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## **Evacuation vulnerability after an urban earthquake: mapping it using a GIS**

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**Abstract** – The danger that buildings and other human constructions pose to people after serious seismic events has been researched for a long time. Vulnerability and risk can now be estimated using well established methods. However, the danger that people face after an earthquake when they are moving to reach a safe spot has not been thoroughly researched. Accordingly, we address evacuation vulnerability in this paper. We chose four parameters of danger - seismic risk of the buildings lining the street, buildings' heights compared to street width, street slope and street traffic conditions, and we then assigned them to those street segments which might make up post-earthquake, evacuation routes. The results were then plotted using a GIS. In this way, we generated a useful map that clearly highlighted the street segments to be avoided as part of evacuation routes. In addition, we identified several areas with urban characteristics that increase evacuation vulnerability.

**Keywords** – evacuation, vulnerability, earthquakes, escape routes, urban planning, seismic risk, GIS

A disaster occurs whenever a potential hazard causes a catastrophic event that affects people - "there is no disaster without people" (Adger, et al., 1999). Overall negative impact is proportional to both the magnitude of the catastrophic event and the vulnerability of systems specific to the type of hazard. Vulnerability can be quantified. For example, the vulnerability of structures after an earthquake can be quantified using structural damage probabilities, and the vulnerability of societies might be quantified using demographic data.

The current research measured vulnerability after an earthquake, but part of our method can also be used for other hazard types. By examining urban and seismic characteristics of street segments we estimated the chances that any street's residents will be able to evacuate quickly and safely to a more secure neighborhood. We used indices and a GIS model to map these levels of vulnerability. The location of our implementation was the dense urban area of Kalamaria, Greece.

## 1. Earthquake-evacuation vulnerability

Because of the density of the population and related systems there, an earthquake has graver effects when it occurs within an urban area. Many systems are affected simultaneously, and this leads to both greater disruption of operations and high recovery costs. Hence the capability to cope with a disaster is related to the resilience, or the adaptive capacity of a system (Uitto, 1998; Adger et al., 2004; Smit & Wandel, 2006), and it is usually assessed in negative terms.

### 1.1. Vulnerability

There are many definitions of vulnerability. Mitchell (quoted in Cutter, 1996) refers to it as the "potential to loss", and a UN definition is:

*the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard (UNIDSR, 2009),*

and in the case of buildings, vulnerability to earthquakes is:

*the proneness to be damaged by an earthquake" (Eleftheriadou et al., 2012).*

But an urban system also comprises people and operations, and harm to people means not only death and injury but also loss of income, loss of property and disruption to normal life. That is, the factors which affect the outcome of a disaster are complex and interdependent (Turner et al., 2003). The urban planning aspect (Leon & March, 2015; Rahnama et al., 2012), built environment parameters (Eleftheriadou et al., 2012), and the people themselves along with their social characteristics (Armas, 2008 & 2013), are all important considerations.

Accordingly, the frameworks and vulnerability indices which have been proposed (Tamima & Chouinard, 2012; Turner et al., 2003; Wisner et al., 2003; Cutter et al., 2007) incorporate factors related to the above aspects, and their spatial dimension has also been taken into account. Vulnerability and risk maps have been in use for some time (Kasperson, 2005). Note also that vulnerability is related to the response at the time the disaster takes place, and in the case of an earthquake, the immediate response is evacuation of population to safe spots by travelling through the street network.

The value of vulnerability is an estimation of the negative impact of the catastrophic event, which is known as risk. According to Dandoulaki (2008):

$$\text{Risk} = \text{Vulnerability} \times \text{Hazard} \quad (1)$$

and hazard refers to the possibility of the emergence of the disastrous event. By contrast vulnerability, and subsequently risk, are mainly associated with the characteristics of the system in danger. For buildings, risk is estimated by classifying structures and their related square meter estimate of damage needing repair given different levels of earthquake magnitude. We can then estimate total expected damage and, therefore, expected loss in monetary terms (risk).

Alternatively, to address the type of vulnerability that stems from the characteristics of people, the concept of social vulnerability has been introduced. Literature about it can be found in the social sciences, disaster management publications and climate change impact studies, and Armas (2008) provides a broad definition of social vulnerability:

*the capacity of a human community exposed during the impact of a natural hazard event to resist, cope with, and recover from that impact.*

The exact vulnerability of people is a combination of their actual insecurity and their perceptions of insecurity (Adger et al., 2004). So in this sense, vulnerability should be conceived as a real risk and a social response. Moreover, social vulnerability has a spatial aspect - a geographic domain (Cutter, 1996), which:

*varies significantly within a community and over time” (UNIDSR, 2009).*

Looking at this in greater detail, social vulnerability to disasters depends upon factors like age, handicaps, disabilities, financial resources and education (Rygel et al., 2006), and these are being used in formal indices of vulnerability. For example, the Social Vulnerability Index (SVI) was developed by Cutter et al. (2007) and it incorporates a total of 42 variables (Armas & Gavris, 2013), such as:

- age,
- gender,
- income,
- unemployment,
- dependence on social services,
- residential property,
- infrastructure,
- occupation,
- social networks,
- education,
- urban-rural dichotomy,
- population growth,
- built environment, and,
- health status,

which are reduced to about 11 factors. Another version of the SVI (Flanagan et al., 2011), incorporates 15 census variables covering social factors and neighborhood characteristics.

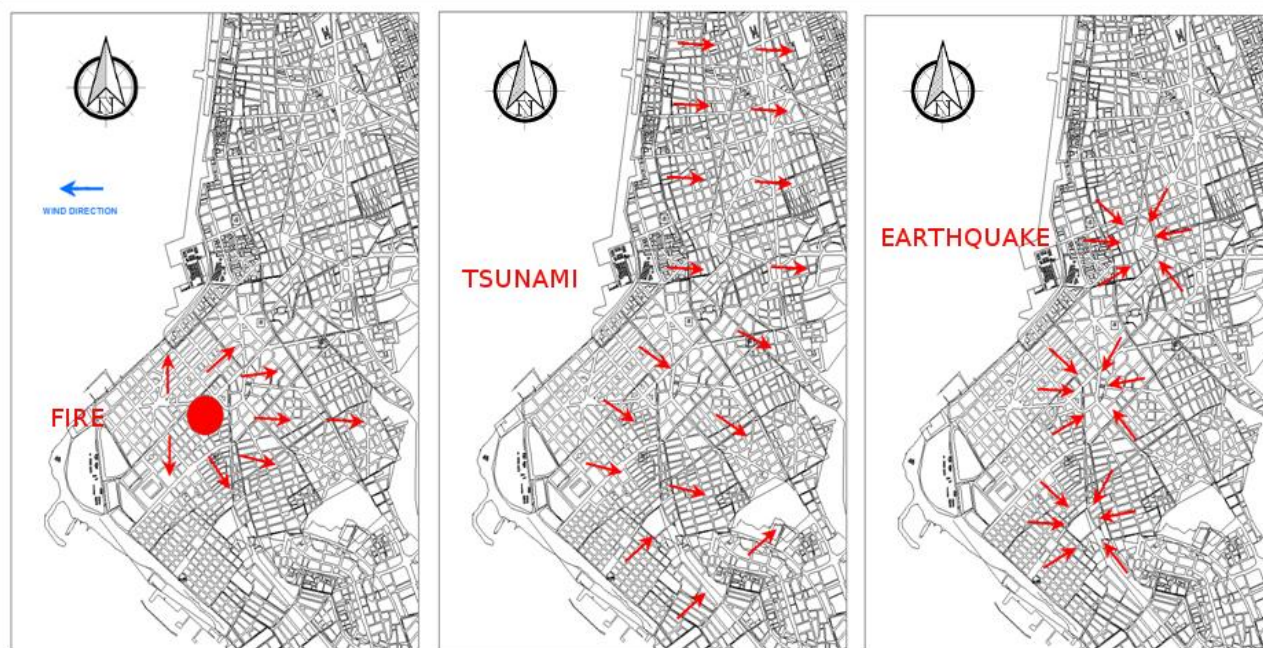
More recently, inter-disciplinary approaches have been presented. They address the physical, social and economic components of vulnerability (Guzey et al., 2013). Moreover, urban form, which includes land uses, width of streets, availability of open areas has been examined with respect to vulnerability (Gao et al., 2013; Uitto 1998).

## **1.2. Evacuation vulnerability**

In the case of an earthquake, preparedness and response are important. At the preparedness stage, we can reduce the vulnerability parameters. The response stage is more short-term, but it is critical because it may result to fatalities and injuries, and it relies heavily on the preparedness stage. The immediate response for an earthquake hazard is the evacuation. Its spatial pattern, along with the spatial pattern of the hazard, differ from that of other hazards. The difference lies in the location of the hazard and the destination of the evacuation.

For example, in the case of a fire the origin of evacuation is the exact location where the hazard appears and the immediate area it affects. The desired safety depends on the distance from the hazard, taking into account its spread pattern. Alternatively, in the case of a tsunami the same distance rule applies but the evacuation follows a linear front. And in the case of an earthquake, people do not flee from the danger itself, but from secondary sources of danger. People must leave the interior of buildings, distance themselves from areas that pose danger (practically the whole urban area) and seek a shelter (an open area).

In short, the process of post-earthquake evacuation is destination-driven whereas most other types of disaster are origin-driven. Such knowledge is crucial when assessing and planning evacuation route decisions, as indicated in Figure 1.



**Figure 1** – How the spatial pattern of evacuation depends upon the type of hazard

Until they reach the safe spots, people are vulnerable, and although the role of the urban form has been recognized as important, it has not yet reached the point of proposing evacuation-based urban design standards (Leon & March, 2015). According to these authors, all urban spots along the evacuation paths which are poorly maintained, badly designed and host improper uses of public space will actually increase vulnerability.

In their framework for earthquake evacuation planning Tamima & Chouinard (2012) identified three steps:

1. vulnerability assessment,
2. evacuation planning, and,
3. preparation/dissemination of evacuation maps.

They separated synergistic effects from social and physical vulnerabilities.

Others, such as D'Orazio et al (2014), have used agent-based simulation approaches where the behavior of people during evacuation has been modeled and simulated. Still others, like Ye et al. (2012), employed a shortest path algorithm, and Shen et. al. (2015) have implemented the transportation-location problem.

Finally, FEMA chose to implement a multi-hazard approach (earthquakes, hurricane winds and floods) for its HAZUS-MH methodology, and Anhorn & Khazai (2015) proposed an Open Space Suitability Index for identifying open spaces that could be used as shelters in the event of an earthquake.

Clearly, the need to model the urban space with evacuation-oriented parameters is essential. Accordingly, our contribution is to focus upon the urban design aspect, which is the most long-term of the above identified aspects, and we duly propose a model for evacuation vulnerability.

### 1.3. Parameters chosen

For the duration of an earthquake, and for the time period that another one is possible,

people should remain at the safe spots, away from the buildings and other constructions which are dangerous. People should then evacuate by exiting the buildings (if they are inside) and advance towards a safe spot. Until they reach a safe spot, they are vulnerable because collapsing structures and falling objects detached from constructions may cause injuries and fatalities. The maximum distance that people should travel to reach a safe spot, according to national standards, is between 250 to 350 meters (OASP, 1994). The surrounding constructions, especially buildings, traffic condition and the condition of the route itself constitute threats to safety.

For each building, the mean seismic,  $R_m$ , is calculated as the square meters that might be damaged by the earthquake, based upon the building's structural characteristics and its type (Baltzopoulou et al, 2008; Eleftheriadou et al, 2008, 2011). The more damage prone a building is, the greater the possibility is that it will collapse or have objects detached from it. This danger is higher near the buildings and lower away from them. So during the evacuation people are safer if they walk at the centre of the street rather than on the pavements at either side.

Although the use of vehicles during the evacuation is not recommended, many people will be using their vehicles at the time of the event, and some will even choose to do it. This behavior might be amplified if the communication networks fail because people will try harder to connect with their family in other parts of the city. The mental state of the drivers will obviously be different to that of everyday drivers and it will be dangerous for pedestrians. In short, abnormal traffic and high pedestrian loads down the middle of roads will increase the danger for evacuees.

It should also be noted that the geometric characteristics of the path followed in the streets (slope, width, length of travel) will affect how vulnerable anyone is. Steep streets are more difficult to negotiate and narrow streets bring people closer to the dangers of buildings and vehicles. These are urban design parameters which affect vulnerability, and we now proceed to propose a model that quantifies them.

The spatial units we chose as a basis for estimating evacuation vulnerability were street segments along a path. A street segment is defined as the part of a street from one crossroad to the next, and a path is the sequence of street segments that an evacuee travels in order to reach a safe spot (Tarabanis & Tsionas, 1999). Both are variable length units.

We proposed a vulnerability index, which incorporate the urban characteristics described above, by ranking each street segment for every vulnerability parameter:

1. seismic risk of nearby buildings,
2. anticipated traffic,
3. slope, and,
4. expected debris.

Combining these parameters, we calculated an overall vulnerability assessment for each segment.

In terms of the seismic risk of the buildings, each  $i$ 'th segment was ranked by calculating its value for  $V_{bi}$ :

$$V_{bi} = R_i / R_{\max} \quad (2)$$

where,

$R_i$  is the total risk of the buildings on both sides of the  $i$ 'th street segment, and,  
 $R_{\max}$  the maximum risk in the area of study.

A second vulnerability parameter quantifies the danger caused by vehicular traffic. Since the greater the traffic load that the  $i$ 'th street segment carries, the more dangerous it

becomes:

$$V_{ti} = T_i / T_{\max} \quad (3)$$

where,

$T_i$  is the traffic load of  $i$ 'th street segment, and,

$T_{\max}$  is the maximum traffic load in the study area.

It was expected that the streets which host more traffic in regular conditions - picking up children from school, commuting to and from work and leaving the city, would also host high volumes in the case of an earthquake because people are familiar with them. This enabled us to use traffic data as inputs for  $T_i$ .

Another vulnerability parameter is how “easily” (unhindered) one can travel along a street segment, based on its characteristics. This translates to geometric and structural characteristics such as slopes and pavement conditions as well as urban equipment and other obstacles to movement like traffic signs, restaurant tables, bus stops, advertisements, and, in the case of earthquake, fallen objects from buildings. We constructed two vulnerability parameters for this, one regarding the slope and another regarding the existence of debris, or falling objects.

Whereas street slopes less than 2% are comfortable to travel, those up to 5% begin to present difficulty for people in wheelchairs or old age. Greater slopes should be avoided, but in many cases street segments exist that are steeper than that. So 12% is considered a maximum slope for people with disabilities (Americans with Disabilities Act of 1990) and we calculated the  $i$ 'th street segment's value for  $V_s$  as

$$V_{si} = S_i / S_{\max} \quad (4)$$

where,

$S_i$  is the mean slope of the  $i$ 'th street segment, and,

$S_{\max}$  is the maximum slope in the study area.

Vulnerability due to debris and fallen objects,  $V_d$ , was calculated by measuring the portion of the street segment that will probably be covered by fallen objects or debris from the nearby buildings. This zone where objects may fall was delineated at half the height of the buildings (according to OASP standards). Therefore, the fallen objects and debris parameter  $V_d$  for the  $i$ 'th street segment was calculated as:

$$V_{di} = S_{di} / S_{di,\max} \quad (5)$$

where,

$$S_{di} = S_{i,\text{unsafe}} / S_{i,\text{total}},$$

$S_{i,\text{unsafe}}$  is the part of the street segment that is unsafe due to these obstacles, and,

$S_{i,\text{total}}$  is the total length of  $i$ 'th street segment against which it is compared.

Note that  $S_{di}$  has values in the interval [0, 1].

Whereas in wide street segments the debris falling near the buildings may be away from the path that the evacuees follow, in narrow street segments the debris may cover the whole breadth of the street segment. In this sense the  $V_d$  parameter complements the  $V_b$  parameter. The four parameters are summarized in Table 1.

Vulnerability parameter	Description	Calculation	Range
$V_b$	Vulnerability due to seismic risk from nearby Buildings	$V_{bi} = R_i / R_{max}$	[0,1]
$V_t$	Vulnerability due to vehicular Traffic	$V_{ti} = T_i / T_{max}$	[0,1]
$V_s$	Vulnerability due to street Slope	$V_{si} = S_i / S_{max}$	[0,1]
$V_d$	Vulnerability due to Debris	$V_{di} = S_{di} / S_{di,max}$ $S_{di} = S_{i,unsafe} / S_{i,total}$	[0,1]

**Table 1** -The four vulnerability parameters

A total vulnerability index  $V$  for the street segments was calculated as:

$$V = w_b \cdot V_b + w_t \cdot V_t + w_s \cdot V_s + w_d \cdot V_d \quad (6)$$

where,

$w_b$ ,  $w_t$ ,  $w_s$  and  $w_d$  are the respective weights for each vulnerability factor.

Since we have not yet studied their relative significance, we calculated an overall vulnerability,  $V$ , by using equal weights of 0.25 (25% for each parameter) thereby calculating a simple mean.

## 2. GIS implementation

The area of interest was the municipality of Kalamaria. It is the southeastern suburb of Thessaloniki, the second largest city in Greece. The municipality occupies a total area of 750 hectares and has a population of 91,518 residents (Census, 2011). It is a dense urban area with approximately 50 hectares of open spaces. This is low for an urban area, although relatively high compared to other urban areas in Greece. The buildings are high (up to 7 floors) and many streets are narrow. A typical street is 8 to 12 meters wide.

The last great earthquake in the area occurred in 1978 (magnitude 6.5) and a large scale evacuation of the city took place at that time. The population was 36,978 (Census, 1971), and a large part of the city was not yet incorporated in the urban fabric as it is today. Furthermore, the urbanized part of the city was less dense, and the mean height of buildings was significantly lower.

In order to calculate the vulnerability parameters, data were collected from the *Hellenic Statistics Authority* (ELSTAT, 2000, 2001) and the local authority. The basic spatial data sets that were necessary for the above analysis were the blocks, the buildings, the street network (centerlines) and the locations of safe spots. The main statistical data needed were data for the construction of the buildings and details of the population.

### 2.1. Analysis

Correlation of structural damage with economic loss (Kappos et al., 1998; Karabinis et al., 2006) is central to estimation of seismic risk, so in order to apply the aforementioned methodology, the classification of Kalamaria building stock (buildings) in distinct structural types was required. The spatial unit of the statistical data is the building block but the *Hellenic Statistics Authority* merges the data collected per building into larger spatial units due to personal data restrictions imposed by law, as stated in Decision 52/2011 of the *National Committee on Telecommunications*. This means that each building cannot be uniquely identified, and so calculations were required in order to combine the information

and estimate the mean seismic risk per building block.

The total buildings in the area numbered 6,770; they were spread across 20 urban sectors and 614 building blocks, and the total built area was 4,561,816 m<sup>2</sup>. Buildings' characteristics are shown in Table 2.

Floors	No of Buildings	Material	No of Buildings	Construction Year	No of Buildings
Ground floor	908	Beton	5775	Before 1919	3
One-storey	693	Metal	38	1919÷1945	190
Two-storey	789	Wood	7	1946÷1960	576
3 to 5 floors	3786	Bricks	887	1961÷1970	1084
Over 6 floors	594	Stone	31	1971÷1980	1431
		Other Material	30	1981÷1985	1090
		Undeclared	2	1986÷1990	1100
				1991÷1995	694
				1996÷2000	489
				under construction	100
				undeclared	13

**Table 2** - Characteristics of buildings in the area

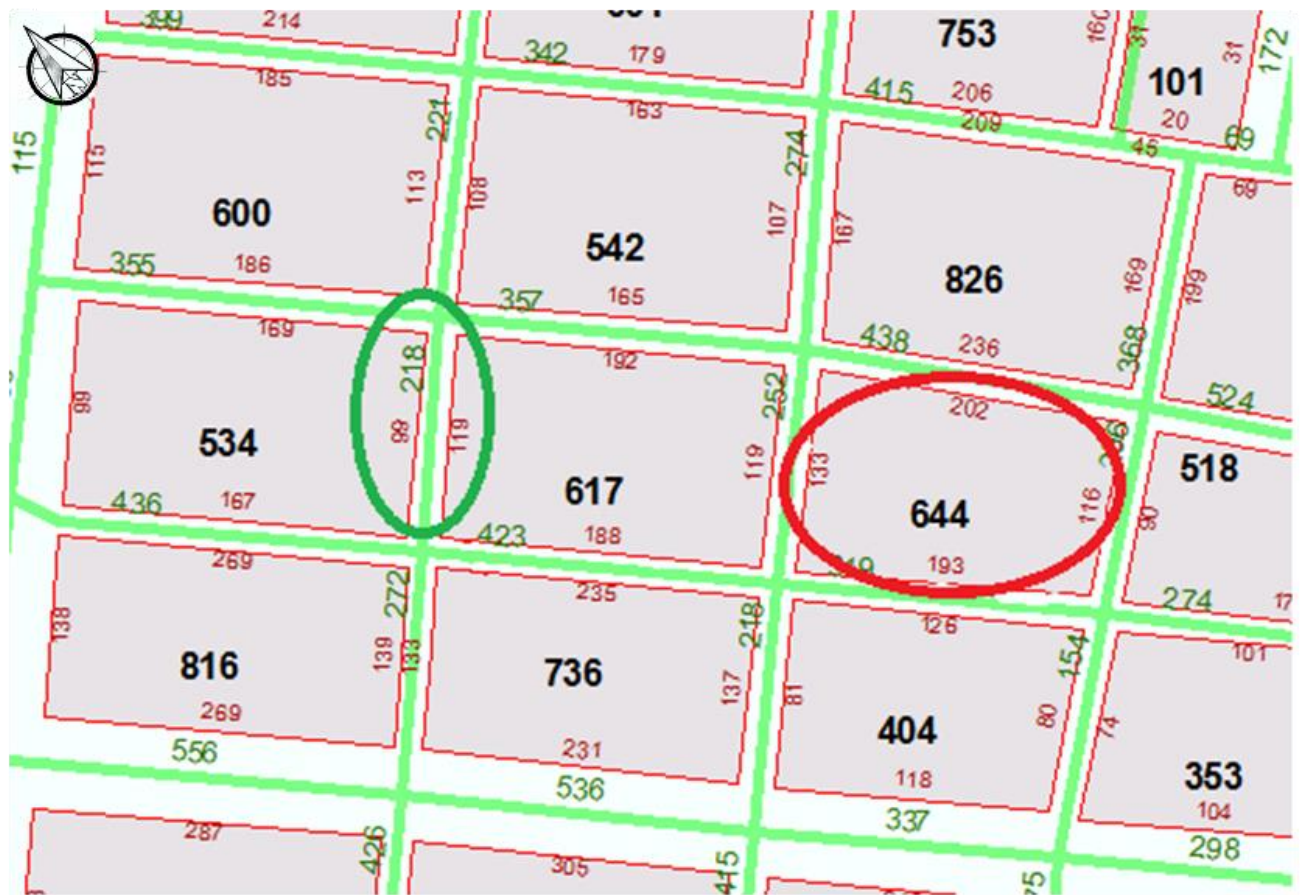
The seismic risk factors for Kalamaria were based on the hazard map of the *Greek Seismic Code*, 2003. The mean  $R_m$  was 299,218 m<sup>2</sup>, or 6.6%, while the maximum value was 5,203,419 m<sup>2</sup>, and seismic risk estimation per building block ( $R_m$  in m<sup>2</sup>) were assigned to the street segments in order to evaluate the  $V_b$  parameter.

## 2.2. Mapping

In Figure 2 the mean risk values  $R_m$  (m<sup>2</sup>) per building block are shown in black, bold font. Risk was then distributed to the sides of the building block using the ratio:

$$\text{Risk per side} = (\text{Side length} / \text{Perimeter}) * \text{mean risk } R_m \quad (7)$$

and the calculated risk values for each side of the building blocks is shown in red font. As an example, a closed red shape to the right encircles the value 644, which has been distributed to the sides of the building block (values: 202-116-193-133). The risk from both sides of each street segment were added and then attributed to that segment (green text). For example, a green closed shape at the left of the figure shows the sum of 218 (green) which is the sum of 119 and 98 from the sides of that street segment.



**Figure 2 -** Distributing the mean risk of buildings to each building block's sides and then to the street centerlines in order to estimate  $V_b$

Each segment now displayed a risk value derived from the building blocks that face it and so the  $V_b$  parameter was calculated as a percentage of the maximum mean risk value ( $R_m$ ) of street segments found in the area - 2.629 m<sup>2</sup>. The result is shown in Figure 3.



**Figure 3** - The  $V_b$  parameter per street segment

This  $V_t$  parameter depends on the traffic conditions. Ideally we would have a model predicting the traffic at the moment of the hazard, but this would be difficult to obtain and validate. So we ranked the street segments depending on their role in handling everyday traffic loads.

According to the urban planning classification, street segments are either pedestrian streets, local streets, local arteries or principal arteries. Risk was, therefore, assigned to each class ranging from a value 1 for the principal arteries, down to 0 for the pedestrian streets, with intermediate categories receiving intermediate values. This approach enabled calculation of  $V_t$ .

The  $V_s$  parameter depends on the slope of the street segment and it was calculated according to the heights at the intersections. That is, the mean slope of each segment was:

$$\text{Street segment slope (in \%)} = ((\text{end H} - \text{start H}) / \text{Length}) * 100 \quad (8)$$

where,

H is the ground height at each endpoint of the street segment.

Due to the fact that values were not available for all intersections, a 3D model of the city was created as a TIN surface and missing values were obtained from it. The resulting slopes were then used to calculate the  $V_s$  parameter as described in the model. The maximum value of slope in the area was 14.4%.

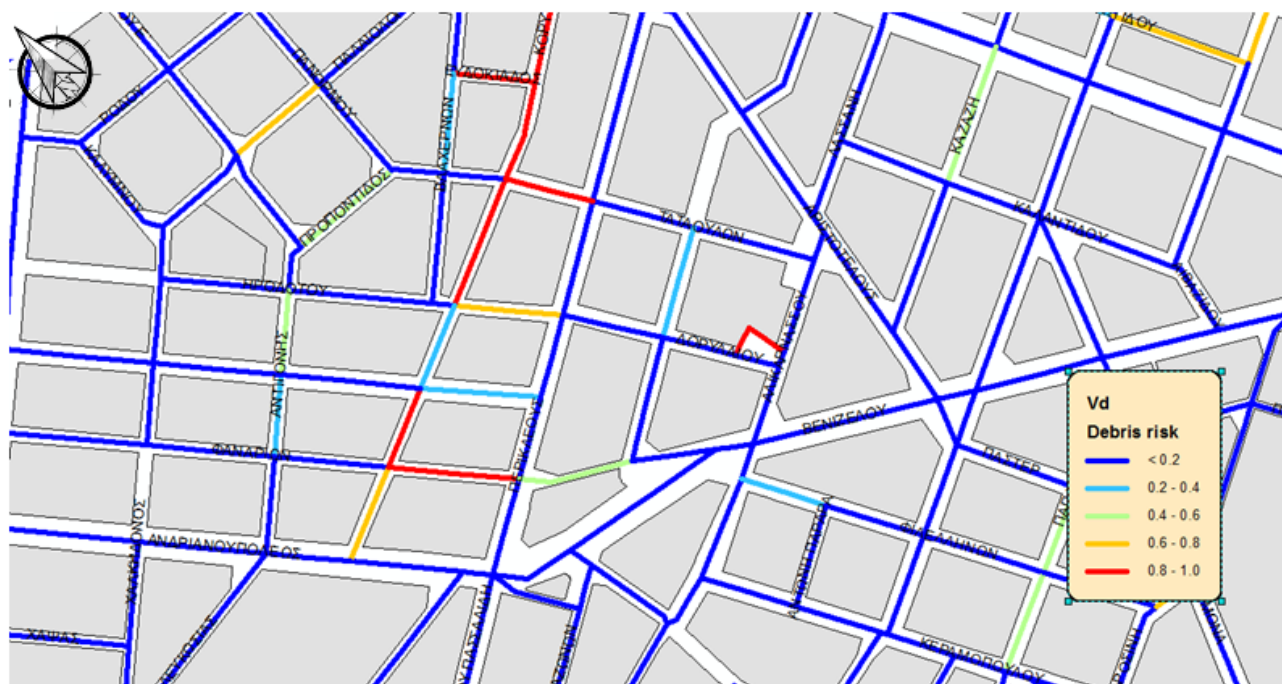
The debris zone was delineated by buffering the buildings at half their height, in accordance with current standards (OASP, 1994), as shown in Figure 4. It is immediately clear which streets may present danger from fallen objects or debris because a large percentage of their width is covered by the debris zone.



**Figure 4** – Buffering in order to plot the debris zone.

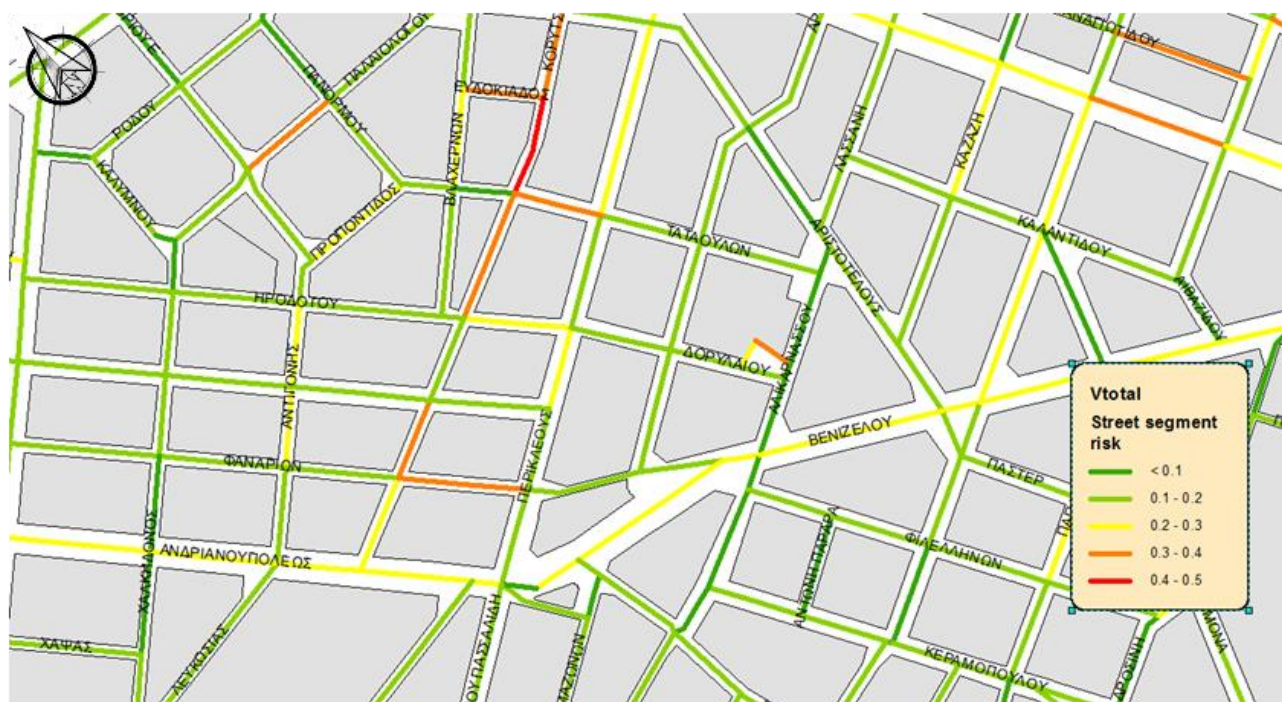
To calculate the  $V_d$  parameter (Figure 5), each street segment was split into parts bearing the attribute “covered by debris zone” and “not covered by debris zone”, depending upon the relative position of the street segment’s centerline in relation to this zone, and their respective lengths were measured. As that part of the street segment which is “covered by” the danger zone becomes larger, the street segment was considered to be more dangerous.

Since the value that the length with the attribute “covered by” can be zero up to the total length of the street segment, the value range for the  $V_d$  parameter was  $[0,1]$  and the maximum value was  $V_{d,max} = 1$ . That is, there was at least one street segment ranked as totally unsafe.



**Figure 5** - Street segments classified according to the parameter  $V_d$

The total ranking of the street segments was the simple average of the four aforementioned urban parameters, and results are shown in Figures 6 and 7. These maps offer an easy way to pinpoint areas that have many street segments ranking low and, therefore, need special attention.



**Figure 6** - The value of overall vulnerability,  $V$ , of street segments

Figure 7 shows that areas in the north-northwest and especially the north-northeast part of the city need more attention. Such a result is not surprising to someone familiar with the urban characteristics of the area. High buildings and narrow streets are characteristics of these two areas, especially the north-northeast one. The north-northwest area is the commercial and administrative center where there are high traffic volumes. Large areas to

the east and south are now more densely populated today than in 2001, and many buildings, some of them of great height, now exist in the area. Unfortunately, the 2011 data on buildings are not yet available from the statistics authority.



**Figure 7** - The value of overall vulnerability,  $V$ , across the whole area of study

What we generated was an objective classification of each street segment that can not only assist in urban interventions to improve the current status, but also help authorities to select those street segments that will function as safe routes leading to safe spots. Figure 7 can also be used to estimate the vulnerability of individual paths that the population is bound to use if one wants to optimize them, as will be presented in a future paper.

### 3. Conclusions and further research

The risk that people face while evacuating is complex and depends upon the catastrophic event itself, the vulnerability parameters of the area they need to traverse in order to avoid the danger and the people themselves. We studied vulnerability parameters based on urban characteristics of the area affected, which influence the vulnerability of the people seeking safe spots, in an urban environment in the case of earthquake. People travel along streets, and each street segment differs in its characteristics and consequent risk. We proposed four vulnerability parameters at street segment level.

Taking into account similar work of other authors, our approach emphasizes the urban characteristics that contribute to vulnerability of street segments along evacuation routes and it proposes a model to quantify them. It can demonstrate its full merit in the subsequent path-vulnerability analysis.

The vulnerability parameters we studied were related to the buildings' seismic risk, the buildings' height in comparison to street width, and geometrical and functional characteristics of the streets - their slope and traffic conditions. Calculations were conducted using a GIS, based on data available from the *Hellenic Statistical Authority*. These parameters allowed us to rank the streets (at street segment level) in terms of the risk they present to the people whenever they are evacuating after an earthquake. When

combined, they generated an overall vulnerability parameter, which proved to be consistent with general knowledge about the characteristics of the area.

The overall vulnerability parameter ranked each street segment which, when mapped, presents patterns that allowed us to identify areas with high vulnerability, or identified isolated street segments with high vulnerability that must be avoided when evacuating. The parameters were calculated based on a linear model and standardized to the area's maximum values. Therefore, they can be used for conclusions about the specific area.

For the calculation of the combined parameter we considered the four vulnerability parameters to be of equal importance. However varying weights might be more appropriate, and these can be proposed after further research.

Also, the parameters identified, studied and calculated in the present paper are not the only ones affecting the risks that people face. Additional parameters can be identified and studied. For example, parameters should be proposed that assess vulnerability due to public space housing urban equipment; traffic signs, advertisements, bus stops or temporary facilities, such as restaurant tables. One cannot describe the complexity of the urban environment with a simple model, but not all parameters are significant enough to qualify for research focus. But whichever parameters are ultimately selected, it is desirable that they allow comparison of different areas.

The parameters proposed above provide insight for the risk which people face during evacuation after an earthquake in an urban environment. They generate a picture of the areas that need attention and interventions, and they also provide a basis for informing people how to respond. In this way we can reduce people's risk and assist them to take informed decisions during an event.

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