Bull Earthquake Eng (2016) 14:2607–2626
DOI 10.1007/s10518-015-9837-8

ORIGINAL RESEARCH PAPER

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

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Received: 6 August 2015 / Accepted: 18 October 2015 / Published online: 27 October 2015

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., 1 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 weekly expected number of: (1) collapsed buildings, (2) displaced residents, and (3) 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: (1) illustrating all the features of the OELF system in place; (2) providing insights to evaluate whether if it would have been a useful additional tool for short-term management; (3) recognizing common features, if any, among the losses computed for different sequences.

Keywords Seismic risk management · Emergency management · Seismic swarms

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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, 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). 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 risk 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 for the area of the sequence, are shown; i.e., the expected values of fatalities, unusable buildings, and displaced residents, in the time-horizon of 1 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, then 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, $\lambda[t, x, y|H(t)]$, 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 covering the whole Italian territory and 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 $\mathrm{M_L}$ 4.0+ events produced by each point source in a time-horizon of 1 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–Richter-type relationship (Gutenberg and Richter 1944), with unbounded maximum magnitude and b-value equal to one. This is common to all the point sources, that is, differences among the sources derive only from the seismic rates.

Although a prototypal version of the system has started working on the 7th of April 2009 (Marzocchi and Lombardi 2009), the complete Italian seismic catalogue from April 2005 to June 2014 has been analysed offline by the OEF-Italy system and the seismic rates for the whole grid of point sources have been computed at 00:00 of each day. A database collecting all the results for the analysed period (about 3300 days) has been provided to the authors (Warner Marzocchi, personal communication, July, 2014) and has been used for the analyses presented in the following.

An example of the seismic rates provided by OEF-Italy system is reported in Fig. 1 for illustrative purpose. The picture, arbitrarily, refers to the OEF-Italy results computed at 00:00 of the 6th of April 2009.

In Iervolino et al. (2015a), it has been demonstrated that, starting from the rates resulting from the OEF-Italy system, it is possible to derive indices of seismic losses via a probabilistically sound procedure. The latter involves models used in the classical probabilistic seismic hazard analysis (PSHA; e.g., McGuire 2004), and is consistent with the performance-based earthquake engineering (Cornell and Krawinkler 2000) framework. While the interested reader should refer to the given reference for details, such a procedure for OELF is summarised here for the sake of readability of the results of the study. In fact, the equation and the models required are recalled, as well as the data and models used for Italy.

2.1 Hazard (shaking intensity)

Starting from the weekly seismic rates from OEF-Italy described above, $\lambda[t, x, y|H(t)]$, associated to each point-like seismic source in Italy, MANTIS-K associates probabilities of shaking intensity in terms of macroseismic (MS) intensity. This is because the vulnerability models considered (to follow) are function of MS.

Prediction equations allow estimating the probability of a specific MS intensity at the generic site, identified by the couple of coordinates $\{w, z\}$, conditional on the occurrence of an earthquake of known magnitude, M, at a given point-like seismic source; i.e., $P[MS = ms|m, R(x, y, w, z)]$, being $R(x, y, w, z)$ the source-to-site distance. The chosen

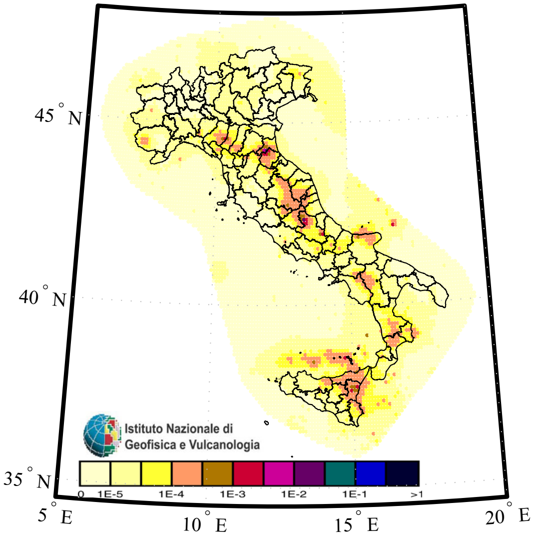

Fig. 1 Map of expected number of M_L 4+ events in the week following 00:00 of 06/04/09, estimated through OEF-Italy

prediction equation for macroseismic intensity is that of Pasolini et al. (2008) that identified intensity as defined by the Mercalli–Cancani–Sieberg (MCS) scale (Sieberg 1931). The model applies to the [0, 220 km] interval of the distance,[1] and between V and XII of intensity.

2.2 Vulnerability

Structural vulnerability is accounted for in MANTIS-K via a damage probability matrix (DPM) that, according to the definition of Whitman et al. (1973) and Braga et al. (1982), provides the probability of observing a damage state (*ds*) to a building of a given structural typology (*k*), given a value of intensity, *ms,* at the site; i.e., $P[DS^{(k)} = ds|ms]$. The DPM considered is based on Italian observational data (Zuccaro and Cacace 2009; Iervolino et al. 2014a). It accounts for four different vulnerability classes in which the Italian building stock is divided, from A to D (the same as indicated in European Macroseismic Scale EMS 98), and six damage levels (D0—no damage, D1—slight damage, D2—moderate damage, D3—heavy damage, D4—very heavy damage, D5 collapse).

Another model used is, for the *k*-th structural typology and conditional on damage state, the probability for an occupant to suffer casualties, $P[Cas^{(k)}|ds]$. Casualty probabilities, conditional on structural damage and vulnerability class, are those of Zuccaro and Cacace (2011). Such a model refers to two types of casualties; i.e., (1) fatalities and (2) injuries (someone requiring hospital treatment is considered as injured).

2.3 Exposure

In Italy, the elementary units for which dwelling building exposure data are made publicly available from the population census are municipalities. For this reason, all computations

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

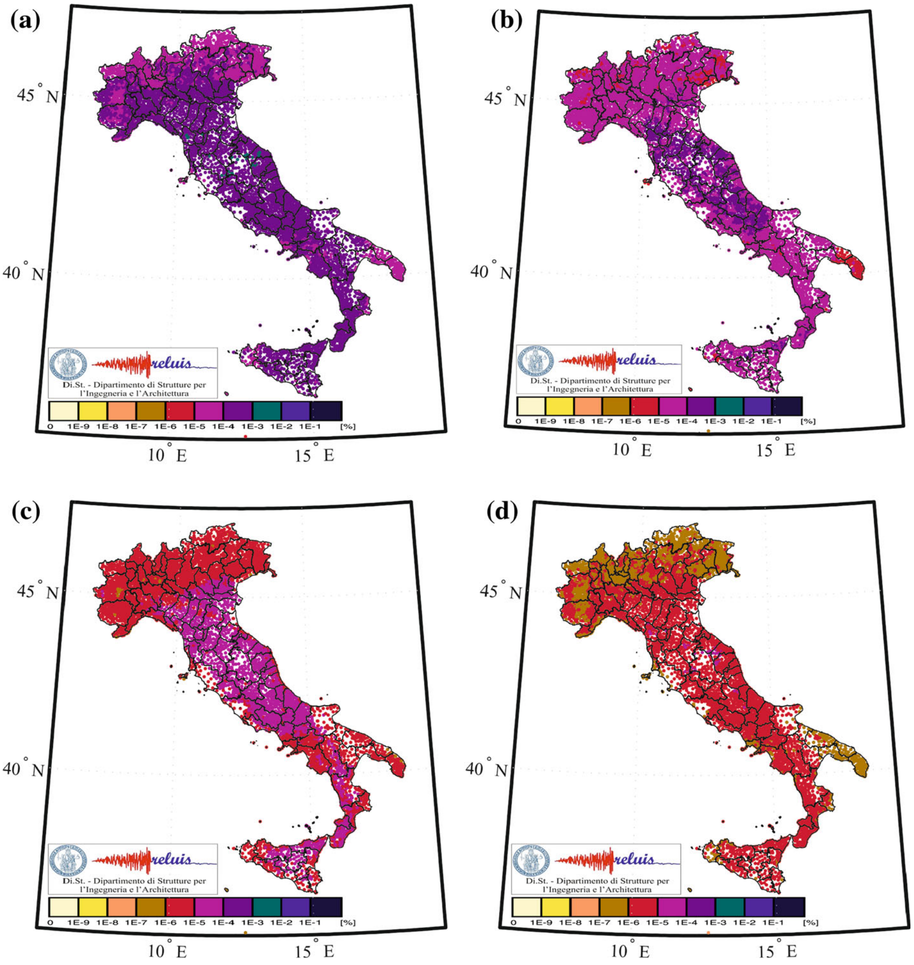

Fig. 2 Illustrative example of MANTIS-K outputs: maps of the expected values of **a** unusable and **b** collapsed buildings (per 100 municipality buildings), and the expected values of **c** injuries and **d** fatalities per 100 municipality residents. These results are computed using the OEF-Italy data of Fig. 1 as the input. Therefore they refer to the week after 00:00 of 06/04/09

performed by MANTIS-K refer to the municipality level and to dwelling buildings only: the centroid of each municipality area is the $\{w, z\}$ point used for computing the source-to-site distance, and in which all exposed assets in the municipality are supposed to be concentrated. For each municipality, exposure in terms of buildings is the number of buildings of k-th typology, $N_b^{(k)}$. The number of residents living in the k-th building typology, $N_p^{(k)}$, is a measure of exposure in terms of residents. Both kinds of data are derived from the National census of 2001 (Zuccaro et al. 2012). Note that these exposure measures depend on the municipality, that is on $\{w, z\}$; however, the coordinates are dropped for simplicity in the symbols.

2.4 Losses

Assuming that the stochastic process of events causing damage to the building at the site is approximated, in the short time interval (Δt), by a homogeneous Poisson process, the expected number of casualties (fatalities or injuries) in the considered $\{w, z\}$ municipality, $E[N_{Cas,(t,t+\Delta t)}|H(t)]$, can be computed via Eq. (1). According to Zuccaro et al. (2012), casualty and injury assessments are carried out considering that 65 % of the total population is exposed at the time of occurrence of the earthquake, which justifies 0.65 in the equation.

$$E\left[N_{Cas,(t,t+\Delta t)}|H(t)\right] \approx \Delta t \cdot \sum_{k} 0.65 \cdot N_p^{(k)} \cdot \iint_{x,y} \lambda[t,x,y|H(t)] \cdot \sum_{ds} P\left[Cas^{(k)}|ds\right] \cdot \\ \cdot \sum_{ms} P\left[DS^{(k)} = ds|ms\right] \cdot \int_{m} P[MS = ms|m, R(x,y,w,z)] \cdot f_M(m) \cdot dm \cdot dx \cdot dy \tag{1}$$

Zuccaro and Cacace (2011) also provide the probability of a building to be unusable for a given damage state, $P[Unus|ds]$. 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, $E[N_{Unus,(t,t+\Delta t)}|H(t)]$, can be computed via Eq. (2).

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

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, Fig. 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 Fig. 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.

3 Considered Italian seismic sequences

From 2004 to 2014 more than two-hundred 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).[2] Epicentral locations of these events are plotted in Fig. 3; the size of each circle is proportional to the

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

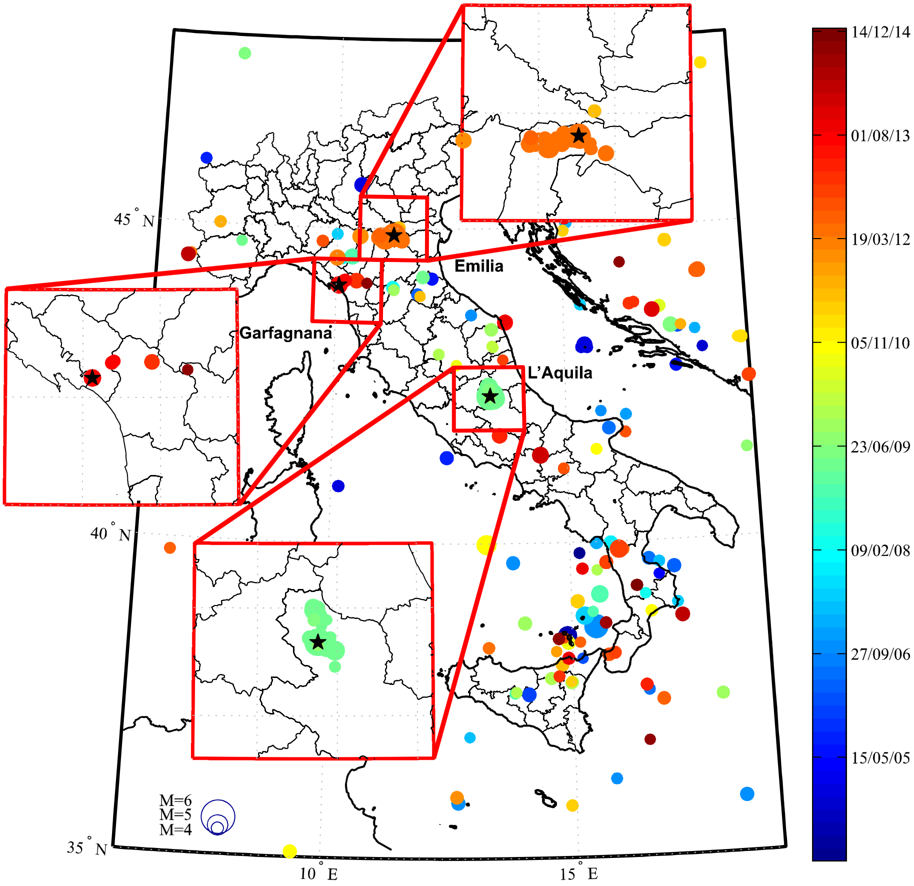

Fig. 3 Epicentres of M 4+ seismic events occurred from 01/01/04 to 31/12/14 and geographic areas considered for the three sequences analysed

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 *Garfagnana*, due to the areas where they occurred (identified in the same figure). For each sequence, the epicentre of the largest magnitude event (i.e., the mainshock) is indicated as a star; these points are referred to as the centres of the corresponding seismic sequence hereafter.

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

The retrospective analysis of each sequence consisted of the computation of the expected losses for the week following each day for which forecasted seismicity was available by OEF-Italy. In the following, each seismic sequence is presented first and the rates computed by OEF-Italy are reported as a function of time and summed up over the point-like sources within 30 km from the centre of the sequence, to get a sense of the forecasted seismicity in the area. Then, the evolution of some indices of seismic losses

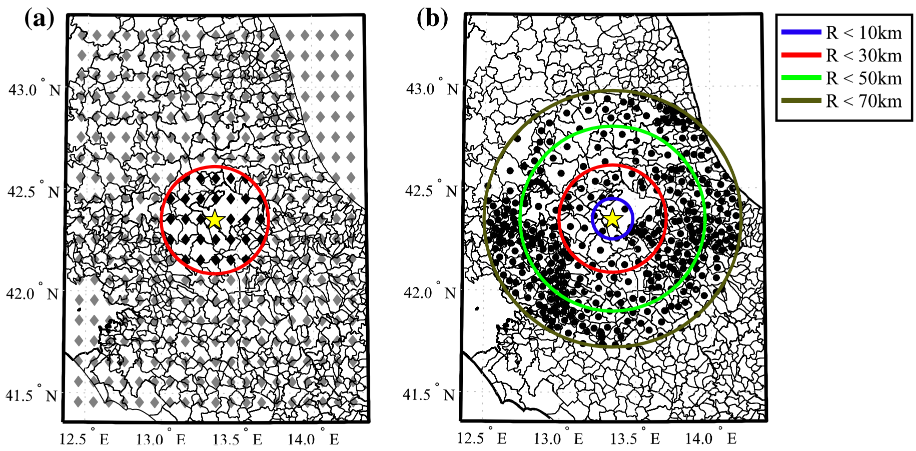

Fig. 4 Geographic representation of the mainshock epicentre together with **a** the grid of the point-like seismic sources according to OEF-Italy and **b** the centroids of municipalities within 70 km from the epicentre

from MANTIS-K are reported and compared among sequences. Finally, a discussion with respect to the observed consequences is given.

The considered risk metrics, computed by MANTIS-K for each municipality, are the expected values in 1 week of: (1) fatalities and (2) displaced residents, (3) unusable and (4) collapsed dwelling buildings. Results are reported as the expected value of total loss within four areas identified by the maximum distance (10, 30, 50 and 70 km) from the epicentre of the mainshock[3]; see Fig. 4b. For the sake of presentation, arbitrarily, a time window spanning 3 months before and 1 year after the mainshock is considered.

3.1 L'Aquila 2009

The main event of L'Aquila sequence, moment magnitude (M_W) 6.1, struck on the 6th of April 2009; it produced a maximum observed peak ground acceleration (PGA) equal to 644 cm/s^2 (e.g., Chioccarelli et al. 2009; Dolce and Di Bucci 2015). In the area identified by 41.8–42.8°N latitude and 12.6–14.1°E longitude (red square in Fig. 1), a single M 4+ event occurred before the mainshock since the 1st of January 2009, that 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 3.0+. On the other hand, the aftershock sequence was characterised by 8 M 4.5+ earthquakes, reported in Table 1 (along with mainshock data), and more than 300 events M 2.5+ in the 24 h after the mainshock.

The geographic area affected by the sequence is reported in Fig. 4a, b; both panels show boundaries of municipalities and the mainshock epicentre (represented by a star). Figure 4a displays the grid of point-like seismic sources, the OEF-Italy system assigns earthquake

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[3] 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.

Table 1 M 4.5+ aftershocks in a geographic area within latitude 41.8°–42.8° and longitude 12.6°–14.1° (mainshock in bold)

#	Date and time (UTC)	Latitude (°)	Longitude (°)	Depth (km)	Magnitude	
1	**06/04/09 01:32**	**42.342**	**13.380**	**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

Reported information are event date and time, hypocentre latitude, longitude and depth, event magnitude. Data are extracted from the Seismological Instrumental and parametric Data-base (ISIDe) website (last accessed 22/07/15)

rates to. Figure 4b reports the centroids of each municipality for which loss indices are computed together with contours of the distance from the epicentre of the mainshock, R.

In order to provide a synthetic representation of the forecasted seismicity during the whole sequence, the values of seismic rates provided by OEF-Italy, for each point-like source within 30 km from the epicentre of the mainshock (see Fig. 4a), are summed up and plotted in Fig. 5 as a function of the day in which rates were released by the INGV system. In the same figure, the dates of occurrence of all M_W 4.2+ events are also reported with dotted vertical lines. It is to note that the event rates during the seismic crisis are two orders of magnitude larger than those computed at the beginning of 2009. It is also to underline that the maximum is on the day after the mainshock of the sequence; this is a feature of the OEF-Italy system according to which the rates peak right after the maximum seismic moment release (Marzocchi and Lombardi 2009). Similarly, a significant increment of forecasted rates can be identified after all the *strong* events of the sequence. In fact, although discussion of pro and cons of OEF is out of the scope of this paper, it has to be anticipated that trend of the seismic loss estimates from the MANTIS-K system reflect the trend in time of OEF-Italy rates.

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

At the beginning of 2009 the expected value of fatalities in 1 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, 30, 50 and 70 km, respectively.[4] One year after the mainshock, the maximum value of the expected number of fatalities is around 0.4 that is

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[4] 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.

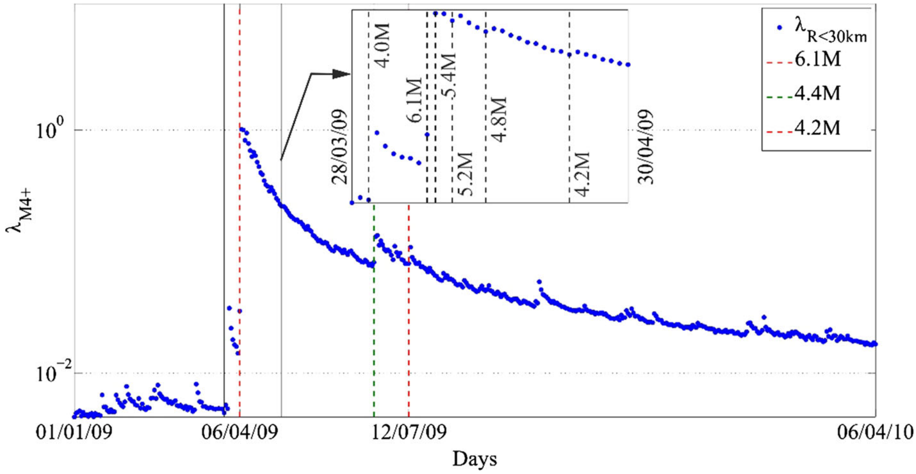

Fig. 5 Sum of the following week's (with respect to the date in the abscissa) rates of M 4+ events within 30 km from the centre of the sequence, and dates of M 4.2+ events occurred in the area of Fig. 1 (see also Table 1 for date of each event). In the picture, M refers to moment magnitude M_W

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).

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 Fig. 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 of the largest magnitude events occurred few hours after the two mainshocks.) The recorded largest (corrected) horizontal PGAs are about 259 and 495 cm/s^2 for the 5.8 and 5.6 M_W event, respectively.[5]

Following the first strong event, on the 22nd of May, the Italian government declared the emergency for the provinces of Modena, Ferrara, Bologna and Mantova. On the 30th of May, after the M_W 5.6 event, the state of emergency was extended to the provinces of Reggio Emilia and Rovigo.

Similarly to L'Aquila, Fig. 7a shows the point-like seismic sources in the area of interest, identifying those within 30 km from the epicentre of the mainshock; Fig. 7b

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[5] 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 was 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.

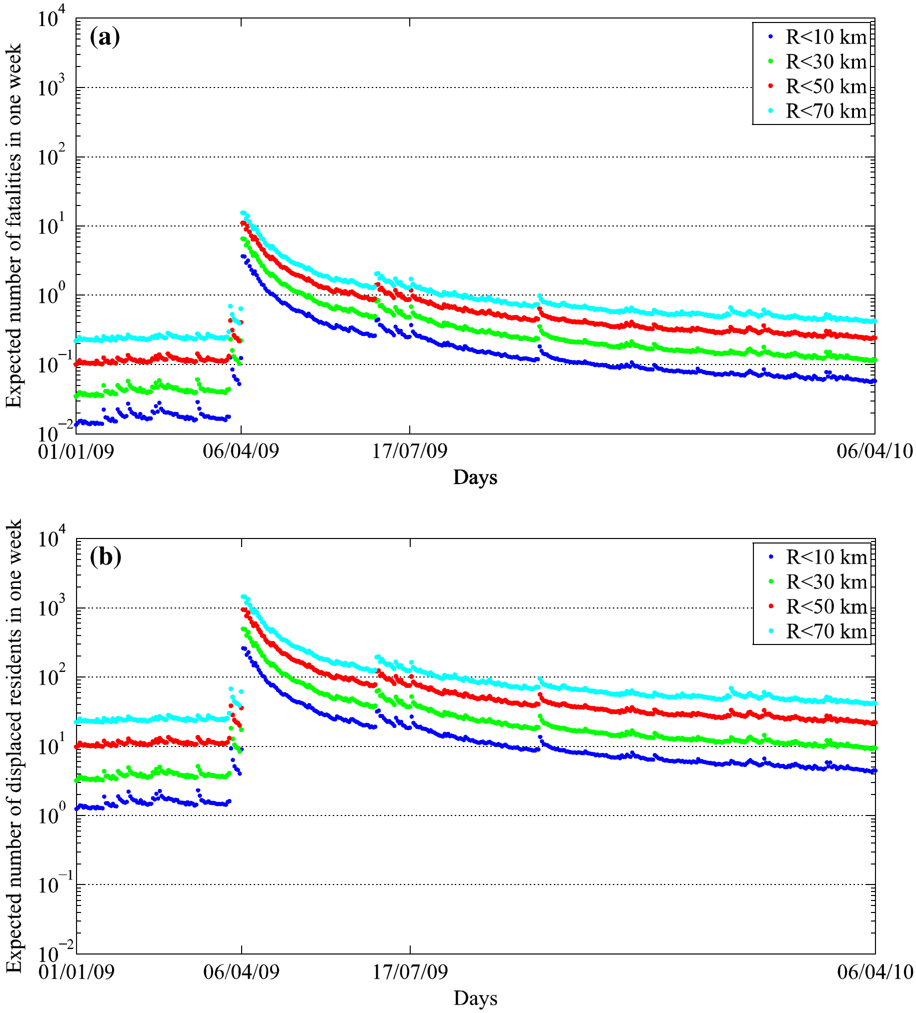

Fig. 6 Expected number of **a** fatalities and **b** displaced residents in the week following the date in the abscissa, summed over all municipalities within 10, 30, 50 and 70 km from the centre of the sequence

displays the centroids of municipalities within the four boundaries presented results refer to; i.e., radii lower than 10, 30, 50 and 70 km.

The distribution in time of the main aftershocks, clustered in the few days after the mainshock, is reflected by the evolution of forecasted seismic rates (Fig. 8) that has a regular trend decreasing with the increasing time after the M_W 5.6 event. It is to note that maximum forecasted seismicity corresponds to the day after the second mainshock that has, in fact, a magnitude lower than the first one.

Figure 9 shows the expected values of fatalities and unusable buildings in the time interval of Fig. 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

Table 2 M 4.5+ earthquake in a geographic area within latitude 44.5°–45.5° and longitude 10.5°–12.0° (mainshocks in bold)

#	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

Reported information are event date and time, hypocentre latitude, longitude and depth, event magnitude. Data are extracted from ISIDe website (last accessed 20/07/15)

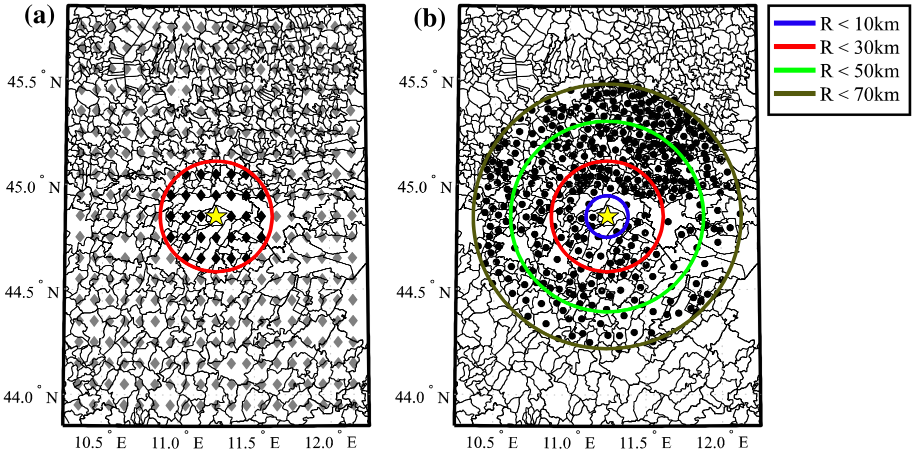

Fig. 7 Geographic representation of the mainshock epicentre together with **a** the grid of the point-like seismic sources according to OEF-Italy and **b** the centroids of municipalities within 70 km from the epicentre

10, 30, 50 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.

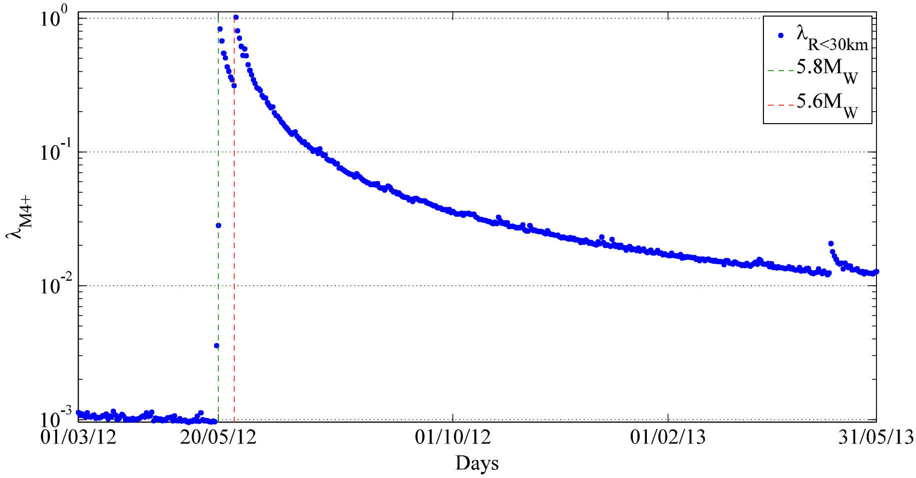

Fig. 8 Sum of the following week's (with respect to the date in the abscissa) rates of M 4+ events within 30 km from the centre of the sequence, and dates of main events occurred in the area

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 1 year after this date. However, on the 25th of January 2013, a M_W 4.8 struck in the same area (identified in Fig. 1; 43.5–44.5°N and 9.5–11.0°E). Thus, available data were analysed starting from about 3 months before this event; i.e., from the 1st of November 2012.

From November 2012 to the mainshock, 20 M 2.5+ earthquakes stroke 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 h 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 five events with M equal to or larger than four in the considered area and time interval.

During the sequence, someone claimed similarities with respect to seismic events preceding L'Aquila mainshock (authors are not aware of scientific studies supporting such a similarity). In fact, the sequence focalised the attention of mass media and the worries of residents, and the Italian civil protection department was constantly in state of attention.[6]

The point-like seismic sources within 30 km from the epicentre of the mainshock are reported in Fig. 10a while centroids of municipalities and boundaries of interest are shown in Fig. 10b. The evolution of the sum OEF rates within 30 km from the epicentre of the mainshock is clearly affected by the two largest magnitude events as reported in Fig. 11a.

Expected values of fatalities are reported in Fig. 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 6 days before the mainshock: about 0.3 is the expected number of fatalities within 70 km for the week

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[6] See http://terremoti.ingv.it/it/ultimi-eventi/921-evento-sismico-tra-le-province-di-lucca-e-massa.html, last accessed 20/07/15.

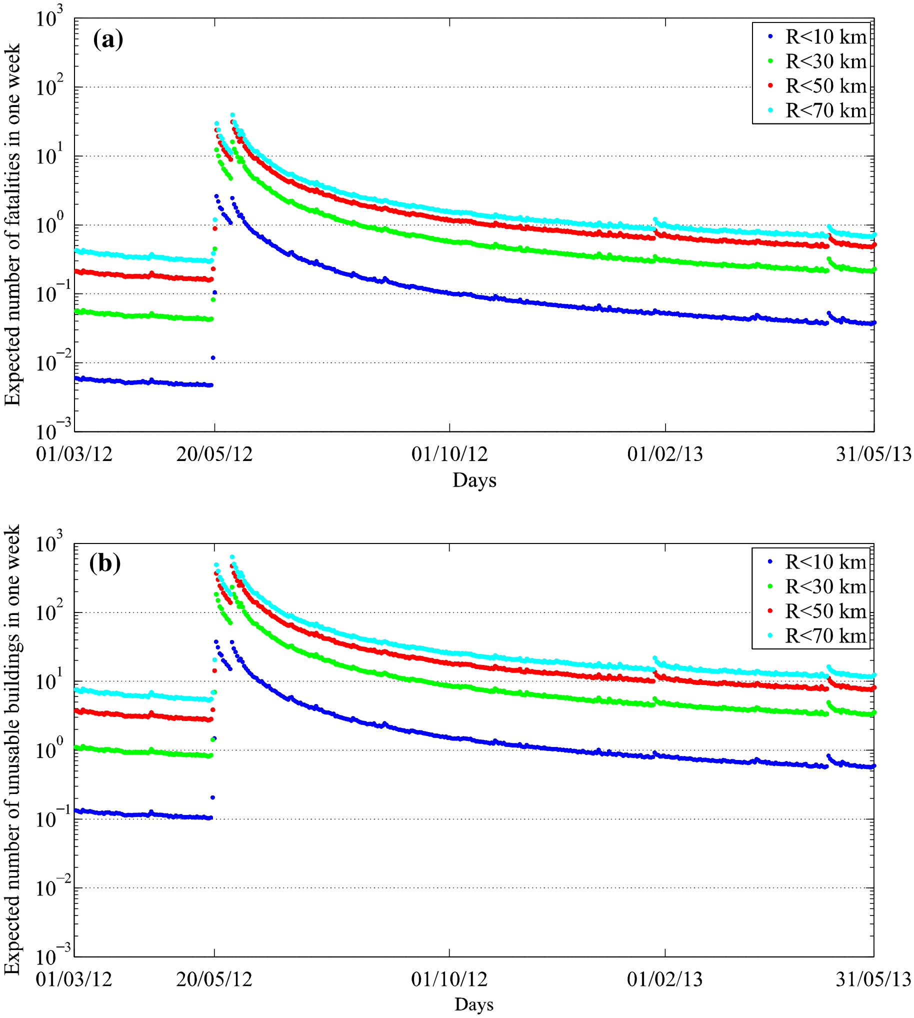

Fig. 9 Expected number of **a** fatalities and **b** unusable buildings in the week following the date in the abscissa, summed over all municipalities within 10, 30, 50 and 70 km from the centre of the sequence

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 sake of comparison, the days of the mainshocks are coincident and the chosen time window goes from 100 days before to 50 days after the mainshock.

Table 3 M 4.0+ earthquake in a geographic area within latitude 43.5°–44.5° and longitude 9.5°–11.0° (mainshock in bold)

#	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**	$\mathbf{M_W}$
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

Reported information are event date and time, hypocentre latitude, longitude and depth, event magnitude. Data are extracted from ISIDe website (last accessed 20/07/15)

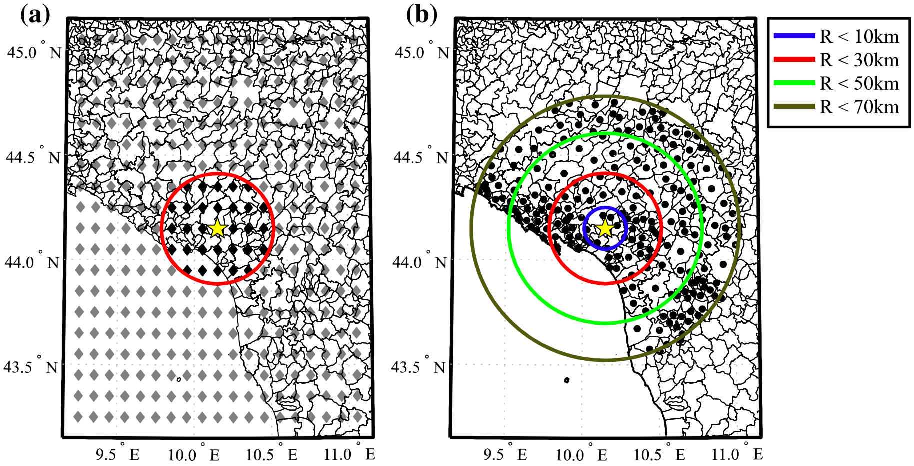

Fig. 10 Geographic representation of the mainshock epicentre together with **a** the grid of the point-like seismic sources according to OEF-Italy and **b** the centroids of municipalities within 70 km from the epicentre

The comparison between Fig. 12a, b underlines, once again, that the results of MANTIS-K are more informative than those of OEF, because it accounts not only for hazard but also for vulnerability and exposure. Indeed, in the whole considered time-window before the mainshock, seismic rates for L'Aquila are larger than those for Garfagnana and Emilia (in this latter case the rates are the lowest). Conversely, the expected fatalities for L'Aquila and Garfagnana are comparable, while the largest are associated to the Emilia sequence.[7] Similarly, after the mainshock, the seismicity rates for L'Aquila and Emilia are comparable, and both higher than Garfagnana. On the other hand, the expected losses for Emilia are significantly higher than those expected in L'Aquila, and the expected losses in Garfagnana are lower than those of the other sequences. Considering only the 7 days before the mainshock, it is also interesting to note that L'Aquila shows some increment of expected losses with respect to previous weeks, while the Emilia shows significant

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

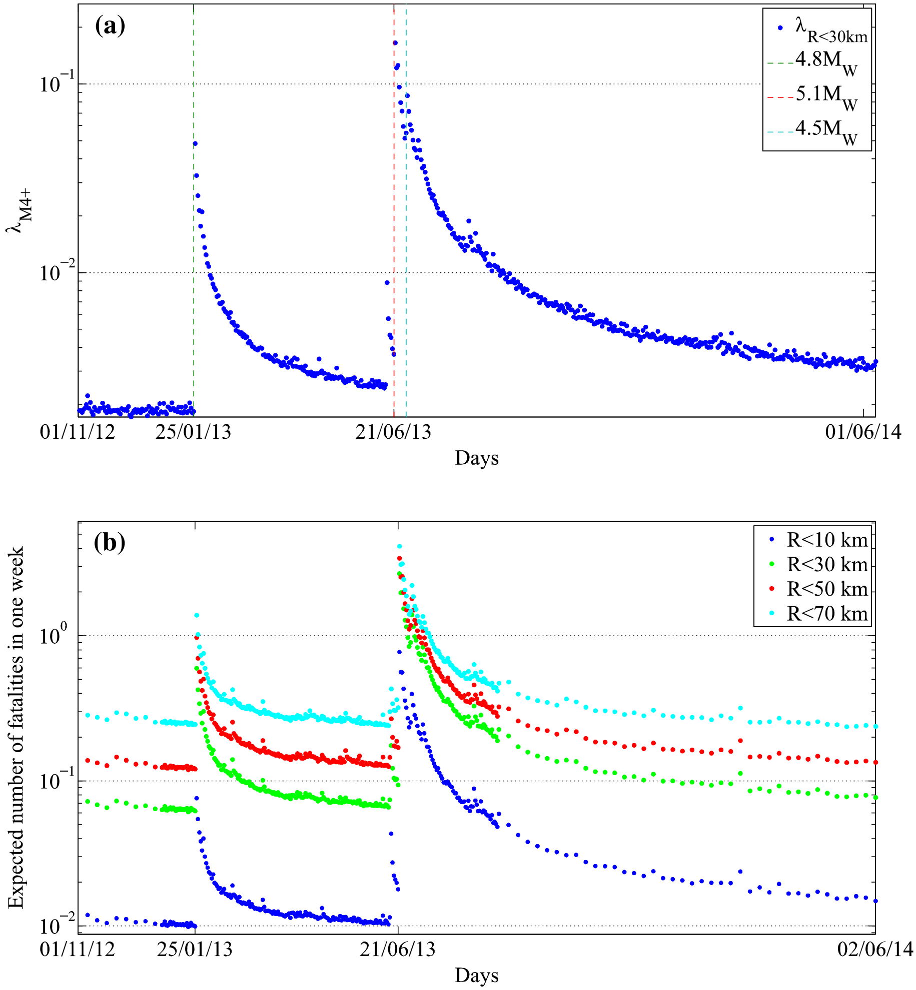

Fig. 11 **a** Sum of the following week's (with respect to the date in the abscissa) rates of M 4+ events within 30 km from the centre of the sequence, and dates of main events occurred in the area; **b** weekly expected number of fatalities summed over all municipalities within 10, 30, 50 and 70 km from the centre of the sequence

expected loss variations only since the day before the mainshock, Fig. 12b. This trend can be also identified in terms of seismic rates (Fig. 12a).

3.5 Observed losses and the meaning of OELF results

In this section the consequences observed in the analysed earthquakes are reported (see Dolce and Di Bucci 2015, for details). Indeed, it is believed appropriate to discuss the losses produced in the seismic sequences to better understand the intrinsic meaning of OELF and the current features and/or limitations of MANTIS-K.

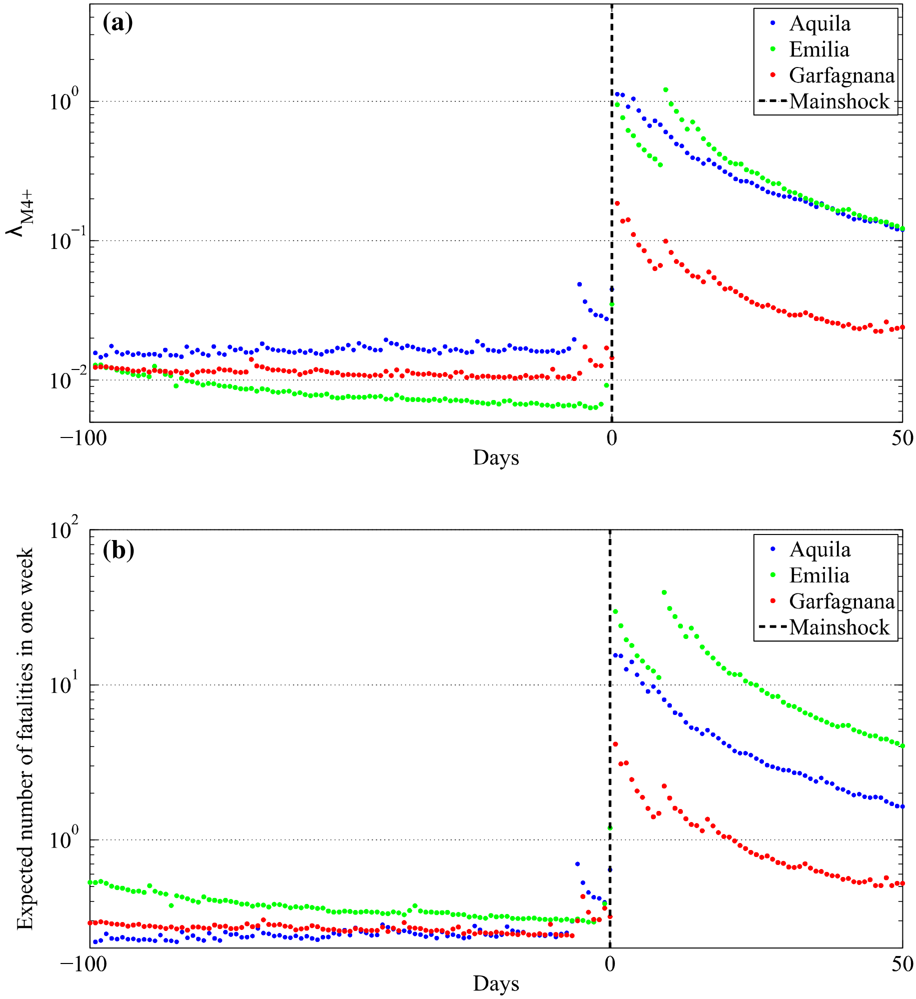

Fig. 12 **a** Sum of the following week's (with respect to the time in the abscissa) rates of M 4+ events within 70 km from the centre of each sequence; **b** weekly expected number of fatalities within 70 km from the centre of each sequence

For what concerns L'Aquila, 308 total fatalities were counted. Approximately 34,000 buildings failed or resulted unusable, at least 1500 residents were injured and more than 65,000 were temporarily displaced. During the Emilia sequence the number of dwelling buildings declared unusable after a survey was in the order of 15,000. Fatalities reported are 26, 7 of which are due to the mainshock on the 20th of May, and 19 to the second event on the 29th of May. Finally, in the Garfagnana sequence, no significant damage or injuries were observed.

Even if OELF provides losses' predictions, there is a number of reasons why direct comparison of the observed consequences with the results of OELF, if not inappropriate, requires at least particular caution. First of all, OELF provides weekly expected values. In statistical terms, the expected value is the limit of the arithmetic mean over a virtually infinite number of nominally equivalent trials. In this respect, the observed losses are individual realizations only, which do not allow validation (see also Iervolino 2013, for a discussion of similar issues). It is also to note that OELF, by nature of the OEF models providing the input rates, provides the largest expected losses only after the strongest event of the sequence, while a significant portion of the consequences observed is due to the main events (e.g., in the L'Aquila case).

In addition to this basic discussion of the meaning of OELF, it has to be recalled that at this stage there are some features/limitations of MANTIS-K, which are relevant to the analysis of the observed losses. For example, most of the fatalities occurred during the Emilia sequence were in industrial buildings and not in residential buildings, which are those at the basis of damage vulnerability matrices and exposure data. 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, 2015b). Finally, also exposure may vary singificantly 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 sequence, risk measures for areas characterised by different values of radius from the mainshock epicentre (10, 30, 50 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 increments 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 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 interpretation 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.

Acknowledgments The study presented in this paper was developed in the framework of *AMRA—Analisi e Monitoraggio dei Rischi Ambientali scarl* (http://www.amracenter.com) for the *strategies and tools for real-time earthquake risk reduction* (REAKT; http://www.reaktproject.eu) funded by the European Commission via the *Seventh Framework Program for Research*, with Contract No. 282862. Professor Mauro Dolce and Dr. Warner Marzocchi are gratefully acknowledged for their comments, which improved quality and readability of this paper.

References

Braga F, Dolce M, Liberatore D (1982) Southern Italy November 23 1980 earthquake: a statistical study on damaged buildings and an ensuing review of the M.S.K.-76 Scale. In: Proceedings of 7th European conference on earthquake engineering, ECEE, CNR-PFG n.503, Rome, Italy

Chioccarelli E, De Luca F, Iervolino I (2009) Preliminary study of L'Aquila earthquake ground motion records V5. 20. ReLUIS report. http://www.reluis.it/doc/pdf/Aquila/Peak_Parameters_L_Aquila_Mainshock_V5.2.pdf

Cornell CA, Krawinkler H (2000) Progress and challenges in seismic performance assessment. PEER Cent News 3:1–3

Dolce M, Di Bucci D (2015) Comparing recent Italian earthquakes. Bull Earthq Eng. doi:10.1007/s10518-015-9773-7

Gerstenberger M, Wiemer S, Jones LM, Reasenberg PA (2005) Real-time forecasts of tomorrow's earthquakes in California. Nature 435:328–331

Gutenberg B, Richter CF (1944) Frequency of earthquakes in California. Bull Seismol Soc Am 34:185–188

Iervolino I (2013) Probabilities and fallacies: why hazard maps cannot be validated by individual earthquakes. Earthq Spectra 29:1125–1136

Iervolino I, De Luca F, Chioccarelli E (2012) Engineering seismic demand in the 2012 Emilia sequence: preliminary analysis and model compatibility assessment. Ann Geophys Italy 55:639–645

Iervolino I, Chioccarelli E, Giorgio M, Marzocchi W, Lombardi AM, Zuccaro G, Cacace F (2014a) Operational earthquake loss forecasting in Italy: preliminary results. In: Proceedings of 2nd European conference on earthquake engineering and seismology, 2ECEES, Istanbul, Turkey

Iervolino I, Giorgio M, Chioccarelli E (2014b) Closed-form aftershock reliability of damage-cumulating elastic-perfectly-plastic systems. Earthq Eng Struct D 43:613–625

Iervolino I, Chioccarelli E, Giorgio M, Marzocchi W, Zuccaro G, Dolce M, Manfredi G (2015a) Operational (short-term) earthquake loss forecasting in Italy. Bull Seismol Soc Am 105:2286–2298

Iervolino I, Giorgio M, Polidoro B (2015b) Reliability of structures to earthquake clusters. Bull Earthq Eng 13:983–1002

Jordan TH, Chen Y-T, Madariaga R, Main I, Marzocchi W, Papadopoulos G, Sobolev G, Yamaoka K, Zschau J (2011) Operational earthquake forecasting—state of the knowledge and guidelines for utilization. Ann Geophys Italy 54:319–391

Marzocchi W, Lombardi AM (2009) Real-time forecasting following damaging earthquake. Geophys Res Lett 36:L21302

Marzocchi W, Lombardi AM, Casarotti E (2014) The establishment of an operational earthquake forecasting system in Italy. Seismol Res Lett 85:961–969

Marzocchi W, Iervolino I, Giorgio M, Falcone G (2015) When is the probability of a large earthquake too small? Seismol Res Lett. doi:10.1785/0220150129

McGuire RK (2004) Seismic hazard and risk analysis. Earthquake Engineering Research Institute Publication, Oakland, California, Monograph MNO-10

Ogata Y (1988) Statistical models for earthquake occurrences and residual analysis for point processes. J Am Stat Assoc 83:9–27

Ogata Y (1998) Space-time point-process models for earthquake occurrences. Ann Inst Stat Math 50:379–402

Pasolini C, Albarello D, Gasperini P, D'Amico V, Lolli B (2008) The attenuation of seismic intensity in Italy, part II: modelling and validation. Bull Seismol Soc Am 98:692–708

Sieberg A (1931) Erdebeben. In: Gutenberg B (ed) Handbuch der Geophysik, vol 4, pp 552–554 (in German)

Whitman RV, Reed JW, Hong ST (1973) Earthquake damage probability matrices. In: Proceedings of 5th world conference on earthquake engineering, 5WCEE, Rome, Italy

Zuccaro G, Cacace F (2009) Revisione dell'inventario a scala nazionale delle classi tipologiche di vulnerabilità ed aggiornamento delle mappe nazionali di rischio sismico. In: Proceedings of XIII Convegno l'Ingegneria Sismica in Italia, ANIDIS, Bologna, Italy (in Italian)

Zuccaro G, Cacace F (2011) Seismic casualty evaluation: the Italian model, an application to the L'Aquila 2009 event. In: Spence R, So E, Scawthorn C (eds) Human casualties in earthquakes: progress in modelling and mitigation. Springer, London

Zuccaro G, Cacace F, De Gregorio D (2012) Buildings inventory for seismic vulnerability assessment on the basis of census data at national and regional scale. In: Proceedings of 15th world conference on earthquake engineering, 15WCEE, Lisbon, Portugal