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Flood vulnerability assessment at the local scale using remote sensing and GIS techniques: a case study in Da Nang City, Vietnam

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ABSTRACT

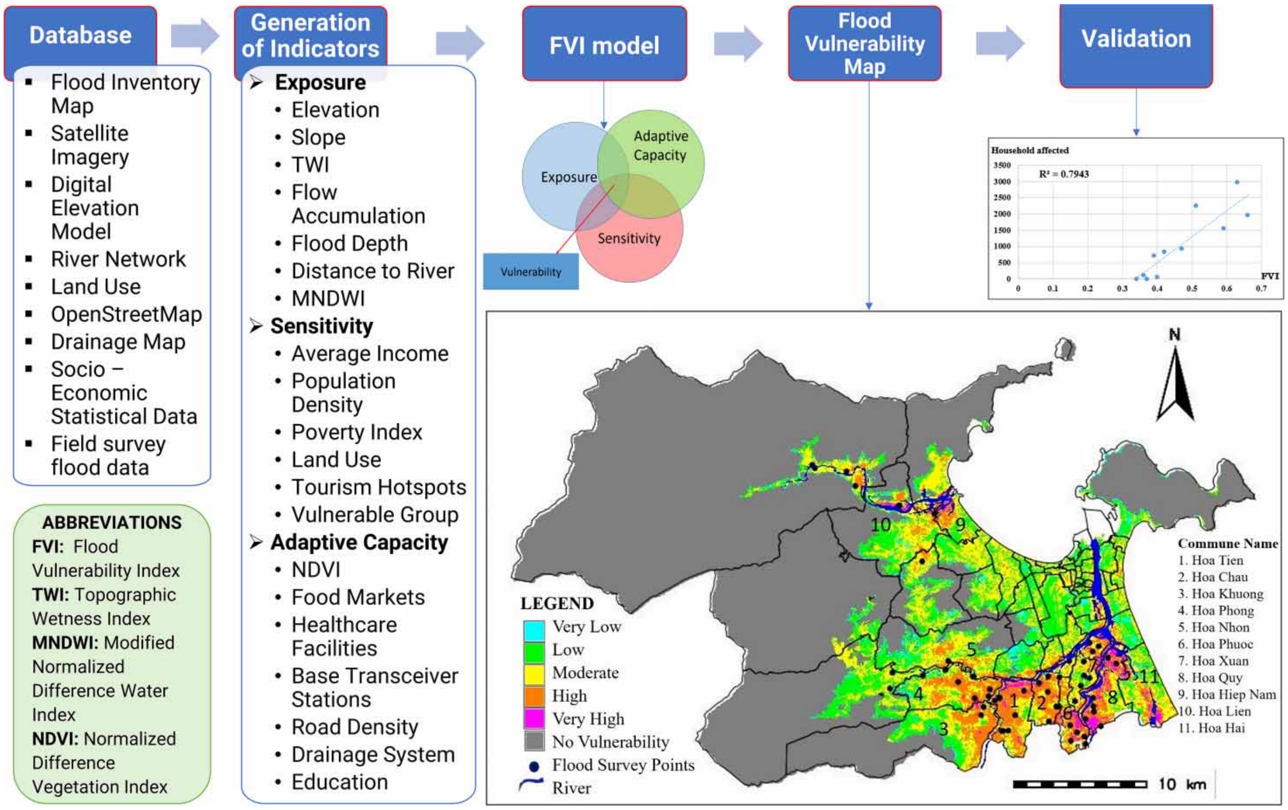
This paper has developed a cost-efficient framework for flood vulnerability assessment at a local scale using a multi-parametric approach integrated with the Open Source Geographical Information System (GIS) and Open Remote Sensing data. The study focuses on generating a set of criteria considering three dimensions of flood vulnerability: exposure, sensitivity, and adaptive capacity (AC) on an index-based approach. These indicators were decided based on a robust analysis considering the physical and socio-economic conditions of the study area. The flood exposure was generated from the geomorphological and hydrological parameters integrated with the flood water depth, the distance to river channels, and the Modified Normalized Difference Water Index. The flood sensitivity was determined by the aggregation of local income, land use, poverty index, population density, and other parameters reflecting the socio-economic condition. The AC has been evaluated based on the Normalized Difference Vegetation Index, the density of the community service facilities, and other factors related to the coping capacity to flood. Finally, the flood vulnerability at the local scale was determined based on the integration of its contributing factors using the Analytical Hierarchical Process-based aggregated model. Results indicated that a total of 20 parameters impacted the flood vulnerability of the research area. The findings also confirmed that among the indicators of flood vulnerability of Da Nang City, the flood depth, land-use condition, and drainage system are the key factors affecting the vulnerability level. The empirical assessment showed that the study area is significantly affected by flood vulnerability with more than 60% of the area having the vulnerability level from moderate to very high. In addition, this paper points out that the vulnerability research should be localized and is not always based on the administrative units. This practice can make the decision-making process and adaptation plan more appropriate locally. Especially, this study attempted to evaluate the accuracy of the flood vulnerability map for the first time by using field survey data and the statistical report on flood damage that most of the previous studies have not conducted yet. This framework provides a valuable toolkit for flood management in data-scarce regions all over the world.

Key words: adaptive capacity, Da Nang City, exposure, flood vulnerability, sensitivity

HIGHLIGHTS

- The generation of an indicator scheme for flood vulnerability assessment is performed.
- The indicators focus on the characteristics of the coastal lowland area as Da Nang City.
- The development of a framework for flood vulnerability assessment at a local scale is described.
- A good field survey data verification on flood hazard and vulnerability is carried out.
- Open Remote Sensing and GIS data sources and applications are used effectively in flood vulnerability assessment.

GRAPHICAL ABSTRACT



INTRODUCTION

Flooding has been recognized as one of the most devastating calamities among climate-induced natural disasters across many regions over the world. Under the context of recent climate change with occurrences of heavy rain and different climate stressors, floods have caused overwhelming loss for human society throughout history. Understanding of the flood impact in relation to climate change and unpredictable catastrophes has become an urgent need in many lowland regions worldwide. Various studies have attempted to identify flood-prone areas and evaluate the flood hazard potential on different scales from locally to regionally (Forkuo 2011; Ho & Umitsu 2011; De Risi *et al.* 2014; Do & Nagasawa 2014; Kazakis *et al.* 2015; Abdelkarim *et al.* 2020). However, fewer studies have comprehensively assessed the flood hazard in a vulnerable context which is more relevant to the community. The flood itself might not be a hazard since it sometimes can bring benefits to surrounding regions (FAO 2011) or less damage if the local community is well-resilient to flood. Assessing flood vulnerability has become a vital need in disaster risk management and developing strategies to mitigate the damage caused by floods.

There is still a significant research gap between flood hazard zonation and flood vulnerability assessment. While previous studies on flood hazard zonation have primarily focused on the physical vulnerability of floods and based on a pixel-based approach, research on flood vulnerability assessment focuses on the physical, social, and economic vulnerabilities as well, but the assessment is primarily based on an administrative scale, which is not always effective. Several methods for flood hazard assessment have been developed using various hydrological, meteorological, and geomorphological data (e.g., Ballais *et al.* 2005; Forkuo 2011; Manfreda *et al.* 2011; Kwak 2017). Some authors also tried to characterize the flood hazard potential using remote sensing and Geographical Information System (GIS) data. Kazakis *et al.* (2015) have developed an index-based approach for regional-scale flood hazard assessment in the Rhodope–Evros region, Greece, using multiple physical indicators extracted from remote sensing and GIS data including elevation, flow accumulation, slope, rainfall, land use, geology, and distance from the drainage network. This study, however, did not integrate the socio-economic data for flood hazard assessment, except the land use. Ho & Umitsu (2011) has developed a flood hazard map for Thu Bon alluvial plain, Vietnam, based on a landform classification utilizing the Shuttle Radar Topographic Mission (SRTM) and LANDSAT

ETM remote sensing data. Do & Nagasawa (2014) have generated the potential flood hazard map for the Hoa Chau commune in the Hoa Vang district, Da Nang City, Vietnam based on the integration of inundation and flow direction maps using the ALOS PALSAR remote-sensed and ASTER GDEM elevation data. Nguyen *et al.* (2021) have developed an observational network for a real-time flood warning system in the Vu Gia-Thu Bon river basin based on an automatic hydrometeorological approach. Although these studies have almost accurately identified the potential flood hazard areas, those studies mostly focused on evaluating the flood hazard exposure or partly combined with the social condition, mainly the land-use data with the lack of consideration of other aspects in the flood risk evaluation, especially the resilience and adaptive capacity (AC) of the community.

Recently, there have been several studies on flood vulnerability assessment considering not only flood exposure but also flood sensitivity and resiliences (Balica *et al.* 2012, Ouma & Tateishi 2014; Nasiri *et al.* 2016; Feyissal *et al.* 2018; Van *et al.* 2022). Understanding the vulnerability can help people proactively reduce the damage caused by the disasters by informing decision-makers or specific stakeholders about options for adapting to the impact of flood hazards (Douben 2006). Flood vulnerability is one of the significant components of risk management and flood damage assessment (Nasiri *et al.* 2016). Flood vulnerability is evaluated using the approach proposed by the Intergovernmental Panel on Climate Change (IPCC 2014), in which vulnerability is considered as a function of exposure, sensitivity, and AC (Figure 1). Exposure refers to 'the nature and degree to which a system is exposed to significant climatic variations'. Sensitivity refers to 'the degree to which a system is affected, either adversely or beneficially by climate-related stimuli'. AC refers to 'the ability of a system to adjust to climate change – including climate variability and extremes – to moderate potential damages, to take advantage of opportunities, or to cope with the consequences' (McCarthy *et al.* 2001). The flood vulnerability assessment has been more widely studied from various perspectives (McCarthy *et al.* 2001; Hinkel 2011, Balica *et al.* 2012, Feyissal *et al.* 2018). It has been guided by several global prestige organizations such as IPCC (2014) and UNESCO-IHE (http://unesco-ihe-fvi.org). Although all the contributing factors have been considered in flood vulnerability studies and generated a comprehensive index, those evaluations are mostly based on the administrative units with various scales from the national, provincial, and district to commune, so that the flood mitigation plan and the government investment budget are distributed based on these units. In fact, the vulnerability does not rely on such units but more respect for the community and local conditions. A commune might have varying levels of flood vulnerability, and therefore, the same action plan cannot be applied to the whole commune. Thus, it is of importance to evaluate the local flood vulnerability which considers both the local flood exposure and the socio-economic condition as well as the AC of each unit in a system based on a pixel-based approach.

This study aims to identify the flood vulnerable areas at a local scale according to the different susceptibility degrees under the impacts of the natural and socio-economic conditions. Our primary approach integrates GIS and satellite image processing combined with field survey data verification on an index-based approach. Such a process to assess the impact of natural disasters is considered as an effective way with the advantage of quick and accurate updating temporal and spatial changes of natural disasters. Specifically, we calculate the flood vulnerability index (FVI) from each component of the vulnerability function to assess flood impact quantitatively. This index is elaborated by the Analytical Hierarchical Process (AHP) (Saaty 2008) to determine the weights for component variables, thereby determining the FVI for each area. The output enables identifying areas with different flood vulnerability levels from low, moderate to high, and very high. As such, this study provides a baseline for proposing a number of adaptive solutions for areas under high flood vulnerability. The proposed flood vulnerability map is assessed by field survey data and the statistical report on flood damage that previous studies have never implemented. Our FVI toolkit is useful for assessing the urban flood vulnerability and facilitating the adaptation and coping capacities of the local communities.

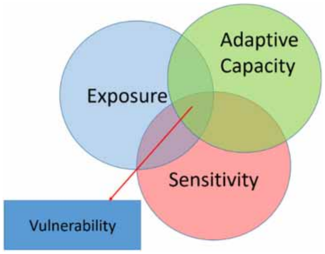


Figure 1 | Research approach for flood vulnerability assessment (adapted from IPCC 2014).

Case study

Vietnam is reported as one of the regions most affected by climate change and natural disasters (Eckstein *et al.* 2020). The areas in Central Vietnam, especially Da Nang and Quang Nam provinces located downstream of the Vu Gia – Thu Bon River system, have experienced several severe floods and are often inundated in the rainy season. Climate-induced flooding occurs almost annually in Da Nang City, especially under the impact of recent climate change, and the flood damage has become more exacerbated. We set a case study area in Da Nang City that has faced several historical floods causing huge damage to economic and urban life. A local government statistical report informed that from 1998 to 2020, flooding in Da Nang killed 83 people and injured 100 people, 15,633 households were affected, and 130,861 houses were destroyed leading to more than 2,600 billion Dongs economic loss (Figure 3). Flooding is the most devastating natural disaster in the history of Da Nang City. Assessing the socio-economic vulnerability of floods is vital in managing natural disaster risks and developing strategies to mitigate the damage caused by floods for Danang City. Previous studies only evaluated the vulnerability of Da Nang City based on quantitative analysis using statistical data on the damage caused by climate change and natural disasters on a provincial scale (ISET International and Da Nang City Government 2009; ISET International and Da Nang Climate Change Coordination Office (CCCO) 2017). This approach was costly, time-intensive, and labor-intensive by the statistical measurement and social surveys. In this sense, we develop a comprehensive flood vulnerability assessment method using GIS and remote sensing applications as an effective and cost-benefit approach that is easily applicable to developing countries such as Vietnam.

The study area comprises 960 km^2 of Da Nang City in seven inland districts (Figure 2). The Paracel Islands are excluded as this island is not affected by river floods. The study area is crossed by two main river systems (Cu De and Han Rivers). This area is characterized by two seasons: a rainy season from August to December and a dry season from January to July. This area is almost annually affected by typhoons and floods occurring mainly from September to December (Figure 3). The

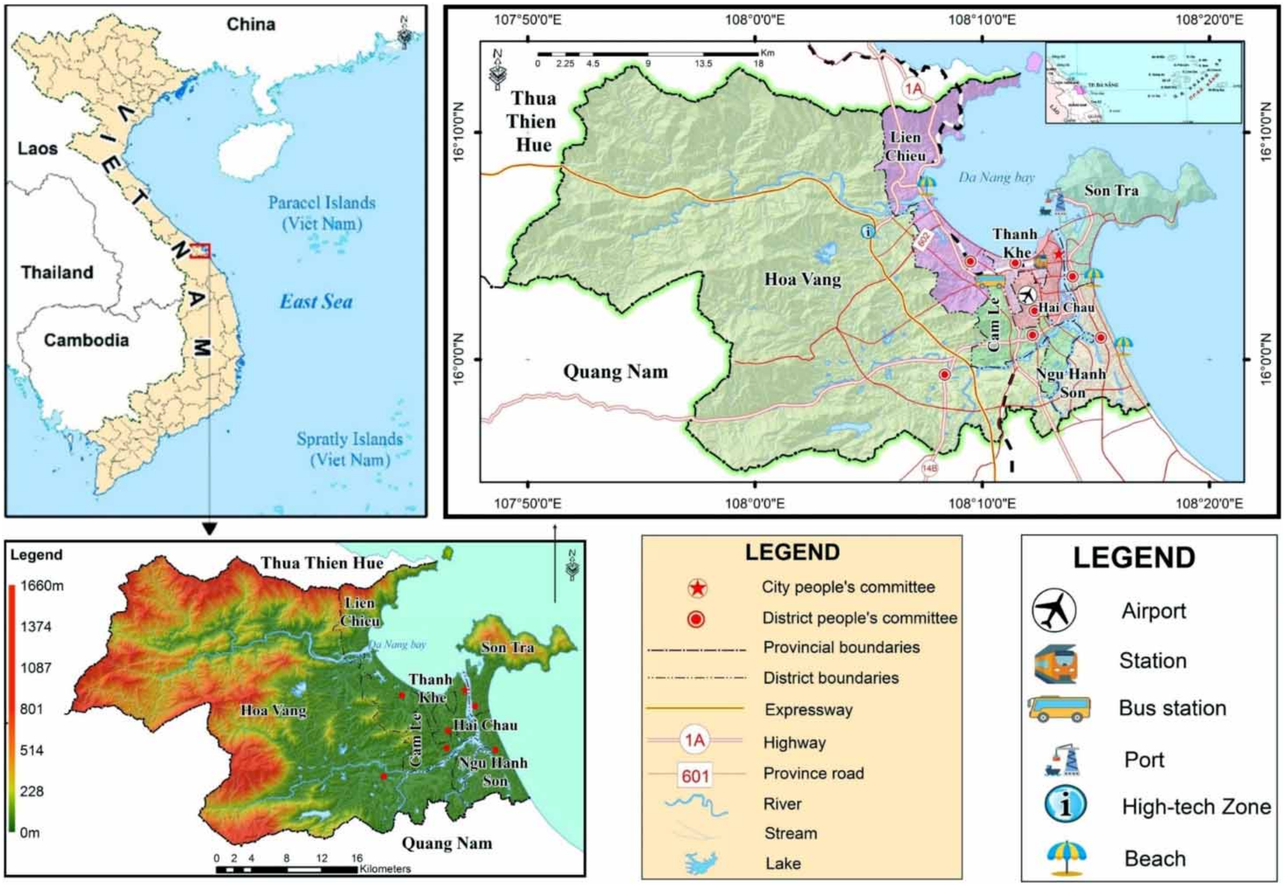


Figure 2 | Overviews of the study area.

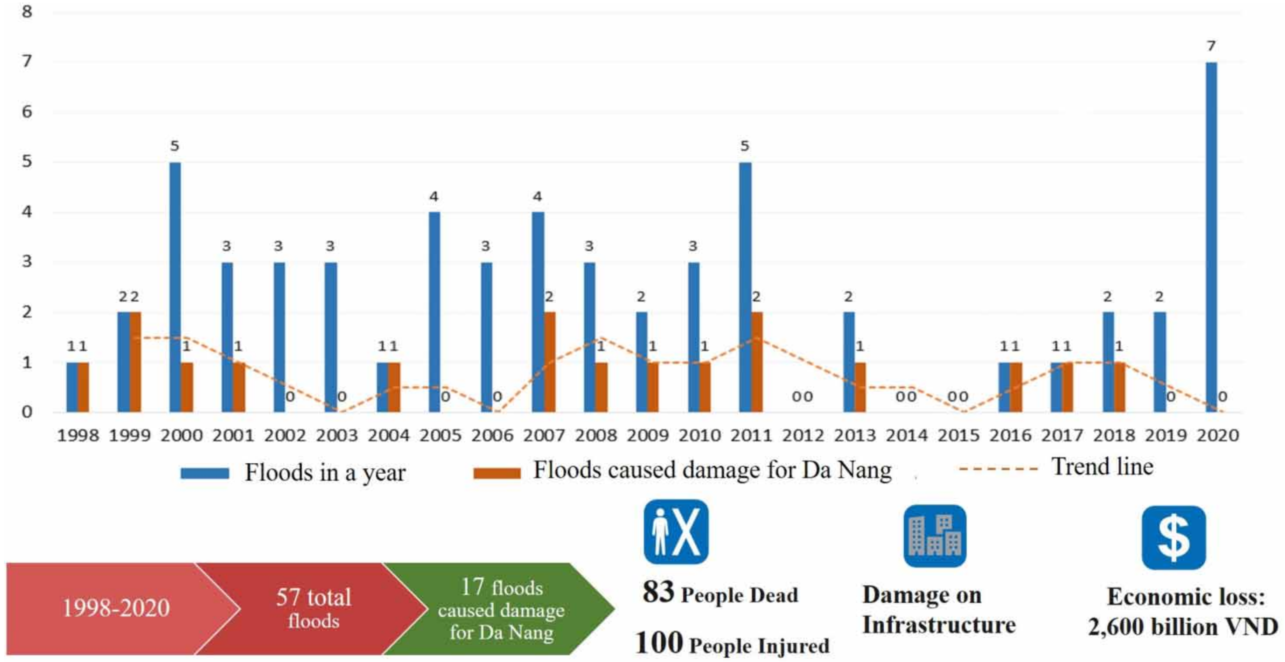


Figure 3 | Flood frequency in Da Nang City from 1998 to 2020. (*Source*: Da Nang Steering Committees for Disaster Prevention and Search and Rescue 2020).

topographic characteristic of the study area is varied with elevation ranging from 0 to 1,663-m above mean sea level and spreading from the mountain in the west to the lowland region in the east. There is a relatively narrow distance between the mountainous region in the west to the coastline in the east which is one of the factors making the flood more exacerbated in the study area.

METHODOLOGY

Data processing

Based on the vulnerability assessment approach suggested by IPCC (2014) and UNESCO-IHE, this study has attentively focused on selecting criteria for flood vulnerability assessment in Da Nang City. We have selected 20 indices for FVI calculation through the evaluation of the physical conditions, a review of previous research related to flood vulnerability (Ballais *et al.* 2005; Manfreda *et al.* 2011, Balica *et al.* 2012, Tran *et al.* 2017), and a questionnaire survey to scientific experts on flood studies and local stakeholders (Appendix 6). The exposure component includes seven criteria, in which the flood depth, elevation of the topography, and distance to the river channels are the main causative factors. Regarding the flood sensitivity, this study has chosen six criteria including local income, poverty index, population density, land use, tourism hotspot, and vulnerable population group including children under 5 years and elderly people over 60 years. The indicators were selected based on the analysis of their relationship to the economic condition of the study area and the potential to be affected by floods as well as natural disasters. AC is measured by the ability of a system to cope with or overcome the difficulties caused by the flood and other disasters. Seven indices have been selected for measuring the AC, including the Normalized Difference Vegetation Index (NDVI), and the density of the community service facilities such as healthcare centers, food markets, Base Transceiver Stations (BTS), road density, drainage system, and education index.

The open geospatial data sources have been used in this study. Freely accessible SRTM digital elevation model (DEM) version 4 with the spatial resolution of 30 m (https://earthexplorer.usgs.gov) and the Landsat 8 OLI satellite images with 30-m spatial resolution provided by USGS (https://earthexplore.usgs.gov) were used to extract the physical indicators related to flood exposure such as elevation, slope, flow accumulation, Topographic Wetness Index (TWI), and Modified Normalized Difference Water Index (MNDWI). The statistical data on the socio-economic condition of Da Nang City provided by the Statistical Yearbook of Da Nang City in 2020 were used for evaluating the flood sensitivity and AC. We obtained information on the community service such as the number of tourism hotspots, healthcare facilities, food market centers, and BTS via the Open Data Portal (https://congdulieu.vn) built by the Da Nang City Government. These are very important variables in the determination of flood sensitivity as well as AC. To evaluate the accuracy of the flood vulnerability map, the field survey on historical flood signs and statistical data on flood damage reported by the local government are also used.

A field survey was conducted in October 2020 to collect the historical flood locations in the study area by measuring the location and historical flood water depth marked on the flood pillar points built by the local government (Figure 4). These flood pillar point data were used as a reference flood dataset for the accuracy assessment of flood vulnerability results developed in this study. In addition, during the field survey, we consulted with the local officers and inhabitants to discuss the factors affecting flood vulnerability that facilitated the selection of indicators and judgment of the appropriate important level of each index. By consulting with local people in the field survey, we also have a background on the severity of floods in the study area and initially evaluated the most flood-affected areas and the local resilience from that analysis of the contributing factors to flood vulnerability. To generate the flood exposure map, we have utilized the flood inventory map provided by the Vietnam Institute of Meteorology, Hydrology and Climate Change (IMHEN). According to the flood inventory map and the flood pillar point data, the mountainous and upland areas located in the western and northern parts of the study area with elevation above 30 m have almost no flood occurrence. There are no flood-survey points located in the upland area, and this area is also categorized as a non-flood level in the flood inventory map provided by IMHEN. Therefore, we have masked the areas with elevation above 30 m as an exclusion criterion and focus on evaluating flood vulnerability for the low-lying alluvial plain located downstream of the Cu De and Han River systems. This low-lying study area is also the center of Da Nang City, concentrating on inhabitants and urban infrastructures.

Our GIS-based approach for the flood vulnerability assessment is summarized in Figure 5. First, a set of indicators to determine the components of flood vulnerability have been developed including variables that reflect the level of exposure (E), sensitivity level (S), and AC. These data were then standardized in a GIS environment and normalized on a scale from 0 to 1. Finally, the research identifies the FVI at a pixel level using a multi-criterion analysis based on the AHP method (Saaty 2008), taking into account the weights of the driving factors. The details are as below.

Development of indicator system for flood vulnerability assessment in Da Nang City

The most important task in an index-based vulnerability assessment is to select appropriate indicators. The previous practices (Balica *et al.* 2012; Nasiri *et al.* 2016; Van *et al.* 2022) have tried to assemble a list of indicators using criteria such as suitability, following a conceptual framework considering data availability and sensitivity to formats, usefulness, and ease of the

Figure 4 | Measuring the flood location and depth during the field survey in 2020: (a) measuring location and depth at the flood pillar point; (b) asking local people about the severity and contributing factors to local flood; and (c) measuring flood location and depth inside the household.

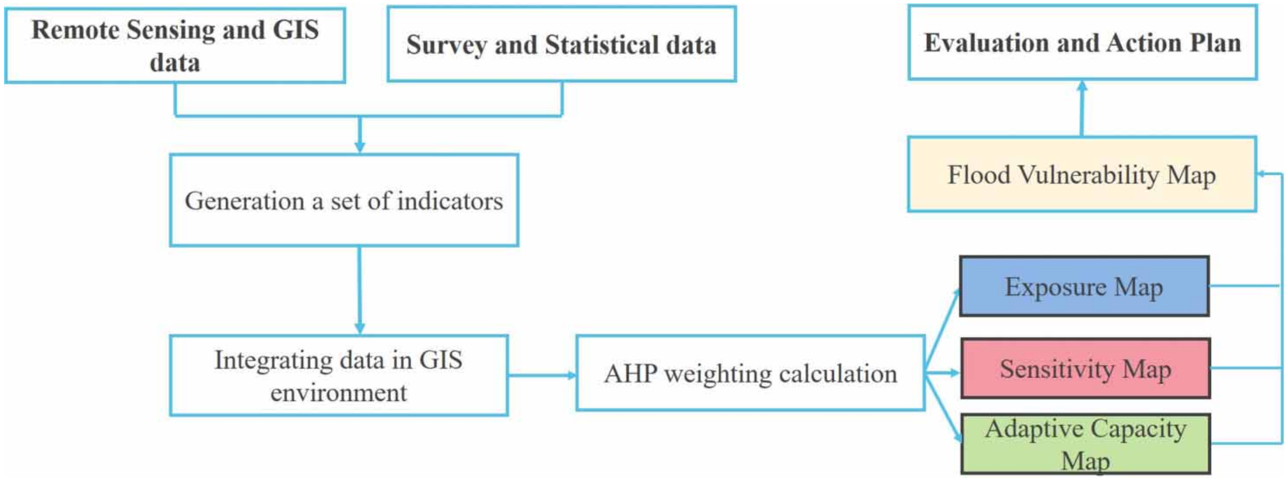


Figure 5 | GIS-based approach for data processing.

collection of data. Understanding each concept and considering the relationship of certain indicators to the FVI may help characterize the vulnerability of different systems, by which actions can be identified to decrease it (Balica *et al.* 2012).

In this study, the contributing factors to the FVI including 20 indices have been carefully selected based on analyzing the characteristics of the study area, the literature reviews, and interview with experts (Figure 6). The role of each parameter in the context of flood vulnerability is characterized in the following sections.

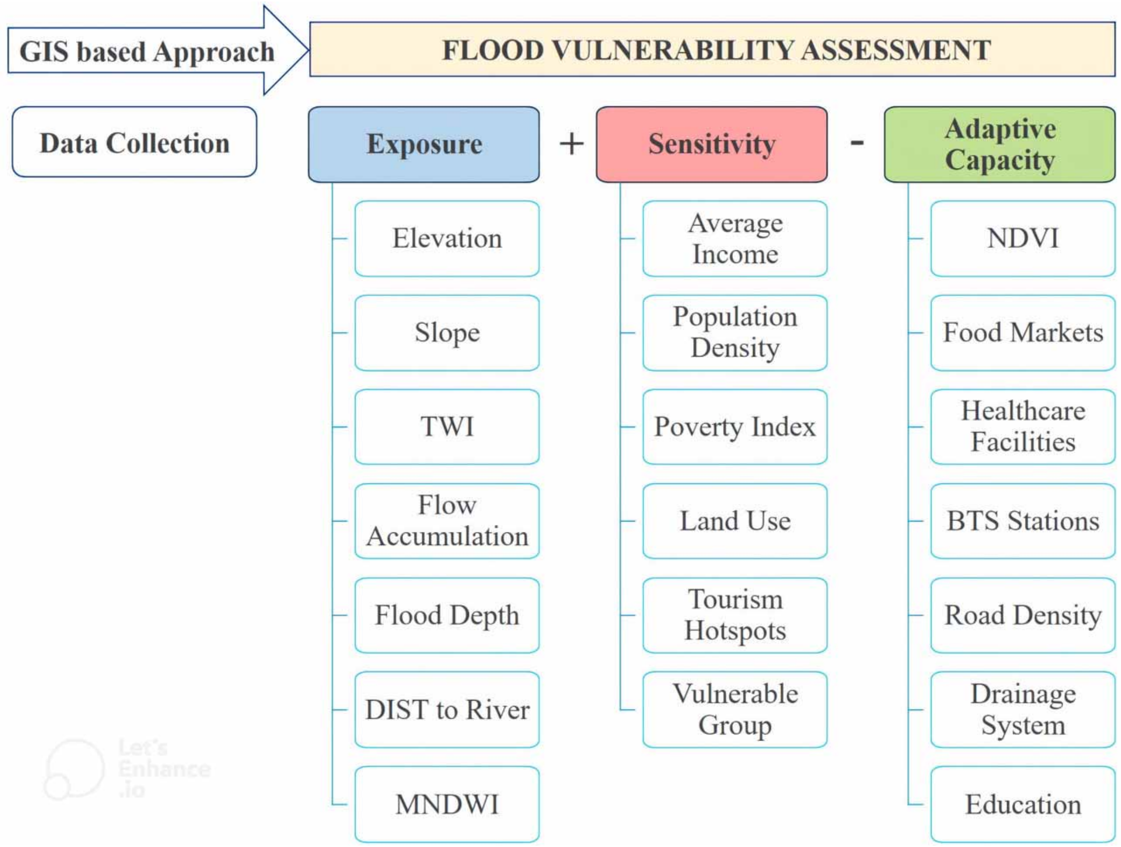


Figure 6 | Indicator scheme and calculation method for flood vulnerability assessment.

Generation of criteria for flood exposure in Da Nang City

Flood exposure is determined basically based on the physical condition of the study area. Through the field survey, we have judged that the first driving factor that is directly related to flood exposure is the flood depth. It is evident that the areas under higher values of flood depth are correlated to regions more exposed to flooding hazard and vice versa. For this reason, flood depth measured by the water level in the inundated areas has been used as the most important input indicator since it reflects the actual flood situation of an area. The flood depth data applied for flood vulnerability assessment in this study were taken from the flood inventory map provided by IMHEN, Vietnam. This flood inventory map was generated based on the elevation of the study area and the flood depth in 1999, which was the most severe historical flood in Central Vietnam. The flood inventory map of IMHEN was processed using the MIKE flood model (https://mikepoweredbydhi.com) and presented in the GIS format as a polygon with different flood levels for the whole area of Da Nang City (Figure 7(d)).

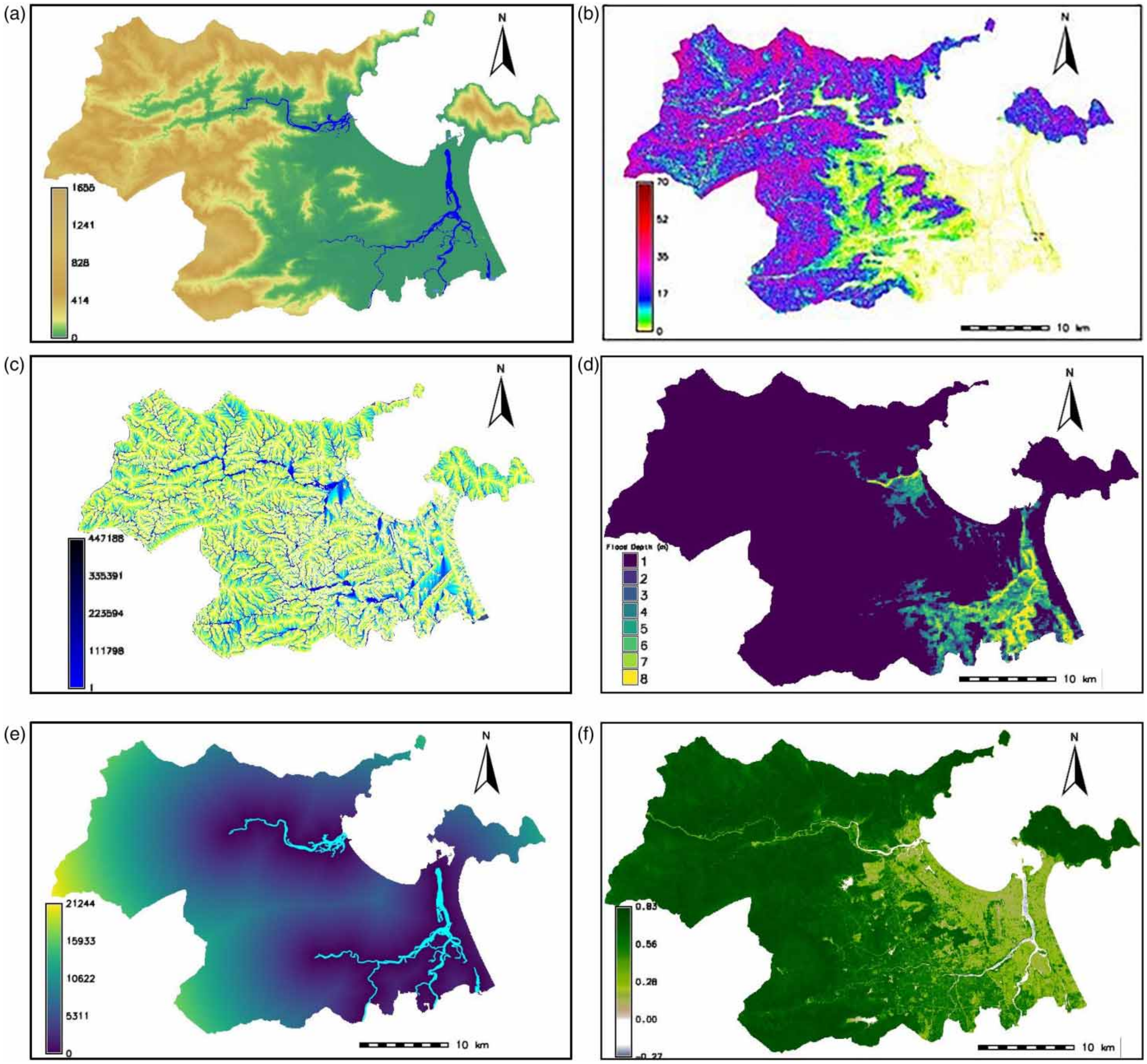


Figure 7 | Parameters used in the generation of the FVI: (a) digital elevation model (DEM); (b) slope calculated from the DEM; (c) flow accumulation; (d) flood inventory recorded depth (m); (e) distance to the river channel (m); and (f) Normalized Difference Vegetation Index.

Elevation and distance to the river channel are considered the second most important criteria in flood exposure in alignment with relevant studies (Ballais *et al.* 2005; Manfreda *et al.* 2011; Kazakis *et al.* 2015; Tran *et al.* 2021). Flood is defined as the inundation of the land surface and hence it closely depends on the topography of the surface. Flood frequency increases with decreasing elevation, meaning that lower elevations are more susceptible to flooding (Choubin *et al.* 2019). In this study, using SRTM DEM (Figure 7(a)), the topographic indices including slope (Figure 7(b)), TWI, and flow accumulation (Figure 7(c)) are extracted. In addition to elevation, the distance from the river channel (DIST) plays a vital role in flood hazard since floods are caused mainly by water overflows from rivers. Areas near the river channels are at a higher exposure to flooding hazards (Tran *et al.* 2017, 2021). Due to its important role, DIST has been assigned as a major criterion for flood exposure. The distance from the river channel in this study was determined by the Euclidean distance method, which is measured by the nearest distance between points to the river channel (Zhang *et al.* 2019). The calculation of DIST was conducted using the module of *r.grow.distance* in the GRASS GIS software with the Euclidean method (Figure 7(e)). Distance from the drainage network and elevation are assigned equal importance since flooded areas are often located at low elevations and near the drainage network (Kazakis *et al.* 2015).

The slope, flow accumulation, and TWI were assigned as the third important level since our expert discussions confirmed that these parameters were all desired from elevation data. The slope was calculated from the SRTM using a terrain analysis module in GRASS GIS namely *r.slope.aspect* (https://grass.osgeo.org) (Figure 7(b)). The flow accumulation map was generated from the SRTM using a hydrological module called *r.watershed* in GRASS GIS (Figure 7(c)). Flow accumulation is considered as an indispensable parameter in flood inundation mapping as suggested in various studies (Kazakis *et al.* 2015; Tehrany *et al.* 2015; Vojtek & Vojtekova 2019). Flow accumulation was derived from the flow direction raster generated from the input DEM data. In the flow accumulation raster, each cell contains information on the number of cells that flow into it, which means that each cell is also a discharge profile. Therefore, an increase in flow accumulation should reflect an increase in flood susceptibility (Vojtek & Vojtekova 2019). The TWI has been proved to have a close relationship to flood hazards as shown in previous studies (Manfreda *et al.* 2011; Bangira 2013; De Risi *et al.* 2014; Tehrany *et al.* 2015; Pourali *et al.* 2016). The TWI provides a more cost-efficient approach to flood determination than conventional hydrodynamic models (Pourali *et al.* 2016). The TWI is defined by Equation (1):

$$\mathrm{TWI} = \ln\left(\frac{a}{\tan(b)}\right) \tag{1}$$

where a is the source contributing catchment area and $\tan(b)$ is the ground surface slope. The TWI was developed by Beven & Kirkby (1979) within the rainfall-runoff model named 'TOPMODEL'. The TWI is commonly used to quantify the topographic control on hydrological processes (Sorensen *et al.* 2006) and has been reported as one of the driving factors for flood inundation by Tehrany *et al.* (2015). The TWI allows for delineating a portion of a hydrographic basin that is potentially exposed to flood inundation by using an appropriate threshold (De Risi *et al.* 2014). In the present study, the *r.topidx* module in GRASS GIS was used to calculate the TWI.

The MNDWI derived from satellite remote-sensed data images has been proved to be correlated to flood susceptibility (Ho *et al.* 2012; Kwak 2017; Li *et al.* 2018; Ramesh *et al.* 2021), since it has been successfully applied to extract surface water bodies that are most sensitive to flood hazard. Li *et al.* (2018) have successfully utilized the MNDWI to separate water and land surface from which the flood extent mapping was conducted (Li *et al.* 2018). The satellite images taken during the flood event are usually limited by cloud coverage. However, the remotely sensed images of other acquisition dates also contain certain MNDWI values that are correlated with flooding hazard. The high MNDWI has been found in flood inundated areas; therefore, the utilization of this index could be considered more effective than conventional flood mapping by using remote sensing data taken during the flood event. Xu (2005) introduced this index as a calculation as follows:

$$\mathrm{MNDWI} = (\rho\ \mathrm{Green} - \rho\ \mathrm{SWIR})/(\rho\ \mathrm{Green} + \rho\ \mathrm{SWIR}) \tag{2}$$

These bands are selected to maximize the reflectance of water features by using green light wavelengths and minimize the low reflectance of SWIR by water features by taking advantage of the high reflectance of vegetation and soil features in the SWIR band (Hasan *et al.* 2013). The generation of the MNDWI in this study is based on Landsat 8 OLI data from 2016 to

2021 using the formula mentioned in Xu (2005) via the Google Earth Engine which is a web-based computing platform (https://code.earthengine.google.com).

Criteria for the flood sensitivity in Da Nang City

Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and the lack of capacity to cope and adapt (IPCC 2014). Based on the definition of sensitivity as well as considering the driving factors on flood hazard in the study area, this study has selected six criteria for the evaluation of flood sensitivity including average income, population density, poverty index, land use, tourism hotspot, and the ratio of vulnerable population group. Income was identified to have a close relationship to flood sensitivity since the high-income household can self-supply its demand and adapt well during floods, and thereby is less sensitive to flood vulnerability. Land use and population are widely known as principal factors for flood hazards. The population index is calculated by the number of people in an area unit (population density) and normalized on a standard scale. In addition, the poverty index, which was extracted from the statistical data on poor and near-poor households, was also evaluated as a component of flood sensitivity since it reflects the severity of a community under the impact of disasters. Both population and poverty data were collected from the statistical yearbook of Da Nang City (Da Nang GSO 2020).

Land use influences the infiltration rate and the inter-relationship between surface and groundwater (Kazakis *et al.* 2015). The land-use map in 2020, provided by the Department of Natural Resource and Environment (DONRE), Da Nang City, has been utilized to generate the land-use index in flood sensitivity. Based on the analysis of the characteristics of each land-use type, including the settlement, agriculture, tourism, industrial and other infrastructure types, bare land, public spaces, and permanent water, in relation to flood susceptibility, and referring to previous studies (Mishra 2013; Kazakis *et al.* 2015; Tehrany *et al.* 2015; SEPA 2018), we have assigned the values for land-use index ranging from 0 to 1. The settlement land-use types including urban and rural residential areas were recognized as the most vulnerable land use when floods occurred and hence were given the highest vulnerable value of 1. Following the settlement, agriculture and tourism land-use types were considered the highly vulnerable areas to flooding hazards and thus were assigned a value of 0.8. Subsequently, the industrial land and other infrastructure land use including the traffic area were given a moderate value of 0.6. Bare land was considered less vulnerable than other land-use types since it has less impact on human life and hence was assigned a value of 0.4. Public areas such as parks, squares, or monuments along with the forest type were arranged in the low vulnerable class in the land-use map with the value of 0.2. Finally, permanent water was assigned as a value of 0 since it has no flood susceptibility.

Da Nang City is considered one of the famous tourist destinations in the Coastal Central of Vietnam. Recently, Da Nang City has experienced an increasing occurrence of natural disasters including floods reported by the city government (Da Nang Steering Committees for Disaster Prevention and Search and Rescue 2020). Therefore, it is very necessary to assess flood vulnerability to the tourism of Da Nang City toward the sustainable tourism development. This study has selected an indicator on the tourism hotspots that can represent the potential impact of flood hazards on tourism which is the main economic activity in Da Nang City (Da Nang GSO 2020). This index was generated by taking the number of tourism hotspots including the hotels, resorts, travel agencies, and sightseeing places via the density analysis in the GIS to obtain the average values for each area unit in square kilometers. Information on the tourism hotspots in Da Nang City was collected from the Da Nang Open Data portal (https://congdulieu.vn) and then standardized in a GIS format and the density was calculated using the spatial analysis tool in GRASS GIS (*r.stats.zonal*).

It is necessary to consider the most vulnerable group in the population to evaluate flood susceptibility. Children and the elderly are more vulnerable to flood hazards since they have a low ability to self-evacuate and self-care compared to other groups experiencing negative impacts from disasters (Mason *et al.* 2021). This study has calculated the ratio of children under 5 years and people over 60 years in the total population as a vulnerable group indicator for the determination of flood sensitivity. The population data were also taken from the Statistical Yearbook of Da Nang City in 2020 at the commune level (Da Nang GSO 2020).

Assessment of the flood adaptive capacity in Da Nang City

The AC is related to social conditions and strategies responding to flooding. AC is assessed in terms of the ability to remain and cope with hazards (Turner *et al.* 2003). The AC can be understood as the flood resilience or coping capacity of a system or a community to mitigate threats and damages of floods. Among three components, AC often has a negative relation with vulnerability (Smit & Wandel 2006).

In this study, seven indicators, namely, the NDVI, density of the community service facilities such as healthcare centers, food market, BTS, road density, drainage system, and an index related to the education level have been investigated to determine the AC.

It is understandable that the area with vegetation cover can slacken the water flow and be more sensitive to draining water. That is why most urban planning focuses on enhancing the green area rate. For that reason, this study uses the NDVI as a criterion for measuring flood resilience for the first time, measured by the ratio between the red band and the NIR band in remote sensing data as follows:

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{RED})/(\mathrm{NIR} + \mathrm{RED}) \tag{3}$$

The NDVI was calculated from time-series Landsat 8 OLI data from 2016 to 2021 using Google Earth Engine (https://code.earthengine.google.com) (Figure 7(f)).

The road density is calculated by the total length of the road network in a unit area (km^2), which is obtained via the Open Street Map (OSM) (https://openstreetmap.org). Road density is a relatively important indicator of AC since it reflects the government's investment in enhancing the transportation infrastructure with respect to the citizen's demand supplementation, and represents local resilience to evacuate during flood, and even capacity to deliver necessary items and supporting post-flood recovery efforts.

Education is an indicator that reflects the capacity of communities to respond to floods. A community with a higher population of well-educated people will increase its ability to adapt and respond to natural disasters (Hoffmann & Blecha 2020). This study has taken the ratio of teachers in each thousands of individuals as an indicator for education in Da Nang City.

Other parameters reflecting resilience to flood hazards have been utilized in this study including the density of food markets, healthcare facilities, BTS, and drainage systems. These data were calculated using the spatial data analysis with the help of the Da Nang City Open Data Portal (https://congdulieu.vn) and the Da Nang Department of Natural Resource and Environment (DONRE). The density food markets, healthcare facilities, and BTS represent the accessibility of a local community to the primary service for food, healthcare, and communication. These indicators were calculated by density analysis in the GIS environment as applied to the tourism hotspot.

As suggested by local stakeholders and experts, the drainage system is considered the most important parameter in flood resilience. This index is measured by taking the total length of the drainage convert extracted from the drainage map provided by the Da Nang Department of Natural Resource and Environment (DONRE). Subsequently, the length density is calculated by the ratio of drainage convert length in a unit area (km/km^2). Due to the direct relationship of this index on the drainage capacity of the study area, the drainage system has been assigned the highest important value compared to other criteria in the AC component.

The details of all input criteria used for flood vulnerability assessment and the method of generation as well as supported processing tools are explained in Table 1. In this study, we used the Google Earth Engine to develop the indices which require the calculation from time-series remote sensing data such as the MNDWI and the NDVI. The Google Earth Engine provides an interactive platform for geospatial processing at the scale, which is powered by the Google Cloud Platform. By coding the algorithm in GEE, with the support of automatically connecting to remote sensing databases such as Landsat or any other system via cloud service, we quickly obtain the output indices from time-series satellite data. The GRASS GIS version 7.8 (https://grass.osgeo.org) and QGIS version 3.16 (https://grass.osgeo.org) Open Source Software were used to generate different indices including slope, flow accumulation, DIST, TWI, and visualization of the resulting maps. In this study, QGIS and GRASS GIS have been used extensively to update the spatial and attribute data, normalize, and calculate most of the indices for flood vulnerability assessment.

Data normalization and weighting

Each indicator's value uses different units, so the normalization was carried out to convert all values into a standard scale from 0 to 1, in which 1 is the highest vulnerability found in the samples and 0 is the lowest. The input data after collection and calculation in the GIS environment were normalized as follows (Connor & Hiroki 2005):

$$X_i = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}} \tag{4}$$

$$X_i = \frac{X_{\max} - X_i}{X_{\max} - X_{\min}} \tag{5}$$

Table 1 | Indicators used for the evaluation of flood vulnerability in Da Nang City

Components	Criteria	Data source	Method of generation	Processing tools
Exposure	Elevation (ELEV)	SRTM version 4 (https://earthexplorer.usgs.gov)	Local elevation of each pixel	Raster Map Calculator in GRASS GIS
	Slope (SL)	SRTM	Local slope of each pixel	Terrain analysis
	Flow accumulation (FA)	SRTM	Local accumulation of each pixel	Hydrologic analysis
	Topographic wetness index (TWI)	SRTM	Ratio between the source contributing area and the ground surface slope	*r.topidx* module in GRASS GIS
	Distance to river channels (DIST)	River channel	Closest distance from a pixel to the nearest river	Euclidean distance
	MNDWI	Landsat 8 (https://earthexplorer.usgs.gov)	Xu (2005)	Google Earth Engine (https://code.earthengine.google.com)
	Flood depth (FD)	IMHEN, Vietnam	Highest historical flood depth (1999 flood event) for each pixel	Field survey and MIKE hydrological model
Sensitivity	Population density (POP)	Da Nang GSO (2020)	Number of persons in square kilometers	Statistic
	Average income (INC)	Da Nang GSO (2020)	Average income in the Vietnamese dong of each household	Statistic
	Poverty (POV)	Da Nang GSO (2020)	Percentage of poor households in each commune	Statistic
	Tourism hotspot (TOU)	Da Nang Open Data Portal (https://congdulieu.vn)	Total number of hotels, resorts, tourism agencies, and sightseeing places in an area unit (km^2)	GIS spatial analysis
	Land use (LU)	Land-use map of DONRE, Da Nang City (2020)	Reclassification of the land-use map and normalization of the values from 0 to 1 based on analyzing the relationship of each class to flood hazard	GIS spatial analysis
	Vulnerable group (VUL)	Da Nang GSO (2020)	Percentage of children under 5 years old and people elder than 60 in each commune	Statistic
Adaptive capacity	NDVI	Landsat 8 from 2016 to 2021	Ratio between the RED band and the NIR band	Google Earth Engine (https://code.earthengine.google.com)
	BTS	Da Nang Open Data Portal (https://congdulieu.vn)	Number of BTS in an area unit (km^2)	Statistic
	Food market density (FM)	https://congdulieu.vn	Number of food markets in an area unit (km^2)	Spatial analysis
	Healthcare facilities (HC)	https://congdulieu.vn	Number of healthcare centers in an area unit (km^2)	Spatial analysis
	Road density (RD)	https://congdulieu.vn	The total length of road in an area unit (km/km^2)	Spatial analysis
	Drainage culvert (DRG)	DONRE, Da Nang City	Length of drainage culvert in an area unit (km/km^2)	Spatial analysis
	Education (EDU)	Da Nang GSO (2020)	Number of teachers per thousand citizens	Statistic

where X_i is the normalized value, $X_{\max}$ refers to the maximum value of the indicators, and $X_{\min}$ is the minimum value of the indicators.

To synchronize the variables, Equation (4) is applied when the parameter is in a positive relationship with the component that the variable contributes to and Equation (5) is applied when the index has a negative functional relationship with its component. For example, elevation has a negative relationship with flood exposure since the flood occurs by the inundation of the topography. The lower elevation areas are more exposed to flood and vice versa, and the higher elevation will be less susceptible to flood hazards. In this case, Equation (5) should be applied for the normalization of elevation data. The flood vulnerability is determined by integrating all the criteria and their corresponding weights. This study used the AHP, a method developed by Saaty (2008), to calculate the weight of the causative parameters to flood vulnerability. The detail of applying the AHP method to generate the comparison matrix for FVI calculation in Da Nang City is shown in Appendices 1–6. The most crucial step in the AHP is determining priorities among the decision elements of the hierarchy. Based on the rating scale of Saaty (2008), with values from 1 to 9 indicating less important to much more important (Appendix 1), a questionnaire survey was conducted for the flood experts and local stakeholders (Appendix 6). This step evaluates the priorities of criteria in relation to the flood vulnerability and assigns the values subjecting to the judgments in the form of a pair-wise comparison matrix. The assignment of the relative significance between criteria and the normalized values according to the AHP method is presented in Appendices 3– 5. The last step is checking the consistency of the subjective evaluations. To evaluate the consistency of the pair-wise comparison in the AHP, the consistency index (CI) is determined by the equation as follows:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} \tag{6}$$

where $\lambda_{\max}$ is the maximum Eigenvalue of the comparison matrix (Vargas 2010) and n is the number of evaluated criteria. To verify whether the CI is adequate, Saaty (2008) suggests the consistency ratio (CR) which is determined as the ratio between the CI and the random consistency index (RI). The calculation of CR is given by the following equation:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{7}$$

where CR is the consistency ratio, CI is the consistency index, and RI is the random consistency index. Values of the RI are dependent on the number of criteria (n), which are specified in Danumah *et al.* 2016 (Appendix 2). The comparison matrix is consistent if the resulting CR is less than 0.1 or 10% (Saaty 2008). When the CR exceeds 0.1, it is necessary to revise the comparison matrix and re-calculate the weights for a better weighting scheme.

As a result, the weighting system corresponding to each flood vulnerability indicator calculated by the AHP method is shown in Table 2. These weights were applied to determine the components of the flood vulnerability by the following equation:

$$E = \sum_{i=0}^{n} x_i * w_i \tag{8}$$

where E represents the flood exposure. A similar weighting averaging method was applied to the calculation of the flood sensitivity (S) and AC.

In this study, the FVI was developed by integrating the three main contributing components in order to measure the spatial pattern of flood vulnerability. The approach of IPCC (2014) was applied to determine the flood vulnerability as shown in the following equation:

$$\mathrm{FVI} = E + S – \mathrm{AC} \tag{9}$$

where FVI is the flood vulnerability index, and E, S, and AC stand for exposure, sensitivity, and adaptive capacity representing the three main components of the FVI, respectively.

RESULTS AND DISCUSSION

FVI for Da Nang City

The results of weighting calculation using the AHP method for flood vulnerability assessment are shown in Table 2. The CR for the analysis of exposure, sensitivity, and AC is always less than 0.1, satisfying the condition of AHP validation and revealing that this weighting scheme could be applied reasonably for this case study. Table 2 indicates that among the criteria, the

Table 2 | Results of weighting calculation for FVI indicators using the AHP method

Components	Indicators	Weight	Consistency check
Exposure (*E*)	ELEV	0.17	$\lambda_{\max}$=7.046
	DIST	0.17	CI=0.0076
	SL	0.10	CR=0.0056
	TWI	0.10	
	FA	0.10	
	MNDWI	0.06	
	FD	0.30	
Sensitivity (*S*)	POP	0.17	$\lambda_{\max}$=6.015
	INC	0.09	CI=0.0030
	POV	0.09	CR=0.0024
	TOU	0.17	
	LU	0.31	
	VUL	0.17	
Adaptive capacity (AC)	NDVI	0.19	$\lambda_{\max}$=7.059
	BTS	0.07	CI=0.0099
	FM	0.07	CR=0.0073
	HC	0.11	
	RD	0.19	
	DRG	0.30	
	EDU	0.07	

flood depth is the major component affecting the flood exposure. Meanwhile, land use is the most important contributing factor in flood sensitivity with the highest weight of 0.31. Subsequently, among the indicators related to AC, the drainage system occupies the highest weight (0.30) and therefore mostly affects the AC. For a better preparedness for urban flood vulnerability, it is evident that the local government needs to not only focus on building warning systems in the highly flood inundated area but also carefully master plan for any urban land-use development projects and enhance the capacity of the drainage system. In addition, it is necessary to pay attention to other contributing factors such as elevation, flow accumulation, population density, tourism hotspots, vulnerable population groups, road density, and NDVI that relatively affect the urban flood vulnerability in Da Nang City.

The FVI for Da Nang City ranged from 0.01 to 1.02. Subsequently, FVI values were reclassified into five levels from very low, low, moderate to high, and very high with equal intervals (Figure 8). The division schemes using equal range are referred from Balica *et al.* 2012 and represented as follows: 0.01–0.20 (very low); 0.21–0.40 (low); 0.41–0.60 (moderate); 0.61–0.80 (high); and greater than 0.81 (very high) (Table 3).

Results of the FVI calculation for Da Nang City show that more than 20% of the study area has high and very high vulnerable levels to flood. Considering areas from moderate to high and very high vulnerabilities, it can be seen from Table 3 that the city has more than 60% of the area under the FVI levels from moderate and higher. This is a significant number requiring the city to have an urgent response to flood risk vulnerability, and the local inhabitants need to be aware of this vulnerability.

Identification of vulnerable areas to flood hazard in Da Nang City

The flood vulnerability map was then overlaid with the administrative map of Da Nang City including 7 districts with 56 communes and wards. Statistics of the FVI by districts show that the Hoa Vang district always holds the largest area of high and very high levels, as represented in Table 4. Considering the areas with the FVI from moderate to very high levels, Hoa Vang is also most vulnerable to flood hazards (Table 4). Hoa Vang, located in the southwest of Da Nang City, is on the outlet of the Vu Gia River system to the Han estuary. Moreover, Hoa Vang consists largely of the lowland areas between hilly mountains in the west and the coastal zone in the east. This topographical characteristic makes the Hoa Vang district the most significant flood-prone area in Da Nang City. In another aspect, the Hoa Vang district mostly has the low and very low AC as shown in Figure 8. This is the home of mainly agricultural activities in Da Nang City and the economic scale is also smaller compared to other urban districts. This is the only suburban district in Da Nang City, except for Hoang Sa Island. These physical and social-economic characteristics make Hoa Vang the most vulnerable district in Da Nang City to flood hazards that need powerful measures for enhancing the adaptation capability and minimizing the flood damage. The result of FVI mapping

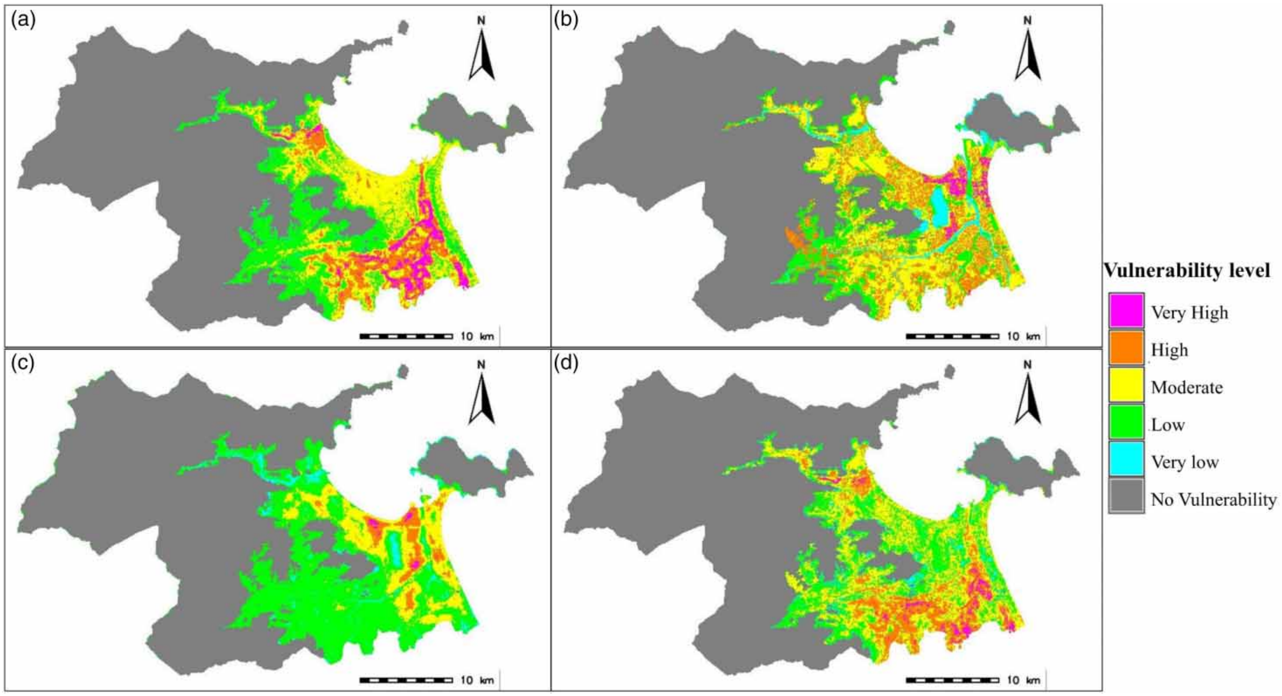
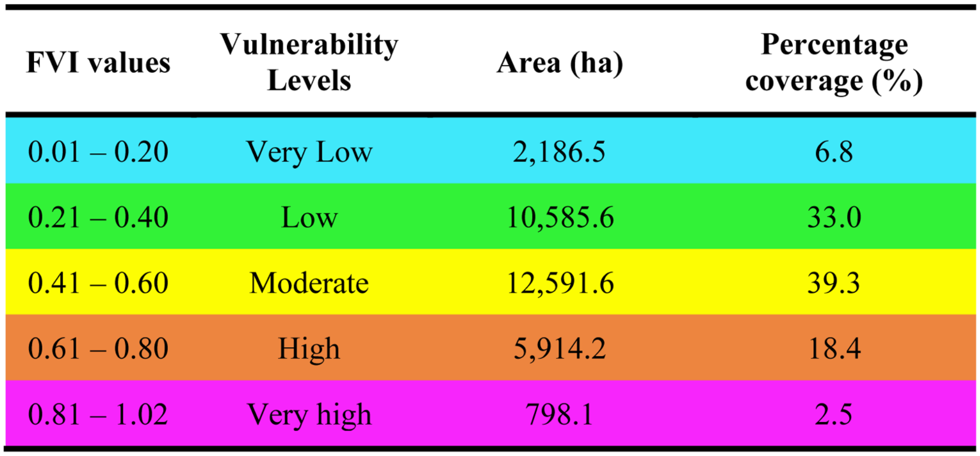


Figure 8 | Flood vulnerability components and FVI map for the study area: (a) exposure, (b) sensitivity, (c) adaptive capacity, and (d) integrated flood vulnerability map.

Table 3 | Reclassification FVI for Da Nang City

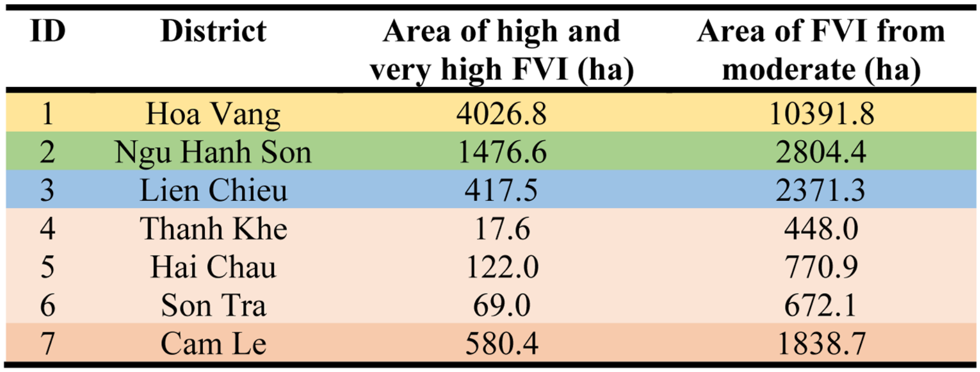


FVI values	Vulnerability Levels	Area (ha)	Percentage coverage (%)
0.01 – 0.20	Very Low	2,186.5	6.8
0.21 – 0.40	Low	10,585.6	33.0
0.41 – 0.60	Moderate	12,591.6	39.3
0.61 – 0.80	High	5,914.2	18.4
0.81 – 1.02	Very high	798.1	2.5

in Figure 9 also indicates that the most vulnerable areas to flooding hazards in Da Nang City are located in the low-lying southern part of the city which mostly belongs to the Hoa Vang district.

Among the 56 communes and wards of Da Nang City, 11 are under high and very high levels of the FVI as shown in Table 5. It can be seen from Table 5 that there are seven communes that are extremely vulnerable communes in Da Nang belonging to the Hoa Vang district. Here, communes of Hoa Tien, Hoa Chau, Hoa Phuoc, and Hoa Phong have more than 40% coverage of high and very high vulnerability levels. These areas require robust strategies to respond to and mitigate the impact of flood hazards in the future. Moreover, from Figure 9 and Table 5, it is clear that flood vulnerability assessment should be localized and not always based on the administrative units since a commune may have different FVI levels. For

Table 4 | Statistics of the FVI by districts in Da Nang City



ID	District	Area of high and very high FVI (ha)	Area of FVI from moderate (ha)
1	Hoa Vang	4026.8	10391.8
2	Ngu Hanh Son	1476.6	2804.4
3	Lien Chieu	417.5	2371.3
4	Thanh Khe	17.6	448.0
5	Hai Chau	122.0	770.9
6	Son Tra	69.0	672.1
7	Cam Le	580.4	1838.7

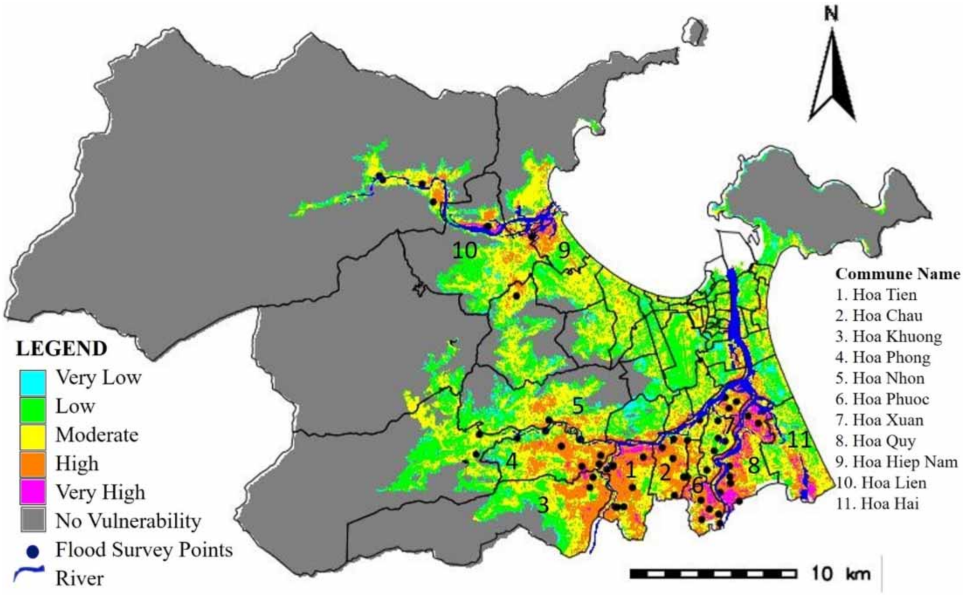


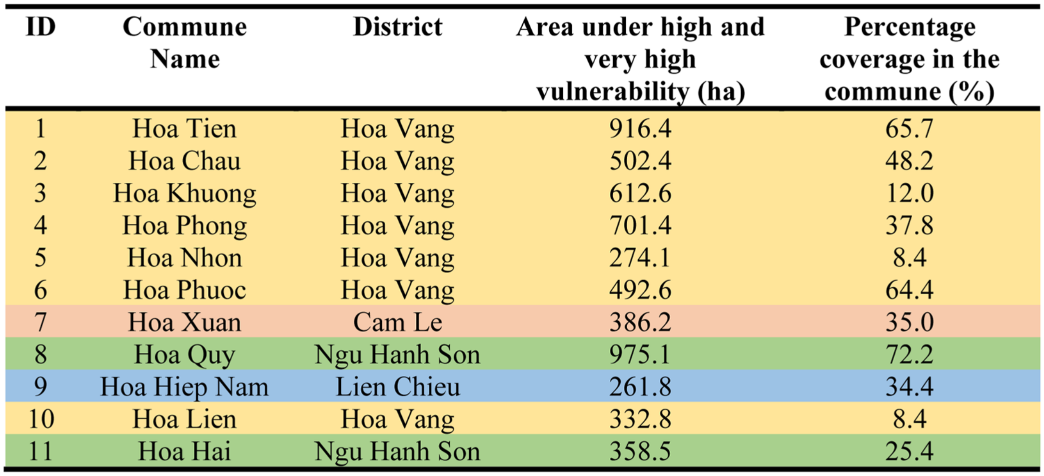
Figure 9 | FVI map over the commune boundary in Da Nang City and the location of field survey flood pillar points.

instance, the Hoa Khuong commune has all kinds of vulnerability levels from very low to very high (Figure 9), and the coverage of the area under high and very high FVI in this commune is only 12.0% (Table 5). However, the actual areas of high and very high FVI in Hoa Khuong are significant compared to other communes in Da Nang City as shown in Table 5 (612.6 ha). The high and very high FVI areas in Hoa Khuong, along with Hoa Phong and Hoa Tien communes (Figure 9) that are the major agriculture hotspots of Da Nang City and the home of many villages, are annually affected by flood damage as seen by the number of households affected in Table 7. There is an urgent need for flood responsibilities and adaptation plans for this area, and the proposed solutions should be inter-regional considering the most vulnerable area. It is unfair if the governmental investment budgets or the deployment of flood control projects are distributed based on the average FVI by districts or communes. Instead, it is more important to consider the most vulnerable areas and apply an inter-regional solution.

Evaluation of the flood vulnerability map in Da Nang City

The accuracy assessment of the vulnerability map is still challenging as seen in many studies till now. There has been no generalized workflow that could conclusively validate the flood vulnerability mapping results as yet. Both IPCC and UNESCO-IHE do not suggest any method for vulnerability assessment, but foremost, the input data source used to calculate the indicators should be verified, and then the vulnerability index is used as a baseline to propose measures for the locality as well as

Table 5 | Statistics of flood vulnerability for some typical communes in Da Nang City



ID	Commune Name	District	Area under high and very high vulnerability (ha)	Percentage coverage in the commune (%)
1	Hoa Tien	Hoa Vang	916.4	65.7
2	Hoa Chau	Hoa Vang	502.4	48.2
3	Hoa Khuong	Hoa Vang	612.6	12.0
4	Hoa Phong	Hoa Vang	701.4	37.8
5	Hoa Nhon	Hoa Vang	274.1	8.4
6	Hoa Phuoc	Hoa Vang	492.6	64.4
7	Hoa Xuan	Cam Le	386.2	35.0
8	Hoa Quy	Ngu Hanh Son	975.1	72.2
9	Hoa Hiep Nam	Lien Chieu	261.8	34.4
10	Hoa Lien	Hoa Vang	332.8	8.4
11	Hoa Hai	Ngu Hanh Son	358.5	25.4

Table 6 | Statistics of flood damage by districts in Da Nang City from 2016 to 2018

ID	District	Flood 2016	Flood 2017	Flood 2018
1	Hoa Vang	847 ha paddy, 208 ha cropland, 3.7 ha aquaculture were damaged, 100 households were evacuation	10,431 households were flooded, 175 ha aquaculture, 92.7 ha cropland were damaged	3.4 ha paddy, 88.5 ha cropland, 29.8 ha aquaculture were damaged
2	Hai Chau	No recorded	No recorded	No recorded
3	Thanh Khe	No recorded	No recorded	No recorded
4	Son Tra	No recorded	No recorded	No recorded
5	Ngu Hanh Son	60 ha paddy, 55 ha cropland, 3 ha aquaculture were damaged, 30 households were evacuation	1,089 households were flooded, 02 ha aquaculture, 27 ha cropland	87 ha cropland and 11.5 ha aquaculture were damaged
6	Lien Chieu	13 ha paddy, 5.8 ha cropland, and 10 ha aquaculture were damaged	3.5 ha aquaculture, 7 ha cropland	9 ha paddy and 1.6 ha cropland were damaged
7	Cam Le	02 ha paddy and 17.5 ha cropland were damaged, and three households were evacuated	10.9 ha cropland	15.8 ha cropland and 0.5 ha aquaculture were damaged

Source: Da Nang Steering Committees for Disaster Prevention and Search and Rescue (2020).

predict the future impact of the disasters. Balica *et al.* (2012) pointed out that since the vulnerability assessment is based on indicators, its main limitation is the accuracy of the data on which it is based. For the results to be valid, all data must be derived from reliable sources (Balica *et al.* 2012). Most recently, Van *et al.* (2022) have also confirmed that the accuracy of the input data remains to be the weakness of their approach on flood vulnerability assessment. Many studies (Balica *et al.* 2012, Nasiri *et al.* 2016; Hussain *et al.* 2021; Van *et al.* 2022) reflect accuracy assessment as an existing issue of their vulnerability studies that needs to be addressed in their future works. In this study, apart from the selection of the data from reliable sources provided by local government departments such as the Da Nang Statistical Office, Da Nang City Government or Da Nang Department of Natural Resource and Environment, we attempt to ensure the reliability of the flood vulnerability map by using field survey flood depth data and the local statistical data on flood damage.

Field survey flood pillar data for Da Nang City, including 52 points, have been used to validate the flood exposure map developed from this study. Our survey indicates that all these flood pillar points are located in areas with exposure levels from moderate to very high. There are 42 of the 52 flood pillar points (80% of total pillars) lying in the high and very high

Table 7 | Comparison between the statistical data of households affected by flood and the FVI in Hoa Vang District, Da Nang City

ID	Commune	Households affected	FVI
1	**Hoa Phuoc**	**1,974**	**0.66**
2	**Hoa Chau**	**1,564**	**0.59**
3	**Hoa Tien**	**2,975**	**0.64**
4	**Hoa Phong**	**2,261**	**0.51**
5	**Hoa Khuong**	**936**	**0.47**
6	**Hoa Nhon**	**728**	**0.39**
7	Hoa Phu	10	0.34
8	Hoa Son	111	0.36
9	Hoa Ninh	11	0.37
10	**Hoa Lien**	**833**	**0.42**
11	Hoa Bac	61	0.40

Source: Data on households affected by flood were provided by Da Nang Steering Committees for Disaster Prevention and Search and Rescue (2020).

levels in the flood exposure map. Based on the assumption that the exposure map that represents the physical component of the FVI has been verified and the data on flood sensitivity and AC were published by the local official organizations, our proposed flood vulnerability map for Da Nang City could be valuable for both local inhabitants and stakeholders. The flood pillar points in Figure 9 also indicate that the flood hazard in Da Nang City is the most serious in the low-lying southern area which matches with the most vulnerable area in the FVI map.

Apart from the field survey flood pillar data, the local government reports also affirm the high flood vulnerable areas in Da Nang City. According to the annual reports of Da Nang Steering Committees for Disaster Prevention and Search and Rescue, Da Nang City Government about disaster loss and prevention in Da Nang City, Hoa Vang district is invariably the most seriously affected region in the city as indicated in Table 6. Regarding the FVI map retrieved from this study, Hoa Vang also has the largest area of the high and very high levels of vulnerability represented in Table 4, following the Ngu Hanh Son, Cam Le, and Lien Chieu districts. The correspondence between FVI map and the statistical data on flood damage confirms the reliability of the flood vulnerability assessment developed in this study.

Among the 11 communes in the Hoa Vang district, seven were evaluated as the most affected considering the number of households affected by flood as reported by the local government. Annual survey results from Da Nang Steering Committees for Disaster Prevention and Search and Rescue also identified Hoa Tien, Hoa Chau, Hoa Phuoc, Hoa Khuong, Hoa Nhon, Hoa Phong, and Hoa Lien as hotspots of flood damage in the Hoa Vang district (Table 7). Taking the average FVI for these

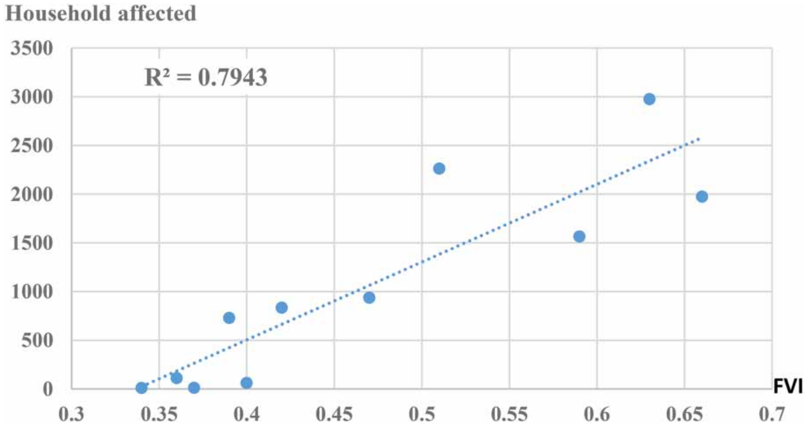


Figure 10 | Correlation between the FVI and statistical data on flood damage.

communes, we have seen a good relationship between the FVI and the number of households affected as reported by the local government (R^2=0.79, as shown in Figure 10). This result again confirms the efficacy of the flood vulnerability map generated from this study. There is an urgent need to enhance the flood preparedness for the local communities in these vulnerable areas.

Although the results offer valuable insights into flood vulnerability assessment at a local scale, this study could not overcome the limitations that most vulnerability studies are facing, and further investigations could be considered to enhance the reliability of the results. First, the FVI criteria were selected based on the literature review and expert discussions that are still sensitive and the same indicator scheme cannot be applied to all study areas. Moreover, although the AHP is a popular weighting method that is widely used in many applications, its judgment scale is still subjective. In future work, sensitivity analysis of indicators could be considered to verify the uncertainty of the flood vulnerability assessment method.

CONCLUSIONS

Flood vulnerability assessment is always an important need in any lowland river basin, especially in cities like Da Nang that are coastal. The present study demonstrates the utilization of Remote Sensing and the GIS approach integrated with the multi-parametric AHP method for flood vulnerability assessment in Da Nang City, Vietnam. This study has generated the GIS database and a robust indicator scheme for flood vulnerability assessment considering the physical, social, and economic conditions of the study area. This study has first time applied the approach of IPCC (2014) in the flood vulnerability assessment for Da Nang City at the local scale and identified the areas that are highly vulnerable to floods. The AHP method was applied to determine the weights for each parameter and compute the FVI, including three main components: exposure, sensitivity, and AC. The flood vulnerability map has been generated based on categorizing the FVI into five levels: very low, low, moderate, high, and very high. The AHP analysis of criterion priorities and weighting calculation results showed that the flood depth, land-use condition, and drainage system are the key factors affecting the flood vulnerability level of Da Nang City. Results of vulnerability assessment also revealed that more than 60% of the study area is under moderate-to-very high flood vulnerability levels. This could be a valuable input for local government to take timely measures for mitigating flood hazard. This study also indicates that the identification of highly vulnerable areas could help in devising flood response strategies and government budget allocations to appropriately address local needs. This study has also, for the first time, attempted to evaluate the accuracy of the flood vulnerability map by using the field survey of historical flood signs as well as local reports on the flood damage. The correlation R^2=0.79 between the FVI and statistical data on the household affected by the flood again confirms the reliability of the flood vulnerability assessment results for Da Nang City in this study. The present study provides the scientific basis for designing sustainable policies on flood hazard mitigation. The proposed method affirms the potential of applying the AHP model using Open Remote Sensing and GIS data for flood vulnerability assessment based on IPCC's approach for Da Nang City.

As the methodology is still under development, there is no standardized way to measure vulnerability, and the assessment. depends on the characteristics of each study area, the hazard that occurs, and its frequency. The FVI model developed from this study can be used as a toolkit to evaluate and manage the urban flood vulnerability and facilitate the adapting capacity. The application of FVI workflow should carefully consider the local physical and socio-economic conditions as well as the flood occurrence in each case study.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abdelkarim, A., Al-Alola, S., Alogayell, H., Mohamed, S., Alkadi, I. & Ismail, I. 2020 Integration of GIS-based multicriteria decision analysis and analytic hierarchy process to assess flood hazard on the Al-Shamal train pathway in Al-Qurayyat Region, Kingdom of Saudi Arabia. *Water* **12** (6), 1702. https://doi.org/10.3390/w12061702.

Balica, S., Wright, N. & van der Meulen, F. 2012 A flood vulnerability index for coastal cities and its use in assessing climate change impacts. *Natural Hazards* **64** (1), 73–105. https://doi.org/10.1007/s11069-012-0234-1.

Ballais, J. L., Garry, G. & Masson, M. 2005 Contribution of hydrogeomorphological method to flood hazard assessment: the case of French Mediterranean Region. *Comptes Rendus Geoscience* **337** (13), 1120–1130.

Bangira, T. 2013 *Mapping of Flash Flood Potential Areas in the Western Cape (South Africa) Using Remote Sensing and In-Situ Data*. *Master Thesis*, Faculty of Geo-information Science and Earth Observation, University of Twente, The Netherlands.

Beven, K. J. & Kirkby, M. J. 1979 A physically based variable contributing area model of basin hydrology. *Hydrological Sciences – Bulletin des Science Hydrologiques* **24** (1), 43–69.

Choubin, B., Moradi, E., Golshan, M., Adamowski, J., Sajedi-Hosseini, F. & Mosavi, A. 2019 An ensemble prediction of flood susceptibility using multivariate discriminant analysis, classification and regression trees, and support vector machines. *Science of the Total Environment* **651**, 2087–2096. https://doi.org/10.1016/j.scitotenv.2018.10.064.

Connor, R. & Hiroki, K. 2005 Development of a method for assessing flood vulnerability. *Water Science and Technology* **51** (5), 61–67. https://doi.org/10.2166/wst.2005.0109.

Da Nang Statistics Office (Da Nang GSO) 2020 *Da Nang City Statistical Yearbook 2019*. Statistical Publishing House 2020, Da Nang City.

Da Nang Steering Committees for Disaster Prevention and Search and Rescue 2020 *Report on the Natural Disasters in Da Nang City from 1998 to 2020 (Annual Report in Vietnamese)*.

Danumah, J. H., Odai, S. N., Saley, B. M., Szarzynski, J., Thiel, M., Kwaku, A., Kouame, F. K. & Akpa, L. Y. 2016 Flood risk assessment and mapping in Abidjan District using multi-criteria analysis (AHP) model and geoinformation techniques (cote d'ivoire). *Geoenvironmental Disasters* **3** (10), 1–13.

De Risi, R., Jalayer, F., De Paola, F. & Giugni, M. 2014 Probabilistic delineation of flood-prone areas based on a digital elevation model and the extent of historical flooding: the case of Ouagadougou. *Boletín Geológico y Minero* **125** (3), 329–340.

Do, T. V. H. & Nagasawa, R. 2014 Potential flood hazard assessment by integration of ALOS PALSAR and ASTER GDEM: a case study for the Hoa Chau commune, Hoa Vang District, in Central Vietnam. *Journal of Applied Remote Sensing* **8**, 1–12.

Douben, N. 2006 Flood Management, UNESCO-IHE, *Lecture Notes*. In *Development and application of flood vulnerability indices for various spatial scales*. (Balica, S.F., ed.) UNESCO-IHE, Delft.

Eckstein, D., Hutfils, M.-L. & Winges, M. 2020 Global Climate Risk Index 2019, German Watch, ISBN 978-3-943704-70-9. Available from: www.germanwatch.org.

FAO 2011 *Developing Farming Systems and Best Practice for Flood-Prone Areas*. Available from: https://www.fao.org/3/ac120e/AC120e16.htm?fbclid=IwAR1mSHCh-aLxlfL1BFlPZYOx5CQoMxV5Ke_Uu3wssYhi8rekPWKG79DzWCw.

Feyissal, G., Zeleke, G., Gebremariam, E. & Bewket, W. 2018 GIS based quantification and mapping of climate change vulnerability hotspots in Addis Ababa. *GeoEnvironmental Disasters* **2018**, 5–14. doi:10.1186/s40677-018-0106-4.

Forkuo, E. K. 2011 Flood hazard mapping using ASTER image data with GIS. *International Journal of Geomatics and Geosciences* **1** (4), 933–950.

Hasan, M., Zhang, L., Wang, S., Jiang, G., Lu, S. & Tong, Q. 2013 Comparison of MNDWI and DFI for water mapping in flooding season. In: *IEEE International Symposium on Geoscience and Remote Sensing (IGARSS) 2013*, pp. 2876–2879. doi:10.1109/IGARSS.2013.6723425.

Hinkel, J. 2011 Indicators of vulnerability and adaptive capacity towards a clarification of the science-policy interface. *Global Environment Change* **21**, 198–208. doi:10.1016/j.gloenvcha.2010.08.002.

Ho, T. K. L. & Umitsu, M. 2011 Micro-landform classification and flood hazard assessment of the Thu Bon alluvial plain, central Vietnam via an integrated method utilizing remotely sensed data. *Applied Geography* **31** (3), 1082–1093. doi:10.1016/ j.apgeog.2011.01.005.

Ho, T. K. L., Yamaguchi, Y. & Umitsu, M. 2012 Rule-based landform classification by combining multi-spectral/temporal satellite data and the SRTM DEM. *International Journal of Geoinformatics* **8**, 27–38.

Hoffmann, R. & Blecha, D. 2020 Education and disaster vulnerability in Southeast Asia: evidence and policy implications. *Sustainability* **12** (4), 1401. https://doi.org/10.3390/su12041401.

Hussain, M., Tayyab, M., Zhang, J., Shah, A., Ullah, K., Mehmood, U. & Al-Shaibah, B. 2021 GIS-based multi-criteria approach for flood vulnerability assessment and mapping in District Shangla: Khyber Pakhtunkhwa, Pakistan. *Sustainability* **13** (6), 3126. https://doi.org/10.3390/su13063126.

Institute for Social and Environment Transition (ISET) International and Da Nang City Government 2009 *Report on Climate Change Impact and Vulnerability Assessment for Da Nang City, Project on the 'Asian Cities Network Resilient to Climate Change (ACCCRN)', 100 Resilient Cities – Pioneered by The Rockefeller Foundation*.

Institute for Social and Environment Transition (ISET) International and Da Nang Climate Change Coordination Office (CCCO) 2017 *Experience of Urban Development and Climate Change Adaption in Da Nang City, Lessons from ACCCRN in Vietnam Series*. The Rockefeller Foundation. https://www.preventionweb.net/files/56172_phongll05peridn171113.pdf

Intergovernmental Panel on Climate Change (IPCC) 2014 *Climate Change 2014: The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change on Climate, Copenhagen*.

Kazakis, N., Kougias, I. & Patsialis, T. 2015 Assessment of flood hazard areas at a regional scale using an index-based approach and analytical hierarchy process: application in Rhodope-Evros Region, Greece. *Science of the Total Environment* **538**, 555–563.

Kwak, Y. 2017 Nationwide flood monitoring for disaster risk reduction using multiple satellite data. *ISPRS International Journal Geoinformation* **6** (7), 203.

Li, J., Yang, X., Maffei, C., Tooth, S. & Yao, G. 2018 Applying independent component analysis on sentinel-2 imagery to characterize geomorphological responses to an extreme flood event near the non-vegetated Río Colorado Terminus, Salar de Uyuni, Bolivia. *Remote Sensing* **10**, 725. doi:10.3390/rs10050725.

Manfreda, S., Di Leo, M. & Sole, A. 2011 Detection of flood-prone areas using digital elevation models. *Journal of Hydrologic Engineering* **16**, 781–790.

Mason, K., Lindberg, K., Haenfling, C., Schori, A., Marsters, H., Read, D. & Borman, B. 2021 Social vulnerability indicators for flooding in Aotearoa New Zealand. *International Journal of Environmental Research and Public Health* **18** (8), 3952. https://doi.org/10.3390/ijerph18083952.

McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J., White, K. S. 2001 *Climate Change 2001: Impacts, Adaptation, and Vulnerability – Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK.

Mishra, K. 2013 *Geomorphological Studies and Flood Risk Assessment of Kosi River Basin Using Remote Sensing and GIS Techniques*. *Master Thesis*, Indian Institute of Technology, M.Tech. 2011–2013.

Nasiri, H., Yusof, J. M. & Ali, T. A. M. 2016 An overview to flood vulnerability assessment methods. *Sustainable Water Resource Management* **2**, 331–336.

Nguyen, L. D., Nguyen, H. T., Dang, P. D. N., Duong, T. Q. & Nguyen, L. K. 2021 Design of an automatic hydro-meteorological observation network for a real-time flood warning system: a case study of Vu Gia-Thu Bon river basin, Vietnam. *Journal of Hydroinformatics* **23** (2), 324–339. https://doi.org/10.2166/hydro.2021.124.

Ouma, Y. O. & Tateishi, R. 2014 Urban flood vulnerability and risk mapping using integrated multi-parametric AHP and GIS: methodological overview and case study assessment. *Water* **6**, 1515–1545.

Pourali, S. H., Arrowsmith, C., Chrisman, N., Matkan, A. A. & Mitchell, D. 2016 Topography wetness index application in flood-risk-based land use planning. *Applied Spatial Analysis and Policy* **9** (1), 39–54. doi:10.1007/s12061-014-9130-2.

Ramesh, S., Kevin, M. J., Chloe, M. M. & Ela, V. P. 2021 Rapid flood inundation mapping by differencing water indices from pre- and post-flood Landsat images. *Frontiers of Earth Science* **15**, 1–11.

Saaty, T. L. 2008 Decision making with the analytic hierarchy process. *International Journal of Services Sciences* **1** (1), 83–98.

Scottish Environment Protection Agency (SEPA) 2018 *Flood Risk and Land Use Vulnerability Guidance, Land Use Planning System SEPA Guidance, Version 4, July 2018*.

Smit, B. & Wandel, J. 2006 Adaptation, adaptive capacity and vulnerability. *Global Environmental Change* **16** (3), 282–292. https://doi.org/10.1016/j.gloenvcha.2006.03.008.

Sorensen, R., Zinko, U. & Seibert, J. 2006 On the calculation of the topographic wetness index: evaluation of different methods based on field observations. *Hydrology and Earth System Sciences* **10**, 101–112.

Tehrany, M. S., Pradhan, B. & Jebur, M. N. 2015 Flood susceptibility analysis and its verification using novel ensemble support vector machine and frequency ratio method. *Stochastic Environmental Research and Risk Assessment* **29** (4), 1149–1165.

Tran, T. A., Raghavan, V., Masumoto, S. & Yonezawa, G. 2017 Application of multi-parametric AHP for flood hazard zonation in coastal lowland area of Central Vietnam. *International Journal of Geoinformatics* **13** (1), 23–34.

Tran, T. A., Raghavan, V., Long, N. V., Izuru, S. & Narumasa, T. 2021 A GIS-based approach for flood vulnerability assessment in Hoa Vang District, Da Nang City, Vietnam. *IOP Conference Series: Earth and Environmental Science* **652** (2021), 012003. doi:10.1088/1755-1315/652/1/012003.

Turner, B., Kasperson, R., Matson, P., McCarthy, J., Corell, R. & Christensen, L. 2003 A framework for vulnerability analysis in sustainability science. In: *Proceedings of the National Academy of Sciences*, pp. 8074–8079.

Van, C. T., Tuan, N. C., Son, N. T., Tri, D. Q., Anh, L. N. & Tran, D. D. 2022 Flood vulnerability assessment and mapping: a case of Ben Hai-Thach Han River basin in Vietnam. *International Journal of Disaster Risk Reduction* **75**, 102969. https://doi.org/10.1016/j.ijdrr.2022.102969.

Vargas, R. 2010 Using the Analytic Hierarchy Process (AHP) to select and prioritize projects in a Portfolio. In: *PMI Global Congress 2010*, North America, Washington, DC. EUA.

Vojtek, M. & Vojtekova, J. 2019 Flood susceptibility mapping on a national scale in Slovakia using the analytical hierarchy process. *Water* 11–364. doi:10.3390/w11020364.

Xu, H. 2005 A study on information extraction of water body with the modified normalized difference water index (MNDWI). *Journal of Remote Sensing* **9**, 589–595.

Zhang, Z., Gao, J. & Cai, Y. 2019 The effects of environmental factors and geographic distance on species turnover in an agriculturally dominated river network. *Environmental Monitoring and Assessment* **191** (4). doi:10.1007/s10661-019-7309-3.

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