Operational earthquake loss forecasting: a retrospective analysis of some recent Italian seismic sequences

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Abstract

Operational earthquake forecasting (OEF) relies on real-time monitoring of seismic activity in an area of interest to provide constant (e.g., daily) updates of the expected number of events exceeding a certain magnitude threshold in a given time window (e.g., one week). It has been demonstrated that the rates from OEF can be used to estimate expected values of the seismic losses in the same time interval OEF refers to. This is a procedure recently defined as *operational earthquake loss forecasting* (OELF), which may be the basis for rational short-term seismic risk assessment and management.

In Italy, an experimental OELF system, named MANTIS-K, is currently under testing. It is based on weekly rates of earthquakes exceeding magnitude (M) 4, which are updated once a day or right after the occurrence in the country of an M 3.5+ earthquake. It also relies on large-scale structural vulnerability and exposure data, which serve to the system to provide continuously the expected number of: (i) collapsed buildings, (ii) displaced residents, and (iii) casualties.

While the probabilistic basis of MANTIS-K was described in previous work, in this study OELF is critically discussed with respect to three recent Italian seismic sequences. The aim is threefold: (i) illustrating all the features of the OELF system in place; (ii) providing insights useful to evaluate whether if it would have been a useful additional tool for short-term management; (iii) recognizing common features, if any, among the losses computed for different sequences.

Keywords: seismic risk management; seismic loss.

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1. Introduction

The seismological community is investing in development and application of stochastic models for forecasting the space-time distribution of earthquakes conditional on the seismic history at the time of the probabilistic evaluation: e.g., epidemic type aftershock sequence or ETAS (Ogata, 1988 and 1998) and short-term earthquake probability or STEP (Gerstenberger et al., 2005) models. The common assumption is that each event of a seismic sequence can trigger new events causing an alteration of the seismicity in the area where it strikes; i.e., no physical differences are assumed among foreshocks, mainshocks and aftershocks (Jordan et al., 2011). Coupling this kind of models with real-time data acquired from monitoring seismic networks, the resulting systems can constantly provide *operational earthquake forecasting* (OEF). In Italy, an OEF prototype (OEF-Italy) of the national institute of geophysics and volcanology (INGV) is currently under testing in order to evaluate whether it is suitable to provide information about the short-term seismic hazard to the Italian civil protection system (Marzocchi et al., 2014).

In fact, the output of OEF can be useful for risk management if the rates of events above a magnitude threshold of interest may be used as an input for probabilistic assessment of seismic losses (e.g., Marzocchi et al., 2015). A procedure to do so, that is converting outputs of OEF into loss-related measures in a probabilistically consistent manner, has been recently developed and defined as *operational earthquake loss forecasting* (OELF; Iervolino et al., 2015a). In fact, a prototype system for OELF, called MANTIS-K, is also currently under experimentation in Italy. It starts from the weekly earthquake rates continuously provided (i.e., daily or after an event 3.5+ in magnitude) by OEF-Italy, and combines them with exposure data (at the scale of municipality) and models about seismic vulnerability of the building stock, to compute weekly expected values of seismic loss metrics after each OEF rates release.

Validation of expected losses requires a large amount of observed data, certainly unavailable in the case of MANTIS-K at this point. In fact, validation is out of the scope of this paper; however, referring to past seismic sequences, a critical analysis of the results provided by the system, during seismic sequences that raised risk management issues, may be useful. It may help understanding whether OELF, in the analysed cases, would have been a useful additional instrument for short-term management. Moreover, the retrospective analyses herein presented allow describing the type of information provided by MANTIS-K and recognizing

common features, if any, among the losses forecasted during three sequences, which are quite different from the seismological perspective.

As it regards the structure of the paper, even if details can be found in Iervolino et al. (2015a), the main equations and implemented models of MANTIS-K are summarised first. Subsequently, the three selected Italian seismic sequences are presented. They are those with the largest magnitude events occurred in Italy from 2004 to 2014 (excluding those offshore) and are named as *L'Aquila* (2009), *Emilia* (2012) and *Garfagnana* (2013). For each sequence, a general description is provided and the evolution of the earthquake rates forecasted by OEF-Italy, for each day in a selected period, is presented. Then, the daily-updated loss indices, forecasted by MANTIS-K in the area of the sequence, are shown; i.e., the expected values of fatalities, unusable buildings, and displaced residents, in the time-horizon of one week after each OEF data release. These indices are computed referring to four groups of municipalities characterised by increasing distance from the epicentre of the mainshock of the sequence. The work is concluded by a comparison of the OELF results among the sequences and a discussion with respect to the observed losses.

## 2. MANTIS-K system for operational earthquake loss forecasting in Italy

If data from a seismic sensor network monitoring a given region are available at each time instant *t*, that is, the seismic history, $H(t)$, is known, OEF models provide an estimation of future seismicity. More specifically, according to OEF, the territory is divided into elementary areas which are identified by pairs of coordinates $\{x, y\}$. Each area is considered as a point-like seismic source to which OEF assigns an expected number of generated earthquakes above a magnitude of interest per unit-time; i.e., the seismic rate. Such a rate, $\lambda\left[t, x, y \mid H(t)\right]$, depending on the recorded seismic history, varies with t.

In Italy, an OEF system is operating (Marzocchi et al., 2014). It is based on the country-wide seismic network of INGV and provides, for a grid of about 9000 point-like seismic sources spaced of about 0.1° and covering the whole Italian territory and some sea, the seismic rates updated at least once a day and every time an earthquake of local magnitude (M_L) equal or larger than 3.5 occurs. These rates are the forecasted mean number of M_L 4.0+ events produced by the point source in a time-horizon of one week. The probability density function of the magnitude of the events, $f_M(m)$ in the following, is assumed to be derived from a Gutenberg-

79   Richter-type relationship (Gutenberg and Richter, 1944), with unbounded maximum magnitude and *b*-value

80   equal to one. This is common to all the point sources, that is, differences among the sources derive only from

81   the seismic rates.

82   Although a prototypal version of the system has started working on the 7th of April 2009 (Marzocchi

83   and Lombardi, 2009), the complete Italian seismic catalogue from April 2005 to June 2014 has been analysed

84   offline by the OEF-Italy system and the seismic rates for the whole grid of point sources have been computed

85   at 00:00 of each day. A database collecting all the results for the analysed period (about 3300 days) has been

86   provided to the authors (Warner Marzocchi, personal communication, July, 2014) and has been used for the

87   analyses presented in the following.

88   An example of the seismic rates provided by OEF-Italy system is reported in Figure 1 for illustrative

89   purpose. The picture, arbitrarily, refers to the OEF-Italy results computed at 00:00 of the 6th of April 2009.
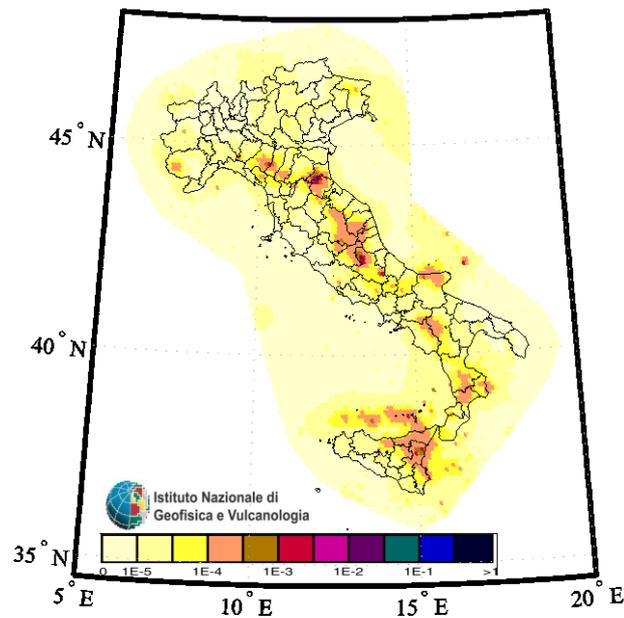
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91   Figure 1. Map of expected number of M_L 4+ events in the week following 00:00 of 06/04/09, estimated through OEF-
92   Italy.

93   In Iervolino et al. (2015a), it has been demonstrated that, starting from the rates resulting from the OEF-Italy

94   system, it is possible to derive indices of seismic losses via a probabilistically sound procedure. The latter

95   involves models used in the classical probabilistic seismic hazard analysis (PSHA; e.g. McGuire, 2004), and

96   is consistent with the performance-based earthquake engineering (Cornell and Krawinkler, 2000) framework.

97   While the interested reader should refer to the given reference for details, such a procedure for OELF is

98   summarised here for the sake of readability of the results of the study. In fact, the equation and the models

99   required are recalled as well as the data and models used for Italy.

2.1 Hazard (shaking intensity)

101   Starting from the weekly seismic rates from OEF-Italy described above, $\lambda\big[t,x,y\,|\,H(t)\big]$, associated to each

102   point-like seismic source in Italy, MANTIS-K associates probabilities of shaking intensity in terms of

103   macroseismic (MS) intensity. This is because the vulnerability models considered (to follow) are function of

104   MS.

105   Prediction equations allow estimating the probability of a specific MS intensity at the generic site,

106   identified by the couple of coordinates $\{w,z\}$, conditional on the occurrence of an earthquake of known

107   magnitude, M, at a given point-like seismic source; i.e., $P\big[MS = ms\,|\,m, R(x,y,w,z)\big]$, being $R(x,y,w,z)$

108   the source-to-site distance. The chosen prediction equation for macroseismic intensity is that of Pasolini et al.

109   (2008) that identified intensity as defined by the Mercalli-Cancani-Sieberg (MCS) scale (Sieberg, 1931). The

110   model applies to the [0 km, 220 km] interval of the distance,[†] and between 5 and 12 of intensity.

2.2 Vulnerability

112   Structural vulnerability is accounted for in MANTIS-K via a damage probability matrix (DPM) that, according

113   to the definition of Whitman et al. (1973) and Braga et al. (1982), provides the probability of observing a

114   damage state (ds) to a building of a given structural typology (k), given a value of intensity, *ms,* at the site;

115   i.e., $P\big[DS^{(k)} = ds\,|\,ms\big]$. The DPM considered is based on Italian observational data (Zuccaro and Cacace,

116   2009; Iervolino et al., 2014a). It accounts for four different vulnerability classes in which the Italian building

117   stock is divided, from A to D (the same as indicated in European Macroseismic Scale EMS 98), and six damage

118   levels (D0 – no damage, D1 – slight damage, D2 – moderate damage, D3 – heavy damage, D4 – very heavy

119   damage, D5 collapse).

[†] However, in the loss assessment, contributions from sources with epicentral distance larger than 150 km are neglected.

120   Another model used is, for the *k*-th structural typology and conditional on damage state, the probability

121   for an occupant to suffer casualties, $P\left[Cas^{(k)}|ds\right]$. Casualty probabilities, conditional on structural damage

122   and vulnerability class, are those of Zuccaro and Cacace (2011). Such a model refers to two types of casualties;

123   i.e., (i) fatalities and (ii) injuries (someone requiring hospital treatment is considered as injured).

124   **2.3 Exposure**

125   In Italy, the elementary units for which dwelling building exposure data are made publicly available from the

126   pokpulation census are municipalities. For this reason, all computations performed by MANTIS-K refer to the

127   municipality level and to dwelling buildings only: the centroid of each municipality area is the $\{w,z\}$ point

128   used for computing the source-to-site distance and in which all exposed assets in the municipality are supposed

129   to be concentrated. For each municipality, exposure in terms of building is the number of buildings of *k*-th

130   typology, $N_b^{(k)}$. The number of residents living in the *k*-th building typology, $N_p^{(k)}$, is a measure of exposure

131   in terms of residents. Both kinds of data are derived from the National census of 2001 (Zuccaro et al., 2012).

132   Note that these exposure measures depend on the municipality, that is on $\{w,z\}$; however, the coordinates are

133   dropped for simplicity in the symbols.

134   **2.4 Losses**

135   Assuming that the stochastic process of events causing damage to the building at the site is approximated, in

136   the short time interval (Δt), by a homogeneous Poisson process, the expected number of casualties (fatalities

137   or injuries) in the considered $\{w,z\}$ municipality, $E\left[N_{Cas,(t,t+\Delta t)}|H(t)\right]$, can be computed via equation (1).

138   According to Zuccaro et al. (2012), casualty and injury assessments are carried out considering that 65% of

139   the total population is exposed at the time of occurrence of the earthquake, which justifies 0.65 in the equation.

$$
\begin{aligned}
E\left[N_{Cas,(t,t+\Delta t)}|H(t)\right] &\approx \Delta t \cdot \sum_{k} 0.65 \cdot N_p^{(k)} \cdot \iint_{x,y} \lambda\left[t,x,y|H(t)\right] \cdot \sum_{ds} P\left[Cas^{(k)}|ds\right] \cdot \\
&\cdot \sum_{ms} P\left[DS^{(k)}=ds|ms\right] \cdot \int_m P\left[MS=ms|m,R(x,y,w,z)\right] \cdot f_M(m) \cdot dm \cdot dx \cdot dy
\end{aligned}
$$

140 (1)

Zuccaro and Cacace (2011) also provide the probability of a building to be unusable for a given damage state, $P\big[Unus|ds\big]$. Such a probability, which does not depend on the structural typology, is 1 for damage state D4 and D5, whereas it is 0.5 for buildings in D3, and it is 0 for lower damage levels. Thus, the expected number of unusable buildings in one time unit, $E\big[N_{Unus,(t,t+\Delta t)}\big|H(t)\big]$, can be computed via equation (2).

$$E\big[N_{Unus,(t,t+\Delta t)}\big|H(t)\big] \approx \Delta t \cdot \sum_k N_b^{(k)} \cdot \iint_{x,y} \lambda\big[t,x,y\big|H(t)\big] \cdot \sum_{ds} P\big[Unus|ds\big] \cdot$$
$$\cdot \sum_{ms} P\big[DS^{(k)}=ds\big|ms\big] \cdot \int_m P\big[MS=ms\big|m,R(x,y,w,z)\big] \cdot f_M(m) \cdot dm \cdot dx \cdot dy \qquad (2)$$

Replacing the number of buildings, $N_b^{(k)}$, with the number of residents, $N_p^{(k)}$, the expected number of displaced residents may also be computed. Indeed, all the residents living in an unusable building are considered as shelter-seeking.

To give a sense of the results MANTIS-K provides with these models and data, Figure 2 shows, for each municipality, the expected values of: (a) unusable and (b) collapsed buildings (values are per 100 buildings), and the expected value of (c) injuries and (d) fatalities (both per 100 residents), on the basis of the OEF-Italy data of Figure 1. Indeed, these results are the losses forecasted for the week after the OEF rates' release (00:00 on 06/04/09), and the same weekly horizon will be maintained for all results shown in the following sections of the paper.

The previous equations may be considered as site-specific risk measures as they apply to municipalities; however, they can be summed over an area of interest to compute total expected losses.
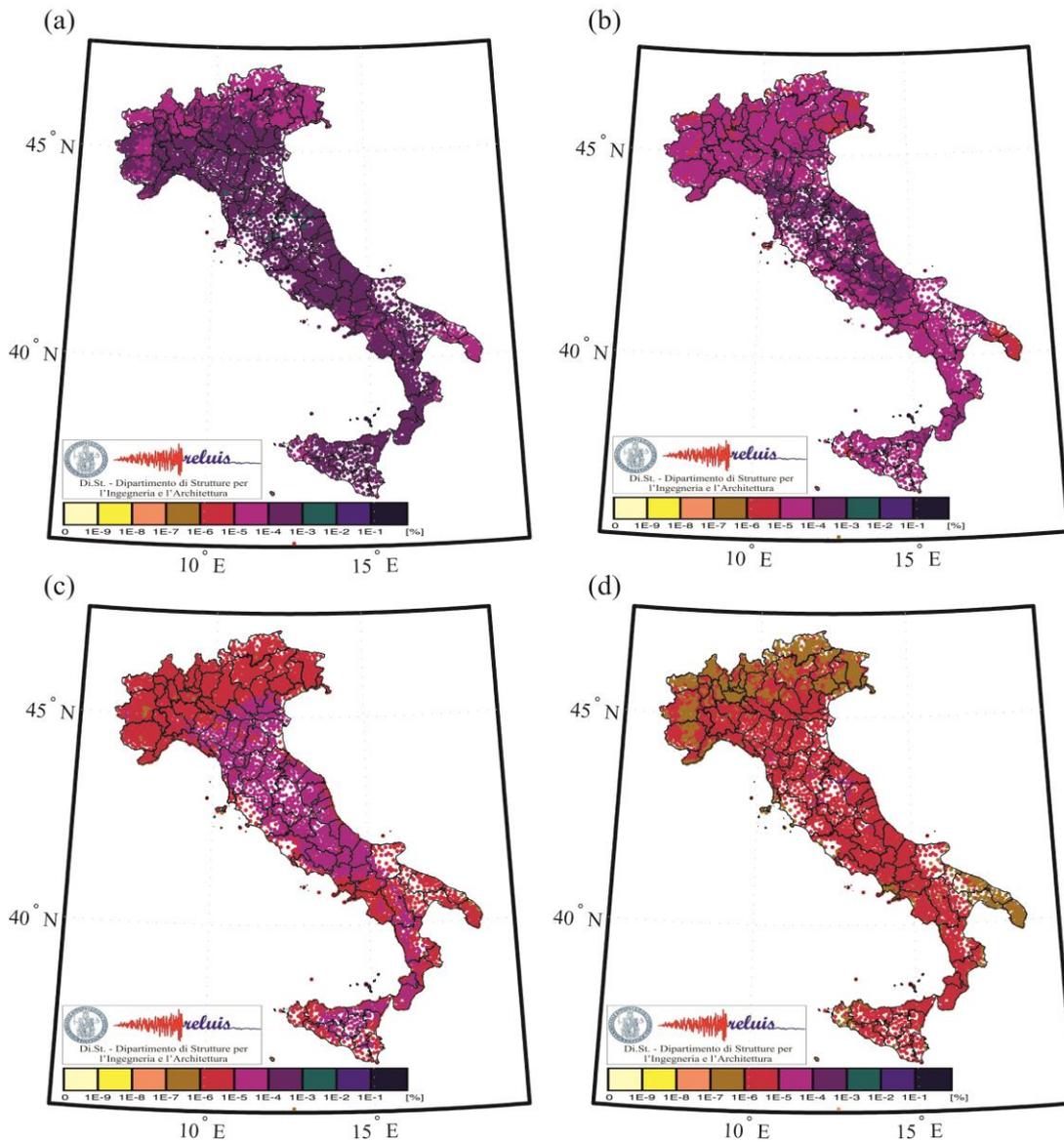
Figure 2. Illustrative example of MANTIS-K outputs: maps of the expected values of (a) unusable and (b) collapsed per 100 buildings, and the expected values of (c) injuries and (d) fatalities per 100 municipality residents. These results are computed using the OEF-Italy data of Figure 1 as the input. Therefore they refer to the week after 00:00 of 06/04/09.

3. Considered Italian seismic sequences

From 2004 to 2014 more than two-hundreds M 4.0+ events occurred in Italy (i.e., in a geographic area identified by 35.0-48.0 °N latitude and 6.0-19.0 °E longitude).[‡] Epicentral locations of these events are plotted in Figure 3; the size of each circle is proportional to the magnitude and the colour relates to the date of the event. Earthquakes with the largest magnitude identify three seismic sequences named *L'Aquila*, *Emilia* and

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[‡] Data from ISIDe, http://iside.rm.ingv.it/, last accessed 20/07/15. Because ISIDe does not provide measures is a unique magnitude scale for all the events, M without subscripts is used where necessary.

166 *Garfagnana*, due to the areas where they occurred (identified in the same figure). For each sequence, the
167 epicentre of the largest magnitude event (i.e., the mainshock) is indicated as a star; these points are referred to
168 as the centres of the corresponding seismic sequence hereafter.
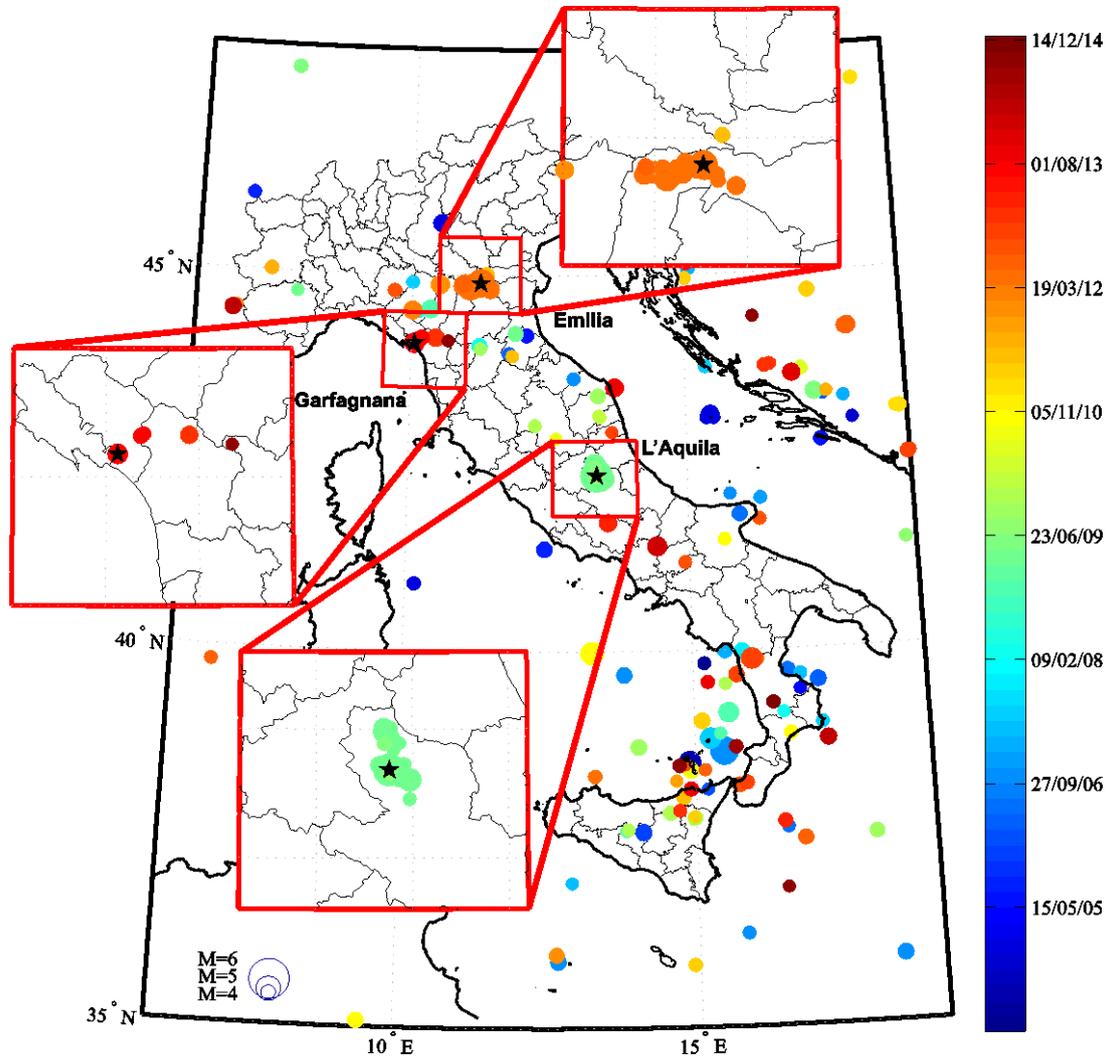
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170 Figure 3. Epicentres of M 4+ seismic events occurred from 01/01/04 to 31/12/14 and geographic areas considered for the
171 three sequences analysed.

172 L'Aquila and Emilia sequences were characterised by significant losses in terms of structural damages and
173 fatalities. The same did not happened in Garfagnana; however, during this sequence, the Italian civil protection
174 system was in state of alert for the possible occurrence of damaging events, after a M_W 5.1 earthquake. For
175 this reason, the Garfagnana seismic sequence has been considered in the context of this study.

176   The retrospective analysis of each sequence consisted of the computation of the expected losses for the
177 week following each day for which forecasted seismicity was available by OEF-Italy. In the following, each
178 seismic sequence is presented first and the rates computed by OEF-Italy are reported as function of time and

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179 summed up over the point-like sources within 30 km from the centre of the sequence, to get a sense of the

180 forecasted seismicity in the area. Then, the evolution of some indices of seismic losses from MANTIS-K are

181 reported and compared among sequences. Finally, a discussion with respect to the observed consequences is

182 given.

183   The considered risk metrics, computed by MANTIS-K for each municipality, are the expected values in

184 one week of: (i) fatalities and (ii) displaced residents, (iii) unusable and (iv) collapsed dwelling buildings.

185 Results are reported as the expected value of total loss within four areas identified by the maximum distance

186 (10 km, 30 km, 50 km and 70 km) from the epicentre of the mainshock;[§] see Figure 4b. For the sake of

187 presentation, arbitrarily, a time window spanning three months before and one year after the mainshock is

188 considered.

3.1 L'Aquila 2009

226 The main event of L'Aquila sequence, moment magnitude (M_W) 6.1, struck on the 6th of April 2009; it

227 produced a maximum observed peak ground acceleration (PGA) equal to 644 cm/s^2 (e.g., Chioccarelli et al.,

228 2009; Dolce and Di Bucci, 2015). In the area identified by 41.8-42.8 °N latitude and 12.6-14.1 °E longitude

229 (red square in Figure 1), a single M 4+ event occurred before the mainshock since the 1st of January 2009, that

230 is, the M_W 4.0 on the 30th of March 2009. In the same area and period, there were 29 M 2.5+ events and 10 M

231 3.0+. On the other hand, the aftershock sequence was characterised by 8 M 4.5+ earthquakes, reported in Table

232 1 (along with mainshock data), and more than 300 events M 2.5+ in the 24 hours after the mainshock.

233 Table 1. M 4.5+ aftershocks in a geographic area within latitude 41.8°-42.8° and longitude 12.6°-14.1°. Reported
234 information are event date and time, hypocentre latitude, longitude and depth, event magnitude. Data are extracted from
235 the Seismological Instrumental and parametric Data-base (ISIDe) website (last accessed 22/07/15).

| #	Date and Time (UTC)	Latitude [°]	Longitude [°]	Depth [km]	Magnitude	
1	**06/04/09 01:32**	**42.342**	**13.38**	**8.3**	**6.1**	**M_W**
2	06/04/09 01:36	42.352	13.346	9.7	4.7	M_L
3	06/04/09 02:37	42.360	13.328	8.7	4.8	M_W
4	06/04/09 23:15	42.463	13.385	9.7	5.0	M_W
5	07/04/09 09:26	42.336	13.387	9.6	4.9	M_W
6	07/04/09 17:47	42.303	13.486	17.1	5.4	M_W
7	09/04/09 00:53	42.489	13.351	11.0	5.2	M_W
8	09/04/09 19:38	42.504	13.350	9.3	5.0	M_W
9	13/04/09 21:14	42.498	13.377	9.0	4.8	M_W

236

[§] It is to note that, the epicentre location of the mainshock of the sequence is known only afterwards. Conversely, in using MANTIS-K during a seismic sequence, some hypotheses on the location of the geographic area to be monitored would be required.

237　The geographic area affected by the sequence is reported in Figure 4a and Figure 4b; both of them show

238　boundaries of municipalities and the mainshock epicentre (represented by a star). Figure 4a displays the grid

239　of point-like seismic sources, the OEF-Italy system assigns earthquake rates to. Figure 4b reports the centroids

240　of each municipality for which loss indices are computed together with contours of the distance from the

241　epicentre of the mainshock, R.
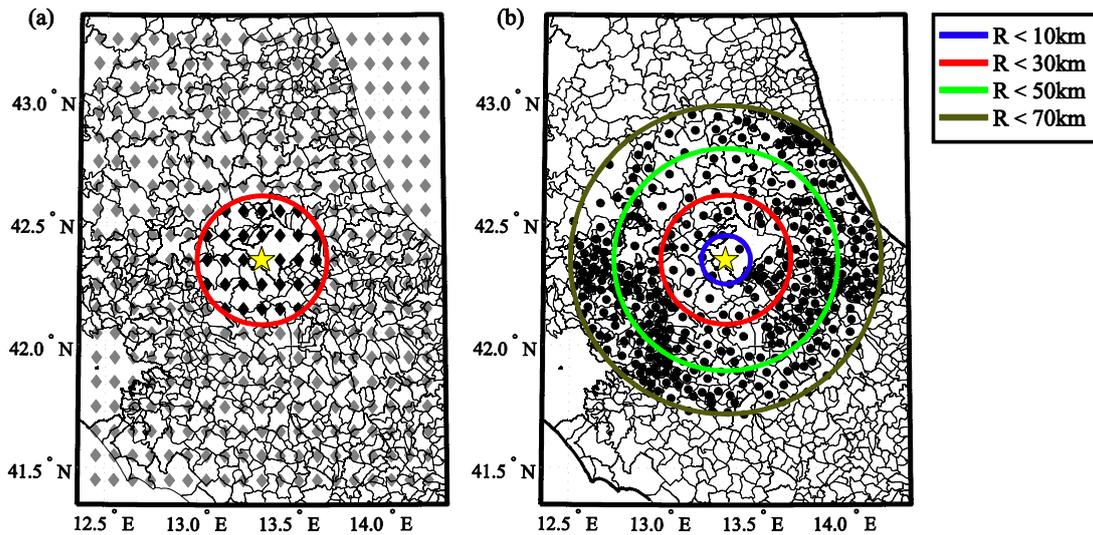
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243　Figure 4. Geographic representation of the mainshock epicentre together with (a) the grid of the point-like seismic sources
244　according to OEF-Italy and (b) the centroids of municipalities within 70 km from the epicentre.

245　In order to provide a synthetic representation of the forecasted seismicity during the whole sequence, the values

246　of seismic rates provided by OEF-Italy, for each point-like source within 30 km from the epicentre of the

247　mainshock (see Figure 4a), are summed up and plotted in Figure 5 as a function of the day in which rates were

248　have been released by the INGV system. In the same figure, the dates of occurrence of all M_W 4.2+ events are

249　also reported with dotted vertical lines. It is to note that the event rates during the seismic crisis are two orders

250　of magnitude larger than those computed at the beginning of 2009. It is also to underline that the maximum is

251　on the day after the mainshock of the sequence; this is a feature of the OEF-Italy system according to which

252　the rates peak right after the maximum seismic moment release (Marzocchi and Lombardi, 2009). Similarly, a

253　significant increment of forecasted rates can be identified after all the *strong* events of the sequence. In fact,

254　although discussion of pro and cons of OEF is out of the scope of this paper, it has to be anticipated that trend

255　of the seismic loss estimates from the MANTIS-K system reflect the trend in time of OEF-Italy rates.

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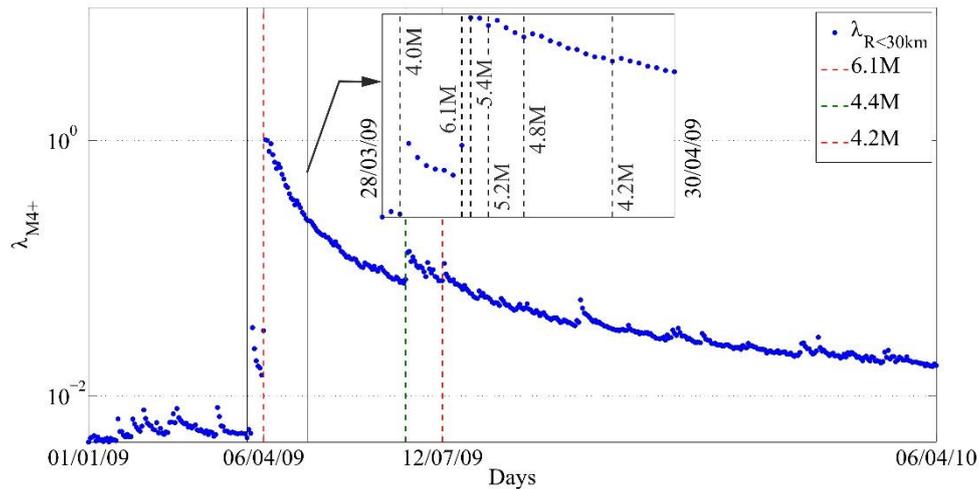
Figure 5. Sum of the following week's (with respect to the date in the abscissa) rates of M 4+ events within 30 km from the centre of the sequence, and dates of M 4.2+ events occurred in the area of Figure 1 (see also Table 1 for date of each event). In the picture, M refers to moment magnitude M_W.

Figure 6a shows the evolution of the expected number of total fatalities, for municipalities within 10 km, 30 km, 50 km and 70 km from the epicentre of the mainshock (see Figure 4 for the identification of such municipalities).

At the beginning of 2009 the expected value of fatalities in one week is lower than one for the whole area considered around the centre of the sequence (i.e., about 0.22 for R<70 km on 01/01/2009). Five days before the mainshock, the trend of loss shows some increments (due to the M_W 4.0 event on the 30th of March) and the expected fatalities for the week after 06/04/09 are about 0.64 within 70 km. Results change right after the mainshock when the expected number of total fatalities becomes larger than one; i.e., 3.7, 6.5, 11.1 and 15.5 for radii of 10 km, 30 km, 50 km and 70 km, respectively.[**] One year after the mainshock, the maximum value of the expected number of fatalities is around 0.4 that is comparable with the reported value computed at the beginning of 2009; i.e., the sequence seems have come to an end.

Figure 6b shows the expected number of total displaced residents. The maximum value is equal to 1452.5 within 70 km from the epicentre of the mainshock (940.1, 493.4 and 259.8 for radii in descending order).

[**] Note that after a damaging earthquake, evacuation is likely to be expected, while at this stage the algorithm of MANTIS-K assumes stable exposure (and also vulnerability), despite the occurred earthquake.

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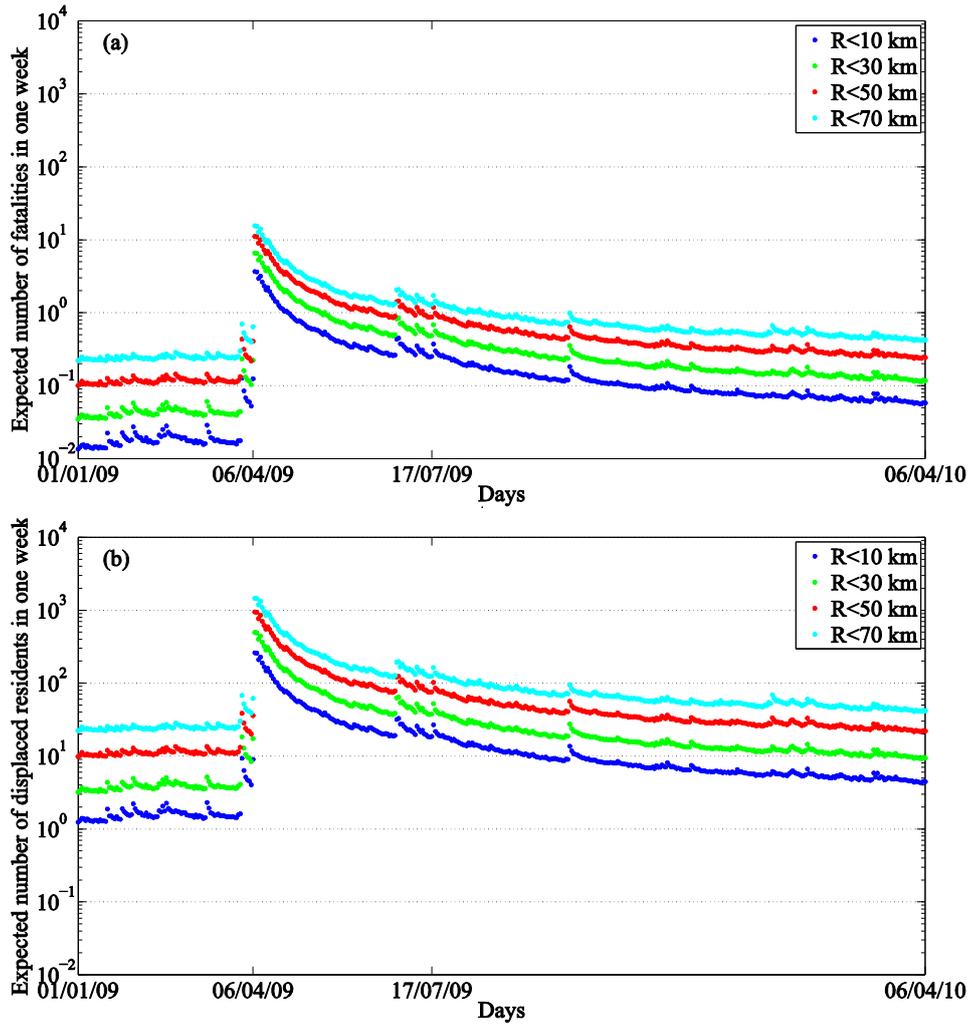
Figure 6. Expected number of (a) fatalities and (b) displaced residents in the week following the date in the abscissa, summed over all municipalities within 10 km, 30 km, 50 km and 70 km from the centre of the sequence.

3.2 Emilia 2012

The prominent magnitude event of the sequence, the mainshock, is the M_W 5.8 occurred on the 20th of May 2012 (see also Iervolino et al., 2012). The aftershock sequence, until the end of May 2013, and in the box identified by 44.5-45.5 °N latitude and 10.5-12.0 °E longitude (see also Figure 1), includes 13 M 4.5+ events reported in Table 2 (data from ISIDe, last accessed 20/07/15). The (*first*) mainshock and the M_W 5.6 event on the 29th of May (sometimes referred to as *second* mainshock; e.g., Dolce and Di Bucci, 2015) were felt in the whole Northern Italy. (Dates in Table 2 show a difference with respect to the case of L'Aquila. Indeed, most

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283 of the largest magnitude events occurred few hours after the two mainshocks.) The recorded largest (corrected)

284 horizontal PGAs are about 259 cm/s^2 and 495 cm/s^2 for the 5.8 and 5.6 M$_W$ event, respectively.[††]

285   Following the first strong event, on the 22nd of May, the Italian government declared the emergency for

286 the provinces of Modena, Ferrara, Bologna and Mantova. On the 30th of May, after the M$_W$ 5.6 event, the state

287 of emergency was extended to the provinces of Reggio Emilia and Rovigo.

288 Table 2. M 4.5+ earthquake in a geographic area within latitude 44.5°-45.5° and longitude 10.5°-12.0°. Reported
289 information are event date and time, hypocentre latitude, longitude and depth, event magnitude. Data are extracted from
290 ISIDe website (last accessed 20/07/15).

#	Date and Time (UTC)	Latitude [°]	Longitude [°]	Depth [km]	Magnitude	
1	**20/05/12 02:03**	**44.896**	**11.264**	**9.5**	**5.8**	**M$_W$**
2	20/05/12 02:06	44.879	11.120	5.0	4.8	M$_L$
3	20/05/12 02:06	44.905	11.165	4.3	4.8	M$_L$
4	20/05/12 02:07	44.874	11.270	6.1	5.0	M$_L$
5	20/05/12 03:02	44.860	11.152	9.1	5.0	M$_L$
6	20/05/12 13:18	44.814	11.441	3.4	4.9	M$_w$
7	20/05/12 17:38	44.880	11.253	3.7	4.6	M$_L$
8	**29/05/12 07:00**	**44.842**	**11.066**	**8.1**	**5.6**	**M$_W$**
9	29/05/12 08:25	44.865	10.948	7.9	5.0	M$_L$
10	29/05/12 08:27	44.883	11.042	6.0	4.6	M$_L$
11	29/05/12 10:55	44.865	10.980	4.4	5.3	M$_W$
12	29/05/12 11:00	44.856	10.941	8.7	5.0	M$_L$
13	29/05/12 11:00	44.866	10.976	7.2	5.1	M$_L$
14	03/06/12 19:20	44.886	10.950	8.7	4.7	M$_W$

291

292 Similarly to L'Aquila, Figure 7a shows the point-like seismic sources in the area of interest, identifying those

293 within 30 km from the epicentre of the mainshock; Figure 7b displays the centroids of municipalities within

294 the four boundaries presented results refer to; i.e., radii lower than 10 km, 30 km, 50 km and 70 km.

295   The distribution in time of the main aftershocks, clustered in the few days after the mainshock, is

296 reflected by the evolution of forecasted seismic rates (Figure 8) that has a regular trend decreasing with the

297 increasing time after the M$_W$ 5.6 event. It is to note that maximum forecasted seismicity corresponds to the day

298 after the second mainshock that has, in fact, a magnitude lower than the first one.

[††] The values of PGA are available on the Italian Accelerometric Archive – ITACA - http://itaca.mi.ingv.it/, last accessed 20/07/15.
However, note that for the second event ITACA does not specifies whether the PGA has been recorded in free field conditions. In fact,
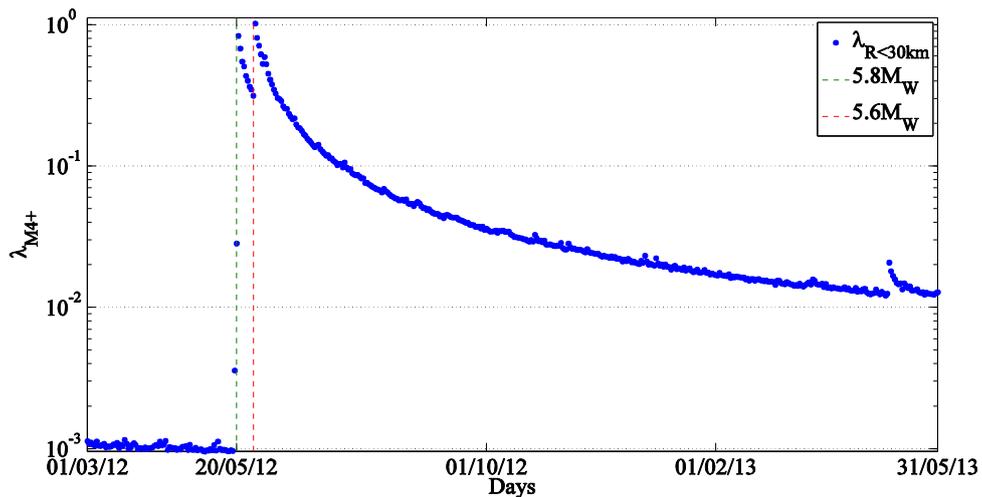Dolce and Di Bucci (2015) report a maximum horizontal PGA value for the second event of 289 cm/s^2.
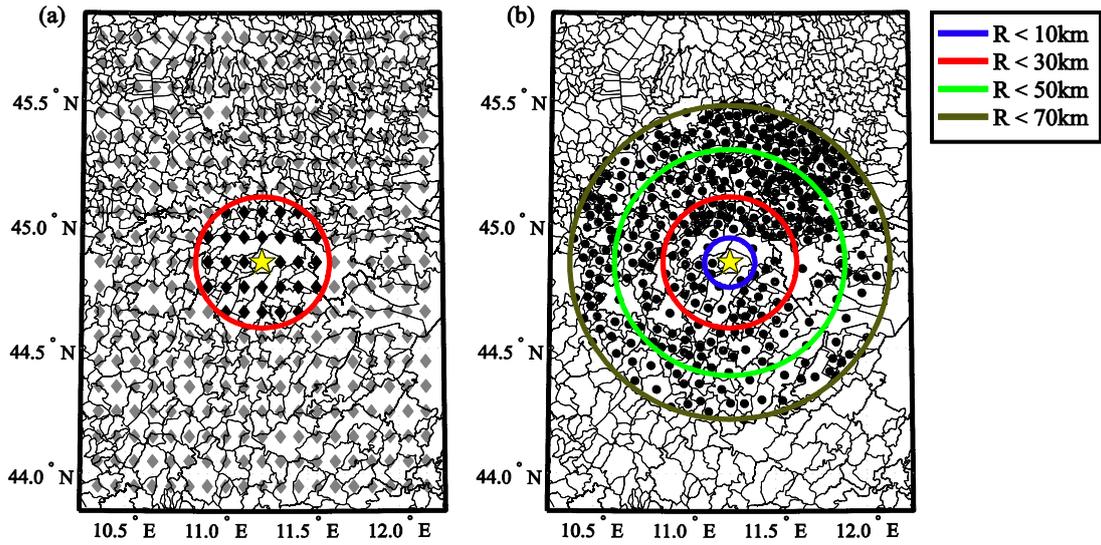
Figure 7. Geographic representation of the mainshock epicentre together with (a) the grid of the point-like seismic sources according to OEF-Italy and (b) the centroids of municipalities within 70 km from the epicentre.

Figure 9 shows the expected values of fatalities and unusable buildings in the time interval of Figure 8. Expected number of fatalities for the week after 00:00 of 20/05/12 (i.e., right before the mainshock) are 0.1, 0.5, 0.9 and 1.2 for the municipalities within radii of 10 km, 30 km, 50 km and 70 km from the centre, respectively. The same estimates right after the mainshock (i.e., for the week after 21/05/12) become 2.6, 12.3, 23.8 and 29.7, respectively. For the week after 29/05/12, values are about 1.1, 4.8, 8.9 and 11.1 and become 2.5, 16.0, 31.2 and 39.5, after the M_W 5.6. In the same period, the largest numbers of expected unusable buildings are 36.9, 232.9, 471.9 and 639.0.

Figure 8. Sum of the following week's (with respect to the date in the abscissa) rates of M 4+ events within 30 km from the centre of the sequence, and dates of main events occurred in the area.
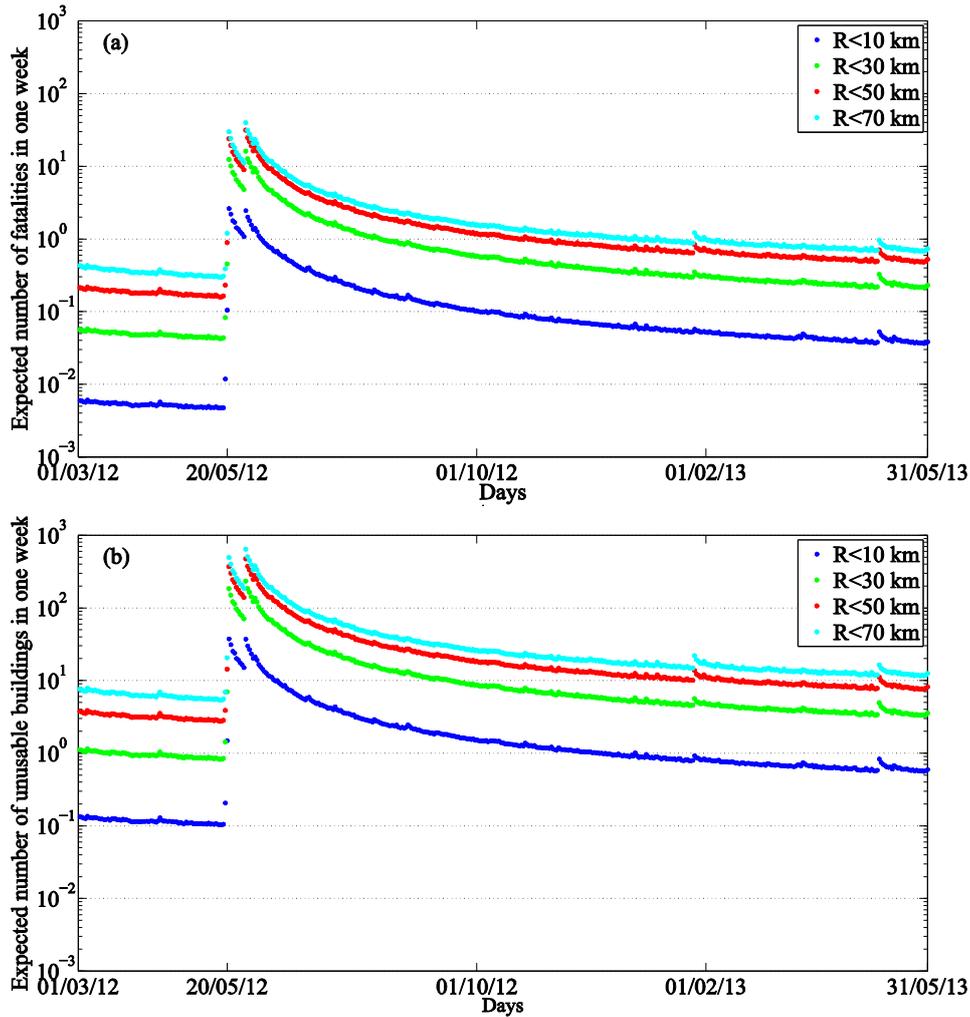
Figure 9. Expected number of (a) fatalities and (b) unusable buildings in the week following the date in the abscissa, summed over all municipalities within 10 km, 30 km, 50 km and 70 km from the centre of the sequence.

3.3 Garfagnana 2013

The mainshock of this sequence was the M_W 5.1 on the 21st of June 2013 and, consistent with previous cases, the considered time window extends to about one year after this date. However, on the 25th of January 2013, a M_W 4.8 struck in the same area (identified in Figure 1; 43.5-44.5 °N and 9.5-11.0 °E). Thus, available data were analysed starting from about three months before this event; i.e., from the 1st of November 2012.

From November 2011 to the mainshock, 20 M 2.5+ earthquakes stoke in the area; among these events, 6 had magnitude equal to or larger than 3.0, and 1 larger than 4.0 (the one of M_W 4.8). In the 24 hours after the mainshock, 12 earthquakes occurred in the area, all with magnitude between 3 and 4. The subsequent event with M equal to 4.5 occurred on the 30th of June 2013. Table 3 shows the 5 events with M equal to or larger than 4 in the considered area and time interval.

16

325   During the sequence, someone claimed similarities with respect to seismic events preceding L'Aquila

326 mainshock (authors are not aware of scientific studies supporting such a similarity). In fact, the sequence

327 focalised the attention of mass media and the worries of residents, and the Italian civil protection department

328 was constantly in state of attention.[‡‡]

329 Table 3. M 4.0+ earthquake in a geographic area within latitude 43.5°-44.5° and longitude 9.5°-11.0°. Reported
330 information are event date and time, hypocentre latitude, longitude and depth, event magnitude. Data are extracted from
331 ISIDe website (last accessed 20/07/15).

#	Date and Time (UTC)	Latitude [°]	Longitude [°]	Depth [km]	Magnitude	
1	25/01/13 14:48	44.164	10.446	19.80	4.8	M_W
2	**21/06/13 10:33**	**44.090**	**10.062**	**5.70**	**5.1**	**M_W**
3	21/06/13 12:12	44.162	10.135	8.10	4.0	M_W
4	23/06/13 15:01	44.168	10.201	9.20	4.4	M_W
5	30/06/13 14:40	44.160	10.187	6.10	4.5	M_W

332

333 The point-like seismic sources within 30 km from the epicentre of the mainshock are reported in Figure 10a

334 while centroids of municipalities and boundaries of interest for results are shown in Figure 10b. The evolution

335 of the sum OEF rates within 30 km from the epicentre of the mainshock is clearly affected by the two largest

336 magnitude events as reported in Figure 11a.
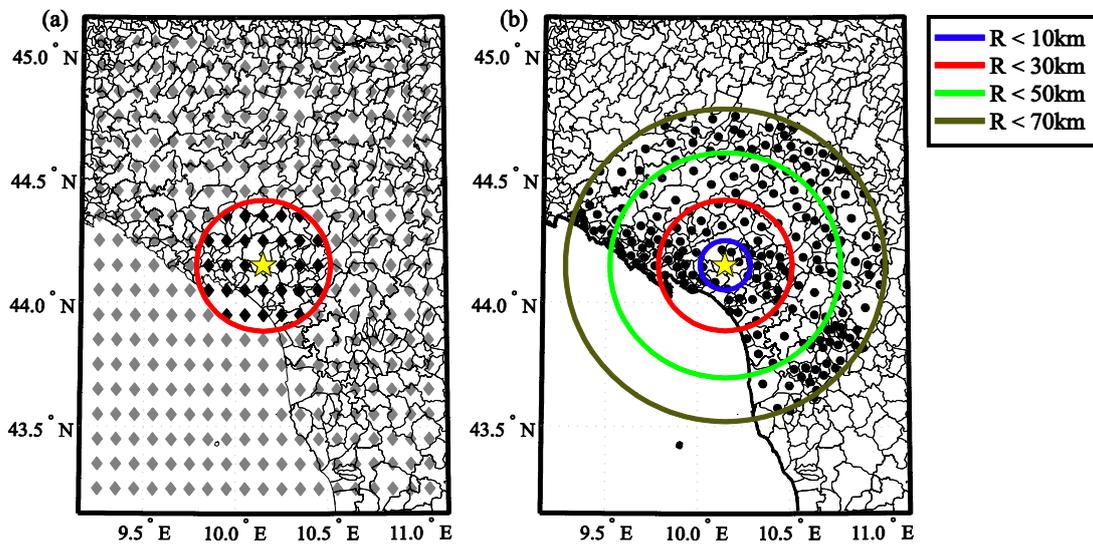
338 Figure 10. Geographic representation of the mainshock epicentre together with (a) the grid of the point-like seismic
339 sources according to OEF-Italy and (b) the centroids of municipalities within 70 km from the epicentre.
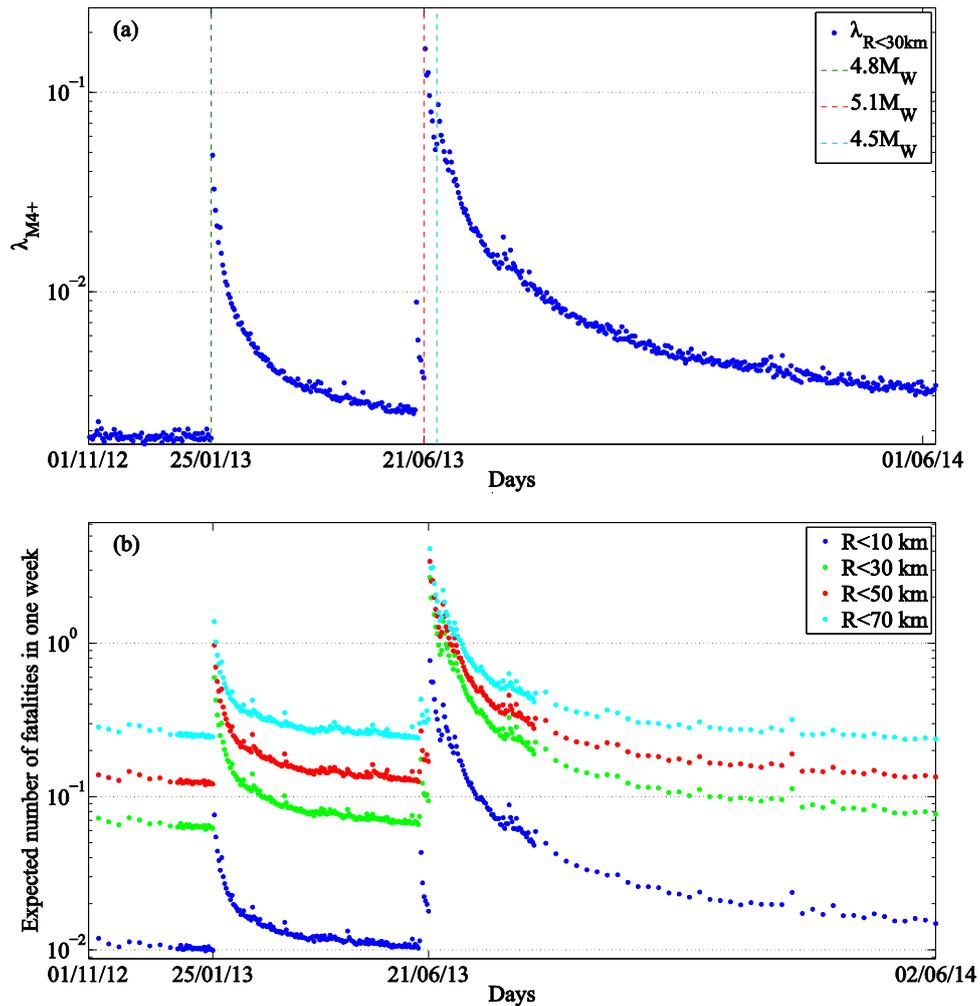
Figure 11. (a) Sum of the following week's (with respect to the date in the abscissa) rates of M 4+ events within 30 km from the centre of the sequence, and dates of main events occurred in the area; (b) weekly expected number of fatalities summed over all municipalities within 10 km, 30 km, 50 km and 70 km from the centre of the sequence.

Expected values of fatalities are reported in Figure 11b. For the week after 25th of January 2013, loss estimates are lower than one (0.2 within 70 km form the centre of the sequence). For the week after 26/01/13, the same estimation becomes about 1.4 and decreases in the subsequent days with a regular path. A peculiar trend can be identified in the six days before the mainshock: about 0.3 is the expected number of fatalities within 70 km for the week after 21/06/13 (i.e., right before the mainshock), and it becomes 4.1 for the week after the day of the mainshock.

3.4 Sequences' comparison

Figure 12 shows, for the three analysed sequences, (a) the sum of the weekly rates of M 4+ events within 70 km from the centre of the shock and (b) the weekly expected fatalities in the same areas. In the figure, for the

18

353 sake of comparison, the days of the mainshocks are coincident and the chosen time window goes from 100

354 days before to 50 days after the mainshock.

355
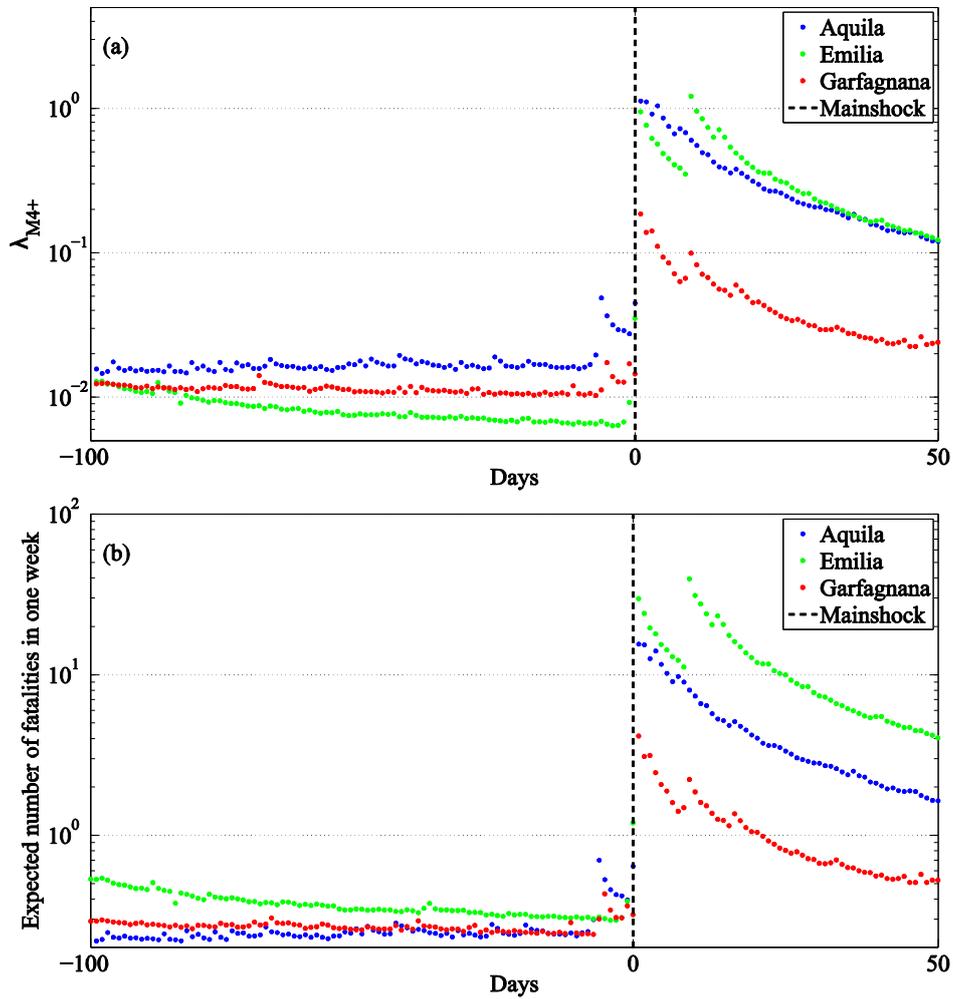
Figure 12. (a) Sum of the following week's (with respect to the time in the abscissa) rates of M 4+ events within 70 km
from the centre of each sequence; (b) weekly expected number of fatalities within 70 km from the centre of each sequence.

358 The comparison between Figure 12a and Figure 12b underlines, once again, that the results of MANTIS-K are

359 more informative than those of OEF, because it accounts not only for hazard but also for vulnerability and

360 exposure. Indeed, in the whole considered time-window before the mainshock, seismic rates for L'Aquila are

361 larger than those for Garfagnana and Emilia (in this latter case the rates are the lowest). Conversely, the

362 expected fatalities for L'Aquila and Garfagnana are comparable, while the largest are associated to the Emilia

363 sequence. [§§] Similarly, after the mainshock, the seismicity rates for L'Aquila and Emilia are comparable, and

364 both higher than Garfagnana. On the other hand, the expected losses for Emilia are significantly higher than

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[§§] See Dolce and Di Bucci (2015) for a discussion, related to exposure, which may help in understanding this result.

365 those expected in L'Aquila, and the expected losses in Garfagnana are lower than those of the other sequences.

366 Considering only the seven days before the mainshock, it is also interesting to note that L'Aquila shows some

367 increment of expected losses with respect to previous weeks, while the Emilia shows significant expected loss

368 variations only since the day before the mainshock, Figure 12b. This trend can be also identified in terms of

369 seismic rates (Figure 12a).

370 **3.5 Observed losses and the meaning of OELF results**

371 In this section the consequences observed in the analysed earthquakes are reported (see Dolce and Di Bucci,

372 2015, for details). Indeed, it is believed appropriate to discuss the losses produced in the seismic sequences to

373 better understand the intrinsic meaning of OELF and the current features and/or limitations of MANTIS-K.

374 For what concerns L'Aquila, 308 total fatalities have been counted. Approximately 34000 buildings failed

375 or resulted unusable, at least 1500 residents were injured and more than 65000 were temporarily displaced.

376 During the Emilia sequence the number of dwelling buildings declared unusable after a survey was in the order

377 of 15000. Fatalities reported are 26, 7 of which are due to the mainshock on the 20th of May, and 19 to the

378 second event on the 29th of May. Finally, in the Garfagnana sequence, no significant damage or injuries have

379 been observed.

380 Even if OELF provides losses' predictions, there is a number of reasons why direct comparison of the

381 observed consequences with the results of OELF, if not inappropriate, requires at least particular caution. First

382 of all, OELF provides weekly expected values. In statistical terms, the expected value is the limit of the

383 arithmetic mean over a virtually infinite number of nominally equivalent trials. In this respect, the observed

384 losses are individual realizations only, which do not allow validation (see also Iervolino, 2013, for a discussion

385 of similar issues). It is also to note that OELF, by nature of the OEF models providing the input rates, provides

386 the largest expected losses only after the strongest event of the sequence, while a significant portion of the

387 consequences observed is due to the main events (e.g., in the L'Aquila case).

388 In addition to this basic discussion of the meaning of OELF, it has to be recalled that at this stage there

389 are some features/limitations of MANTIS-K, which are relevant to the analysis of the observed losses. For

390 example, most of the fatalities occurred during the Emilia sequence were in industrial buildings and not in

391 residential buildings, which are those at the basis of damage vulnerability matrices and exposure data.

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Moreover, it is to also underline that MANTIS-K does not account for damage accumulation. Although it is something feasible to consider, it is not yet implemented, while it may be relevant to sequences with multiple potentially-damaging events, such as the Emilia one. In these cases, the vulnerability of the building stock varies during the sequence (e.g., Iervolino et al., 2014b and 2015b). Finally, also exposure may significantly vary, affecting the losses, in a sequence featuring at least one damaging event due to precautionary evacuations; e.g., L'Aquila. Also this issue could be accounted for in the MANTIS-K approach, yet it is something not yet in place.

4. Conclusions

The study focused on a retrospective analysis of three Italian seismic sequences through the recently developed MANTIS-K system for short-term earthquake loss forecasting. Indeed, seismicity rates estimated by the OEF-Italy system are the input data for MANTIS-K that, performing a probabilistic analysis, is able to convert them into weekly estimates of seismic losses (e.g., expected values of fatalities, displaced residents, and damaged buildings), using vulnerability and exposure data and models at the municipality scale for Italy.

The seismic sequences, chosen for the critical analysis of OELF, are L'Aquila (2009), Emilia (2012) and Garfagnana (2013), which include the main earthquakes occurred in Italy from 2004 to 2014. For each of the sequences, risk measures for areas characterised by different values of radius from the mainshock epicentre (10 km, 30 km, 50 km and 70 km) were considered. It was observed that the trends of forecasted losses are, as expected, strongly influenced by OEF input data. In particular, due to the features of the OEF-Italy system, the largest increment of the expected losses are always right after the maximum seismic moment release (i.e., for the week after the largest events in the sequence).

A discussion of the observed losses in the sequences allowed to discuss the meaning of the OELF predictions as well as the current features and/or limitations of the MANTIS-K system. In fact, the statistical interpretations of the expected loss was recalled. Moreover, the cases of the L'Aquila and the Emilia sequences allowed to point out that during seismic sequence with one or more damaging events, damage accumulation in the building stock and precautionary evacuations, may lead to short-term variations of vulnerability and exposure that may affect the expected losses, yet are not accounted for at this stage. Finally, MANTIS-K relies

on dwelling building exposure, not suitable to reflect peculiar structural typologies, which may also affect the

losses, as observed, for example, with precast industrial buildings in the Emilia sequence.

Even with the discussed issues and limitations, it is believed that OELF implemented in the MANTIS-K

system is a step in the direction of rational decision making for risk management during seismic sequences

due to its quantitative approach, and it is certainly more informative than OEF alone.

5. Acknowledgments

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