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GIS with Fuzzy Clustering Method for the Classification of Road Network Vulnerability

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ABSTRACT

Efficiency measures in a network focus on the assessment of the vulnerability of the road network in its different forms and about its classification, which is very little studied. In the absence of specific criteria for road vulnerability assessment research, it is necessary to find an appropriate method for defining the classification of vulnerabilities under a GIS platform in order to improve the monitoring and management of the vulnerability traffic (requests, costs, flows and behaviours). In this paper, a fuzzy classification methodology is implemented in a GIS environment to define the road network vulnerability categories. We have also presented a method for calibrating the availability of such a classification. The case study, using this methodology, is being implemented in Tlemcen; a city located in the northwest of Algeria. The vulnerability of the road transport system is an accessibility problem that can be classified into three categories: severe vulnerability level, medium vulnerability level and low vulnerability level. Reliability and vulnerability are related concepts; most roads are classified in the acceptable level of vulnerability so that the city's road network vulnerability from this study can be generally defined as the average level of vulnerability.

KEYWORDS: Road network, Vulnerability level, GIS, Fuzzy clustering method, Classification.

INTRODUCTION

Modern society relies upon the collection of systems and institutions known as the infrastructure to support the welfare and the living standard of people (Jenelius et al., 2015).

Road network vulnerability analysis can be defined as the study of potential degradations of the road transport system and their impacts on society, modeling the road infrastructure as a network with links (road segments) and nodes (intersections). Moreover, research interest in this topic has grown in the early 2000s as part of a broader focus on critical infrastructure protection. Several recent natural or anthropogenic disasters have made people aware of the fact that society is vulnerable to the disruption of infrastructure systems (Leng et al., 2018). It was recognized by some researchers that new quantitative methods for assessing severe consequences and disruptions of the road transport system were needed (Berdica, 2002). Furthermore, accessibility is understood as 'ease of reaching' and concerns the opportunity provided by the transport system for people to take part in a particular activity and/or a set of activities from a given location (Al-Kheder et al., 2016). Therefore, this case best describes the performance of the road transportation system. The serviceability of a link/route/road network describes the possibility to use that link/route/road network during a given serviceability (Rupi et al., 2015).

Reducing vulnerability can hence be regarded as reducing the risks involved in various incidents, meaning that the probability of a bridge failure, for example, can be reduced; or adopting a perspective implying a reduction of the resulting consequences when failure occurs (Al-Farajat et al., 2016).

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Subsequent vulnerability research has embraced a rich exploration of pictures, metrics and methods. Several papers have proposed frameworks for metrics for evaluating road network vulnerability (Chen et al., 2007; Jenelius et al., 2006; Memberacedltman-Hall & Scott, 2010; Taylor & Susilawati, 2012; Balijepalli & Oppong, 2014; Rupi et al., 2015).

The classification of road network vulnerability is presented in this study; it is very important to classify a large number of heterogeneous objects in minimum groups like the links of the road network, because it is an adequate method for analyzing road network properties and providing new road planning. At the same time, it contributes to natural disaster prevention and the reduction of daily incidents. Thus, it is significant to select the right indicators to broaden this form of vulnerability and develop them.

However, the factors which influence the displacements in a road network are integrated into the three aspects of vulnerability (material, structural and functional) (Gleyze, 2005) from which the efficiency of the road system is measured in terms of fluidity, the conditions of transport and the reduction of the vulnerability generated by traffic (Husdal et al., 2004; Anass et al., 2016).

This research is basically about vulnerability, which is influenced by the three aspects quoted above deduced by the traffic performance (Gleyze, 2005). We will combine all supply factors (material, structure) and demand (functional, performance) to make a classification based on fuzzy logic. The latter can make similar objects in the same group and different objects in other groups. Vulnerability analysis methods can be useful in improving vulnerable links with ordinary and extraordinary maintenance investments and appropriate management strategies. A fuzzy classification method can be inaugurated here. Thus, this research aims to determine the level of vulnerability and the optimal number of categories to divide different links into different appropriate groups.

According to several researchers, the vulnerability concept still lacks a consensus on its definition, where the definition depends on the application context. Berdica (2002) defined “vulnerability” as “a susceptibility to incidents that can result in considerable reductions in road-network serviceability”. This situation is also characterized by high congestion levels which cause delays, a dense road network and a quantifiable probability of network degradation. In this paper, we use fuzzy logic and GIS platform to clad with road-network vulnerability as: "a vulnerability to events (congestion, traffic, … etc.), which can lead to considerable reductions in the functionality of this road network". The road network is vulnerable when it does not respond to the displacement demand of the population or/and when its infrastructure is degraded.

MANAGEMENT OF VULNERABILITY TRAFFIC

In the logic of transport, we always seek to move at a lower cost with good travel conditions. Therefore, the goal is to solve the problems of population movement by minimizing the possible risks that can reach the transport infrastructure. Hence, a better understanding of the performance of the transport network during disturbances is of great importance (Khalilzadeh and Banihashemi, 2020; Szymula et al., 2020).

The management of transport network vulnerability, following major disturbances which can cause the dysfunction of the road network, can be summarized in three aspects (material, structural and functional).

The high travel demand is concentrated on the material aspect of the road network and the cost of transport. Intense traffic is represented in the functional aspect of the transport network and ultimately it is the behaviour of the road network that is defined by its structural aspect.

ASSESSMENT INDICATORS OF ROAD NETWORK VULNERABILITY

Hardware Travel Dependability

It is considered as a material damage to a network that can be easily and economically quantified in post-disaster assessments. It is sufficient to estimate the damage rate; the latter measures the potential deterioration of the infrastructure’s material value. Hardware vulnerability is evaluated by centrality indicators (S-D) as (Gleyze, 2005):

$$\frac{\sum_{relationk \in E} Pk.POkDk(Ai)}{\sum_{relationk \in E} Pk} \quad (1)$$

where:

O_k, D_k and P_k: represent the origin, destination and weight of the relation k.

Ai: the edge for the set E of relations.

$P_{Ok}, {}_{Dk}$: represents the shortest path between all the components that realize the relation k.

Structural Road Network Vulnerability

Structure is defined as a performance structure which is evaluated by performance parameters (Sl) described by the following relation (Wu, J., 2008):

$$Sl = \alpha 1 Fwl + \alpha 2 Bwl \quad (2)$$

where:

α1+ α2 =1; are coefficients.

Fwl: flow through link l.

Bwl: betweenness of link l.

We adopt for Equation (2) α1 = 0.45 and α2 = 0.55 to find the values of (Sl) arranged in a decreasing way to deduce the structural performance of our case study of the road network.

However, the degrees of viability can be mapped by parameterizing the target objects (links).

Functional Road Network Vulnerability

According to (Wu, J., 2008), the essential indicator is the one based on the fail link rate (LAR) and we call it "Improved Failure Link Rate (ILAR)". The LAR of a link in the road network is defined as the ratio between the failed links caused by its break and the total number of links in the entire road network. Therefore, the relationship between faulty link capacity and total capacity is developed as a solution to the problem in this paper and the Improved Failure Link Rate (ILAR) is defined as follows (Wu, J., 2008):

$$ILAR = l\,(AF / A) + (1-\beta)(KF / K) \quad (3)$$

where:

AF is the number of failing links.

A is the number of the links.

KF is the capacity of failing links.

K is the sum of all the links' capacity.

β is the weight of LAR, where 0< β <1.

Another indicator is the S-T indicator for the performance vulnerability indicators that explain performance/ efficiency measures and clarify the network relationships. It defines the shortest path length between two nodes (origin-destination) (Nagurney et al., 2008).

FUZZY LOGIC & APPLICATION

Fuzzy logic was originally proposed by Professor Zadeh [L.A. Zadeh, 1965], who introduced the concept of a fuzzy set which comes with the idea that complex systems cannot be solved by classical mathematics, because they are not "demonstrative" to distinguish input- exit in a situation of imprecision and uncertainty.

The fuzzy logic method has been used in many types of research areas; for example, economy (for example [Yanhu Chenet et al., 2014], [Meier, A. et al., 2019]), electronics (for example [Ozkop, E. et al., 2015], [Upadhyay, R. et al., 2016]), hydraulics (for example [Sihag, P., 2018], [Sihag, P. et al., 2017]), computer science (for example [Boukadoum, A. et al., 2017], [Mufadhol, M. et al., 2019]), technology (for example [Cao, Y. et al., 2018], [Liu, C. et al., 2019]), … etc. Among its advantages, we find:

- Ease of establishment.
- Solution of complex multivariate problems.
- Robustness toward uncertainties.
- Possibility of integrating expert knowledge.
- Self-adaptive control possibilities to process variations.

It also has disadvantages; the most encountered are:

- Empirical adjustment.
- Closed-loops on expertise.
- There is no general theory starting that the loop closely characterizes closedness.

Several studies have created a technical decision to support a system based on fuzzy logic and the rule-based model to determine different classes of vulnerability; this decision can generate membership functions using surveys.

METHODOLOGY

Clustering analysis gives an overview of similar data groups, where the degree of association is strong between the members of the same cluster and weak between the members in the different clusters to divide vulnerable roads in a road network. The fuzzy average algorithm (Bezdek et al., 1984; Bezdek et al., 1999) is adopted to be implemented under a GIS environment to divide objects into different groups. The main objective of this algorithm is to ensure the similarity of the elements in the same group and the heterogeneity in the elements of different groups which are as distinct as possible. The method is described in the following diagram;

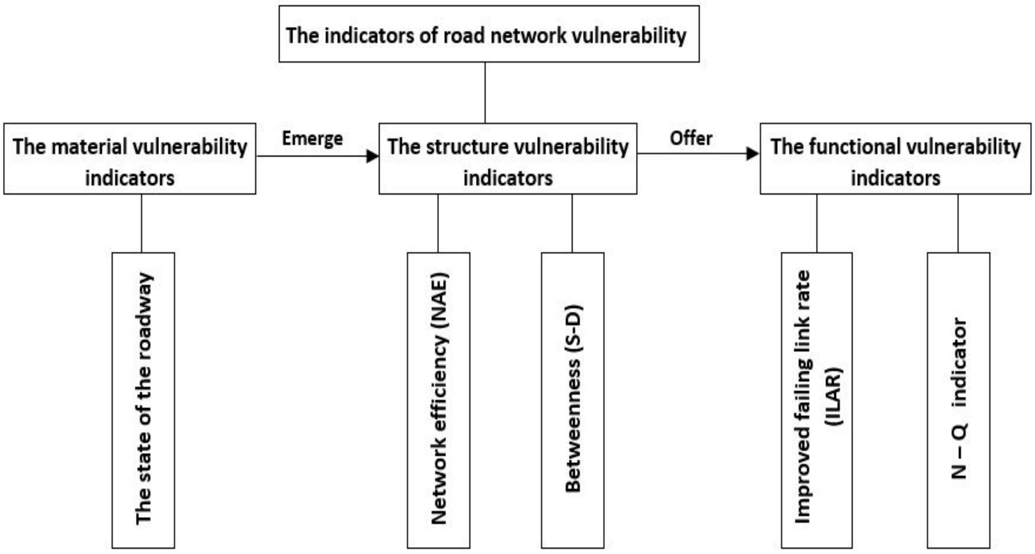

Figure (1): Classification assessment indicators of road network vulnerability

where:

NAE-measure (Lin, J. et al., 2013):

$$E(G) = \frac{1}{n(n-1)} \sum_{i \neq j \in G} \frac{1}{d_{ij}} \quad (4)$$

where:

n: number of nodes.

d_{ij}: the shortest path length between node i and node j.

N-Q measure (Lin, J. et al., 2013):

$$\varepsilon(G,d) = \frac{\sum_{\omega \epsilon w} \frac{d_{\omega}}{\lambda \omega}}{n_{\omega}} \quad (5)$$

where:

n: the number of O/D pairs in the network.

$\lambda\omega$: the minimum equilibrium travel cost (or time) associatedted with the O/D pair ω.

$$X = [x_{ij}]_{nxm} \quad (6)$$

where x_{ij} is the number value in i^{th} row and j^{th} column; i=1,2,…,n j=1,2,…,m.

The indicators of the sample must be standardized to compare them; therefore, the components of the characteristic matrix must be normalized as described in Equation (7).

$$r_{ij}=(x_{ij}-minim(x_j))/(maxim(x_j)-minim(x_j)) \quad (7)$$

the target equation for fuzzy C-means is (Deng, Wen-Qian et al., 2016):

$$\text{Arg min} \sum_{i=1}^{N} \sum_{k=1}^{K} u_{ki}^{m} \|xi - vk\|^2$$

where:

$m \in (1, \infty)$ is the fuzzy weighting exponent upon the membership and m = 2 generally. $\|xi - vk\|^2$ is the Euclidean distance between point xi and cluster center vk and uki is the degree of membership of point xi in cluster k.

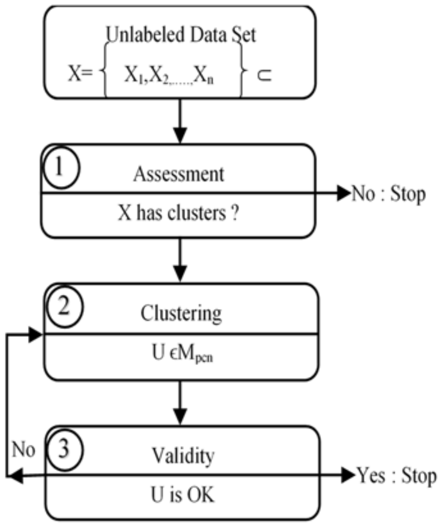

Figure (2): Cluster analysis

$$u_{ij} = \left(\sum_{j=1}^{c}\left(\frac{d_{ik}}{d_{jk}}\right)^{2/(m-1)}\right)^{-1}; \quad 1 \le k \le N; 1 \le i \le c$$

and:

$$cj = \left(\frac{\sum_{i=1}^{k} u_{ij}^{m} v_i}{\sum_{i=1}^{k} u_{ij}^{m}}\right) \quad (8)$$

The iteration process continues unless the maximum $[u_{ij}^{p+1} - u_{ij}^{p}] < \varepsilon$, where ε is the termination criterion between 0 and 1 and p is the iteration step.

CASE STUDY

Our study is about the road network of Tlemcen city in the northwest of Algeria. The road network is ranked into four categories. We loaded the road network of Tlemcen city presented by 593 nodes (localities) and 878 links (roads), using the MapInfo and MapBasic software. The network categories are differentiated by four colours: red for national roads, yellow for city roads, green for communal roads and magenta for secondary roads (Figure 3).

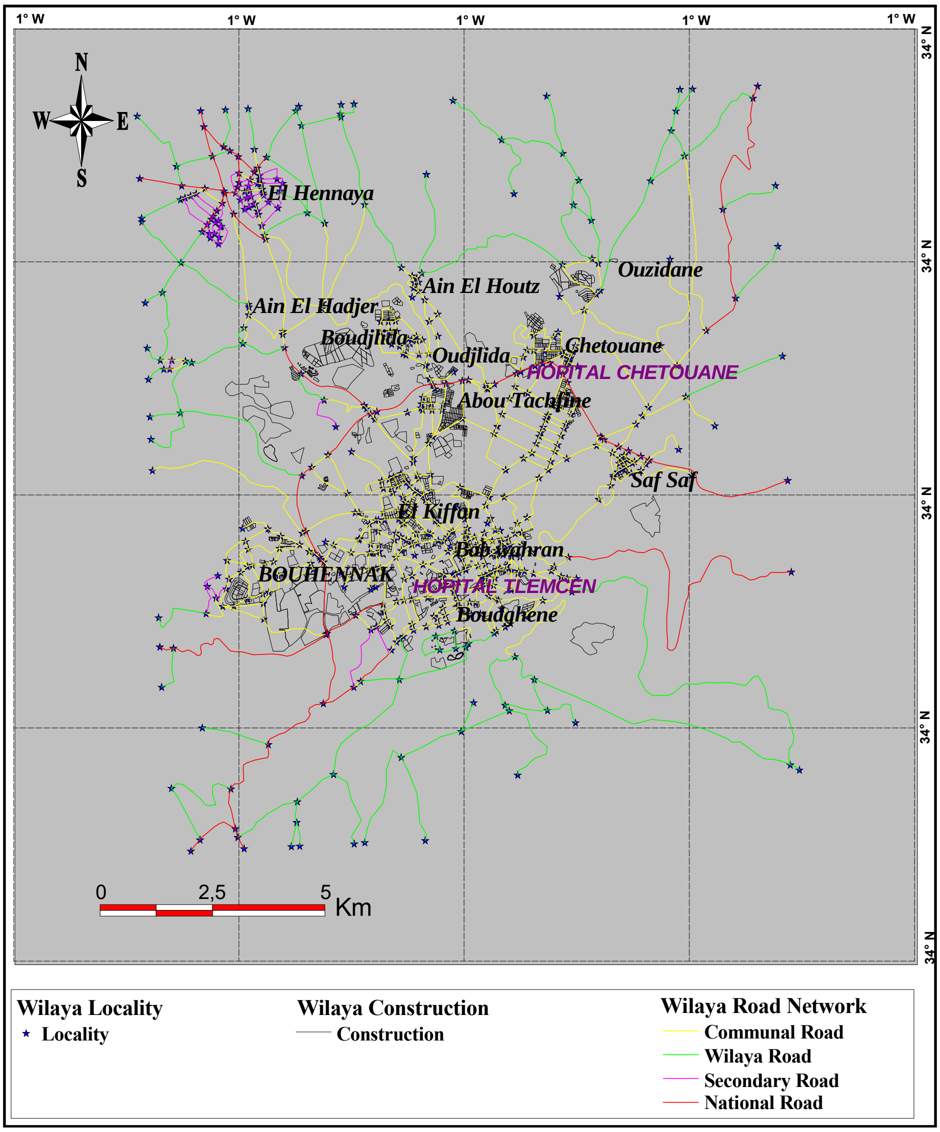

Figure (3): The structural map of the road network of Tlemcen

In urban road networks, efforts should be made to avoid congestions on some key roads and intersections; not only because more vehicles are involved, but also because they block connections among important zones.

The map of the urban road network of Tlemcen city provides information on the most vulnerable trunks following very heavy congestion and road development in each region (A.N.A.T., 2017).

By importing the recommended driving path into GIS, we can know how many expected driving routes pass through a certain road section or intersection. Thus, we can get betweenness values (BV) (Figure 4) (Xue et al., 2010; Goh et al., 2003) of each road section as well as intersections and hence conduct the analysis.

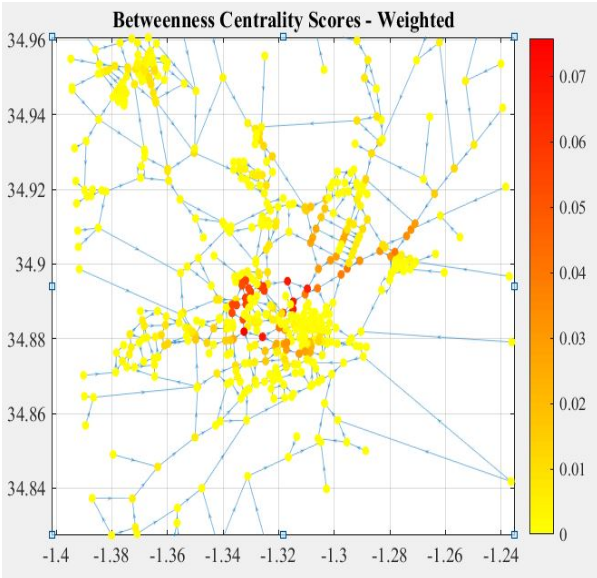

Figure (4): Tlemcen city road network betweenness values

The concept of vulnerability initiated at Tlemcen road network is more strongly related to the consequences of a link failure, whatever the probability of failure and in other cases, statistically a broken link is likely little, but the negative social and economic impacts on the community of this city may be quite significant to explore major problems requiring corrective actions (Taylor et al., 2007; Yohannes et al., 2015).

The map made in a GIS environment (Figure 5) shows the degree of vulnerability of each segment of the road network in the city of Tlemcen as a result of a vulnerability assessment carried out based on field surveys.

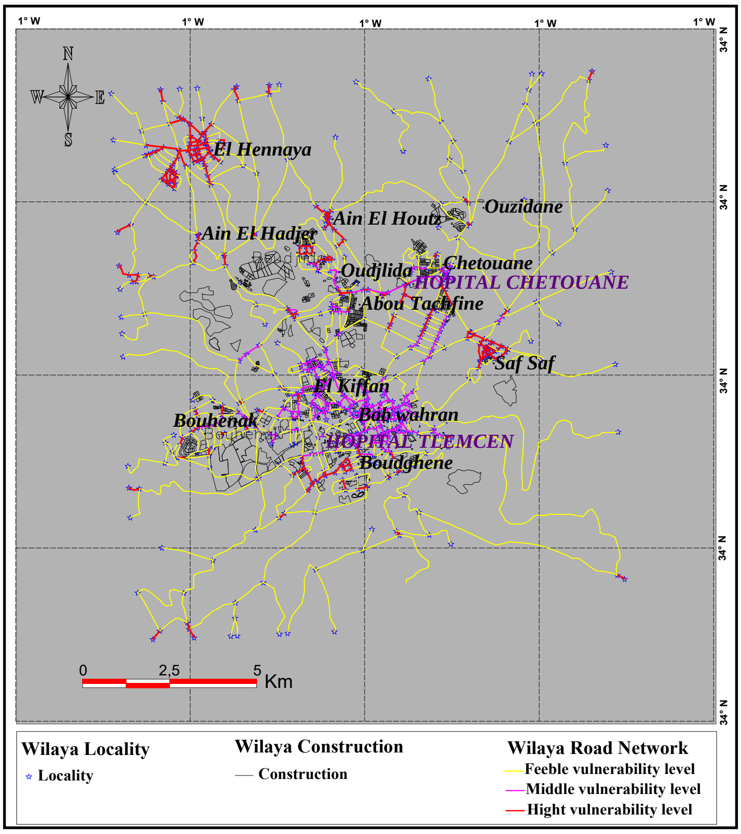

Figure (5): Degrees of vulnerability of the Tlemcen city road network

SIMULATION AND RESULTS

As far as simulation and results are concerned, we tried to find all the vulnerable link indicators defined previously, which were influenced by the distribution of traffic flows. These links were determined by assigning and removing each segment to have definitive values. The default links were selected and their numbers and capabilities were then calculated. Finally, the values of functional vulnerability of the road network were obtained (Scott et al., 2006).

The duration of each path is calculated and the vulnerability performance indicators are calculated accordingly (Guo, Xiang Yang et al., 2014).

In addition, the values of the indicators should be standardized for a better comparison between the segments Table 1 represents these indicators.

Table 1. The standardized indicator values for some target links

ID	NAE	NQ	ILAR	BETWEENNESS
835	0,056	0,445	0,640	0,009
836	0,812	1,000	0,640	0,008
837	0,217	1,000	0,640	0,040
838	0,113	0,907	0,640	0,001
839	0,244	1,000	0,640	0,003
840	0,175	1,000	0,640	0,001
841	0,141	1,000	0,640	0,007
842	0,101	0,812	0,640	0,057
843	0,040	0,323	0,640	0,002
844	0,153	1,000	0,640	0,009
845	0,947	1,000	0,640	0,007
846	0,035	0,281	0,640	0,016
847	0,076	0,607	0,640	0,002
848	0,098	0,787	0,640	0,006
849	0,964	1,000	0,640	0,007
850	0,056	0,449	0,640	0,007
851	0,828	1,000	0,640	0,006
852	0,074	0,588	0,640	0,002
853	0,284	1,000	0,640	0,001
854	0,482	1,000	0,640	0,001
855	0,127	1,000	0,640	0,002
ID	**NAE**	**NQ**	**ILAR**	**BETWEENESS**
856	0,139	1,000	0,640	0,001
857	0,130	1,000	0,640	0,014
858	0,567	1,000	0,640	0,001
859	0,108	0,864	0,640	0,009
860	0,036	0,286	0,640	0,001
861	1,000	9,120	0,640	0,009
862	0,039	0,309	0,640	0,001
863	0,143	1,000	0,640	0,008
864	0,040	0,322	0,640	0,001
865	0,172	1,000	0,640	0,004
866	0,177	1,000	0,640	0,002
867	0,609	1,000	0,640	0,007
868	0,384	1,000	0,640	0,064
869	0,015	0,118	0,640	0,002
870	0,519	1,000	0,640	0,002
871	0,079	0,634	0,640	0,008
872	0,256	1,000	0,640	0,016
873	0,031	0,249	0,640	0,008
874	0,120	0,959	0,640	0,007
875	0,262	1,000	0,640	0,014
876	0,352	1,000	0,640	0,001
877	0,353	1,000	0,640	0,001
878	0,030	0,243	0,640	0,006

The exploration of vulnerability degrees of the different segments of the road network of the Tlemcen city is based on a combination between the different maps drawn up for the different indicators used and cited previously. These maps are presented as follows:

Map of Figure 6 is deduced from the NAE indicator.

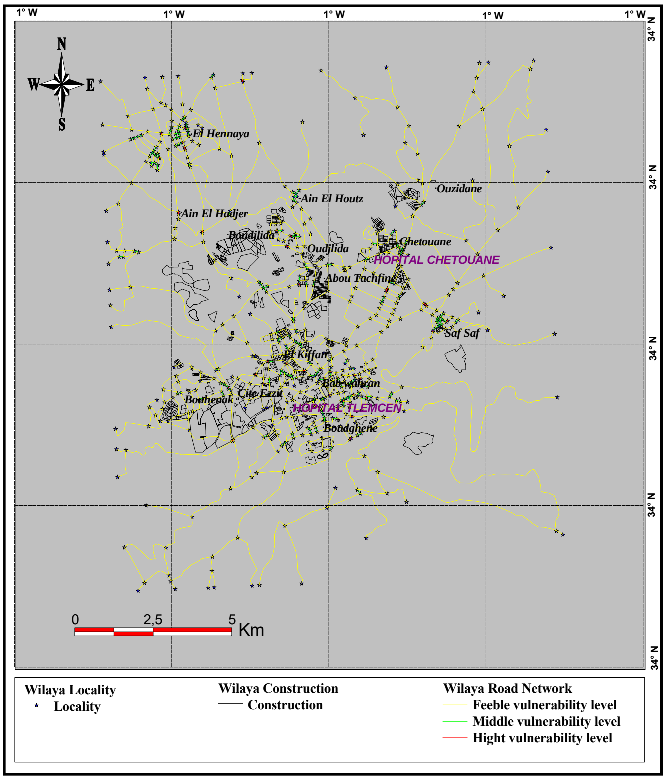

Figure (6): Degrees of road network vulnerability based on NAE indicator

Map of Figure 7 is deduced from the NQ indicator.

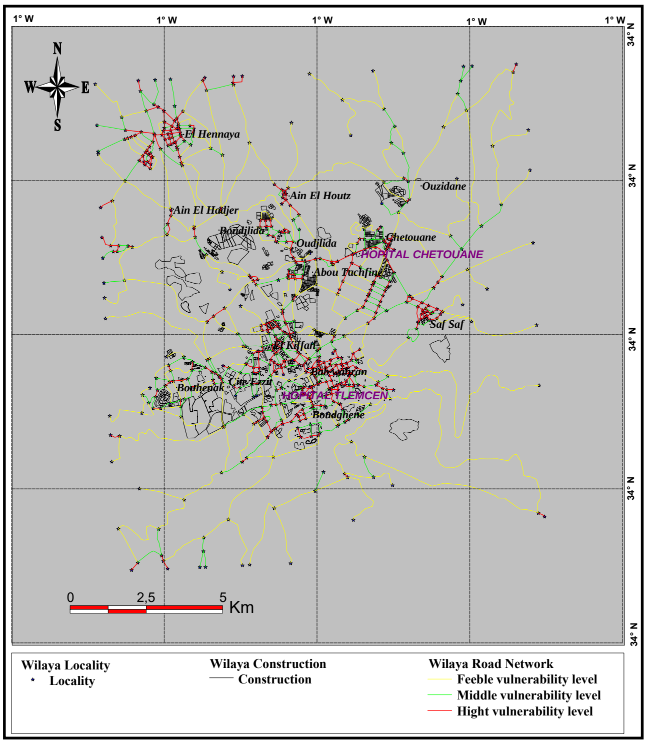

Figure (7):Degrees of road network vulnerability based on NQ indicator

Map of Figure 8 is deduced from the ILAR indicator.

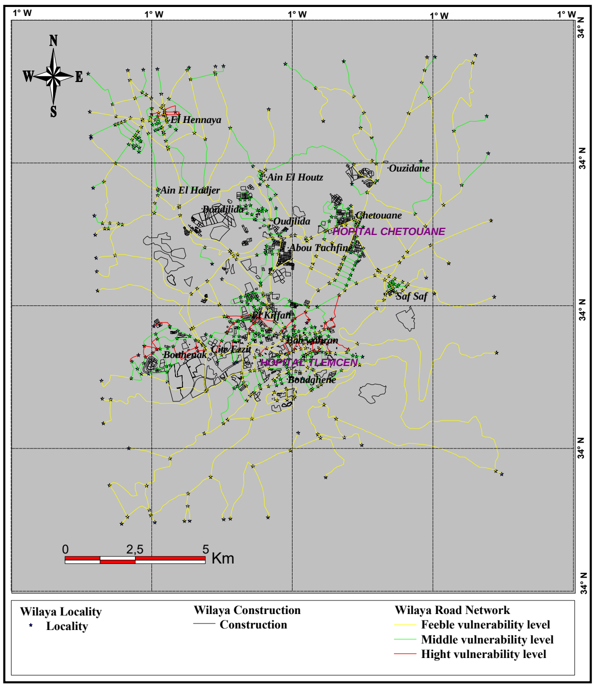

Figure (8):Degrees of road network vulnerability based on ILAR indicator

The last indicator is "betweenness" which represents the load supported by the various nodes which form the segments of the road network of the Tlemcen city and is presented in the map of Figure 4.

Based on the optimal number of clusters validated by 3levels, the membership degree is then calculated according to the Fuzzy Clustering Method (FCM). By looking for the degree of belonging of each segment of the road network, we obtained the characteristic value of the category, which makes it possible to attribute the vulnerability of the links in the district in three levels: (1) a low level of vulnerability, (2) an average level of vulnerability and (3) a severe level of vulnerability. The levels and proportions of vulnerability of the city road network can then be obtained, as shown in Table 1. The rate of vulnerability can then be calculated according to these levels: severe, average and low (Jun Shi et al., 2008).

According to the statistics made on different vulnerable trunks on the road network of Tlemcen city only at the three levels mentioned before, the following results were obtained:

Low vulnerability level .... 44.42%.

Average vulnerability level .... 47.38%.

Severe vulnerability level .... 08.20%.

The map in Figure 9 shows the results of vulnerability levels for the Tlemcen road network:

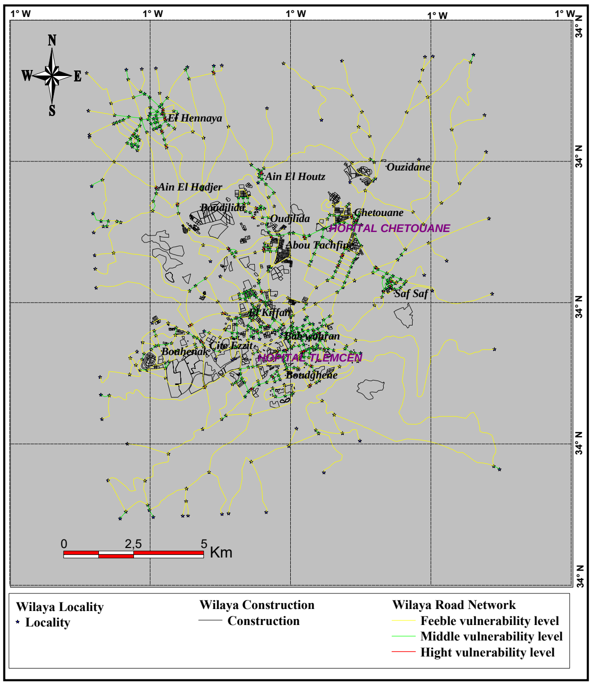

Figure (9): Map of vulnerability levels for the sections of the Tlemcen city road network

INTERPRETATION

Recent works made it possible to determine the level of vulnerability of the links of the Tlemcen road network illustrated in Figure 9 to explore the network for each level of vulnerability, taking into account the absence of a link as well as the possible demand for displacement.

This study was carried out by using the Fuzzy Clustering Method (FCM) (Mohammadrezapour et al., 2018) to classify the road network of Tlemcen, by using the parameters that define the vulnerability in terms of three aspects: material vulnerability, structural vulnerability and functional vulnerability and for the important measure for each link (route). The two maps in Figures 5 and 9 represent the levels of vulnerability. Only the first is deduced through a simulation of the traffic, delays, flow and surveys conducted on the ground, while the second is the fruit of our fuzzy C-means algorithm-based research, integrated into a GIS environment to represent a map of vulnerability. At the end of this approach, we have obtained the desired ranking for all routes in the network, in the ascending order of gravity.

Figure 10 summarizes the statistics of this road network according to three degrees of vulnerability.

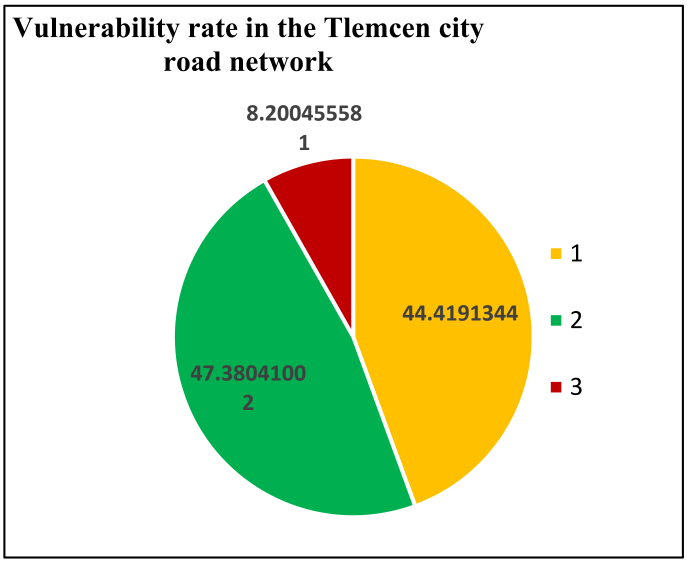

Figure (10): Statistics of vulnerable sections of Tlemcen city road network

Table 1 represents the results of all the parameters described above for each of the routes in the road network and their implications, which makes it possible to define the levels of vulnerability based on the fuzzy C-means algorithm (FCM) for the 878 main routes of the final ranking of the importance of routes.

The most critical link in the network is the access to the city centre of Tlemcen and also its outskirts located on roads with relatively high traffic and no alternative routes. Thus, if they are closed, part of the demand is not affected and has high values of global importance index on our network.

This study gives an idea of the network traffic according to origin and destination and thus, the choice of the route by eliminating all the risks caused by the black spots and the congestions deduced by the application of the fuzzy C-means algorithm are the subject of the daily traffic pressure of the city. In addition, it illustrates the concept of network vulnerability and the difference between network reliability and vulnerability. The concept of vulnerability is more strongly related to the consequences of link failure, regardless of the probability and cause of failure. In some cases, a broken link may be statistically unlikely, but the negative social and economic impacts on the community may be significant enough to indicate a major problem requiring a corrective action that focuses on user-friendly studies and data from the road network.

According to a recent study conducted and published by the researchers (2019) based on the generalized travel time and the structural aspect of the road network to choose a good route in a shorter duration between the two hospitals which are in the outskirts of Tlemcen city, it was preferred to choose the periphery route which presents a better path and it is also maintained even here based on the results mapped in Figure 9 of this study which is based on the fuzzy logic method.

CONCLUSION

To conclude, standard approaches to the reliability of transportation networks have focused on network connectivity and reliability of travel time and capacity, while this one provides valuable information on some aspects of network performance, where reliability arguments based on probabilities and absolute connectivity can mask potential network problems, particularly the vulnerability of Tlemcen road network.

Our set of measures is designed to reflect the intensity of vulnerability as well as the spatial extent in our study area. The assessment and classification of the vulnerability of the road network system are established according to three points: material, structural and functional sides. The fuzzy C-means algorithm under the GIS platform is adopted to obtain the appropriate categories that will rely on the paradigm of the complex system. This system makes it possible to obtain immediate answers to traffic planning and provide better information to local decision-makers concerning the reduction of vulnerability.

Most links in the city of Tlemcen road network fall into three levels of vulnerability: low, average and severe. Due to the statistics on our road network, it can be classified to have an average level of vulnerability; i.e., the vulnerability of this district is average and requires quite significant security measures.

In our network, the values of its parameters (material-structural-functional) of the route links are high and it is taken into account that their demands show an important role in the residents' movement. The key segments are ranked on the map and are mostly at the average vulnerability level, forcing engineers and planners to identify critical network locations and develop strategies and corrective actions to maintain the performance of the Tlemcen city road network.

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