AN APPLICATION OF EMS98 IN A MEDIUM-SIZED CITY: THE CASE OF L'AQUILA (CENTRAL ITALY) AFTER THE APRIL 6, 2009 Mw 6.3 EARTHQUAKE

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Abstract This paper describes the damage survey in the city of L'Aquila after the 6 April 2009 earthquake. The earthquake, whose magnitude and intensity reached Mw=6.3 and Imax=10 MCS, struck the Abruzzi region of Central Italy producing severe damage in L'Aquila and in many villages along the Middle Aterno River valley. After the event, a building-to-building survey was performed in L'Aquila downtown aiming to collect data in order to perform a strict evaluation of the damage. The survey was carried out under the European Macroseismic Scale (EMS98) to evaluate the local macroseismic intensity. This damage survey represents the most complex application of the EMS98 in Italy since it became effective. More than 1700 buildings (99% of the building stock) were taken into account during the survey at L'Aquila downtown, highlighting the difficult application of the macroseismic scale in a large urban context. The EMS98 revealed itself to be the best tool to perform such kind of analysis in urban settings. The complete survey displayed evidence of peculiar features in the damage distribution. Results revealed that the highest rate of collapses occurred within a delimited area of the historical centre and along the SW border of the fluvial terrace on which the city is settled. Intensity assessed for L'Aquila downtown was 8-9 EMS.

Keywords Macroseismic intensity. EMS98. Damage survey. L'Aquila. 6 April 2009 earthquake.

1 Introduction

On 6 April 2009, at 01:32 GMT, a Mw=6.3 earthquake hit the Abruzzi region (Central Italy) (INGV 2009) (Fig. 1). Severe damage was observed in tens of villages located in the vicinity of the town of L'Aquila (~73,000 inhabitants) where the effects of the earthquake were also devastating. The casualties and damages caused by the earthquake left a grievous social impact: around 300 casualties, 2/3 of them in L'Aquila city, 47% of the housing was moderately damaged, 20% of the housing was heavily damaged and more than 40,000 people were left homeless. The impact on religious and monumental heritage was disastrous.

The 6 April 2009 mainshock was the peak of a four-month lasting sequence that progressively increased alarm in the population, especially after a M_L=4.1 foreshock that occurred on 30 March . Two M_L 5+ and twenty M_L 4+ aftershocks occurred in the three months following the mainshock, and more than 10.000 localized events were recorded during the sequence.

The damage outline reconstructed by a macroseismic survey (Galli and Camassi 2009) shows (Fig. 2) that the most affected area is located SE of the instrumental location, with a maximum MCS (Mercalli-Cancani-Sieberg) (Sieberg 1930) intensity of grade IX-X. Sixteen surveyed localities presented damage corresponding to intensity greater than VIII MCS intensity scale.

For the first time in Italy, after the 1908 Messina-Reggio Calabria earthquake, a city was severely struck by a seismic event. Due to the heterogeneity of building types and the density of the urban setting, the macroseismic survey of the city of L'Aquila presented several difficulties. Based on assessments from the European Macroseimic Scale 98 (EMS98) a survey in downtown of L'Aquila was carried out aiming to outline the distribution of damage within the area. In this paper we describe the methodology that was followed and some problems we encountered when performing a macroseismic survey of a typical Italian medium-sized city.

2 Historical and urban setting

L'Aquila (Fig. 3) is a moderate-sized city (about 70,000 inhabitants) located in Central Italy, settled in a tectonic basin delimited by important mountain ranges. In particular the downtown of L'Aquila lies on a fluvial terrace mainly constituted by conglomerates (*Megabrecce*) (Demangeot 1965), with variable stiffness.

L'Aquila was founded in the middle of the XIIIth century, becoming soon the most important centre of the area characterized by a large and valuable historic heritage. Unfortunately, the city is located within a highly seismic region, whose activity is well documented from old historical sources since the early XIVth century. The first event that was reported to cause damage in L'Aquila occurred on 1315 (Guidoboni et al 2007). Since then, L'Aquila has experienced several strong earthquakes in 1349, 1461 and 1703; the city, which was heavily destroyed after all these events, has been restored each time. In particular, the 1461 event is considered, by historians and city planners, responsible for the disappearance of the medieval housing in L'Aquila (Clementi e Piroddi 1986), while the 1703 earthquake marked the birth of the present urban plan.

The current urban setting of downtown is then the result of several modifications and superimpositions occurring over the time, especially after the last major earthquake in 1703. After this event a new building planning characterizes the reconstruction, in search of "antiseismic" techniques. However, the reconstruction of the city was very difficult and took many years, in a social and economic context of widespread poverty (De Matteis 1973).

The building stock is very heterogeneous: buildings located downtown are mainly two to four storeys, built in simple stone masonry, sometimes with tie-rod connections among walls. Massive stones or bricks were used only for some strategic and important edifices, among them there are more recent buildings, built during the last century, in brick masonry and reinforced concrete. In the suburban area, recently developed outside the ancient walls (Fig. 3), most buildings are relatively modern reinforced concrete frame structures with masonry infill.

3 Methodology

The European Macroseismic Scale 98 (EMS98) (Grünthal 1998), largely used in Europe, takes into account an inventory of building types, ranked according their vulnerability, that is the susceptibility to be damaged by an earthquake. This intensity scale is more suitable to assess the macroseismic intensity in a complex urban outline than the Mercalli-Cancani-Sieberg scale (MCS), still the most used intensity scale in Italy.

Although the EMS98 considers it reasonable to assign a single intensity value to moderate-sized city, this practice implicates several difficulties due to the size of the urban area, the heterogeneity of buildings types, as well as the heterogeneity of urban setting.

After the 6 April earthquake, the authorities cordoned off the most affected area of the city of L'Aquila (hereinafter *Red Zone)*, forbidding the public to enter, delimiting an area slightly larger than the whole downtown, and roughly coincident with the ancient walls (Fig. 3).

The *Red Zone* was considered large enough to be a good EMS98 test-area and at the same time, to have manageable size for a prompt investigation. The survey was carried out meticulously by several teams in the span of a week. The survey of the structures, done building-by-building, was complex and tiring due to the fact that buildings generally leant against the others in a tangled grid of alleys and streets. During the field phase of the survey more than 1700 buildings were classified and plotted into a geo-referenced map.

The buildings were classified according to their type and then grouped in vulnerability classes (A to D), (Table 1 and Figs. 4 *a* to *c*) following the guidelines of EMS98 (Grünthal 1998). Other requirements such as regularity of design, workmanship, state of preservation, if observed, affected the assignment to the vulnerability classes, according to the probability ranges also suggested by the EMS98.

Figure 5 shows the general distribution of the vulnerability classes within the surveyed area. The low number of buildings corresponding to class A (Fig. 6) can be explained with the relative modernity (in comparison with the Italian standard) of the building stock of L'Aquila (see for instance Dolce et al. 2003; Bernardini et al. 2008; Bernardini 2008). The area surveyed contains buildings that have mostly been restored or rebuilt after the XVIIIth century, and it also contains many important palaces. In fact, the inventory of buildings shows that class B is the most numerous. Class C is mostly represented by RC buildings (without or with a low anti-seismic design) located in the outer part of the historical centre, outlining the enlargement of the city during the last century (Fig 5), whereas class D (moderate anti-seismic design) is negligible being about the 0.5% of the building stock. To this end, the poor performance of several RC brought us to assign them a lower vulnerability class.

A grade of damage, varying from DG0 (no damage) to DG5 (collapse) was assigned to each building according to the damage description shown in table 2 (Grünthal 1998). The result is a data-base containing all useful information to assess the macroseismic intensity (Fig. 7).

The results of the damage survey are plotted in figure 8 where the grade of damage (DG0, DG1, DG2, DG3, DG4 and DG5) is associated to each class of buildings (type A, B, C and D).

In general we observe that in the study area:

- Class A buildings were all damaged;
- DG 3 (substantial to heavy damage) is the most typical damage grade, especially in classes B and C (Fig. 9);
- More than 90% of the monumental buildings suffered a DG greater than 3.

The survey has also found out that the masonry structures suffered severe damage especially in the upper parts (roofs, cornices, and in general upper floors) (Fig. 10), while buildings in RC were severely damaged (DG3 or DG4) (Fig. 11) at the lower floors. In many masonry houses, despite their undamaged external walls, the collapse of internal floors was observed (DG4).

Focusing on the spatial distribution of the damage(Fig. 8), the following observations can be made:

- DG 4 and DG5 are mainly concentrated in the western part of the city;

- The 80% of DG5 in RC buildings is concentrated along the south-western border of the Red Zone;

4 Results

The building-by-building survey performed in L'Aquila downtown, allowed us to construct a detailed database regarding the vulnerability of the building stock and the damage distribution within the downtown. The field survey and the analysis of the data retrieved on it allowed us to plot a detailed map of the vulnerability and damage distribution within L'Aquila city (Fig. 8).

Analysing the vulnerability classes it was found that classes B and C are the most represented in the building stock at 66% and 27% respectively (Fig. 6 and Tab. 1). The high percentage of class C buildings is consistent with the enlargement of the city especially after the 1960s, whereas the high number of buildings within class B is explained with the fact that a considerable part of the area of study is the historical centre. Buildings belonging to class A are only the 4% of the housing in L'Aquila and class D is negligible.

The analysis of the damage led us to the following general statements concerning the behaviour of the building typologies and the intensity assessment:

- The most vulnerable buildings, class A, as expected were all damaged; about 50% of them suffered very heavy destruction (many DG4 and a few DG5) Their distribution is shown in figure 13. This is a typical diagnostic of grade 8 EMS98.
- A high rate of severe damage (>DG3) was observed in buildings of classes B and C. The level of damage DG3 is the most frequent, at 46% when taking into account the whole building stock. These elements fulfil equally grades 8 and 9 of intensity. The percentage of DG4 and DG5 in classes B and C also fulfils intensity 8 as well as intensity 9.

- More than 90% of the monumental buildings suffered a DG greater than 3. Although the evaluation of damage to monumental buildings is not considered a diagnostic element of the macroseismic scale, we take it into account as complementary evidence of the severity of the ground motion. Moreover it is an important marker to compare the current effects with those from historical earthquakes, for which it is often the only kind of data available.
- The above considerations lead us to assess an intensity 8 or 9 given that the percentage of damage distributed in the vulnerability classes fulfils quite well both intensities. This intensity value means either 8 or 9 and does not imply an intermediate value, as recommended in the Guidelines of EMS98 (Grünthal 1998). The evaluation of the intensity value given in this study cannot be extended to the greater metropolitan area of L'Aquila, which we were not able to study it in detail, and to which another intensity needs to be assessed.

From the spatial distribution of the damage we can infer the following observations:

- A high concentration of damage DG5 (Fig. 15) in buildings class B was observed in the north-western part of downtown, where 39% of the total collapses counted in the city, is located. Within this sector (red circle in figure 8) a clear intensity 9 could be assessed, while around a clear 8 fulfils the assessment. We believe that such a high concentration of destruction in that area may not be due to the vulnerability of the buildings, but to a site effect, probably related to the presence of embankments. As a matter of fact, it should be recalled that the city has been widely reconstructed several times along history after wars or destructive earthquakes. Unfortunately, this hypothesis can not be confirmed, because detailed geotechnical data for L'Aquila downtown is not available currently. This is an interesting topic that needs to be thoroughly investigated in future analysis. In confirmation of this hypothesis it seems, from historical accounts, that about the same part of the city was remarkably damaged after the 1703 event (De Matteis 1973; Clementi e Piroddi 1986; Centofanti 1992).

- Another concentration of substantial to very heavy damage was observed along the south-western edge of the historical centre (see Figs. 14 and 15). In this band the rate of RC buildings (class C) reaching damage corresponding to grade DG3, DG4 and collapses (DG5), is higher than in all the rest of L'Aquila (compare with Fig. 5 and Fig. 8). Total collapses of RC buildings are in particular concentrated (80%) in this area. This area is very close to the lithological contact between the alluvial sediments of the Aterno Valley and the conglomerates (Megabrecce, auct.) on which L'Aquila downtown is settled, and coincides with a remarkable morphological slope (Fig. 16). Moreover the same area was the site of large embankments in the first decades of 1900. Thus this geomorphologic feature can be considered as a probable factor that increased the damage.

The high number of features taken into account to classify buildings vulnerability and damage grade is sometimes difficult to completely fulfil during a prompt survey, especially if earthquakes hit moderate to large settlements, composed by modern and antique buildings. Such a problem could turn therefore into a uncertain estimate of the intensity value, which is common during field surveys.

Anyway this study highlighted that macroseismic investigations on built-up areas, where modern and ancient coexists, cannot further be accomplished by the MCS scale. The case of L'Aquila has evidenced that nowadays the EMS98 is the best tool to perform macroseismic evaluations of urban settings. The application of EMS98 scale allow to draw a comprehensive picture of earthquake impact and therefore to assign an intensity value even where urban settings show high heterogeneity in terms of buildings categories.

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Captions of the figures

1. – Instrumental epicentres map of 2009 L'Aquila sequence. In figure events occurred from 6 April 2009 to 25 June 2009 are shown.
2. – Intensity map of the 6 April 2009 earthquake (from Galli e Camassi, 2009)
3. – Landscape of L'Aquila city (from GoogleEarth). In red the trace of ancient walls is drawn.
4. a- Photo of building type A (photo Quick Earthquake Survey Team (QUEST) INGV)
   b- Photo of building type B located on via XX Settembre (photo QUEST INGV)
   c- Photo of building type C located on via XX Settembre (photo QUEST INGV)
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12. - Image of Via Roma, in the western parte of historical centre (photo QUEST INGV).
13. – Distribution of the grades of damage for class A only
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15. - Distribution of grades of damage 4 and 5
16. - Distribution of the grades of damage 4 and 5 in buildings of class C.

Tables

Type of building	Characteristics	Vulnerability class (EMS 98)
Traditional dwellings. Two to four stories	Masonry construction in field, simple stone, non-manufactured. General bad state of preservation.	**A**
Traditional buildings,. Two to four stories.	Groundwork of masonry in simple stone or manufactured stone units. Many old buildings among them. Presence of tie-rod connections. Variable state of preservation.	**B**
Historical edifices. Two to four stories.	Massive stone, or manufactured stone units. Variable state of preservation	**B-C**
Residential buildings (modern) Two to six stories.	Masonry constructions in manufactured stone units. Brick with RC floors buildings. RC structure without anti-seismic design. Generally in a good state of preservation.	**C**
Monumental buildings (churches, towers etc..)	Masonry construction in field, simple, or massive stone. Most of these buildings are several hundreds years old. Variable state of preservation. Irregular ground plan.	**A-B**
Public buildings and/or residential buildings (very recent)	RC/steel structure with anti-seismic design. Generally in a good state of preservation.	**D**

Table 1 Building types identified into L'Aquila downtown and related vulnerability classes .

Damage grade	Masonry buildings	RC buildings
0 No damage		
1 Negligible to slight damage.	Hair-line cracks in very few walls, fall of small pieces of plaster only, fall of loose stones from parts of buildings in very few cases.	Fine cracks in plaster over frame members or in walls at the base, fine cracks in partition and infills
2 Moderate damage.	Cracks in many walls, fall of fairly large pieces of plaster, partial collapse of chimneys, slipping of roof tiles.	Hair-line cracks in columns and beams, cracks in partitions and infill walls, fall of brittle cladding and plaster, falling mortar from the joints of wall panels.
3 Substantial to heavy damage.	Large and extensive cracks in many walls, general falling of roof tiles, chimneys fracture at the roof line, failure of individual non-structural elements.	Large cracks in partition and infill walls, failure of individual infill panels, cracks in columns and beams with detachment of pieces of concrete, buckling of reinforced rods.
4 Very heavy damage.	Serious failure of walls and roofs, partial structural failure.	Large cracks in structural elements, damage to the joints of the skeleton, destruction of concrete floors, protrusion of reinforcing rods, tilting of columns.
5 Destruction	Very total or near total collapse.	Very total or near total collapse.

Table 2 Description of the damage grades under the EMS98

Abstract This paper describes the damage survey in the city of L'Aquila after the 6 April 2009 earthquake. The earthquake, whose magnitude and intensity reached Mw=6.3 and Imax=10 MCS, struck the Abruzzi region of Central Italy producing severe damage in L'Aquila and in many villages along the Middle Aterno River valley. After the event, a building-to-building survey was performed in L'Aquila downtown aiming to collect data in order to perform a strict evaluation of the damage. The survey was carried out under the European Macroseismic Scale (EMS98) to evaluate the local macroseismic intensity. This damage survey represents the most complex application of the EMS98 in Italy since it became effective. More than 1700 buildings (99% of the building stock) were taken into account during the survey at L'Aquila downtown, highlighting the difficult application of the macroseismic scale in a large urban context. The EMS98 revealed itself to be the best tool to perform such kind of analysis in urban settings. The complete survey displayed evidence of peculiar features in the damage distribution. Results revealed that the highest rate of collapses occurred within a delimited area of the historical centre and along the SW border of the fluvial terrace on which the city is settled. Intensity assessed for L'Aquila downtown was 8-9 EMS.

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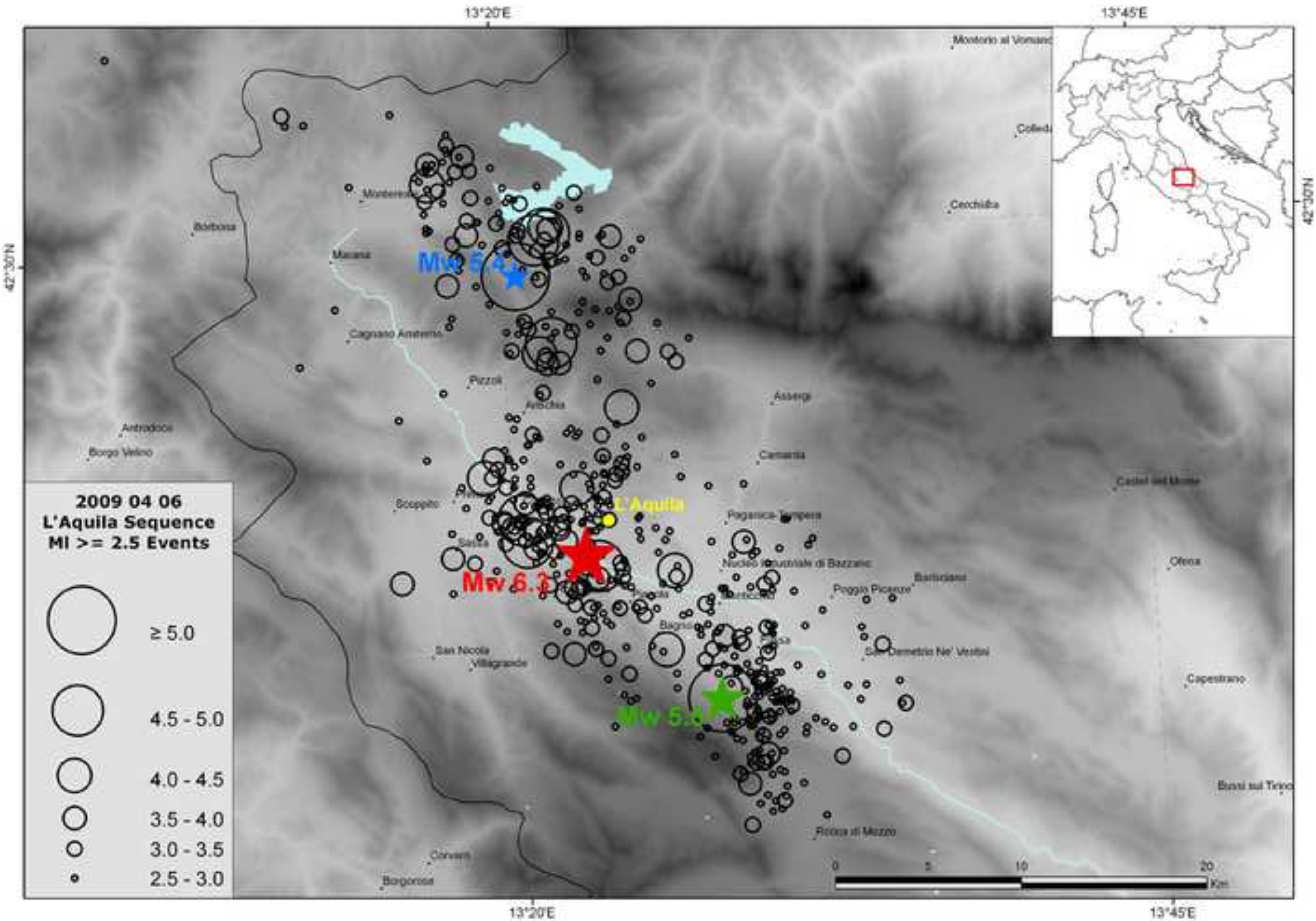

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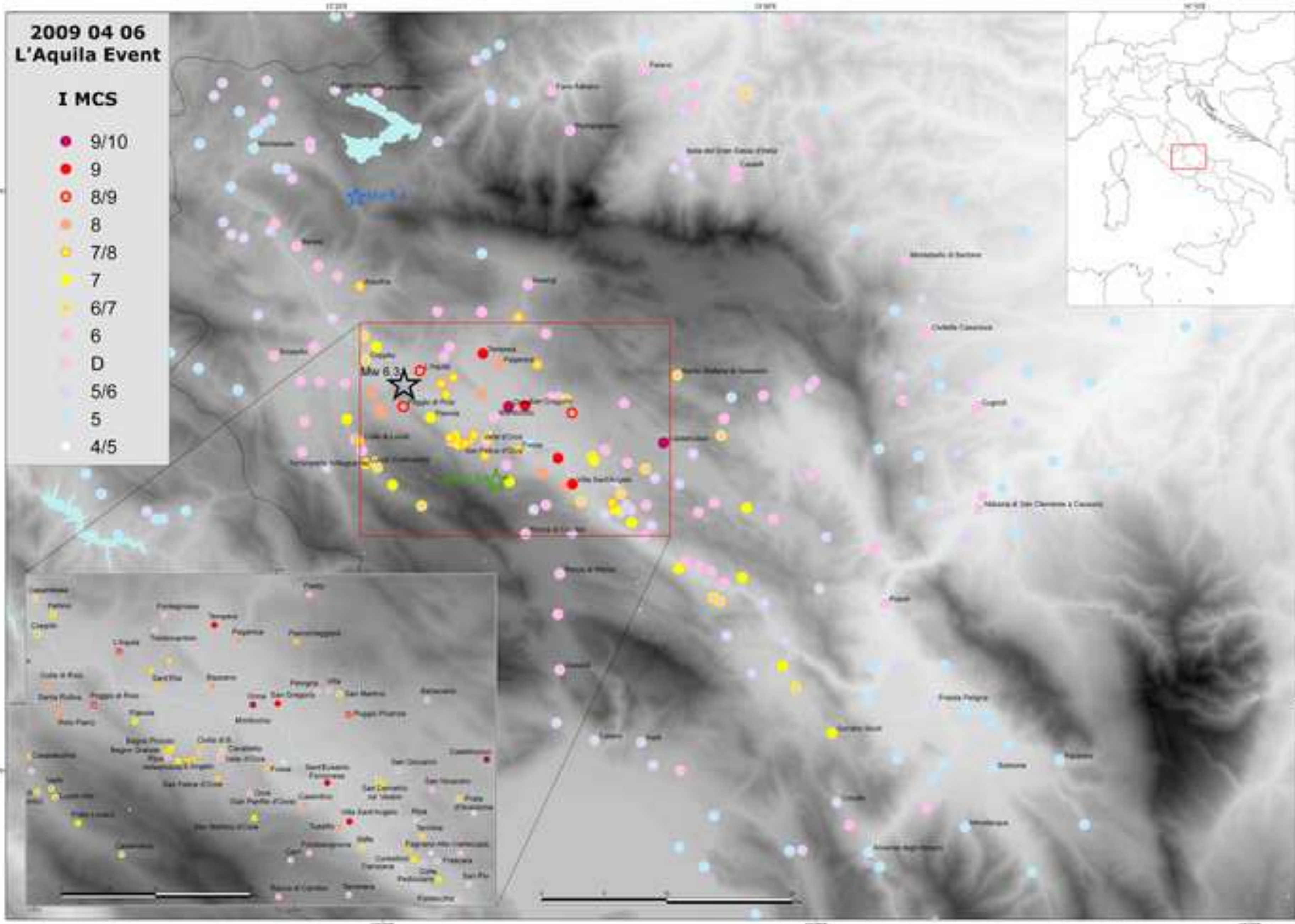

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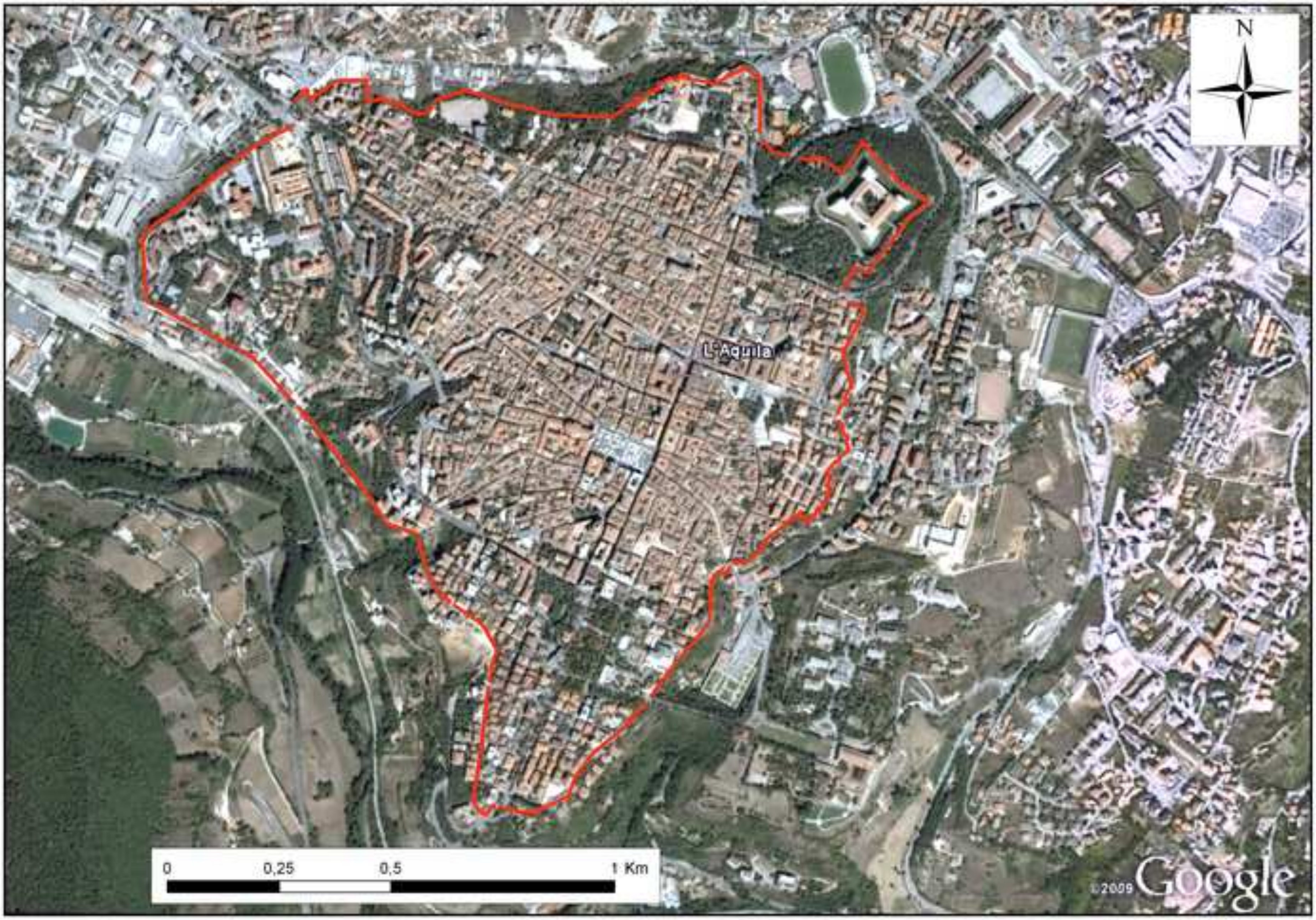

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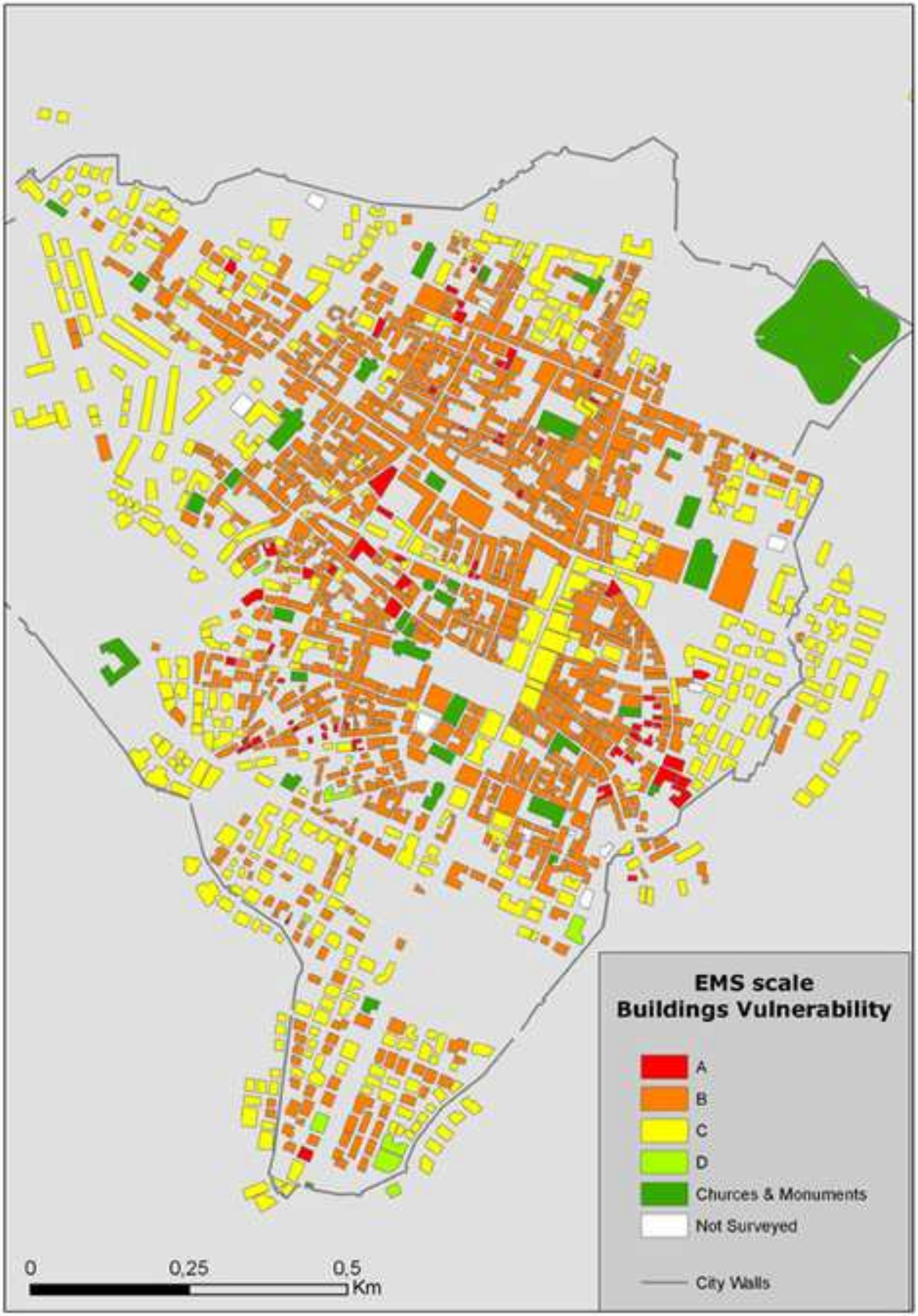

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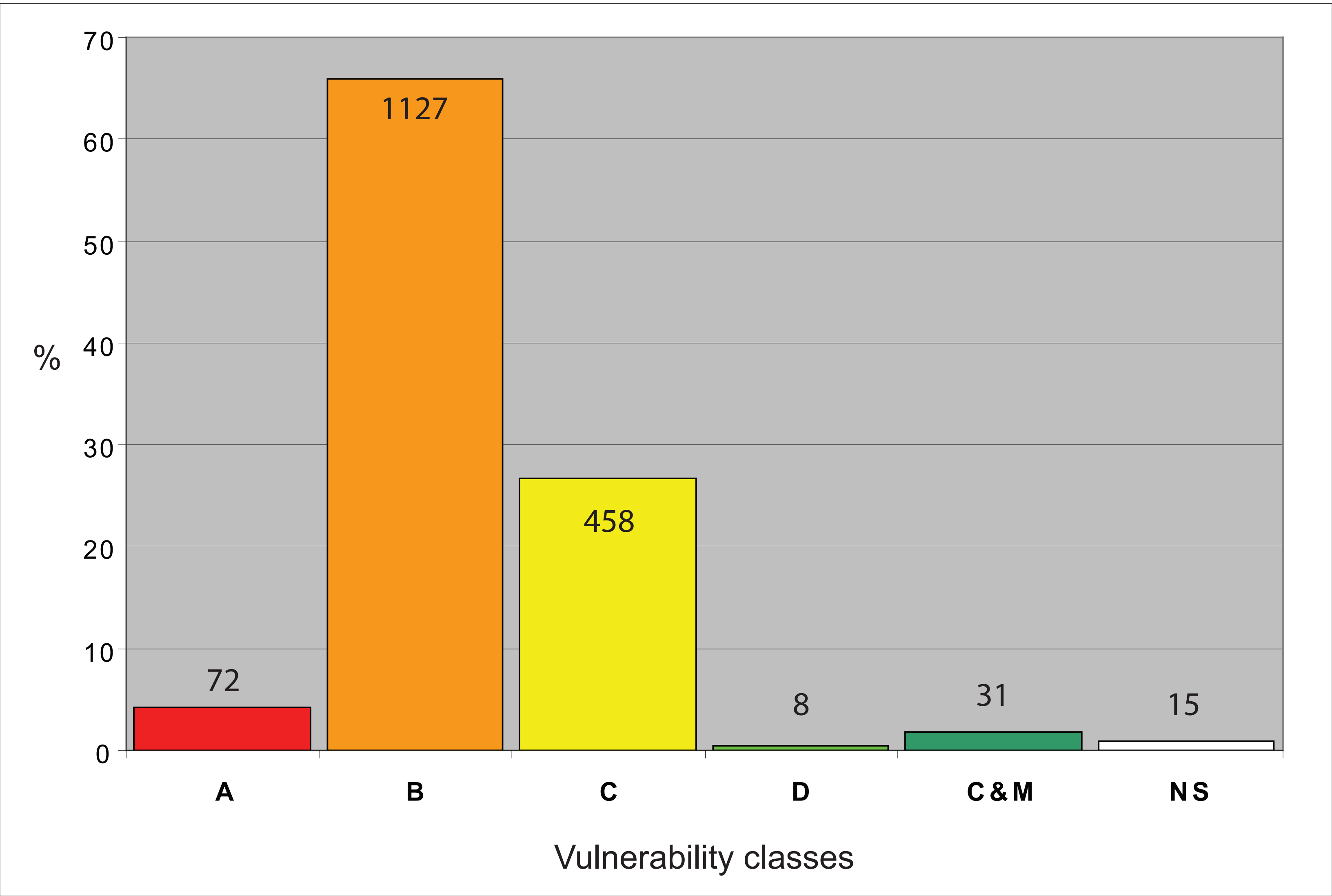

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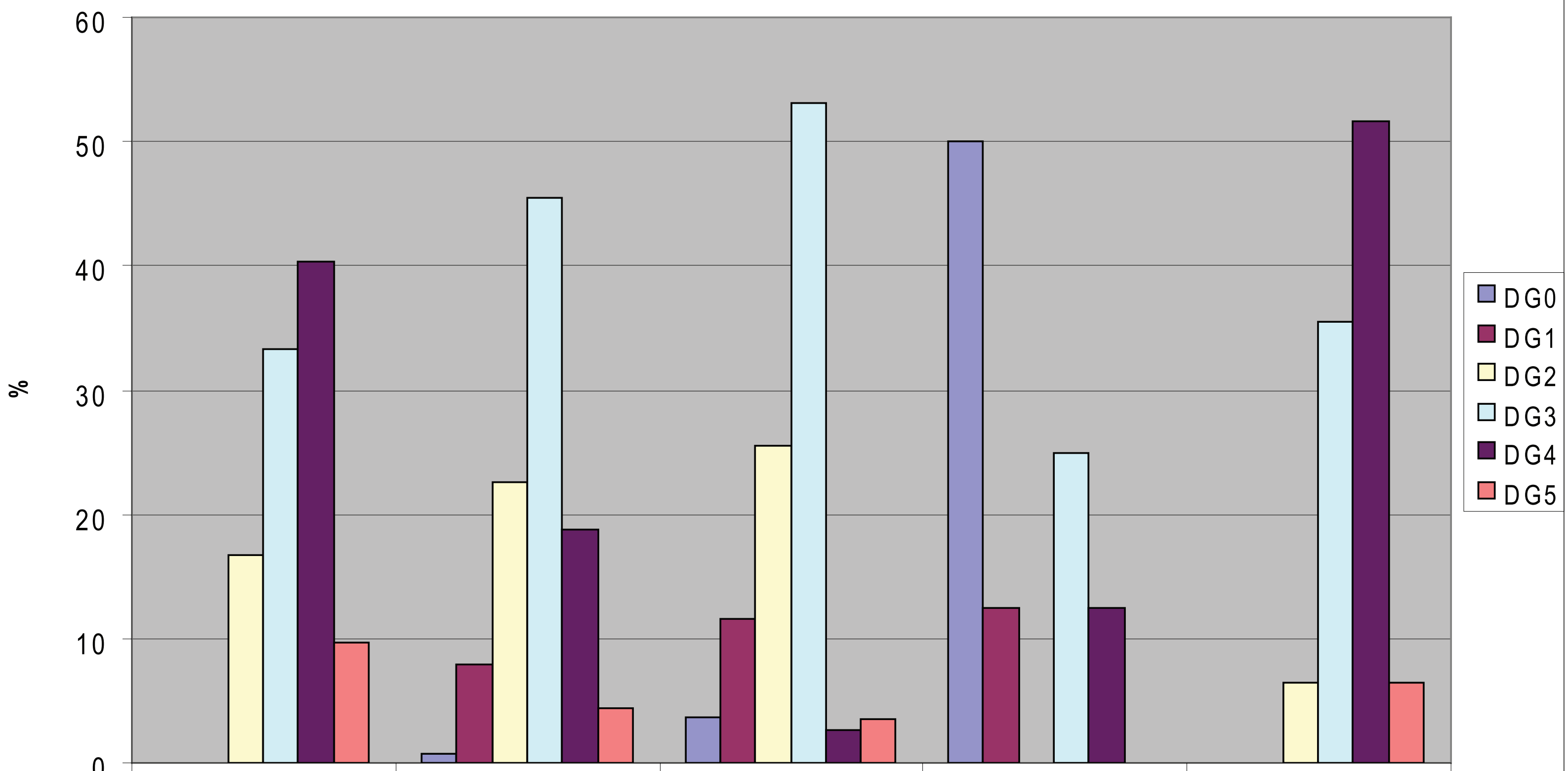

	A	B	C	D	SB
DG0	0,00	0,80	3,71	50,00	0,00
DG1	0,00	7,99	11,57	12,50	0,00
DG2	16,67	22,63	25,55	0,00	6,45
DG3	33,33	45,43	53,06	25,00	35,48
DG4	40,28	18,72	2,62	12,50	51,61
DG5	9,72	4,44	3,49	0,00	6,45

vulnerability classes

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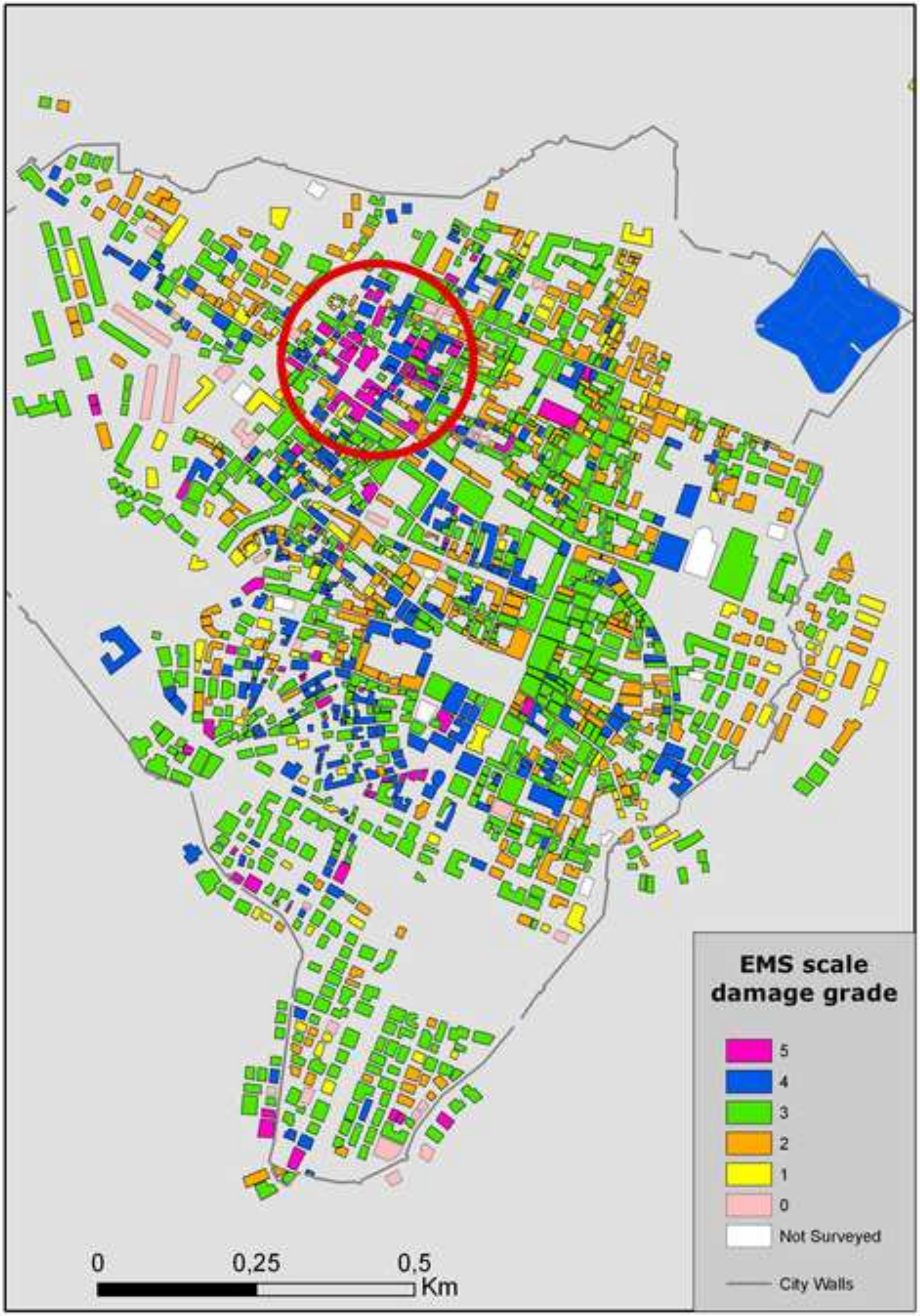

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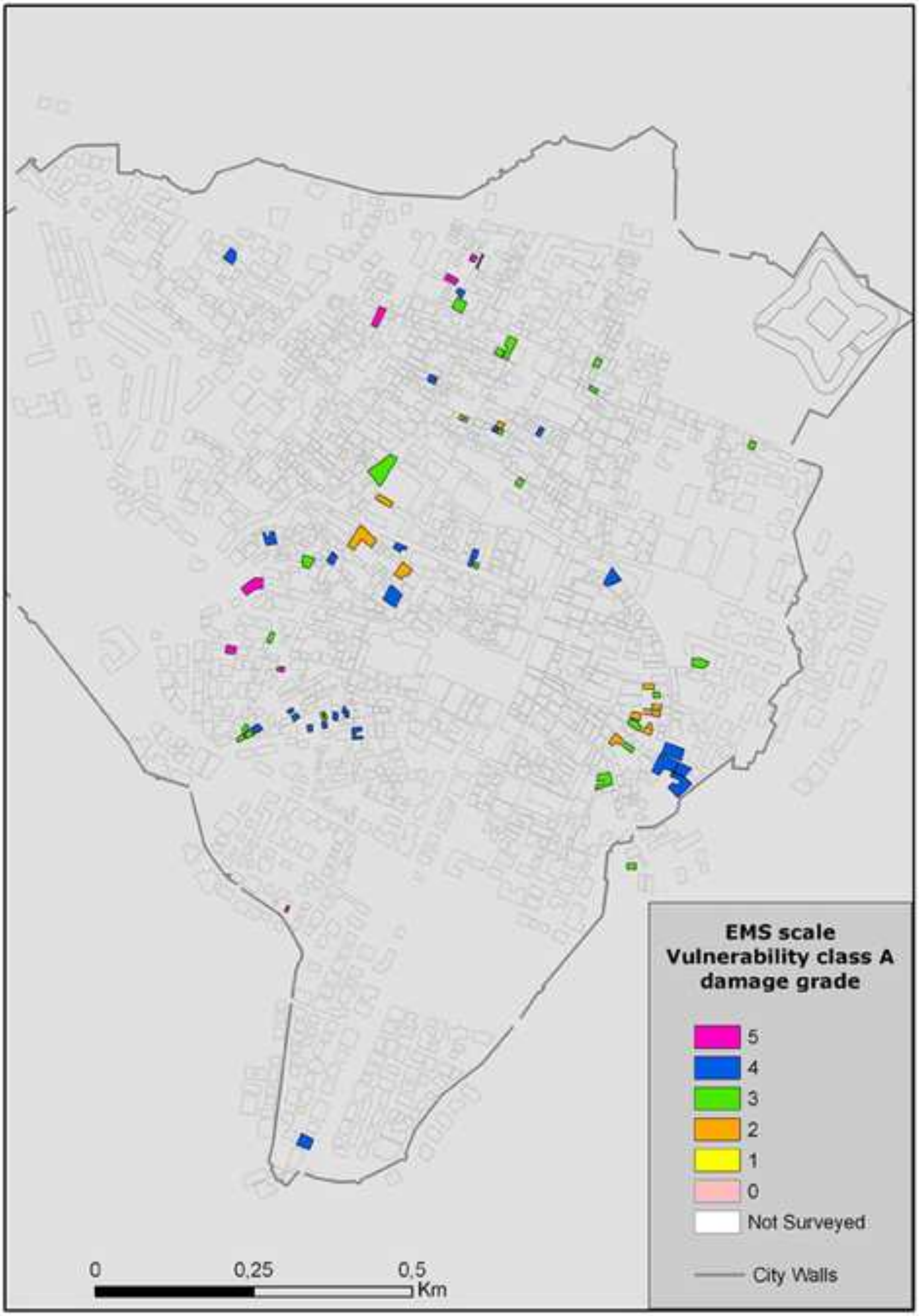

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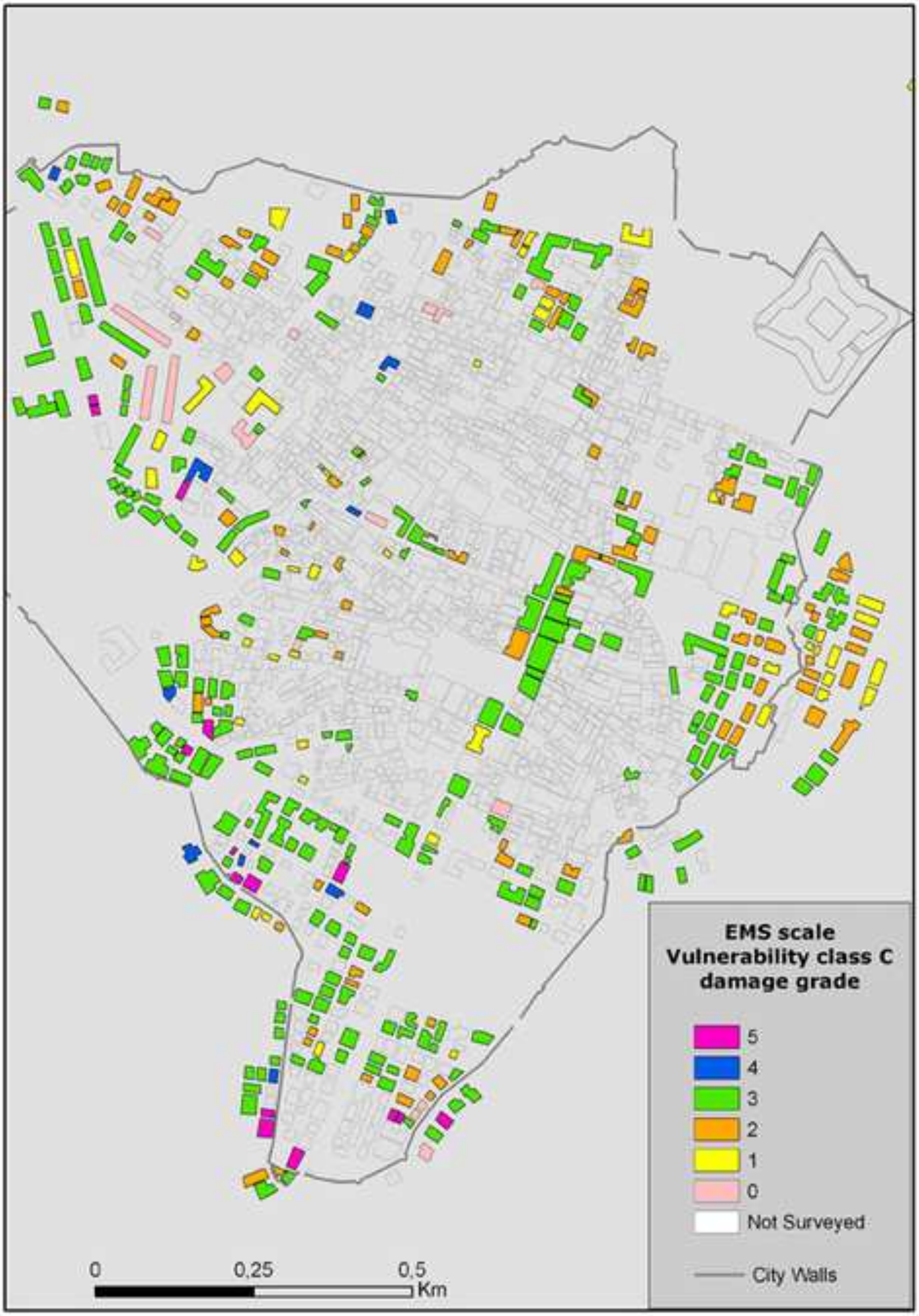

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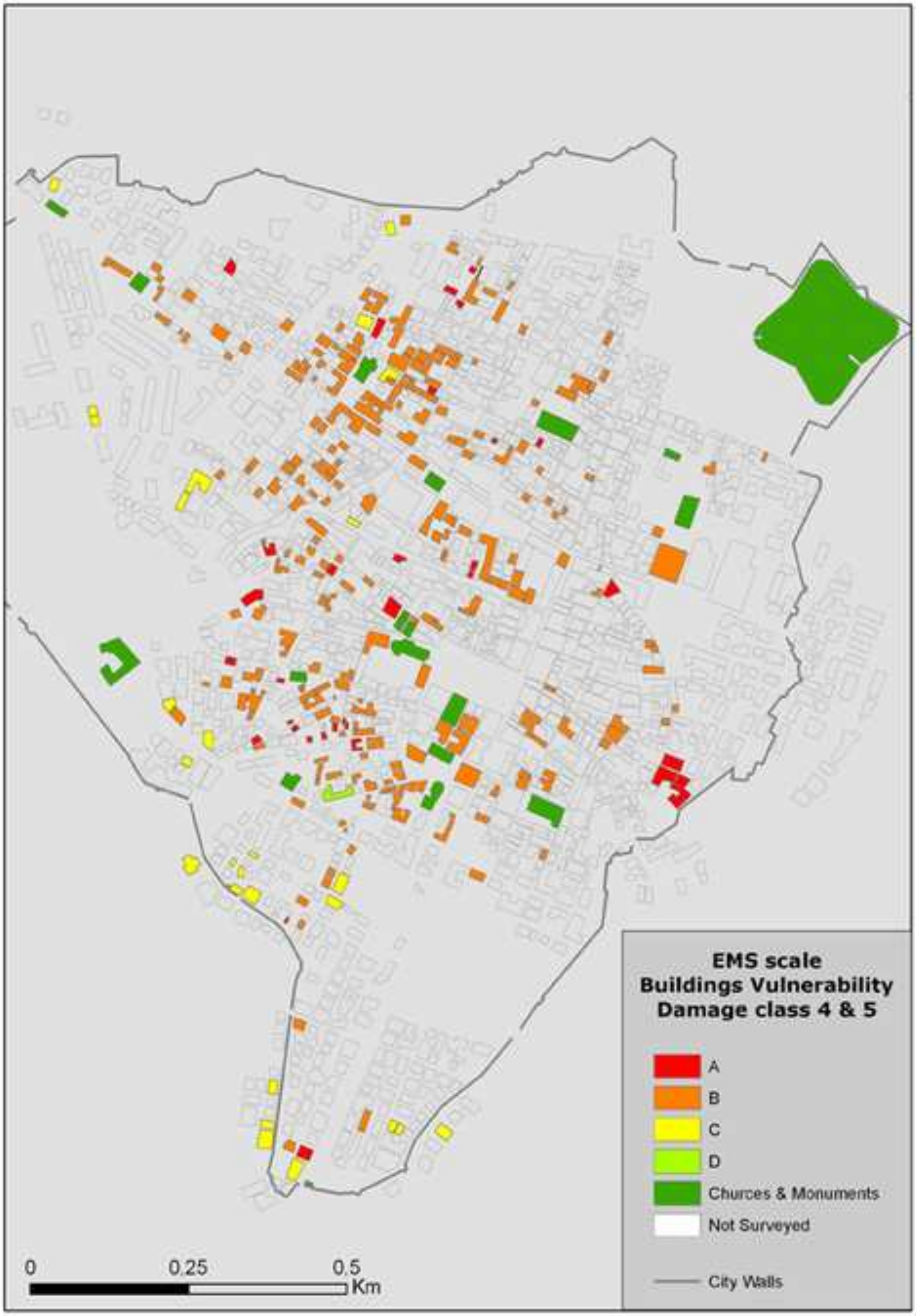

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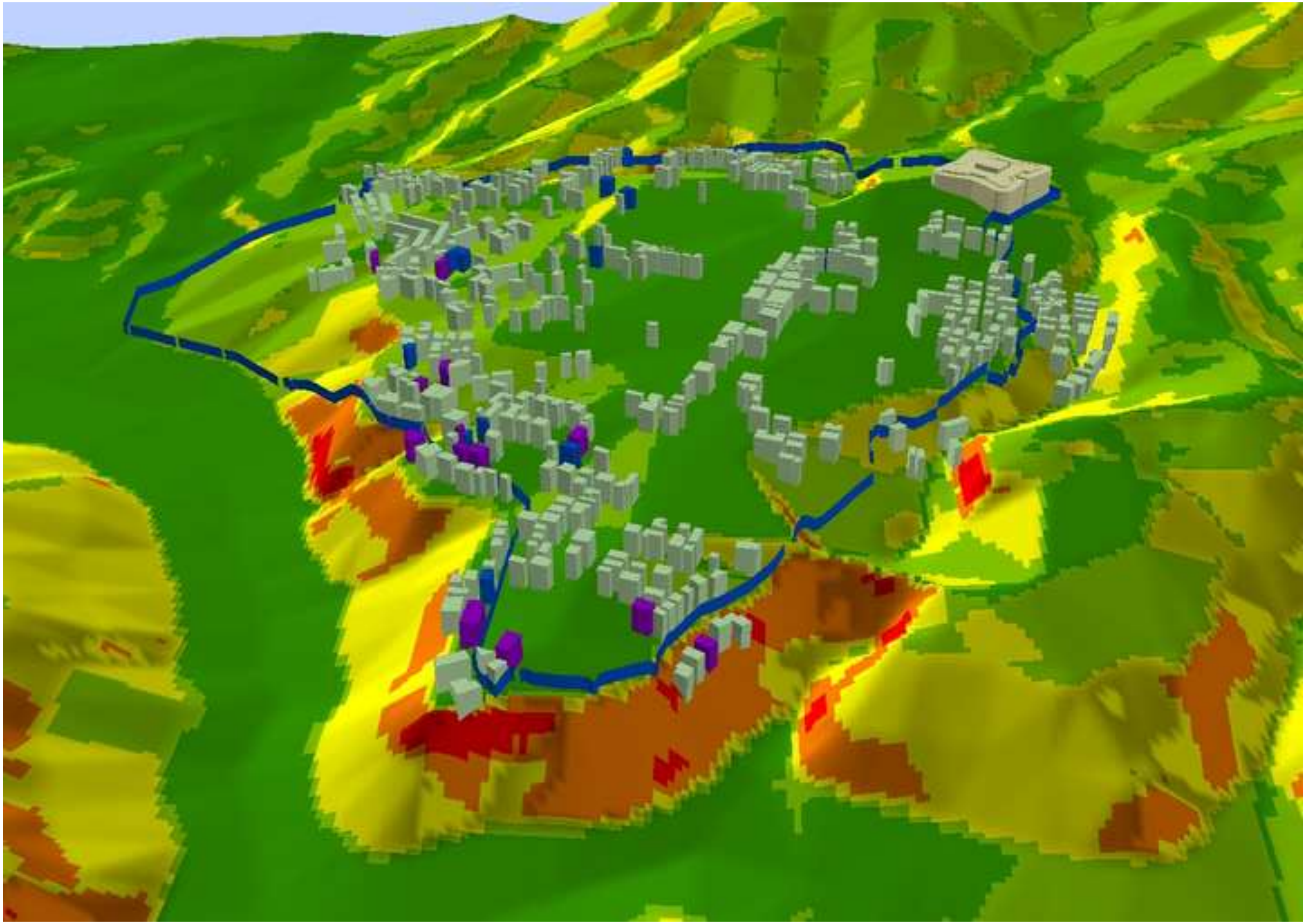

table
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2 Moderate damage.	Cracks in many walls, fall of fairly large pieces of plaster, partial collapse of chimneys, slipping of roof tiles.	Hair-line cracks in columns and beams, cracks in partitions and infill walls, fall of brittle cladding and plaster, falling mortar from the joints of wall panels.
3 Substantial to heavy damage.	Large and extensive cracks in many walls, general falling of roof tiles, chimneys fracture at the roof line, failure of individual non-structural elements.	Large cracks in partition and infill walls, failure of individual infill panels, cracks in columns and beams with detachment of pieces of concrete, buckling of reinforced rods.
4 Very heavy damage.	Serious failure of walls and roofs, partial structural failure.	Large cracks in structural elements, damage to the joints of the skeleton, destruction of concrete floors, protrusion of reinforcing rods, tilting of columns.
5 Destruction	Very total or near total collapse.	Very total or near total collapse.

Table 2 Description of the damage grades under the EMS98