Assessment of Urban Vulnerability to Flooding Using Multi-Criteria Analysis

The Case Study of El Bayadh City, Algeria

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Received: 12 February 2022 | Revised: 7 March 2022 | Accepted: 13 March 2022

Abstract-Urban vulnerabilities must be studied and assessed to make cities more resilient to floods. This study aimed to assess the urban vulnerability of El Bayadh city, located in the west of Algeria, to floods and to identify flood-prone areas. Using the Hierarchical Multi-criteria Analysis (HMA) method, a set of criteria was proposed such as population density, housing typology, type of equipment, and road network to measure the overall fragility of the study area. The Geographic Information System (GIS) was used to translate the obtained results and develop the global vulnerability map. The most important results were: 5.6% of the study area had an extreme vulnerability, 7.97% high vulnerability, 8.5% medium vulnerability, and 77.87% low vulnerability. The results of this study can be used as a tool to assist local authorities during decision-making regarding flood danger assessment.

Keywords-flood; vulnerability; hierarchical multi-criteria analysis; geographic information system; El Bayadh

I. INTRODUCTION

Over time, the world has confronted various natural disasters [1]. Floods are among the most frequent and devastating natural hazards [2] and represent almost a quarter of all disasters due to their unpredictability. Floods are caused by a random combination of severe weather factors and human actions [3] and dramatically affect human life, economy, and environment [4]. Like other Mediterranean countries, Algeria is not immune to the risk of flooding due to the irregularity of rainfall, which has caused numerous disasters during the recent years [5]. Floods in urban areas constitute a severe risk and have become more frequent and severe along with the rapid and unstoppable urban development [6]. Given this situation, the present investigation aimed to assess the urban vulnerability to flooding risk of the city of El Bayadh, located in the west of Algeria. This area has suffered from numerous floods over time, as it happened in the city center in 2011 causing the death of 12 people and affecting 400 families. Its fragility lies in its location, a sloping site, and the crossing by valleys. Creating a global map of urban vulnerability to floods is very important in reducing effects since it is an element of development and risk management. According to the conceptual approach to vulnerability proposed in [7], vulnerability encompasses the potential damage of the exposed issues. Therefore, the global analysis of vulnerability is a complex method that requires the superposition of numerous information on human, material, and environmental issues. For this reason, particular attention was paid in this study to the vulnerability assessment method.

This research followed the Hierarchical Multi-criteria Analysis (HMA) method, one of the most famous methodologies for vulnerability assessments [8]. Multi-criteria decision-making methods are increasingly used in various fields, such as natural resource management, environmental management, and spatial planning [6-9]. The principle of this approach is the division of a complex problem into small parts in a hierarchical structure of importance. This principle allows calculating the weight of all criteria and sub-criteria to determine the synthetic index of global vulnerability. The integration of the results of the multi-criteria analysis in the Geographic Information System (GIS) allows the spatialization of the issues to elaborate the global map of vulnerability. Hence, the combination of HMA and GIS provides a powerful spatial decision support system [10].

II. MATERIALS AND METHODS

A. The Study Area

The municipality of El Bayadh is located in the west of Algeria between latitude 33°40' North and longitude 01°00' East. According to the data from the communal office of statistics in 2020, the city is an integral part of the high plains region that covers an area of 46,350 hectares occupied by a population of 197,313. The case study represents the urban center of the municipality with an area of 4,024 hectares, as shown in Figure 1.

B. Data Collection

The assessment of the overall vulnerability of the study area involves assessing the vulnerability of human, environmental, and material targets [11]. The factors used to

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estimate the vulnerability, according to feedback and data availability, are ranked in terms of their importance. The weight of these criteria was calculated using the HMA method. The use of GIS enables the spatialization of the elements presented and the production of a synthetic map.

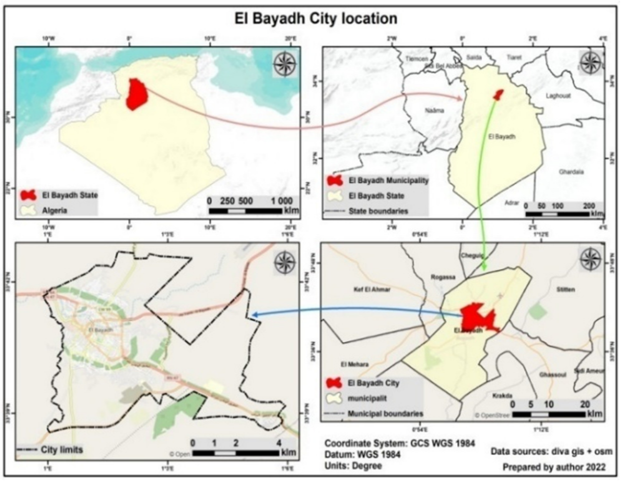

Fig. 1. El Bayadh city location.

1) *Population Density by Neighborhood*

Population density is one of the factors that determine social vulnerability. According to the data from the Directorate of Programming and Budgetary Monitoring of the Wilaya of El Bayadh and the municipal statistics office, the urban population of the study area will reach 109,664 inhabitants in 2020. Figure 2 illustrates the imbalance in the distribution of the population as the density reaches 299 per hectare in some districts.

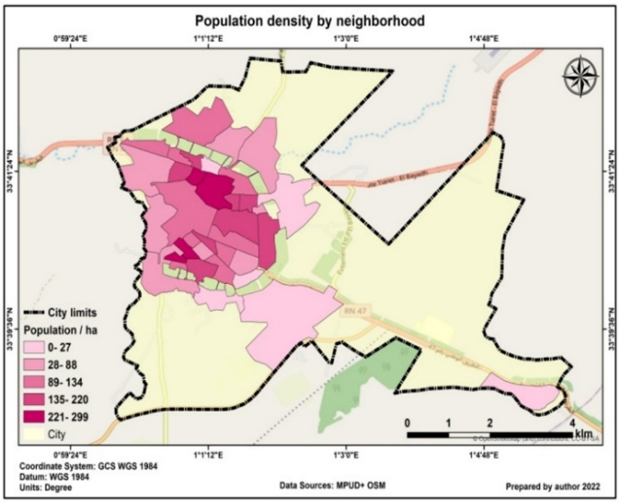

Fig. 2. Population density.

2) *Type of Housing*

The type of housing (individual or collective) plays a role in the overall vulnerability of the city. The Master Plan of Urban Planning and Development (MPUD) shows that individual housing is dominant in the city with 75% of the total housing stock, as seen in Figure 3.

3) *The Equipment*

The facilities are important components of the city, and their vulnerability to flooding influences the overall vulnerability. El Bayadh city has several facilities that occupy approximately 194 hectares, as seen in Figure 4.

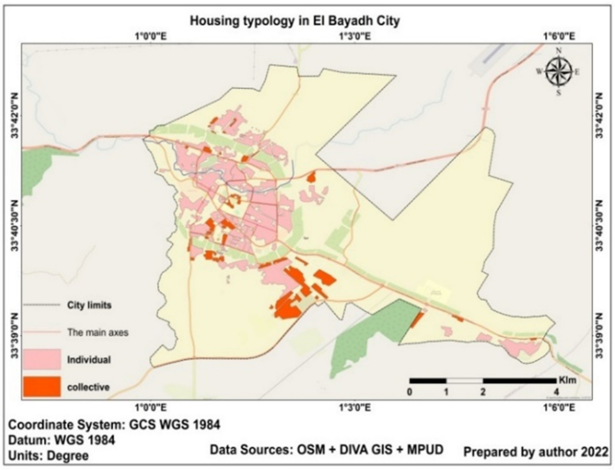

Fig. 3. Housing typology.

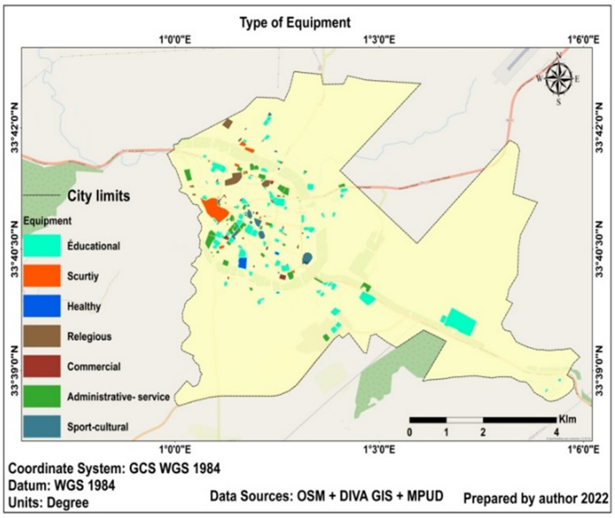

Fig. 4. Type of equipment.

4) *Road Network*

Given the importance of this factor in terms of accessibility and transport, assessing its vulnerability to flooding is essential for the overall assessment. The road network of the city of El Bayadh is divided into three sections, primary, secondary, and tertiary, as seen in Figure 5.

C. *Methods*

The assessment of urban vulnerability to flooding risk is a complex process, knowing that global analysis requires a lot of information on human, material, and environmental issues [11]. Investigating the history of flood events and studying the statistics of previous experiences can build a repertoire of vulnerable issues. The HMA method [12] was used to assess the global vulnerability of the city of El Bayadh and to develop the vulnerability map. HMA is a theory of relative measurement of intangible criteria [13]. This method is a framework for effective and rapid decision-making through simplification and the dissociation of the complex problem into parts [14]. The approach is usually based on three main elements: the decomposition of the complex problem into a hierarchy, measuring the priorities between the elements of each section, validating the consistency between the priorities, and the data of the judgments [12]. This method is used in business management or projects and deals with problems related to choices. Several researchers have already used it to assess a territory's vulnerability to flooding [14-18]. The multi-criteria analysis combined with GIS allows the spatializing and mapping of the vulnerable elements, as seen in Figure 6.

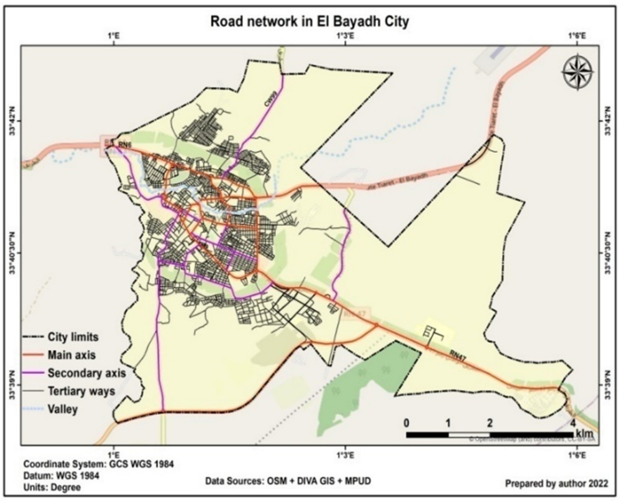

Fig. 5. Road network.

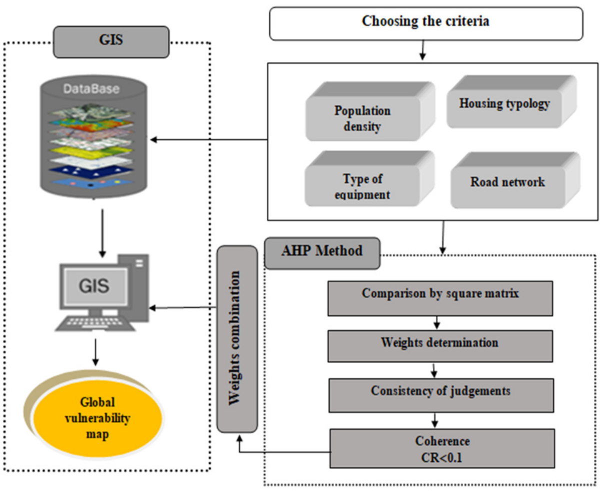

Fig. 6. The analysis method followed in this study.

1) Hierarchical Multicriteria Method (HMA)

HMA is a systematic procedure for representing the elements of any problem [20]. This method provides an approach to calculate weights and evaluate criteria. It consists of three main steps: decomposition of the problem, comparison and synthesis of priorities, and the study of the consistency of judgments.

a) Decomposition of the Problem

The HMA method breaks down the overall problem into smaller assessable criteria while maintaining their impact on the whole. The problem was broken down into three levels: objective, criteria, and possible alternatives [21].

b) The Comparison

This step involves the construction of a square matrix for the relative comparison of criteria of the same nature and level of the hierarchy. The appropriate numerical scale was proposed in 1980, as seen in Table I, to assess the intensity of importance only for the upper part of the matrix, as the lower part contains reciprocal results [22].

TABLE I. THE APPROPRIATE NUMERICAL SCALE [22]

Levels of importance	Explanation
1	Two features contribute equally to the objective.
3	Personal experience and appreciation slightly favor one aspect over another.
5	Experience and appreciation strongly favor one characteristic over another.
7	One characteristic is strongly favored, and its dominance is evidenced in practice
9	The evidence favoring one characteristic over another is as convincing as possible.
2,4,6,8	When a compromise is necessary.

The matrix is filled according to the following equation:

$$M = \begin{pmatrix} 1 & c1.2 & & c1.n \\ 1/c1.2 & 1 & & c2.n \\ & & 1 & \\ 1/c1.n & 1/c2.n & & 1 \end{pmatrix} \quad (1)$$

c) Consistency of Judgments

To test for consistency and judge whether the data obtained are logically related to each other, Thomas Saaty proposed the following steps:

$$CI = \frac{\lambda max - n}{n-1} \quad (2)$$

where CI is the consistency index, λmax is the largest eigenvalue of the matrix, and n is the number of criteria. In (3), CR is the final consistency rate, CR controls whether the evaluations are sufficiently consistent, and RI is the random consistency index based on the number of criteria used in the matrix (Table II).

$$CR = CI\ /\ RI \quad (3)$$

If CR is higher than 0.1, there is an inconsistency in the assessments. Therefore, the matrix will have to be reassessed.

TABLE II. RANDOM CONSISTENCY INDICES

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

2) Geographical Information System (GIS)

After obtaining the results on the weight of each criterion by the HMA, it was necessary to combine the multi-criteria analysis tools with GIS to spatialize the vulnerable areas [23]. GIS is an ideal tool because of its ability to manage large amounts of spatial data acquired from different sources [24, 26]. GIS provides better results and interpretations in flood management [25]. Integrating MCDA methods into GIS constitutes a powerful spatial decision support system [10].

III. APPLICATION, RESULTS, AND DISCUSSION

This study was based on the HMA method, using sequential prioritization to assess the urban vulnerability of El-Bayadh to flooding. Flood risk criteria were determined by consulting the available documents on the consequences of floods that had already hit the area and discussions with the city's local authorities [27]. The criteria used in the HMA process, as in the comparison matrices, were population density (A), housing typology (B), facility typology (C), and road network (D). The damage levels of each criterion recorded in the previous flood events were applied in the Saaty importance level when constructing the comparison matrices to be translated into weights. The same comparison and evaluation procedure was applied for the sub-criteria of the same level.

TABLE III. CRITERIA COMPARISON RESULTS

	A	**B**	**C**	**D**	**Weight**	**Ranking**
A	1	2	3	5	0.468	1
B	1/2	1	3	3	0.291	2
C	1/3	1/3	1	5	0.172	3
D	1/5	1/3	1/5	1	0.067	4

TABLE IV. RESULTS OF CONSISTENCY CHECK ON EVALUATIONS

N	***λmax***	***CI***	***RI***	***CR***	**Coherence**
4	4.21	0.07	0.9	0.08	$CR<0.1$

TABLE V. RESULTS OF HMA ASSESSMENTS OF THE SUB-CRITERIA

Criteria	**Sub-criteria**	**Weight**	**Ranking**
Density	0-27	00523	5
	28-88	0.089	4
	89-134	0.152	3
	135-220	0.262	2
	221-299	0.443	1
housing typology	Individual	0.75	1
	Collective	0.25	2
Type of equipment	Security	0.205	2
	Education	0.176	3
	Health	0.261	1
	Administrative/service	0.168	4
	Commercial	0.037	7
	Religious	0.071	6
	Sport/cultural	0.081	5
Road network	Main	0.637	1
	Secondary	0.258	2
	Tertiary	0.105	3

Based on the results of the multi-criteria analysis, the weights of the criteria were aggregated into GIS software QGIS. Using raster calculation practices, each raster was multiplied by the criteria weights according to (4) to produce the global urban vulnerability map shown in Figure 7.

$$\text{Global urban vulnerability} = 0.468 \times \mathrm{A} + 0.291 \times \mathrm{B} + 0.172 \times \mathrm{C} + 0.067 \times \mathrm{D} \quad (4)$$

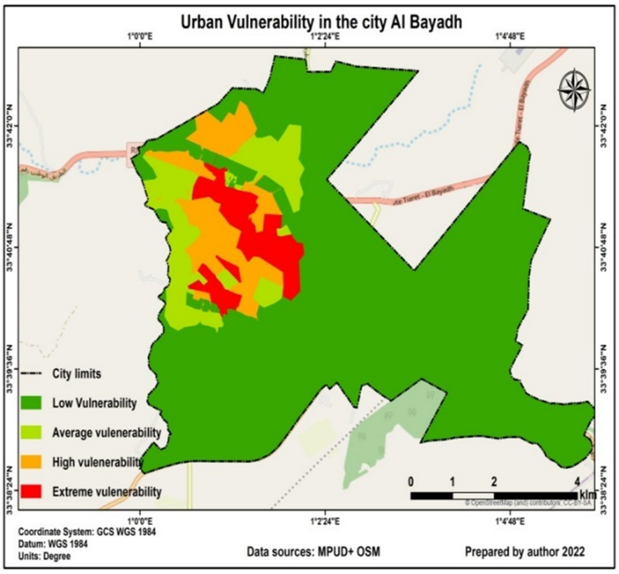

Fig. 7. Global urban vulnerability map.

Table VI shows a numerical interpretation of the global vulnerability map. The surface area of the low vulnerability zones was estimated at 77.87% with a surface area of 3133ha, the medium vulnerability zones were estimated at 8.56% with a surface area of 344.27ha, the high vulnerability zones were estimated at 7.97% with a surface area of 320.60ha, and the remaining 5.6% represents the extreme vulnerability zones with a total surface area of 225.46ha.

TABLE VI. HMA ASSESSMENTS OF GLOBAL VULNERABILITY RESULTS

Degree of vulnerability	**Area (ha)**	**Percentage (%)**
Low vulnerability	3313.42	77.87
Medium vulnerability	344.27	8.56
High vulnerability	320.60	7.97
Extreme vulnerability	225.46	5.6

As shown in Figure 7, the areas of high and extreme vulnerability are located in the city center, where the population density is very high, require adequate planning, and local authorities should investigate optimal solutions.

IV. CONCLUSIONS

This study evaluated the urban vulnerability to flooding risks in El Bayadh, Algeria, using the HMA method, which is based on the division of a complex problem into parts. For this purpose, the previous flood events were examined to bring out the criteria and sub-criteria of the same level that impact global vulnerability. The criteria obtained by consulting the documentation on the history of flooding in the study area and used in the HMA process were: population density, typology of existing housing, classification of installed equipment, and road network. In the second stage, the importance of these criteria and sub-criteria was compared with the grading scale proposed by Thomas Saaty. The consistency of the evaluations was examined by constructing a binary matrix, and was 0.08, less than 0.1, so it was acceptable. After the prioritization and determination of the weights of each criterion and sub-criterion, the results of HMA were integrated into a GIS tool to spatialize the exposed issues and map the vulnerable areas. Based on the results and interpretations obtained through this evaluation, the following conclusions were drawn:

- The development of a global flood risk vulnerability assessment model requires integrating a lot of detailed information on human, material, and environmental issues.
- This research confirms that HMA is a flexible and optimal process for evaluating the various factors and ranking them according to their importance.
- The integration of GIS tools allows the spatialization of vulnerable issues and the mapping of global vulnerability.
- The final results of the general assessment show that the areas of high and extreme vulnerability are located in the city center, where there is a high population density, and represent a 13.57% rate with a surface area of 546ha. In comparison, low- and medium-vulnerability areas represent 86.3% of the study area with a surface of 3,658ha.

The local authorities of El Bayadh city should take appropriate preventive measures to reduce the risk of flooding by restructuring the most vulnerable areas. The originality of the analysis and assessment method was based on the use of a model appropriate to the context of El Bayadh and the criteria used in the HMA method. Furthermore, more studies should be conducted in the future using other criteria that could reduce the risk of flooding.

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