Journal of Environmental and Agricultural Studies
ISSN: 2710-1401
DOI: 10.32996/jeas
Journal Homepage: www.al-kindipublisher.com/index.php/jeas

JEAS
AL-KINDI CENTER FOR RESEARCH AND DEVELOPMENT

| RESEARCH ARTICLE

Assessment of the Vulnerability to Potential Collapse of Buildings in the Old Medina of Beni-Mellal-MOROCCO

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| ABSTRACT
The application of specialized natural hazard mapping is an absolute necessity for the management and prevention of natural hazard events. This paper treats the description of all the procedures carried out in order to produce a map of vulnerability and susceptibility to cave-ins, calculated and evaluated by the multicriteria method (AHP) and by using the GIS tool in the old Medina of Beni Mellal, which is recognized from time to time by cave-ins. The objective of this study is to develop a new method for analyzing the vulnerability of cavities to collapse, which presents a real risk in the urban area of the old cities. The methodology, applied to the old city of Beni-Mellal, consists in identifying and quantifying the stakes linked to the collapse of a cavity using a geographic information system. The weight of each parameter and factor exposed in the vulnerability was estimated using the hierarchical multicriteria method (AHP). The result is presented in the form of a spatialized and synthetic vulnerability map. The detection, mapping and assessment of areas vulnerable to the collapse of these cavities, particularly for large areas of the city, offers the possibility of reducing damage by intervening upstream and introducing preventive and corrective measures against any risk of collapse in the areas deemed vulnerable by our study. The maps show three zones with different degrees of vulnerability. The low and medium vulnerability zones occupy respectively 30 and 20% of the total area of the old city, while the high and very high vulnerability zones occupy respectively 16% and 4%.

| KEYWORDS
Building collapse, Underground cavity, Vulnerability, Natural hazard, Geophysics, AHP method, GIS, Beni Mellal.

| ARTICLE DOI: 10.32996/jeas.2022.3.1.2

1. Introduction
Landslides are phenomena of very diverse origins. Each year, they cause an average of 800 to 1,000 deaths throughout the world and cause economic losses and very significant damage. They include a series of sudden movements of the ground or subsoil of natural or anthropogenic origin. The different types of land movement are Shrinkage and swelling of clays, settling and subsidence, landslides and collapse of underground cavities. Geotechnical risk management is one of the most important concerns. The aim is to minimize not only the construction costs but also those related to the maintenance and upkeep of civil engineering structures. Also, the concept of safety is now so important that it is a major priority for those involved in the sector.

The collapse of an underground cavity is the result of its natural evolution (dissolution of the subsoil rocks) or artificial evolution (quarries and underground works), which leads to the collapse of the roof of the cavity and causes a circular depression on the surface. These underground cavities are present in several Moroccan cities whose foundation is limestone (Najine and al 2006, Najine and al., 2007, El khamari and al., 2007). Karst environments are extremely fragile and vulnerable to a number of hazards, which result from the intrinsic characteristics of karst (White, 1988; Ford and Williams, 2007; Parise and Gunn, 2007; Gutierrez, 2010; Parise, 2010a; De Waele and al., 2011). Many types of karst hazards, of which sinkholes are certainly the most particular (Waltham and Lu, 2007; Parise, 2008; Zhou and Beck, 2011). They are the result of karst processes in soluble rocks, which are outcropping at the surface or covered by other materials (Waltham and al., 2005).

The Medina of Beni-Mellal has a dense network of underground cavities. These cavities, some of which are of natural origin, result from the natural dissolution of the carbonate materials of the ground. Some were dug by the population of the area to satisfy their domestic needs (construction, works, mines, etc.) (Najine and al., 2007). The risks associated with their presence can therefore be divided into two categories:

- When they are of natural origin, the risk is geological. Collapses at the level of sub-cavity surfaces are the result of rock dissociation phenomena.
- When they are of anthropic origin, the danger is technological. The collapse is linked to the dimensioning and solidity of the structure.

These cavities constitute a major risk for the stability of the buildings and infrastructures of the city (constructions, roads, pipes, etc.) and can cause collapses. The evaluation, delimitation and classification of the zones of the old Medina of Beni-Mellal according to the degree of vulnerability to the collapse of its cavities give the possibility of preventing the consequences and reducing the damage by the developers and intervening upstream and offers them a rich database which will be integrated into a geographical information system which will be exploited thereafter in the form of a vulnerability map which covers the whole territory of the old Medina.

The first vulnerability maps were developed to make decision-makers and the public aware of the sensitivity of an aquifer to pollution. The assessment of the vulnerability of groundwater to pollution reflects the ease of being reached by a surface pollutant (Essahlaoui, 2000). The assessment of the vulnerability of the aquifer is carried out using different approaches. (Sinan, 2000) used the DRASTIC model to identify the vulnerability of the aquifer to pollutants. The DRASTIC model corresponds to the seven factors determining the value of the vulnerability index (Aller and al., 1987). The SINTACS method was developed from the DRASTIC method in Italy in response to the great hydrogeological diversity of the country in the early 1990s (Pételet and al., 2000). The SI (Susceptibility Index) method, which estimates the specific vertical vulnerability to agricultural pollution (mainly by nitrates and also by pesticides), was developed in Portugal by RIBEIRO (Ribeiro, 2000). This method takes into consideration five parameters.

There are three types of vulnerability methods:

- The mapping method aims to assess the vulnerability to pollution by current hydrogeological factors (Sotomikova, R and al 1987).
- System methods also use environmental characteristics as parameters, but each is assigned a numerical value. The introduction of a numerical rating system for each class of parameters allows the assessment of the evolution of vulnerability (Sinan, 2000; Pételet and al., 2000; Ribeiro, 2000).
- Analytical and numerical modelling methods allow the simulation of displacement and fluid flow using mathematical equations (AGEOS and INRS-Eau, 1996).

The study of the vulnerability of cavities to collapse first requires a detailed mapping of these cavities and determination of their geometric characteristics (depths, extent, dimensions, etc.).

Technical studies for the recognition and detection of cavities by geophysical methods have been successfully implemented in Canada using three methods: ground-penetrating radar, 2D electrical imaging and magnetic resonance sounding (Al-Fares and al., 2001).In France, for the search for karstification under the TGV Mediterranean platform (Azemard and al., 2001). Detection of karst cavities by ground-penetrating radar in Spain (Casas and al., 1996).Detection of shallow faults and cavities in Canada by application of penetrating radar (Deng and al.,1994). Recognition of karstified areas in Belgium by application of 3D electrical resistivity tomography (Deceuster and al., 2003). Gabrielle and all compared the performance of geophysical methods for the detection of cavities in silts (Lagabrielle and al., 2003). (Miahe et al., 2003) used the electrical imaging method for the detection of a brine filled cavity. Roth et al. worked on a case study on the reliability of multi-electrode earth resistivity tests for geotechnical investigations in karst terrain (Roth and al., 2002).

The urban environment of the city of Beni-Mellal (NAJINE Al and al., 2006, Najine and al., 2007) give satisfactory results by combining both seismic and electrical methods (tomography). These geophysical techniques also allowed to specify the location and the extension of the cavities highlighted in the city of Zawyat Cheikh (El khamari and al., 2007).

2. Geographical location

The city of Beni-Mellal is located at the foot of the northern flank of the central High Atlas on the national road 8 (ex-RP 24), which connects the cities of Marrakech and Fez, about 205 km north-east of Marrakech and about 210 km south-east of Casablanca. The city of Beni-Mellal is the capital of the economic region of Tadla-Azilal and is considered a regional economic centre due to its geographical location as a hub, its historical heritage and the fact that it is the capital of a rich and irrigated region.

Due to its location between the High Atlas and the Tadla plain, the urban area is characterized by a generally uneven topography (average altitude 580 NGM). It extends to the south as far as the source of Ain Asserdoune (coastline 723 NGM) and stretches to the north into the plain as far as the coastline 480 NGM.

Fig. 1: Location map of the city of Beni Méllal

2. Geological context

The Beni Mellal city is part of the hill zone. The substratum of this Atlas range is mainly made up of Maestrichtian material and breccias attributed by J. Bourcart to the continental Upper Eocene. The power of the continental series of the Beni-Mellal is slightly more than 100 m. In general, a succession of red layers more or less cemented conglomerates and generally pink lacustrine limestones, sometimes travertine, are observed. The latter appears, on the one hand, in the lower part and, on the other hand, in the upper part of the series.

The exploratory boreholes show travertine limestones with a bedrock of sand and calcareous sandstone. They are found in banks 2 to 3 metres thick, cemented at the top and powdery at the base. These are soils supersaturated in calcium and with a very high percentage of magnesium. These travertine limestones intercalated in the detritic series are deposited by running water, probably near springs, during a break in the supply of coarse materials. They occur in undulating form and are present in almost all the cavities.

The overlying layer is made up of hard limestone with a quartzite cement of good permeability. The facies of this layer is not always homogeneous, and its strength increases in the general NE-SW direction. In some places in the Medina, the absence of this limestone layer has been observed, especially in the SE and near Tamegnount.

As for the conglomerates, they are relatively coarse, with elements reaching 10 to 20 cm. The pebbles, generally well-trodden, are mainly Liassic limestone or dolomite, but white limestone of the underlying Eocene is also present. There seems to be no doubt that these conglomerates represent a foothill formation of fluvial or even torrential origin. They reflect the proximity of major limestone and dolomitic landforms and are the result of their dismantling. In particular, the angular material of certain levels is due to the immediate proximity of the foothills of the Atlas.

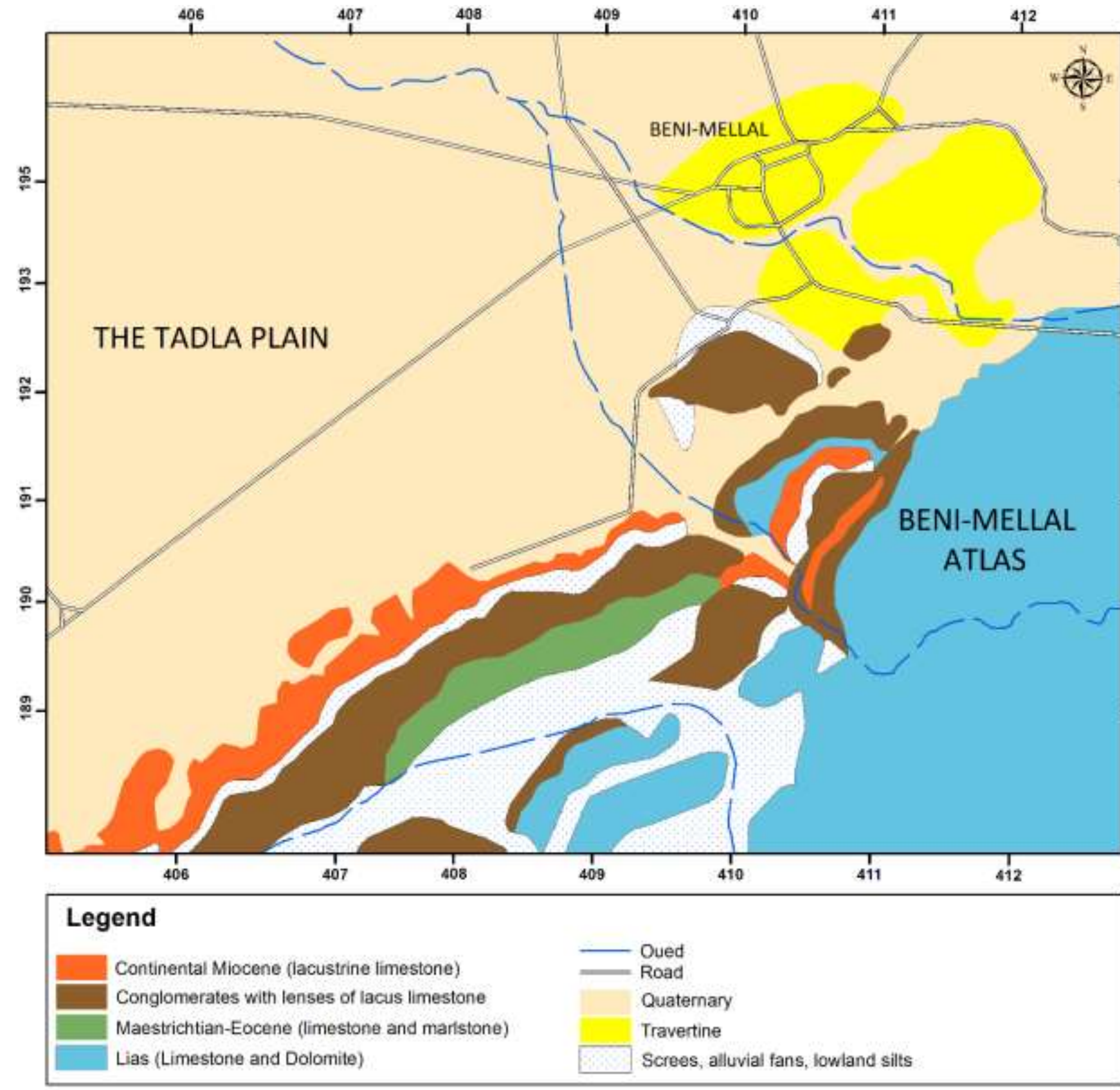

Fig. 2: Geological map of the study area

3. Methodology

3.1 Underground cavities detection by geophysical methods

In order to assess the vulnerability of the cavities to collapse in the city of Beni Mellal, an inventory and detailed mapping of these cavities and their characteristics (dimensions, depths, etc.) are necessary. The city of Beni Mellal was built on land affected by a large network of cavities and underground caves, which are at the root of the numerous land movements currently observed.

In this paper, we consider the use of electrical panels (or tomography) and geological radar techniques for the recognition and delimitation of underground cavities in the old city of Béni Mellal. Electrical tomography is a very efficient method. It uses a multi-electrode device that allows the acquisition of a large number of measurements corresponding to the different combinations of four electrodes (Edwards, 1977). The seismic method consists of studying the propagation of surface waves to explore the surface of the subsurface. It is very effective in detecting cavities in the subsurface, which appear as areas of very low seismic velocity, and also allows variations to be determined (Leproux and al., 2000).

The use of these geophysical methods for the recognition of underground cavities in the ancient city of Beni-Mellal has previously given results that were considered adequate (Najine and al., 2006, Najine and al., 2007)

3.2 Method For Assessing The Vulnerability Of Cavities To Collapse

The notion of vulnerability to the collapse of underground cavities is based on the idea that the physical environment, in relation to these cavities, provides a greater or lesser degree of risk of collapse, depending on the characteristics and anthropic activities practised in the environment.

The analysis of the vulnerability to cave-ins proposed and applied to the old city of Beni Mellal aims to create a general indicator of vulnerability by using the method of hierarchical multicriteria analysis, and the use of a geographic information system will allow us to map the factors affecting vulnerability. The implementation of a global cave-in vulnerability analysis requires a lot of information about the factors affecting the collapse of a cave. These factors should then be collated to form an integrated ranking that reflects the vulnerability of cavities to collapse. At this last stage, we are faced with the difficulty of mapping this synthetic spatial information without losing the relationships between the various components of vulnerability.
The proposed method takes the form of a numerical rating system based on the consideration of the different factors influencing the system. It is based on the combination of eight parameters grouped under two main criteria:

- The Intrinsic criterion: soil lithology, depth of the cavity, moisture and groundwater flow and the use of the cavity;
- The Extrinsic criterion: the height of the buildings, the condition and stability of the buildings, the road system and the land use.

Each parameter is classified into classes associated with scores ranging from 0 to 1. These parameters are then assigned a factor of 1 for the most significant factors and a value of 0 for factors that are less significant. In the GIS, each parameter is noted on a layer by assigning a coefficient corresponding to the weight of the parameter, i.e. its influence on the vulnerability of the site. These layers are then superimposed on a result layer where the vulnerability index is calculated. The weight of each apparent parameter in the vulnerability was calculated by applying the hierarchical method (AHP).

3.3 Determination And Spatialisation Of Vulnerability Factors

In order to elaborate the final cave-in susceptibility map, the following parameter maps were made: building height map, building condition and stability map, road map, land use map, cave depth map, cave use map, subsoil lithology map and finally, the moisture and groundwater flow map.
During processing in the Geographic Information System (GIS), the spatial GIS data can be presented in raster or vector mode, raster (image) or vector (object) mode. In this article, we have chosen to use a vector and raster representation of the data. The factor maps are elaborated by processing spatial data, by digitizing existing maps or by interpolating point data.
Thus the maps are obtained following a series of manipulations carried out on the ArcGIS software:

- Building height: calculated from the shadow of the buildings (Rajji and al., 2021);
- The state and stability of the buildings: based on the development plan and the maps of pathologies of the buildings of the old city of Beni-Mellal;
- Roads: from the development map and by manual extraction from the satellite image of the study area;
- Land use: the processing of the high-resolution Google Earth satellite image enabled us to define all the components that occupy the entire surface of the study area;
- The depth of the cavities: geophysical techniques allowed us to specify the location, the extension and the depth of the cavities of the former City;
- The use of the cavity: mapping through the reading of the literature of the urban agency of Beni-Mellal;
- Lithology of the cavity roofs: determined using the method of correlation of the data of the geotechnical missions carried out in the study area and the data of the urban agency of Beni-Mellal
- Moisture and groundwater flow: established through the superposition of bibliographic data from the urban agency and data from geophysical missions;

The weight of each apparent parameter in the vulnerability map was subsequently calculated by applying the hierarchical method (AHP).

3.3 Application Of Hierarchical Multi-Criteria Analysis To The Study Of The Vulnerability Of Cavities To Collapse

AHP is a multicriteria analysis method developed by mathematician Thomas Saaty in the 1970s, which aims to help decision-makers improve their decision-making processes by taking into account the coherence and logic of choice. It is a method that can be used in the process of quantifying qualitative criteria, by means of qualitative scoring, through its weighting. It has been used with satisfaction in various fields (Saaty and al.,2006; Ramos and al., 2014).

Multicriteria methods are generally used in business or project management when one or more decision-makers are faced with decision or judgement problems in complex situations. They have already been used on several occasions to assess the vulnerability of a territory. In terms of flood risk, hierarchical multicriteria methods (AHP) have been used to compare the vulnerability of different sites according to socio-economic, hydraulic and emergency organization criteria (Griot and al., 2002). Similar methods have been used to assess the vulnerability of an area to the risk of transporting hazardous materials in order to provide decision support to the actors responsible for organizing the emergency response (Griot and al., 2002). It is a rigorous approach that is subdivided into a succession of essential steps, starting with the structure of the hierarchy, prioritization and validation of the logic (Leproux and., 2000).

In the context of this study, the aim is not to select solutions but to prioritize different targets according to their degree of vulnerability to the risk of cave-ins by defining the weights of each parameter and determining a classification within each parameter according to logical and objective operations. The coupling of this method with the GIS geographic information system allows the ability to integrate a large amount of heterogeneous data and the obtaining of the weighting of each factor to be evaluated in a simpler way, even for a large number of criteria (Feiziziadeh and al. 2013). The weighting of each of the factors is a reflection of their relative importance.

The method is based on the comparison of the different parameters, two by two. Through the construction of a square matrix, the relative importance of one characteristic compared to another is assessed using an appropriate scale. SAATY (1991) recommends the use of the scale presented in (Table 1). Once the comparison matrix is filled in, the eigenvalue of each of them and the corresponding eigenvector are calculated. The eigenvector indicates the priority order or hierarchy of the characteristics considered. This result is important for the probability assessment, as it will be used to indicate the relative importance of each operating criterion. The eigenvalue is the measure that will allow us to assess the consistency or quality of the solution obtained, thus representing another advantage of this method.

3.3.1 Design of the hierarchical model

The design of the hierarchical model is an important step in the analysis of the problems, and it is therefore very important to provide more detail to the hierarchy in order to have good analysis and reflection capabilities. If the analysis yields unsatisfactory results or the matrix turns out to be inconsistent, the method allows us to change the entries or add more criteria. The structure of the hierarchy consists of a hierarchical tree of three levels, where the objective is at the top level, the selection criteria at the middle level and the alternatives at the bottom level. The levels of a hierarchy are closely related to each other (Leproux and al., 2000).

The use of the AHP method to assess the vulnerability of cavities to collapse requires the design of the hierarchical structure first.

- Level 0: means the objective which is the assessment of the vulnerability of cavities to collapse;
- Level 1: corresponds to the criteria that will define the objective; two criteria have been retained. These criteria are the intrinsic and extrinsic factors;
- Level 2: the two criteria of level 1 are broken down into four measurable sub-criteria for each.

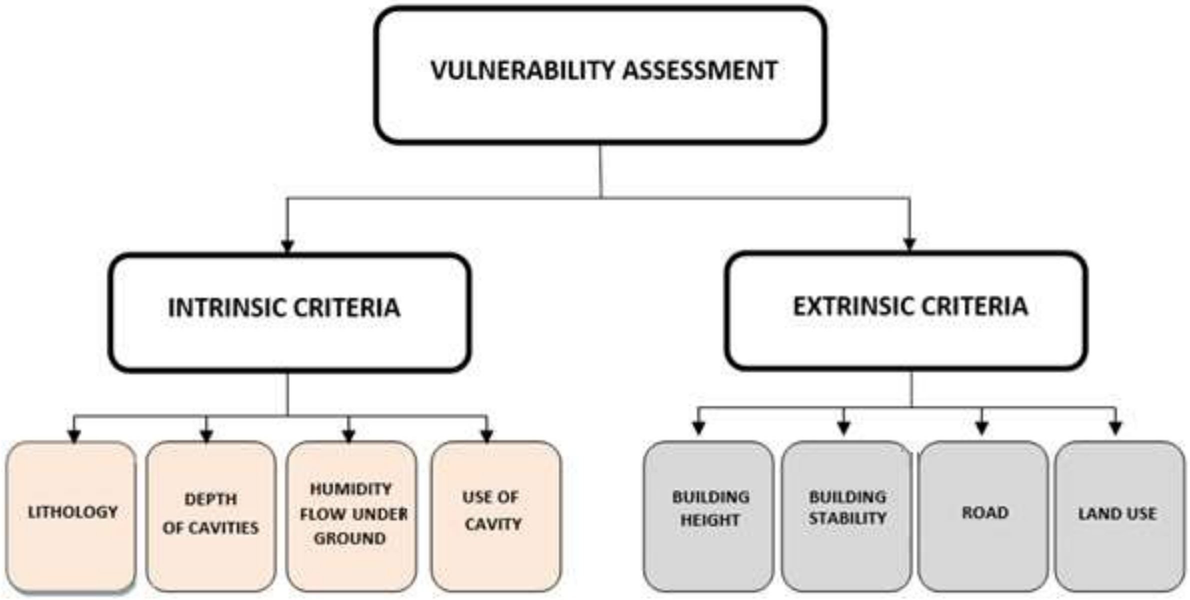

Fig.3: General hierarchical structure

3.3.2 Pairwise comparison

This phase is mainly based on making pairwise comparisons of the different components of the hierarchy by combining logical thinking and practice (simulating the relationships between the criteria by experience and by consulting the literature) (Feiziziadeh and al. 2013). The matrix is the best way to make these comparisons. This matrix grid is designed to assess the relative importance of a certain element compared to another using an appropriate scale. The comparison allows hierarchies or weights to be established for the criteria based on a scale of value judgements or levels of importance—the value judgements or levels of importance established by methodology and experience.
Table 1 presents a weighting scale given by Saaty (1991).

Table.1: Binary comparison scale

Appreciation	Degree of importance
Equal importance of two criteria	1
Low importance of one criterion in relation to another	3
Medium importance of one criterion in relation to another	4
High importance of one criterion in relation to another	5
Proven importance of one criterion in relation to another	7
Absolute importance of one criterion in relation to another	9
Intermediate values between two judgements used to refine the judgement.	*2, 4,6, 8*

After completing the comparison matrix, the weight of each component of the hierarchy must be calculated. Then, we divide all the entries in each column by the total of that column in order to obtain a normalized matrix that allows relevant comparisons between the different elements. Finally, we calculate the row average by adding the values of each row of the normalized matrix and dividing these rows by the number of entries. These operations result in an overall eigenvector for the lowest level of the hierarchy. The eigenvector Wi shows the order of priority or hierarchy of the different parameters and classes studied.

3.3.3 Consistency of judgements

Since errors can be made in the weighting of each criterion, the consistency ratio (CR) is calculated to ensure the consistency of the pairwise comparison and the weights given to each factor (Feiziziadeh and al., 2013). According to Saaty (1977), if the CR is less than 0.10 (10%), the pairwise comparison has a good consistency (Feiziziadeh and. 2013). and the weights are valid and are accepted for the multicriteria. Otherwise, if CR is greater than 0.10, the pairwise comparison is inconsistent, the matrix needs to be adjusted, and the values need to be modified.

The first step in calculating the overall consistency is to take the original matrix, that of the given inputs, and multiply it by the final relative priorities from the last eigenvector extraction step. Then it can sum the total values of each row of the new matrix. Third, the total values of each row will be divided by the value of the associated eigenvector Wi. Fourthly, it will be sufficient to average the results obtained in the previous steps. The result of this calculation is represented by λ max. At this stage, the coherence index (CI) is defined by equation (1).

$$IC = \frac{\lambda max - n}{\mathrm{n-1}} \qquad (1)$$

n: the number of comparison criteria

$$RC = \frac{IC}{\mathrm{RI}} \qquad (2)$$

The consistency ratio (CR) is, therefore, the ratio between CI and a random index derived by simulation (equation (2)).

Table.2: The random index RI

Number of Criteria : n	3	4	5	6	7	8	9	10	11
RI	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

4. Results and Discussion

4.1 Underground Cavity Detection

The geophysical survey results were interpreted to describe the particular structures that characterize the surface of the subsoil of the old city of Beni-Mellal, in particular, the detection of the location of the sewage network and underground cavities. Geophysical prospecting by radar offers excellent performance and a good spatial resolution. Measurements can be taken quickly, and it is possible to intervene in very narrow areas. The time required for the implementation and interpretation of other methods is much longer (Najine and al., 2006, El khamari and al., 2007).

Electrical tomography has also produced interesting results. The measurements show several electrically differentiated levels. A more important level, represented mainly by sands, gravels and conglomerates, and considered to be the environment hosting the majority of the cavities discovered in the old city (Najine and al., 2006, El khamari and al., 2007).

The results obtained clearly reveal the existence of underground cavities represented in the map in figure 4.

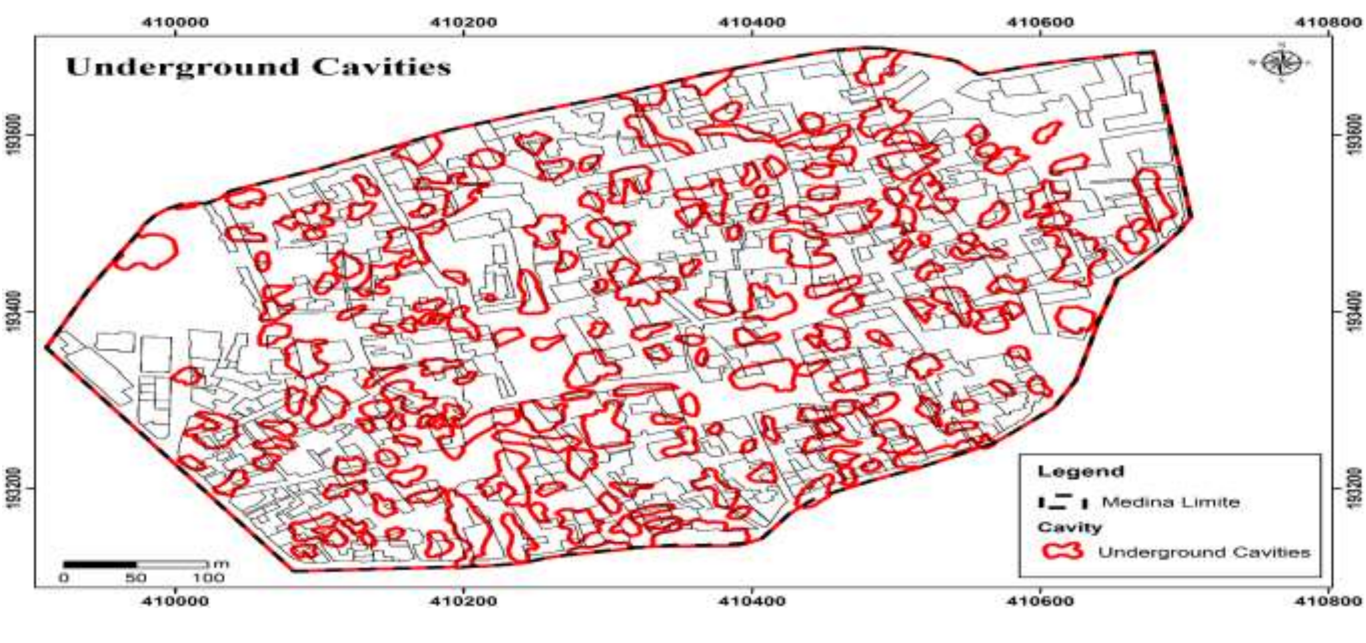

Fig.3: Map of underground cavities in the old city of Beni Méllal

4.2 Results of The Multi-Criteria Analysis

To determine the weights and scores of each parameter, the eigenvectors of the judgment matrices were calculated. The consistency of the judgements was assessed using the consistency ratio.

We have elaborated the class comparison matrices that relativize the behaviour of the classes in relation to each other, and we represent in the above tables the respective weights obtained for the parameters that were considered important for the elaboration of the cave-in vulnerability map.

In order to ensure the quality of the data obtained, the different matrices have been elaborated with the different classes of the same criterion and finally between the intrinsic and extrinsic decisive parameters. For all matrices, the respective consistency ratio (CR) was calculated, and, as recommended by SAATY (1991), only those with a CR value < 0.1 were retained.

Table.3: Calculation of the weighting of the building height criterion

	(A)	(B)	(C)	(D)	Wi
Building (3 Storey and more) (A)	0,60	0,66	0,54	0,44	0,56
Building (2 Storey) (B)	0,20	0,22	0,32	0,31	0,26
Building (1 Storey) (C)	0,12	0,07	0,11	0,19	0,12
Building (GF) (D)	0,08	0,04	0,04	0,06	0,06
RC	**0,04**				1,00

Table.4: Calculation of the weighting of the building condition criterion

	(I)	(J)	(K)	Wi
Low quality (I)	0,68	0,71	0,58	0,66
Medium quality (J)	0,22	0,24	0,33	0,26
Good quality (K)	0,10	0,06	0,08	0,08
RC	**0,02**			1,00

Table.5: Calculation of the weighting of the road criteria

	(F)	(G)	(H)	Wi
Avenue (C1) (F)	0,65	0,69	0,56	0,63
Main Street (C2) (G)	0,22	0,23	0,33	0,26
Secondary Street (C3) (H)	0,13	0,08	0,11	0,11
RC	**0,03**			1,00

Table.6: Calculation of the weighting of the land use criterion

	(I2)	(J2)	(K2)	(L2)	(M2)	Wi
Building (I2)	0,38	0,40	0,40	0,33	0,33	0,37
Green Spaces (J2)	0,19	0,20	0,27	0,22	0,17	0,21
Public places and Spaces (K2)	0,12	0,10	0,13	0,22	0,17	0,15
Road (L2)	0,12	0,10	0,07	0,11	0,17	0,11
Socio-economic area (M2)	0,19	0,20	0,13	0,11	0,17	0,16
RC	**0,03**					1,00

Table.7: Calculation of the weighting of the cavity depth criterion

	(A2)	(B2)	(C2)	(D2)	Wi
depth < 1m (A2)	0,60	0,66	0,54	0,44	0,56
depth (1m < P < 2m) (B2)	0,20	0,22	0,32	0,31	0,26
depth (2m < P < 3m) (C2)	0,12	0,07	0,11	0,19	0,12
depth (P > 3m) (D2)	0,08	0,04	0,04	0,06	0,06
RC	**0,04**				1,00

Table.8: Calculation of the weighting of the criterion Use of cavities

	(L)	(M)	(N)	(O)	(P)	(Q)	Wi
Craft activity (L)	0,32	0,40	0,35	0,26	0,28	0,28	0,31
Mine (M)	0,16	0,20	0,23	0,26	0,17	0,20	0,20
Storage (N)	0,10	0,10	0,12	0,13	0,17	0,16	0,13
Liquid waste (O)	0,32	0,20	0,23	0,26	0,28	0,28	0,26
Solid waste (P)	0,06	0,07	0,04	0,05	0,06	0,04	0,05
Vacuum (Q)	0,04	0,04	0,03	0,04	0,06	0,04	0,04
RC	**0,01**						1,00

Table.9: Calculation of the weighting of the soil lithology criterion

	(R)	(S)	(T)	(U)	Grès (V)	(W)	Wi
Rembali (R)	0,44	0,48	0,44	0,42	0,33	0,30	0,40
Conglomerate (S)	0,22	0,24	0,29	0,25	0,24	0,26	0,25
Poorly consolidated limestone (T)	0,14	0,12	0,15	0,17	0,24	0,26	0,18
Consolidated limestone (U)	0,09	0,08	0,07	0,08	0,10	0,11	0,09
Sandstone (V)	0,06	0,05	0,03	0,04	0,05	0,04	0,04
solid rock (W)	0,05	0,03	0,02	0,03	0,05	0,04	0,04
RC	**0,02**						1,00

Table.10: Calculation of the weighting of the criterion moisture and subsoil flow

	(E2)	(F2)	(G2)	(H2)	Wi
Ecoulement Sous terrains (E2)	0,52	0,53	0,55	0,43	0,51
Réseau d'assainissement (F2)	0,26	0,27	0,27	0,29	0,27
Humidité (moyenne à forte) (G2)	0,13	0,13	0,14	0,21	0,15
Humidité (Faible) (H2)	0,08	0,07	0,05	0,07	0,07
RC	**0,01**				1,00

When the matrices were completed, the weights (Wi) expressed by these matrices were then assigned to the different maps in raster format through the reclassification of the Spatial Analyst extension of ArcGis software.

4.3 Mapping of The Cave-In Vulnerability Map

Having defined the different classes and weights for each parameter mentioned through the hierarchical analysis method, it is then possible to calculate the index of susceptibility or vulnerability of cavities to collapse.
The results obtained allow the vulnerability to collapse of the underground cavities in the study area to be prioritized by developing weighting functions, which group all the issues at the same level of the hierarchical decomposition by assigning them weight according to their respective vulnerability.
For the first row of the hierarchical decomposition, the equation for calculating the overall vulnerability is as follows :

$$\text{Overall vulnerability} = 0.5 \times \text{Intrinsic Vul} + 0.5 \times \text{Extrinsic Vul} \quad (3)$$

This equation shows the dominance of intrinsic and extrinsic issues. They have the same importance of intervention in the collapse of cavities; however, the shares of intrinsic and extrinsic parameters are equivalent.
The equation for calculating the intrinsic vulnerability is as follows:

$$\text{Intrinsic vulnerability} = 0.070 \times \text{Vul lithology} + 0.505\times \text{Vul cavity depth} + 0.187 \times \text{Vul cavity use} + 0.187\times \text{Vul moisture} \quad (4)$$

The vulnerability function for extrinsic parameters is as follows:

$$\text{Extrinsic vulnerability} = 0.557 \times \text{Vul Building H} + 0.258\times \text{Vul Building condition} + 0.071 \times \text{Vul Road} + 0.112\times \text{Vul Land use} \quad (5)$$

Thus, the final formula for calculating vulnerability is as follows:

$$\text{Vulnerability} = (0.5\text{x } (0.070 \times \text{Vul lithology} + 0.505\times \text{Vul cavity depth} + 0.187 \times \text{Vul cavity use} + 0.187\times \text{Vul moisture})) + (0.5 \text{ x } (0.557 \times \text{Vul building} + 0.258 \times \text{Vul building condition} + 0.071 \times \text{Vul road} + 0.112 \times \text{Vul land use})) \quad (6)$$

The overall vulnerability function represented by equation (6) shows the importance of the cavity depth and building height parameters of vulnerability, which each account for 25% of the overall vulnerability.

Once the vulnerability assessment formula is established by covering criteria according to calculated relative weights, the construction of the cave collapse vulnerability map is resorted to using map algebra. The final vulnerability map will be the result of the overlay of the thematic maps, the method used is the Rating System RS.

The analysis of all these thematic maps shows that the areas with the highest
The analysis of all these thematic maps shows that the areas with the highest vulnerability to collapse are spread over the whole of the old medina where there are buildings with more than one floor and the depth of the cavity is less than 1m.

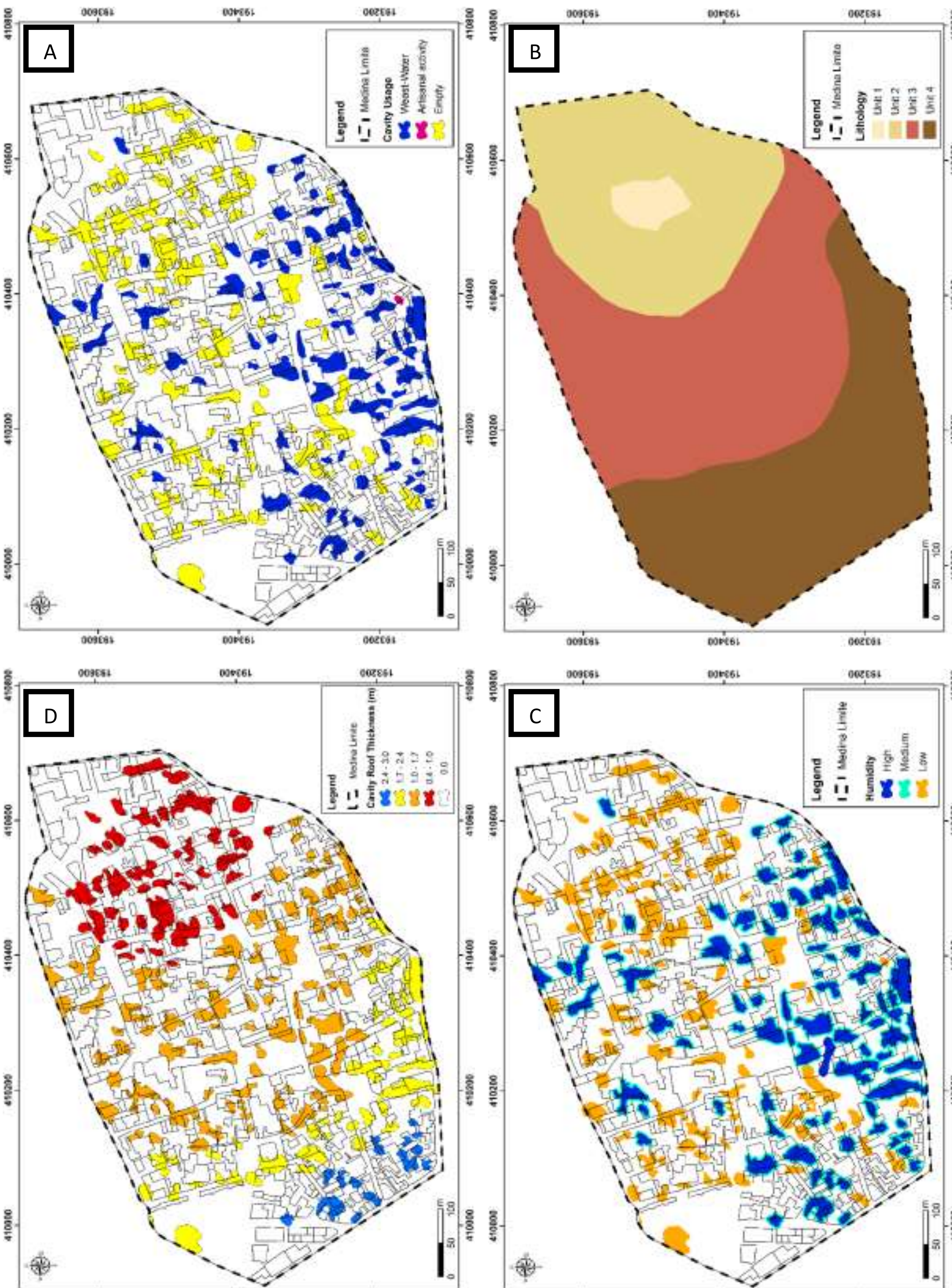
A
B
D
C
Legend
Cavity Usage
Artisanal activity
Empty
Lithology
Unit 1
Unit 2
Unit 3
Unit 4
Humidity
High
Medium
Low

Fig.

5. Classification maps of intrinsic criteria for building collapse vulnerability: A: use of the cavity, B: lithology, C: moisture, D: depth of the cavity.

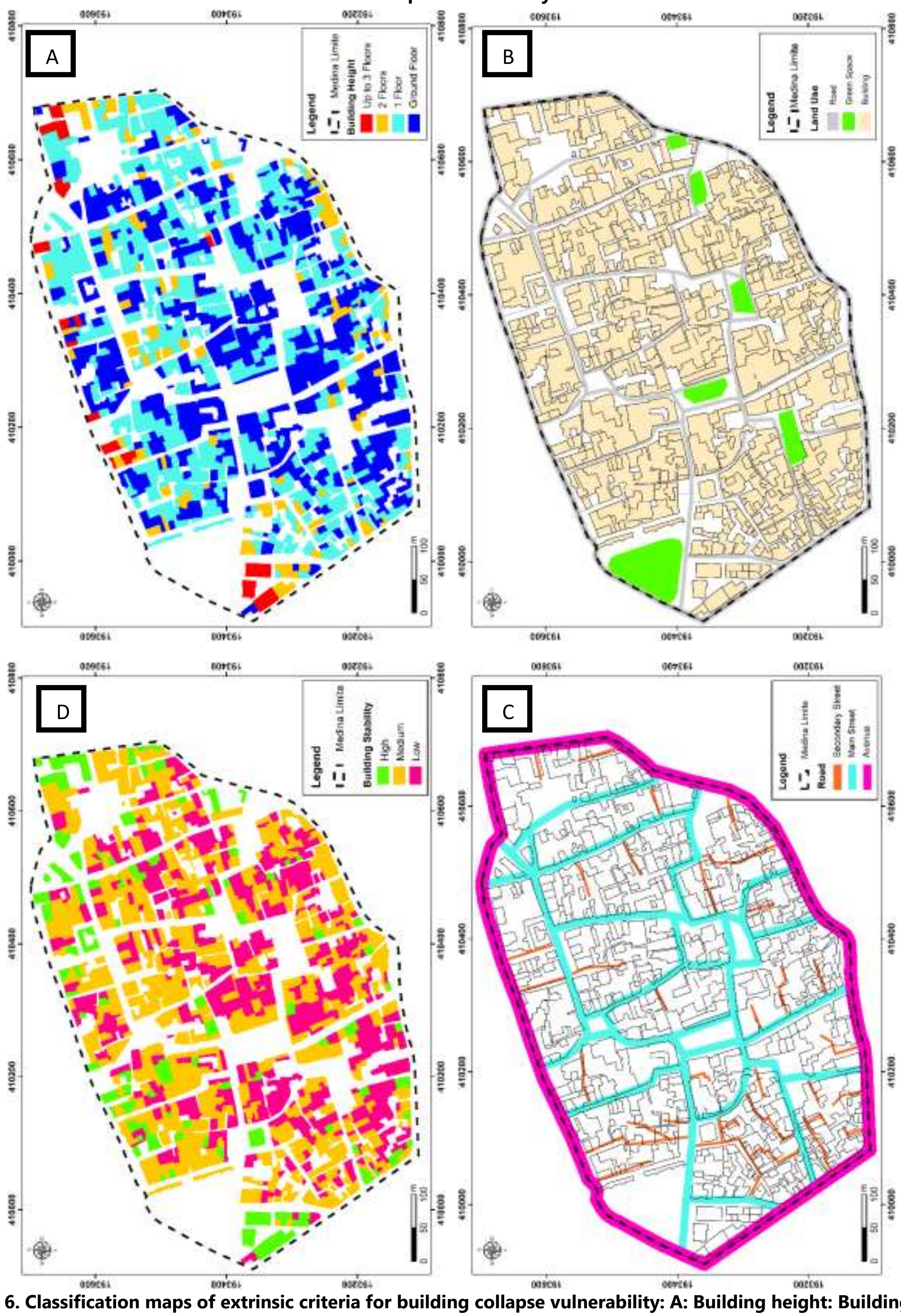

Fig. 6. Classification maps of extrinsic criteria for building collapse vulnerability: A: Building height: Building use, C: Roads, D: Building condition.

The most important vulnerability class is a low class, followed by the medium class. These two classes alternate, especially in the central and western part of the old town, where the lithology is generally conglomerate and limestone. As for the extreme vulnerability class, which highlights the areas threatened by collapse, it covers about 4% of the total surface area of the old town, the equivalent of 1.24 Ha, and is concentrated in the north-eastern zone where there are buildings with more than one floor and cavities with shallow depths of no more than 1 m.

The importance of the depth of the cavities in the assessment of the vulnerability to collapse is well marked in the results obtained. However, the parameter that also strongly influences this vulnerability is the lithology parameter. In fact, the analysis of this map shows that more than half of the areas of extreme and high vulnerability are found in sectors where the type of soil is mainly made up of very fragile materials and characterized by its low coherence and therefore presents real threats. The presence of a very fragile soil associated with a low depth of the cavity and a high degree of humidity linked mainly to an interesting anthropic activity on an infrastructure of poor quality would be a favourable condition to increase the vulnerability of cavities collapse in the old city.

The medium and low vulnerability classes, which alternate in the central and southern parts of the study area, covering almost 51% of the study area, are found in areas where the building height is limited to one floor with buildings of medium stability. Indeed, the analysis of this map shows that the low vulnerability zones are generally observed in the sectors where the soil type is made up of limestone, which are strong formations. The areas of medium vulnerability are generally found on the level of clay conglomerates with limestone, as can be seen in the central, northern and south-western parts.

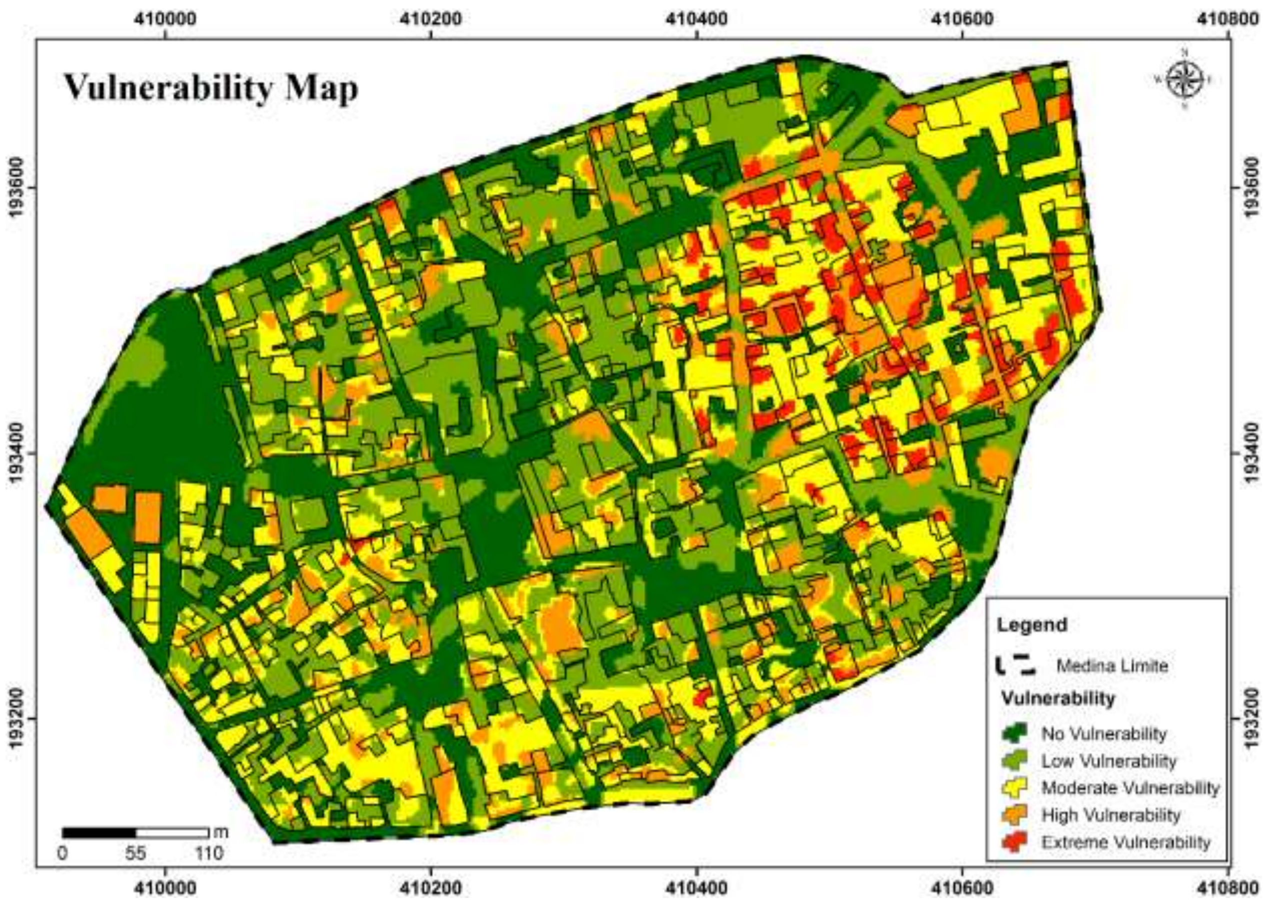

Fig. 7: Map of the vulnerability of cavities to collapse in the old city of Beni-Mellal.

5. Conclusion

The mapping of the vulnerability map carried out in this study allowed the different database elements to be processed using a Geographic Information System (GIS) under ArcGIS and thus to contribute to improving knowledge of the vulnerability of cavities to collapse.

The chosen method takes into account intrinsic and extrinsic elements to elaborate a global vulnerability index. This is quantified using GIS and then weighted using the Hierarchical Multi-criteria Method to obtain the Vulnerability calculation formula. The implementation of these functions in GIS provides a tool that is simple to use, flexible and allows for analytical integrations.

Multicriteria evaluation is a recommended method for this type of analysis because it offers the user the possibility to manage different map coverages related to the problem to be solved and finally to obtain a good result in a reduced time. The initial standardization of criteria maps by the Optimal Value Method is a widespread and functional technique, while the evaluation of concordance (by pair) and its introduction in the Analytical Hierarchy Method (AHP) allows the linear synthesis of criteria whose original source.

A validation of the results of the vulnerability method used should be carried out in the study area by establishing a comparison of the qualitative and quantitative results of the vulnerability with the pathological studies of the buildings surveyed.

Funding: This research received no external funding.
Conflicts of Interest: The authors declare no conflict of interest.

References

[1] Najine A., Jaffal M., Aifa T., Filahi M., Arioua A., Boukdir A., Andrieux P., and Rejiba F. (2006). Reconnaissance de cavités souterraines par tomographie électrique et radar géologique dans le centre-ville de Béni-Mellal (Maroc) ; *Bulletin des Laboratoires des Ponts et Chaussées*, n°260, 83-89.

[2] Abdessamad N, Mohmmed J, Mustapha F, Said B, Abdelkrim A, Kamal E, Pierre A, Mahjoub H, and Albert C. (2007): Détection et cartographie des cavités souterraines par ondes sismiques et imagerie électrique ; cas de la ville de Beni mellal (Maroc), *Geomagheb*, n°4, 107-112

[3] El khamari K., Najine A., Jaffal M., Khatach D., Himmi M., and Andrieux P. (2007). Application de la géophysique et du SIG pour la détection et la cartographie des cavités souterraines en milieu urbain : cas de la ville de Zaouit Ech Cheik (Maroc). n°260,109-110.

[4] White WB (1988). Geomorphology and hydrology of karst terrains. *Oxford Univ Press*, Oxford.

[5] Ford D, and Williams P (2007). Karst hydrogeology and geomorphology. *Wiley*, New York.

[6] Parise M, and Gunn J (2007). Natural and anthropogenic hazards in karst areas: recognition, analysis and mitigation. *Geol Soc*, London (sp publ 279).

[7] Gutierrez F (2010). Hazards associated with karst. In: Alcantara-Ayala I, Goudie AS (eds) Geomorphological hazards and disaster prevention. *Cambridge Univ Press*, England, 161–176.

[8] Parise M (2010). Hazards in karst. In: Bonacci O (ed) Proceedings of the international inter disc scientific conferences on ''Sustainability of the karst environment. Dinaric karst and other karst regions'', *Plitvice lakes* (Croatia), 23–26 Sept. 2009, *IHPUNESCO, Series on Groundwater* 2, 155–162.

[9] De Waele J, Gutierrez F, Parise M, and Plan L (2011). Geomorphology and natural hazards in karst areas: *a review*. *Geomorphology* 134(1–2):1–8.

[10] Waltham T, and Lu Z (2007). Natural and anthropogenic rock collapse over open caves. In: Parise M, Gunn J (eds) Natural and anthropogenic hazards in karst areas: recognition, analysis, and mitigation. *Geol Soc*, London, pp 13–21(sp publ 279)

[11] Parise M (2008). Rock failures in karst. In: Cheng Z, Zhang J, Li Z, Wu F, Ho K (eds) Proceedings of the 10th international symposium on landslides, Xi'an (China), June 30–July 4, 2008. *Landslides and engineered slopes*, vol 1, 275–280

[12] Zhou W, and Beck BF (2011). Engineering issues in karst. In: van Beynen P (ed) *Karst management*. *Springer*, Berlin, pp 9–45

[13] Waltham T, Bell F, and Culshaw M (2005). Sinkholes and subsidence: karst and cavernous rocks in engineering and construction. *Springer*, Berlin, 382 p

[14] Essahlaoui A. (2000). Contribution à la reconnaissance des formations aquifères dans le bassin de Meknès-Fès (Maroc): *Thèse de Doctorat Es-Sciences Appliquées, Ecole Mohammadia d'ingénieurs*, Rabat, 258.

[15] SINAN M. (2000). Utilisation des SIG pour la comparaison des méthodes d'évaluation de la vulnérabilité des nappes à la pollution. Application à la nappe du Haouz de Marrakech, *Atelier international sur l'utilisation des techniques spatiales pour le développement durable, École Hassania des travaux publics*, Rabat, Maroc, 12.

[16] Aller L., Bennet T., Lehr J.H., Petty R.J. and Hacket G. (1987). DRASTIC: A standardized system for evaluating groundwater pollution using hydrological settings. *Prepared by the National Water Well Association for the US Environmental Protection Agency Report* (EPA/600/2-87/035).

[17] Pételet-Giraud E. (2000). RISKE : Méthode d'évaluation multicritère de la cartographie de la vulnérabilité des aquifères karstiques – Applications aux systèmes des Fontanilles et Cent-Fonts (Hérault, France), *Hydrogéologie* – volume 4. 71-88.

[18] Ribeiro L. (2000). Desenvolvimento de um índice para avaliar a susceptibilidade dos aquíferos à contaminação. *Nota interna, (nào publicada)*, ERSHA-CVRM, 8.

[19] Sotomikova, R. and Vrba, J. (1987). Some remarks on the concept of vulnerability maps. In the vulnerability of soil and groundwater to pollutants (W. Van Duijvenbooden and H.G. Van Waegeningh, eds.). TNO Comite on *Hydrological Research, The Hague, Proceedings and Information* No. 38 471-476.

[20] AGEOS et INRS-Eau. (1996). Développement d'outils pour la gestion intégrée des usages de la ressource- eau souterraine et application à la région hydrogéologique Nord de Montréal. EV ARISK : Démonstration de l'applicabilité. *Rapport scientifique annexe au rapport d'activité*

[21] Al-Fares W., Bakalowicz M., Albouy Y., Vouillamoz J.-M., Dukhan M., Toe G., and Guerin R. (2001). Contribution de la géophysique à l'étude d'un aquifère karstique - Exemple: le site karstique du Lamalou, *3èmeColloque GEOFCAN*, Orléans 25-26 septembre.

[22] Azemard., P JL Garciaz (2001). Recherche des karstifications sous la plaque-forme du TGV Méditerrannée, *Actes Journ. Scient. Et Techn. Radar*, Nantes, France, mai, 4.
[23] [23] Casas A., Lazaro R., Vilas M., and Busquet E. (1996). Détection des cavités karstiques au sol radar pénétrant dans différents environnements en Espagne. *Actes du 6eme International conferance on Groud Penetrating Radar.Jaoan*
[24] Deng S., Zuo Z., and Wang H. (1994). L'application d'un radar pénétrant le sol à la détection de failles et cavités peu profondes. *Actes du 5eConférence internationale sur le terrain Radar pénétrant*, Ontario, Canada, 1115–1120.
[25] Deceuster J., and Kaufmann O. (2003). Application des tomographies en résistivité électrique 3D à la reconnaissance de zones karstifiées, Belgique, *4èmeColloque GEOFCAN*, Paris, 23-24 septembre.
[26] Lagabrielle R., Grandsert P., Millereau S., and Nebieridze S. (2003). Performances comparées de méthodes géophysiques pour la détection de cavités dans les limons. Exemple de lagare d'essais de la SNCF sur la LGV Nord, *Actes Journ. Scient. Et Techn. Radar*, Nantes, France, octobre,
[27] Miehe JM, Feuga B., and Vachette C. (2003). Détection d'une cavité remplie de saumure par imagerie électrique, *4èmeColloque GEOFCAN*, Paris.
[28] Roth MJS, Mackey JR, Mackey C., and Nyquist JE. (2002). Une étude de cas sur la fiabilité des tests de résistivité de la terre à plusieurs électrodes pour les études géotechniques dans les terrains karstiques, *Engineering Geology* 65, 225-232.
[29] Edwards LS. (1977). A modified pseudosection for resistivity and induced polarization. *Geophysics* 42:1020-1036.
[30] Leproux D., Bitri A. et Grandjean G. (2000). Underground cavities detection waves.*JEEg*,4:33-53.
[31] Rajji Ab., Najine Ab., Wafik Am., Benmoussa Am. (2022). Building height estimation from high-resolution satellite images, *International Journal of Innovation and Applied Studies*, pp. 268-281
[32] Saaty, T.L.and G. V. Luis. (2006). Decision making with the analytic network process. New York. *Springer Science and Business Media LLC*.
[33] Ramos, A., L. Cunha, and P. P. Cunha. (2014). Application de la Méthode de l'Analyse Multicritère Hiérarchique à l'étude des glissements de terrain dans la région littorale du centre du Portugal: (a) Figueira da Foz-Nazaré. *International Journal of Tropical Geology, Geography and Ecology*, 38(1): 33–44.
[34] Griot C., Sauvagnargues-Lesage S., Dusserre G. Pearson D., Picheral H. (2002). Vulnérabilité face aux risques liés au transport de matières dangereuses : Apports de deux méthodes multicritères d'aide à la decision, In : *Déchets, Sciences et Technique* n° 27, 35-46.
[35] Feiziziadeh, B., Jankowski, P., & Blaschke, T. (2013). Une approche spatialement explicite pour l'analyse de sensibilité et d'incertitude de la cartographie SIG-Multicritères de susceptibilité aux glissements de terrain. *GIScience*, Vol 157, 157 -164.
[36] Saaty, T. L. (1991) - Método de Análise Hierárquica. *São Paulo, McGraw-Hill, Makron*. 367.
[37] Saaty TL. (1977). A scaling method for priorities in hierarchical structures. *J Math Psychol* 15: 234–281.