



Indicator-based approach for flood vulnerability assessment in ancient heritage city of Hoi An, Central Region of Vietnam

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Abstract

The increasing unpredictable floods due to the effect of climate change across regions of Vietnam have threaten the country's socio-economic development goals at local, regional and national scales. This paper employs indicator-based approach to calculate Flood Vulnerability Index and generates vulnerability maps that reflect the spatial distribution of flood vulnerability in the Central region of Vietnam, which is the hardest hit flood region and home to many sites of great cultural-historical value. Data were collected from Hoi An's 2020 statistical yearbook, digital elevation model, land use map, open street map and from surveying experts and civil servants at the city level (representatives of the City People's Committee, the Center for Cultural Heritage Management and Preservation of Hoi An) and at ward/commune level (representatives of 12 wards and communes). GIS techniques and analytical hierarchy process were applied to analysis the obtained data and generate three scenarios that reflect the impact of vulnerability's components. The findings indicate that number of organizations in disaster prevention and historical site preservation, road density, the presence of historical sites, flood frequency and average elevation are the key factors affecting the city's vulnerability to flood hazard in the area of cultural heritage. The empirical results in Hoi An also indicate the importance of the number of poor households as an necessary factor when considering the sensitivity to flood in developing countries. In addition, this study distinguishes the impact of vulnerability's components by generating different scenarios which clearly proof that having more floods does not always mean high vulnerability and vice versa. More importantly, by looking into the reasons (either transportation, education or other indicators) that leads to the gap between Flood Vulnerability Index in different scenarios, the paper subsequently identifies measures for each locality, whereby the governmental investment budget can be prioritized effectively.

Keywords Flood vulnerability index · Indicator-based approach · Cultural heritage area · GIS · Analytic hierarchy process · Vietnam

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1 Introduction

Among several types of natural hazards, floods are considered to be one of the most common one in the world which have been heavily affecting human society through centuries (CRED 2015). Regular flooding alone might not be an issue as it can bring some benefits for nearby and around regions (FAO 2011); however, under the impact of climate change, the frequency and insensitivity of floods in many parts of the world have become less predictable causing hazardous conditions to which humans are remarkably vulnerable (Fernandez et al. 2016; Nasiri et al. 2016; Das and Scaringi 2021; Towfiqul Islam et al 2021; UNEP 2021;). In recent years, climate-induced flood has attracted much attentions across disciplines. As its impact level is varied for each region, system and community, the vulnerability is not identical between research objects (Adger et al 2004). Due to this fact, many scholars have suggested that the vulnerability to climate variabilities should be assessed at a local level (Deressa et al. 2009; Below et al. 2012; Ruidas et al. 2022). Understanding the vulnerability to flood of lower administrative units such as wards and communes, therefore, has been considered as an urgent need to find adaptation strategies and introduce proper solutions in minimizing climate-associated risks and enhancing local resilience, especially in countries that are highly exposed to floods.

Vietnam, the s-shaped country with a 3260 km long coastline, ranks fifth among countries worldwide with the highest proportion of the population exposed to river flood risk (Bangalore et al. 2018). In Vietnam, floods have taken the lives of an estimated over 500 people annually and have resulted in economic losses of about 1.3% the national gross domestic product over the past 20 years (Luu and Meding 2019). An estimated of 30,000 people were killed or injured between 1989 and 2015, with most of them having been from the central region, according to the national disaster loss database (Luu et al. 2019). Researching on the hardest hit region of one of the most flood-prone countries like Vietnam in the Asia Pacific region (World Bank 2017) is therefore greatly essential given limited studies on this urgent issue in the country and region. In recent years, prolonged heavy rains that triggered flooding have been experienced in the central region of Vietnam, which is home to many cultural heritage sites. A series of floods in this region affected many historical destinations causing hundreds of fatalities and nearly a US dollar 2 billion loss (IFRC 2020). Despite being acknowledged of the alarming situation of floods, the country encounters many difficulties that deter the flood management efforts, especially in flood risk reduction in cultural heritage areas. The major difficulty is lack of enough scientific research on flood risk and vulnerability; this explains why flood management is still more on the side of dealing with the consequences rather than being proactive in minimizing the possibility in advance. Moreover, the generation of disaster vulnerability index for disaster support system, especially for flood hazard, has not yet comprehensively conducted in Vietnam; flood response plans are normally either passively implemented depending on the actual situation or set up based on indigenous knowledge and local people's experiences. The local disaster management authorities of the Ministry of Agriculture and Rural Development annually publish the community-based training materials and popularize them among the people living in flood prone areas. However, the proactive accessibility to these kind of materials is limited and uneven across the affected regions. Moreover, despite community-based training materials to response to floods, localities at the commune and ward level have not yet had any official guidelines to self-evaluate their vulnerability or adaptive capacity to floods (Luu and Meding 2019). For these reasons, a study that focuses on generating indicators for flood vulnerability assessment is particularly important and urgent,

especially in cultural heritage areas. The findings of this paper would explicitly help policymakers in introducing appropriate strategies to reduce the flood damage, contribute to preserve the cultural value, and subsequently reduce the poverty and ensure sustainable development goals. In addition, as most previous studies assessed the risk of general natural hazards, or focused on floods at river basin scale, there is a high demand for research that focuses particularly on the most pressing hazards in the region, i.e., flood vulnerability at local scale. Also, the assessment of flood in the areas of historical and cultural heritage is limited. This is also the motivation and main objective of this research which aims to explore the vulnerability at urban scale and disclose the factors that most affect the vulnerability to flood by analysing the Flood Vulnerability Index (FVI), with a case study in Hoi An city. This research, therefore, makes major contributions to the research gap in the disaster assessment particularly the flood vulnerable index in the area of cultural heritage, points out the factors that have the greatest impact on the flood vulnerability. The findings of this research are replicable for future assessment of vulnerability in other hazard-prone areas with cultural preserved sites and provide good references for policymakers to have proper supporting policies to help to plan ahead and, after all, improve the quality of human life. Furthermore, while many previous studies in flood vulnerability assessment faced a major limitation in that the areas most exposed are most vulnerable, the approach of generating different vulnerability scenarios that reflect the impact of vulnerability's components employed in this paper proof that having more floods does not always mean high vulnerability. This, accordingly, reinforces the theoretical background of vulnerability assessment.

2 Study area

Hoi An is an ancient city that known as one of the most attractive cultural heritage sites in south-east Asia (Ando et al. 2015). Situated at the convergence of three major rivers along with complex river system and an increasing rapid urbanization, the city suffers many types of natural disasters every year. The city has 9 wards (Minh An, Son Phong, Cam Pho, Tan An, Thanh Ha, Cam Chau, Cam An, Cua Dai, and Cam Nam) and 3 communes (Cam Thanh, Cam Kim, and Cam Ha) and one island, namely Cu Lao Cham, which belongs to Tan Hiep commune. This research focuses on the inland area of Hoi An city, including 9 wards and 3 communes mentioned above. This research does not include an analysis of Tan Hiep island since this area has completely different geographical features.

The coastal areas and river basins of Hoi An are characterized by low-lying areas, unstable terrain that is easy to erode. The urbanized area of the city is at an altitude of 0–15 m above sea level. On average, Hoi An has two high tides per day with the maximum tidal height (above mean sea level) of 1.4 m. The city has significant rainfall throughout the year, and even the driest month receives much rainfall. Hoi An has two distinct seasons: the dry season lasts from January to July and the rainy season that runs from August to December. There is an average of 2490 mm (98.0 inch) of precipitation falls annually, with the heaviest rainfall in November (about 459 mm or 18.1 inch). Normally, the driest month is April, but still, the rainfall during the month is about 77 mm (3.0 inch). Major storms that cause severe flooding often occur in the rainy season. Out of the total number of storms in Vietnam each year, about 25% affect Hoi An. As reported in the statistical yearbooks of Hoi An, the city has experienced many floods, including major ones in 1998, 1999, 2007 and 2009, with water-flood depth of over 3 m. Storms and heavy rain poured down in torrents

in October 2020 and filled all of Hoi An's streets, with major roads in the city center being inundated to a depth of approximately one meter, thereby halting all economic activities. These facts indicate that a comprehensive vulnerability assessment across multiple dimensions—environmental, economic, social, and cultural—is of great significance for guiding investment policies to improve weaknesses that reduce flood resilience of Hoi An (Fig. 1).

3 Methods and data sources

This paper applies the indicator-based approach and follows the UNESCO-IHE Institute for Water Education's flood vulnerability system to select and analysis the vulnerability by computing Flood Vulnerability Index (FVI) (www.unesco-ihe-fvi.org/). Vulnerability is determined through three components: Exposure (*E*), Susceptibility (*S*), and Resilience (*R*). This description of vulnerability was also introduced and applied in many other scientific documents (Adger 2006; IPCC 2007; UNISDR 2009; Balica and Wright 2010). The exposure to floods can be seen as the presence of important factors (of environmental, physical, or socio-economic dimension) that are subject to potential damages in flood-prone areas (Balica et al. 2012). Susceptibility is the human environmental or socio-ecological conditions that can trigger an impact of hazards (Turner et al. 2003). The resilience (or adaptive capacity) of a system or a community refers to the capacity to mitigate threats and damages of floods. In three FVI components, R often has negative relation with vulnerability (Smit and Wandel 2006). Vulnerability can be reflected

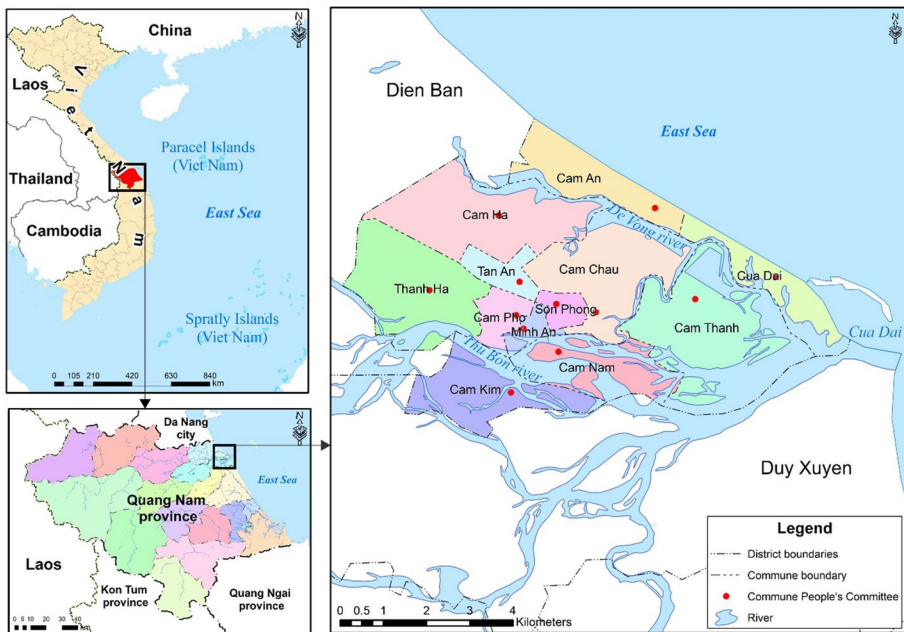


Fig. 1 Location map of Hoi An. The city is at the convergence of the Thu Bon river which is of great influence on hydrological conditions and runs through the central area of the city, De Vong river that runs across the north side of the city, and Co Co river that flows down to the south and has the least impact on hydrological conditions of the city

through indicators which are described as inherent features that quantitatively estimates the condition and status of a system. The indicators usually focus on small, tangible pieces of a system (which reflect the socio-economic, environmental and physical condition) but can provide a sense of the bigger picture. The research process includes four major stages (Fig. 2), each stage involves different methods and input data.

3.1 Stage 1

Based on FVI indicators suggested by UNESCO-IHE for urban scale, and previous studies on indicator-based approach (Balica 2007; Balica and Wright 2010; Balica et al 2012; Nasiri et al. 2018; Das 2020; Das and Gupta 2021; Das and Scaringi 2021; Hus-sain et al 2021), 18 indicators were selected. A survey on the suitability and importance of 18 indicators was conducted with the participation of four civil servants (representatives of the People’s Committee of Hoi An city, the Center for Cultural Heritage Management and Preservation) and three local experts (with expertise in flood hazards, social survey, urban planning). The participation of not only experts but also local civil servants, who are responsible for annual statistics and management of natural disasters including flood, can confirm the validity of the indicator set. Furthermore, the involvement of local authorities can increase the practical applicability of research findings in policy orientation.

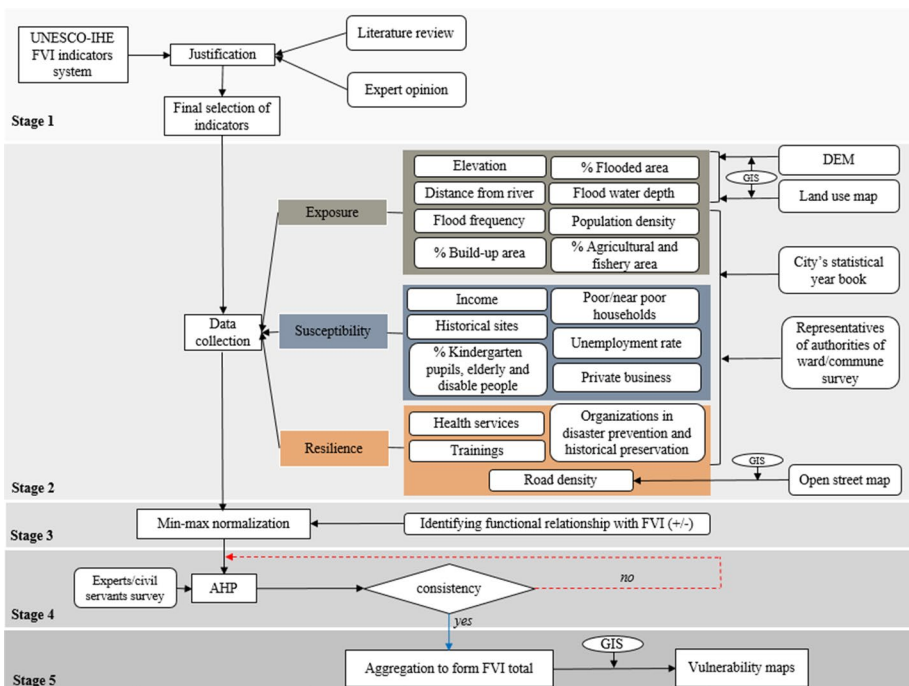


Fig. 2 Methodological flow and data sources of the research

3.2 Stage 2

The 10-m DEM data source provided by the Quang Nam Department of Natural Resource and Environment (DONRE), and the open street map (OSM) and land use map by the environmental and natural resources department of the People's Committee of Hoi An city were used for calculation of topography indicators. Data for indicators of socio-economic and historical aspects were obtained from the 2020 statistical yearbook of Hoi An and a local survey. The primary purpose of these interviews was to get a better understanding of the research's context as well as the situation of flood in the region to set up a list of indicators related to a flood vulnerability assessment. A list of indicators in an electronic questionnaire form was then given to local civil servants and experts to confirm the suitability and also assign the importance of each indicator to the vulnerability. The evaluations of experts were also used in stage 3 (indicators weighting). In the field survey, number of private health services and pharmacy, and organizations in disaster prevention and historical sites preservation were counted and confirmed. In the second survey, an electronic form was sent to representatives of 12 wards and communes to provide information on disaster response training given to local people, data on health services facilities, especially the privately-owned ones, and average income of each ward and commune.

3.3 Stage 3

As each indicator's value is held in different units, the normalization was carried to convert all values into a standard scale from 0 to 1, employing maximum-minimum normalization (Krajnc and Glavic 2005) as shown in Tables 6, 7 and 8 in "Appendix 1". However, before normalizing, the relation of each indicator to FVI needs to be identified (Table 5 in "Appendix 1"). For the indicators that positively correlated with vulnerability, which means that the increase in the value of indicator leads to an increase in vulnerability level and vice versa, the normalized value of indicators would be obtained using Eq. (1). By contrast, for indicators having an inverse relationship with vulnerability, in which the increase in the value of indicator leads to a decline in vulnerability level and vice versa, the normalized value of indicators would be obtained using Eq. (2), where: X_i is the normalized value; X_{\max} refers to the maximum value of the indicator when comparing between wards/communes; X_{\min} is the minimum value of the indicator when comparing between wards/communes.

$$X_i = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}} \quad (1)$$

$$X_i = \frac{X_{\max} - X_i}{X_{\max} - X_{\min}} \quad (2)$$

3.4 Stage 4

After normalization, AHP method by Saaty (1990) was used to determine the suitability and weights for all indicators. Among MCDA techniques, the analytical hierarchy process (AHP) is an effective one that can address a broad decision-making problem involving a

wide range of criteria (Abdelkarim et al. 2020). Different indicators have different level of impact on the vulnerability; therefore, their importance to FVI is needed to be figured. The weighting process follows three steps: *Step 1*: Setting up pairwise comparison matrix among indicators using Saaty rating scale (Table 12 in “Appendix 2”) (the importance of indicators was determined by the evaluation of experts and local civil servants through questionnaire survey). *Step 2*: All comparison values in the initial pairwise comparison matrix were normalized. The weight (W_j) for each indicator was obtained by averaging normalized values. *Step 3*: The consistency of AHP hierarchy was checked by identifying the consistency rate (CR) as in Eq. (3), where RI is the random consistency index and CI is the consistency index.

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

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4}$$

The value of RI depends on the number of indicators in pairwise comparison matrix (Danumah et al. 2016). In this research, RI value for ranking indicators in exposure component is 1.41, which corresponds to 8 indicators; for susceptibility it is 1.24, which corresponds to 6 indicators; and for resilience it is 0.9, which corresponds to 4 indicators. The results are shown in Table 1. CI was determined based on maximum eigenvalue (λ_{max}) as shown in Eq. (4), where, n is number of indicators. λ_{max} was calculated by summing all the multiplication of the relative weights and the respective column total of the original pairwise comparison matrix (Rajput and Shukla 2012). If the preference of all respondents is consistent, the resulting CR will be less than 0.1 or 10% (Saaty 1990). When CR exceeds 0.1, it is necessary to revise the pairwise comparison matrix and re-calculate the weights for better weighting scheme (Tables 9, 10 and 11 in “Appendix 1”).

3.5 Stage 5

All normalized indicators were multiplied with their corresponding weights to compute FVI’s components (E, S, R). GIS techniques were then applied to create vulnerability maps based on FVI value obtained by integrating E, S and R .

Table 1 Weights of FVI indicators

Exposure (E)	AET	FF	DR	FA	FWD	POP	BU	AFA
	0.16	0.21	0.15	0.10	0.10	0.10	0.08	0.10
	RI=1.41, λ_{max} =8.13, CR=0.01							
Susceptibility (S)	HIS	PH	VUL	INC	PRB	UER		
	0.25	0.20	0.19	0.13	0.12	0.10		
	RI=1.24, λ_{max} =6.12, CR=0.02							
Resilience (R)	RD	EDU	HE	ORG				
	0.33	0.15	0.10	0.42				
	RI=0.9, λ_{max} =4.17, CR=0.06							

4 Results

4.1 Analysis of FVI indicators

4.1.1 Flood exposure

Average elevation of terrain (AET): Areas with higher elevation have lesser chances of holding the excess water (causing the flooding) and consequently the vulnerability decreases. AET is of importance when considering flood vulnerability since the topography is the key factor that directly influences on the level damage, as well as the ability to cope and recover after flooding. The AET was calculated using the 10-m DEM data. The DEM surface and the administrative map of Hoi An were imported to GRASS GIS open-source software for calculation of the average elevation by commune. The calculation process was carried out using the Overlay Raster Statistic tool in GRASS GIS with the command of *r.stats.zonal* and the method of statistic called *average*. According to the result (Fig. 3a), the average of elevation of the northwest part of Hoi An is higher than other parts.

Average distance to Thu Bon River (DR) The excess water-flow of Thu Bon mainstream causes most floods in Hoi An. The closer the distance to Thu Bon mainstream, the higher the vulnerability of a ward or commune to floods. The DR data were generated by calculating the Euclidean distance to the river’s mainstream using the *r.grow.distance* tool in GRASS GIS (Fig. 3b). The river network was extracted from hydrology data that was provided by Quang Nam DONRE and then was used as input data source for calculation of

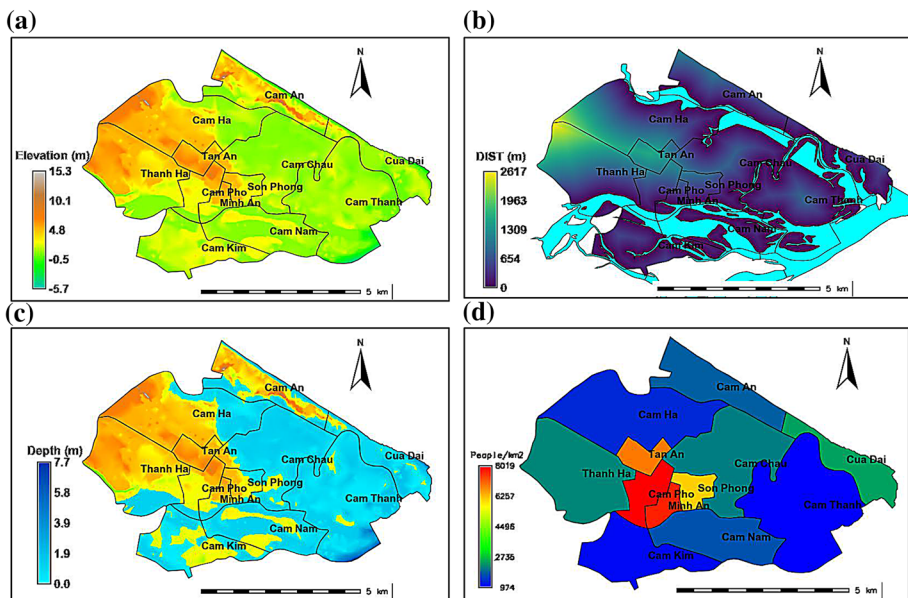


Fig. 3 Calculation of a digital elevation model (DEM) 10 m resolution of Hoi An, **b** distance to river channels using DEM and river network (*r.grow.distance*), **c** flood extension and depth in the scenario that 2 m water rising from river channels (*r.lake.series*), **d** population density by wards/communes (Data source: Quang Nam DONRE; the People’s Committee of Hoi An city)

DR. The zonal statistical method (*r.stats.zonal*) was applied again for calculation of average distance to river's mainstream by commune/ward.

Percentage of flooded area (FA) FA is the percentage of land area susceptible to being inundated by water from any source. FA data have been generated based on water filling algorithm that is implemented as *r.lake.series* module in GRASS GIS software. The *r.lake.series* model fills a lake or any area from a given starting point or river based on the elevation of surrounding areas. The module generates different scenarios of flood inundation containing filled areas for each specified water level which rises from the seeds (river channels). This model requires the DEM data and the river network as input for the elevation-based flood inundation model. According to the Quang Nam Commanding Committee for Disaster Prevention and Evacuation (PCTT 2013) the highest historical flood water depth in Hoi An was 2 m. Therefore, we applied 2 m as input water level parameter for *r.lake.series* model. As a result, the flood extension map along with its corresponding water depth has been created. Subsequently, by using the zonal statistic with the method of cell count, the FA values have been generated for each ward/commune.

Average floodwater depth (FWD) The depth of floodwater has a huge impact on what could be affected in a flood, as even a few inches of water can cause major damage and require costly repairs or replacement of items (Baky et al. 2019). The higher a flood depth, the more damage it can cause. FWD was collected from the output of *r.lake.series* model that have been explained in the previous session. The FWD data were then calculated in a GIS environment by overlaying between the water depth and the Hoi An administrative maps using the zonal statistic tool (*r.stats.zonal*). The result of FWD (Fig. 3c) is validated by surveying representatives of 12 wards and communes; accordingly, the south and south-east parts of Hoi An have the highest floodwater depth.

Flood frequency (FF) The FF values represent for flood occurrence history which is the total number of floods in 5 years (2016–2020). FE in this research is considered as an indicator that can increase the vulnerability rather than an as an indicator that reflects people's past experiences. EF was calculated by summing the total number of floods that occurred from 2016 to 2020 in Hoi An as per local statistics and representatives of wards and communes survey. According to experts and civil servants, FF is an important indicator because it reflects the flood situation over the years which can represent the level of exposure of each ward and commune.

Population density (POP) Population density is the number of individuals per unit geographic area, but in this research, it was number of individuals per square kilometer. The population growth and distribution, especially increased population density, can increase the vulnerability to disasters (Perrow 2007). According to the 2020 statistical yearbook, the central wards such as Minh An, Cam Pho, Son Phong, and Tan An have the highest population densities (Fig. 3d).

Built-up area (BU) Built-up area is defined as the presence of buildings or roofed structures. This indicator includes construction works for specific purposes of citizens and exclude other parts of urban environments or human footprint such as paved surfaces (roads, parking lots), commercial and industrial sites (ports, landfills, quarries, runways) and urban green spaces (parks, gardens). Built up area has positive relationship with vulnerability, because this indicator can be seen as a sign of population concentration in a certain area. Furthermore, when natural disasters occur in a region with high percentage of built-up area, it can cause great damage to the local economy.

Agricultural and fishery area (AFA) Agriculture, fisheries and agricultural/fishing-dependent people are often located in areas that are at particularly high risk of flooding. AFA is an indicator that needs to be considered because, other than being known as a city

famous for historical sites, Hoi An is also a coastal city which has a large portion of its population depending on agriculture and fishing for living. AFA was calculated by taking the percentage of agricultural and fishery area in the total area of each ward/commune.

4.1.2 Flood susceptibility

Number of private businesses (PRB) Private business represents work in the private sector which represents the segment of the economy owned and operated by individuals and for-profit companies. In this research, the number of private businesses is the sum of the number of private businesses operating in the industrial sector and the number of private businesses operating in the service sector as of December 31, 2020. The greater the number of private business in the ward/commune, the greater the economic loss of this ward/commune when a natural flood occur.

Number of historical sites (HIS) Historical sites need particular attention in flood management, not only because they have high and irreplaceable cultural value, but also considering the constructive typologies that they host, they are particularly sensitive to natural hazards (Fabiana and Tiago 2019). Hoi An has 23 sites that have been certified as national-historical site and 47 sites that have been certified as provincial-historical site by the Ministry of Culture, Sports and Tourism of Vietnam as in 2020. The higher the HIS value in the ward, the greater the risk of damage.

Poor and near poor households (PH) According to article number 2, decision number 59/2015/QĐ-TTĐ by the Vietnamese Government (2015) on the poverty line applied for the period 2016–2020, in urban areas, households with average income per month less than 700,000 Vietnamese Dong are considered poor; meanwhile, near-poor households are those with monthly income of 700,000 Vietnamese Dong to 1 million Vietnamese Dong. According to experts and civil servants, PH is an important indicator reflecting the sensitivity of the local community in terms of economy, and social and health aspects.

Percentage of kindergarten pupils, elderly people (> 80 years old) and disabled people (VUL) The scientific basis of the selection of these data is research of social vulnerability to flood in which children, especially kindergarten pupils, older adults, the sick, and disabled people, who have low ability to self-evacuate and self-care, compared to others (Mason et al. 2021).

Unemployment rate (UER) UER has close relationship to vulnerability as the higher the unemployment rate, the greater the vulnerability. A poorly adaptive management can cause social problems financial difficulties related to the budget; consequently, the unemployment rate and income gap may get expanded, the social welfare can be reduced (Kimura 2019).

Average income per person per year (INC) Income contributes to an individual's ability to prepare for a flood and rebuild (Rasch 2015). The per capita income of a ward or commune shows its economic potential, which is related to the resilience of the economy after floods. INC was collected by surveying representatives of 12 wards and communes.

4.1.3 Flood resilience

Number of people joining in flood mitigation training (EDU) EDU reflects the level of concern of local citizens and the capacity to respond to floods. The higher the EDU, the lower the vulnerability. In this research, EDU is the total number of citizens who attended the trainings in 2019 and 2020 (Fig. 4).

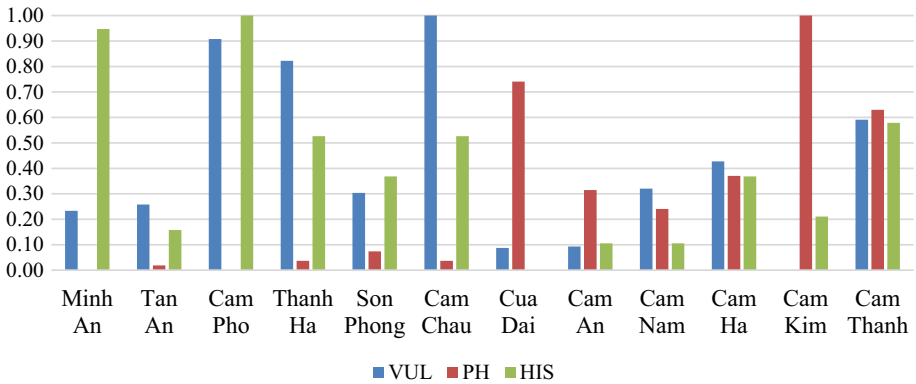


Fig. 4 Normalized value of HIS, VUL and PH indicators in Hoi An city

Road density (RD) The OSM data were downloaded and then imported to GIS environment for updating the total road length and the road density by commune. The zonal statistics method was applied in GIS to take the road length by commune with the based map is the administrative map and the cover map is the road map for Hoi An. These values of road length by ward/commune then were divided into the area of each ward/commune to get the road density. RD is a moderate important indicator of resilience component since it reflects the government’s investment in before-flood management, the local capacity to evacuate during flood, and to provide aid and recover after-flood. The result (Fig. 5) shows that central area has better transportation infrastructure, because it is the concentration of many economic and social activities.

Number of organizations in disaster prevention and historical preservation (ORG) ORG includes government-run organizations, and non-governmental or non-profit

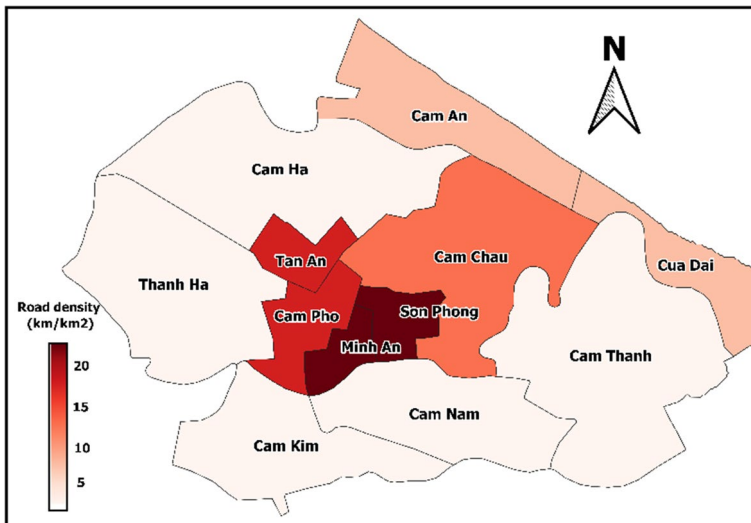


Fig. 5 Road density across wards and communes

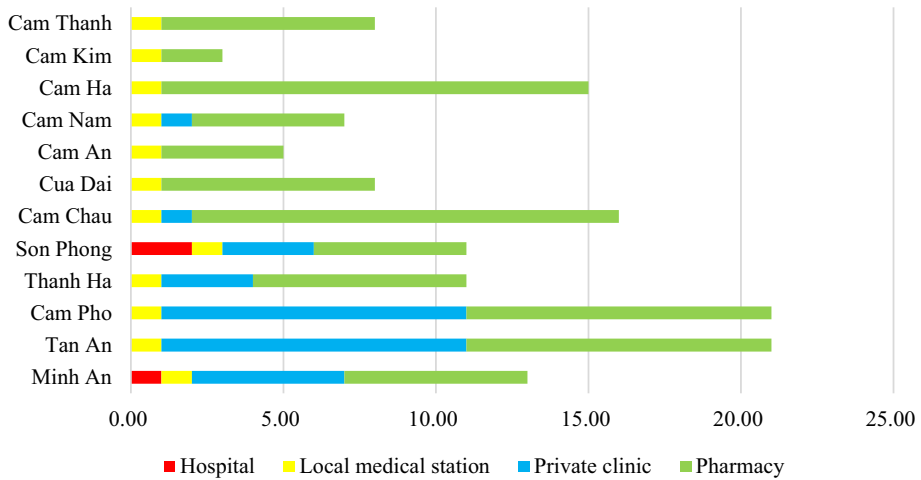


Fig. 6 Number of health services (both governmental-owned and privately-owned) across wards and commune

organizations working in disaster prevention and historical sites preservation in each ward and commune. A community with a higher ORG can increase its ability to adapt and respond to natural disasters (Hoffmann and Blecha 2020). The presence of disaster prevention organizations reflects human resources with experience and expertise in disaster response and mitigation. Moreover, the existence of organizations specializing in historical sites preservation also contributes to protecting important cultural-historical values of locality, increasing emergency response capacity and reducing damage. From such reasons, ORG is assessed as the most important among criteria of resilience.

Number of health services (HE) HE includes all hospitals, clinics, and pharmacies according to statistics from the Health Department of the People's Committee of Hoi An city. As reported by the Health Department, there has never been any risk of disease arising from local floods. However, HE reflects the accessibility of local people to health care services. The presence of medical facilities in the locality also increases adaptability and resilience in responding to emergencies. Son Phong and Minh An are the two wards with hospitals, which area fully equipped, with medical facilities and highly skilled doctors in various fields. Other wards have 1 medical station, none to 1 doctor and 2–5 medical staffs. The distribution of pharmacies is also uneven between wards and communes, with most of them being located in Tan An, Cam Pho, Cam Chau and Cam Ha (Fig. 6).

4.2 Flood vulnerability index computation

The values of E , S and R were calculated by multiplying the normalized value of each indicator with its corresponding weight as shown in Table 1; accordingly, the presence of historical sites, number of organizations in disaster prevention and historical site preservation, road density, number of poor households, average elevation and flood

frequency were found to be the key factors affecting the vulnerability to flood hazard of wards and communes in Hoi An.

The vulnerability with emphasis on exposure was obtained by using Eq. (5), and the vulnerability with emphasis on resilience was calculated via Eq. (6), while the integrated FVI value was achieved by integrating flood exposure, susceptibility and resilience components as in Eq. (7)

$$\text{Vulnerability with emphasize on Exposure } (V_E) = \frac{E + S}{2} \tag{5}$$

$$\text{Vulnerability with emphasize on Resilience } (V_R) = \frac{S + R}{2} \tag{6}$$

$$\text{FVI} = \frac{(E + S + R)}{3} \tag{7}$$

The vulnerability values were converted into a standard scale from 0 to 1 employing maximum-minimum normalization (Table 2) before being classified into five categories by manual classification method (Samanta et al. 2016): Very low (<0.2), low (0.20 – <0.40), medium (0.40 – <0.60), high (0.60 – <0.80), very high (>=0.80) (Fig. 7).

4.3 Visualization of flood vulnerability

According to the spatial distribution of the vulnerability in 3 scenarios (Fig. 7), it is clear that not every area experiencing severe flooding has a high level of vulnerability, and the investment in local adaptation capacity can change the vulnerability. The central wards as Minh An and Cam Pho have high concentration of historical sites, and their exposure to

Table 2 FVI in different scenarios

Ward/commune	<i>E</i>	<i>S</i>	<i>R</i>	<i>V_R</i>	<i>V_E</i>	FVI	Normalized <i>V_R</i>	Normalized <i>V_E</i>	Normalized FVI
Minh An	0.68	0.48	0.56	0.52	0.58	0.57	0.56	0.85	0.68
Tan An	0.27	0.20	0.48	0.34	0.23	0.31	0.00	0.00	0.00
Cam Pho	0.66	0.61	0.42	0.52	0.63	0.56	0.54	0.97	0.65
Thanh Ha	0.56	0.47	0.50	0.49	0.52	0.51	0.45	0.69	0.52
Son Phong	0.64	0.23	0.46	0.35	0.43	0.44	0.03	0.49	0.34
Cam Chau	0.61	0.42	0.42	0.42	0.52	0.48	0.25	0.69	0.44
Cua Dai	0.48	0.19	0.74	0.47	0.34	0.47	0.39	0.25	0.41
Cam An	0.30	0.19	0.79	0.49	0.24	0.42	0.45	0.03	0.29
Cam Nam	0.75	0.22	0.81	0.52	0.48	0.59	0.54	0.61	0.73
Cam Ha	0.34	0.40	0.75	0.58	0.37	0.50	0.73	0.33	0.48
Cam Kim	0.75	0.37	0.96	0.67	0.56	0.70	1.00	0.80	1.00
Cam Thanh	0.69	0.59	0.72	0.66	0.64	0.67	0.96	1.00	0.93

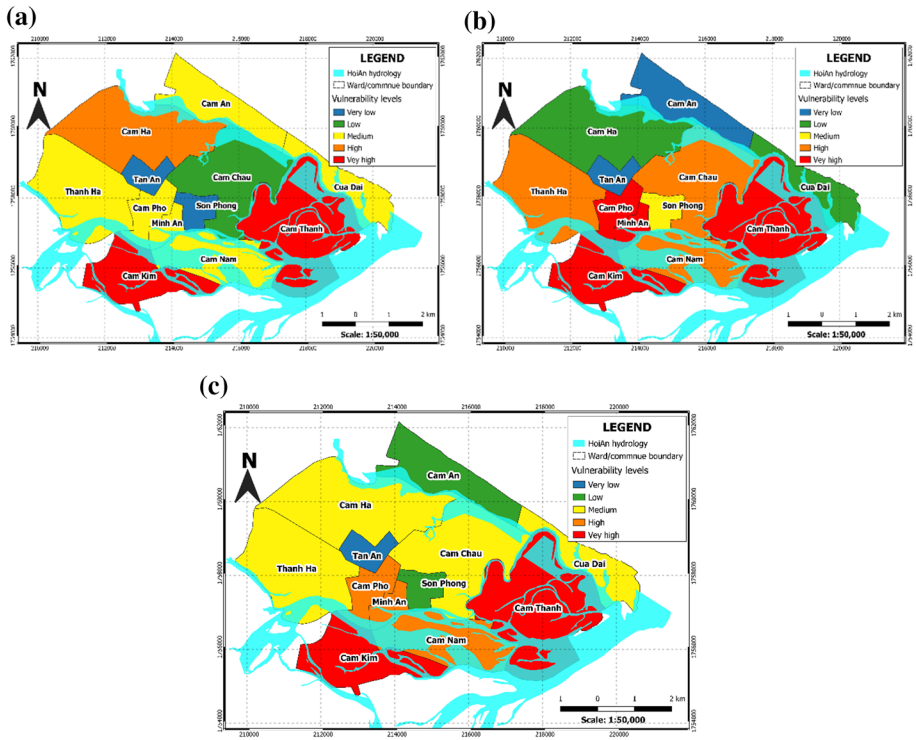


Fig. 7 Flood vulnerability in **a** Scenario 1—Flood vulnerability with emphasis on the level of resilience, **b** Scenario 2—Flood vulnerability with emphasis on the level of exposure, **c** Scenario 3—Integrated flood vulnerability

flood are very high, but the wards' investment on mitigation actions effectively reduces their integrated vulnerability by one rank. Cam Kim and Cam Thuan need to be more careful on finding appropriate flood-related policy since their level of vulnerability are ranked first in all scenarios. The results of exposure level in Minh An, Cam Kim, Cam Thuan and Cam Pho are understandable since these wards are located nearby the mainstream of the Thu Bon River with relatively low elevation. The reduction in vulnerability due to the effects of adaptation are also observed in Thanh Ha, Cam Chau and Son Phong. Except for Cam Nam and Tan An, there are no change in the vulnerability; the remaining wards/communes witness an increase in FVI values due to insufficient adaptability.

4.4 Validation of vulnerability maps

There has been no well-defined method that could completely validate the procedure of flood vulnerability mapping. However, qualitative validation methods were adopted by many scholars through historical flood inventory data (El-Magd 2019; Haltas et al. 2021; Samanta et al. 2018). The historical flood inventory data including 48 flood survey point in Hoi An City are used for validation of the vulnerability map developed from this research. These field survey point data were published by the Quang Nam Commanding Committee

Table 3 Statistics of historical flood inventory data for Hoi An by ward/commune

Ward/commune	Average water depth (m)	Number of points
Cam Chau	0.28	4
Cam Kim	1.68	9
Cam Nam	0.74	10
Cam Pho	1.20	6
Cam Thanh	0.40	4
Minh An	1.51	8
Thanh Ha	1.33	7
Total field survey points		48

for Disaster Prevention and Evacuation. These survey points present the location as well as the water depth recorded by the flood event in 2013. All of the flood survey points are located in the high and very high level in flood vulnerability map which emphasizes on the level of exposure (48/48 points) as provided in Table 3. There are also 38/48 of survey points belong to the high and very high level in the flood vulnerability map. The vulnerability map with emphasis on exposure component demonstrates that the southern portion of the subject locality was high to very high exposed regions, which were similar to the results obtained from the field observation in the 2013 flood (Fig. 8).

5 Discussion and conclusion

5.1 Innovation and limitation

To identify FVI, this paper determined three components, including exposure, susceptibility and resilience, which have been widely used in recent studies; however, many efforts have been made to improving the selection of FVI indicators, increasing the reliability of AHP hierarchy's initial assessments, and generating maps that clearly shows the difference before and after resilience actions. These improvements have contributed to overcoming the shortcomings in some recent studies that undertook the indicator-based approach in flood vulnerability assessment. Nasiri et al. (2018) applied the combination of three components and identified FVI for 6 districts in Kula Lumpur city through assessing 10 indicators over exposure, susceptibility, and resilience components. This research later developed a framework for district flood vulnerability index assessment as a policy-making tool in Malaysia; however, it did not answer the question of how meaningful FVI assessment could be when the most exposure areas always could be the most vulnerable in the vulnerability map. The research done by Hussain et al. (2021) in Shangla Pakistan partially solved the question left by Nasiri et al. (2018) by creating three vulnerability maps on physical, socio-economic and coping capacity aspects. These maps are more applicable for decision-making process in practice; however, Hussain's study did not clarify the method of selecting the appropriate criteria for the study area except mentioned reviewing previous literature and considering data availability. In Vietnam, three studies on flood vulnerability have been carried out at urban scale so far, including the assessment of vulnerability to high floods in An Giang province (Van et al. 2019), flood vulnerability assessment in Mai Hoa Commune, Tuyen Hoa District (Chung and Bao, 2019), flood vulnerability in Hoa

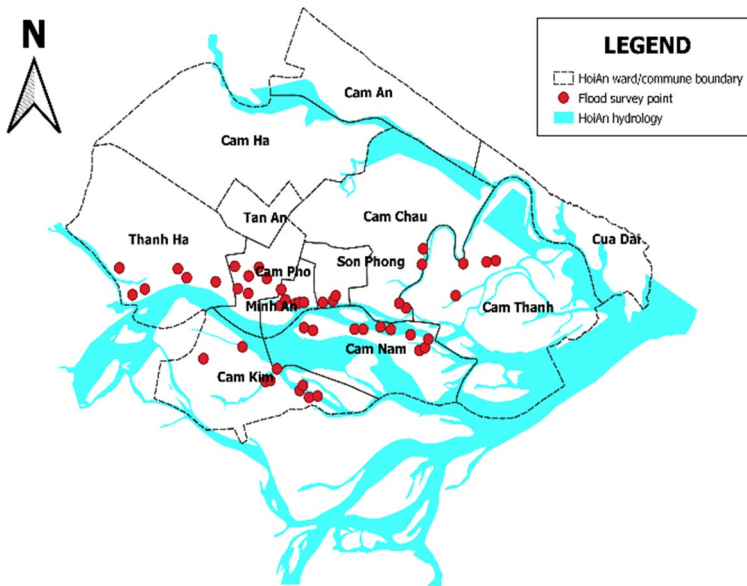


Fig. 8 Flood survey points by Quang Nam Commanding Committee for Disaster Prevention and Evacuation in 2013

Vang District (Tran et al. 2021). These studies also reflect the major limitation in that the areas most exposed are also the most vulnerable. Therefore, the practice of conducting surveys with the participation of local experts and civil servants in this research improved the suitability of indicators system and corresponding weights of all indicators. Besides, the involvement and consensus from local officials also increases the applicability of vulnerability maps when being applied in practice. Moreover, different vulnerability maps with focus on exposure and resilience components were separately created to clearly show that having more floods does not always mean having high vulnerability and vice versa.

Although the paper aims at providing a reference of indicators used for flood vulnerability assessment in the area of heritage sites, it faces geographical limitation. However, the very inclusion of the heritage sites in susceptibility in this research made the FVI results reflect the multi-dimensional value system for the region. In other words, this research contributes to the first step of innovation but there is a need for more empirical studies to generalize the results for the generalized implication for policy-making. The findings of this research can be used as a reference for flood vulnerability assessment in other localities which have the same socio-economic and environmental conditions and backgrounds; or can be used to compare with future studies of the same research direction.

5.2 Conclusion and future research

Flood has become a serious natural hazards in many urban area, many of which are not only places of socio-economic activities, but also places where own and preserve important intangible cultural and historical values that can never be replicated. Besides, the vulnerability of each community or system to floods is not identical; therefore, research on vulnerability should be localized, as this practice can make the policy making process more accurate. Through inputs from experts and civil servants of Hoi An, this research particularly found that road density, number of organizations in disaster prevention and historical sites preservation are the most critical factors influencing the resilience; the presence of historical sites is the most critical factors influencing the susceptibility; number of poor/near poor households is an important factor when considering the susceptibility in developing countries; the average elevation and flood frequency are the key factors affecting the exposure to flood of the research site.

Based on the empirical results, we propose a wide range of policies and suggest priority of investment to reduce flood vulnerability. Minh An, and Cam Pho are highly vulnerable to flood even though the local authorities have devoted attention in building resilience in recent years. Being the central wards with the highest concentration of national historical sites, Minh An and Cam Pho should devote more attention on climate-proofing structures. The deserved investment on this issue can protect highly cultural-valued sites, ensure the safety of local residents and tourist. Moreover, the number of people participating in flood training courses in Minh An is still small compared to other wards, reflecting the ineffectiveness of communication on disaster risk. Cam Kim and Cam Thanh are the top wards in terms of very high vulnerability. One of the important reasons lies in the high unemployment rates, which explains the low per capita income annually. These wards and communes urgently need policies to help promote economic development, and to especially encourage private enterprises to create jobs for local workers. The policy of local economic development can help prevent labour migration and settlement in other areas, thereby changing the status of the high proportion of elderly and disabled people that cause burdens on local health services which are also poor. Although Cam Nam has relatively high resilience, the final vulnerability of this ward remains unchanged because of the lack transport infrastructures upgrading actions. The relative low terrain and the large proportion of preschool age residents explain the high vulnerability of Cam Chau and Son Phong. However, the synchronous investments in the economy, education, infrastructures and health services have reduced the wards' FVI value by one rank; these proper investments should be continued. Son Phong has the highest road density in Hoi An, which is very beneficial in providing relief during or after emergency situations and in facilitating the evacuation process. Thanh Ha has the advantage of a young population, many private businesses, but the participation of local people in trainings programs are relatively low. It is necessary to have propaganda campaigns perhaps through compulsory education or media channels to increase people's interest and awareness about flood prevention. Cam An needs to improve further in terms of its transportation system and number of healthcare services, especially hospitals or clinics, while investment in traffic and education are in need in the case of Cam Ha. Cua Dai should focus more on the construction of health care services, and organization of training programs on disaster reduction.

Since this research faced geographical limitation as mentioned before, future research or case studies with the same research direction are necessary to form a global perspective on flood vulnerability assessment in the area of cultural heritage sites across the world. In addition, new approaches or methods to improve the potential subjectivity when conducting expert's survey to identify the weights for indicators are also needed to be figured out in the future. Lastly, the findings of this Hoi An case study could be an extraordinary literature for future research in analysing the cost–benefit or effectiveness of policies reducing the flood vulnerability since this study's focus is to develop the indicators set to assess flood vulnerability index at local scale in cultural heritage areas and to reveal the factors affecting the vulnerability.

Appendix 1

See Tables [4](#), [5](#), [6](#), [7](#), [8](#), [9](#), [10](#) and [11](#)

Table 4 Some characteristics of the study areas

Ward/commune	Total area (ha)	Build-up area (%)	Pop dense (pp/km ²)	Elevation of terrain (m)	Average distance to the main stream of Thu Bon River (m)
Minh An	70.20	40.36	7726.20	3.30	187.20
Tan An	133.76	45.72	6910.02	5.58	1479.43
Cam Pho	116.49	31.33	8019.37	3.47	530.70
Thanh Ha	615.61	20.99	2216.68	3.90	943.03
Son Phong	67.57	43.60	6127.28	3.14	543.74
Cam Chau	608.68	16.65	2121.80	1.15	1581.93
Cua Dai	242.94	38.91	2452.90	1.01	1320.39
Cam An	355.70	33.99	1842.28	2.96	3636.73
Cam Nam	407.58	13.98	1729.23	1.29	38.11
Cam Ha	703.96	11.53	1350.50	3.80	2625.58
Cam Kim	419.11	5.83	1056.76	1.73	134.25
Cam Thanh	970.42	10.76	974.32	0.89	680.15

Table 5 Indicators and their functional relationship with FVI

FVI component	Indicator	Unit	Abbreviation	Functional relationship with FVI (\pm)	
<i>E</i>	Average elevation of terrain	Meter	AET	-	
	Average distance to the mainstream of Thu Bon River	Meter	DR	-	
	Percentage of flooded area	%	FA	+	
	Average floodwater depth	Meter	FWD	+	
	Flood frequency (average in 5 years 2016–2020)	-	FF	+	
	Population density	People/km ²	POP	+	
	% Build-up area	%	BU	+	
	% Agricultural and fishery area	%	AFA	+	
	Number of private business	-	PRB	+	
	Number of historical sites	-	HIS	+	
<i>S</i>	Poor/near poor households	-	PH	+	
	% Kindergarten pupils, elderly and disable people	%	VUL	+	
	Unemployment rate	%	UER	+	
	Average income	Million VND/pp/year	INC	-	
	Number of people join in trainings	-	EDU	-	
	Road density	km/km	RD	-	
	Organizations in disaster prevention and historical preservation	-	ORG	-	
	Number of health services	-	HE	-	
	<i>R</i>				

Table 6 Normalized value of flood exposure’s indicators

Wards/Communes	AET	DR	FA	FWD	FF	POP	BU	AFA
Minh An	0.49	0.96	0.04	0.80	1.00	0.96	0.87	0.00
Tan An	0.00	0.60	0.00	0.00	0.00	0.84	1.00	0.15
Cam Pho	0.45	0.86	0.03	0.80	1.00	1.00	0.64	0.11
Thanh Ha	0.36	0.75	0.08	0.70	1.00	0.18	0.38	0.59
Son Phong	0.52	0.86	0.07	0.50	0.93	0.73	0.95	0.22
Cam Chau	0.94	0.57	0.47	0.60	0.93	0.16	0.27	0.35
Cua Dai	0.97	0.64	0.46	0.20	0.33	0.21	0.83	0.05
Cam An	0.56	0.00	0.22	0.20	0.33	0.12	0.71	0.30
Cam Nam	0.91	1.00	0.50	1.00	1.00	0.11	0.20	0.62
Cam Ha	0.38	0.28	0.26	0.60	0.33	0.05	0.14	0.64
Cam Kim	0.82	0.97	0.62	1.00	1.00	0.01	0.00	1.00
Cam Thanh	1.00	0.82	1.00	0.60	0.93	0.00	0.12	0.44

Table 7 Normalized value of flood susceptibility’s indicators

Wards/Communes	PRB	HIS	PH	VUL	UER	INC
Minh An	1.00	0.95	0.00	0.23	0.72	0.00
Tan An	0.15	0.16	0.02	0.26	0.65	0.16
Cam Pho	0.36	1.00	0.00	0.91	0.07	1.00
Thanh Ha	0.38	0.53	0.04	0.82	0.53	0.55
Son Phong	0.19	0.37	0.07	0.30	0.36	0.03
Cam Chau	0.29	0.53	0.04	1.00	0.48	0.06
Cua Dai	0.10	0.00	0.74	0.09	0.00	0.09
Cam An	0.10	0.11	0.31	0.09	0.55	0.09
Cam Nam	0.00	0.11	0.24	0.32	0.31	0.42
Cam Ha	0.09	0.37	0.37	0.43	0.36	0.81
Cam Kim	0.00	0.21	1.00	0.00	0.32	0.67
Cam Thanh	0.22	0.58	0.63	0.59	1.00	0.64

Table 8 Normalized value of flood resilience’s indicators

Wards/Communes	ORG	RD	EDU	HE
Minh An	0.85	0.16	0.73	0.39
Tan An	0.60	0.38	0.68	0.00
Cam Pho	0.39	0.39	0.88	0.00
Thanh Ha	0.00	0.95	0.86	0.61
Son Phong	0.99	0.00	0.00	0.46
Cam Chau	0.14	0.55	0.85	0.50
Cua Dai	0.67	0.69	1.00	0.82
Cam An	0.79	0.72	0.84	0.93
Cam Nam	0.62	1.00	0.91	0.82
Cam Ha	0.54	0.98	0.99	0.57
Cam Kim	1.00	0.94	0.89	1.00
Cam Thanh	0.41	0.98	0.91	0.82

Table 9 Weights of flood exposure indicators by AHP

E	AET		FF		DR		FA		FWD		POP		BU		AFA		W _j
	PC	NV	PC	NV	PC	NV	PC	NV	PC	NV	PC	NV	PC	NV	PC	NV	
AET	1.00	0.16	0.67	0.15	1.50	0.20	1.50	0.15	1.50	0.15	1.50	0.15	1.50	0.13	2.00	0.20	0.16
FF	1.50	0.24	1.00	0.22	2.00	0.26	2.00	0.20	2.00	0.20	2.00	0.20	2.50	0.21	2.00	0.20	0.21
DR	0.67	0.11	0.50	0.11	1.00	0.13	2.00	0.20	2.00	0.20	2.00	0.20	1.50	0.13	1.00	0.10	0.15
FA	0.67	0.11	0.50	0.11	0.50	0.07	1.00	0.10	1.00	0.10	1.00	0.10	1.50	0.13	1.00	0.10	0.10
FWD	0.67	0.11	0.50	0.11	0.50	0.07	1.00	0.10	1.00	0.10	1.00	0.10	1.50	0.13	1.00	0.10	0.10
POP	0.67	0.11	0.50	0.11	0.50	0.07	1.00	0.10	1.00	0.10	1.00	0.10	1.50	0.13	1.00	0.10	0.10
BU	0.67	0.11	0.40	0.09	0.67	0.09	0.67	0.07	0.67	0.07	0.67	0.07	1.00	0.08	1.00	0.10	0.08
AFA	0.50	0.08	0.50	0.11	1.00	0.13	1.00	0.10	1.00	0.10	1.00	0.10	1.00	0.08	1.00	0.10	0.10
Sum	6.33	1.00	4.57	1.00	7.67	1.00	10.17	1.00	10.17	1.00	10.17	1.00	12.00	1.00	10.00	1.00	1.00

$$\lambda_{\max} = 0.16*6.33 + 0.21*4.57 + 0.15*7.67 + 0.10*10.17 + 0.10*10.17 + 0.10*10.17 + 0.10*10.17 + 0.08*12.00 + 0.10*10.00 = 8.13, RI = 1.41, CI = 0.02, CR = 0.01$$

PC pairwise comparison value, NV normalized value

Table 10 Weights of flood susceptibility indicators by AHP

<i>S</i>	HIS		PH		VUL		INC		PRB		UER		<i>W_j</i>
	PC	NV	PC	NV	PC	NV	PC	NV	PC	NV	PC	NV	
HIS	1.00	0.24	1.50	0.29	1.50	0.27	2.00	0.26	2.00	0.24	2.00	0.21	0.25
PH	0.67	0.16	1.00	0.19	1.00	0.18	1.50	0.20	2.00	0.24	2.00	0.21	0.20
VUL	1.00	0.24	1.00	0.19	1.00	0.18	1.50	0.20	1.50	0.18	1.50	0.16	0.19
INC	0.50	0.12	0.67	0.13	0.67	0.12	1.00	0.13	1.00	0.12	1.50	0.16	0.13
PRB	0.50	0.12	0.50	0.10	0.67	0.12	1.00	0.13	1.00	0.12	1.50	0.16	0.12
UER	0.50	0.12	0.50	0.10	0.67	0.12	0.67	0.09	0.67	0.08	1.00	0.11	0.10
Sum	4.17	1.00	5.17	1.00	5.50	1.00	7.67	1.00	8.17	1.00	9.50	1.00	1.00

$\lambda_{\max} = 0.25 \times 4.17 + 0.20 \times 5.17 + 0.19 \times 5.50 + 0.13 \times 7.67 + 0.12 \times 8.17 + 0.10 \times 9.50 = 6.12$, $RI = 1.24$, $CI = 0.02$, $CR = 0.02$

PC pairwise comparison value, NV normalized value

Table 11 Weights of flood resilience indicators by AHP

AC	ORG		RD		EDU		HE		<i>W_j</i>
	PC	NV	PC	NV	PC	NV	PC	NV	
ORG	1.00	0.46	2.00	0.56	3.00	0.40	3.00	0.30	0.43
RD	0.50	0.23	1.00	0.28	3.00	0.40	4.00	0.40	0.33
EDU	0.33	0.15	0.33	0.09	1.00	0.13	2.00	0.20	0.15
HE	0.33	0.15	0.25	0.07	0.50	0.07	1.00	0.10	0.10
Sum	2.17	1.00	3.58	1.00	7.50	1.00	10.00	1.00	1.00

$\lambda_{\max} = 0.43 \times 2.17 + 0.33 \times 3.58 + 0.15 \times 7.50 + 0.10 \times 10.00 = 4.17$, $RI = 0.90$, $CI = 0.06$, $CR = 0.06$

PC pairwise comparison value, NV normalized value

Appendix 2

See Tables 12 and 13

Table 12 Saaty rating scale (Saaty 1990)

Numeric value	Intensity of important	Explanation
1	Equal important	Two factors contribute equally to the objective
3	Moderate important	Experience and judgement slightly favor one over the other
5	Strong important	Experience and judgement strongly favor one over the other
7	Very strong important	Experience and judgement very strongly favor one over the other. Its importance is demonstrated in practice
9	Extreme important	The evidence favoring one over the other is of the highest possible validity
2, 4, 6, 8	Intermediate values	When compromise is needed
1/3, 1/5, 1/7, 1/9	Value for inverse comparison	

Table 13 Experts survey form (excerpt)

A Options	Extremely	Very Strongly	Strongly	Moderately	Equally	Moderately	Strongly	Very Strongly	Extremely	B Options								
Average elevation of terrain	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Average distance to the mainstream of Thu Bon River
Average distance to the mainstream of Thu Bon River	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Percentage of flooded area

Given Options A and B, you can judge their relative importance as shown below example:

If you think the option 'Average elevation of terrain' in column **A** is strongly more important than the option 'Average distance to the mainstream of Thu Bon River' in column **B**, then you mark 5 with (X) on the left hand side. If you think the option 'Percentage of flooded area' in column **B** is extremely more important than the option 'Average distance to the mainstream of Thu Bon River' in column **A**, then you mark 9 with (X) on the right hand side

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Data availability The administrative data at commune level for Hoi An city and the river network are available on DIVA-GIS spatial data at <https://www.diva-gis.org>. The Land use map, the Digital Elevation Model at resolution 10 m generated from 10,000 scale topographical map of Quang Nam Province provided by Quang Nam Department of Natural Resource and Environment; and all statistical data, associated metadata on socio-economic index of Hoi An are available at: https://www.mediafire.com/file/68ly315lei86sco/Data_in_Brief-Flood_vulnerability_Index_in_Hoi_An-Nguyen_et_al.rar/file. The road system data is available on Open Street Map at: <https://www.openstreetmap.org> and <https://www.re3data.org/search?query=openstreetmap&dataAccess%5B%5D=open>. The historical flood depth data at point location is published on the Vietnamese Government website of the Quang Nam Commanding Committee for Disaster Prevention and Evacuation at <http://www.pctt.quangnam.vn>.

Code availability Software Name: Quantum GIS, Availability: <https://qgis.org>, Hardware Requirements: None, Software Requirement: Web Browser, Cost: Free of Charge. GRASS GIS, Availability: <https://grass.osgeo.org>, Cost: Free of Charge.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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