DIFFERENT METHODOLOGIES AND INDICATORS TO ASSESS ROAD NETWORK VULNERABILITY.

F. MALTINTI
Department of Land Engineering, University of Cagliari, Italy
maltinti@unica.it

D. MELIS
Comune di Nuoro, Italy
daniela.melis@comune.nuoro.it

F. ANNUNZIATA
Department of Structural Engineering, University of Cagliari, Italy
annunz@unica.it

ABSTRACT

Road networks and transportation infrastructures are important in provinding accessibility and in substaining social and economic development of a country through promoting the safe and efficient movement of people and goods.
In emergy situations they represent the most important lifelines and the delay in rescue operations, caused by inefficiency of transportation systems, can considerably increase the damages. For a long time the vulnerability of a transportation network have been neglected: interest in such studies developed only after the Kobe earthquake in Japan (1995).Thus the concept of vulnerability has not yet been unambiguously defined and in literature there are different approaches and methodologies in analysing it.
The paper presents an introduction on previous researches concerning transportation network vulnerability and a new methodology and index for assessing vulnerability of links of a road network due to natural hazards. The methodology is applied to an existing road network located in a sparsely populated area in Sardinia (Italy).
The authors' aim is to provide a tool for road owners or administrators not only in defining priorities of intervention but also in helping them to limit the consequences of link or network failures in managing emergency situations.

1. INTRODUCTION

Road networks and transportation infrastructures are the most important "lifelines" of a territory. They assure indispensable services for the survival of the population expecially during emergency situations: the reactivation of other lifelines (gas mains, electricity mains, etc.) depends on the viability of the transport network. Thus, good working of these network systems is fundamental for mitigating the damages caused by natural disasters.
Moreover the inefficiency of transport systems may cause delays in rescue operations which could considerably increase the damages. So transportation network are essential to the functioning of modern society and it is important to understand their vulnerability in order to manage risks in emergency situations.
In literature, risk has various definitions. On the whole, risk is expressed as "the product between the probability that an event occurs and the consequences caused by this event" [1]. It is defined as the product of:
- probability of occurrence of the event,
- value (exposure) of the elements at risk and
- vulnerability of the elements at risk.

The study of network vulnerability has attracted much attention recently after great disasters as Kobe earthquake. Today these studies arouse great interest not only because of natural disasters but also because of man-made disasters (see terrorist attacks). Thus in literature there are no universal approach and methodologies applied in analysing it.
After an overview on definitions and methodologies for quantifying vulnerability of transportation network the paper presents a new methodology and index for assessing vulnerability of links of a road network due to natural hazard. A case study is reported to demonstrate the feasibility of the proposed methodology.

2. LITERATURE REVIEW

Transport infrastructure vulnerability is related to natural disaster, terrorist attacks and traffic accidents that will occur with different probabilities and produce different consequences. The scale, the impact, the modality of study, the frequency and the typology of these events can vary a lot. Thus the concept of transport infrastructure vulnerability does not have a commonly accepted definition and its evaluation can be very difficult.
Berdica [1] defines vulnerability in the road transportation system as “a susceptibility to incidents that can result in considerable reductions in road network serviceability” where the serviceability of a road network “describes the possibility to use that road network during a given time period”.
She does not outline a clear distinction between reliability and vulnerability: reliability is the possibility of assuring the use of a road network under specific conditions and in a specific period of time (“serviceability”). Other terms that in the work of Berdica are related to vulnerability are:

- “resilience”, that is, the capacity of a transportation network to reach a new state of equilibrium after an incident;
- “redundancy”, that is, the duplication of the components inside a network which can keep on working in the case of a breakdown in the road network.

Berdica conceptualises and put into a context the notion of vulnerability in the road transportation system but she doesn’t suggest any quantitative metrics or computational tools for transportation network vulnerability analysis.
Afterwards Berdica et al. [2] relate vulnerability to the concept of accessibility in particular, they measure its variation during the change from a normal situation to a crisis generated by the disruption of a link. In particular, for this purpose, they use a measure of accessibility called “logsum”, a weighted average value of generalized travel cost evaluated for all transport modalities and for all destinations; nodes and destinations are weighted in function of how attractive they are.
Cafiso [3] defines the vulnerability as the propensity of goods, people or activities to be damaged or modified as the consequence of an event and he distinguishes between “direct vulnerability” (or structural vulnerability) and “induced vulnerability”(or functional vulnerability) in seismic risk. The former measures the single element’s (simple or complex) propensity to suffer damages or collapse after a seismic event, the latter concerns the effects of the crisis on the organization system. In Cafiso’s et al. [4] work, the vulnerability of a road section is given by the combination between structural vulnerability of components and functional vulnerability: they use check lists for determining structural vulnerability of bridges, viaducts, embankments, slopes, tunnels and retaining and drainage works whereas the functional vulnerability depends on the presence of alternatives in the road network at the failed path.
To formulate a quantitative judgment about structural vulnerability, the analysis must delve into details and specific disciplines like structural analysis or the hydraulics are necessary.

An example of assessment of structural vulnerability of bridges and viaducts can be detected in the work of Cafiso et al. [3] whereas an example of vulnerability assessment of hydraulic works is shown in the works of Bosurgi et al. [5] e [6].
D'Andrea and Condorelli [7] illustrate the concept of "deferred vulnerability": it is correlated to the problems that arise following an event and they also distinguish "functional vulnerability" which refers to the damages, evaluable also in the long term, that derive from the non-functionality of some elements and "socio-economic vulnerability" which depends on the social, economic and political conditions that characterize the region involved in an event.
Cutter et al. [8] speak about "biophysical vulnerability" and "social vulnerability" and they define "regional vulnerability" as the interaction of "biophysical vulnerability" and "social vulnerability". "Biophysical vulnerability" refers to the identification of possible risks, their frequency and magnitude. In this sense, "biophysical vulnerability" is simply the dangerousness of an event. Moreover, this concept can surely be likened to the concept of "nature-related vulnerability" expressed by Husdal [9]. "Social vulnerability" derives from the activities and circumstances that define the social fabric of a region and its changes. Thus the concept of "social vulnerability" is similar to that of "socio-economic vulnerability" expressed by d'Andrea and Condorelli [7].
Husdal [9] identifies three typologies of vulnerability:

- "structure-related vulnerability", which pertains to the constructional, geometric and design characteristics of the road;
- "nature-related vulnerability", which pertains to the characteristics of the land crossed by the road and the natural risks that mark it;
- "traffic-related vulnerability", which refers to traffic flow characteristics and the conditions that describe traffic flow variations in specific situations.

In Husdal's work the concept of vulnerability differs from the concept of reliability: reliability pertains to the functioning of road network links, while vulnerability is connected to the consequences of the collapse or the inadequate functioning of a link.
In Taylor and D'Este's work [10], the concept of vulnerability is related to the concept of accessibility which is defined as the ease of reaching opportunities for activities and services. The authors focus their attention on the vulnerability of the node of a network: a node becomes vulnerable if the loss or substantial deterioration of a small number of links significantly decreases accessibility to the node.
According to Taylor et al. [11] the variation of the generalized cost of transport between two nodes of the network when a link stops working represents a measure of vulnerability. In this case, the generalized cost is a measure of the disutility generated by the link collapse, as the increase in travel distances and time, travel cost, etc.
Taylor and D'Este also underline the existing difference between vulnerability and reliability. They relate the concept of vulnerability to the consequences of an event (for instance the interruption of a road link), while the concept of reliability is related to the probability of the occurrence of an event. Thus, although network vulnerability and reliability are correlated concepts, it is clear that vulnerability concerns the weakness of a network and the consequences due to the interruption of a part of it. On the contrary, reliability mainly concerns the concepts of probability and connectivity. The positions expressed by Taylor and D'Este are close to those expressed in the works of Husdal, of Cafiso et al. [3] and of D'Andrea and Condorelli [7].
Zhang et al. [12] distinguish between network fragility and network vulnerability: a network is fragile when it does not work well even if only few volume-dependent or random links break down; a network is vulnerable when its functionality decreases quickly when its most important links are removed.

Erath et al. [13] consider vulnerability as a combination of the probability of occurrence of a given hazard, the resistance of the infrastructure to it and its consequences (direct financial consequences and indirect consequences to transport traffic) to transport.
Jenelius et Mattsson [14] relate the concept of vulnerability to the concept of criticality of network components. When a network component collapses, the greater the damage caused to the entire system, the greater is the criticality of the component.
Attention is focused on both the assessment of the importance of the link inside the network and the exposure of the municipality (namely the node). In the specific instance, the importance of the link is assessed by determining, for each link, the summation of the increments of travel times from each node weighted according to the movements generated by the node itself towards the node of destination. Whereas the exposure of the municipality is always assessed according to the increments in travel time that the municipality undergoes because of the disruption of one or more nodes, and is weighted through the movements generated from that municipality. In this way, importance and exposure are interpreted as indexes of vulnerability of both the node and the link.
Li [15] proposes an indicator of probability of accessibility which furnishes a measure of connectivity towards the centres from which rescue and emergency operations start. This measure of connectivity is defined by the author as “probability of access”. Every section of the network possesses a specific probability of being disrupted, which is directly proportional to both disaster magnitude and road characteristics. In this specific case, the probability of access is estimated by using the techniques of simulation of Monte Carlo.
In Chang’s works [16], [17] measures and indexes of accessibility are used for assessing the performance of a transportation network after a calamitous event. Chang tests this model on the impacts generated by the earthquake of Kobe and compares them to impacts generated by other earthquakes.
Sohn [18] proposes the distance-decay effect and the influence of the volume of traffic on the transportation network after a link breakdown as a measure of accessibility. This accessibility index is useful in identifying critical links and establishing the priority of retrofit.
Chen et al. [19] propose a measure of transportation network vulnerability based on accessibility measures deriving from the combined travel demand model. This model has been formulated as a variational inequality problem [20] to consider the effects of the multi-dimensional travel responses of network users (changing route, switching mode, changing destination and cancelling or postponing a trip) on network vulnerability.
Network Trip Robustness (NTR) defined by Sullivan et al. [21] can also provide information about transportation network vulnerability. Actually, network robustness is defined as the degree to which the transportation network can function in the presence of various capacity disruptions on component links. NTR is a measure of accessibility and of performance of the transportation system since it considers the consequences of one or more link failures in terms of network travel cost.
As above mentioned, the concept of vulnerability appears to be particularly varied and applicable to several fields.
In particular, we can distinguish between the vulnerability of a region, of a comprehensive network and of network elements (sections, links, nodes), or due to design, constructional and structural characteristics of a specific section of a road network or a specific construction (bridges, embankments, tunnels, etc.) or related to the natural characteristics and risk of the land crossed by the infrastructure.
Likewise the methodologies used in literature for quantifying vulnerability of a transportation network depend on the basis of the scale of study (vulnerability analyses of road networks, single road links, bridges, hydraulic structures, etc.), of the typology of the determined risk (seismic risk, avalanches, floods, landslides, etc.) and of the modalities of study (quantitative analyses that use indexes of vulnerability or qualitative analyses).

3. A NEW ACCESSIBILITY MEASURE FOR VULNERABILITY ANALYSIS

The aim of this paper is to present a new methodology and a new index to assess vulnerability of a road network using characteristics of a road [22] [23] [24].
The methodology studied quantifies transportation–related consequences of link failure due to natural hazards (in particular floods and landslides) because the Italian territory and especially Sardinia are very exposed to this risk and there are known hazard maps that allow identification of the links most exposed to the risk of failure.
The first step of the methodology consists of territorial analysis: the urban nodes have to be identified, where the urban node coincides with the centre of the urban network. Therefore it is necessary to separate the origin of rescue operations and the centres considered as destinations for these operations. Then, by means of hazard maps it is possible to identify higher hazard areas.
The following step is the road network analysis. The infrastructural system has been depicted as a road network composed of nodes and links, of which the spatial position has to be known. It is assumed that the index is calculated for rural roads.
Overlapping the road network and high hazard areas, the "weak links" are identified; weakness indicates a high probability of link closure.
It is assumed that during a hazardous event, the link will be completely disrupted. So the vulnerability has been calculated only for those links exposed to risk (weak links). Also it is assumed that all links have the same weight. This means that all the road links have the same importance, irrespective of their travel demand or their travel movements: this approach is particularly effective in low volume traffic road networks where a link failure could completely isolate a small town.
The link closure will modify the shortest paths, between all the origins and the destinations of the road network. Obviously this happens if this link is part of one or more of the shortest paths.
The index is based on the increase in travel time considering the shortest path, between a node i and a node j when a link k is interrupted.
The total vulnerability index can assume a value between zero and three and will be given by:

$$\text{vulnerab}^{k}_{\text{tot}} = \text{vulnerab}^{k}_{\text{glob-norm}} + \text{vulnerab}^{k}_{\text{O/Dresc\_norm}} + \text{vulnerab}^{k}_{\text{short\_path\_norm}} \quad (1)$$

where

$$\text{vulnerab}^{k}_{\text{glob\_norm}} = \frac{\sum_i \sum_j (t^k_{ij} - t^0_{ij}) - \min_k \sum_i \sum_j (t^k_{ij} - t^0_{ij})}{\max_k \sum_i \sum_j (t^k_{ij} - t^0_{ij}) - \min_k \sum_i \sum_j (t^k_{ij} - t^0_{ij})} \quad (2)$$

is the normalized indicator for the vulnerability assessment connected to the whole network,

$$\text{vulnerab}^{k}_{\text{O/Dsocc\_norm}} = \frac{\sum_{i \in C_R} \sum_j (t^k_{ij} - t^0_{ij}) - \min_k \sum_{i \in C_R} \sum_j (t^k_{ij} - t^0_{ij})}{\max_k \sum_{i \in C_R} \sum_j (t^k_{ij} - t^0_{ij}) - \min_k \sum_{i \in C_R} \sum_j (t^k_{ij} - t^0_{ij})} \quad (3)$$

is the normalized indicator for the vulnerability assessment connected to the rescue operation and

$$\text{vulnerab}^{k}_{\text{short\_path\_norm}} = \frac{\sum_i \sum_j (n^k_{ij}) - \min_k \sum_i \sum_j (n^k_{ij})}{\max_k \sum_i \sum_j (n^k_{ij}) - \min_k \sum_i \sum_j (n^k_{ij})} \quad (4)$$

is the normalized indicator for the vulnerability assessment connected to the number of shortest paths involved in link closure.

Link vulnerability referred to the whole network is defined by:

$$vulner^{K}_{glob} = \sum_i \sum_j (t^k_{ij} - t^0_{ij}) \quad (5)$$

where:
- $t^k_{ij} - t^0_{ij}$ denotes the increase in travel time from i to j if link k fails;
- $i, j \in N^c$ are the urban nodes in the considered network;
- $k \in A^W$ is a “weak link”.

whereas the following equation shows how to calculate the importance of the link for rescue operations:

$$vulnerab^{K}_{O/Dresc} = \sum_{i \in C_R} \sum_j (t^k_{ij} - t^0_{ij}) \quad (6)$$

where:
- N^{CR} is the set of nodes, centres of relief operations.
- $i \in N^{CR}$ is a relief operation centre
- $j \in N$ is an urban node destination of relief.

As a matter of fact some links of the network are more important for emergency management purposes. This occurs when the link belongs to the shortest path that connects a node i (centre of relief operation) with another one j (relief destination).
At last vulnerability connected to the number of shortest paths involved in link closure is expressed by:

$$vulnerab^{K}_{short\_path} = \sum_i \sum_j (n^k_{ij}) \quad (7)$$

where:

$$n^k_{ij} = \begin{cases} 1 \text{ if } \Delta t^k_{ij} > 0 \\ 0 \text{ if } \Delta t^k_{ij} = 0 \end{cases}$$

Also, it is interesting to assess municipality exposure to the event to complete the analysis. Thus it has been studied an index to evaluate it:

$$exposure_i = \sum_k \sum_j (t^k_{ij} - t^0_{ij}) \quad (8)$$

where:
$i, j \in N^c$
$k \in A^w$
This index does not consider the population of the municipality so all the municipalities have the same weight. If it is necessary to consider population the eq. 8 can be rewrite as follows

$$exposure^{wei}_i = \frac{P_i}{P_{tot}} \sum_k \sum_j (t^k_{ij} - t^0_{ij}) \quad (9)$$

where:
P_i is local population in referential municipality;
P_{tot} is total population in referential area.

A shortest path algorithm is used to calculate the travel time costs, and build the matrix of travel times for all origin-destination nodes of the network (in this work ArcGis Network Analyst is used);
The travel time of each link is obtained by dividing length by travel speed of the road link. Travel speed is determined by the design and correlation of the physical features of a road

which influence the behaviour of a vehicle, more specifically these hypotheses have been formulated, according to Italian Geometric Design Standards [25]:

1. the vehicle is isolated: its speed is not affected by traffic conditions (this hypothesis is not easily verified but it appears valid for roads located in sparsely populated areas with low traffic volumes);
2. the road gradient does not influence vehicle speed;
3. on tangents the vehicle follows the equations of uniformly accelerated linear motion until it reaches the designed speed limit;
4. on curves vehicle speed depends on the radius of the curves and on the road category.

Thus, the aforementioned assumptions allow assessment of the vulnerability of the network, which depends only on the intrinsic design characteristics of the road.

4. A CASE STUDY

The analytical approach and the vulnerability index were applied to an existing road network located in Italy, in particular in Sardinia. The road network is located in a sparsely populated area (the Ogliastra region), which has been interrupted because of landslides and floods (see Figure 1), on different occasions.

Figure 1 - Road failures in Sardinia caused by intense precipitation (photos by ANAS)

Figure 2 shows the final result of the application of the methodology: the vulnerability map of the road network.
Central links are the most vulnerable because they belong to different shortest paths and they are used for rescue services for which there are no alternative routes.

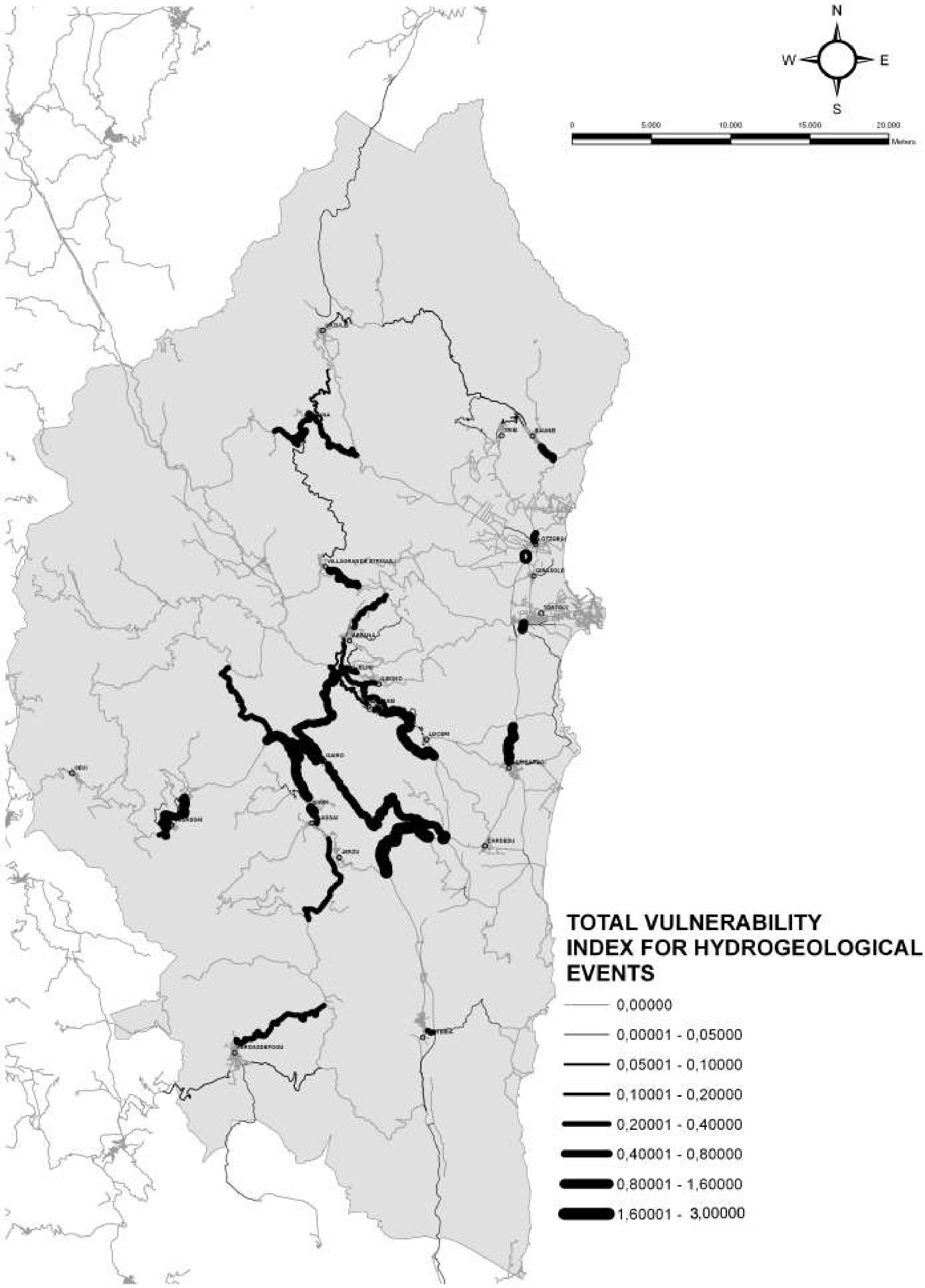

Figure 2 - The vulnerability map of the road network in Ogliastra region

Next three figures show the maps of Ogliastra region referred to vulnerability assessment of the whole network (eq. 5), connected to the rescue operation (eq.6) and connected to the number of shortest paths involved in link closure (eq.7).

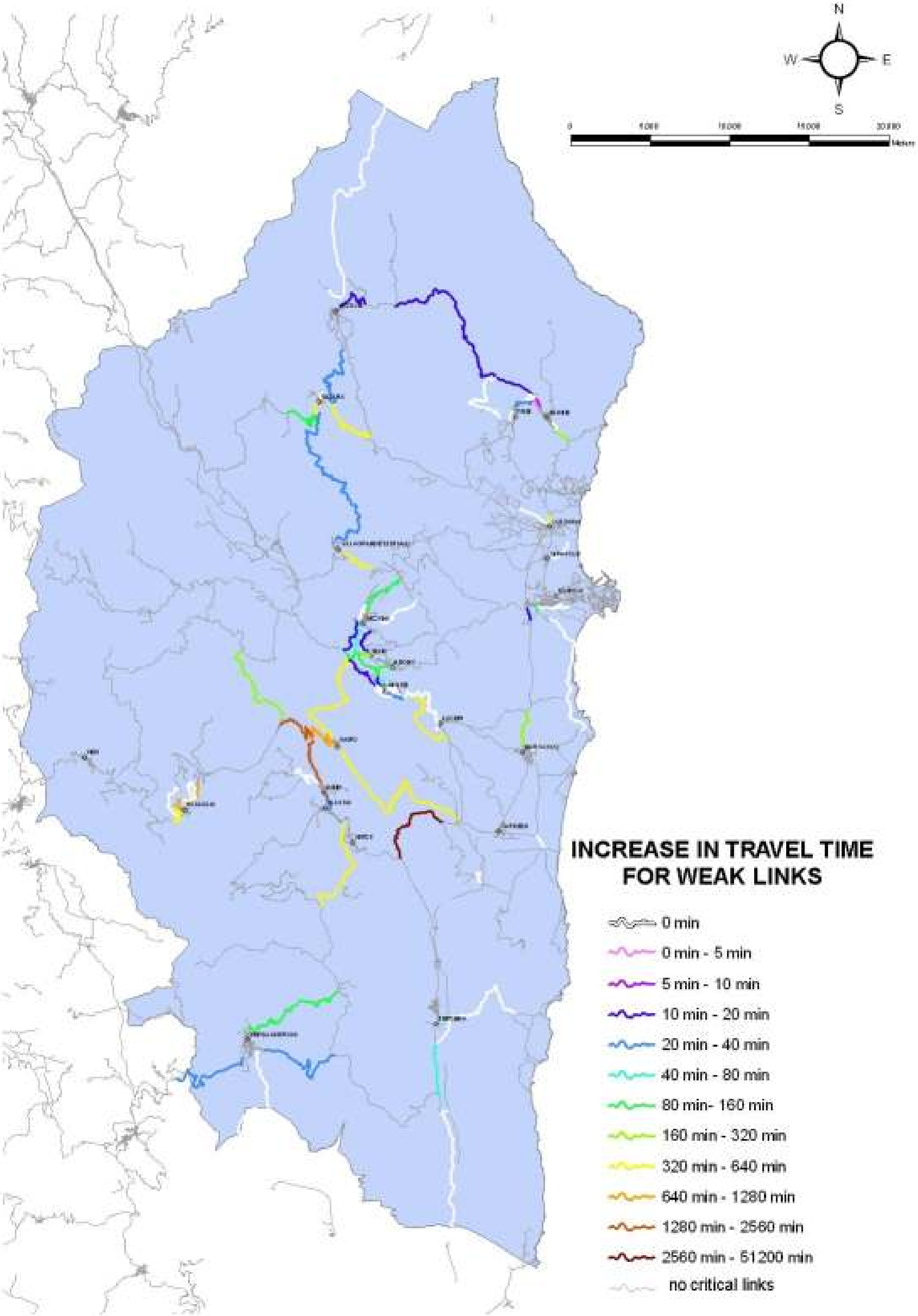

Figure 3 - The map of Ogliastra region referred to vulnerability assessment of the whole network

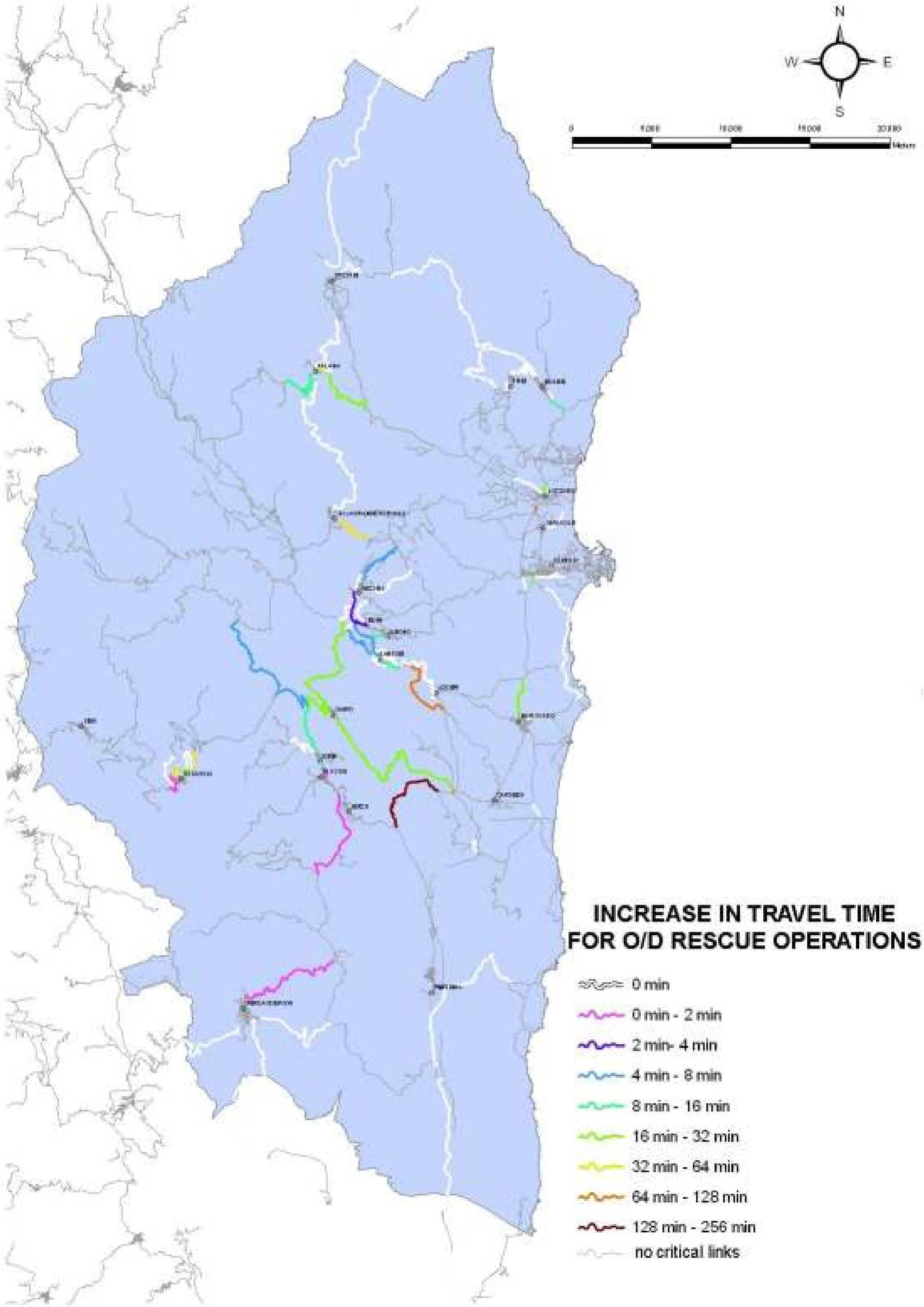

Figure 4 - The map of Ogliastra region referred to vulnerability assessment connected to the rescue operation

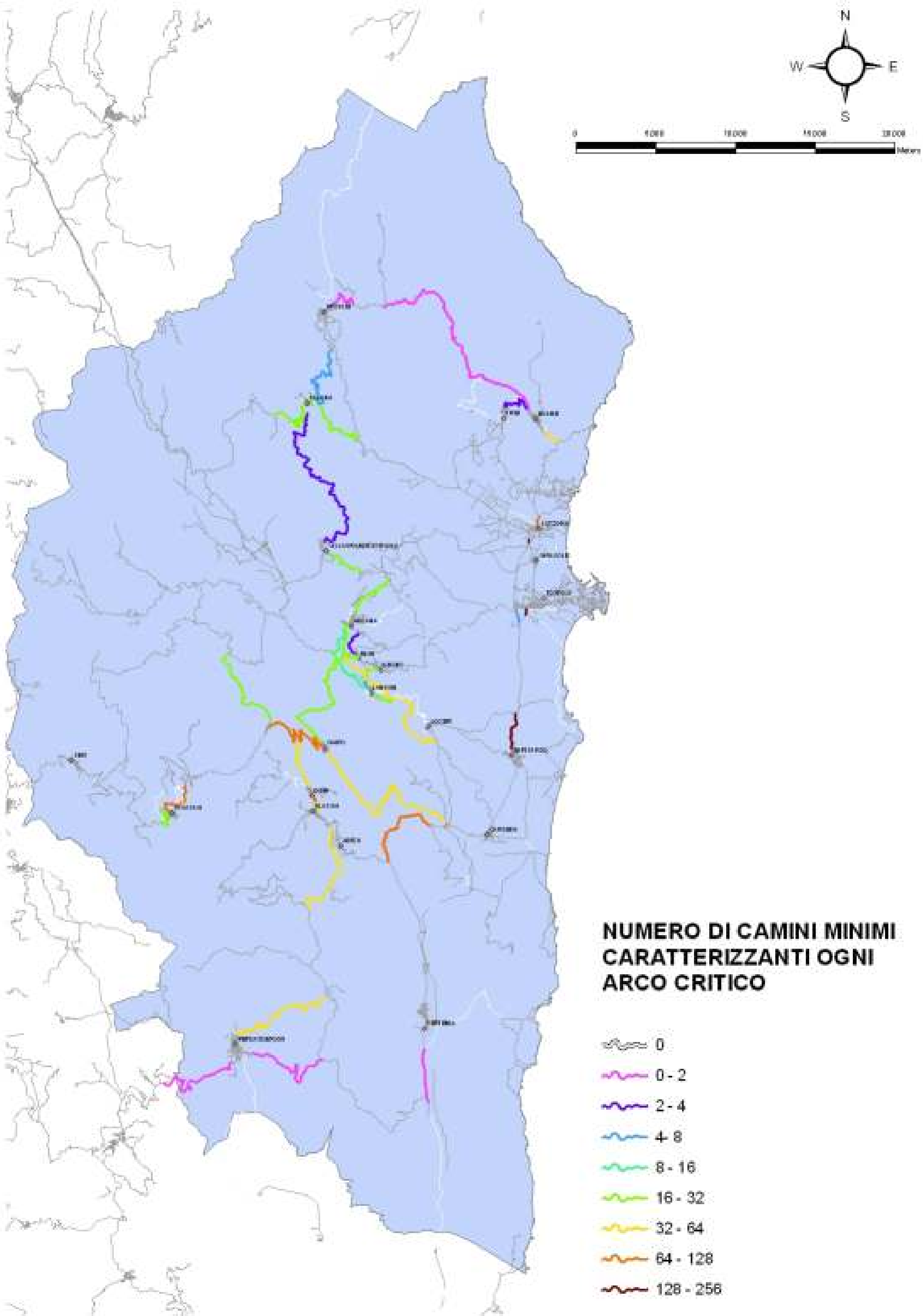

Figure 5 - The map of Ogliastra region referred to vulnerability assessment connected to the number of shortest paths involved in link closure (eq.7)

The values of the first index are bigger for central than peripheral links.
For the second index most important links are still in the centre of the region, whereas links connecting peripheral urban nodes each other have no importance.

The third index shows the number of shortest paths involved in link closure and represents the importance of that link in road network. According to third index internal links are most important too.
Also, it is interesting to study consequences of closure of most vulnerable link for municipalities. Figure n°6 represents increases in travel time in links connecting municipalities each other when the most vulnerable link is closed.

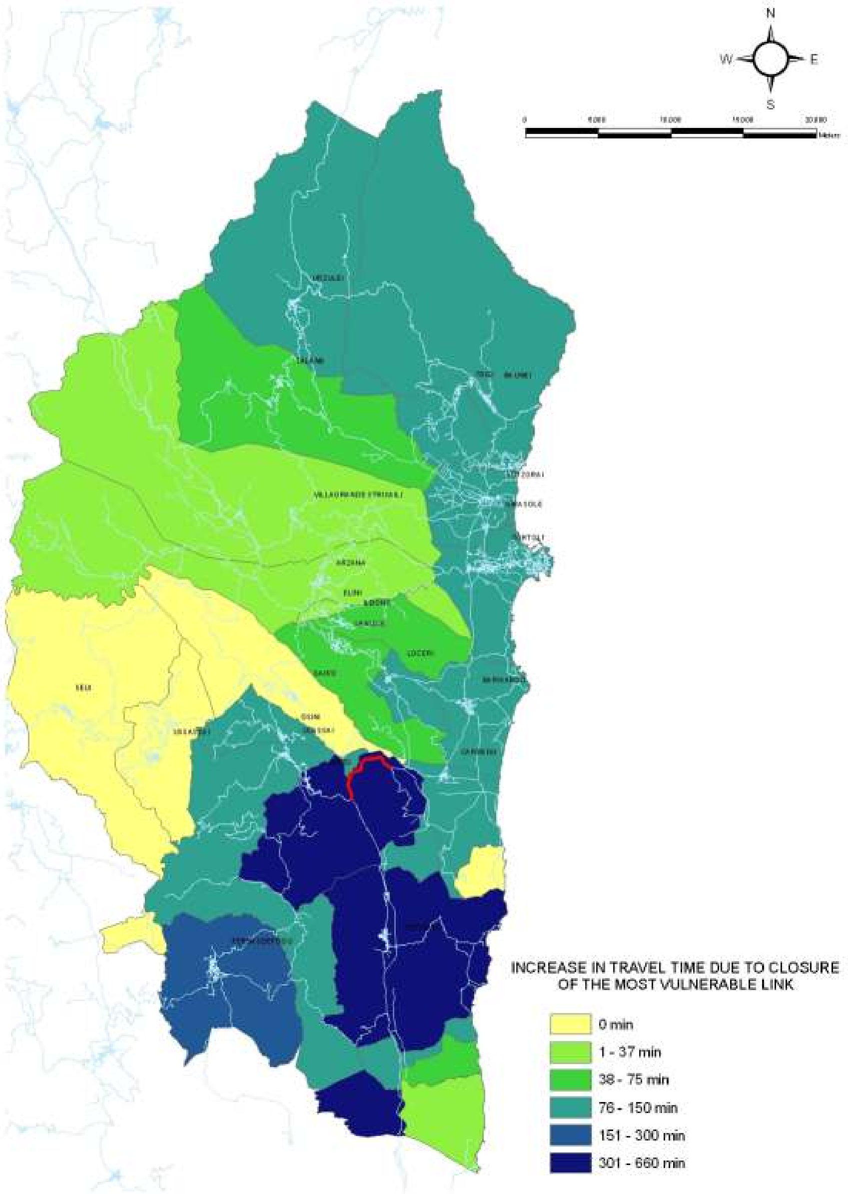

Figure 6 - Consequences due to closure of the most vulnerable link

This map could be done for every weak link to understand which municipalities are interested by its closure.
To complete the analysis it is interesting to assess municipality exposure to the event.
Figure 7 shows the application of eq.8: more vulnerable municipalities are localized in central-southern area of the region, in particular Ussassai is the town which has the highest exposure.

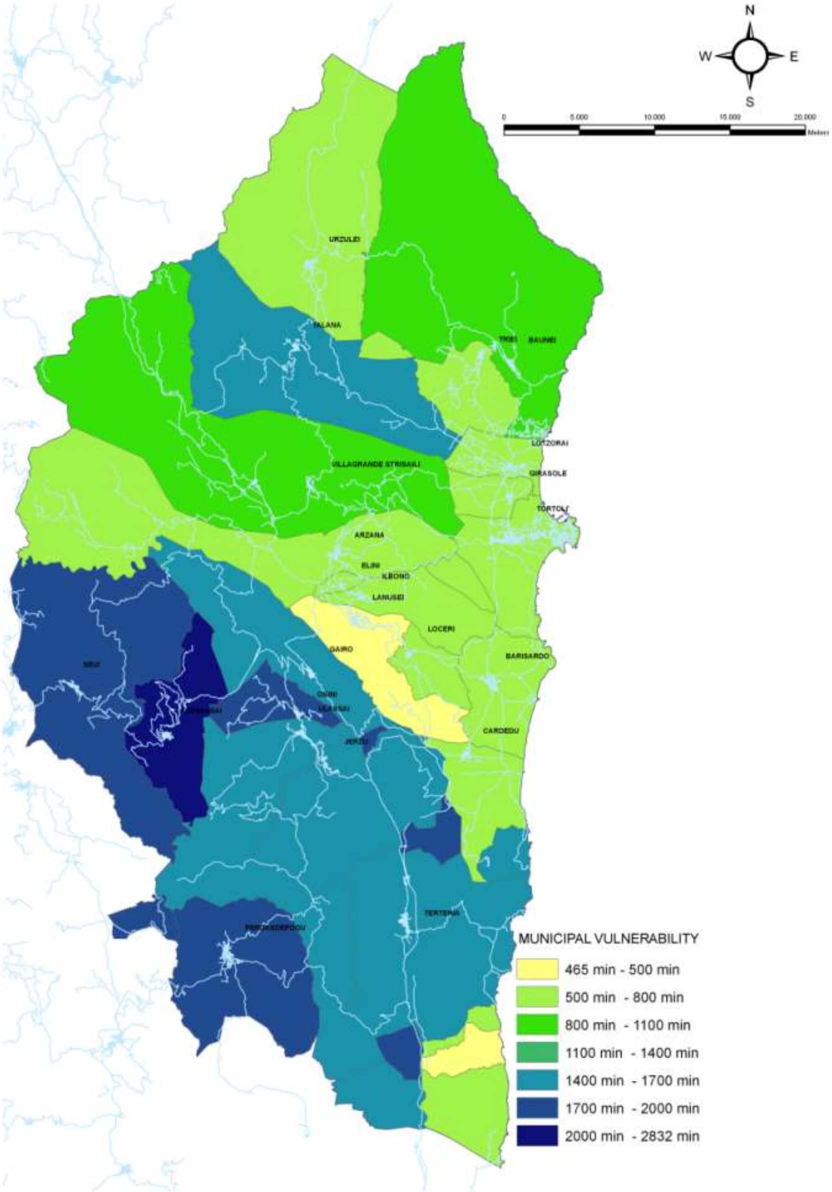

Figure 7 - Vulnerability of single municipalities

The situation is completely different using eq.9 and considering local population (see figure n°8): Tortolì has the highest index of exposure whereas Ussassai, which is sparsely populated, has lower index of exposure.

This case study shows how the proposed methodology can express vulnerability of a road network considering geometric characteristics of the elements of road, the function of the link within the road network and the importance of the link for rescue operations. The methodology attaches more importance to peripheral links which are particularly critical because they have not alternative paths and their closure can completely isolate an area.

Thus the methodology is specifically effective in areas of low population density and in which traffic flows are poor.

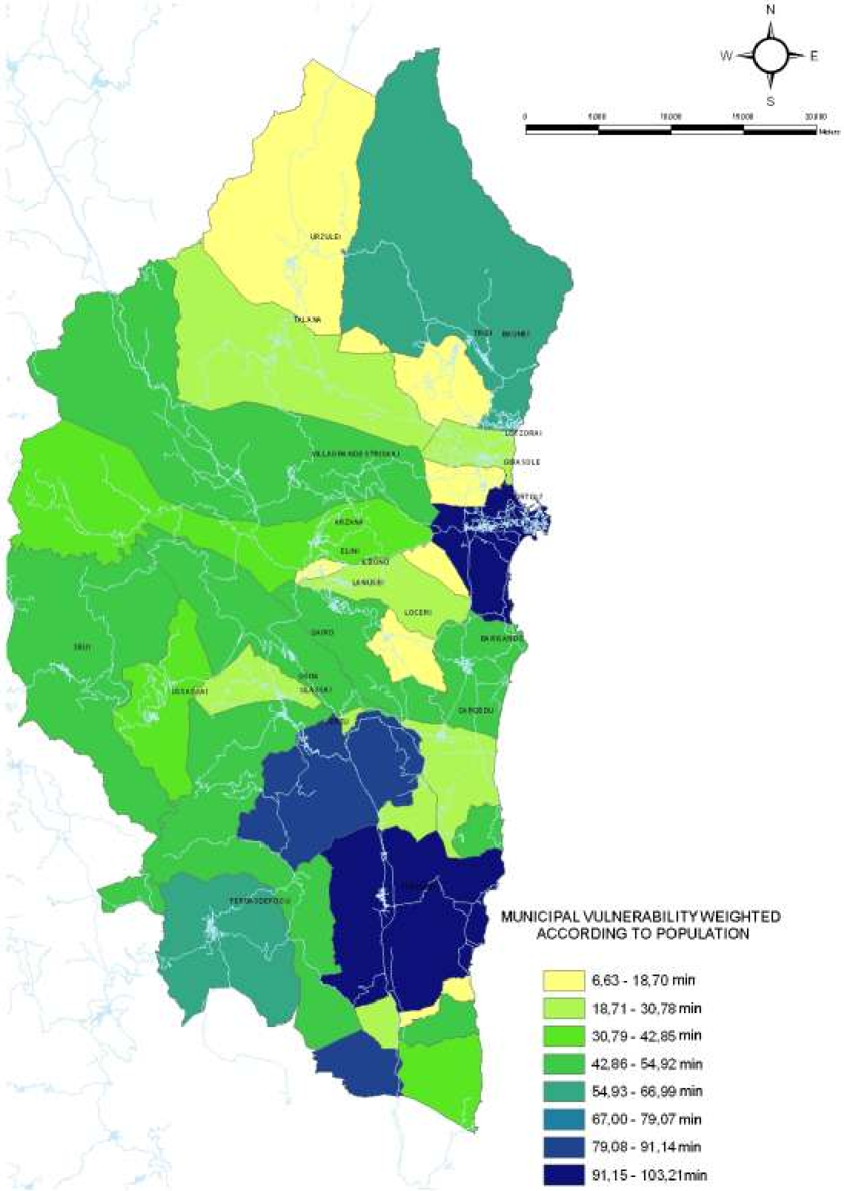

Figure 8 - Vulnerability of single municipalities weighted according to population

5. CONCLUSIONS

Studies of vunerability of transportation networks has attracted much attention recently following disastrous events such as the Kobe earthquake in Japan (1995). Today, these studies arouse great interest, not only because of natural risks, whose extent and frequency are on the increase, but also because of anthropic risks (consider, for example, terrorist attacks). The difficulty still resides in the presence of very different approaches.

This paper attempts to provide an overview on definitions and methodologies used in literature for studying the vulnerability of a transportation network and presents a new methodology and index for assessing vulnerability of links of a road network due to natural hazards. The index is based on the increase in travel time, considering the shortest paths connecting an urban node to another one when a link is closed.

Three indicators were adopted to determine the index: the first reflects functional vulnerability, the second reflects the importance of the link for relief operations during an emergency and the third reflects the importance of the link in connecting areas of region.

The index is based on design characteristics of the road (road geometry and horizontal alignment), and it does not consider traffic flows or traffic demand: this allows a more impartial approach to the problem, because all the links initially have the same importance, regardless of their traffic condition. This approach is more effective in low volume traffic road networks where a link failure could completely isolate a small town as it is shown in the case study proposed.
The methodology could be surely improved including other road design charactristics (e.g. road gradient) in the definition of the index or studying more in dept the way to assign travel time to links, for example, but the aim has been to provide a tool for road owners or administrators not only in defining priorities but also in helping them to limit the consequences of link or network failures in emergency conditions.

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