Climate Change Vulnerability Assessment Using GIS and Fuzzy AHP on an Indicator-Based Approach

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Abstract
This study aims at integrating GIS method and fuzzy AHP to evaluate the impact of climate change under the vulnerability concept. The results of this empirical study in Da Nang city have significant scientific contribution to the generation of comprehensive indicators for assessing the climate vulnerability of coastal cities in the Central region of Vietnam. The approach of the Intergovernmental Panel on Climate Change in climate change vulnerability assessment was examined considering three main components of vulnerability which are exposure to hazards, local sensitivity and adaptive capacity. A GIS-based approach was applied to generate a set of indicators and the fuzzy AHP method was investigated for the determination of a weighted scheme for parameters included in the climate vulnerability assessment. The study results indicated that the coastal and lowland districts including Ngu Hanh Son, Hoa Vang, Cam Le and Thanh Khe districts are most vulnerable to climate change due to high exposure, high sensitivity and limited adaptive capacity. On the contrary, the district with high level of adaptive capacity such as Hai Chau district is usually ranged in low level of vulnerability. The results confirm the importance of enhanced adaptive capacity in responding to the impact of climate change.

Keywords: Climate change, Da Nang City, GIS, Multi-criteria, Vulnerability

1. Introduction

Climate change is now widely regarded as humanity's greatest challenge in the 21st century, with global warming and sea level rise being two major events. Climate change has affected many different communities, leading to them facing an increase in natural disasters and becoming more vulnerable. According to a report by Eckstein [1], Vietnam is one of the countries most severely affected by climate change due to its location in tropical monsoon and coastal region. Despite the increasing frequency of natural hazards and catastrophes, as well as the increasing susceptibility of communities to disaster risks and health concerns, the awareness and preparedness of local individuals and communities are still limited. Evaluating the impact of climate change has become an urgent need for any region, especially urban areas. This is an important baseline for planning solutions to mitigate the impact of climate change in order to build and strengthen resilience.

There have been multiple approaches to evaluating the impact of climate change for a specific area. Most of the previous studies have focused on identifying a climate issue such as temperature changes, precipitation anomalies and evaluating the potential impact of climate variables or natural hazards such as droughts or flooding on human life under different climate change scenarios [2] [3] [4] and [5]. Many scholars are also interested in characterizing the potential impacts of climate change on an economic sector such as agriculture or tourism in order to provide information for managers, decision makers or policymakers [6] [7] and [8]. The assessment methods widely used in most of the previous studies are statistical analysis integrated with multiple regression and social survey. The major difficulty of these studies is that climate change is an interrelationship issue and evaluation of its impact on a specific aspect is not enough. Moreover, a comprehensive climate change assessment not only considers the exposure of an area to hazards or climate stressors, the susceptibility of an economic sector, but more importantly community resilience that most of previous studies have not addressed. This explains why disaster management is still more about dealing with the consequences rather than being proactive in minimizing the possibility in advance.

In recent years, there have been several researches on the evaluation of climate change vulnerability [9] [10] [11] [12] [13] [14] and [15] in order to find adaptation strategies and propose possible solutions in minimizing climate-associated risks. However, the vulnerability is not identical between research subjects [16] and the method for climate change vulnerability assessment is case-by-case application. Indicator-based approach is an effective way to assess climate change vulnerability that not many studies have utilized up to date. Recently, several authors have applied the vulnerability approach in assessment of the impact of different natural hazards such as floods [12] [13] [15] and [17] or droughts [18] and [19]. These studies tried to applied Geographic Information System (GIS) and multi-criteria analysis in vulnerability evaluation, but their assessment only focused on a specific hazard. Climate change vulnerability assessment is therefore attractive to researchers. However, the generation of climate change vulnerability index is still challenging since there is no common framework for identifying the criteria and people have difficulty quantitatively evaluating the severity of climate change impact. This study, therefore, tried to assess, quantify and map the climate change vulnerability by integrating the GIS method and fuzzy Analytical Hierarchy Process (AHP) analysis. The main objective is the generation of indicators to determine the vulnerability of climate change in Da Nang city based on a comprehensive assessment of three factors: exposure to hazards, local sensitivity, and adaptive capacity [20]. In order to quantitatively assess the impact of climate change, the vulnerability index is calculated based on the parameter set for each component of the vulnerability function. The parameters are standardized from 0 to 1 and integrated with the fuzzy AHP method [21] to determine the weights for component variables, thereby determining the vulnerability index for each area. The results of the project identified areas with different levels of vulnerability to climate change from low to medium and high levels. The study also proposed a number of adaptive solutions for areas that are highly vulnerable to climate change.

2. Methodology

2.1 Understanding the Climate Change Vulnerability Assessment

Climate change refers to long-term shifts in temperatures and weather patterns. These changes could be the result of human action or natural variability. According to the Intergovernmental Panel on Climate Change (IPCC), “climate change” is specifically defined as “a change in the state of the climate that can be identified by changes in the mean and/or the variability of its characteristics, and that continues for a long time, typically decades or longer” [20]. Assessing vulnerability to climate change is important for defining the risks posed by climate change and provides information for identifying measures to adapt to climate change impacts [22]. The definition of vulnerability has been mentioned in various studies in the literature [10] [20] [22] [23] and [24]. The IPCC defined vulnerability as “the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes” [20]. Although there have been many different definitions of vulnerability due to the differences in research fields and scientific viewpoints, there is a general consensus that vulnerability can be determined by three components: exposure, sensitivity, and adaptive capacity (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”. Adaptive capacity refers to “the ability of a system

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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" [25].

Vulnerability assessments are commonly distinguished as either top-down or bottom-up approaches [9]. Top-down approaches are usually preferred at global, national and regional levels, while the bottom-up approaches start their analysis at the local level (e.g., households, villages, communities). There is no one-size-fits-all solution. Assessment of the vulnerability should be conducted on a case-by-case basis and cannot generally be taken by a single ready-made method. This study applied the vulnerability assessment approach that was proposed by the IPCC [20] and described in Figure 1.

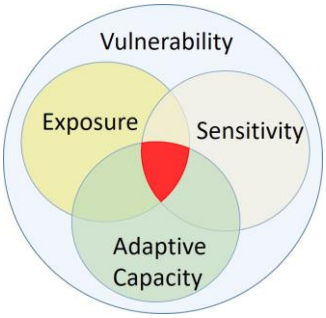

Figure 1: Concept of climate change vulnerability (Adapted from [20])

2.2 Climate change Vulnerability Calculation Approach

As mentioned above, vulnerability (V) of climate change is a function of three components: Exposure (E) to disasters, Sensitivity (S) to the local environment, and Adaptive Capacity (AC). This study used the calculation approach suggested by the IPCC [20] and UNESCO-IHE [26]:

$$V = E + S - AC$$

Equation 1

Based on this approach, an empirical study in Da Nang city was carried out. The GIS-based approach integrated with the fuzzy AHP weighting method was applied to determine the climate change vulnerability index for the study area. The case study focused on the following main outcomes in order to quantitatively determine the vulnerability of climate change:

- Firstly, it is to build a set of indicator parameters to determine the level of vulnerability due to climate change based on the natural and socio-economic conditions of Da Nang city. This set of parameters includes variables that reflect the level of exposure (E), sensitivity (S), and adaptive capacity (AC), thereby quantifying the level of vulnerability due to climate change.
- Second, it is to determine the exposure index (E). The study focused on assessing the spatial impact of climate stressors in Da Nang using remote sensing and GIS, and focused on the following main types of natural disasters: typhoons, inundation, and temperature extremes.
- Third, it is to evaluate the sensitivity (S) of the local environment in Da Nang based on the natural, residential, economic, social and infrastructure conditions.
- Next, the study also focused on determining the adaptive capacity (AC) index of each area to climate change based on the capacity of local authorities, the awareness of communities, the policies and activities in relation to climate change adaptation that had been implemented in each local community.
- Finally, the research identified the climate change vulnerability index (V) of each district using multi-criteria analysis (fuzzy AHP method of Buckley, [21]), taking into account the weights of the driving factors.

The GIS-based approach for climate change vulnerability assessment for Da Nang city is summarized in Figure 2. In the first stage of this study, a set of indicators to determine the components of climate change vulnerability was developed. These indicators were then standardized in a GIS environment and normalized into a unique scale from 0 to 1. Finally, the research applied fuzzy AHP method [21] to calculate the weight scheme and to generate the climate change vulnerability index (V) of each district.

2.3 GIS-Based Multi-Criteria Decision Analysis for Climate Change Vulnerability Assessment

The main approach that was implemented in this study is indicator-based multi-criteria integrated with GIS. In order to quantitatively measure climate change vulnerability, index-based approach is an effective method that has been adopted in previous studies [11] [12] [15] and [27]. However, the indicator system should be developed case-by-case since vulnerability depends on local characteristics of the study area and the types of disasters. On another aspect, using GIS methods to assess the impact of natural disasters (floods, droughts, salinization, etc.) is considered an effective method with the advantages of quick and accurate updates according to temporal and spatial changes of disasters [11] [28] [29] and [30].

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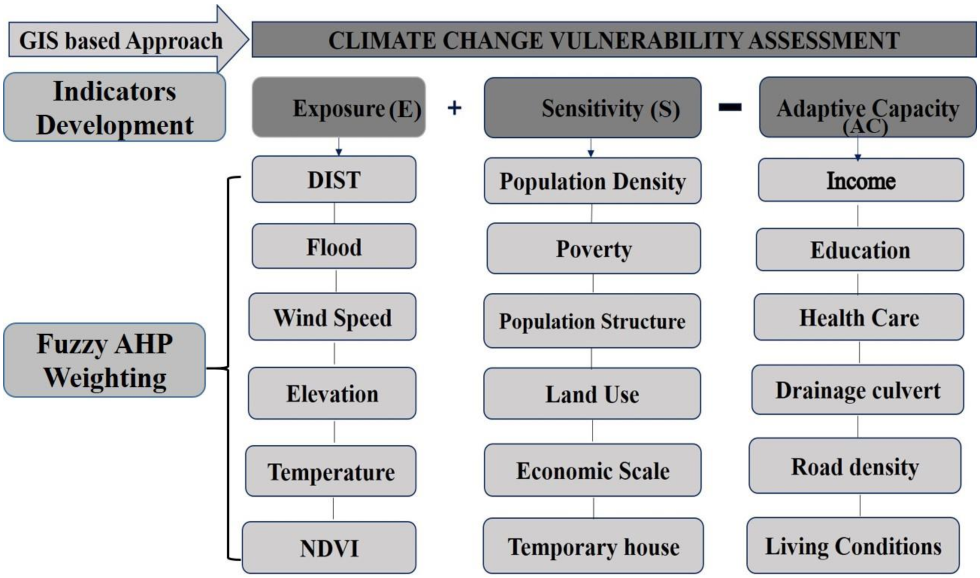

Figure 2: GIS-based approach for climate change vulnerability assessment in Da Nang city

Since climate change vulnerability assessment generally uses an index-based approach, it is highly recommended to apply the GIS method for generating a set of indicators containing both spatial and attribute information. Remote sensing data including a series of satellite images support calculating various indices that are not available in the field measurement or cannot be calculated from statistical data. This study used the Landsat 8 remotely sensed images for the generation of the Normalized Different Vegetation Index (NDVI) and the Land Surface Temperature (LST) which are two contributing factors to the exposure component. Other indicators were calculated and generated in the GIS environment (via QGIS and GRASS GIS software) with the help of statistical data and spatial data analysis techniques.

2.4 Study Area and Data Used

2.4.1 Study area

The study area is Da Nang city, which is located in the Central Coast of Vietnam and belongs to a typical tropical monsoon region. Its climate is characterized by two seasons in a year: a rainy season from August to December and a dry season from January to July, with rainfall mainly concentrated from September to December [31]. The average rainfall is 2,505 mm per year which concentrates in October and November [32]. Da Nang has an average humidity of 83.4%, and an average temperature of about 26^{0}C. The highest temperature is 28-30^{0}C in June, July, and August, and the lowest is 18-23^{0}C in December, January and February. The location of the study area is shown in Figure 3. The topographic characteristic of Da Nang city is varied with elevation ranging from 0 m to 1663 m above mean sea level and spreads from the mountain in the west to the flat region in the east. There is a relatively narrow distance between the mountainous region to the coastline of the study area, which is one of the factors making disasters become more exacerbated in this area. The varying topography is also one of the reasons causing the different exposure to climate change and its consequences.

Da Nang city has recently experienced the increasing intensity of natural disasters related to climate change (storms, floods, droughts, and salinization). The statistics from Da Nang People's Committee about disaster history in Da Nang from 1998 to 2020 prove that floods annually occur with at least 2 events per year and typhoons also happen yearly [33]. The damage caused by climate change and its consequences in the aspects of economic and human loss in Da Nang city during this period was remarkable (Table 1). Due to the geographical, topographic and geomorphological characteristics of the study area along with the impact of global climate change, the situation of natural disasters in Da Nang city is very complicated and tends to increase in quantity and severity.

The city has a natural land area of 1,285 km^2, comprising 980 km^2 of the mainland and 305 km^2 of Hoang Sa Archipelago [32]. Da Nang borders Thua Thien-Hue Province in the north, Quang Nam Province in the south and the west, and the East Sea in the east (Figure 3). Its sea area consists of the Hoang Sa archipelago (also known as Paracel Islands), which is located from 15^{0}45′N to 17^{0}15′N and from 111^{0}E to 113^{0}E.

Table 1: Impact of climate change and its threats in Da Nang city by the economic loss [33]

Damage Categories	Unit	2013	2015	2017	2018
Injured People	Person	19	1	5	0
House Damage	House	7,048	70	1,109	925
Agricultural Damage	Ha	417	103	135.2	3,326
Total Loss	**USD**	**45,123,478**	**48,260**	**2,415,652**	**478,043**

Figure 3: Administrative map of Da Nang city

Currently, Da Nang city is one of the three largest economic cities in Vietnam and the key socio-economic region in the Central Highlands. The Da Nang's territory is divided into 8 districts including 7 inland districts (Hai Chau, Thanh Khe, Son Tra, Ngu Hanh Son, Lien Chieu, Cam Le and Hoa Vang) and 1 island district (Hoang Sa). This study focused on the assessment of climate change vulnerability only for the inland area of Da Nang city due to the difference in natural and socio-economic conditions between the mainland and islands, and the limitation in data collection for the Hoang Sa Archipelago.

2.4.2 Data used

Freely accessible data was used in this study. The Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) version 4 which is freely accessible at *https://srtm.csi.cgiar.org* [34] and Landsat 8 OLI satellite image provided by USGS [35] were used to extract the physical indicators related to exposure such as elevation variation, the Normalized Different Vegetation Index (NDVI) and surface temperature. The Open Street Map [36] data was used for extraction of the index on road density which is one of the factors contributing to the adaptive capacity. The statistical data on the socio-economic conditions of Da Nang city generated from the Statistical Yearbook of Da Nang city in 2020 was used for evaluating the sensitivity and adaptive capacity. Moreover, the GIS database provided by the Da Nang Department of Natural Resource and Environment (DONRE), including the land use map and the drainage culvert map, was used for extraction of indicators related to land use and drainage system. These data are very important in the determination of sensitivity as well as adaptive capacity. In this study, QGIS [37] and GRASS GIS [38] open source GIS software's have been used frequently to generate the spatial and attribute data, normalize and analyze most of the indices for climate change vulnerability assessment. The Google Earth Engine platform [39] was utilized for processing of a time-series remote sensed data and extraction of the indices related to climate change vulnerability.

3. Results and Discussions

3.1 Indicators for Climate Change Vulnerability Assessment in Da Nang City

3.1.1 The selection of indicators

The selection of appropriate indicators for climate change assessment in Da Nang is based on (1) references from empirical studies that applied IPCC framework and GIS-based approach [9] [10] [11] [15] [40] and (2) experts survey. Firstly, the suggested set of indicators was given to 20 experts in the fields of GIS, environmentalists of Da Nang People's Committee, and specialists in climate change and disaster management in Da Nang city. After being evaluated by those experts, an initial set of indicators was determined. This expert survey data was also valuable to assess the suitability of the indicators in climate change vulnerability assessment. Subsequently, based on the statistical data on the natural hazard and socio-economic conditions of Da Nang city, a set of indicators for climate change vulnerability assessment for Da Nang city including 18 indices was developed as shown in Figure 2 and Table 2. In the exposure component, we selected six indices considering the main natural hazards in Da Nang city and the hazard resistance factor related to the vegetation. The indicators forming the exposure include typhoon intensity which relies on the distance to the coastline and river channels (DIST), wind speed, flood depth, elevation variation and the NDVI. The DIST is an important indicator reflecting the impact of typhoon intensity. The area near the coastline and river channels are first and directly affected when the tropical cyclones and typhoons land. In this study, DIST was calculated using the Euclidean distance method that was integrated into GRASS GIS software (*r.grow.distance*) (Figure 4a).

Table 2: Indicators used for climate change vulnerability assessment for Da Nang city

Components	Indicators	Detail	Abbreviations
Exposure	DIST	Distance to the coastline and river channels	**E1**
	Wind Speed	Average wind speed during typhoon	**E2**
	Flooding	Average flood depth by district	**E3**
	Elevation Variation	Difference in elevation per unit area	**E4**
	Temperature	Surface temperature during hot season by district	**E5**
	NDVI	Normalized Difference Vegetation Index	**E6**
Sensitivity	Population Density	Population density by district	**S1**
	Poverty Index	Percentage of poor household/ total household	**S2**
	Population Structure	Percentage of women and children under 5 years old, people over working age and disabled persons in the total population	**S3**
	Economic Scale	Total number of enterprises and total revenue by district	**S4**
	Land Use	Percentage of built-up and agricultural areas	**S5**
	Temporary House	Percentage of temporary house by district	**S6**
Adaptive Capacity	Income Index	Average income of each household	**AC1**
	Health Care	Percentage of medical staff in total population	**AC2**
	Education Level	Percentage of people having high-education levels	**AC3**
	Living condition	Percentage of households having cars and boats	**AC4**
	Drainage culvert	The average length of water pipe per unit area	**AC5**
	Road density	Average road length per unit area	**AC6**

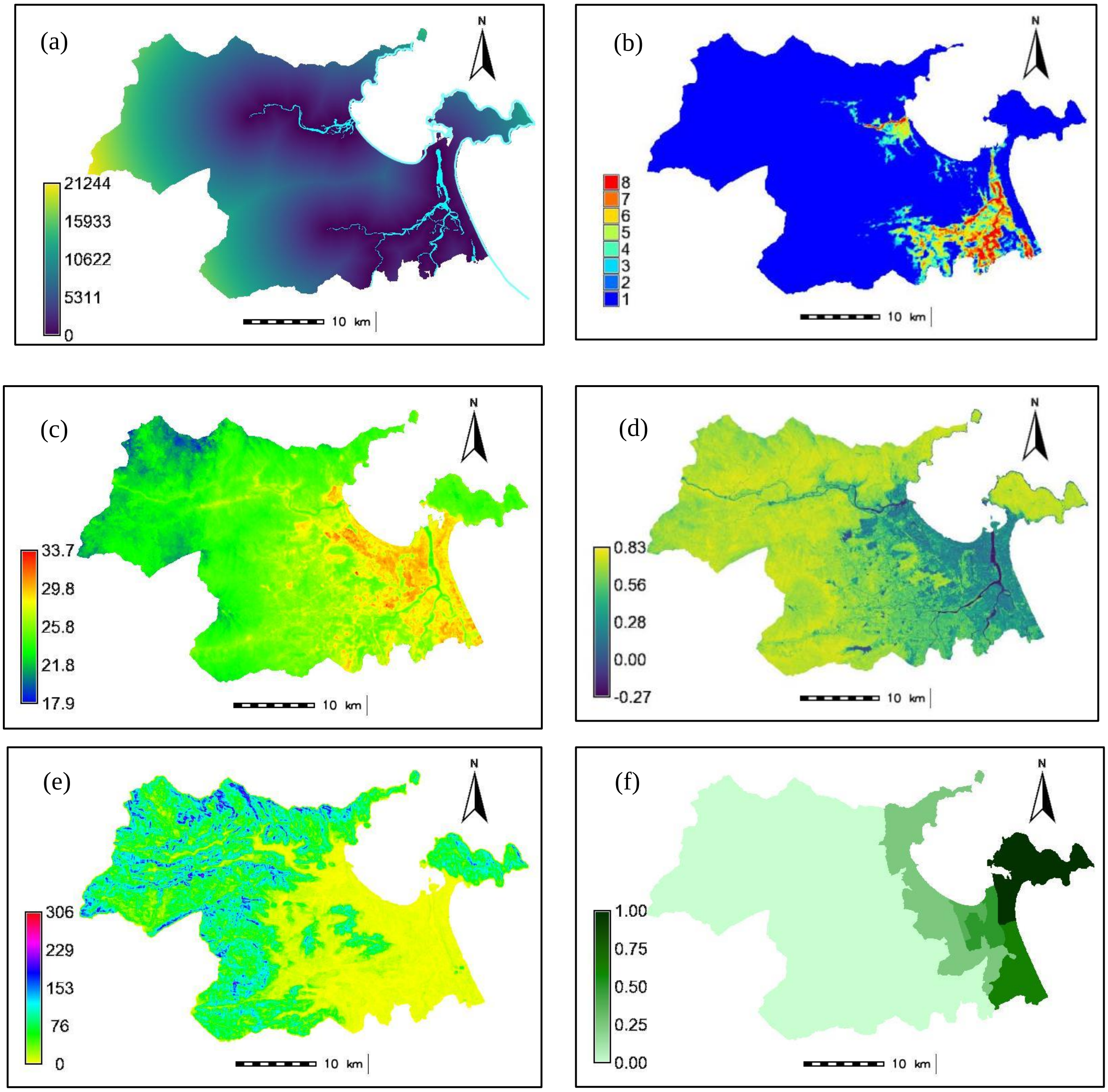

Figure 4: Parameters used in generation of climate change vulnerability indices. (a) Distance to coastline and river channel (m); (b) Flood inventory recorded depth (m); (c) Surface Temperature (ºC); (d) Normalized Difference Vegetation Index; (e) Elevation variation calculated from DEM (m); (f) Wind speed index by district

The flooding index in this study was measured by the average flood depth by districts. We used the flood inventory map provided by the Vietnam Institute of Meteorology, Hydrology and Climate Change (IMHEN) for the generation of the flood index. This flood inventory map was generated based on the elevation of the study area and the flood depth in 1999 which is the most severe historical flood in Central Vietnam. The flood inventory map of IMHEN was processed using the MIKE flood model [41] and presented in GIS format as a polygon with different flood levels for the whole area of Da Nang city (Figure 4b). Wind speed data which is recorded for different areas during the typhoon in Da Nang was collected from the open climate database on *windy.com* which is an open global weather database; the elevation variation was generated from the SRTM digital elevation model [34]; the temperature was calculated by the average of LST from series of Landsat 8 data from 2016 to 2021 during the hottest season from June to August to identify the hotspot areas in Da Nang (Figure 4c). The NDVI which is a common and widely used remote sensing index representing the density of vegetation in an area that could be one of factors reducing the intensity of disasters. The generation of NDVI is based on Landsat 8 data from 2016 to 2021 using the formula mentioned in Weier and Herring [42] (Figure 4d). In order to process the time series remote sensing data, this study took the advantage of the Google Earth Engine [39] for extraction of the Temperature and NDVI for Da Nang city.

The indicators for the sensitivity components including population density, poverty, population structure, economic scale, land use and temporary houses represent how severe an area will be affected when hazards occur. On the contrary, the adaptive capacity index is formed by the average income, education level, health-care services, living condition, road density and the drainage culvert calculated by the district. These data were generated based on the statistical yearbook data [32] with the help of GIS software including QGIS [37] and GRASS GIS [38]. The road density index was calculated from the OpenStreetMap data [36] and the spatial analysis tool in GIS. The drainage culvert data was referred from the water pipe map provided by DONRE. All of the indicators were calculated at the district level and explained in detail in Table 2.

3.1.2 Indicator processing

Indicator normalization: After being determined, all the indices were normalized into the same scale from 0 to 1. Since each indicator's values hold different units, the normalization was carried out to convert all values into a standard scale from 0 to 1. The input data after collection and calculation in the GIS environment was normalized into a scale from 0 to 1 using the method suggested by Connor and Hiroki, [43] as described below:

$$X = \frac{X_i - X_{min}}{X_{max} - X_{min}}$$

Equation 2

$$X = \frac{X_{max} - X_i}{X_{max} - X_{min}}$$

Equation 3

Where: X is the normalized value; X_i is the value of indicators at each observed point; X_{max} refers to the maximum value of the indicators and X_{min} is the minimum value of the indicators. Equation 2 is used when the parameter is in a positive relationship to the climate vulnerability and equation 3 is applied when the index has a negative impact on the vulnerability. These indices then were integrated with the fuzzy AHP model for weighted calculation and generating a combined index for climate change vulnerability. The calculation results of some parameters are shown in Figure 4.

Indicators weighting: In this study, a fuzzy AHP approach developed by Buckley [21] has been applied to determine the weight for indicators in climate change vulnerability assessment for Da Nang city. In order to deal with a complex decision-making, weighting by AHP [44] has been widely used in many studies [2] [3] [28] [29] [40] [44] and [45] in the literature. However, due to the complexity and uncertainty involved in the traditional AHP method, a decision maker sometimes feels more confident to provide fuzzy comparison matrices [46].

The Saaty-proposed AHP methodology [44] has been recognized by the research community as a reliable and adaptable multi-criteria decision-making (MCDM) technique to solve complicated decision problems [46]. The initial step in the traditional AHP method is to transform the subjective judgments of experts to the numerical information, where a fixed value was chosen to represent the relative importance of the different criteria. Subsequently, a pairwise comparison matrix is created. Finally, using the eigenvector approach, the weight coefficients for each criterion were determined. In most cases, this quantification method relies heavily on the subjective evaluation, and the preferences and accessibility of experts will significantly affect the outcomes. Due to the existence of a subjective preference, it is challenging to describe the relative importance of the many criteria as the fixed value in Saaty's traditional AHP technique [44]. The fuzzy AHP, which replaces fixed values with triangular fuzzy numbers to thoroughly express subjective features included in the consultation phase, realized the improvement over traditional AHP and can effectively address the aforementioned issue. This study applied the fuzzy AHP method suggested by Buckley [21] which focus on using the geometric mean of the triangular fuzzy values to determine the weighted scheme for various criteria. The main steps of fuzzy AHP to identify the weight combination for criteria associated with the climate change vulnerability are:

Step 1: Assigning the experts' evaluation into the triangular fuzzy number to reflect the importance degree between any two criteria involved in the climate change vulnerability, where the 1-to-9 scale method was used (Table 3, Table 4, Table 5 and Table 6).

Step 2: Building a fuzzy evaluation matrix according to a hierarchical structure. The establishment of the hierarchical structure is a prerequisite for the fuzzy AHP method. The

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fuzzy evaluation matrix A = (aij) n × n was established as follows:

$$\tilde{A} = \left(\tilde{a}_{ij}\right)_{n\times n} = \begin{pmatrix} (1,1,1) & (l_{12},m_{12},u_{12}) & \cdots & (l_{1n},m_{1n},u_{1n}) \\ (l_{21},m_{21},u_{21}) & (1,1,1) & \cdots & (l_{2n},m_{2n},u_{2n}) \\ \vdots & \vdots & \vdots & \vdots \\ (l_{n1},m_{n1},u_{n1}) & (l_{n2},m_{n2},u_{n2}) & \cdots & (1,1,1) \end{pmatrix}$$

$$\tilde{a}_{ij} = \left(l_{ij},m_{ij},u_{ij}\right) = \tilde{a}_{ji}^{-1} = \left(\frac{1}{u_{ji}},\frac{1}{m_{ji}},\frac{1}{l_{ji}}\right), i,j = 1,\cdots,n; i \neq j$$

Equation 4

Where the (*l*, *m*, *u*) corresponds to the lower, the medium and upper values of the triangular fuzzy number. These values are arranged according to Table 3 which is the relative importance ratio scale used in fuzzy AHP method [21].

Step 3: Calculate the geometric mean [21] for computing the weights w_i which is easily extended to fuzzy positive reciprocal matrices. Given a positive reciprocal matrix A = [aij], first compute the geometric mean of each row as:

$$r_i = \left(\prod_{j=1}^{m} a_{ij}\right)^{1/m}$$

Equation 5

For Example: From Table 4, the first Geometric mean values for E1 is calculated as:

*l (E1) = (1*1*1/5*1*1*1)^(1/5) = 0.765*
*m (E1) = (1*2*1/4*2*1*2)^(1/5) = 1.122*
*u (E1) = (1*3*1/3*3*1*3)^(1/5) = 1.442*

It is obvious that the Geometric mean of the triangular fuzzy values of the criteria E1 are [0.765, 1.122, 1.442]. Similar steps were applied for other criteria and then we can obtain the Geometric mean values for the whole matrix A [aij].

Step 4: Calculate the fuzzy weight values for each criterion. After getting the Geometric mean values for the matrix A = [aij], following the fuzzy AHP method of Buckley [21], we calculate the sum values by column and the took the reciprocal values for the matrix A [aij]. For example, from the Table 4 we can get the sum of Geometric mean values for Exposure are [4.66, 6.55, 8.73], and then the reciprocal values are calculated as [1/8.73,1/6.55,1/4.66]. Subsequently, the fuzzy weights for each criterion were determined by multiplying the Geometric mean values of each criterion by the reciprocal values of the matrix A [aij] sum of Geometric mean data. In the example above, the fuzzy weigh values of the criteria E1 are [0.765*1/8.73, 1.122*1/6.55, 1.442*1/4.66].

Step 5: Normalized weights for fuzzy AHP. In the final step, the fuzzy weights were converted into the fixed weights by taking the average values of the fuzzy weights row by row in the matrix A [aij]. This weighting scheme was then normalized again by dividing each weight by the sum of individual weights, in order to ensure that the total weights in each component is always equal to 1. The results of apply fuzzy AHP in determination of the weights for parameters in climate change vulnerability in Da Nang city are explained in the Table 3 to Table 6.

Table 3: Relative importance ratio scale used in fuzzy AHP method (Adapted from [21])

Relative Importance	**Triangular fuzzy number**	**Reciprocal values**
Equal importance	(1,1,1)	(1,1,1)
Weak importance	(2,3,4)	(1/4,1/3,1/2)
Strong importance	(4,5,6)	(1/6,1/5,1/4)
Very strong importance	(6,7,8)	(1/8,1/7,1/6)
Absolute importance	(9,9,9)	(1/9,1/9,1/9)
Intermediate values	(1,2,3); (3,4,5); (5,6,7) and (7,8,9)	(1/3,1/2,1); (1/5,1/4,1/3); (1/7,1/6,1/5) and (1/9,1/8,1/7)

Table 4: Triangular fuzzy values and corresponding weights for indicators of Exposure

Criteria	**E1**	**E2**	**E3**	**E4**	**E5**	**E6**	**Weight (w)**
E1	(1,1,1)	(1,2,3)	(1/5,1/4,1/3)	(1,2,3)	(1,1,1)	(1,2,3)	**0.17**
E2	(1/3,1/2,1)	(1,1,1)	(1/4,1/3,1/2)	(1,1,1)	(1/3,1/2,1)	(1,1,1)	**0.10**
E3	(1,2,3)	(2,3,4)	(1,1,1)	(2,3,4)	(1,2,3)	(2,3,4)	**0.33**
E4	(1/3,1/2,1)	(1,1,1)	(1/4,1/3,1/2)	(1,1,1)	(1/3,1/2,1)	(1,1,1)	**0.10**
E5	(1,1,1)	(1,2,3)	(1/3,1/2,1)	(1,2,3)	(1,1,1)	(1,2,3)	**0.20**
E6	(1/3,1/2,1)	(1,1,1)	(1/4,1/3,1/2)	(1,1,1)	(1/3,1/2,1)	(1,1,1)	**0.10**

Table 5: Triangular fuzzy values and corresponding weights for indicators of Sensitivity

Criteria	S1	S2	S3	S4	S5	S6	Weight (w)
S1	(1,1,1)	(1,2,3)	(1,1,1)	(1,2,3)	(2,3,4)	(2,3,4)	**0.26**
S2	(1/3,1/2,1)	(1,1,1)	(1/3,1/2,1)	(1,1,1)	(1,2,3)	(1,2,3)	**0.15**
S3	(1,1,1)	(1,2,3)	(1,1,1)	(1,2,3)	(2,3,4)	(2,3,4)	**0.26**
S4	(1/3,1/2,1)	(1,1,1)	(1/3,1/2,1)	(1,1,1)	(1,2,3)	(1,2,3)	**0.15**
S5	(1/4,1/3,1/2)	(1/3,1/2,1)	(1/4,1/3,1/2)	(1/3,1/2,1)	(1,1,1)	(1,1,1)	**0.09**
S6	(1/4,1/3,1/2)	(1/3,1/2,1)	(1/4,1/3,1/2)	(1/3,1/2,1)	(1,1,1)	(1,1,1)	**0.09**

Table 6: Triangular fuzzy values and corresponding weights for indicators of Adaptive Capacity

Criteria	AC1	AC2	AC3	AC4	AC5	AC6	Weight (w)
AC1	(1,1,1)	(1,2,3)	(1,2,3)	(1,1,1)	(2,3,4)	(2,3,4)	**0.26**
AC2	(1/3,1/2,1)	(1,1,1)	(1,1,1)	(1/3,1/2,1)	(1,2,3)	(1,2,3)	**0.15**
AC3	(1/3,1/2,1)	(1,1,1)	(1,1,1)	(1/3,1/2,1)	(1,2,3)	(1,2,3)	**0.15**
AC4	(1,1,1)	(1,2,3)	(1,2,3)	(1,1,1)	(2,3,4)	(2,3,4)	**0.26**
AC5	(1/4,1/3,1/2)	(1/3,1/2,1)	(1/3,1/2,1)	(1/4,1/3,1/2)	(1,1,1)	(1,1,1)	**0.09**
AC6	(1/4,1/3,1/2)	(1/3,1/2,1)	(1/3,1/2,1)	(1/4,1/3,1/2)	(1,1,1)	(1,1,1)	**0.09**

3.2 Identification of Vulnerable Areas to Climate Change in Da Nang City

Climate Change Vulnerability Index (CCVI) is calculated by combining the exposure, sensitivity and adaptive capacity using equation 1 in which the weighting scheme is taken into account. As the result, the CCVI for Da Nang city ranged from 0.22 to 0.62. Subsequently, CCVI values were reclassified into four-level as low, medium, high to very high with equal intervals. The division schemes using equal range are as below: 0.22 to < 0.32 (low); 0.32 to < 0.42 (medium); 0.42 to < 0.52 (high) and >= 0.52 (very high).

Figure 5 indicates that most of areas in Da Nang city are vulnerable to climate change and its consequences. The very highly vulnerable areas in Da Nang city belong to Hoa Vang, Ngu Hanh Son, Cam Le and Thanh Khe districts. These areas are characterized by the coastal or lowland topography, close proximity to the coastline and river channels or high density of population. These areas are also under high impact of tropical cyclones and floods as reported by local government [33]. On the other hand, the low vulnerability level corresponded to the city center located in Hai Chau district which has a high rate of economic development and comparable adaptive capacity.

Although Hai Chau district has a relatively high value of sensitivity, it is leading in the adaptive capacity map of Da Nang city (Figure 5c), which makes the vulnerability level of the district kept at a low level in the study area. It can be concluded that enhancing adaptive capacity is one of the key factors in responding to the climate change vulnerability.

Ngu Hanh Son is categorized as the most vulnerable district to climate change (Table 7). This is the coastal district which has highest exposure, relative sensitivity and medium level of adaptive capacity. This district has been recognized with significant impact of floods and typhoons in Da Nang city. This is also a high development urban area in Da Nang with relatively high density of population as well as the enterprises.

Hoa Vang district is a rural district of Da Nang city with high elevation in the west and lowland topography in the east. Although this district is ranged as low level in the exposure map (Figure 5a), Hoa Vang has the lowest value of adaptive capacity (Figure 5c) which is negatively affected by CCVI. Therefore, Hoa Vang along with Ngu Hanh Son, Cam Le and Thanh Khe districts are categorized as having a very high level of vulnerability to climate change (Table 7).

3.3 Recommendations and Possible Responsibilities to Climate Change in Da Nang City

The results of climate change vulnerability assessment in this study pointed out that enhancing adaptive capacity is the key factor in coping with the climate risk. Da Nang city government has early been aware of the role of improving the City’s adaptive capacity in responding to the climate change vulnerability. In addition to the development of construction, the city focused on social welfare work, completing the construction and maintenance of residences for low-income families. Da Nang was the first locality to finish a plan to rehabilitate veterans' homes in 2014. In addition, from 2011 to 2015, the program for storm-resistant housing, funded by Rockefeller Foundation and implemented by the Da Nang Women’s Union built and renovated a number of houses for typhoon resilience [47].

Table 7: The climate change vulnerability values and its components by districts

Districts	Exposure	Sensitivity	Adaptive Capacity	Vulnerability
Son Tra	0.42	0.32	0.27	0.47
Lien Chieu	0.37	0.27	0.31	0.33
Thanh Khe	0.49	0.59	0.49	0.59
Ngu Hanh Son	0.80	0.41	0.59	0.62
Cam Le	0.61	0.33	0.33	0.61
Hai Chau	0.58	0.53	0.89	0.22
Hoa Vang	0.26	0.38	0.12	0.52

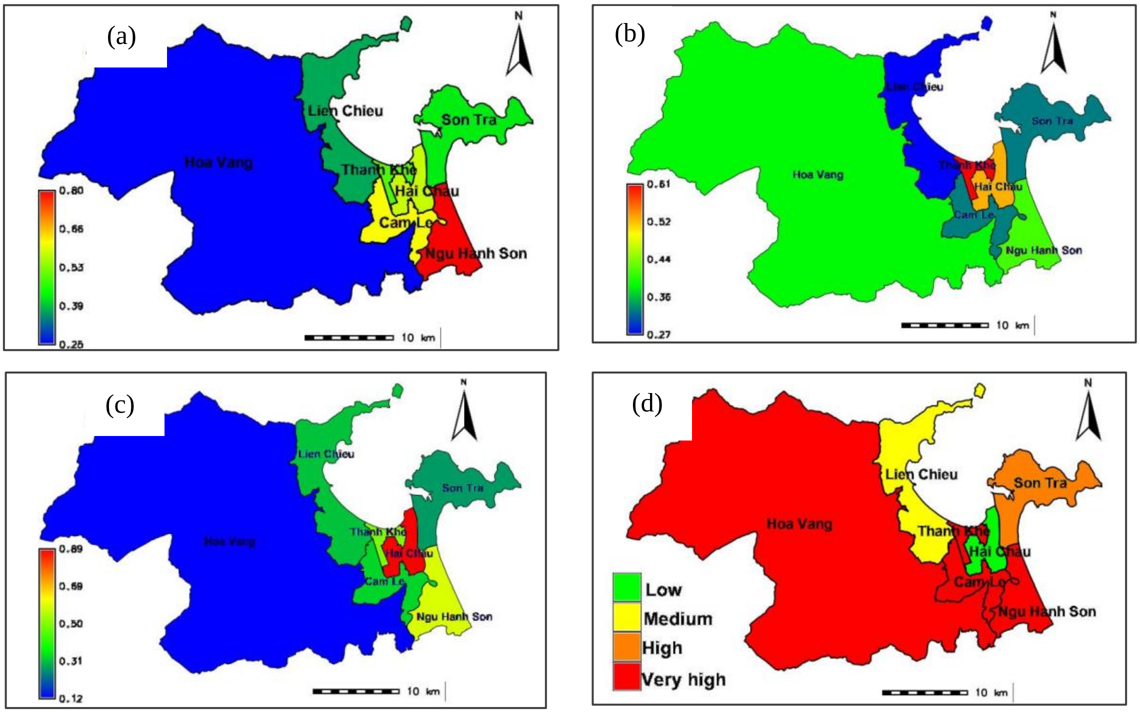

Figure 5: Climate change vulnerability map and its components for Da Nang city. (a) Exposure; (b) Sensitivity; (c) Adaptive Capacity; (d) Climate change vulnerability

Education is an important part of the adaptive capacity of Da Nang city. Various education programs and activities have been conducted on Education for Sustainable Development (ESD) at different levels from primary schools to universities [48] and [49]. Da Nang city also expensed a significant investment on ESD projects to the local communities with the goal of enhancing the resident's adaptive capacity to the risk of climate change.

Building resilience allows residents, neighbourhoods, and all of a city's systems to better prepare for and recover from climatic shocks and pressures. The city's residents should actively take part in the climate change mitigation and disasters prevention through various programs. With the support of 4.0 technology, Da Nang city should further develop its e-government system to provide all online public administrative services and non-business services on multiple digital platforms. Information about climate change and disasters in the city should be rapidly transformed on mobile devices and further all governmental agencies could provide open data. Currently, Da Nang is using the 1022 public service portal (known as Chatbot 1022) allowing the citizens to rapidly access all of the city information including disasters and risk warnings. This chatbot app developed by the Da Nang

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Government has become Vietnam's only product shortlisted for the final round of the GO Smart Awards 2020 organized by the Global Organisation of Smart Cities [50].

3.4 Limitations and Future Research

Although the goal of this study is to develop indicators for assessing climate change vulnerability using GIS and fuzzy AHP method, there are still certain limitations that need to be addressed in future research. Firstly, the accuracy assessment for climate change vulnerability map has still not been carried out, since the vulnerability is a multi-dimensional problem and hence it is difficult to obtain the field measurement data of this index for validation. However, previous studies [12] [15] [17] and [22] has pointed out that the accuracy of the vulnerability assessment mainly depends on the accuracy of the input data. Up to now, the accuracy assessment of the vulnerability map is still challenging for many studies. There has been no specified method that could definitely validate the procedure of vulnerability mapping yet. The IPCC does not provide a technique for assessing vulnerability, but first and foremost, the input data source used to compute the indicators should be confirmed, and then the vulnerability index is used as a baseline to propose solutions for localities as well estimate future disaster impact. This study has selected input data from reliable sources provided by local government departments such as the Da Nang Statistical Office, Da Nang city Government, Da Nang DONRE, and GIS-derived parameters. Therefore, the climate change vulnerability assessment results from this study are valuable as we have a set of reliable input indicators. In the future, we plan to investigate the statistical data of the damage caused by climate change integrated with the household surveyed data for validation of the climate change vulnerability map for Da Nang city.

Secondly, while weighting method by using fuzzy AHP in this study could overcome some limitations in the traditional AHP method, its results still depend on the judgements of surveyed experts which are still sensitive. In the future work, we aim at investigating the machine learning technique with the training data based on the field survey of the most vulnerable locations for estimation of the weighting scheme. With the support of GIS technique and machine learning algorithms, we may automatically obtain the accurate weights for all input parameters. This approach is expected as a robust and comprehensive assessment of climate change vulnerability for any other extents of study areas.

4. Conclusions

This research is an empirical study of applying IPCC framework and GIS indicator-based approach to calculate the climate change vulnerability index via the generation the vulnerability maps at the district level that reflect the spatial distribution of climate change vulnerability in Da Nang city. Integrating the GIS approach and fuzzy AHP method, this study developed a set of indicators for climate change vulnerability assessment for Da Nang city, including 18 indices covering both natural and socio-economic conditions of the city. Data was collected from the Statistical Yearbook of Da Nang city in 2020, SRTM DEM, flood depth, land use map, open street map, Da Nang open portal data and other remote sensing data sources. Weighted aggregation of the indices on a GIS environment effectively created a picture of climate change vulnerability in Da Nang city in which having more exposure to hazards does not always mean high vulnerability and vice versa. The empirical results indicated that the coastal and lowland districts, including Ngu Hanh Son, Hoa Vang, Cam Le and Thanh Khe districts, are most vulnerable to climate change due to high exposure, high sensitivity and relatively low adaptive capacity. On the contrary, the district with a high level of adaptive capacity such as Hai Chau district is usually ranged in a low level of vulnerability. The paper subsequently proposed policies and priority of investment in order to enhance the city's adaptive capacity in response to climate change.

The present study demonstrated the effectiveness of integrating the GIS method and fuzzy AHP model for climate change vulnerability assessment for Da Nang city. The proposed method confirmed the potential use of the climate change vulnerability model for other study areas that have similar socio-economic and environmental conditions.

In future work, we will focus on developing the indicator system for climate change vulnerability assessment and estimation of the weights using machine learning technique. The field survey and interview for improving the database on climate change impact and responsibility will be also integrated. In addition, future scenarios on climate change will be also considered for the comprehensive vulnerability assessment.

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