Integration of GIS and Hierarchical Multi-Criteria Analysis for Mapping Flood Vulnerability

The Case Study of M'sila, Algeria

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Abstract-This paper proposes the integration of GIS (Geographic Information System) and HMA (Hierarchical Multi-criterion Analysis) offering a low-cost methodology to produce vulnerability maps. The quintessential role the rivers play in urban development has long been asserted and accepted. However, one of the subsequent consequences of these urban development activities is the increased frequency of floods. The case in point is the city of M'sila, Algeria. The subject city was settled along the banks of a river known as Oued El Ksob, which undoubtedly had a significant influence on its development. In the last 50 years, M'sila has experienced significant spatial growth, especially in its north and northwest sides. As such, the work presented in this article aims to assess the vulnerability of the city to the risks of flooding. The approach used is based on the combined use of the HMA method coupled with the GIS. The process allowed the graphical representation of the resulting analysis of complex data of the territory, i.e. the mapping of its vulnerability to flooding. The map has four vulnerability categories ranging from low to very strong. The proposed system serves as an essential decision-making tool for local government officials.

Keywords-flood risk; vulnerability; GIS; hierarchical multi-criteria analysis; M'sila city

I. INTRODUCTION

Floods in urban arrears constitute a severe risk and have become more frequent and severe along with the rapid urban development [1]. The urbanization along the river banks has contributed to the increased risk, severity, and frequency of floods. This is one of the most common and destructive risks of natural disasters. The city of M'sila is a good case in point. M'sila is the capital of the M'sila Province and is located on the Plains of Hodna, along Oued El Ksob river, between the saline lake Chott El-Hodna and a range of the Tell Atlas mountains. Known as a farming and trading center, the city of M'sila derives its true geographical personality from its relative wealth of water [2]. The city it has been a site of numerous catastrophic floods, such as the one of September 23rd, 2007. Although flooding is a natural phenomenon, the urban explosion that the city has experienced creates these risks. As such, our research focused on analyzing and assessing the city vulnerability to flooding through integrated risk management. This study also intended to provide a decision-making tool to minimize the frequency and the impact of flooding on M'sila and its inhabitants. To address the issue of urban growth impact on flooding risks requires a multi-criteria approach concerning several and different elements, conditions, and factors. Such an approach, when associated with the Geographic Information System (GIS), has been widely used in different contextual areas including flood management. It also plays a major role in developing reference maps for damage prevention and charting, the integration of any type of information, a better presentation of ideas and a better understanding of the scope of possible solutions [3]. The method has also been used successfully to assess a territory's vulnerability to flood risks [4-7].

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II. STUDY AREA

M'sila is a city in the North-Central part of Algeria. It is seated between 35°66' and 36°75' North latitude and between 4°47' and 4°57' East longitude. The land of the city used to be primarily agricultural. Under the effect of human pressure, this situation has changed. This change is marked by the extension of artificial land and the decrease in agricultural areas as it is given in Table I and Figures 1-2.

III. METHODOLOGY

To conduct this study, the Hierarchical Multi-criteria Analysis (HMA) method [8] was adopted. This approach is ideal for quantifying and prioritizing complex problems into an orderly hierarchical structure of criteria and sub-criteria [9]. The approach in our case study is to assess the risk of flooding in the city of M'sila by applying GIS features that take into account interpolation and recovery, based on multi-criterion analysis, in order to develop a vulnerability map. In addition, GIS coupled with a multi-criterion analysis offers opportunities to study the risks of flooding incorporating all the relevant conditions and parameters. It also identifies and prioritizes impact factors [10]. The method as used herein is based on the steps described below.

A. Phase 1: Evaluation Criteria Identification

The evaluation criteria were identified in relation to the factors that have the greatest impact on the vulnerability or proneness of the city to flooding. Judgments were, therefore, exercised between the following four parameters: (1) proximity to a water stream, (2) population density, (3) land use, and (4) terrain slope. Each parameter or criterion was consequently linked to several categories. These categories were established in relation to the data from the study area. Each evaluation resulted in a map representing, for all elementary surfaces, their suitability to the considered criterion [11]. These maps were obtained from digital aerial images taken based on satellite images dating as of 2020 from Algeria's National Institute of Mapping and Remote Sensing.

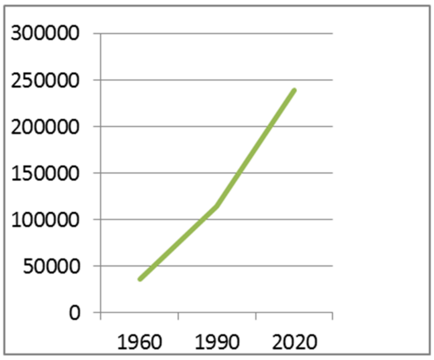

Fig. 1. Evolution of population.

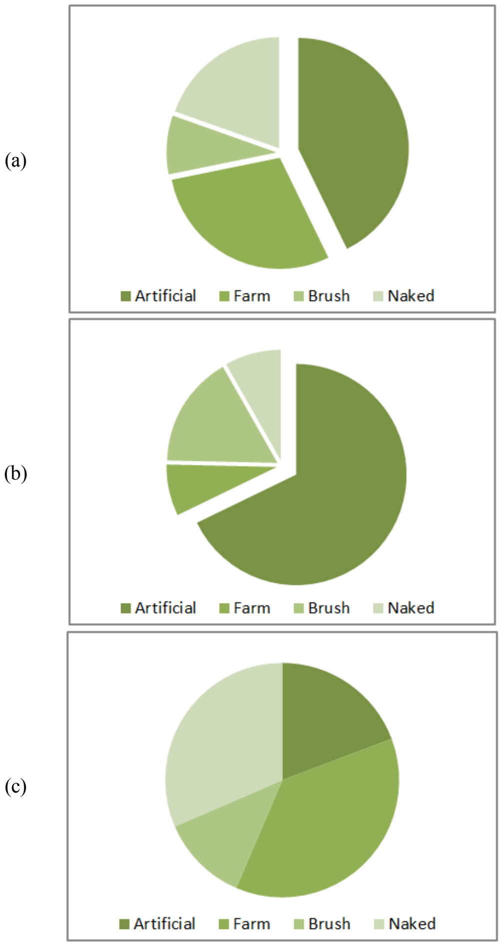

Fig. 2. Land use in (a) 1960, (b) 1990, (c) 2020.

TABLE I. EVOLUTION OF LAND USE IN M'SILA

Year	1960	1990	2020
Artificial	19.26%	42.75%	81.09%
Farm	37.18%	29.08%	9.00%
Brush	12.09%	8.55%	19.62%
Naked	31.47%	19.62%	9.85%
Population	35,377	113,683	238,689

B. Phase 2 : Weighting Criteria

The process of calculating the relative importance of each criterion is known as the standardization of the criteria [12]. The comparative weight scale as used in this study is given in Table II.

TABLE II. COMPARATIVE SCALE

Scale	Description
1	Equal importance of two elements.
3	One element is a little more important than the other.
5	One element is more important than the other.
7	One element is much more important than the other.
9	One element is much more important than the other.
2, 4, 6, 8	Intermediate values between two judgments.

C. Consistance Verification

In order to check that the transitivity of our judgment was respected, the author in [13] proposes the following mathematical formula:

$$IC = \frac{(\lambda max - N)}{(N-1)} \quad (1)$$

where IC is the consistency index, N is the number of elements compared, λmax is the average Saaty matrix values of own vectors that indicates the order of priority or hierarchy of the studied characteristics.

The consistency ratio (RC) is calculated by:

$$RC = \frac{IC}{IA} \quad (2)$$

where IA is defined as the Random Index of a matrix of the same size presented in Table III.

TABLE III. RANDOM INDEX

n	1	2	3	4	5	6	7
IA	0	0	0.58	0.9	1.12	1.24	1.32

D. Phase 4: Aggregation of Criteria

This operation consisted of multiplying each factor layer by its respective weighting as confirmed in the hierarchical structure [14]. Then, the AHP method is used, in combination with the integration of the criteria cards in accordance with their weight on the GIS software, through a linear combination method of weighting in order to obtain a summary map.

IV. RESULTS AND DISCUSSION

The results of the pairwise comparison of the sub-criteria relatively to the criteria considered for our case study are summarized in Table IV (the comparison matrix is standardized so that the sum of all weights is equal to 1).

Regarding the results, we have RC = 0.095, so the consistency ratio is less than 0.1 which allows us to state that the judgments for the assessment of the criteria have been consistent.

TABLE IV. PAIRWISE COMPARISON RESULTS

Criterion	Categories	Rank	Weight
Terrain slope	0-3	7	0.511
	3-6	6	0.262
	6-9	4	0.118
	9-12	2	0.067
	12 >	1	0.041
Proximity to a water stream	0-50	9	0.518
	50-200	7	0.263
	200-500	5	0.129
	500-800	3	0.063
	800>	1	0.032
Population density	0-60	1	0.087
	60-600	3	0.444
	600>	7	0.467
Land usage	Building	9	0.628
	Industrial	7	0.254
	Bare soil	1	0.399
	Vegetation	3	0.771

The evaluated criteria are mapped in the Figures 3-6 using the spatial analysis functionalities of GIS. The layers with a common, registered map base are joined on the basis of their occupation of space. These outputs can reflect simple operations such as laying a road map over a map of local wetlands to determine averages and co-occurrences [15]. The result of the sum of the different criteria maps according to their weight under the Arc GIS software allowed obtaining the decision-making spatial reference map shown in Figure 7. The interpretation of the resulting map allowed us to discuss the relationship between the urban growth and the risk of flooding. The map shows flood potential areas. The level of risk varies from one residential area to another. This level of risk is higher primarily in the northern and northwestern districts of the city, which have experienced significant urban extensions. These areas of greater flood concern include the two colonial and historical quarters, El-Kouch and El Argoub that are considered as the central nucleus of the city which were built at the edges of Oued El Ksob.

Large land areas have been used for urbanization purposes resulting in significant increase in population density. This accelerated rate of urbanization has generated multiple challenges and environmental issues. The growth of the city of M'sila constitutes a form of urbanization that has become widespread encroaching onto agricultural lands. The diachronic analysis of land use has shown an increase in built-up areas. This urbanization is intensifying at the expense of agricultural land because the areas open to urbanization do not always meet the increasing needs of the population. Moreover, these changes in land use, associated with urban development, affect flooding risk. In urbanized areas, much of the permeable soil is replaced by impermeable infrastructure such as roads and buildings, minimizing its capacity to store rainfall and water. After the construction of any dam, the fluvial regime of the river is subjected to consequential change and its system or pattern of erosion may undergo metamorphosis.

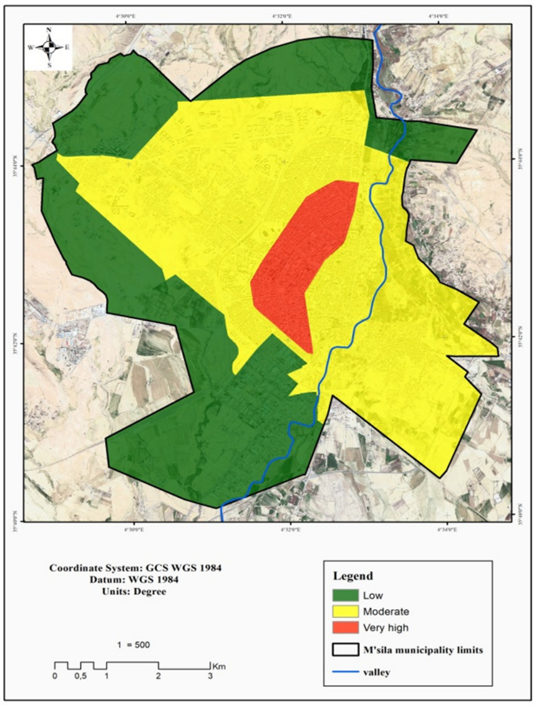

Fig. 3. Population density mapping.

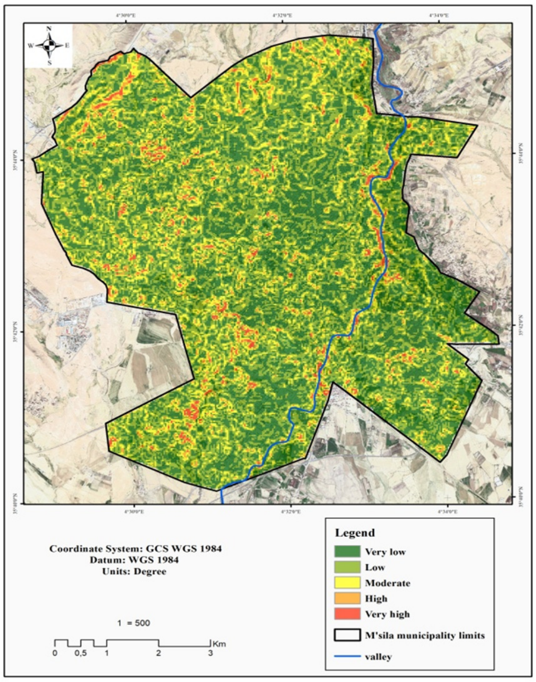

Fig. 4. Terrain slop mapping.

Dam construction alters the amount of sediment production, retention and transportation of the sediments in the system [16]. As a result, rain, which used to penetrate the ground, now flows directly into streams, increasing their flow. Furthermore, buildings on floodplains can interfere with the passage of flood waters. The entropic risks are driven by the strong demographic changes coupled with the creation of new residential areas in the northern territory of the city.

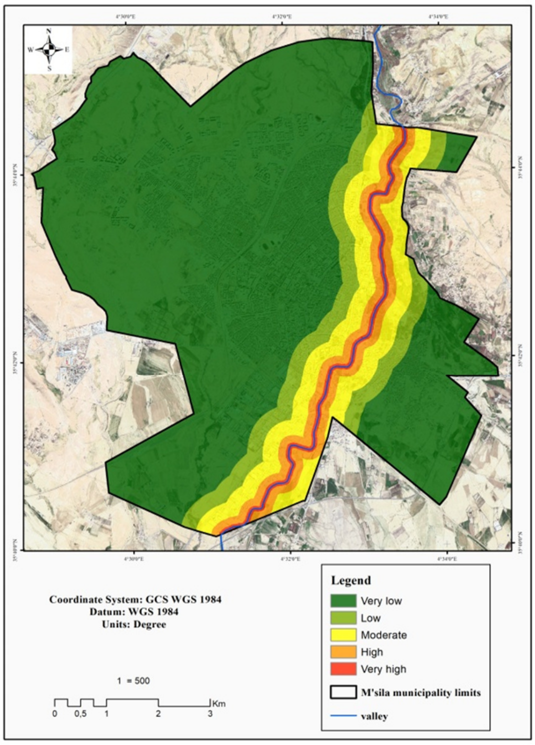

Fig. 5. Proximity to a water slop mapping.

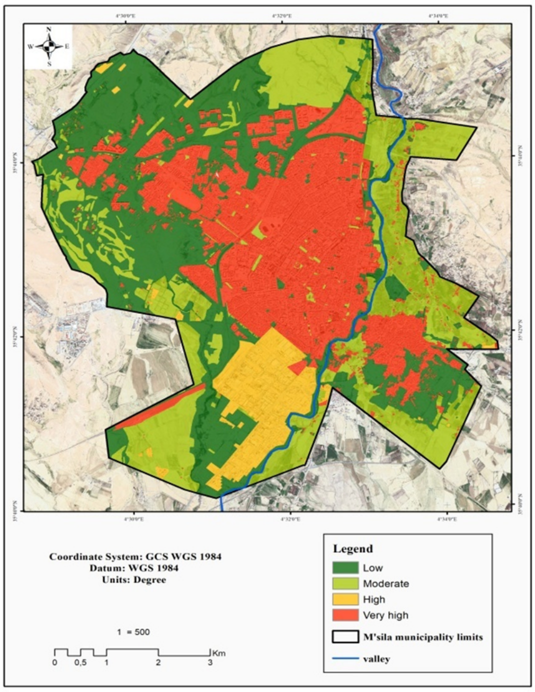

Fig. 6. Land used mapping.

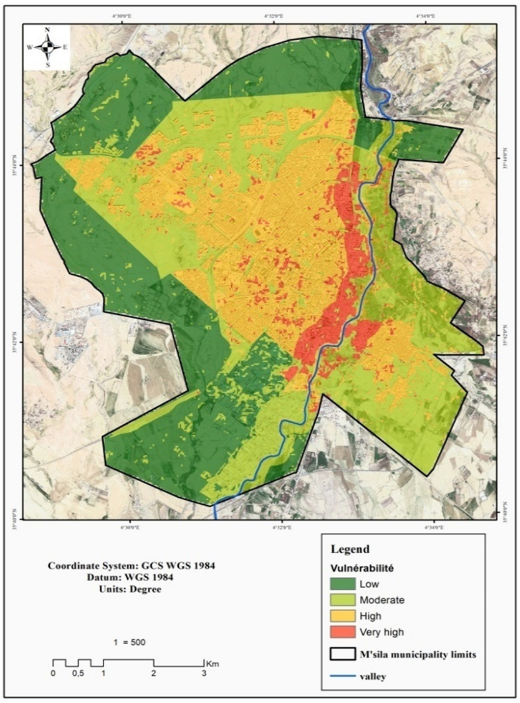

Fig. 7. Overall vulnerability mapping.

V. CONCLUSION

The city of M'sila is built on the banks of the Oued El-Ksob between the mountain ranges that make it a natural water collector. Due to this reason the subject land was initially and mainly agricultural. The villages used to be established in elevated areas in order to minimize flood risk. But under the influence of human pressure, the situation has changed. This change is marked by the extension of artificialized land to agricultural spaces, which has aggravated, or even created hazardous conditions. This growth of building has also resulted in a dense concentration of populations over restricted spaces, which mechanically increases risk exposure. The city is increasingly spreading in areas of flat reliefs and around several water points where flood overflows can spread out. The inadequate work on waterways promotes flooding possibility in urban areas and increases the vulnerability of exposed areas, or, for the most localized events, a worsening of flows.

The HMA method used in our research allowed us to study the risk of flooding, integrating all the parameters relating to the studied area. It also enabled us to determine the extent of flooded areas at the intra-urban level of the city as well as the water height at all points of these areas. This technique can play an important role, not only in terms of specific applications for urban risk management, but also in timely disseminating information to public and private stakeholders involved in the prevention and management of this risk.

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