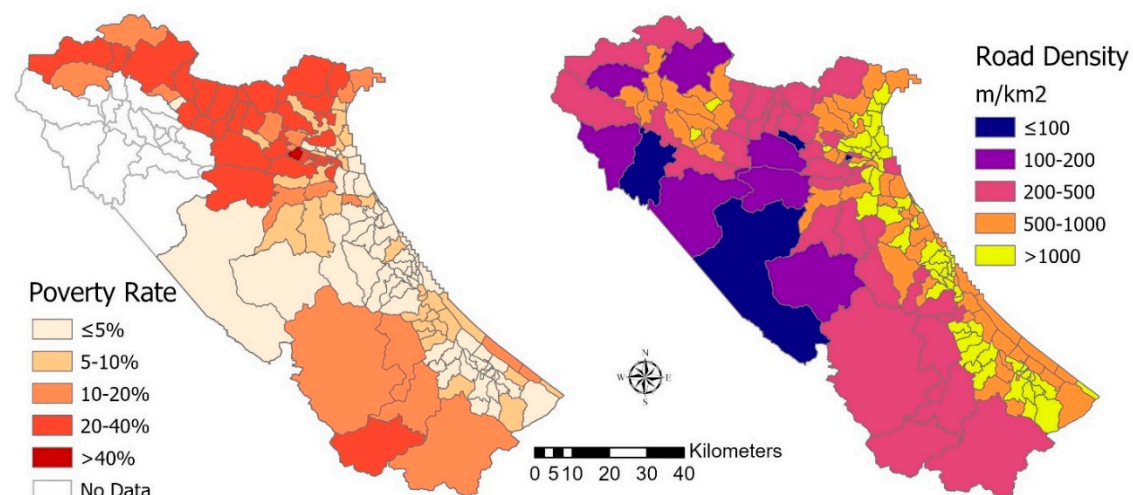


Figure 7. Flood vulnerability criteria distribution, including poverty rate and road density.

Table 2. AHP model for flood vulnerability criteria.

Component	Criteria	Weight	Sub-Criteria	Weight
Flood vulnerability	Poverty rate (%)	0.577	≤5	0.066196
			5–10	0.098437
			10–20	0.161901
			20–40	0.265226
			>40	0.408239
	Road density (m/km ²)	0.298	<100	0.413598
			100–200	0.238857
			200–500	0.164538
			500–1000	0.106464
			>1000	0.076542

4.4. Flood Risk Assessment

Flood risk is assessed based on the framework in Figure 1 and Equation (1). In this study, a flood inundation map is considered a flood hazard map. Flood exposure and vulnerability maps are generated using Weighted Sum technique in ArcGIS software. The results of flood inundation, vulnerability, and exposure are displayed in Figure 8. The final flood risk assessment map is generated based on a combination of flood inundation (hazard), exposure, and vulnerability maps.

The flood risk assessment result is displayed in Figure 9. In the map, the flood risk score is normalised within the range of 0–1. Areas located near and along Nhat Le and Gianh river basins are at higher risk of flooding. The total inundation area is 64,348 ha, in which 5361 ha of low risk (0.14–0.312), 10,518 ha of medium risk (0.312–0.484), 7702 ha of high risk (0.484–0.656), 23,901 ha of very high risk (0.656–0.828), and 16,868 ha of extremely high risk (0.828–1.000). Alternatively, the distribution of risk levels in the research area is 8.3% of low risk, 16.3% of medium risk, 12.0% of high risk, 37.1% of very high risk, and 26.2% of extremely high risk.

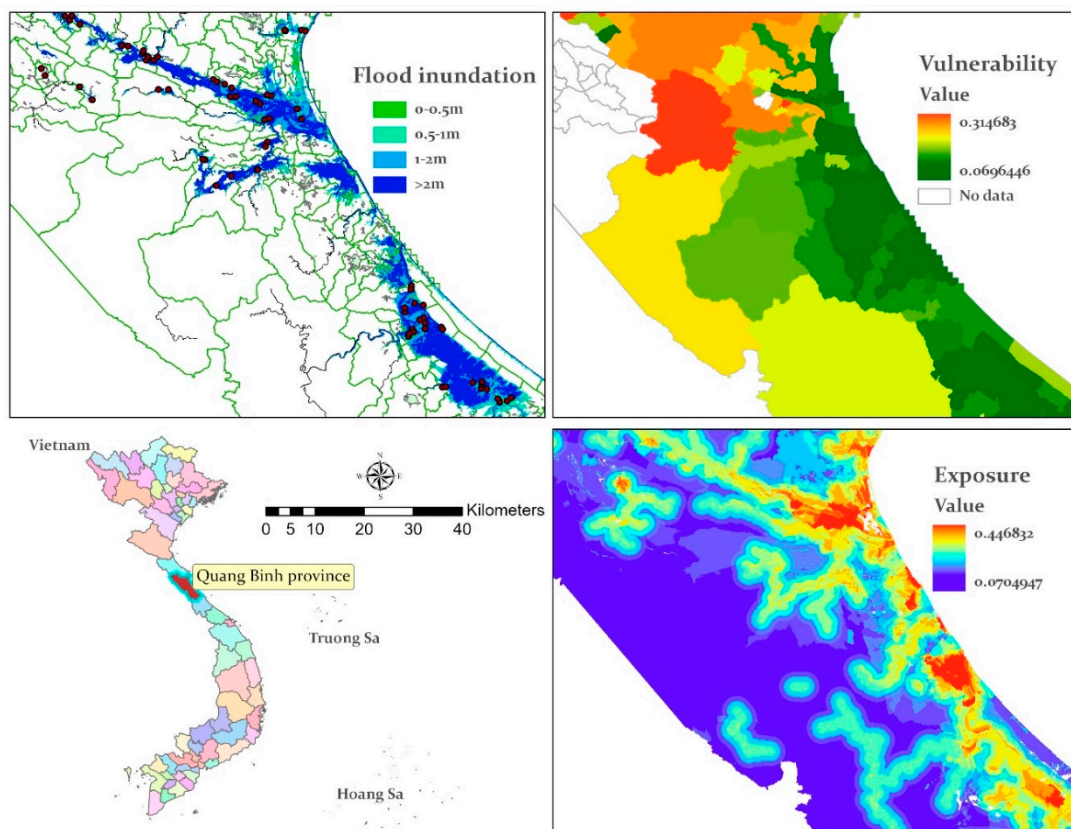


Figure 8. Spatial analysis of flood hazard, exposure, and vulnerability for Quang Binh province.

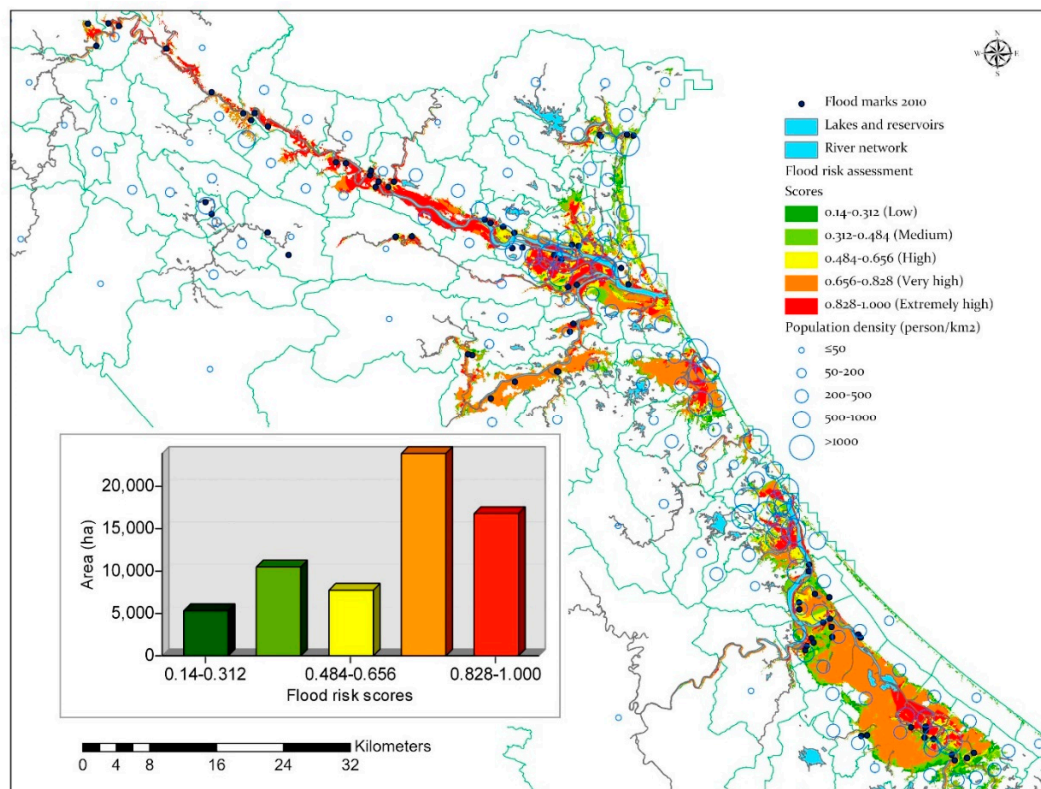


Figure 9. Spatial flood risk assessment of Quang Binh province, which is combined three components: flood hazard, exposure, and vulnerability.

5. Discussion

Although studies on flood risk analysis have been increasingly conducted in Vietnam, there is a lack of research on detailed flood risk assessment maps, particularly at local levels. In this study, we developed a detailed flood risk assessment map for Quang Binh province of Vietnam. The flood risk map was generated by combining flood hazard, exposure and vulnerability maps. Some studies have focused on flood risk assessment in terms of combining flood vulnerability and flood hazard [70,72,73]. However, flood risk is often considered by the combination of hazard, exposure, and vulnerability, which fully reflects aspects of flood risk. This approach has been applied in many studies at both global [30,36,74] and local scales [29,37,75].

Successive flood events have significantly impacted on the residents' livelihood and socio-economic development in Quang Binh province (see Figure 2). A practical risk management approach can help to reduce the adverse impacts of flood risk in the area. Before a disaster ever materialises, we can work to reduce risks and discuss the avoidance of activities that actually create risk [76]. The holistic flood risk assessment map would provide a useful tool and source for flood preparedness activities at the local scale.

The study has been based on the regulations for the establishment of component maps for constructing flood risk assessment. These maps are gathered from reliable and high-resolution data sources. Maps are constructed in raster format using geographic information technology application for the study area. The research results include a new modelling methodology for developing flood risk assessment mapping tool using historical flood marks, high-resolution DEM, and MCDA approach. MCDA methods are often used to incorporate the three components of hazard, exposure, and vulnerability due to several advantages of the methods such as criteria and sub-criteria systematization [53], suitable for GIS integration [77], and consistency in judgement [54]. The methodology would contribute not only to the development of theoretical and methodological modelling of flood risk assessments, but also as a tool to assist managers, decision-makers, and policy-makers in developing flood risk management action plans.

In this study, flood risk is assessed with the integration of various indicators of flood depth, population density, land use category, distance to rivers, poverty rate, and road density using AHP and spatial analysis techniques. Some previous studies in the field of flood risk analysis in Vietnam focused on the flood hazard assessments (for example, [17,39,78,79]). The present study used AHP method and spatial techniques to combine flood inundation map with flood exposure and vulnerability data to provide an integrated flood risk assessment map.

The flooded areas calculated from the model of this study are compared with the flood areas of an equivalent flood in Quang Binh, which were calculated in another study to ensure the reliability of the model. The flood frequency of November 1999 and October 2010 flood events are approximately the same [80]. The inundation map of October 2010 flood event was generated in this study using historical flood mark data and high-resolution DEM. The inundation map of November 1999 flood event was generated in the study [81]. We compared the flooded areas in communes along the Nhat Le river basin of October 2010 flood event and November 1999 flood event. The result in Figure 10 shows that the inundation areas of October 2010 flood event, which was created in this study by using historical flood marks and a high-resolution DEM, are quite compatible with the inundation areas of November 1999 flood event, which was created in the study of Nguyen and Phan [81].

Floods have severely affected communities' livelihoods and socioeconomic development in Quang Binh over the years (Figure 10). Low-land areas, including agricultural areas along Nhat Le and Gianh river basins, are often subjected to flooding in annual rainy seasons (Figure 5). This study developed a holistic flood risk assessment map incorporating hazard, exposure, and vulnerability for Quang Binh province that could provide helpful information for decision-makers and policy-makers to implement and improve flood mitigation and response measures for the area. The map is also essential for accurate communication about the local flood risk situation in the floodplain for affected communities. The study developed a geospatial database and a theoretical framework for developing flood risk

assessment maps using historical flood marks, DEM, other geospatial data and social-economic data. The framework does not require time series meteorological and streamflow data or updated river cross-section data, which are not available in many data-scarce areas. Therefore, the framework could potentially be applied to other provinces, especially those in central Vietnam with similar topographic and climatic conditions to create flood risk assessment maps.

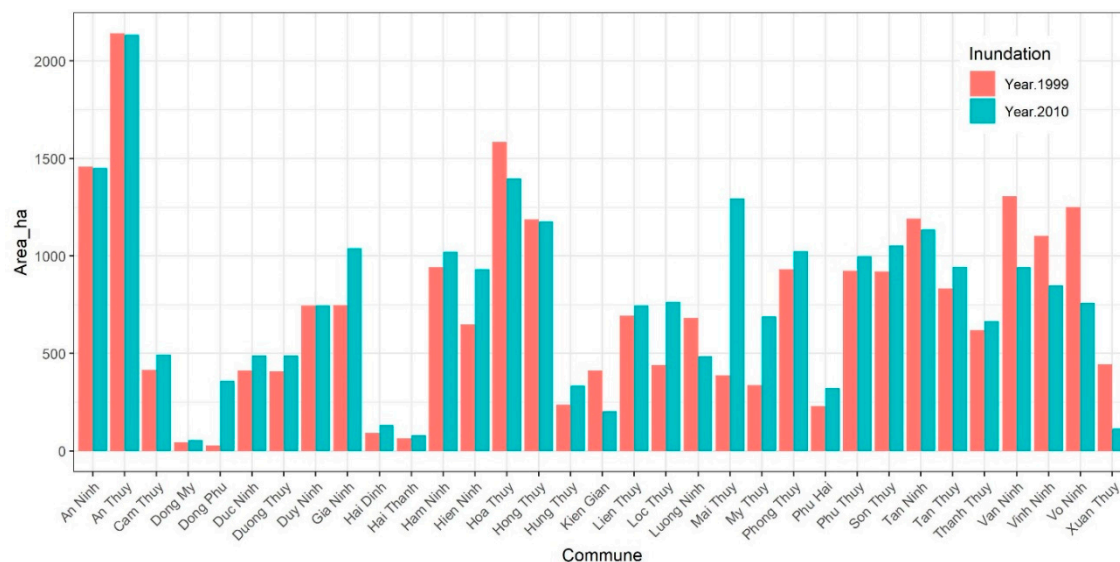


Figure 10. Flood inundation area of communes in October 2010 and November 1999 flood events.

Besides these strengths, the present study has some limitations of flood vulnerability data and MCDA approach. More data could be added to analyse flood vulnerability such as healthcare facilities, gender, and persons with disabilities; however, such data is not available in the research area. The MCDA approach, in general, and AHP, in particular, require subjective judgments in weighting indicators [55] and subjective model validation [45].

6. Conclusions

The present study provides a new approach to assess the flood risk for the local area of Quang Binh province. We used historical flood marks and a high-resolution DEM to create an inundation map, and then combined the inundation map with exposure and vulnerability data to create a flood risk assessment map using spatial multicriteria decision analysis techniques. The detailed flood risk assessment map could support the implementation of strategies and specific actions of government authorities to control, reduce, and transfer the flood risks. The framework developed in this study could provide a methodology to rapidly simulate flood risk assessment maps using available data in local areas, especially in areas where there is insufficient data for hydraulic models. In addition, it is a potential way to engage local decision-makers in the approach and framework of this study for further investigation and validation of flood risk in the study area.

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References

- Mitchell, B. Integrated Water Resource Management, Institutional Arrangements, and Land-Use Planning. *Environ. Plan. A Econ. Sp.* **2005**, *37*, 1335–1352. [\[CrossRef\]](#)
- López, E.; Bocco, G.; Mendoza, M.; Duhau, E. Predicting land-cover and land-use change in the urban fringe: A case in Morelia city, Mexico. *Landsc. Urban Plan.* **2001**, *55*, 271–285. [\[CrossRef\]](#)
- Tanoue, M.; Hirabayashi, Y.; Ikeuchi, H. Global-scale river flood vulnerability in the last 50 years. *Sci. Rep.* **2016**, *6*, 36021. [\[CrossRef\]](#) [\[PubMed\]](#)
- Luu, C.; von Meding, J. Analyzing Flood Fatalities in Vietnam Using Statistical Learning Approach and National Disaster Database. In *Resettlement Challenges for Displaced Populations and Refugees*; Asgary, A., Ed.; Springer International Publishing: Cham, Switzerland, 2019; pp. 197–205. ISBN 978-3-319-92498-4.
- Kreft, S.; Eckstein, D.; Melchior, I. *Global Climate Risk Index 2017*; Chapman-Rose, J., Ed.; Germanwatch e.V.: Berlin, Germany, 2016; ISBN 978-3-943704-49-5.
- Nguyen, K.-A.; Liou, Y.-A.; Terry, J.P. Vulnerability of Vietnam to typhoons: A spatial assessment based on hazards, exposure and adaptive capacity. *Sci. Total Environ.* **2019**, *682*, 31–46. [\[CrossRef\]](#) [\[PubMed\]](#)
- Luu, C.; von Meding, J.; Mojtahedi, M. Analyzing Vietnam's national disaster loss database for flood risk assessment using multiple linear regression-TOPSIS. *Int. J. Disaster Risk Reduct.* **2019**, *40*, 101153. [\[CrossRef\]](#)
- Le, H.; Ha, L.B. *Flood Vulnerability and Resilience in Peri-urbanizing Vietnam: A Case Study from Ninh Binh Province BT—Urban Climate Resilience in Southeast Asia*; Danieri, A.G., Garschagen, M., Eds.; Springer International Publishing: Cham, Switzerland, 2019; pp. 83–101. ISBN 978-3-319-98968-6.
- Zhou, Q.; Mikkelsen, P.S.; Halsnaes, K.; Arnbjerg-Nielsen, K. Framework for economic pluvial flood risk assessment considering climate change effects and adaptation benefits. *J. Hydrol.* **2012**, *414–415*, 539–549. [\[CrossRef\]](#)
- Masuya, A.; Dewan, A.; Corner, R.J. Population evacuation: Evaluating spatial distribution of flood shelters and vulnerable residential units in Dhaka with geographic information systems. *Nat. Hazards* **2015**, *78*, 1859–1882. [\[CrossRef\]](#)
- Cutter, S.L. Vulnerability to environmental hazards. *Prog. Hum. Geogr.* **1996**, *20*, 529–539. [\[CrossRef\]](#)
- Kundzewicz, Z.W.; Luger, N.; Dankers, R.; Hirabayashi, Y.; Döll, P.; Pińskwar, I.; Dysarz, T.; Hochrainer, S.; Matczak, P. Assessing river flood risk and adaptation in Europe—Review of projections for the future. *Mitig. Adapt. Strateg. Glob. Chang.* **2010**, *15*, 641–656. [\[CrossRef\]](#)
- Luu, C.; Von Meding, J.; Kanjanabootra, S. Flood risk management activities in Vietnam: A study of local practice in Quang Nam province. *Int. J. Disaster Risk Reduct.* **2018**, *28*, 776–787. [\[CrossRef\]](#)
- Davis, I. *Disaster Risk Management in Asia and the Pacific*; Taylor and Francis: Florence, UK, 2014; ISBN 978-131-764-4873.
- Burby, R.J. Hurricane Katrina and the Paradoxes of Government Disaster Policy: Bringing About Wise Governmental Decisions for Hazardous Areas. *Ann. Am. Acad. Pol. Soc. Sci.* **2006**, *604*, 171–191. [\[CrossRef\]](#)
- Sayers, P.B.; Hall, J.W.; Meadowcroft, I.C. Towards risk-based flood hazard management in the UK. *Proc. Inst. Civ. Eng. Civ. Eng.* **2002**, *150*, 36–42. [\[CrossRef\]](#)
- Tien Bui, D.; Hoang, N.D. A Bayesian framework based on a Gaussian mixture model and radial-basis-function Fisher discriminant analysis (BayGmmKda V1.1) for spatial prediction of floods. *Geosci. Model Dev.* **2017**, *10*, 3391–3409. [\[CrossRef\]](#)
- Tran, P.; Shaw, R.; Chantry, G.; Norton, J. GIS and local knowledge in disaster management: A case study of flood risk mapping in Viet Nam. *Disasters* **2009**, *33*, 152–169. [\[CrossRef\]](#)
- Chau, V.N.; Holland, J.; Cassells, S.; Tuohy, M. Using GIS to map impacts upon agriculture from extreme floods in Vietnam. *Appl. Geogr.* **2013**, *41*, 65–74. [\[CrossRef\]](#)
- Luu, C.; Von Meding, J.; Kanjanabootra, S. Assessing flood hazard using flood marks and analytic hierarchy process approach: A case study for the 2013 flood event in Quang Nam, Vietnam. *Nat. Hazards* **2018**, *90*, 1031–1050. [\[CrossRef\]](#)
- UNISDR. *Sendai Framework for Disaster Risk Reduction 2015–2030*; United Nations Office for Disaster Risk Reduction (UNISDR): Geneva, Switzerland, 2015.

22. Phong, T.V.; Phan, T.T.; Prakash, I.; Singh, S.K.; Shirzadi, A.; Chapi, K.; Ly, H.-B.; Ho, L.S.; Quoc, N.K.; Pham, B.T. Landslide susceptibility modeling using different artificial intelligence methods: A case study at Muong Lay district, Vietnam. *Geocarto Int.* **2019**, 1–24. [\[CrossRef\]](#)
23. Wassmann, R.; Hien, N.; Hoanh, C.; Tuong, T. Sea Level Rise Affecting the Vietnamese Mekong Delta: Water Elevation in the Flood Season and Implications for Rice Production. *Clim. Chang.* **2004**, *66*, 89–107. [\[CrossRef\]](#)
24. Yokoi, S.; Matsumoto, J. Collaborative Effects of Cold Surge and Tropical Depression–Type Disturbance on Heavy Rainfall in Central Vietnam. *Mon. Weather Rev.* **2008**, *136*, 3275–3287. [\[CrossRef\]](#)
25. UNISDR Global Assessment Report on Disaster Risk Reduction, 2015. Available online: <https://www.unisdr.org/we/inform/publications/42809> (accessed on 10 January 2020).
26. Winsemius, H.C.; Aerts, J.C.J.H.; van Beek, L.P.H.; Bierkens, M.F.P.; Bouwman, A.; Jongman, B.; Kwadijk, J.C.J.; Ligtoet, W.; Lucas, P.L.; van Vuuren, D.P.; et al. Global drivers of future river flood risk. *Nat. Clim. Chang.* **2015**, *6*, 381–385. [\[CrossRef\]](#)
27. Bouwer, L.M.; Bubeck, P.; Aerts, J.C.J.H. Changes in future flood risk due to climate and development in a Dutch polder area. *Glob. Environ. Chang.* **2010**, *20*, 463–471. [\[CrossRef\]](#)
28. Kron, W. Flood Risk = Hazard · Values · Vulnerability. *Water Int.* **2005**, *30*, 58–68. [\[CrossRef\]](#)
29. Budiyo, Y.; Aerts, J.; Brinkman, J.; Marfai, M.A.; Ward, P. Flood risk assessment for delta mega-cities: A case study of Jakarta. *Nat. Hazards* **2014**, *75*, 389–413. [\[CrossRef\]](#)
30. Hirabayashi, Y.; Mahendran, R.; Koirala, S.; Konoshima, L.; Yamazaki, D.; Watanabe, S.; Kim, H.; Kanae, S. Global flood risk under climate change. *Nat. Clim. Chang.* **2013**, *3*, 816–821. [\[CrossRef\]](#)
31. Seneviratne, S.I.; Nicholls, N.; Easterling, D.; Goodess, C.M.; Kanae, S.; Kossin, J.; Luo, Y.; Marengo, J.; McInnes, K.; Rahimi, M.; et al. *Changes in Climate Extremes and their Impacts on the Natural Physical Environment*; Cambridge University Press: Cambridge, UK, 2012.
32. Crichton, D. The risk triangle. *Nat. Disaster Manag.* **1999**, *102*, 103.
33. Cardona, O.D.; Birkmann, J.; Fordham, M.; Perez, R.; Schipper, E.L.F.; Sinh, B.T.; Field, C.B.; Barros, V.; Stocker, T.F.; Qin, D.; et al. Determinants of risk: Exposure and vulnerability. In *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*; A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC); Cambridge University Press: Cambridge, UK, 2012; pp. 65–108.
34. Maaskant, B.; Jonkman, S.N.; Bouwer, L.M. Future risk of flooding: An analysis of changes in potential loss of life in South Holland (The Netherlands). *Environ. Sci. Policy* **2009**, *12*, 157–169. [\[CrossRef\]](#)
35. De Moel, H.; van Alphen, J.; Aerts, J.C.J.H. Flood maps in Europe methods, availability and use. *Nat. Hazards Earth Syst. Sci.* **2009**, *9*, 289–301. [\[CrossRef\]](#)
36. Winsemius, H.C.; Van Beek, L.P.H.; Jongman, B.; Ward, P.J.; Bouwman, A. A framework for global river flood risk assessments. *Hydrol. Earth Syst. Sci.* **2013**, *17*, 1871–1892. [\[CrossRef\]](#)
37. Foudi, S.; Osés-Eraso, N.; Tamayo, I. Integrated spatial flood risk assessment: The case of Zaragoza. *Land Use Policy* **2015**, *42*, 278–292. [\[CrossRef\]](#)
38. Jongman, B.; Kreibich, H.; Apel, H.; Barredo, J.I.; Bates, P.D.; Feyen, L.; Gericke, A.; Neal, J.; Aerts, J.C.J.H.; Ward, P.J. Comparative flood damage model assessment: Towards a European approach. *Nat. Hazards Earth Syst. Sci.* **2012**, *12*, 3733–3752. [\[CrossRef\]](#)
39. Ho, L.T.K.; Umitsu, M. Micro-landform classification and flood hazard assessment of the Thu Bon alluvial plain, central Vietnam via an integrated method utilizing remotely sensed data. *Appl. Geogr.* **2011**, *31*, 1082–1093. [\[CrossRef\]](#)
40. Roy, D.C.; Blaschke, T. Spatial vulnerability assessment of floods in the coastal regions of Bangladesh. *Geomat. Nat. Hazards Risk* **2015**, *6*, 21–44. [\[CrossRef\]](#)
41. Malczewski, J.; Rinner, C. GIS-MCDA for Group Decision Making. In *Multicriteria Decision Analysis in Geographic Information Science*; Springer: Berlin/Heidelberg, Germany, 2015; pp. 223–247. ISBN 978-3-540-74756-7.
42. Dewan, A. *Floods in a Megacity: Geospatial Techniques in Assessing Hazards, Risk and Vulnerability*; Springer: Dordrecht, The Netherlands, 2013; ISBN 978-94-007-5874-2.
43. Luu, C.; von Meding, J. A flood risk assessment of Quang Nam, Vietnam using spatial multicriteria decision analysis. *Water (Switzerland)* **2018**, *10*, 461. [\[CrossRef\]](#)

44. Huang, I.B.; Keisler, J.; Linkov, I. Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends. *Sci. Total Environ.* **2011**, *409*, 3578–3594. [[CrossRef](#)]
45. De Brito, M.M.; Evers, M.; Almoradie, A.D.S. Participatory flood vulnerability assessment: A multi-criteria approach. *Hydrol. Earth Syst. Sci.* **2018**, *22*, 373–390. [[CrossRef](#)]
46. Chung, E.-S.; Lee, K.S. Identification of Spatial Ranking of Hydrological Vulnerability Using Multi-Criteria Decision Making Techniques: Case Study of Korea. *Water Resour. Manag.* **2009**, *23*, 2395–2416. [[CrossRef](#)]
47. Solin, L. Spatial variability in the flood vulnerability of urban areas in the headwater basins of Slovakia. *J. Flood Risk Manag.* **2012**, *5*, 303–320. [[CrossRef](#)]
48. Hwang, C.-L.; Yoon, K. *Multiple Attribute Decision Making*; Springer: Berlin/Heidelberg, Germany, 1981; ISBN 978-3-540-10558-9.
49. Markovic, M. Multi criteria Analysis of Hydraulic Structures for River Training Works. *Water Resour. Manag.* **2012**, *26*, 3893–3906. [[CrossRef](#)]
50. Su, H.-T.; Tung, Y.-K. Multi-criteria decision making under uncertainty for flood mitigation. *Stoch. Environ. Res. Risk Assess.* **2014**, *28*, 1657–1670. [[CrossRef](#)]
51. Malekian, A.; Azarnivand, A. Application of Integrated Shannon's Entropy and VIKOR Techniques in Prioritization of Flood Risk in the Shemshak Watershed, Iran. *Water Resour. Manag.* **2016**, *30*, 409–425. [[CrossRef](#)]
52. Malczewski, J. *GIS and Multicriteria Decision Analysis*; John Wiley & Sons: New York, NY, USA, 1999; ISBN 047-132-9444.
53. Ishizaka, A.; Labib, A. Analytic Hierarchy Process and Expert Choice: Benefits and limitations. *ORI* **2009**, *22*, 201–220. [[CrossRef](#)]
54. Koczkodaj, W.W.; Magnot, J.P.; Mazurek, J.; Peters, J.F.; Rakhshani, H.; Soltys, M.; Strzałka, D.; Szybowski, J.; Tozzi, A. On normalization of inconsistency indicators in pairwise comparisons. *Int. J. Approx. Reason.* **2017**, *86*, 73–79. [[CrossRef](#)]
55. Schmoldt, D.; Kangas, J.; Mendoza, G.A. Basic Principles of Decision Making in Natural Resources and the Environment. In *The Analytic Hierarchy Process in Natural Resource and Environmental Decision Making*; Schmoldt, D., Kangas, J., Mendoza, G., Pesonen, M., Eds.; Springer: Dordrecht, The Netherlands, 2001; Volume 3, pp. 1–13. ISBN 978-90-481-5735-8.
56. Millet, I.; Harker, P.T. Globally effective questioning in the Analytic Hierarchy Process. *Eur. J. Oper. Res.* **1990**, *48*, 88–97. [[CrossRef](#)]
57. Velasquez, M.; Hester, P.T. An analysis of multi-criteria decision making methods. *Int. J. Oper. Res.* **2013**, *10*, 56–66.
58. Saaty, T.L. What is the Analytic Hierarchy Process? In *Mathematical Models for Decision Support*; Mitra, G., Greenberg, H., Lootsma, F., Rijkaert, M., Zimmermann, H., Eds.; Springer: Berlin/Heidelberg, Germany, 1988; Volume 48, pp. 109–121. ISBN 978-3-642-83557-5.
59. Ramanathan, R. A note on the use of the analytic hierarchy process for environmental impact assessment. *J. Environ. Manag.* **2001**, *63*, 27–35. [[CrossRef](#)] [[PubMed](#)]
60. Vaidya, O.S.; Kumar, S. Analytic hierarchy process: An overview of applications. *Eur. J. Oper. Res.* **2006**, *169*, 1–29. [[CrossRef](#)]
61. Li, G.-F.; Xiang, X.-Y.; Tong, Y.-Y.; Wang, H.-M. Impact assessment of urbanization on flood risk in the Yangtze River Delta. *Stoch. Environ. Res. Risk Assess.* **2013**, *27*, 1683–1693. [[CrossRef](#)]
62. Kandilioti, G.; Makropoulos, C. Preliminary flood risk assessment: The case of Athens. *Nat. Hazards* **2012**, *61*, 441–468. [[CrossRef](#)]
63. Saaty, T.L. How to make a decision: The analytic hierarchy process. *Eur. J. Oper. Res.* **1990**, *48*, 9–26. [[CrossRef](#)]
64. Moghadas, M.; Asadzadeh, A.; Vafeidis, A.; Fekete, A.; Kötter, T. A multi-criteria approach for assessing urban flood resilience in Tehran, Iran. *Int. J. Disaster Risk Reduct.* **2019**, *35*, 101069. [[CrossRef](#)]
65. Godfrey, A.; Ciurean, R.L.; van Westen, C.J.; Kingma, N.C.; Glade, T. Assessing vulnerability of buildings to hydro-meteorological hazards using an expert based approach—An application in Nehoiu Valley, Romania. *Int. J. Disaster Risk Reduct.* **2015**, *13*, 229–241. [[CrossRef](#)]
66. Kokangül, A.; Polat, U.; Dağsuyu, C. A new approximation for risk assessment using the AHP and Fine Kinney methodologies. *Saf. Sci.* **2017**, *91*, 24–32. [[CrossRef](#)]

67. Kienberger, S.; Lang, S.; Zeil, P. Spatial vulnerability units—Expert-based spatial modelling of socio-economic vulnerability in the Salzach catchment, Austria. *Nat. Hazards Earth Syst. Sci.* **2009**, *9*, 767–778. [CrossRef]
68. Tran, N.A. *Integrated Flood Risk Manual for Vietnam*; Ministry of Agriculture and Rural Development: Hanoi, Vietnam, August 2016.
69. Hachijo, Y. Reviewing Resent Structural and Non-Structural Measures and Result of Lood Simulation in Quang Binh, 2015. Available online: https://www.jica.go.jp/project/vietnam/031/materials/ku57pq00001y1feh-att/Present_Measures_and_Flood_Simulation.pdf (accessed on 10 January 2020).
70. Masuya, A. Flood Vulnerability and Risk Assessment with Spatial Multi-criteria Evaluation. In *Dhaka Megacity: Geospatial Perspectives on Urbanisation, Environment and Health*; Dewan, A., Corner, R., Eds.; Springer: Dordrecht, The Netherlands, 2014; pp. 177–202. ISBN 978-94-007-6735-5.
71. Whitaker, R.; Adams, W. *Developers of Superdecisions Software*; Decisions Foundation: Pittsburgh, PA, USA, 2005.
72. Scheuer, S.; Haase, D.; Meyer, V. Exploring multicriteria flood vulnerability by integrating economic, social and ecological dimensions of flood risk and coping capacity: From a starting point view towards an end point view of vulnerability. *Nat. Hazards* **2011**, *58*, 731–751. [CrossRef]
73. Lee, G.; Jun, K.S.; Chung, E.S. Integrated multi-criteria flood vulnerability approach using fuzzy TOPSIS and Delphi technique. *Nat. Hazards Earth Syst. Sci.* **2013**, *13*, 1293–1312. [CrossRef]
74. Jongman, B.; Ward, P.J.; Aerts, J.C.J.H. Global exposure to river and coastal flooding: Long term trends and changes. *Glob. Environ. Chang.* **2012**, *22*, 823–835. [CrossRef]
75. Zhou, Q.; Leng, G.; Feng, L. Predictability of state-level flood damage in the conterminous United States: The role of hazard, exposure and vulnerability. *Sci Rep* **2017**, *7*, 1–11. [CrossRef]
76. Schanze, J. Flood Risk Management: A basic framework. In *Flood Risk Management: Hazards, Vulnerability and Mitigation Measures*; Schanze, J., Zeman, E., Marsalek, J., Eds.; Springer: Dordrecht, The Netherlands, 2006; pp. 1–20. ISBN 978-1-4020-4598-1.
77. Malczewski, J. GIS-based multicriteria decision analysis: A survey of the literature. *Int. J. Geogr. Inf. Sci.* **2006**, *20*, 703–726. [CrossRef]
78. Tran, P.; Marincioni, F.; Shaw, R. Catastrophic flood and forest cover change in the Huong river basin, central Viet Nam: A gap between common perceptions and facts. *J. Env. Manag.* **2010**, *91*, 2186–2200. [CrossRef]
79. Nam, D.H.; Udo, K.; Mano, A. Future fluvial flood risks in Central Vietnam assessed using global super-high-resolution climate model output. *J. Flood Risk Manag.* **2014**, *8*, 276–288. [CrossRef]
80. Phan, V.T. Climate Change-Induced Water Disaster and Participatory Information System for Vulnerability Reduction in North Central Vietnam, 2015. Available online: <http://danida.vnu.edu.vn/cpis/vn/cat/59> (accessed on 10 January 2020).
81. Nguyen, X.; Phan, V.T. Đánh giá tác động của Biến đổi khí hậu đến ngập lụt lưu vực sông Nhật Lệ, Việt Nam. *Tạp chí Khoa học ĐHQGHN Khoa học tự nhiên và Công nghệ* **2015**, *31*, 125–138.

