Assessment of Urban Flood Vulnerability Using Integrated Multi-parametric AHP and GIS

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Abstract
Flooding is considered the most dangerous natural disaster in Vietnam. The purpose of this study is to assess the flood vulnerability level based on the pre-event characteristic in Hoan Kiem district, Hanoi, Vietnam. The flood vulnerability zoning map was generated by using a multi-parametric approach and integrates some of the flooding causative factors namely slope, land use, percentage of green, and per capita sewer length line. The analytic hierarchy process (AHP) was applied to determine the weighted correlation among components based on their importance to this phenomenon. As the result, the Consistency Ratio (CR) in this case was 0.025 and the land use was determined as the weightiest parameter at 0.52. The flood vulnerability was quantified and classified into four levels, namely low, moderate, high, and very high with the support of GIS software. The result showed that Hoan Kiem district faces a high level of flood vulnerability, distributed mainly in the Old Quarter area, where the population is densely populated and the drainage system is outdated. In which, 61.3 ha (11.3%) is in low-vulnerability zones, 123.3 ha (22.7%) in moderate vulnerability zones, 328.8 ha (60.5%) in high-vulnerability zones, and 30.2 ha (5.5%) in very high-vulnerability zones.

Keywords: AHP Method, Flooding, GIS and Disaster, Hoan Kiem District, Remote Sensing, Vulnerability

1. Introduction

Natural disasters are a big challenge worldwide. Flood is one of the most frequent and devastating natural disasters, it causes heavy damage to the economy, society, and environment [1]. Too much rain or melting snow are the main causes of floods. However, they are often promoted by negative impacts from humans e.g. deforestation, uncontrolled urbanization, or the greenhouse effect. Urban flooding is caused by heavy rainfall and overwhelming drainage capacity. It disturbs the daily life of urban people. It causes traffic congestion, and all production and living activities are disrupted [2]. Vulnerability to flood is defined as a measure of a region's susceptibility to flooding damage [3]. Urban flood vulnerability maps provide important information for urban planning and management. In general, vulnerability is often assessed based on natural factors. Recently, social factors have also been considered as an important part affecting the degree of vulnerability [4].

The assessment of flood vulnerability has been of interest in many studies. They help the reader understand the "potential for loss" by flooding, traditionally the research focused on the nature of the hazard and who and what is the most affected. Research on flood vulnerability is considered an important and urgent topic in disaster and climate change research. This is evidenced by the rapidly increasing number of studies on urban flooding and the diversity of methods and approaches [5]. By reviewing the content of a total of 318 articles published in prestigious journals over the course of 10 years (2006 - 2016), Cho and Change [6] identified four main approaches to solving the problem of urban flood vulnerability including technological and engineering, socio-economic, planning and policy, and comprehensive approach. Research results have shown that more and more articles are using a comprehensive approach to flood vulnerability assessment, which shows the need for a new paradigm shift towards a more comprehensive approach for a multidimensional understanding of flood vulnerability across different sectors. Advances in technology and techniques have made flood research easier and more efficient. One of the widely applied methods in flood research is the use of hydraulic and hydrological models, such as MIKE FLOOD, SOBEK, and HEC-RAS models. These models are designed to visually simulate flooding in the study area based on natural features and measured flood data. At the same time, this model also helps to predict the extent of damage according to the scenarios. The modeling method is also applied effectively in flood studies in urban areas.

Tayyab et al., [7] used the urban flood resilience model (UFResi-M) to determine flood sensitivity and ability to cope with urban flood resilience in Peshawar city and some other cities in Pakistan. Christopher et al., [8] created a flood model to simulate and evaluate the flood situation for Ouagadougou city based on Digital Elevation Model (DEM), urban blocks, and drainage axis. (e.g. road or sewer). However, using such models is very difficult because they require a detailed hydrological database from the measurement stations. In addition, the paucity of monitoring records of surcharge conditions for model calibration and validation is also a great challenge in the research process.

In addition, the hydraulic and hydrological modeling methods are mainly concerned with the external natural factors of flood risk. The socio-economic factors of the study area have not been taken into account. Although these are very important factors determining flood risk reduction. This is also considered one of the limitations of this method. Indicators such as education level, poverty rate, infrastructure, etc. are considered indispensable parameters in assessing flood vulnerability [9] and [10]. Flood is a natural phenomenon but it is motivated by human activity. Accordingly, policies and plans are the factors that have a strong impact on community consciousness and resilience to natural disasters. The collaborative decision-making process leads to consensus among stakeholders in providing appropriate solutions to reduce the harm caused by flooding [11]. Therefore, a comprehensive approach combining natural components and typical social characteristics typical of the study area is considered an appropriate direction.

Due to its superiority in spatial analysis, GIS is widely used in the creation of flood risk and vulnerability maps [12] and [13]. GIS software assists in spatial analysis, data overlay, and map export. Remote sensing provides important data regarding the physical condition in the study area extracted from the satellite image. In order to assess vulnerability to extreme climate events, the index method is one of the widely used, highly effective methods and has been applied in many studies. Szlafsztein and Sterr [14] created a composite vulnerability index (CVI), which includes 16 variables of both physical and socio-economic conditions to assess flood vulnerability in Para, Brazil. Similarly, Ghosh and Kar [15] used analytical hierarchical processes (AHP) and GIS to evaluate the flood risk in the Malda district of West Bengal, India. In which, the flood risk map is created based on the unique morphological and hydrometeorological factors of the study area, whereas the flood vulnerability map is the result of the combination of three factors, namely demographic, socio-economic factor, and infrastructure. The space analysis function in GIS was used to incorporate heterogeneity geography characteristics and classified in study areas [16]. It is found that remote sensing and GIS combined with multi-criteria analysis have been used effectively for flood vulnerability zoning, especially in developing countries, where there is a serious shortage of measuring and disaster warning stations.

Located in the Southeast Asia region, Vietnam's territory stretches across 15-degree latitudes, situated completely in the interior tropical zone of the Northern hemisphere. The geographic location and diverse topography have formed a special climate for Vietnam – a monsoon tropical climate. It is also the reason that lead to the diversified natural disasters in Vietnam. Hanoi is the capital of Vietnam and the country's second largest city by population. It is located in the Red River Delta, north of Vietnam (Figure 1). The area is covered by 5.29 km^2. The old sewerage system and the low flat terrain made Hanoi more sensitive to urban floods. Inundation taking place frequently caused damage to infrastructure, transport, environment, and human health. However, due to the lack of available data, there is too little thorough research on the flood in Hanoi so far. Moreover, in almost all developing countries, the serious shortage of flood warning systems limits the abilities of flood prevention and is a big challenge for researchers. In recent years, along with the quick development of science and technology, the integration of remote sensing (RS) and Geographic Information System (GIS) has become an effective solution to studying natural disasters. In this context, the study aims to answer the following questions: (1) What criteria contribute to the cause of urban floods? (2) How do determine the weight of the criteria and their impact on the spatial distribution of flooding in the study area? (3) Which locations are at high flood vulnerability in the study area? A flood vulnerability map is built based on the integration of GIS and the Analytic Hierarchy Process (AHP) model to classify the flood vulnerability levels in the study area.

2. Materials and Methods

2.1 Materials

Based on the actual characteristics of the flood history in the study area, the collected data includes data related to on-site physical, population, and infrastructure that directly affect the formation of flooding in the study area. In this study, vulnerability to flood was defined based on four criteria, namely slope index, land use index, percentage of green index, and per capita sewer line length index.

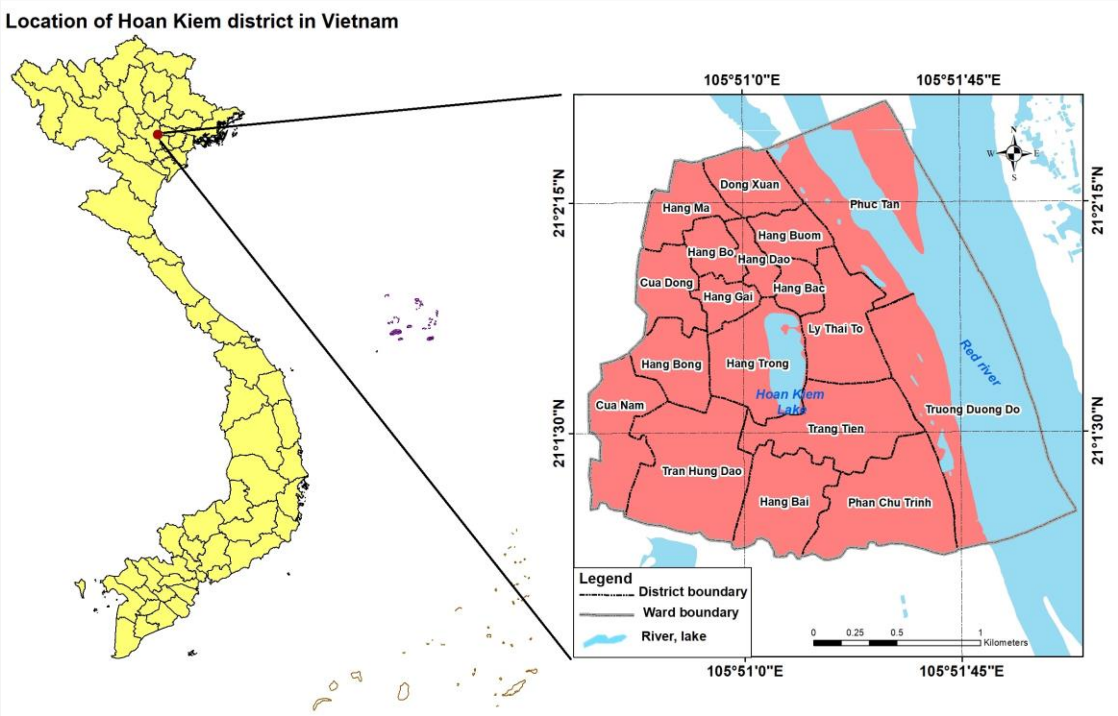


Figure 1: Location of the study area

The spatial databases (topography map, administrative map) provided by the Hanoi Department of Natural Resources and Environment were used to create the slope index. The land use map at 1:100.000 scale provided by Hanoi Department of Survey and Mapping was utilized to create land use index. Landsat 8-OLI taken in 30th July 2020 freely downloaded from the website of United States Geological Survey (https://earthexplorer.usgs.gov/), and it was used to analyze the percentage of green index in the study area. The drainage system data was provided by the Hanoi Department of Planning and Architecture. The population data of Hoan Kiem in 2020 was collected from Hanoi's statistical yearbook.

2.2 Methods

Based on the on-site characteristic and database of the study area, index maps were created. After that, each one was classified into four classes, namely low, moderate, high, and very high corresponding to susceptibility to flooding. To derive a vulnerability flood map, all index maps were overlaid and then weighted using the AHP (Analytic Hierarchy Process) method. Based on the outcome, the values were classified and mapped. The vulnerability was divided into four classes, namely low, moderate, high, and very high by the equal interval method in GIS software. Accordingly, the values were less than 0.25 corresponding to a low level. Similarly, moderate level, high level, and very high level were assigned the value from 0.25 to 0.5, from 0.5 to 0.75, and greater than 0.75 respectively. The steps were presented in Figure 2.

3. Results

3.1 Identify the Slope Index

The slope is an important factor that directly affects the flow rate, which in turn promotes the concentration or drainage capacity of the subsurface in an area. Accordingly, the slowest run-off finds on the flat slope while the highest run-off occurs on the medium or high slope. Several studies have shown a proportional relationship between flow velocity and slope. Accordingly, areas with steep slopes have high flow rates and vice versa, especially in places with relatively flat terrain such as urban areas, this relationship is clearly shown [17] and [18]. In this study, slope map was derived from DEM (Figure 3). In the next step, the value range was reclassified into levels. The low slope areas were identified at high potential inundation level while the high slope areas with the rapid drainage capability were given at low level and shown in Table 1. The highest susceptibility was assigned the value of 4 and the smallest one was at 1 (Table 1). In general, Hoan Kiem has a relatively flat terrain, and the slope is mostly below 8 degrees (Figure 4). Vulnerability values for different slope categories.

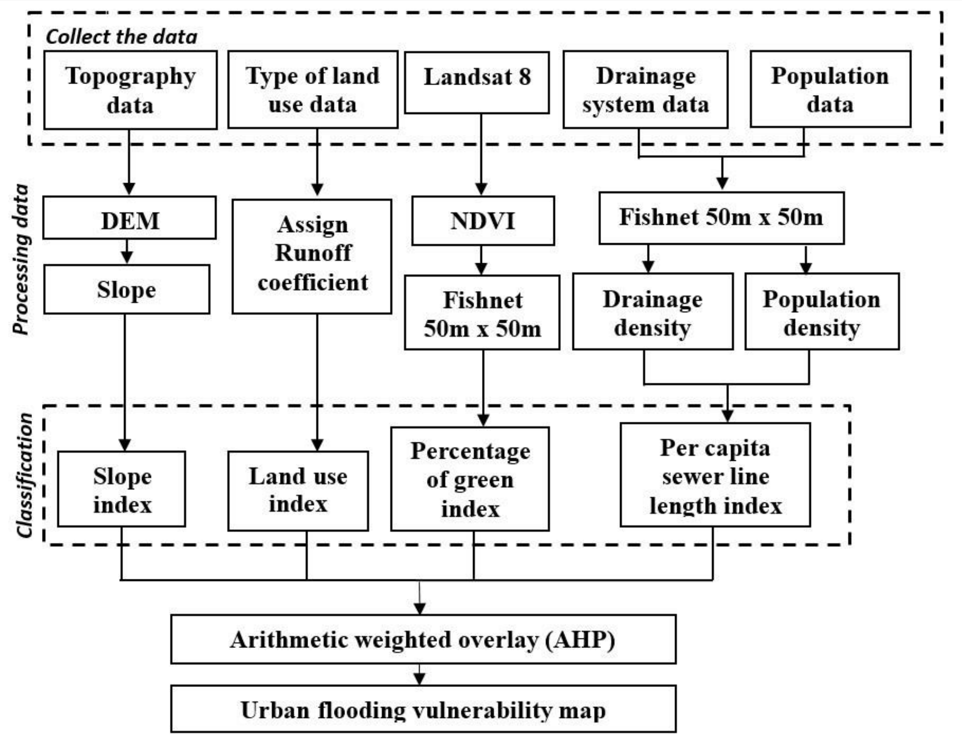
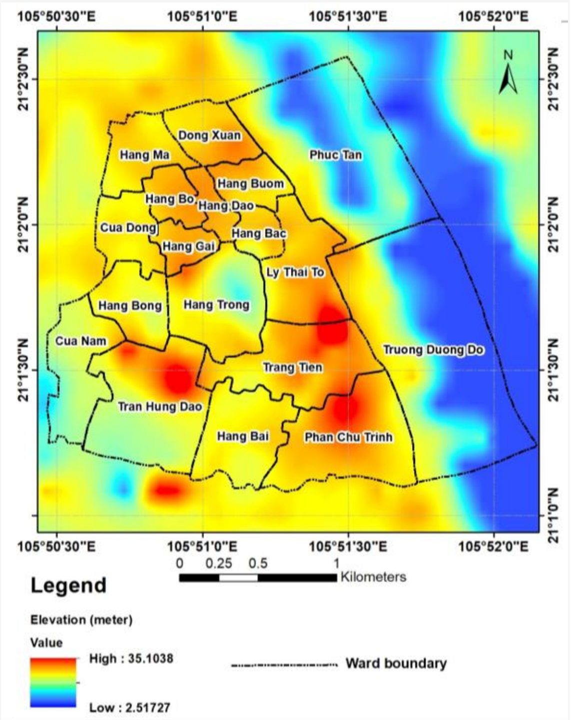


Figure 2: Flow chart of flood vulnerability



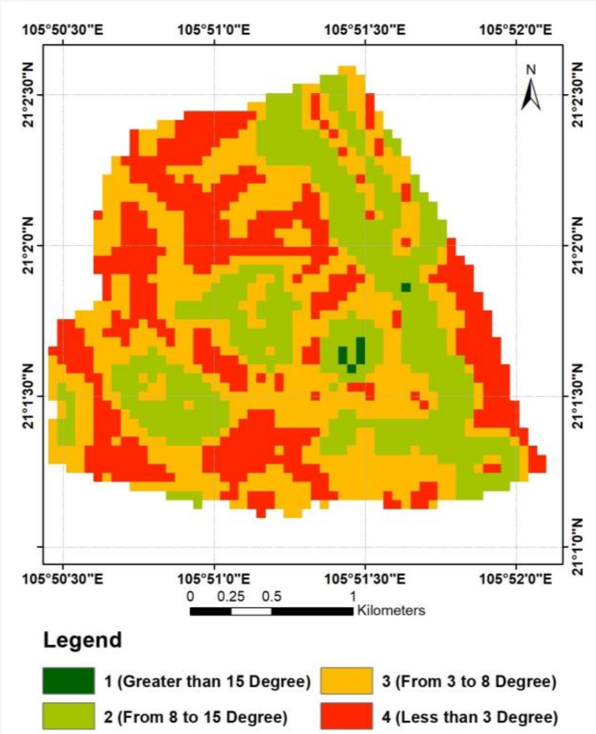


Figure 3: Digital elevation map

Figure 4: Slope index map

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Table 1: Vulnerability values for different Slope categories

Slope (Degree)	Vulnerability ranking
Less than 3	4 (Very high)
From 3 to 8	3 (High)
From 8 to 15	2 (Moderate)
Greater than 15	1 (Low)

Table 2: Vulnerability values for different Land-use categories

Types of land use	Runoff coefficient	Vulnerability Ranking
Commercial	0.80	4
Institutional	0.70	3
Park, garden, road side green	0.25	1
Residential	0.65	3
Street (Asphalt and Concrete)	0.95	4
Pavement (Brick)	0.85	4
Water	1.00	4
Playground	0.35	2
Agricultural	0.30	2

Table 3: Vulnerability values for Land use index

Ranking of vulnerability	Area (ha)	Percentage (%)
1 (Low)	9.8	1.8
2 (Moderate)	25.7	4.8
3 (High)	146.0	27.5
4 (Very high)	350.0	65.9

3.2 Identify the Land Use Index

Land use is an extremely important factor in determining flood vulnerability in a certain area. Due to the difference in types of surface materials such as wood, reinforced concrete, cement, vegetation, grass, stone, and mixing, it leads influences the infiltration capacity of water - causing the flood. In this study, the land use index was determined based on the difference of coefficient run-off corresponding to each type of land (Table 2). The study area was covered by categories, namely commercial, institutional, park, garden, roadside green, residential, street, water, playground, and agricultural land (Figure 5). As a result, commercial land and residential land are two types of land occupying the largest area in the study area. Commercial land (e.g. Hotel, Shop, Market, Commercial Workshop/garage, Restaurant/bar, Supermarket, and other commercials) is 143.27 ha, accounting for 26.96% total area. The second largest area is the residential land with 130.90 ha, accounting for 24.63 % total area. The street accounts for above 20% total area. The area for green space is quite small at under 5%. Based on the runoff coefficient value corresponding with each land use the vulnerability ranking was assigned. Moreover, the difference in land uses affect significantly to the concentration-time of water. If the geographic distance between two points is the same, the time for runoff flow from the start-point to the end-point will be slowest with the residential land and become faster with the Commercial and industrial or business area [19]. The higher the runoff coefficient is, the higher the susceptibility level is. In this manner, the water and street (asphalt and concrete) were considered at maximum ranking while the lowest position corresponded to the park, garden, and agricultural land (Figure 6). As a result, the high-vulnerability area occupies a quite large area over 65% of the total area, while the low-vulnerability area only accounts for nearly 2%. (Table 3).

3.3 Identify Percentage of Green Index

Green space is an indispensable part of urban planning in any country. It is defined as urban land, partly or completely covered with grass, trees, shrubs, or other vegetation [20]. Green space plays a very important role in the development of urban areas. Green space greatly affects surface runoff, one of the main causes of urban flooding. It helps to limit the flow rate of floods, and prevent soil erosion, thereby reducing the risk of damage caused by floods [21] and [22].

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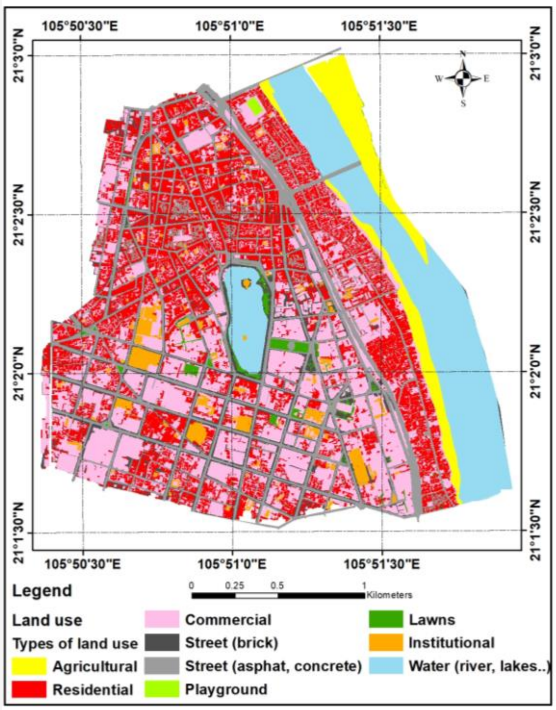

Figure 5: Land use map

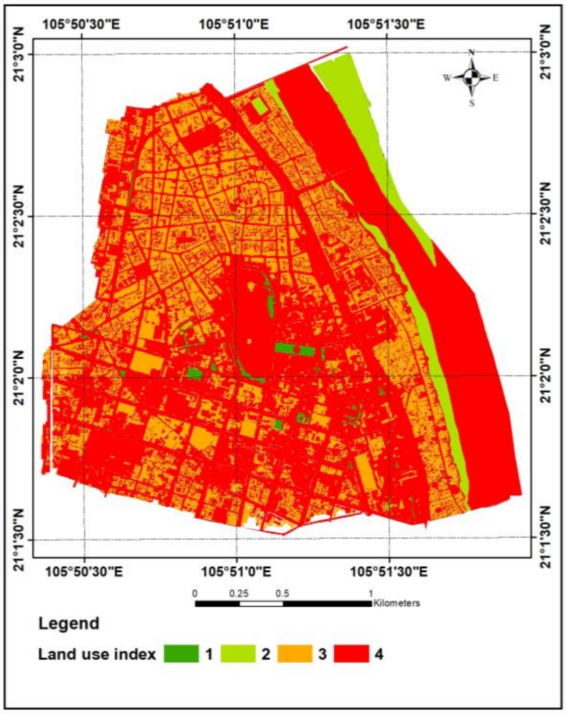

Figure 6: Land use index map

In this study, the green space index is extracted from Landsat satellite data. In which, the Normalized Difference Vegetation Index (NDVI) is selected to quantify the distribution area and canopy density of green space. This index is calculated based on the spectrum radiance difference between red band and the near-infrared band, as Equation 1.

$$NDVI = \frac{(NIR - R)}{(NIR + R)}$$

Equation 1

Where:

NDVI = Normalized Difference Vegetation Index

NIR = Spectral reflectance acquired from near-infrared region

R = Spectral reflectance acquired from red region

As the result, the negative values of NDVI were identified as non-green and positive values were defined as green class. A threshold value was decided to classify NDVI into non-green and green. After that, the 50 m × 50 m grid was overlaid on the binary image to calculate the percentage of green in each cell area (as Equation 2). Based on the percentage, each cell was classified into four classes, namely less than 25%, from 25% to 50%, from 50% to 75%, and greater than 75% (Table 4). Accordingly, the higher percentage of green is, the lower ranking of vulnerability is. Areas without trees are considered as the most vulnerable place to floods.

The percentage of green in each cell less than 25% is assigned at a very high level (ranking at 4). In the same manner, ranking at 3, 2, and 1 are given to cells where the percentage of green is from 25 to 50%, from 50 to 75%, and more than 75%, respectively (Table 3).

$$PG = \frac{A_{ci}}{A_i} * 100$$

Equation 2

Where:

PG = percentage of green

A_{ci} = Area of the green in i_{th} cell

A_i =Area of the i_{th} cell

As the result, the value NDVI ranges from –0.717189 to 0.794543 (Figure 7). The values less than zero are identified as non-green, and values greater than zero are classified as green class. The result shows that Hoan Kiem district has a relatively low percentage of green space, most of which are less than 25%. In which, cells with a percentage of green above 75 % are only 106.1 ha, accounting for 19.5 % while the cells with a percentage of green less than 25% occupy 61.5% (Table 4). Figure 8 shows the distribution unevenly of green space in the study area. The urban green is quite densely distributed in the northeastern mudflats and along the street in the south while it becomes poor in the north (Hang Dao, Hang Buom, Hang Ma ward) – where is at the highest population density.

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Table 4: Vulnerability values for Percentage of green index

Percentage of green	Ranking of vulnerability	Area (ha)	Percentage (%)
Below 25	4 (Very high)	329.4	61.6
From 25 – 50	3 (High)	55.2	9.1
From 50 – 75	2 (Moderate)	55.2	10.3
Above 75	1 (Low)	106.1	19.5

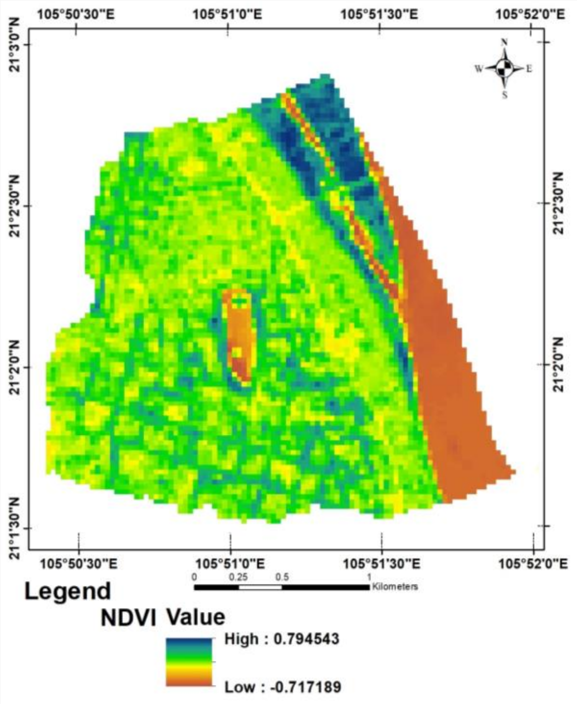

Figure 7: NDVI

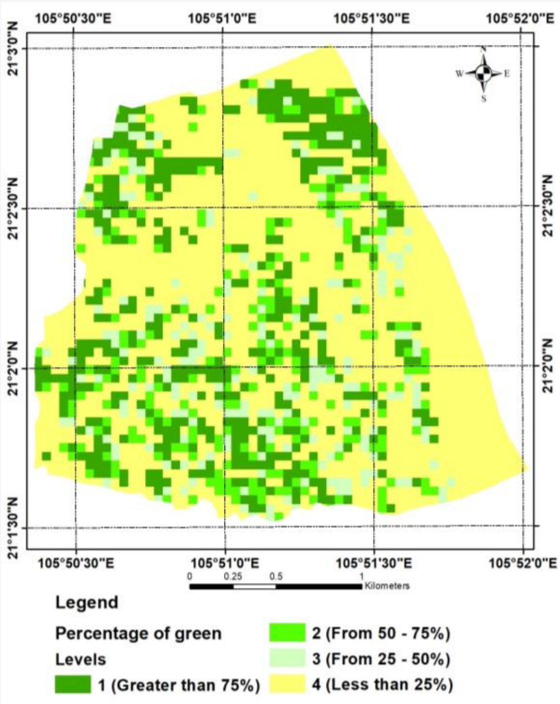

Figure 8: Percentage of green index

3.4 Identify the Per Capita Sewer Line Length Index

Hoan Kiem district was designed by a combined system. It means both water from rainfall and sewage were collected together. General information about the city´s infrastructures was also provided including street network, sewer network, and administrative districts. These shape files were used as the basis for comparison. The database includes the information about coordinates of manholes and the length of pipe (Figure 9). The sewer system was divided into cells 50m x 50 m to calculate the density. After that, the line density value was used for the distribution of the sewer system in the study area. The second data is the population in the study area (Figure10). This data was collected from Hanoi General Statistics office. Population distribution influences the drainage capacity of the system. In general, in the crowded population area, the demand for domestic water and production wastewater is quite big. In densely populated areas, the amount of wastewater will be very large, affecting the water treatment capacity of the system. The point density tool in ArcGIS was used to determine the population distribution by cell (50 m x 50 m).

In the next step, data of sewer system density and population distribution density corresponding to cell (50m x 50m) were used to generate the sewer length per capita (as equation 3) (Figure 11). Based on the standard about the ratio of sewer length per capita in the countries of the world [23] and the actual situation of the study area, this ratio was divided into 4 classes, namely less than 0.05, from 0.05 to 0.1, from 0.1 to 0.2, and greater than 0.2 m/capita. This ratio affects the drainage capacity, so the vulnerability ranking was assigned for each class. Below 0.05 m/capita presented from the areas with very high vulnerability (ranking = 4). In the same manner, from 0.05 to 0.1, from 0.1 to 0.2, and above 10 m/capita were given the ranks of 3, 2, and 1 respectively.

$$PC = \frac{SL}{P}$$

Equation 3

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Where:

PC = Per capita sewer line length index
SL = Sewer length density
P = Population density

The final values were classified into four classes, including very high, high, moderate, and low as Table 5. The result showed that the water supply and drainage network in Hoan Kiem district is quite poor. Nearly 90% of the area in the study area has a ratio of sewer length per person below 0.05 m, much lower than other countries in the region and the world, such as China at 1 meter, Germany at 6.13 meters [23] and United States at 6.18 meters [24]. Only 1% of the total area has a ratio of sewer length per capita greater than 0.2 meters (Figure 12).

3.5 Flood Vulnerability Index

Flood Vulnerability Index (FVI) map was generated based on the four indicators, namely slope, land use, percentage of green, and per capita sewer line length. The importance of indicators and their relationship to flood vulnerability is assessed by AHP (Analytic Hierarchy Process) method. Accordingly, each criterion will be assigned a corresponding weight based on the opinions of experts. The determination of priority will directly affect decision-making, thereby affecting the accuracy of research results [25]. In this study, 15 experts from fields such as geography, hydrology, irrigation engineering, and urban management were selected to give their assessment of four variables related to flooding in the area. By contrasting and comparing pairs, the degree of correlation between variables is determined. After that, these opinions were collected and analyzed by Decision software to decide the weights for each index.

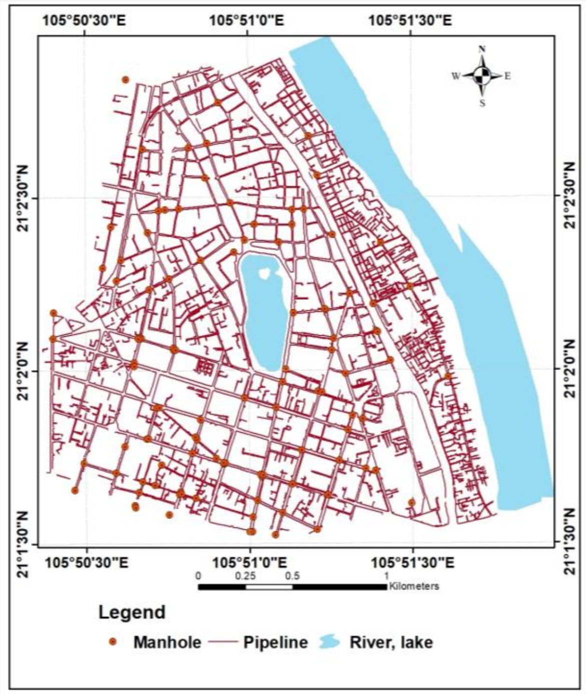

Figure 9: Drainage system

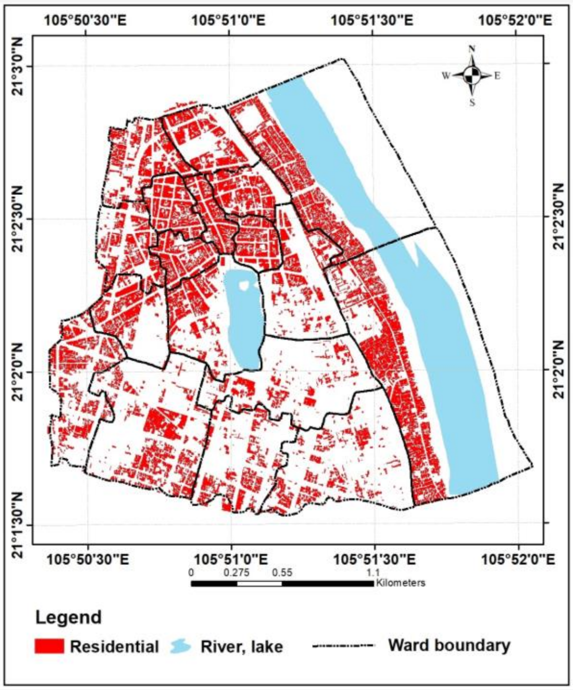

Figure 10. Population distribution

Table 5: Vulnerability values for Per capita sewer line length index

Per capita sewer line length	Ranking of vulnerability
Less than 0.05 m	4 (Very high)
From 0.05 m – 0.1 m	3 (High)
From 0.1 m – 0.2 m	2 (Moderate)
Greater than 0.2 m	1 (Low)

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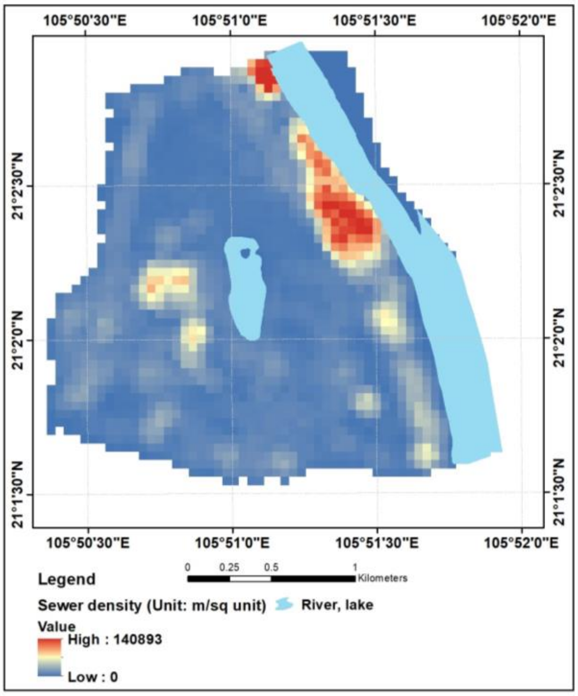

Figure 11: Sewer length density

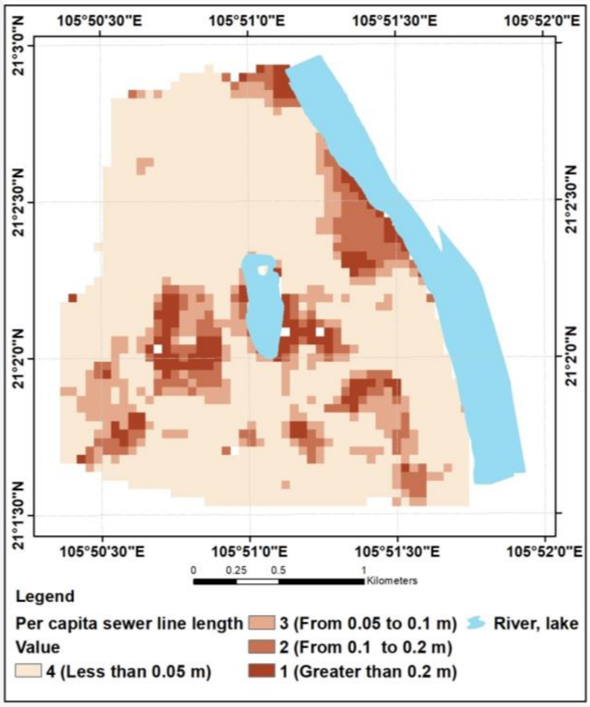

Figure 12: Per capita sewer line length index

Table 6: Pairwise comparison matrix

	Land use	Percentage of green	Per capita sewer line length	Slope
Land use	1	2	4	6
Percentage of green	1/2	1	2	3
Per capita sewer line length	1/4	½	1	2
Slope	1/6	1/3	2/3	1

Table 7: Normalized pairwise comparison matrix

	Land use	Percentage of green	Per capita sewer line length	Slope	Criteria weights	λ
Land use	0.52	0.52	0.52	0.50	0.52	4.12
Percentage of green	0.26	0.26	0.26	0.25	0.26	4.12
Per capita sewer line length	0.13	0.13	0.13	0.17	0.14	4.14
Slope	0.09	0.09	0.09	0.08	0.08	3.96

The relationship between the pairwise was shown in Table 6. Accordingly, higher weight values are given to indexes that have a higher degree of impact than the remaining index and the opposite. At the next step of AHP, the mathematical process commences to normalize and find the relative weights for each matrix. The result was described in Table 7. In the next step, calculate the consistency ratio and check its value. The purpose of doing this is to make sure that the original preference ratings were consistent. The consistency index CI was given by Equation 4.

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

Equation 4

Where:

CI = Consistency Index

λ = an eigen value, λ_{max} = Principal of Eigen value, in this case $\lambda_{max} = 4.08$

n = the number of compared elements, in this case n = 4

The final consistency ratio (CR), usage of which lets the user conclude whether the evaluations are sufficiently consistent, is calculated as the ratio of the CI and the random index (RI), as expressed in Equation 5. The values of RI are referred to in Table 8. In this case, RI = 0.90 equivalent to n = 4.

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

Equation 5

Where:

CR = Consistency Ratio
CI = Consistency Index
RI = Random Index

After the computation of weights using Saaty's pairwise comparison method, the Consistency Ratio (CR) in this case was 0.025. The obtained CI was much lower than the threshold value of 0.1 and indicated a high level of consistency in the pairwise judgments, and implied that the determined weights were acceptable. Flood vulnerability was created from four component maps. From the result of AHP, the weights were assigned for the criteria. In which, land use was considered as the most important factor (weight = 0.52) while slope was assessed as the least important factor (weight = 0.09). The average rank method was used to classify the values into 4 levels, namely low, moderate, high, and very high (Equation 6). Accordingly, the values were greater than 0.75 corresponding to very high level. Similarly, high level, moderate level, and low level were given the value from 0.5 to 0.75, from 0.25 to 0.5, and less than 0.25 respectively.

$$FVI = \frac{0.52L + 0.26G + 0.14PC + 0.08S}{4}$$

Equation 6

Where:

FVI = Flood Vulnerability Index;
L = Land use; G = Percentage of green
PC = Per capita sewer line length; S = Slope

The vulnerability map was generated based on four indicators, namely land use, percentage of green, per capita sewer line length, and slope using the arithmetic weighted overlay approach (AHP method). Figure 13 presents visually a vulnerability to flooding in the whole study area.

Table 8: Random index (RI) [25]

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

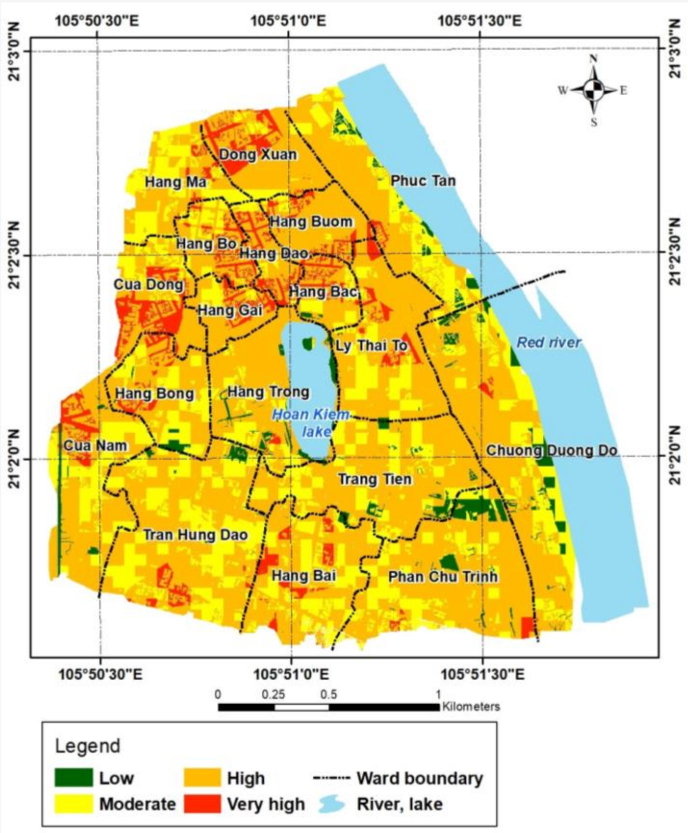

Figure 13: Flood vulnerability map

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Table 9: Flood vulnerability by levels

Levels	Area (hectare)	Percentage (%)
Low	61.3	11.3
Moderate	123.3	22.7
High	328.8	60.5
Very high	30.2	5.5

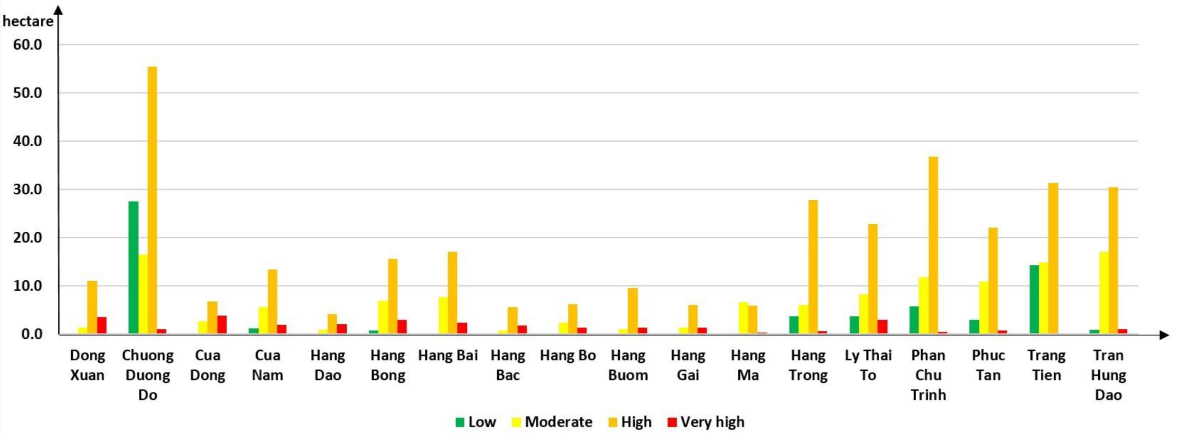

Figure 14: Classification of flood vulnerability by wards in Hoan Kiem urban district

Table 10. Characteristics of flood events in history

Name	Date	Total rainfall (mm)	1h max. rainfall (mm)	Time of rainfall (hours)	Average intensity (mm/h)
Event 1	From 21-22 September,1978	223.7	69.7	19	11.8
Event 2	3 August, 2001	321.4	46.2	39	8.2
Event 3	From 20-21 August, 2006	109.3	84.9	3	36.4
Event 4	From 16 -17 July, 2008	167.5	47.3	7	23.9
Event 5	From 30 October -1 November, 2008	479.3	69.9	24	10.9
Event 6	From 8 - 9 August, 2013	234.2	33.8	31	7.6

As the result, most of the wards in Hoan Kiem urban district have areas of high vulnerability to flooding (over 50%), in which Hang Trong, Hang Buom, and Dong Xuan are typical wards with areas of high–vulnerability zones at 72.8%, 79.7%, and 69.2% respectively. The very high-vulnerability zones occupy 5.5% of the total area and are distributed at Cua Dong (3.8ha), Dong Xuan (3.5 ha), Ly Thai To (3.0 ha), and Hang Dao (2.1 ha) (Figure 14). It can be seen that high flood vulnerability areas are very densely populated areas, and population pressure on land resources is significant. This is the central area of Hanoi, hence the economic, social, and tourism activities take place very vibrantly, bringing a huge source of income for local people. The relocation of people to reduce population pressure on land resources will affect people's livelihoods, it requires a huge compensation budget. In addition, the construction of the resettlement area also faces many difficulties, because the land fund in Hanoi has reached its limit. This is a big challenge for city managers.

The areas at moderate-vulnerability and low-vulnerability levels are 123.3 ha and 61.3 ha, accounting for 22.7% and 11.3% respectively (Table 9). It can be clearly seen that the low-vulnerability areas are distributed in areas with lower population densities, and large green spaces (e.g. parks, flower gardens, and botanical gardens). This shows the important role of green space in limiting the negative impact caused by flooding.

4. Validation

To perform the result validation, data about historical flood events were used to compare with the result in this study. There are 6 historical flood events (from

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1978 to 2013) selected to verify (Table 10). These are the most typical floods in the last 40 years in the study area. In which, floods in the years 2006 and 2008 were the biggest rainfall intensity with values of 36.4 and 23.9 mm/h, respectively. The flood in 2008 was considered as the heaviest flood in Hanoi's 50-year history with extremely serious damage. In 2001 and 2016, although the intensity of rainfall is not too large, due to last for many hours, it also caused heavy losses. Areas of high vulnerability often correspond to those with high inundation depth. Accordingly, based on the historical floods in Hoan Kiem, the areas with frequent inundation of more than 1 m were identified as the most vulnerable areas. Areas with a depth inundation of 0.5 to 1 m were identified as high vulnerability. The moderate and low vulnerability correspond to areas with a depth of 0.2 to 0.5 m and less than 0.2 m respectively. Information about twelve typical flooding points in previous floods provided by Hanoi Department of Natural Resource and Environment was used to validate the results (Figure 15). All survey points located on the streets are fully inundated frequently when heavy rain. These points were used to compare the similarity between historical floods and flood vulnerability maps. In the next step, the checkpoints are marked in the result maps of this study for comparison and verification. As the result, all points identified as flood points are ever inundated in the previous floods. There are 8/12 points (points 1, 2, 3, 6, 8, 10, 11, and 12) with inundation depth corresponding to the range of the inundation depth of previous floods, accounting for 66.7% of total checkpoints. There are four points close to the real data from the historical flood risk map, accounting for 33.3%, including points 4, 5, and 9 (Table 11). From the analysis results, the floods in history can be a reliable basis to verify flood risk in the study area.

5. Discussion

The flood vulnerability map keeps a very important role in the study and management of natural resources in any study area. The flood vulnerability map shows the areas most susceptible to flooding. In this study, this map was generated based on some indicators, including slope, land use/land cover, percentage of green, and sewer length line per capita. Based on pre-event characteristics to identify high-risk areas, the result plays an important role in predicting flood damage and vulnerability in the study area. From there, propose appropriate solutions to minimize the damage caused by floods.

Table 11: Comparison of flooding points in the past and research results

Point	**Inundation depth (m)**						Average inundation depth (m)	Ranking based on historical flood events	Ranking based on flood vulnerability map
	From 21- 22 Sep, 1978	3 Aug, 2001	From 20 – 21 Aug, 2006	From 16- 17 Jul, 2008	From 31 Oct - 1 Nov, 2008	From 8- 9, Aug, 2013			
1	0.48	0.51	0.49	0.52	0.60	0.40	0.50	High	High
2	0.57	0.47	0.60	0.58	0.65	0.45	0.55	High	High
3	0.23	0.17	0.25	0.23	0.31	0.11	0.22	Moderate	Moderate
4	0.28	0.20	0.30	0.23	0.30	0.09	0.23	Moderate	High
5	0.26	0.22	0.35	0.32	0.32	0.12	0.27	Moderate	High
6	0.41	0.37	0.43	0.41	0.46	0.28	0.39	Moderate	Moderate
7	0.07	0.16	0.06	0.18	0.26	0.07	0.13	Low	Moderate
8	0.27	0.18	0.28	0.24	0.28	0.05	0.22	Moderate	Moderate
9	0.17	0.15	0.18	0.16	0.43	0.11	0.20	Low	Moderate
10	1.22	1.30	0.80	1.17	1.31	1.22	1.17	Very high	Very high
11	0.62	0.71	0.57	0.63	0.81	0.60	0.66	High	High
12	0.86	0.83	0.89	0.87	0.95	0.74	0.86	High	High

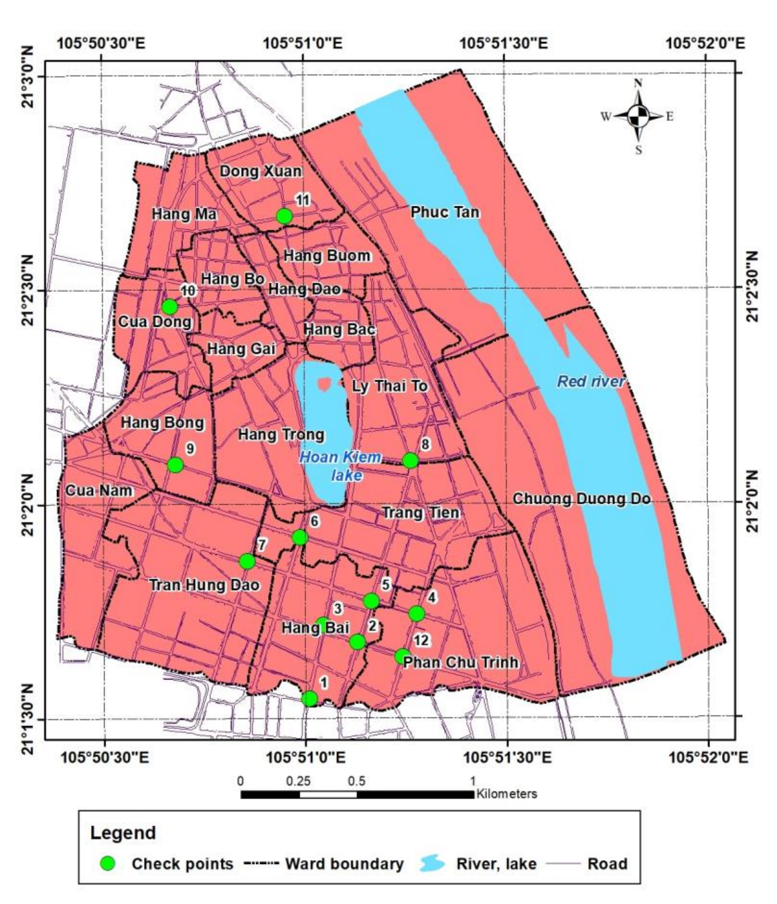

Figure 15: Location of survey points

Reality has proven that flood is a major challenge to the environment, and it cannot be fully prohibited. Floods have been causing heavy losses in human lives and properties, seriously affecting socio-economic activities. Population growth, destruction of green space, and climate change are the trigger factors that make flooding serious in recent years.

This research, however, is subject to several limitations. Landsat with 30 m resolution was used to identify urban greenness. From there, the percentage of green was calculated based on the area of green per 1 unit of area (50m x 50m). Due to the low spatial resolution of the image, the research results are not really clear. Especially in urban areas where green space is often dispersed. The use of higher-resolution satellite imagery such as Sentinel-2, SPOT will bring better reliability to the research results. This should be considered in further research. The assessment of flood vulnerability can be based on many factors. Besides those mentioned in this study, namely slope, land use, percentage of green, and sewer line length per capita, some other factors can also be considered such as rainfall intensity, distance from the river, elevation, topographic wetness index (TWI), and socio-economic data etc., [27]. However, in this case, some factors do not really affect significantly flood vulnerability in this study area. Because Hoan Kiem district is quite small, only 5.29 km2, combined with the flat terrain, it makes climate conditions (temperature, rainfall) almost the same in the whole area. In addition, the factor of elevation and TWI are not considered to be profound impacts on the level of inundation in the study area because the study area is located on a low and relatively flat plain. Moreover, the study area is close to a large river - the Red River. Hence, distance from the river could also be considered as a factor affecting flood vulnerability. However, this river is protected by a very solid and continuous dyke system, the previous floods were mainly caused by the quality of urban infrastructure. The four indicators selected are considered as the most typical factors affecting susceptibility to flooding in this study.

The integration of GIS, remote sensing, and AHP method bring highly effective in flood vulnerability zoning studies. The research results are consistent with existing data on the historical flooding situation of Hanoi. The high and very high-vulnerability points coincide with the deepest floodplain in the history of natural disasters in Hanoi [26].

In this study, the author uses the AHP- one of the multiple criteria decisions making (MCDM) to compare and identify the weight of four indicators. The opinions of many experts in related fields such as geography, hydrology, hydraulic engineering, and urban management are given. On the one hand, this method helps to make decisions based on multi-dimensional views from many experts, on the other hand, it helps to limit one-sided evaluation. However, it is also not immune to limitations caused by the nature of this method. That is, the weights are given based on the opinions of people, who are said to always be associated with biases [28]. To overcome this shortcoming, in the AHP method that takes into account the consistency index, in this case, CR is determined to be 0.025, so the evaluation results can be considered reliable. That confirms the opinions of experts in different fields are quite consistent.

From the research results, it is possible to draw the basic causes leading to the level of flood vulnerability in Hoan Kiem district as follows (1) Population pressure on land resources. Most of the areas at high risk of flooding are those with a large population density, with an average population density of over 10,000 people/sq.km. Population pressure on land resources is huge. The area of urban green space is the lowest in the country. (2) The water supply and drainage network were built during the French colonial period, is old and degraded, and the drainage capacity cannot meet heavy rain. (3) Climate change with the occurrence of more and more intense and prolonged rains has aggravated the inundation situation in the study area. Research results indicate a strong impact of the land use-land cover on flood risk in the study area. At the same time, it also points out the important role of green space in reducing the flow rate and negative impacts of floods. Therefore, the development of urban green space is one of the "Nature-based Solutions" that is very necessary for sustainable urban development planning.

Inundation in Hanoi in general and Hoan Kiem, in particular, depends on both physical and artificial factors. Based on the research result, it is found that inundation condition could be controlled by solutions as follows: (1) Hanoi Sewerage and Drainage Limited Company need to upgrade drainage infrastructure, proactively widen river, ditch, and manholes to ensure drainage promptly rainfall water in earlier of rain season. (2) Flood plain zones should be considered as content of land use planning policies. These policies can play a very fundamental role to reduce the negative impact of flooding. At the same time, it contributes to mitigating the risks caused by floods. At the same time limit the risks caused by floods. (3) An early warning system should be built in susceptible locations in the study area, to provide early warning information to residents, contributing to minimizing human and property losses. (4) It is essential to improve the citizen's awareness and let them understand well the damage potential in the living area. There should be close cooperation between people and local authorities in propagating and disseminating knowledge about flood prevention in particular and natural disasters in general. Need to minimize the negative impact of the large population, especially preventing littering from the household – the main reason obstructing drainage and negatively affecting the environment.

5. Conclusion

Research results show the zoning of flood vulnerability in the study area with four levels: low, medium, high, and very high. The result indicated the most susceptible areas to flood. Some parts are flooded more frequently and more seriously than other parts, but all parts have ever experienced inundation in history. It is evidence to prove that these are susceptible zones and high potential risk to be flooding again in the future. Therefore, these areas need special attention more than other areas. Flood risk is the potential at most of the places in the study area. Besides the causes of nature, the crowded population, the dense built-up density, and the weak drainage system are the main reasons that lead to flooding frequently when heavy rain.

The combination of RS and GIS contributes to taking advantage of both tools: being able to explore the newest and various data, effective spatial processing, and spatial analysis. Using the Mathematical Model of the Multi-Criteria Decision, namely AHP has brought about remarkable results by combining the opinions of many experts with high consistency. The results also indicated that the integration of AHP and GIS is an effective approach to assessing flood vulnerability in a given area with multiple criteria. Research effectiveness depends on the accuracy and level of detail of the database. This means that this research method can be applied in other study areas, in the same way, however, the change of inputs and the level of detail of the data will lead to research results. The result is different, even when in the same study area.

The most flood-susceptible places in this study also match previous research but in more detail. Moreover, there has not yet been any professional research about flooding in this study area so far. In fact, most of them are just brief reports of floods and flood damage situations after flooding provided by meteorological stations and Sewerage Drainage Companies in the city, so this research will be an

important reference in the study of urban environmental and urban planning.
Although this study has its limitations, it provides an essential document for urban design and planning. It is also a base to propose development strategies to reduce maximum damage by flood risk in the future. In addition, it is a useful reference for studies on floods in general and urban flooding in particular in Vietnam.

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