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Estimation of the flood vulnerability index (FVI) for Alexandria city-Egypt: A case study

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Urban Flood, Vulnerability Index, GIS, Decision making.

Abstract

Climate change and urbanization are likely to increase the flood vulnerability of cities, which causes damage and interruption of services to the communities. The objective of this study is to estimate the Flood Vulnerability Index (FVI) for Alexandria City to assist decision-makers in developing priority urban flood plans and identifying methods for reducing flood risk. In this study, the FVI is estimated through three components: social, physical, and environmental. Eleven major indicators are used to represent these three components, and they are classified according to three flood factors: exposure, susceptibility, and resilience. Geographic information system (GIS), and remote sensing (RS) are used to obtain the required data and develop maps for identifying the significant urban flood indictors. The study area is divided into sixteen zones regarding its administrative classification. The overall FVI is estimated for each of the sixteen zones based on social, physical, and environmental components. Population, population density, population access to sanitation, and warning system are used as the four indicators for the social component, whereas the four indicators used for the physical components, are proximity to stream, elevation, rainfall amount, and slope. The environmental component is evaluated by using three indicators, land use, urban growth, and flood recovery time. The FVI assigns a number between 0 and 1, indicating relatively low to high urban flood vulnerability. The findings demonstrate that FVI offers an efficient way to assess flood vulnerability and obtain appropriate adaptation choices.

1. Introduction

Extreme rainfall is considered as the main source of the urban flooding that resulted in an overflow of sanitary networks. This type of flood is impacted by the properties of the flooded area [1]. Flood management has various approaches to reduce floods and for mitigating their consequences [1]. The infrastructure such as drinking water and sanitation is vulnerable to flooding events, especially in coastal areas [2]. Flood management is crucial for diminishing the exposure factor for citizens,

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property and environment to flood risk, the current situation of flood damage, develop appropriate resilience system [1]. An important part of urban flood management is to estimate the vulnerability to floods. Tools for vulnerability assessment must be developed and used to provide a clear connection between flood vulnerability theory and daily decision-making, and to capture this connection in a tool that is simple to use [3].

Vulnerability is an essential characteristic necessary to estimate the potential consequences of various hazards and to identify appropriate mitigation measures [4]. The increase of flood phenomena due to intensity and extreme rainfall event and other hazard is an evident on climate change impact on urban area [4]. Climate change is considered as a factor in developing urban areas, which is the combination of the natural and human activities in the urban area [1]. Alexandria city annually experienced severe rainfall event causing severe flooding [3]. As floods are the most common natural disasters worldwide, the identification of the flood vulnerability factor is crucial to mitigate its damage [5]. Such risks cannot be properly managed using only structure methods such as the work of downstream of the affected areas and the installation of high-capacity pumps, as these actions are short-term and limited impact, as they lack integrated dynamic modeling and flexible scenarios associated with variables on the ground to develop the best sustainable solutions.

The flooding can produce widespread impacts on urban areas. Almost any type of industrial, commercial, or residential development located on floodplain is vulnerable to flooding. In flood incidents, buildings can sometimes experience small damage that can be easily repaired, but sometimes they will incur significant damage that is beyond repair. Very often urban floods caused extensive damage to public utilities, disruptions to the delivery of services, to community life and to the economy. Loss of electric power and failure of communications due to floods are also very common [5]. Vulnerability and related concepts are used in flood management. The concept of vulnerability determines whether or in what circumstance such a hazard will result in a disaster [1]. The vulnerability of risk elements depends on their ability to sustain the constraints caused by the event and the intensity of the event itself [6].

Therefore, identifying the areas subject to flooding as defined by homogeneous categories indicating the presence of elements of value such as residential areas, buildings, public buildings where users are constantly present, road and rail infrastructure – makes it possible to delimit areas at flood risk [6].
The risk assessment approach combined RS and GIS usually analyses the spatial risk based on RS data, basic data, and related socio-economic data [7]. People are vulnerable to floods due to three main factors, exposure, susceptibility, and resilience [2]. Humans and nature together have affected the urban flood. A quick response is needed to delineate flood zones within the urban area. The flood zone will have to be based on the natural and manmade objects [8]. Vulnerability indexes were applied quickly and consistently to characterize the relative vulnerability of different areas [9]. This type of analysis has allowed municipal authorities to have access to appropriate information to make decisions about the future development of urban and social infrastructure at the city level [10]. Total population and population density are crucial parameters for effective vulnerability assessment [11]. If there are no vulnerable elements in the area, the damage and hence the risk can be considered as null. In other words, the risk level is defined by the characteristics of the vulnerable category and the degree of hazard, i.e., the probability of an event occurring [6] in this case study, which it is pluvial flood, because it happens due to heavy rainfall directly on the urban area such that the runoff exceeds the capacity of the drainage systems [8].

2. Study Area

Alexandria is the second capital of Egypt, Area of Alexandria is about 2,818 km^2 which consists of 16 zones, is located between 31° 12' 56.30" N latitude and 29° 57' 18.97" E longitude, extending about 63 km along the shoreline of the Mediterranean Sea, population of Alexandria governorate is

5,160,793 (capita), with density 1,900/km^2. Its low level on the Nile delta makes it highly vulnerable to rising sea levels and flooding. Figure (1) shows the location of the study area. The coast of the city of Alexandria is characterized by its diverse topography. Surveys and recent assessment indicated that about 60 km or 67% of Alexandria's seafront; represented by a narrow coastal strip extending from Abu Qir to Al-Agamy, lays on a hill or a raised barrier of limestone, with an average elevation of +4 meters above sea level [12].
The characteristics of the climate of the city of Alexandria is Mediterranean with warmth and, dry in summer and mild, rainy in winter, moreover it has about 196 mm annual amount of precipitation, from October to February, the exceed rainfall amount is discharged to the combined sewage systems. The system receives domestic and industrial wastewater and stormwater. Recent data from the Alexandria Sanitary Drainage Company (ASDCO) indicate approximately 93.4% of the urban area is connected to the sewer system and the system has a capacity of approximately 1.6 million m^3 /day [13].
Alexandria is characterized by the absence of a separate network for the collection of rainwater, where the rainwater is collected from the roofs and streets through catch basins, which in turn give the collected rainwater to the sewage network, and to the pumping and treatment stations, rainwater works to increase the load on pumping and treatment stations. Alexandria governorate has a seasonal pump station that work only in case of increasing the loads and discharges on the pumping stations, it can distinguish the type of the urban flood occurs in this case study, which it is pluvial flood, because it happens due to heavy rainfall directly on the urban area such that the runoff exceeds the capacity of the drainage systems [8].

3. Methods and tools

In this study, we divide the study area according to its administrative division into 16 zones. Fig (2) shows the distributed zones of Alexandria city. Fig (3) shows the link between the eleven indicators affecting urban flooding and the three vulnerability components, susceptibility, exposure, and resilience. The flood vulnerability index is estimated using Eq. (1).

$$\mathrm{FVI} = \frac{\mathrm{Exposure} + \mathrm{Susceptibility}}{\mathrm{Resilience}} \quad \ldots\ldots (1)$$

The term Exposure is used to reflect the number of people or other elements at risk that can be affected by a particular event [4], and the susceptibility is described as the degree of effect and the term resilience is referred to the capacity to adjust to threats and to mitigate or avoid them [4].

First, to weigh each indicator, a scale 1-5 is applied with 5 refers to high vulnerability and 1 refers to low vulnerability, the scale of one to five used for each indicator standardize the rating system and allows indicators measured in different units for mathematical combination. Second, for calculating FVI for each component, it is required to convert each indicator into a normalized number as the maximum value be 1. The expression for normalizing the indicators is calculated using Eq. (2) [14].

$$\mathrm{Ni} = \frac{\mathrm{Ai}}{\mathrm{Max\ (AI)}} \quad \ldots\ldots (2)$$

Where Ni represents the normalized value of the indicators, Ai; represents the actual indicator value, as well as the max AI; is the maximum value from a set of n actual values computed from indicator.

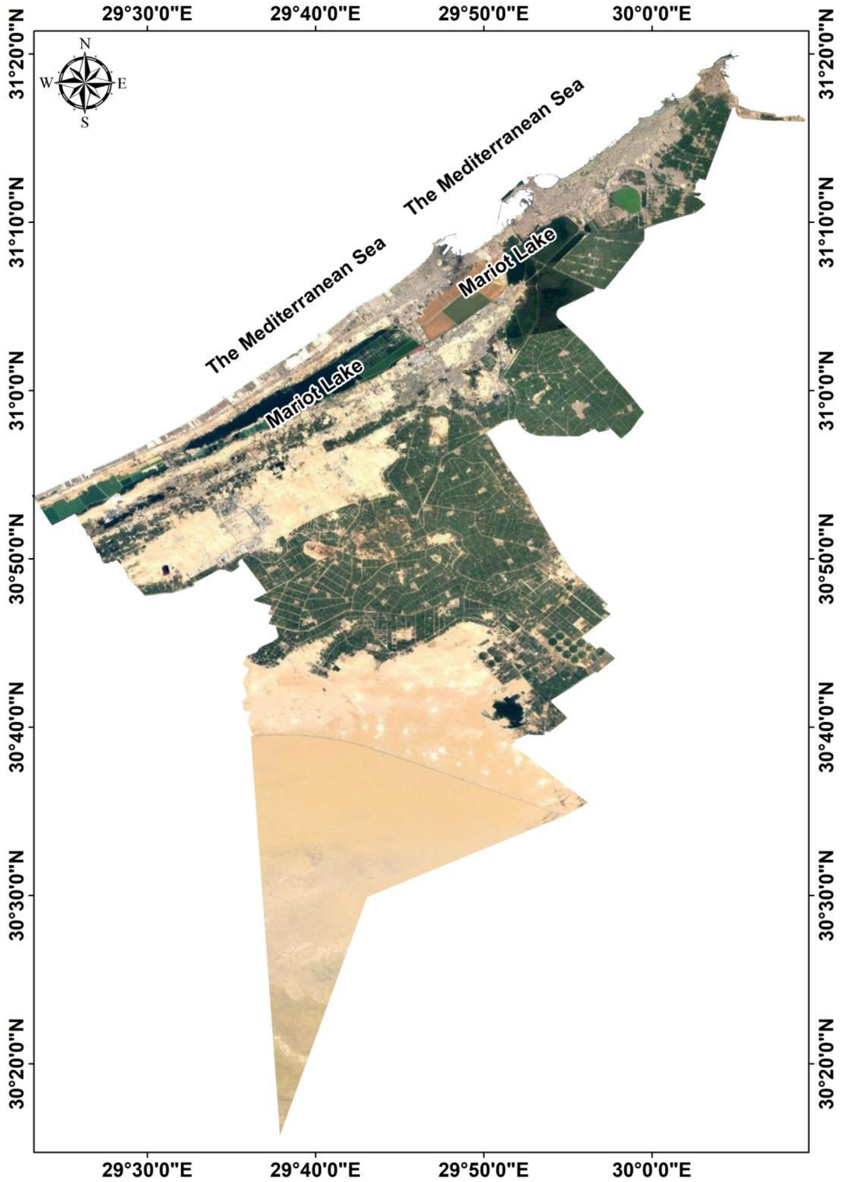

Figure1. The study area location (Alexandria city). (Source: the researchers)

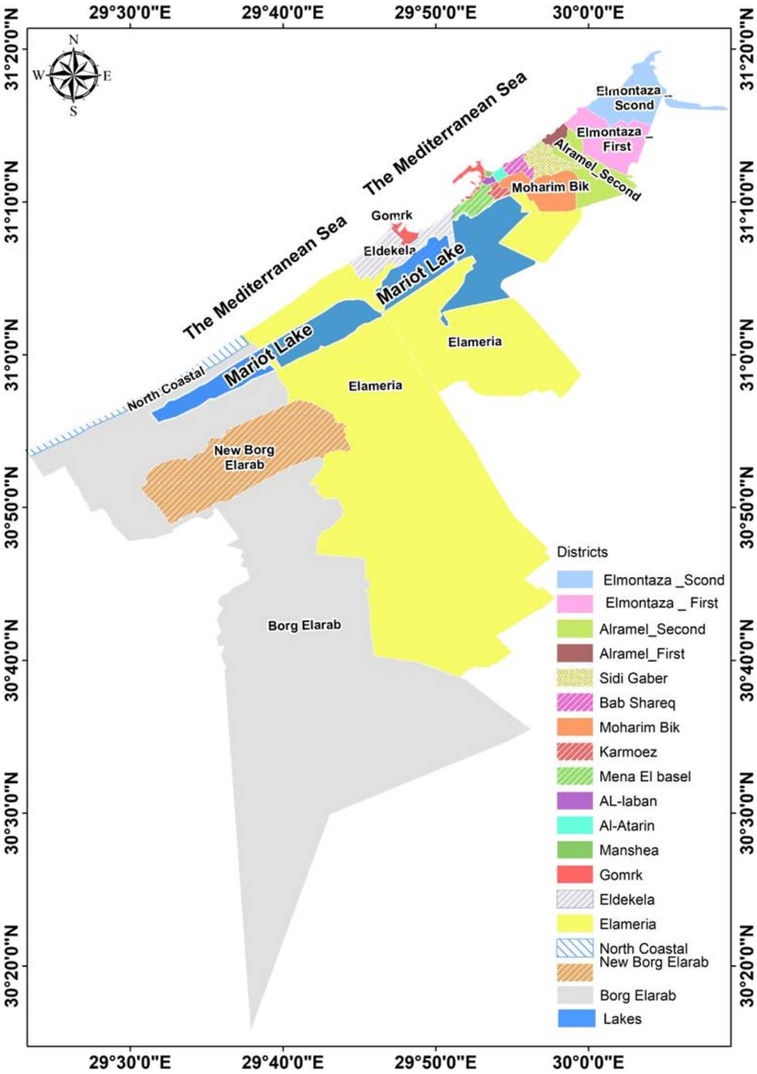

Figure 2. The city of Alexandria 16 Zones. (Source: the researchers)

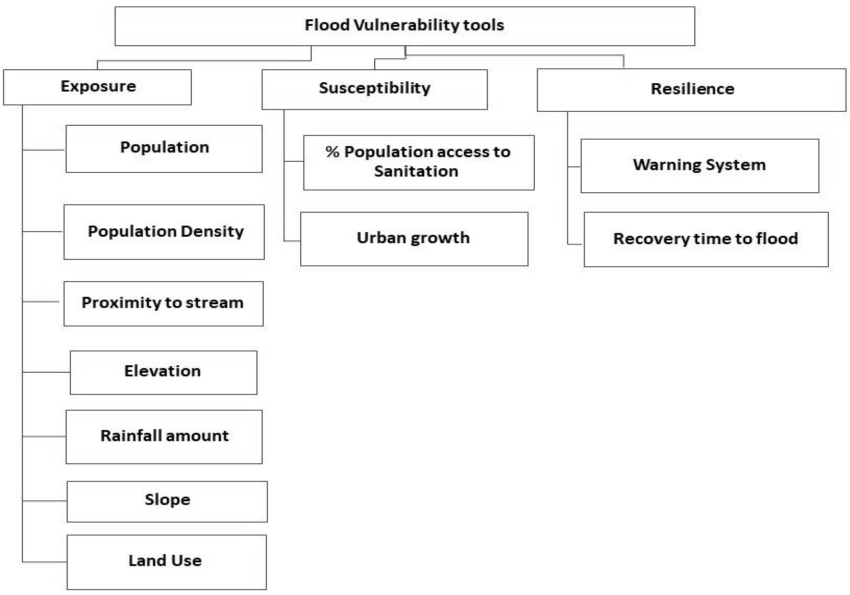

Figure 3. The link between the indicator's components and factors. (Source: the researchers)

3.1 Social Components (FVI_S):

The definition of the social component of flood vulnerability is the susceptibility of a society to a specific risk. This is the most complex type of vulnerability, and up to this point, efforts to understand social vulnerability have largely relied on analytical methods [4]. Floods may cause damage of houses and building and disruption the communication ways or even kill people [3]. Table (1) shows the indicators for social component, as well as Table (2) shows the weighted value for each indicator, moreover the social vulnerability index is calculated by Eq. (3). To estimate the social flood vulnerability index applying "(3),"

$$FVIs = \frac{P,PD,PS}{WS} \quad \ldots\ldots (3)$$

whereas.

FVIs: Social flood vulnerability Index, P: The population indicator,

PD: Refers to the Population density, PS: Percentage of the population access to sanitation and,

WS: The application of the warning system.

Table 1. Indicators information of social (FVI_S) components:

Factors	Indicators	Relation to Vulnerability
Exposure	Population (P)	High P, high the Vulnerability
	Population Density (PD)	High PD, high the Vulnerability
Susceptibility	% Population access to sanitation (PS)	Low PS, high the Vulnerability
Resilience	Warning System (WS)	More awareness, low Vulnerability

Table 2. The degree and index value for each indicator:

Indicators	Degree	Range	Index -Value
Population (cap.)	5	> 1000 x (10^3)	1
	4	600- 1000 x (10^3)	0.8
	3	400-599 x (10^3)	0.6
	2	100-399 x (10^3)	0.4
	1	<100 x (10^3)	0.2
Population Density (Cap/Km^2)	5	> 45 x (10^3)	1
	4	35.1-45 x (10^3)	0.8
	3	25.1 -35 x (10^3)	0.6
	2	10-25 x (10^3)	0.4
	1	<10 x (10^3)	0.2
Population access to sanitation (%)	1	100	0.2
	2	80-99	0.4
	3	70-79	0.6
	4	69-50	0.8
	5	<50	1.0
Warning System	5	There is a warning system	1
	1	There is not Warning system	0

3.2 Environmental Components (FVI_E):

The ability of the ecosystem to withstand and recover from flood episodes is referred to as the environmental component of flood vulnerability [4]. Table (3) shows the indicators for Environmental component, as well as Table (4) shows the weighted value for each indicator. The environmental flood vulnerability index is estimated using Eq. (4)

whereas FVI E, Environmental flood vulnerability Index, LU the Land use indicator, UG; refers to the Urban growth, RTF; the Recovery time to flood.

$$FVI_E = \frac{LU, UG}{RTF} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Table 3. Indicators information of Environmental components:

Factors	Indicators	Relation to Vulnerability
Exposure	Land use (LU)	The high-density urban is the high vulnerability
Susceptibility	Urban growth (UG)	Increasing of urban growth may result people more venerable
Resilience	Recovery Time to Flood (RTF)	Time required for the city to re-establish a functional operation following a flood.

Table 4. The degree and index value for each indicator:

Indicators	Degree	Range	Index -Value
Land use	5	High density Urban area	1
	4	Medium density Urban area	0.8
	3	Low density Urban area	0.6
	2	Agriculture area	0.4
	1	Desert	0.2
Urban growth (%)	5	>2.5	1
	4	2-2.5	0.8
	3	1.5-2	0.6
	2	1-1.5	0.4
	1	<1	0.2
Recovery time to floods (days)	5	5	1
	4	4	0.8
	3	3	0.6
	2	2	0.4
	1	1	0.2

For the land use data, LULC map is developed from the Landsat 8 USGS-earth explorer, and the reclassification process is made by ArcMap 10.8 system, accordingly the study area is classified as five categories, (High density urban area, medium density urban area, Low density urban area, Agriculture area, and desert area). The average population in Alexandria city grows annually about 2-3%. Alexandria's urban area has increased by approximately 40% over the last 15 years, this finally causing increased of paved street, and decreases the green or open areas [15]. the population, and population density are provided from the Egyptian central agency for public mobilization and statistics (CAPMAS), as well as the population access to sanitation and the applicable of the warning system from the Alexandria sanitation company.

3.3 Physical Components (FVI_{ph}):

The expression "physical Component of vulnerability" generally refers to the built environment's vulnerability to flooding. [3], Table (5) shows the indicators for Environmental component, as well as Table (6) shows the degree value for each indicator.

Table 5. Indicators information of Environmental components:

Factors	Indicators	Relation to Vulnerability
Exposure	Proximity to stream (DS)	The high closed to stream, the high Vulnerability
	Elevation (EL)	The low Elevation, the high vulnerability.
	Rainfall amount (R)	The high rainfall amount, the high vulnerability
	Slope (S)	The low Slope, the high vulnerability

To estimate the flood vulnerability index applying Eq. (5)
whereas FVI $_{Ph}$, Physical flood vulnerability index, DS is the distance from nearest stream, EL refers to the Elevation, R; the average annual rainfall amount, and S refers to the Slope.

$$FVI_{Ph} = [DS, EL, R, S] \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Table 6: The degree and index value for each indicator:

Indicators	Degree	Range	Index -Value
Proximity to stream (Km)	5	<2005	1
	4	2006-4463	0.8
	3	4464-7504	0.6
	2	7505-11000	0.4
	1	<11000	0.2
Elevation (m)	5	<12	1
	4	12.1-36	0.8
	3	36.1-64	0.6
	2	64.1-100	0.4
	1	100-127	0.2
Rainfall amount (mm/year)	5	>135	1
	4	119-135	0.8
	3	72.2-118	0.6
	2	50-72.1	0.4
	1	<50	0.2
Slope (%)	5	<1.54	1
	4	1.55-4.22	0.8
	3	4.23-8.44	0.6
	2	8.45-16.5	0.4
	1	>16.5	0.2

Regarding the factors affecting floods, the choice of the most influential parameters is essential for the analysis of flood susceptibility. Flooding is triggered by precipitation, the largest variable in flood frequency. However, many other influencing factors are crucial as well [16]. The rainfall amount is obtained based on GIS environment. The higher rainfall amount usually increases a chance of flood prone area where other parameters may be related. The spatial distribution of rainfall and its intensity have substantial influence on the modeling of flooding events. These values are obtained based on the annual mean precipitation of the study area, the annual amount of rainfall data was downloaded from the climatic research unit –university of East Anglia, then theses data was inserted to produce the rainfall amount layer in GIS environment. Using a linearly weighted combination of a collection of sample points inverse distance weighted (IDW) interpolation calculates cell values, Fig. (4) shows the rainfall map.

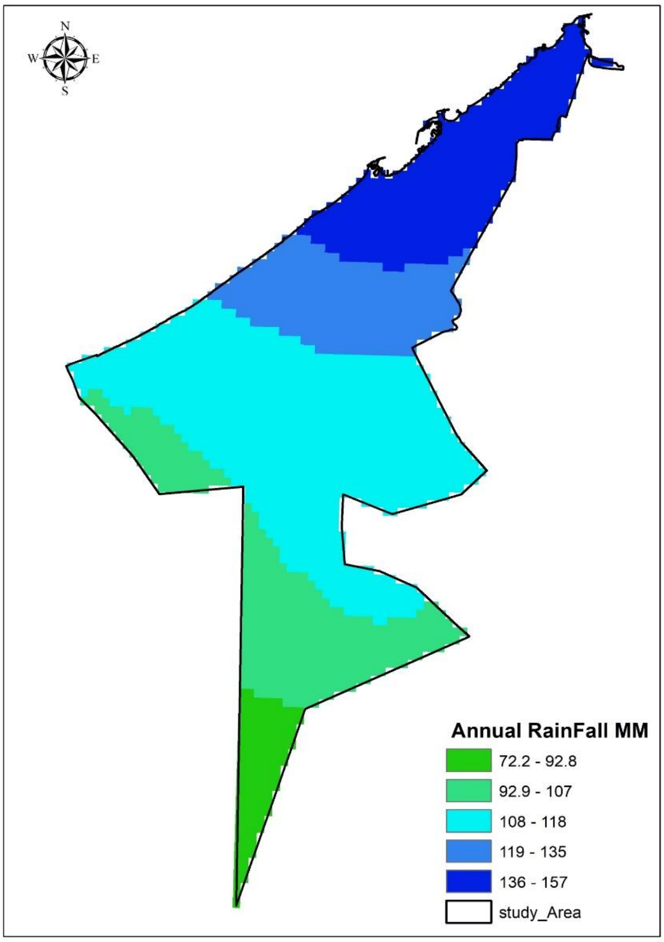

Figure 4. Rainfall data map (Source: the researchers)

Fig. (5), and Fig. (6) show the elevation map and slope map for Alexandria city, which are created using the DEM (Digital Elevation Model) from the shuttle radar topography mission (SRTM) from USGS explorer using ArcMap GIS software 10.8. The distance from the stream map was created by digitizing satellite image and drawing the stream on the shapefile layer then using spatial analyst – Euclidean tool in ArcMap GIS software 10.8, the Euclidean tool estimates the distance from each cell in the stream raster to the closed source, moreover from the literature review, it is stated that the zones where are closed to the stream bed are highest flood risk area.

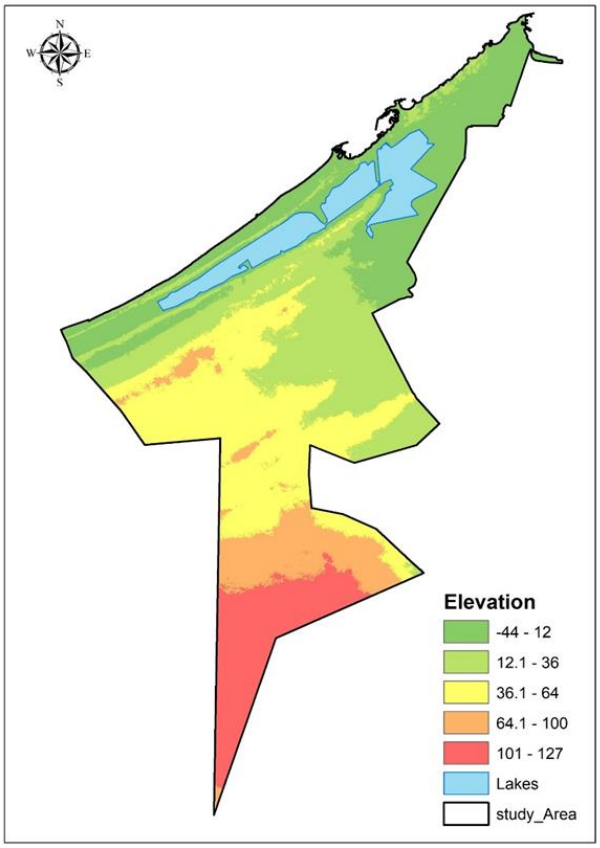

Figure 5. The Elevation map of Alexandria city**.** (Source: the researchers)

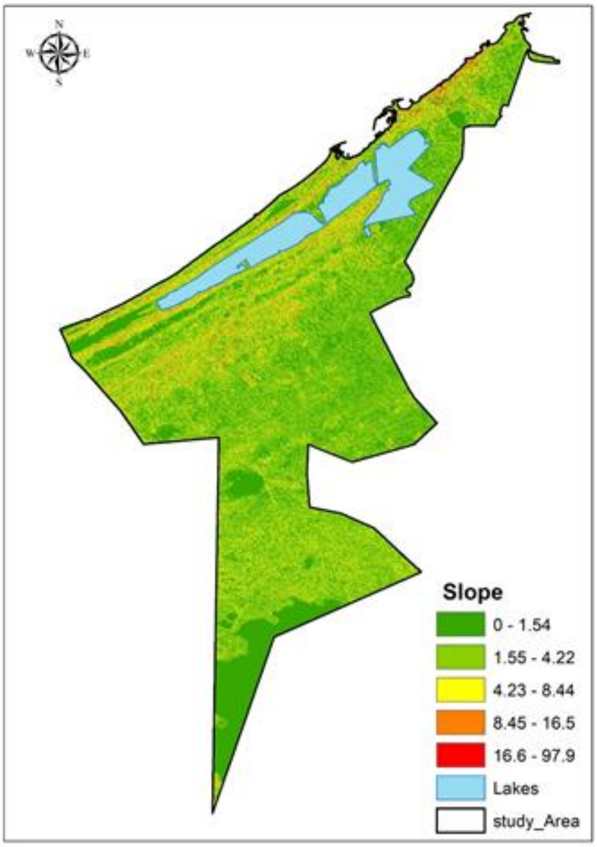

Figure 6. The Elevation map of Alexandria city**.** (Source: the researchers)

4. Results and Discussion

A suitable tool was created for estimating the flood vulnerability index through three main components (social, physical, and environmental) to help decision-makers identify and create an action plan to deal with floods.

4.1 The Social Flood Vulnerability Index (FVI_S):

The results from social components are shown in Fig. (7) ranges from 0.63 to 0.23. Four indicators were used to determine the social flood vulnerability index (FVI_S). These were population, population density, percentage of population with access to sanitation, and warning system, using these indicators to calculate the FVI_S, Elmontaza-First zone is particularly susceptible to urban flooding, mostly because of its large number of populations, the second most vulnerable zone is Alramel -first for the similar reason. Al-Atarin, Moharim Bik and Borg Elarab are ranked as the lowest vulnerable to urban floods, caused by their low number of populations and low population density.

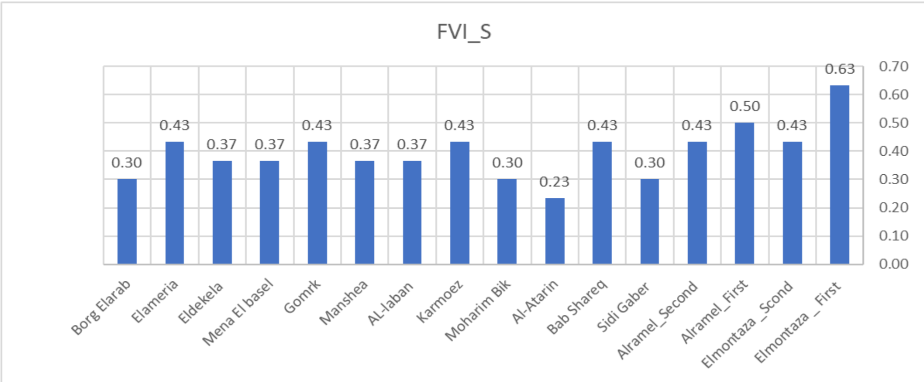

Figure 7. The Social Flood Vulnerability Index (FVI_S) for Alexandria city. (Source: the researchers)

4.2 The Environmental Flood Vulnerability Index (FVI_E):

Three indicators were used to determine the Environmental flood vulnerability index (FVI_E). These were land use, urban growth, and recovery time from floods. Using these indicators to calculate FVI_E shows that the Alramel-first, and Gomerk zones are more vulnerable to urban flooding. The main reason for that is due to the high density of the urban area and high urban growth rate, the second most vulnerable zones are Bab shareq, Karmoz, Al-laban and Manshea for the similar reason. Otherwise Emontaza second, Alramel first, Sidi gaber , Al-Atarin, Moharim Bik and Elameria are ranked as the lowest vulnerable to the urban flood , caused by their low urban growth rate. The results of environmental component are shown in Fig. (8).

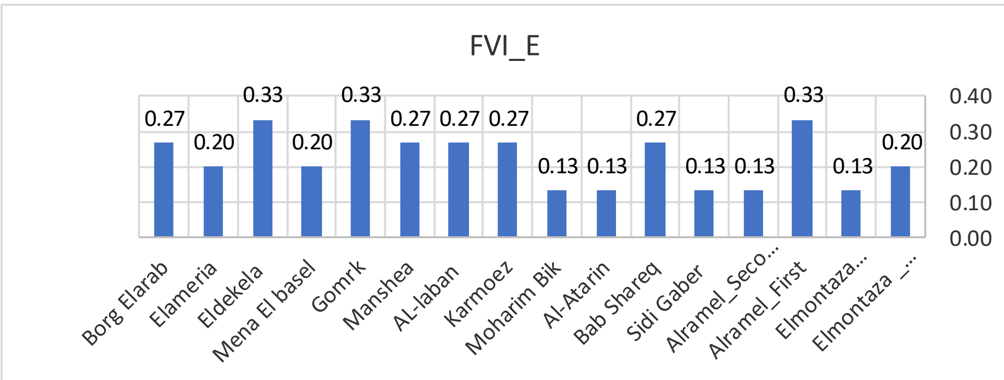

Figure 8. The Environmental Flood Vulnerability Index (FVI_E) for Alexandria city. (Source: the researchers)

4.3 The Physical Flood Vulnerability Index (FVI_{Ph}):

Four indicators were used to determine the Physical flood vulnerability index (FVI_{Ph}). These were the proximity to stream, the elevation, the annual rainfall amount, and the slope. Using these indicators to calculate the (FVI_{Ph}) shows that the zones which are located near to the sea are vulnerable to the Physical vulnerability index with a range from 0.95 to 0.85). Elameria and Borg Elarab are ranked as the lowest vulnerable to the flood, caused by their lower value in proximity to stream, and the elevation indicators. The results of physical component are shown in Fig. (9).

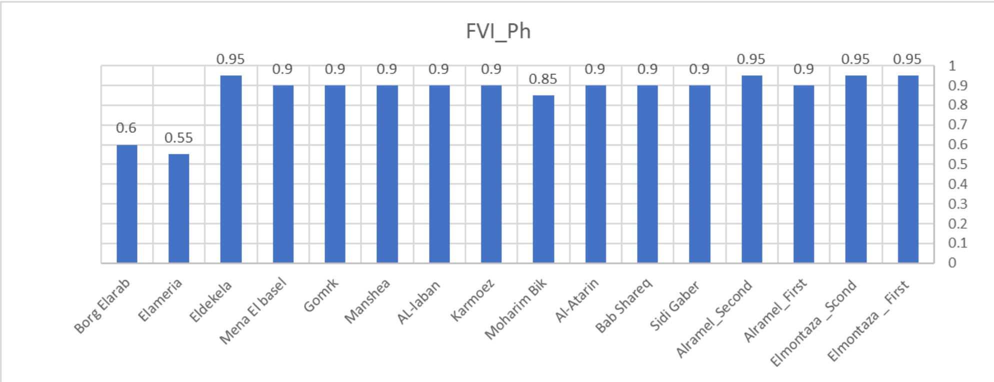

Figure 9. The Physical Flood Vulnerability Index (FVI_{Ph}) for Alexandria city (source: the researchers)

4.4 The overall flood vulnerability Index (FVI):

Sixteen zones in Alexandria city were classified using FVI, and they are ranked from 0.59 to 0.37. The most vulnerable zones are Elmontaza first, Alramel first and Gomrk, as well as they have a highly vulnerable social, physical, and environmental indexes, and Elameria and Borg Elarab have the Lowest flood vulnerability index because they have the lowest vulnerable social, physical, and environmental indexes. Fig. (10) shows the total flood vulnerability index (FVI) for the sixteen zones of Alexandria city. Fig. (11) shows the results on the map.

Validation on the result data mostly done with the satellite image or the reports issued by the governorate.

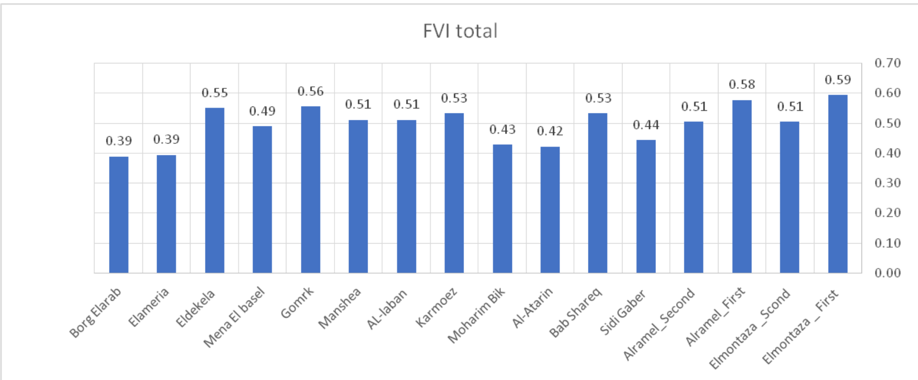

Figure10: The Total Flood Vulnerability Index for Alexandria city (source: the researchers)

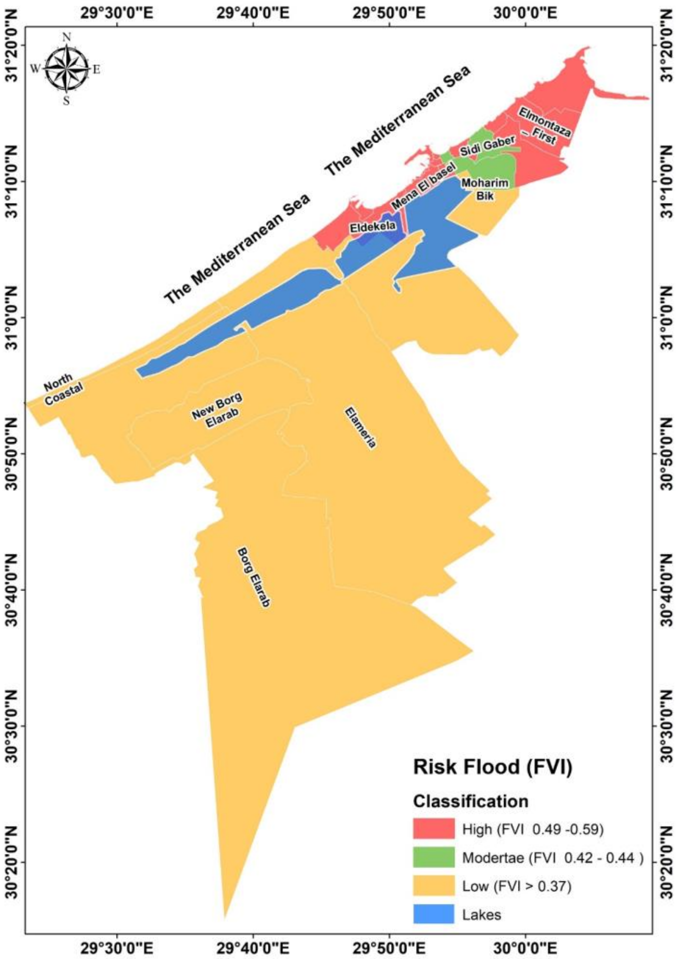

Figure 11: The map of the Total Flood Vulnerability Index for Alexandria city (source: the researchers)

5. Conclusions

Globally, the population is vulnerable to natural disasters because of a combination of escalating socioeconomic and land use development as well as climatic variability. The FVI model is utilized as a simplified method of defining a complex system. The results will assist in determining if the service is resilient, vulnerable, or likelihood of flooding exposure, and will be used as a tool in decision-making [14]. The first step regarding developing flood management plan and strategies for ability to adapt is correctly having an awareness of the vulnerability. An analysis factor of the system's exposure, susceptibility, and resilience is considered the vulnerability [6]. The FVI is a useful tool for formulating policy, assisting decision-makers in prioritization investments, and might be appropriate in the decision-making process. Finding regions with a high risk of flooding could help decision-makers arrive at more effective flood management strategies [2].
The research's methodology, which focuses on the urban flood in Alexandria city, is based on eleven indicators through three main components (social, physical, and environmental). Various indicators were considered to assess the flood vulnerability.
The FVI model was made available for Alexandria city to help decide the best ways to cope with flooding using a variety of options and scenarios based on the unique social, physical, and environmental circumstances of each situation. The FVI model utilizes cutting-edge geographic information systems, remote sensing technologies, linking and integration with all spatial data from Land use maps, drainage maps, elevation maps, and slope maps to provide dynamic flood maps and strategies for handling situations involving its risk level.

The estimated flood vulnerability index's (FVI) main goals are to identify the degree of risk areas from various perspectives; assess the seriousness of risk; find out how the community views such risk; determine what kind of mitigation measure would be most effective in reducing its negative effects; produce a plan for the implementation of mitigation plans; and finally, put the plan into action.
With eleven indicators in the prospective for the three components of social, physical, and environmental factors, the estimation of the flood vulnerability index is used in this study for sixteen zones in Alexandria city. The necessary land use, drainage, elevation, and slope maps were created using remote sensing and GIS techniques. The vulnerability index in three components is calculated by classifying each indicator into five categories and weighting it from 0 to 1, after which the total vulnerability index for each zone was calculated. This information would help the responsible implemented authority priorities its mitigation plans and preparedness efforts in an efficient and timely manner.

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تقدير مؤشر التعرض للفيضانات (FVI) لمدينة الإسكندرية - مصر: دراسة حالة

الملخص العربي

من المرجح أن يؤدي تغير المناخ والتحضر إلى زيادة ضعف المدن عن طريق زيادة شدة الفيضانات، مما تسبب في أضرار مباشرة وغير مباشرة للمجتمعات.
الهدف من هذا البحث هو تقدير مؤشر التعرض للفيضانات (FVI) لمدينة الإسكندرية لمساعدة صانعي القرار على تطوير خطط للفيضانات الحضرية ذات الأولوية وتحديد طرق الحد من مخاطر الفيضانات.
في هذه الدراسة، تم تقدير مؤشر FVI بشكل عام من خلال ثلاثة مكونات: اجتماعية، ومادية، وبيئية. علاوة على ذلك، يتم استخدام أحد عشر مؤشرًا رئيسيًا لتمثيل كل من هذه المكونات الثلاثة، ويتم تصنيفها وفقًا لعوامل الفيضانات الثلاثة: التعرض، القابلية للتأثر، والمرونة. يتم تطبيق نظام المعلومات الجغرافية (GIS)، وتطبيقات الاستشعار عن بعد (RS) للحصول على البيانات المطلوبة ووضع خرائط لتحديد مؤشرات الفيضانات الحضرية الهامة. تم تطوير هذه المؤشرات بعد مراجعة الأدبيات ذات الصلة ومناقشة فنية مع خبراء في قطاع المياه. تم تقسيم منطقة الدراسة إلى ١٦ منطقة من حيث التصنيف الإداري.
بالنهاية، تم تقدير ١٦ منطقة في مؤشر الضعف لمدينة الإسكندرية للمكونات الثلاثة (الاجتماعية والبيئية والمادية) و FVIالكلي. يتم استخدام السكان والكثافة السكانية وإمكانية وصول السكان إلى الصرف الصحي ونظام الإنذار كمؤشرات أربعة للمكون الاجتماعي، في حين يتم استخدام أربعة مؤشرات للمكونات المادية، المسارات المائية والارتفاع وكمية هطول الأمطار والمنحدرات. المكون البيئي، والذي يتم تقييمه باستخدام ثلاثة مؤشرات، استخدام الأراضي، والنمو الحضري، ووقت التعافي من الفيضانات.
يقوم المؤشر بتعيين رقم بين ٠ و١، مما يشير إلى ضعف أو ارتفاع نسبة التعرض للفيضانات في المناطق الحضرية، مما يدل على ضرورة تحديد المناطق لأولويات صانعي القرار. توضح النتائج أن FVI يوفر طريقة لتقييم قابلية التأثر بالفيضانات والحصول على خيارات التكيف المناسبة والفعالة.