# Network-risk: an open GIS toolbox for estimating the implications of transportation network damage due to natural hazards, tested for Bucharest, Romania

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**Abstract.** Due to their widespread and continuous expansion, transportation networks are considerably exposed to natural hazards such as earthquakes, floods, landslides or hurricanes. The vulnerability of specific segments and structures among bridges, tunnels, pumps or storage tanks can translate not only in direct losses but also in significant indirect losses at systemic level. Cascading effects such as post-event traffic congestion, building debris or tsunamis can contribute to an even greater level of risk. To support the effort of modelling the natural hazards implications at full transportation network scale, we developed a new applicable framework relying on i) GIS to define, analyze and represent transportation networks; ii) methods for determining the probability of network segments to fail due to natural hazard effects; iii) Monte Carlo simulation for multiple scenario generation; iv) methods to analyze the implications of connectivity loss on emergency intervention times and transit disruption, v) correlations with other vulnerability and risk indicators. Currently, the framework is integrated in ArcGIS Desktop as a toolbox entitled “Network-risk”, which makes use of the Model Builder functions and is free to download and modify. Network-risk is an attempt to bring together interdisciplinary research with the goal of creating an automated solution to deliver insights on how a transportation network can be affected by natural hazards, directly and indirectly, assisting in risk evaluation and mitigation planning. In this article we present and test Network-risk at full urban scale, for the road network of Bucharest. This city is one of Europe’s most exposed capitals to earthquakes, with high seismic hazard values and a vulnerable building stock, but also significant traffic congestion problems not yet accounted in risk analyses and risk reduction strategies.

## 1 Introduction

The complexity and exposure of our society to natural hazards has significantly increased in the last decades (Gu, 2019; Pesaresi et al., 2017; Fleischhauer, 2008), and will keep on doing so. Transportation networks are one of the fundamental pillars of development and support for countries, whether they consist of roads, railways, pipelines, communication lines, maritime, aerial or other types of networks. Transportation networks are a requirement for almost every inhabited place - residential, commercial or industrial and they continue to upgrade per location and also expand. As such, they become more and more exposed, if not also more vulnerable. Recent large-scale natural hazard events, such as earthquakes (in Italy 2016 and 2009, Nepal 2015, Haiti 2010, China 2008 etc.), some accompanied by very destructive tsunamis (Japan 2011 or Indonesia 2018 and 2004), hurricanes and typhoons (in Mozambique 2019, Puerto Rico 2017, Philippines 2013 and 2012, Myanmar 2008 or USA 2005) or heat-waves (constant in the last years in countries such as USA, Australia, Greece or Spain) proved that transportation networks are extremely vulnerable, but also vital immediately after the event occurrence. Directly contributing on the economic loss balance of such events, transportation networks have a more and more significant percentage, especially in developed countries (Wilkerson, 2016). Taking into account also the indirect losses (hard to quantify), it is even more obvious that their vulnerability needs to be reduced.

The functionality of transportation networks is very important both immediately after a hazardous event - constituting support for emergency intervention and long time after - in the recovery and prevention phases. Damage on networks can inflict direct risks - collapse of vehicles or trains, fire outbreaks etc. Still, functionality and redundancy are essentials, in order to ensure that socio-economic losses do not increase significantly. In any transportation network analysis it should be considered also the interconnectivity between systems and with other networks. In the post-disaster reaction phase, especially road networks prove to be very important (Jenelius and Mattsson, 2015), since they link almost all destinations; in some cases other transportation networks can be also relevant: railways, maritime or aerial networks. Communication networks are critical in all disaster cycle phases. Utilities are important for a faster recovery and overall, for ensuring resilience. Previous experiences show that transportation networks are mostly affected by natural disasters:

- Directly: by the collapse of critical components such as bridges, tunnels, storage tanks, pumps etc., cracks in roadways due to ground motion effects (settlement, liquefaction), railway displacement, pipe cracks;
- Indirectly: road blockage due to collapsed buildings (especially in urban areas), blockage due to triggered landslides, flooding or tsunamis, due to traffic congestion generated by post-disaster behavior, emergency imposed restrictions etc.

For studying the impact of natural disasters on transportation networks, multi and inter-disciplinary approaches are needed, combining methods belonging to geosciences, engineering, sociology, economy or informatics. Also, multiple perspectives need to be considered (Franchin et al., 2011):

- Temporal (the disaster management cycle);
- Spatial: local (structural element studies), regional, national or multinational;
- Actor involved (level of management).

In the last two decades, significant progress has been achieved in transportation network vulnerability and risk analysis - not just at structural level but also at functional level. For a comprehensive review we recommend the studies of Jenelius and Mattsson (2015), Miller (2014), Tesfamariam and Goda (2013), Franchin et al. (2011) in the framework of the Syner-G Project or Kiremidjian et al. (2007). These reveal that the fundamental steps in evaluating the seismic risk of transportation networks are:

- the proper definition of the network, with detailed data regarding component characteristics and connectivity. One of the problems is still in most cases the lack of official data: in developed countries there can be available good and updated

GIS databases, however in most other countries transportation network data (at least for roads or railways) is not well officially defined and/or shared with the general public, therefore alternative data sources need to be used, such as OpenStreetMap (open-source), Google Maps, Here Maps etc. There are currently many software solutions capable of network development (including AutoCAD Civil 3D, OpenRoads or ESurvey Road Network), but not so many with risk analysis capabilities; among them we mention popular solutions such as ArcGIS for Desktop with the Network Analyst extension, PTV Visum/Vissim, Maeviz/Eqvis or STREET;

- the determination of direct damage probability of individual components. For this, earthquake engineering analysis methods are mostly used, such as dynamic elastic and inelastic analysis using grids and numerical methods: finite element method, pushover or time-history analysis, response spectra etc. A good synthesis of these methods can be found in Crowley et al. (2011) and Costa (2003);
- the need to define relevant performance indicators, reflecting time or cost differences between pre and post-disaster network behavior; many performance indicators for networks can be found in literature, some of the most common at system level being Driver Delay, Simple/Weighted Connectivity Loss (Pinto et al., 2012; Poljanšek et al., 2011), System Serviceability Index (Wang et al., 2010) or Serviceability Ratio (Adachi and Ellingwood, 2008).

In the recent years, new technologies such as Internet of Things devices, Big Data, Remote Sensing, drones, low-cost sensors and Machine Learning started to be quickly adopted as they can provide practical solutions for transportation network data collection and analysis. It is expected that the impact of future natural hazards on transportation networks will be much better recorded (as shown by Voumard et al., 2018), allowing for a better validation of risk models and opportunities to create more representative methodologies for the analysis of network risk, also in near-real time.

In order to analyze systemic risk (and not only component risk), networks need to be evaluated from the perspective of direct damage implication on connectivity, traffic changes or new traffic flows created, leading to indirect damage. Recent studies have addressed these aspects (Koks et al., 2019; Vodak et al., 2015; Caiado et al., 2012; Bono and Gutierrez, 2011; Douglas et al., 2007; Franchin et al., 2006), going beyond the simple summarization of direct effects and eventually of reconstruction costs generated. These studies also highlight an important aspect to consider (Pitilakis and Kakderi, 2011): interactions between the components of the system (inter-interactions) and with components of other systems (intra-interactions).

After analyzing available methodologies and solutions in the field of study, we reached the conclusion that nowadays capabilities can be better exploited, enabling a more flexible but also standardized analysis of transportation network implications due to natural hazards, compared to previous works. We consider that many has been done theoretically and too little practically (at least at full city scale analysis), leaving also room for new technologies and that is what motivated us to create a new GIS solution sharable with the community and applicable world-wide. In this paper that provides a settled methodology after preliminary studies such as Toma-Danila (2018) or Toma-Danila et al. (2016), we will focus on:

- presenting a methodology for evaluating direct and indirect transportation network risk due to natural hazards, embedded in ArcGIS Desktop as an open-source toolbox called “Network-risk”;

- demonstrating its capabilities for a representative case study: Bucharest - one of the most under risk capitals in Europe due to the implications of earthquakes; results represent an important contribution to emergency management risk reduction planning.

## 2 Methodology and implementation

The generalized steps of the methodology comprises of:

- defining a transportation network in a GIS;
- evaluating which segments could be affected by a natural hazard (directly or indirectly) - accounting also for the probability of damage;
- generating random damaged network scenarios based on this probability;
- evaluating which are the implications, in terms of connectivity and serviceability losses and then socio-economic consequences.

This concept was previously defined in studies such as Hackl et al. (2018), Zanini et al. (2017), Vodak et al. (2015), Chang et al. (2012) or Argyroudis et al. (2005). However, the way each of the tasks are treated, linked and implemented in GIS is what we consider to be a progress toward standardization and usability in real situations (also in near-real time). The methodology presented in Fig. 1 allows among others the consideration of multiple transportation network types (road, railway, utilities etc., represented at local, regional or national level) and of different natural hazards. The methodology can accommodate, for example, to the analysis of earthquake implications, where damage is widespread and building debris, traffic patterns and a good level of details for network definition are necessary to be considered. For landslides, the factors to be considered will change, since damage will be much more punctual and random simulations might not be so representative. For flooding, vulnerability analysis of networks such as road or railways will require knowledge on topography - not so representative for earthquake analysis. Still, the methodology will accommodate all these hazard types and influences, as long as, for example, loss analysis will lead to the identification of possibly affected network segments. There is also flexibility in the way the risk analysis is oriented - toward emergency intervention, economic losses evaluation or urban planning.

Most of the input data (yellow boxes in Fig. 1) is required, also with GIS reference, with the exception that, depending on the analysis type, emergency intervention facilities or origin-destination (OD) pairs will not necessary be needed. In addition, an analysis without typical traffic data can be performed, although it might be representative just for night traffic conditions.

The process of building a consistent transportation network, from more or less complex datasets, is an essential part in every network analysis. To assist in this effort we created a guide, models and layer symbologies for properly converting and editing data partially manually, following also the ArcGIS Desktop Network Analyst extension recommendations. An alternative solution can be to use the ArcGIS OSM editor (https://github.com/Esri/arcgis-osm-editor) for OpenStreetMap data (possible however to have limitations in expressing Z-elevation), GRASS GIS v.net or procedures such as Karduni et al. (2016). Eventually, the converted data is expected by Network-risk to be similar to the sample files provided on the Network-risk webpage. At the moment, the compulsory columns required in the analysis are “name”, “oneway”, “F_ZLEV”, “T_ZLEV”, “hierarchy”, “maximum_speed”, “FT_minutes” and “TF_minutes”. To these, further columns accounting for traffic, scenario travel times or lack of functionality due to natural hazard effects will be added, depending on data availability and analysis type. In the process of defining the rules for the Network Dataset (ND), the Network-risk toolbox requires to add more evaluators beside the ArcGIS Network analysis extension defaults, with the most important being for obstructions (used in service area analysis in the impedance field to reveal inaccessible road areas) and other for different typical traffic scenarios or for economic costs.

Both pre and post-earthquake traffic data are highly important, since they show the typical functionality status of the network and the premises for new traffic congestions, immediately after an earthquake (with correlations also to road segments blocked by e.g. building debris or bridge collapse). Typical traffic data can be retrieved from local data sources (such as traffic management authorities) or from companies taking advantage of new device capabilities, such as Google Traffic, Here Traffic or Waze. This sources provide live (or statistical) data regarding traffic values and reported incidents, although to integrate this data into our framework it is needed to convert this data into travel speed per road segment or to turn into barriers or restrictions GIS layers. Other solutions with near-real time analysis capabilities can be to use GPS data - from emergency vehicles, or the expertise of their drivers, especially for emergency management analysis.

The network layer represents the exposure; to evaluate the vulnerability of network segments to a specific natural hazard (or multi-hazard - the analysis can also take this dimension), it is required to associate failure probabilities. For individual structures (such as bridges, tunnels, pump facilities, electricity poles) or for buildings (including network buildings), vulnerability functions are commonly used to determine damage probability or even more: functionality loss or resilience functions such as closure time or recovery cost. Although it is recommended to use structure-specific (local) functions, considering particular properties of the structure and of the construction practices in the specific country/region, there are currently available fragility function libraries, collected and harmonized in projects such as Hazus, Syner-G or SERA, which can be associated, preliminary, to some of the assets in other region. In some cases, analyzing the probability of a building to collapse can be further linked to the probability of road blockage, due to debris for example (in case of earthquakes, there are equations in this purpose such as Santarelli et al., 2018; Zanini et al., 2017; Argyroudis et al., 2005; Moroux et al., 2004). Knowing where affected areas are also contributes to the evaluation of indirect risk, aiding for example to calculate the chance of people caught under debris to survive, using results of on-field studies such as Hekimoglu et al. (2013), Coburn and Spence (2002) or Goncharov (1997).

After including references to the natural hazard, in the form of maps with transferable values to vulnerability functions, the result would be an evaluation of the direct possible damage and as such a probability of network segment blockage. This can be used for generating random scenario simulations using the Monte Carlo approach (potential acknowledged by Burt and Graham, 1971), in order to test the behavior of the network in multiple probable situations. Assigning a probability of 100% for the failure of a network segment (indicating certain blockage) is useful for worst-case scenarios or clear cases of vulnerability (for example: a highly vulnerable bridge which will certainly not withstand high acceleration values due to an earthquake or a road segment where rock falls happen even without a significant trigger). However, in most of the cases this probability will need to be smaller, allowing for random simulations to show multiple implication patterns. Also, post-disaster traffic can be considered independently for each simulation. Monte Carlo scenarios are usually supposed to come in large number (hundreds or thousands of runs) and, depending on the size of the network, the amount of computational time is expected to be considerable. However, the need for a vast number of Monte Carlo scenarios might not be really necessary. The existence of many viable detour routes in urban areas or the small number of identified network segments expected to be highly damaged can determine the need of a smaller sample of Monte Carlo scenarios - that is why the stabilization of results must be traced.

For estimating post-event traffic patterns, it is needed to include assumptions providing travel speed modifications for road segments located close to affected areas, especially in urban agglomerations. Some hints for determining these patterns can be found in the work of Zanini et al. (2017) or Chang et al. (2012). More complex approaches relying on individual driver behavior simulations or decision patterns, as described in Asaithambi and Basheer (2017) or Munigety and Mathew (2016) can be implemented.

At the core of the network implication analysis there can be used different shortest path routing algorithms (by short not referring always to distance, but also to less risk), such as Dijkstra, A*, Johnson's Algorithm or Floyd-Warshall. In our implementation and case study we preferred the Dijkstra algorithm, which was used for computing the shortest distance (in real meters or costs) for various network configurations - pre and post event (for Service Area/Route/Closest Facility/OD Matrix analysis). This algorithm is widely used in systemic network analysis (Sniedovich, 2016), providing a good balance between precision and performance (Bast et al., 2016), being also chosen as preloaded algorithm in ArcGIS. Depending on user preferences, other algorithms can be applied – using for example an alternate approach relying on QGIS with pgRouting (https://pgrouting.org/) or A* in ArcGis. For Service Area analysis, used in the emergency intervention travel time evaluation, we recommended as analysis method using Detailed Polygon Generation, with results of prior analysis for identifying inaccessible network areas as barriers, since the results will better reflect small inaccessible areas.

The entire methodology is embedded in a toolbox called Network-risk, which currently runs under ArcGIS Desktop Advanced (10.1+ version) with the Network Analyst extension enabled, using ModelBuilder capabilities (Fig. 2). This toolbox takes advantage of the already available geo-processing and location-allocation algorithms and enables a standardized, non-hazard dependent and automated large-scale network risk analysis. In this direction, we acknowledge the previous works of Vodak et al. (2015), Pinto et al. (2012) or Sevtsuk and Mekonnen (2012), which we consider however not fully usable especially in the more recent context. Having the methodology implemented in ArcGIS offers extended analysis support, through cartographic, spatial analyst modules, available basemaps, plug-ins such as ArcCASPER (Shahabi and Wilson, 2014) for computing evacuation routes and others. We chose to split Network-risk in multiple separate modules (such as for network creation, Monte Carlo scenario creation, disrupted network building, service area analysis or aggregation of results into a final index), making it easy to identify errors at different steps. The toolbox is available for download at www.infp.ro/network-risk and is free to use and customize.

Considering the steps described in Fig. 2, ArcGIS Network Analyst capabilities and the results which are later shown by our case study, Network-risk toolbox is capable to answer important questions for emergency management, city planning, commercial, insurance, industrial or real-estate agents and many others, such as:

- Which areas could become inaccessible after a natural disaster? Which are the vital access routes in case of a disaster? Are there viable detour routes?
- Which is the socio-economic impact (in terms of human or financial losses) in case of a natural disaster, correlated also with emergency management capabilities?
- How would new network segments, hospitals, fire stations or other facilities contribute to reducing the risk? Where should they be placed?

## 3 Bucharest road network case study, considering seismic hazard

### 3.1 Case study area description

For testing the methodology, we selected Bucharest - one of Europe's endangered capitals due to high seismic risk (Toma-Danila and Armas, 2017; Pavel, 2016). The city was previously affected by strong earthquakes in the Vrancea seismic area (such as the ones on November 10th, 1940, Mw 7.7 at 150 km depth and on March 4th, 1977, Mw 7.4 at 94 km depth) and is currently still poorly prepared (Pavel, 2016) for a next major event which will most certainly happen anytime in the next 100 years. Compared to 1977 (when 1578 people died in Romania, from which 90% in Bucharest), the city now faces an additional challenge, beside the high vulnerability of the building stock: the vulnerability due to road network and urban traffic. In a city with over 2 million inhabitants there are 1.2 million registered vehicles (NIS, 2018). To this number can also be added the contribution of transit vehicles not adequately serviced by an external ring road (Fig. 3c) or vehicles of numerous commuting persons from nearby counties or students. In the absence of efficient urban development and mobility measures, in combination with mentality issues (the self-requirement to own and use a car), the city faces regular traffic jams, being ranked as Europe's number 1 capital (and 5th in the world in 2017/11th in 2018) when it comes to typical congestion level (TomTom, 2018; typical traffic examples in Fig. 3d, 3e and 3f). Beside traffic, Bucharest's road network maintenance and serviceability status is precarious, with many dysfunctions related to the quality of embankment, bridges, over or underpasses (Fig. 3a), poor repairing works, limitations in the full utilization of road's length due to illegal (and unsanctioned) parking in many cases (Fig. 3b) or constantly exceeded deadlines for repair or new road works. Another important aspect is that many buildings, not solely in the city center, are highly vulnerable to earthquakes (Toma-Danila et al., 2017). More than 31430 residential buildings were constructed prior to 1946 (294 having more than 4 storeys - a vulnerable category due to long fundamental periods of intermediate-depth Vrancea earthquakes), according to the 2011 National Population and Housing Census. In addition, 26349 residential buildings (237 having more than 4 storeys) were constructed between 1946 and 1960, in a period with no compulsory seismic design code, enduring at least one major earthquake with limited evaluation and seismic retrofitting afterward (Georgescu and Pomonis, 2018). One should realize that if only 1% of them will completely or partially collapse, it could clearly lead to many deaths and injuries, difficult to manage considering hospital capacity and equipment, as the recent Colectiv Club fire disaster proved (Marica, 2017), but also due to severe road blockages. In 1977, central boulevards such as Magheru were closed for at least 3 days after the March 4th earthquake, still the typical traffic was not severely affected due to low traffic values and the wide use of public transport in those days. We aim to how that nowadays, such a measure would have much more adverse implications. Considering also the nowadays much wider expected damage scale (Armas et al., 2016; Pavel and Vacareanu, 2016), emergency interventions will have to be provided from multiple locations (inside and outside the city) and usual traffic patterns (not to mention the ones right after a major earthquake, depending also on the time of occurrence) will clearly act against proper reaction. All these problems make Bucharest a highly representative testbed for the methodology proposed in this article.

Preliminary analysis of the associated seismic risk of the Bucharest road network was performed in the recent years, using slightly different approaches (Toma-Danila, 2018; Ianos et al., 2017), however not so flexible or at full city scale, concentrating only on the city center. Our goal for the analysis is to play an important role in the mitigation of seismic risk in Bucharest, being the first analysis for entire Bucharest.

### 3.2 Data and methods considered for Bucharest

The starting point for the analysis was the development of a road network GIS database, respecting connectivity and elevation rules. Currently, an official database of such kind is not available for Bucharest. That is why we used data from OpenStreetMap (OSM), which is one of the most successful crowdsourcing project aiming to create a geospatial database of the whole world, with relatively up-to-date data for Romania thanks also to the involvement of many local volunteers (https://forum.openstreetmap.org/index.php), with good applicability in vehicle routing (Graser et al., 2014). OSM road vector data was downloaded using the Geofabrik GIS Data Portal (http://download.geofabrik.de), requiring additional processing in ArcGIS Desktop's ArcMap (Network-risk toolbox template and guidelines are provided), in order to convert it in the ArcGIS network format, accounting for connectivity, hierarchy, travel direction (From-To - FT and To-From - TF), Z-elevation (creating distinctions between roads at ground level, bridges or underpasses) and travel time. For Bucharest - up to the external ring road and its connections to city center, the final number of individual road segments resulted (everything represented in Fig. 3) was 50412. We used data from September 2016; since then, up to December 2019, no major road network modifications happened in Bucharest (the main exception being the extension of A3 up to north-eastern Bucharest, but with no major influence on our analysis). When analyzing statistics (especially road length) it is important to account for road segments difference of drawing roads per lane or as a whole in OSM - otherwise the real number of kilometers will in some cases be doubled. That is why we prefer not to present statistical road length graphs.

For determining which road segments can be affected by earthquakes we used the procedures described in Table 1. In total were determined, totaling 1.41% of the total number of road segments in Bucharest:

- 1324 segments with variable length which can become affected by debris (partially shown in Fig. 4, just 32,6% however with a damage probability > 50%);

- 985 which can become affected by bridge collapse.

After performing 20 Monte Carlo simulations (each with an average runtime of 12 minutes on a normal desktop computer - from simulation to service area results), we considered results stable enough to reflect the damage patterns for the rather extended road network of Bucharest and stopped our simulations, which are not time intensive but still difficult to summarize automatically.

In order to account for traffic - a major issue for Bucharest, we followed the patterns shown by typical Google Traffic, for various representative scenarios:

- Monday 2:00 AM - no traffic;
- Monday 8:00 AM - morning traffic;
- Monday 6:00 PM - end of work traffic.

Traffic values were obtained by:

- digitizing areas described qualitatively in Google Traffic (very slow, slow, moderate or fast traffic);
- identification of roads in these areas (also considering FT and TF ways);
- modification of travel times (for fast traffic - using the maximum allowed speed, for very slow traffic - 2 km/h);
- validation with the Google Traffic Direction service (for representative routes crossing the city);
- corrections applied in areas with a considerable deviation from the expected values.

Although time consuming, this procedure yielded good results. Giving that our analysis focuses on the intervention of emergency vehicles, the influence of traffic lights was neglected (although it can be considered for other analysis purposes) and the travel speed was considered 50 km/h for fast traffic road segments. For regional and national studies, detailed traffic values might not be needed, since many highways or inter-city roads (generally not crossing urban areas) do not have typical traffic jams impacting furthermore the emergency management intervention times.

For estimating post-event traffic patterns, we used a simplified approach, based on the following traffic modification parameters:

- For areas closer to 100 meters (calculated on roads as service area, not as buffer): 2 km/h;
- For areas closer to 500 meters: 5 km/h.

This approach has obvious limitations and uncertainties; however, it provides a flexible and easy-to-compute method of accounting for traffic shifts right after an earthquake, following the findings of Zanini et al. (2017). Modeling traffic driver individual behavior, also over time, is a next step which we will integrate in future studies, also trying to create the means for validation (recording the traffic patterns after major earthquakes affecting Bucharest or after local incidents in the area of vulnerable buildings).

In order to enable service area analysis for emergency intervention, hospitals and fire stations were used as facilities. We identified all representative locations in Bucharest and nearby (not including children emergency hospitals, therefore the analysis can be considered as relevant for the adult population). Although of high importance, we could not include for the moment data regarding the capacities of each facility (for example: number of ambulances, hospitals treatment capacity or fire engine's equipment); these can be considered, reflecting limitations or restrictions in the emergency intervention process (for example: how many addresses can be reached within an amount of time due to vehicle availability, how many people can be transported to and hosted by a hospital or where are vehicles with ladders, necessary for intervention in areas with high rise buildings). We will address these issues in further studies when more complex data become available; ArcGIS Network Analyst extension can easily accommodate such information and also special evaluators can be added.

The main toward-risk analysis for Bucharest was represented by service area analysis for emergency management facilities (ambulances for emergency hospitals and fire engines), reflecting which are the times of intervention right after a major earthquake affecting Bucharest (the ultimate limit state design earthquake), at three different times for which traffic values are considered. Results provide a check upon the capabilities to offer intervention within the golden hour in medicine (Lerner and Moscatti, 2001) - when emergency treatment is most likely to be successful. We also analyzed the pre and post-earthquake time differences for representative economic transit routes, through closest-facility analysis. The parameters used in analyzes are described in Table 2.

The total amount of service area maps resulted for all Monte Carlo scenarios, for service area analysis, is considerably large and not relevant independently (the map by map evaluation is more important for quality check and in order to see the stabilization of result patterns). That is why it is needed a further procedure for aggregating data - as it happens with big-data. Providing a data synthesis easier to grasp is very important for stakeholders. In this purpose we developed a procedure based on the following reclassification and aggregation procedure:

a) reclassification of service area polygons for post-earthquake scenarios, according to Table 3;
b) for each service area polygon with identified number of facilities providing the best and second-best intervention time: determination based on Eq. (2) of a counter (C1) reflecting the dependency to a specific facility;

$$C1 = Ni + 0.5 * Ns, \tag{2}$$

where Ni = number of facilities providing the best intervention time; Ns = number of facilities providing the second best intervention time; if the service area polygon ≥ 30 minutes, Ni = 0;

c) determination of an index (Vi) for each scenario, reflecting the reclassified vulnerability, applied to all polygons, following the considerations in Table 4;
d) weight overlay of Vi values calculated for emergency hospitals and fire stations, for a specific scenario, applying 25% (0.25) for emergency hospitals and emergency hospitals in category I of importance (in order to reflect the contribution of truly important hospitals in emergency situations), and 50% (0.5) for fire stations (in Bucharest it is relevant to have an important weight for fire stations since they do not provide just equipment for fire extinguishing, but also Mobile Services for Emergency, Reanimation and Extrication, abbreviated SMURD units), leading to a new final vulnerability index per scenario: Vf;
e) averaging of Monte Carlo scenario simulations with Vf values;

f) further averaging of resulted maps with Vf values (6 in total for Bucharest: 3 for the worst-case model and the three traffic scenarios, 3 for Monte Carlo averaged scenario results) for a final result map, revealing the combined index of vulnerable accessibility (Fig. 7).

By merging polygons representing areas which can become inaccessible after an earthquake (for each simulation) and also accounting for the number of times these polygons are generated, a very useful representation of areas difficult to reach can be generated. After reclassification (in our case based on 5 equal intervals), a qualitative probability for areas to become inaccessible can be expressed. Areas with the lowest probability are generated just for the worst-case model, not appearing during the Monte Carlo limited number of simulations (Fig. 8).

A different product which can be obtained using the network database and Closest Facility Analysis are maps showing relations between emergency hospitals or fire stations (as destinations) and high-risk buildings (as origins), as routes or best facility in terms of safe to reach proximity. Useful maps or routing services which could become available in near-real time can be obtained by combining the fastest routes for OD pairs, for a given scenario, showing also which roads are vital in an emergency situation (need to remain functional since they are critical, providing the quickest access time in the origin).

The seismic risk due to road network dysfunctionalities can be expressed not just by considering the impact of road blockage and traffic on emergency intervention, leading to time limitations in reaching patients. When roads are closed, connectivity throughout the city can be lost for days, weeks or years, with a high impact on economy - due to delays in stock supplies and production, greater costs for carburant or loss of clients. Our network dataset can also be used to monitor which are the differences between pre and post-earthquake travel times, for representative OD pairs. For this case study we selected 8 pairs in relevant cardinal points, some with links to the city center and some aimed to show if in case of an earthquake the initially preferred route throughout the city is going to change in favor of the external ring road.

Uncertainties and limitations are an important aspect to account for. As a preliminary evaluation we provide the following qualitative uncertainty evaluation, regarding:

- the road network dataset accuracy - small source of uncertainties;
- the limited dataset regarding buildings which could collapse during an earthquake – moderate source of uncertainties;
- limitation in evaluating and validating the travel times for emergency intervention vehicles (as recently the allowance of using tramway separated tracks lead to improved intervention times) – moderate source of uncertainties.
- typical traffic scenarios considered – small source of uncertainties;
- post-earthquake traffic patterns – high source of uncertainties.

### 3.3 Results

The figures presented in this subchapter summarize our main findings and are obtained for the multiple Monte Carlo and worst-case scenarios run with Network-risk toolbox. Results are foreseen to contribute to:

- operational procedures of the Inspectorates for Emergency Situations (such as the National Concept for Post-Earthquake Intervention - implementation discussion on-going);

- risk-reduction strategies elaborated at national and local level;
- the new planning of new emergency hospitals in Bucharest;
- the identification of easy to access locations for emergency containers.

Figure 5a and 5b reflect differences between worst-case scenario (all roads and bridges with a probability of damage affected) and results from Monte Carlo simulations. As such, Fig. 5a presents, for some areas, slightly more increased intervention time values. Figure 5c shows service area intervals when considering only emergency hospitals in category I of importance. It can be seen that their distribution is generally satisfactory, however there is an area with significantly greater intervention times, reflected also by Fig. 5a and 5b, in the south-west area of Bucharest (Rahova and Ferentari neighborhoods) - an area known also for its socio-economic vulnerability (Armas et al., 2016), also with no major hospital in adjacency. Due to the significant damage expected in the central area, intervention times are expected to be considerable (given also the traffic values for the considered scenario). The impact of a central hospital such as Coltea is reflected in the partial decrease of ambulance intervention times for city center. However, in the post-earthquake chaos, especially if the earthquake will strike at rush hour, traffic jams are going to pose a considerable threat to road accessibility; our study reveals some of these effects (Fig. 5-9) and that some areas could be much easier accessed by ambulances from non-central locations. Bridge dysfunctionalities do not seem to pose great influences (when comparing also with no damaged bridge scenarios), since in general there are many nearby alternatives. Basarab Overpass (north-west to the center - labeled in Fig. 3) is the only one who, if inaccessible, could lead to considerable increase of intervention times. Figure 5d is, although difficult to comprehend at first sight, important since it provides a visual check upon the correlations between minimum intervention times and the number of hospitals who provide this time; if an area is colored towards green and is also hatched, this means that the area is close to multiple emergency hospitals, having a lower vulnerability in case of medical emergencies. Data behind this type of maps adds an additional understanding to the overall accessibility analysis, being however more demanding in their creation (requiring service area analysis per facility and counting of number of overlapping polygons with a certain value).

Figure 6 shows service area results for fire stations; the distribution of fire stations is more symmetrical in Bucharest then the distribution of hospitals, also with a unit in the city center (“Mihai Voda” fire department), behind the Bucharest City Hall building. For the chosen scenario (Monday 8AM typical traffic), the influence of this distribution can be seen south of Piata Unirii (Fig. 6b zoom map), were also boulevards are not expected to be blocked by debris, but north - toward Piata Universitatii and Piata Romana, post-earthquake congestion and road segment blockages are expected to significantly increase the travel times. To help in the effort of reducing the intervention times in the central area, the “Victoria Palace” fire department (devoted to the Government’s building) could contribute, however we did not find appropriate at the moment to consider it in the analysis, until learning more about their attributions.

In order to facilitate the understanding of results, also from the point of view of non-experts, we further show the results of the aggregation methodology used for creating a final index of vulnerable road accessibility for Bucharest. Figure 7 - the first map of this kind for the entire territory of Bucharest, reflects some of the expected features: a high vulnerability of accessibility in central area of the city, due to vulnerable buildings and difficult to reach (in case of an earthquake) hospitals (especially in

Category I of importance) and fire stations. Also, the figure shows other areas more difficult to reach by all types of emergency vehicles right after an earthquake: western Bucharest (Militari neighborhood) or south-western and south-eastern Bucharest. Areas with good accessibility appear to be in the inner green belt north to the inner ring road – where there are hospitals and fire stations nearby and no disruptive traffic (although quite intense during rush-hours) and disrupted road segments.

Another important result of the analysis, proving the Network-risk capabilities, is presented in Fig. 8. As expected, inaccessible areas are mostly in the city center (streets such as Blănari, Lipscani, Șelari, Smârdan, Sf. Dumitru, Franceză, Tonița, Eforiei or Biserica Doamnei), where many buildings are expected to block roads and detour routes to the locations. Other blocked road segments, with lower probability, could be on streets such as Bărăției, Pătrașcu Vodă, Vasile Lascăr, Poiana Narciselor, Dr. Vasile Sion, Ion Brezoianu, Tudor Arghezi, Batiștei, Jules Michelet etc. Due to the algorithm for Service Area computation, some areas between roads are colored as being blocked (as in Cismigiu Central Park for example), however this is a method limitation and can be eliminated through clipping.

Fig. 9 is the result of Closest Facility Analysis, showing the safest and fastest routes (and the density of these routes) between buildings in seismic risk class I and emergency hospitals and which hospitals would be the preferred facility for a certain building, based on adjacency (no medical capabilities are considered) - setting premises for a better preparedness of hospitals expected to have a high patient demand (medical supplies, hospital beds, doctors etc.). Figure 9a highlights, for the specific scenario, 3 routes in high demand: from city center toward east, west and north-west. Figure 9b shows that Coltea Hospital is not although in the city center, not the best option for many vulnerable buildings.

Table 5 and Fig. 10 show results for representative OD pairs to the economic transit routes – any other OD pairs can be introduced. For the 2 AM traffic scenario, differences are not significant, as post-earthquake traffic is not expected to be a significant problem, however for the 8 AM and 6 PM scenarios - especially for routes which need to reach the city center (Piata Universitatii for example), there are clear values showing a mean travel time increase from 110-120% to 300-432%, for the Centura (external ring road) - Otopeni -> Piata Universitatii route.

## 4 Conclusions

In this paper we presented a new methodology for evaluating direct and indirect implications of natural hazards on transportation network. This methodology was designed to be generally applicable and adaptive to various types of hazards, networks or available vulnerability and exposure data. Starting from structural evaluation, the analysis focuses on systemic or functional assessment, expressing furthermore the risk inflicted mainly by connectivity loss. After determining hazard, exposure and vulnerability factors - leading to the definition of the network and the identification of segments which can become unusable (and the probability of this to happen), Monte Carlo simulations can be performed. This enables the creation of multiple scenarios evaluated individually in terms of generated risk (for emergency intervention or socio-economic aspects) and aggregated into final risk indexes. There are also capabilities of accounting for pre and post disaster traffic and for emergency facilities capacity or equipment. In order to facilitate the use of the methodology we integrated it into an open toolbox (collection of models) entitled Network-risk, which is free to download and customize.

To prove its capabilities, Network-risk was tested on the entire road network of Bucharest, Romania, one of Europe's most endangered capitals due to earthquakes, considering the high seismic hazard values generated by intermediate-depth Vrancea earthquakes, the vulnerable building stock (349 high or moderate rise buildings are categorized in the seismic risk class I in January 2016, representing just the tip of the vulnerability "iceberg") but also major traffic congestion patterns. One of the most difficult parts in the analysis was the proper input data collection. As we showed, this can be achieved (at least for a preliminary form) in a satisfactory form, by using OpenStreetMap data along with a Network-risk module designed to arrange (partially automatically) the network data into ArcGIS network format. Digitized traffic areas based on Google Traffic layers or empirical formulas, literature fragility functions and expert judgement for determining road segment failure probabilities also contribute to the input. Our analysis focused both on the evaluation of emergency intervention times (for emergency hospitals and fire stations) and on the evaluation of economic implications for representative commercial routes (time delays in post-earthquake conditions).

Results show that the city center would be significantly vulnerable not just because of collapsing buildings but also due to the difficulty to reach these sites by ambulances and firefighters; although there are facilities nearby, such as the Coltea Hospital (however not of category of importance I) and the "Mihai Voda" fire department, these do not provide safe routes to all potentially affected buildings, due to road blockages and traffic jams, considering especially the Monday 8AM and 6PM typical traffic scenarios. Aggregated results in Fig. 7 and 8 show that also for the western, south-western and south-eastern parts of Bucharest overall intervention times can be significant – valid supposition confirmed verbally by members in the emergency intervention forces.

### 4.1 Discussion

Stakeholders such as emergency situations managers provided us important feedback, acknowledging that the final products can fit well in their procedures, both for scenarios development (prevention) and for near-real time implementation (reaction). Practical applications can consist on determining new locations for emergency facilities, on increasing facility capacities, for traffic management planning or efficient and safer routing of emergency intervention vehicles. As a comment for future methodology users, we want to mention that, when calculating service areas, it is very useful to account for the dependency to a single facility to provide the minimum intervention time and we will aid a module in Network-risk to provide a performance indicator in this purpose.

In our opinion, the service area analysis for Bucharest shows the necessity of an emergency hospital in the south-western part of Bucharest - an area also known for its high socio-economic vulnerability. For the city center, a strategy in case of an earthquake has to be elaborated and put into place, referring to measures to facilitate/restrict the access in the area in case of natural disasters, traffic redirection and design of safe road access corridors. As highlighted, the vulnerability of routes connecting the city center, especially with north or south destination, can be significant, with travel time increase greater than 150% in typical scenario conditions.

As Network-risk is for now dependent on the commercial software ArcGIS Desktop Advanced, with Network Analyst extension, we will try in the near future to integrate its methodology also in non-commercial GIS software such as QGIS. However, this still require at the moment more development toward advanced network analysis. The current Network-risk toolbox is under continuous development and in future versions more features will be available, so please check regularly the website. We also aim to test it more consistently, with analyzes at regional/national scale (using also rapid seismic loss estimations generated by the Seisdaro System of INFP, presented by Toma-Danila et al., 2018), for multiple hazard scenarios and also for more detailed vulnerability datasets comprising also on the social behavior and interaction of people with transportation networks.

We hope that this article will provide researchers important practical guidelines on how to analyze the risks of transportation networks affected by natural hazards and a useful tool to be applied in other parts of the world and stakeholders an example of useful results which they could benefit from, in their efforts to better understand and mitigate risks.

## Code and data availability

The Network-risk toolbox for ArcGIS Desktop and sample data for Bucharest (used for this study) can be downloaded, with user manual, at www.infp.ro/network-risk. Please revisit the address and check for new versions, since the toolbox is constantly being upgraded.

## Author contribution

DT-D and IA developed the methodology and DT-D and AT implemented and tested it in GIS, obtaining results analyzed also by IA. DT-D prepared the manuscript with contributions from all co-authors.

## Competing interests

The authors declare that they have no conflict of interest.


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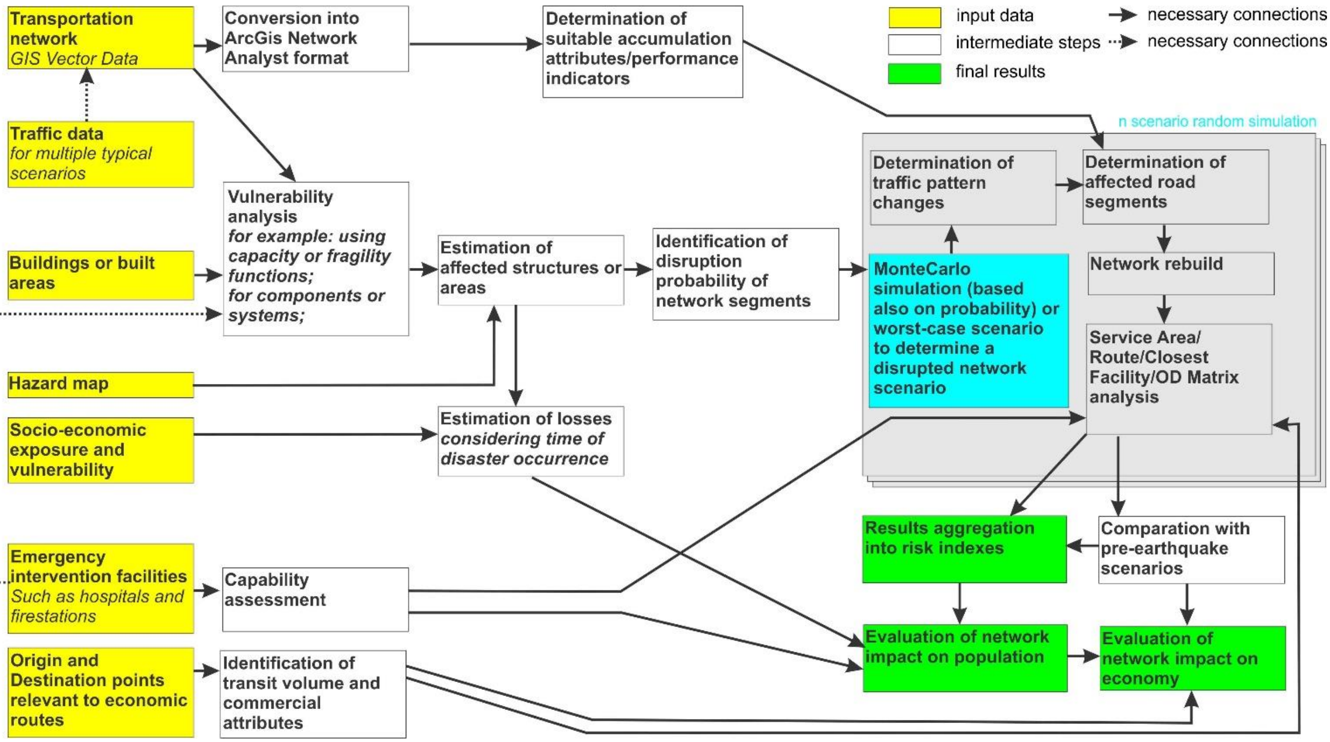



**Figure 1: Graphical representation of the proposed methodology for evaluating the implications of transportation network damage due to natural hazards, integrated in the Network-risk toolbox.**

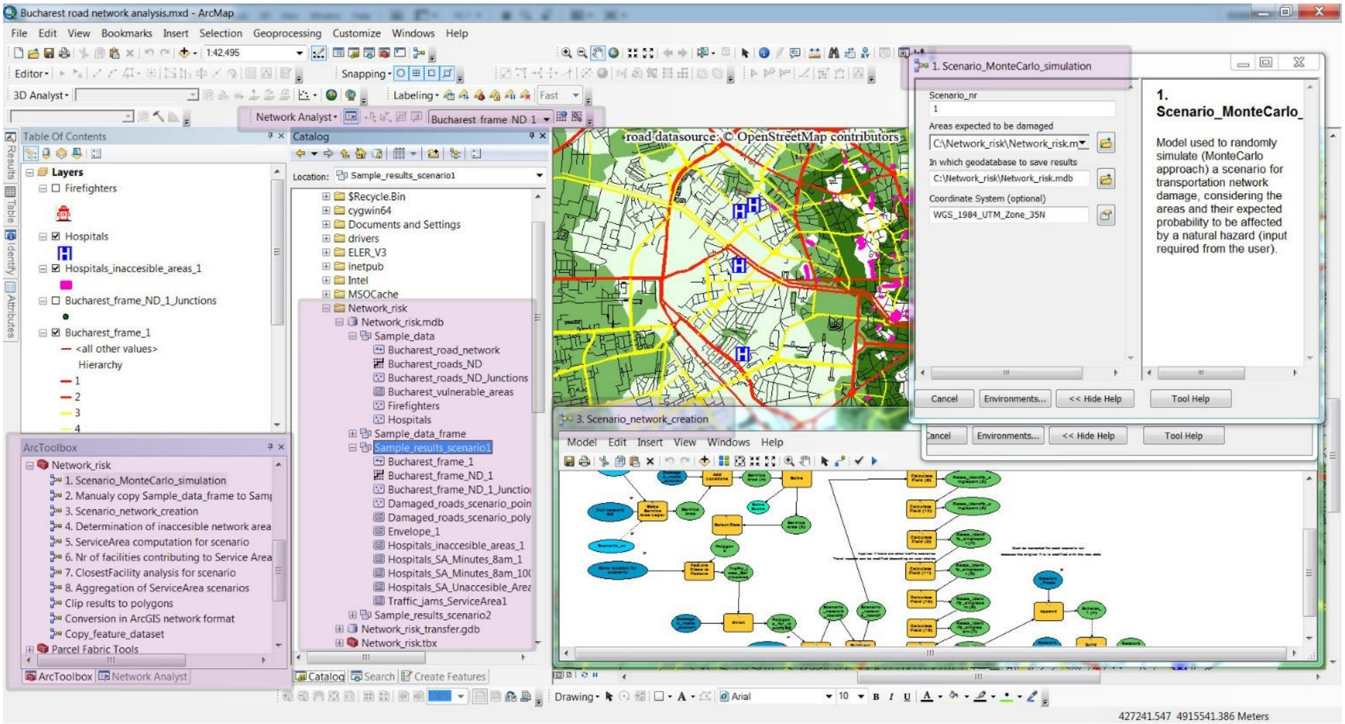



**Figure 2: Screen capture of ArcGIS Desktop ArcMap with Network-risk toolbox added, contributing to the analysis of Bucharest's road network risk analysis; the framework of one of the models (3. Scenario network creation) can be seen, as well as the model run interface (1. Scenario Monte Carlo simulation), the Network-risk toolbox modules and the sample data results created using these modules (highlighted with purple).**

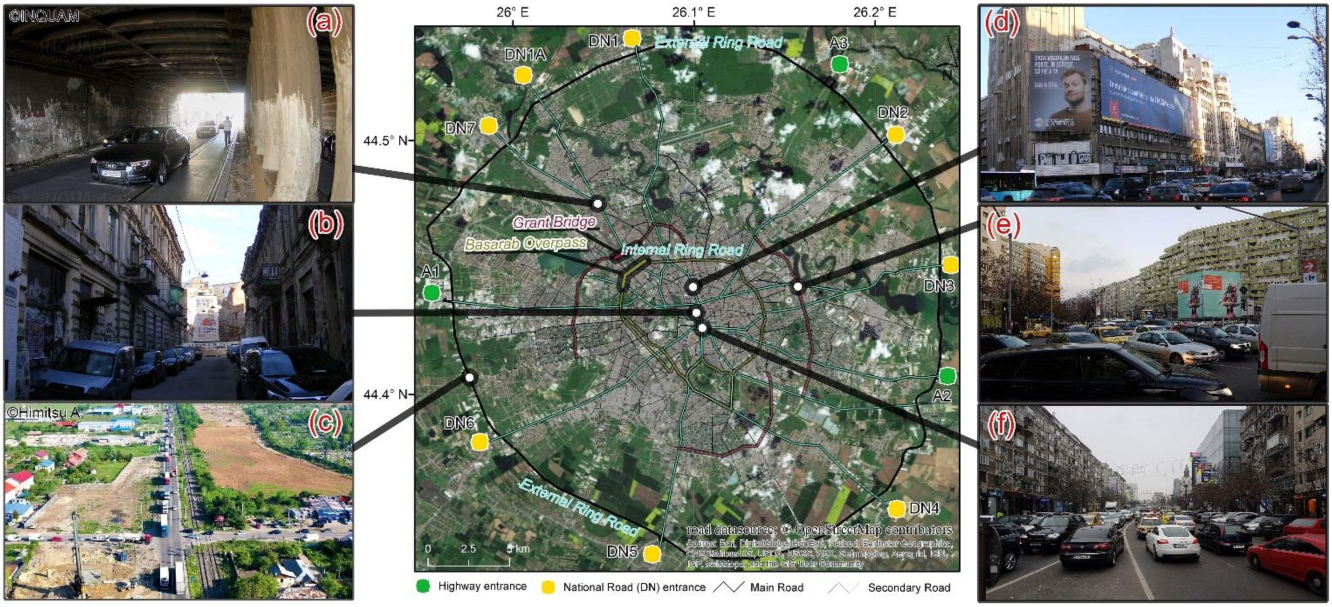



**Figure 3: Bucharest road network map, highlighting main roads and connections with highways and national roads (datasource: © OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License, data from September 2016; basemap: © ESRI and contributors), and examples of vulnerable underpasses [(a) Constanta Bridge, © INQUAM], illegal parking (b), southern External Ring Road dysfunctionalities [(c) © Himitsu A.], typical rush-hour traffic (d, e, f) and vulnerability due to old buildings with seismic risk (b).**

**Table 1: Factors considered for determining the probability of road segments to be affected by earthquakes.**

| **Factor** | **Method of analysis** |
|---|---|
| Bridges | Mean fragility functions from Crowley et al. (2011), for the corresponding structural typology (mostly reinforced concrete) were used. Considering the microzonation map of Marmureanu et al. (2010) for maximum PGA values in Bucharest due to the largest probable earthquake in Vrancea, the complete damage probabilities obtained were small: 1.5 - 2%. For the Basarab Overpass fragility functions were adapted due to different characteristics (suspension and steel arch bridge sections, seismic passive dampers), considering descriptions in Sartori M. (2012). |
| Roads blocked by building debris | We used Eq. (1) (from Moroux et al., 2004) to determine the probability of roads to be blocked by the debris generated by the collapse of buildings in the seismic risk class I, which are most likely to collapse during the design earthquake (349 in total, mostly with more than 4 storeys, according to Bucharest City Hall data from January 2016 - https://amccrs-pmb.ro/liste-imobile); the footprint of buildings was determined, and buffers were added according to debris area; the output (Fig. 4) was supplemented by expert judgement based on satellite images, building structural considerations and building vicinity, road width etc., to attribute road blockage probabilities - ranging from 1 to 70%, since no building is certain to collapse.<br>$\text{Debris area (meters)} = \frac{2}{3} * \text{Number of floors} \quad (1)$ |
| Liquefaction | We attempted to use some data (Neagu et al., 2018), but eventually the liquefaction map was considered too generic; after more detailed analysis we can integrate it into the analysis. |

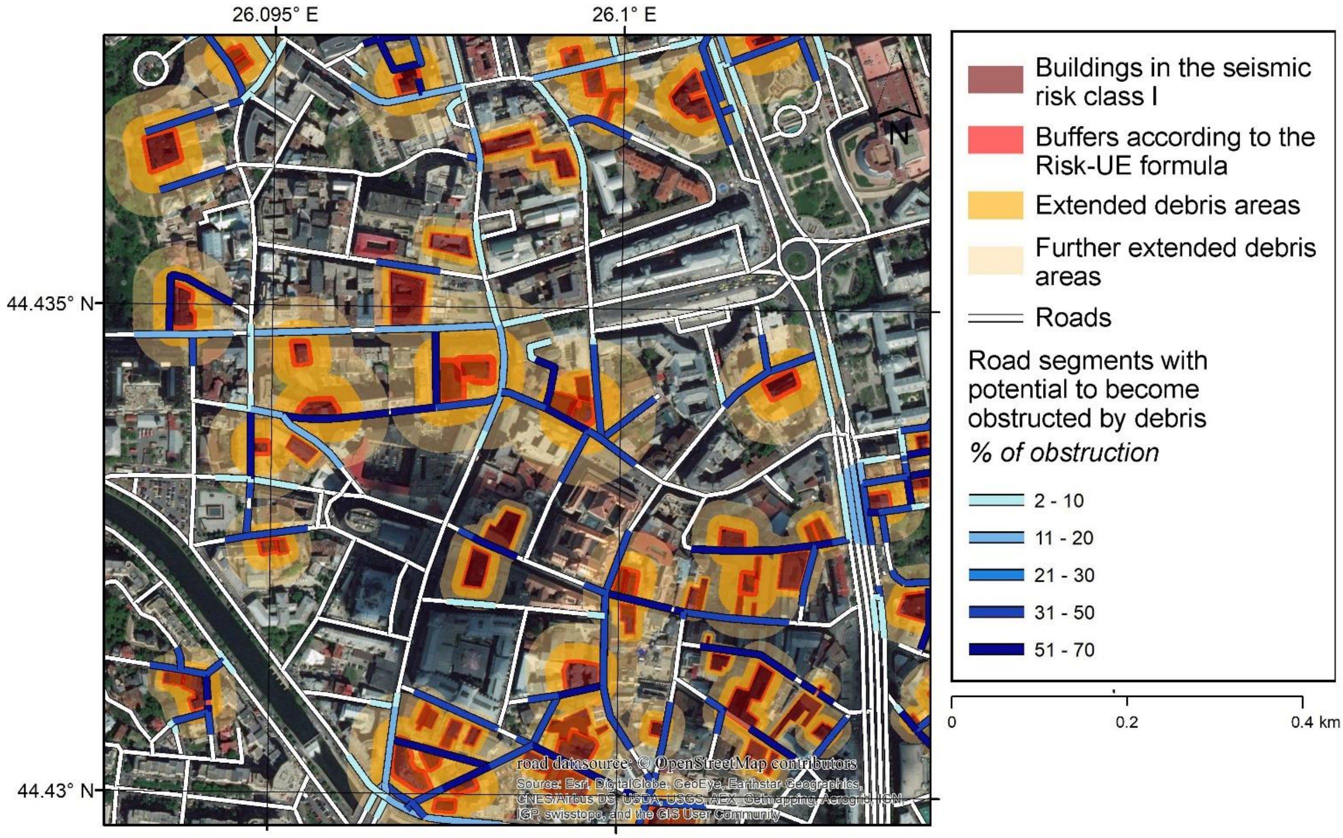



**Figure 4: Example of road blockage analysis due to building debris, applied for the historical center of Bucharest (datasource: © OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License, data from September 2016; basemap: © ESRI and contributors).**

**Table 2: Parameters used for of Bucharest post-earthquake road network risk analysis.**

| **Facilities** | **Analysis parameters** | **Considered scenarios** | **Number of maps resulted** |
|---|---|---|---|
| Emergency hospitals | Analysis type: Service Area<br>- impedance attributes: minutes (depending on traffic scenario);<br>- Default breaks: 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60 minutes;<br>- no one way restrictions (emergency management vehicles are allowed not to respect these restrictions);<br>- travel from facility;<br>- restrictions: polygon barriers (inaccessible areas provided by identifying holes from initial Service Area analysis using the "obstruction" column as impedance attribute - module provided in the Network-risk toolbox). | For three traffic scenarios (2AM, 8AM and 6PM) - pre and post-earthquake, considering 20 Monte Carlo scenarios and the worst-case model (failure of all listed segments) for blocked roads and bridges (which for Bucharest have a very low damage probability and that is why for our worst-case simulations we made a custom selection based on their health condition, year of construction and length). | 3 (pre-earthquake) + 9 (post-earthquake - worst-case model, including analysis of facilities which provide the number best and second-best times for intervention) + 20 (post-earthquake, Monte Carlo scenarios) + 3 (post-earthquake, Monte Carlo averaged scenarios) |
| Emergency hospitals in category I of importance (since they have the main capacity and responsibilities in case of an earthquake) | | | 3 + 9 + 20 + 3 |
| Fire stations | | | 3 + 9 + 20 + 3 |

| Facilities | Analysis parameters | Considered scenarios | Number of maps resulted |
|---|---|---|---|
| Origin-destination pairs for representative economic transit routes | Analysis type: Closest Facility - impedance: minutes (depending on traffic scenario); - Facilities to Find: the total number of origins/destinations (to be able to extract not just the statistics as with Cost Matrix analysis, but also the path of the route). - accumulators: minutes (depending on traffic scenario) and meters; - analysis was performed also by changing initial origins within destinations (to show differences due to traffic ways and one-way restrictions). | For three traffic scenarios (2AM, 8AM and 6PM) - pre and post-earthquake | 3 (pre-earthquake) + 3 (post-earthquake - worst-case scenario) + 3 time difference tables |

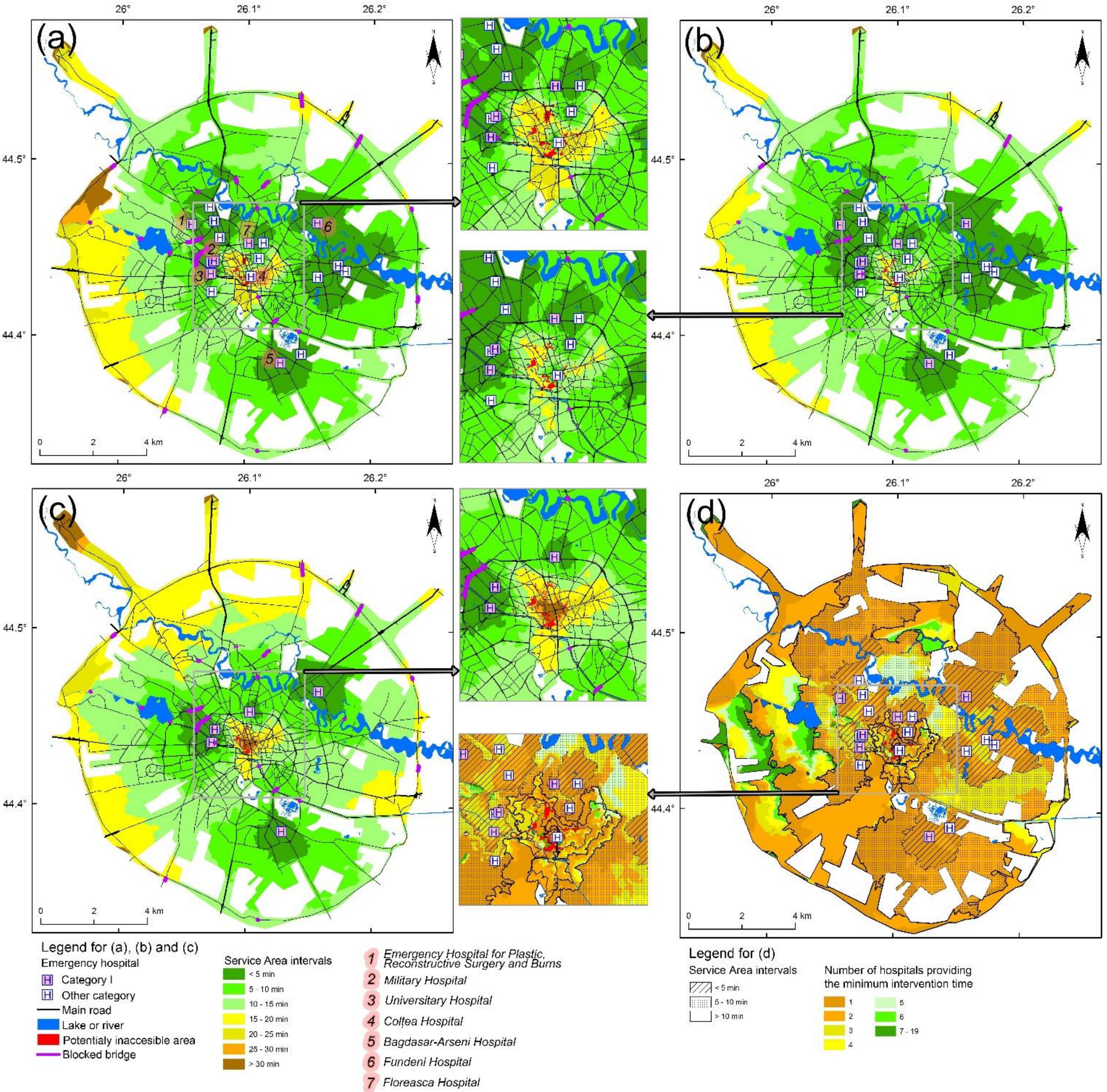



**Figure 5: Service Areas for emergency hospitals, for the Monday 8AM typical traffic scenario and for: (a) the worst-case model; (b) a Monte Carlo scenario; (c) emergency hospitals in category I of importance and the worst-case model; (d) the number of emergency hospitals providing the minimum intervention time in the worst-case model (datasource: © OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License, data from September 2016); (a) also shows the labels of emergency hospitals in category I of importance and the Coltea Hospital in the city center.**

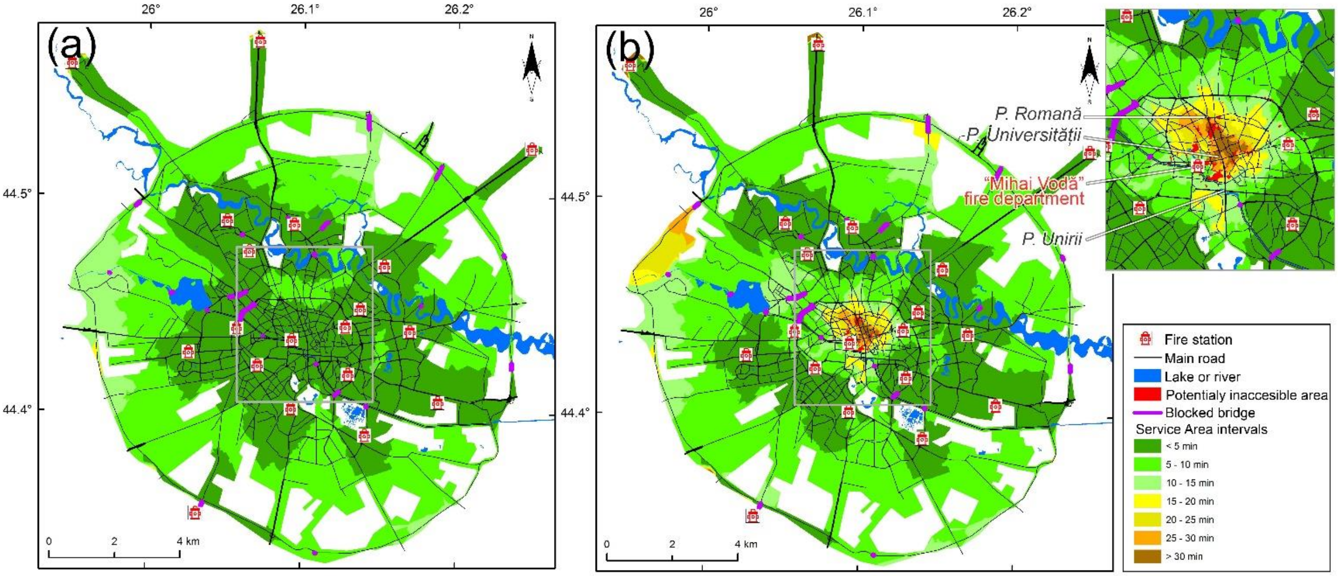


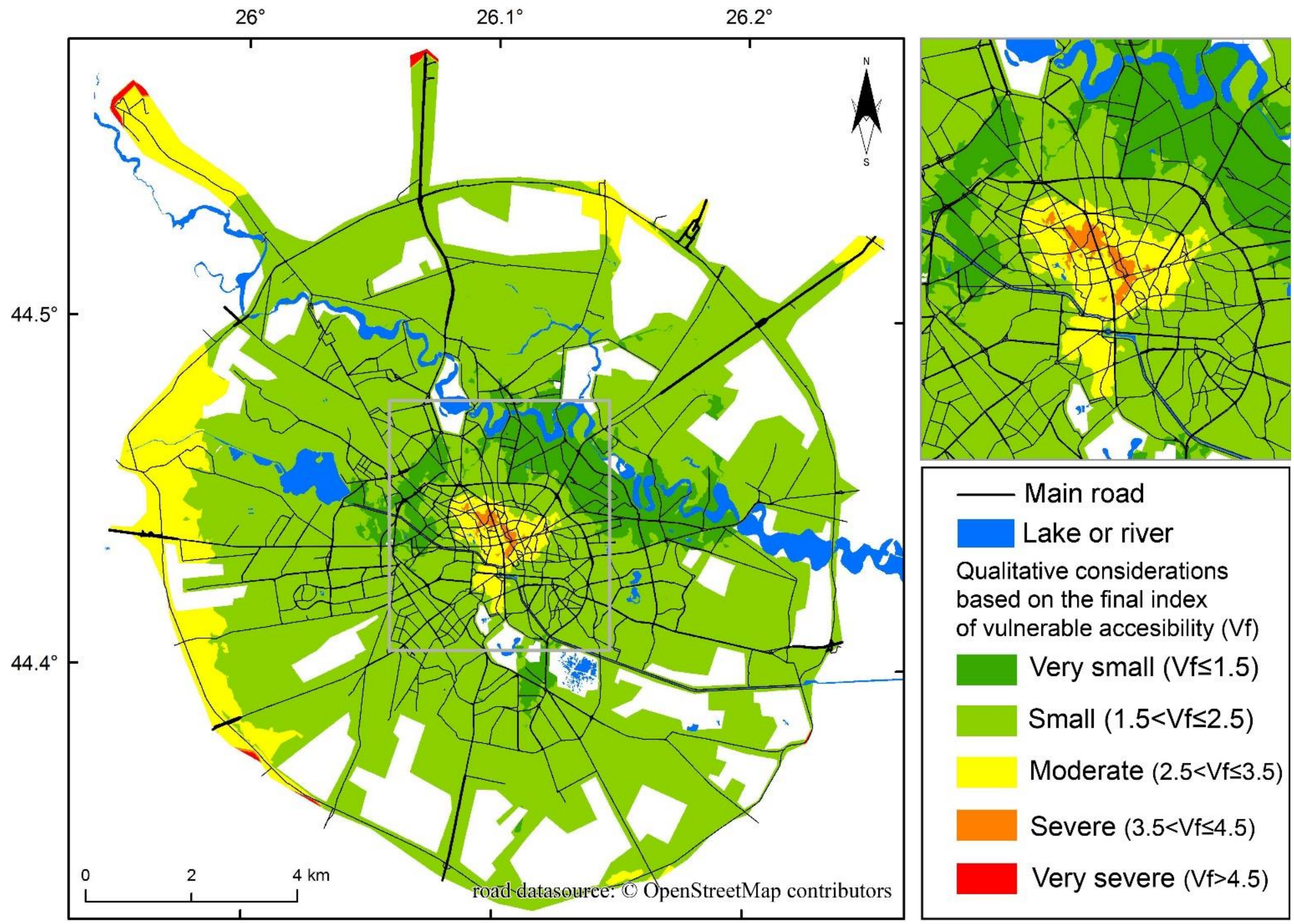

**Figure 6: Service Areas for fire stations, (a) pre-earthquake and (b) post-earthquake, considering the worst-case model, for the Monday 8AM typical traffic scenario (datasource: © OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License, data from September 2016).**

**Table 3: Reclassification intervals for service area polygons.**

| **Default breaks for service areas** | **Reclassification values (Vr)** |
|---|---|
| ≤ 10 minutes | 1 |
| 10 - 15 minutes | 2 |
| 15 - 20 minutes | 3 |
| 20 - 30 minutes | 4 |
| > 30 minutes, chosen to correspond to the golden hour in medicine principle - Lerner and Moscatti (2001), given also the necessary round-trip. | 5 |

**Table 4: Formulas for calculating the index for reclassified vulnerability (Vi); C1 intervals are relative to the facility database and study area characteristics.**

| **Formula for Vi** | **Conditions - depending on C1 values** |
|---|---|
| Vi = Vr - 0.5 | if C1 >= 5 for emergency hospitals and fire stations |
| | if C1 >= 3 for emergency hospitals in category I of importance |
| Vi = Vr (applied also to scenarios without calculated C1 values) | if 2 <= C1 < 5 for emergency hospitals and fire stations |
| | if 2 <= C1 < 3 for emergency hospitals in category I of importance |
| Vi = Vr + 0.5 | if C1 < 2 for emergency hospitals and fire stations |
| | if C1 < 2 for emergency hospitals in category I of importance |




705 **Figure 7: Final map showing qualitative values for the combined final index of vulnerable road network accessibility (Vf) for Bucharest (datasource: © OpenStreetMap contributors 2019. Distributed under a Creative Commons 625 BY-SA License, data from September 2016).**

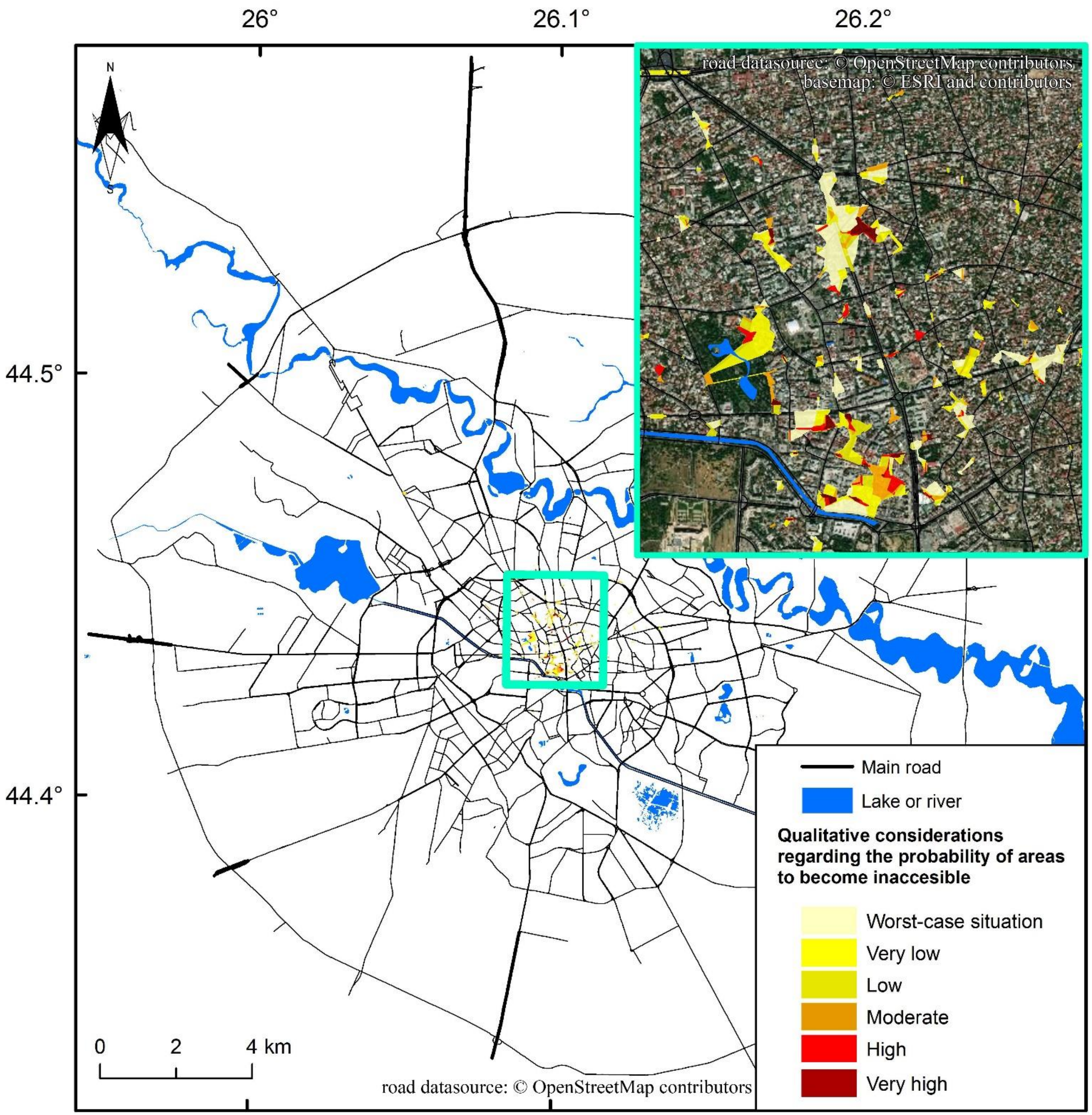



**Figure 8: Areas who can become inaccessible immediately after an earthquake (datasource: © OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License, data from September 2016; basemap: © ESRI and contributors).**

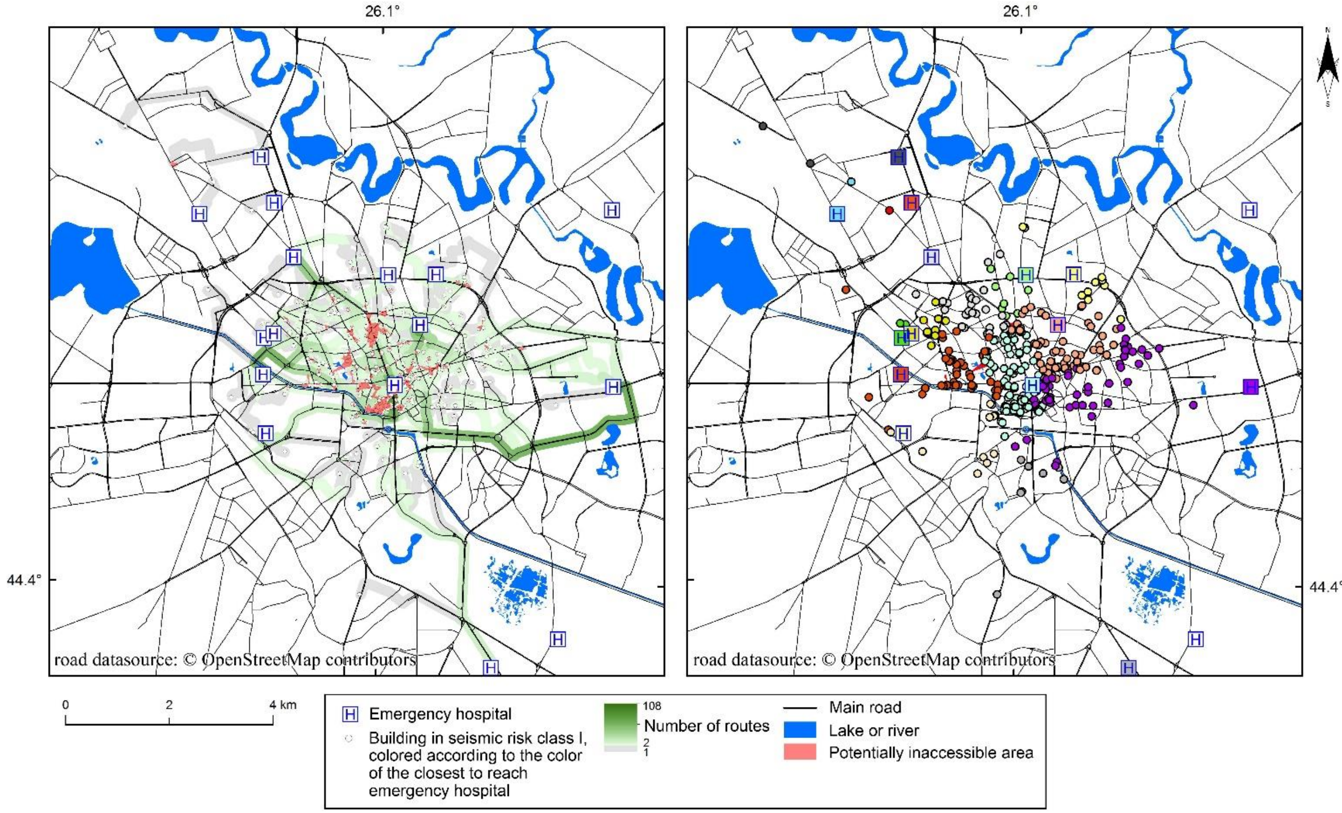



**Figure 9: Maps reflecting fastest routes (and the density of these routes) between buildings in seismic risk class I and (a) emergency hospitals, and (b) the closest hospital, for the Monday 8AM typical traffic scenario (datasource: © OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License, data from September 2016).**

**Table 5: Time differences (expressed in minutes) between various OD pairs shown in Figure 10 and for pre and post-earthquake conditions.**

| Route | From-To (FT), minutes | | | To-From (TF), minutes | | |
|---|---|---|---|---|---|---|
| | 2 AM | 8 AM | 6 PM | 2 AM | 8 AM | 6 PM |
| Centura-A1 -> Piata Unirii | 0 | 25 | 19 | 1 | 24 | 21 |
| Piata Unirii -> Metrou Pantelimon | 0 | 11 | 14 | 0 | 8 | 10 |
| Centura-Otopeni -> Piata Universitatii | 5 | 72 | 77 | 8 | 62 | 63 |
| Piata Universitatii -> Centura-Giurgiului | 1 | 30 | 33 | 3 | 45 | 44 |
| Centura-Chitila -> Centura-Oltenitei | 1 | 0 | 0 | 1 | 10 | 0 |
| Drumul Taberei -> Centura-Splai | 0 | 4 | 5 | 0 | 5 | 4 |
| Centura-Magurele -> Gradina Zoologica | 0 | 18 | 7 | 0 | 1 | 9 |
| Metrou Eroii Revolutiei -> Spitalul Fundeni | 1 | 6 | 11 | 1 | 6 | 10 |

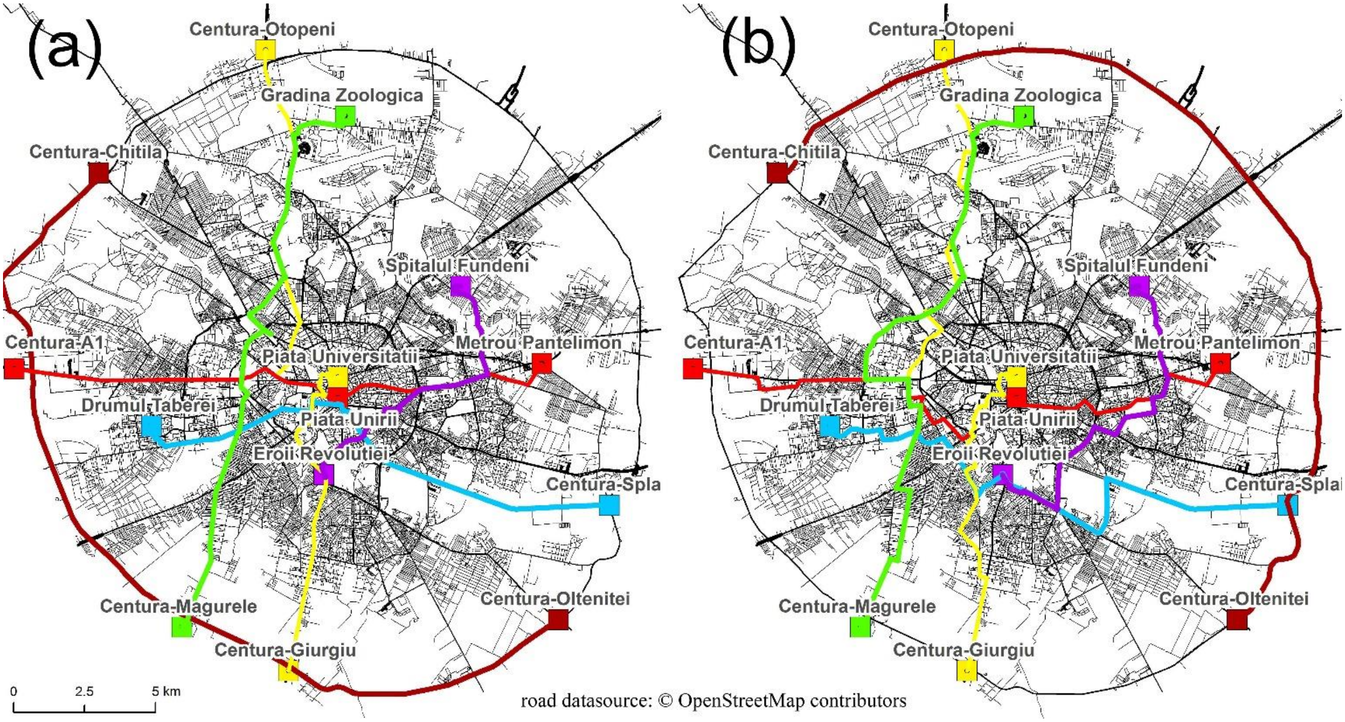



**Figure 10: Fastest routes for 8 representative OD pairs for Bucharest, for the (a) FT directions and for the Monday 2AM and (b) 6PM typical traffic scenario (road datasource: © OpenStreetMap contributors 2019. Distributed under a Creative Commons BYSA License, data from September 2016).**