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Are short-term evacuations warranted? Case of the 2009 L'Aquila earthquake

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[1] The disastrous earthquake in L'Aquila Italy (Mw 6.3, 6 April 2009) again highlights the issue of potentially reducing seismic risk by releasing warnings or initiating mitigation actions. Earthquakes cluster strongly in space and time, leading to periods of increased seismic hazard. During such seismic crises, seismologists typically convey their knowledge of earthquake clustering based on past experience, basic statistics and "gut feeling." However, this information is often not quantitative nor reproducible and difficult for decision-makers to digest. We define a novel interdisciplinary approach that combines probabilistic seismic hazard and risk assessment with cost-benefit analysis to allow objective risk-based decision-making. Our analysis demonstrates that evacuation as mitigation action is rarely cost-effective. Future mitigation strategies should target the weakest buildings and those on the poorest soil.
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1. Introduction

[2] Increased seismic activity in the days to months before a significant earthquake can be a sign for an upcoming catastrophic event. Strong foreshocks to subsequent devastating mainshocks as well as precursory swarms have saved many human lives throughout history; it is in fact the only known precursory activity that has saved lives. For example, it was a widely accepted practice in Italy in the 17th century to remain outside of buildings for two days after a moderate to strong earthquake, in order to avoid casualties due to subsequent events [*Boscarelli*, 1992]. However, the observation that the vast majority of earthquakes and swarms are not followed by damaging events leads to the fact that measures are taken very rarely in modern days. A recent example is the devastating M_w6.3 L'Aquila earthquake of 6 April 2009, which killed 299 people. There was a volley of reproaches that the Italian Civil Protection had ignored foreshock activity. Because swarm-like activity was detected in the region for some weeks (Figure 1), a meeting of seismologists and civil protection had been conducted on the evening of 31 March 2009. This meeting recommended no further mitigation actions and no evacuation, a decision criticized heavily in hindsight by the mass media and public.

[3] Currently, it is believed that a "foreshock" is physically indistinguishable from any other earthquake, until a subsequent "mainshock" retroactively marks it as special [*Christophersen and Smith*, 2008; *Felzer et al.*, 2004; *Reasenberg*, 1999]. Therefore, seismologists are constrained to using probabilistic models to translate knowledge on earthquake clustering for the benefit of the society.

[4] A typical statement that seismologists make to the public, media and decision-makers after the occurrence of a moderate earthquake is: "It is possible but unlikely that this event will be followed by a subsequent larger event in the next few days." In regions, such as California, Italy and Japan, quantitative "aftershock" probabilities are calculated [*Gerstenberger et al.*, 2005; *Marzocchi and Lombardi*, 2009]. In rare instances, based on these calculations, authorities issue a statement of increased probability, such as recently done by the California Earthquake Prediction Evaluation Council on 24 March 2009, when swarm-like activity near Bombay Beach was punctuated by a M_w4.8 earthquake. The panel reported (based on the work by *Agnew and Jones* [1991]): "The probability for a large earthquake (magnitude 7.0 or greater) on the San Andreas Fault over the next few days is 1% to 5%." No event occurred in this case. A more refined approach to time-dependent seismic hazard assessment is the "Short-Term Earthquake Probabilities" [*Gerstenberger et al.*, 2005] model that converts earthquake probabilities into ground motion hazard in real-time (http://earthquake.usgs.gov/eqcenter/step).

2. Method

[5] To make a real difference to societies and to assist civil protection in rapidly making very difficult decisions, we introduce Short-Term Earthquake Risk (STEER) analysis (Figure S1 of the auxiliary material), combining time-dependent probabilistic seismic risk assessment with Cost-benefit Analysis (CBA).[3] As an example, we consider the 2009 L'Aquila earthquake sequence (Figure 1). A region's seismic risk is defined as the joint product of the regional seismic hazard, the local site conditions, the building vulnerability, and the distribution of people in buildings. To perform time-dependent probabilistic seismic hazard assessment, we use a time-dependent occurrence model [*Reasenberg and Jones*, 1989, 1994] with region-specific parameters [*Lolli and Gasperini*, 2003] to compute hazard between 1 November 2008 and 1 May 2009 for 24 hours time windows, updated after each earthquake or every three hours. The forecasted rates combined with a predictive ground motion model, using

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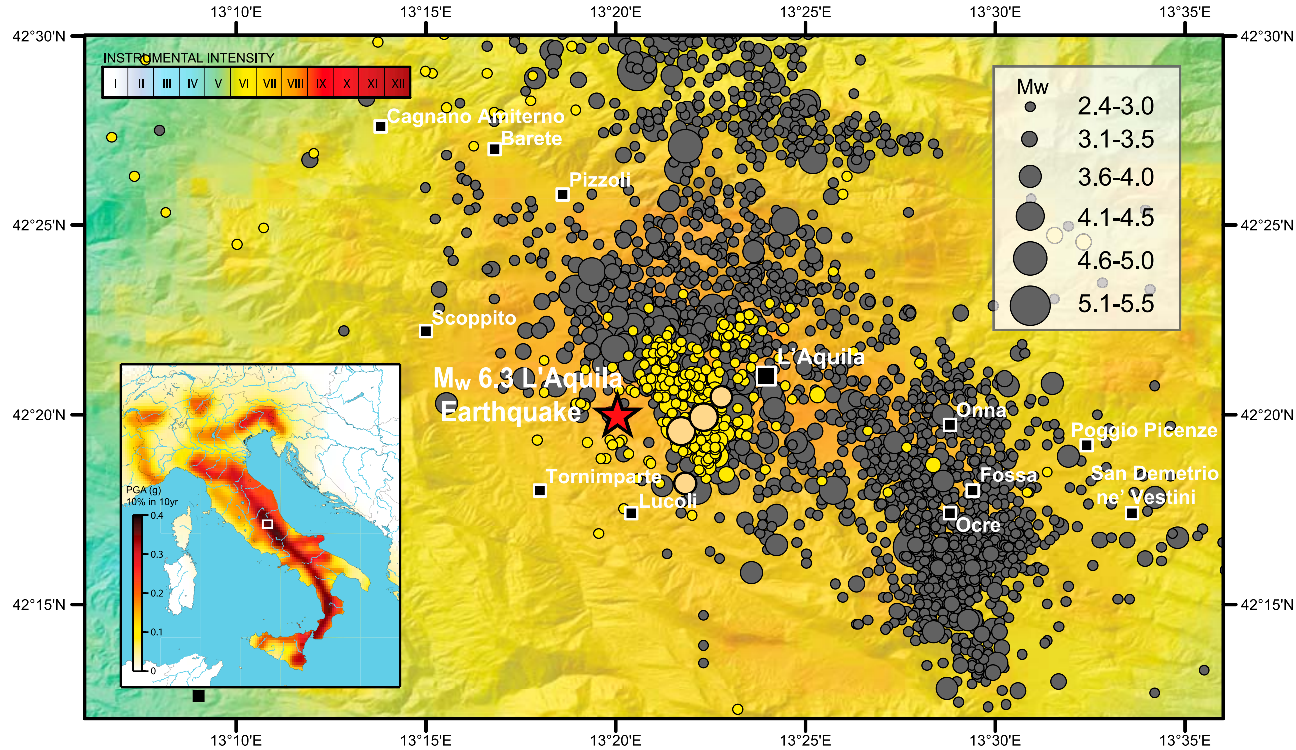

Figure 1. Map of the region affected by the 6 April 2009 L'Aquila M_w6.3 earthquake (red star), including the ground motion predicted by the ShakeMap approach, the foreshocks between 1 November and 6 April (yellow), aftershocks between 6 April and 1 May (gray), and the settlements (black squares). Inset shows the national seismic hazard map [*Meletti et al.*, 2008] with the white box indicating the region in the main panel.

the ShakeMap implementation for Italy [*Michelini et al.*, 2008], define time-dependent probabilistic hazard. The site amplification is assumed to be +1.25 intensity units. This site amplification is chosen based on the verification of the loss model. For L'Aquila, it estimates fatalities of 160 (low), 240 (mean), 355 (high), which matches with the observed number of fatalities. We determine the rates of exceeding a given intensity by stacking up the rates at each settlement. Combining time-dependent probabilistic hazard with loss estimations [*Trendafiloski et al.*, 2009] yields the time-dependent probabilistic risk. The loss estimation follows established procedures, which are used either for scenario based risk [*Fah et al.*, 2000; *Wyss*, 2007], real-time loss [*Earle et al.*, 2003; *Wyss*, 2004], or probabilistic loss [*Crowley and Bommer*, 2006] assessments. The probabilistic loss curve per se allows risk-based decision-making, albeit with no clear systematic empirical or quantitative basis for decision-making criteria [*Marzocchi and Woo*, 2009]. We therefore employ CBA to derive a Boolean indicator—take or not take an action—which can be used by decision-makers around the globe. CBA is commonly used in other disciplines, such as climate forecasts [*Katz and Murphy*, 1997], earthquake retrofitting of buildings [*Smyth et al.*, 2004], avalanche risk mitigation [*Fuchs et al.*, 2007], or volcanic risk mitigation [*Marzocchi and Woo*, 2007, 2009] and allows a transparent and quantitative scheme for the decision-making process. This is important because it can justify any mitigation action (even a posteriori in the case of false alarm). To evaluate if a probability supports a mitigation action or not, it is necessary to define an optimal probability threshold that represents the "acceptable risk": Given the cost, C, of a mitigation action and the potential loss, L, the action is favourable whenever the probabilistic risk exceeds C/L.

3. Risks and CBA for Evacuation in L'Aquila

[6] Figure 2 shows the probabilistic loss curve for the city of L'Aquila (72,000 inhabitants; distributed in EMS-98 vulnerability classes A(30%), B(30%), C(30%), and D (10%), where A refers to the most vulnerable buildings [*Grunthal*, 1998]) on 6 April 2009 at 2 a.m., 1.5h before the M_w6.3 L'Aquila earthquake. The chance of 100 fatalities or more in the subsequent 24 hours period is about $5*10^{-4}$. This time-dependent risk of having 100 fatalities exceeds the long-term probability [*Meletti et al.*, 2008] by a factor of about 30 ($1.4*10^{-6}$). By integrating the probabilistic loss curve and normalizing it by the population, we can estimate, for an individual person living in a house of EMS-98 building class A the probability of dying in a destructive earthquake in the next 24 hours. Immediately preceding the L'Aquila earthquake, this probability reaches 10^{-5}. To put these numbers into perspective, the typical estimated probability of dying in an earthquake for an individual person in the next 24 hour is 10^{-9}, whereas the average probability of dying in a car accident in Italy in any 24 hours period is $2.7*10^{-9}$ [*Istituto Nazionale di Statistica*, 2009]. Thus, the average risk of dying in an earthquake in L'Aquila is about the same as dying in a car accident; however, during the

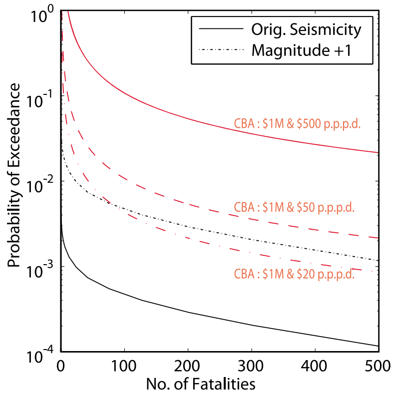

Figure 2. Probabilistic loss curve and cost-benefit curves for EMS-98 building class type A, using site amplification of 1.25, in L'Aquila at 6 April 2009 at 2a.m. local time, for a duration of 24 hours using earthquake data from November through May. The probabilistic loss curve is shown for two cases: 1. previous seismicity (black); 2. hypothetical seismicity with increase in magnitude by 1 (dash-dotted-black). Three CBA thresholds are indicated for the mitigation action based on different assumptions, i.e., the cost of the evacuation of $500 (red), $50 (dashed-red), and $20/person/day (p.p.p.d.) (dash-dotted-red).

2009 seismic crisis, the risk of dying in an earthquake increased by three to four orders of magnitude.

[7] Given such a high probability gain, one might assume that mitigation actions, even a widespread evacuation, must certainly be warranted. However, one has to keep in mind that the absolute probabilities are still small and that with more than 99.99% probability, fewer than 100 people will die. Indeed, with more than 99% probability nobody will die at all. To decide if, in light of these numbers, mitigation actions are warranted and which mitigation actions may be most appropriate, a CBA can be performed.

[8] We consider an evacuation of all people in vulnerable buildings (EMS-98 class A), costing $500/person/day on average and the willingness to pay for a life saved by the government is $1M; latter is based on a study of volcanic risk around Vesuvius [*Marzocchi and Woo*, 2009]. The resulting CBA threshold (Figure 2) is always more than two orders of magnitude greater than the probabilistic loss curve. Therefore, evacuation even of only the weakest buildings as a mitigation action is not cost effective. The CBA thus confirms the decision of "no evacuation" taken by the Italian civil protection in the hours and days preceding the M_w6.3 mainshock. Even if the observed seismicity before the mainshock would have been one magnitude larger, the CBA threshold is exceeded only when costs are taken to be less than $20/person/day.

[9] During an ongoing seismic crisis, the probability of losses will change continuously, increasing as each new event occurs and gradually decreasing until the next event occurs. We therefore suggest that instead of analyzing the probabilistic loss curve and CBA threshold at a given time, it is sensible to view a time series of the probability of exceeding a specific loss. To illustrate this procedure, we show in Figure 3 the time-varying probability of having 100 fatalities in

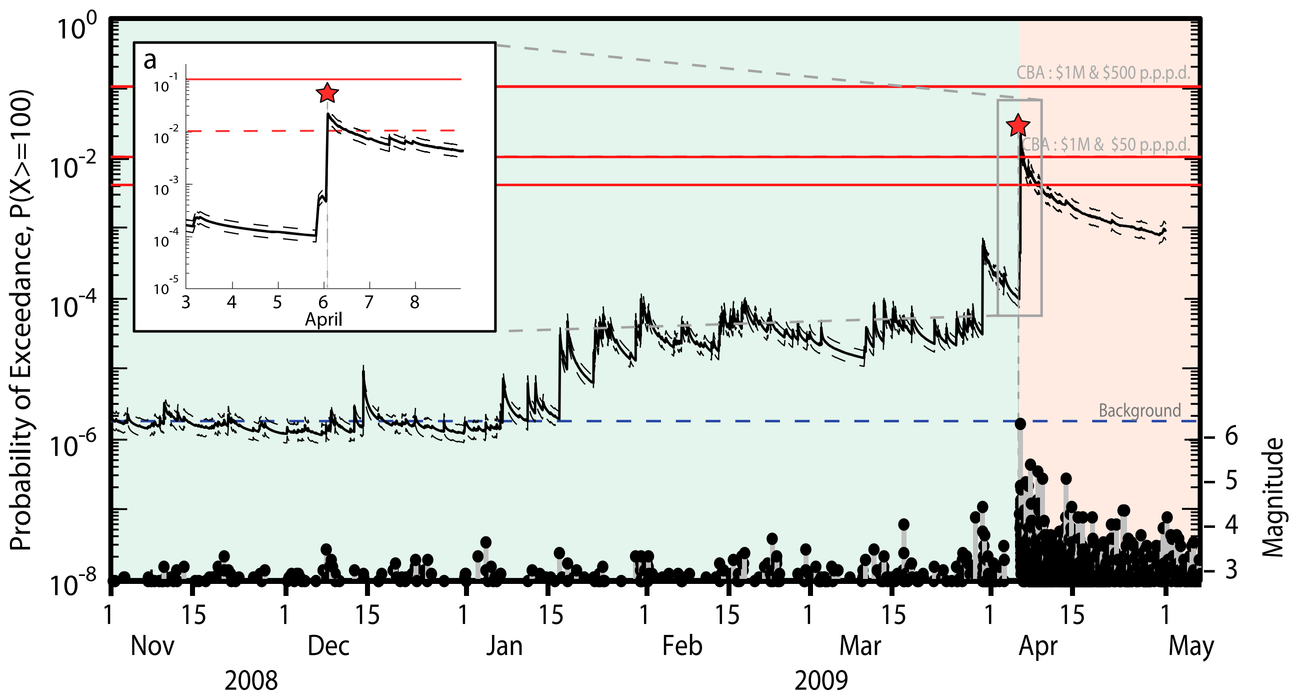

Figure 3. Probability of exceeding 100 fatalities in the next 24 hours, updated after each earthquake or every three hours (black), and the CBA for evacuation of people in EMS-98 class A buildings and site amplification of 1.25 for L'Aquila. The CBA thresholds are equivalent to Figure 2. Figure 3 shows the mainshock (red-star), the probability of exceeding 100 fatalities with the next 24 hours based on the background [*Meletti et al.*, 2008] (blue-dashed), and the uncertainties by the loss estimation that correspond to the high and low plausible estimates (dashed-black). The inset shows details of the curve immediately preceding and following the occurrence of the mainshock. Right axis: earthquake magnitudes as a function of time. Note: the probability is based on the seismicity within a box 25 by 25 km around L'Aquila.

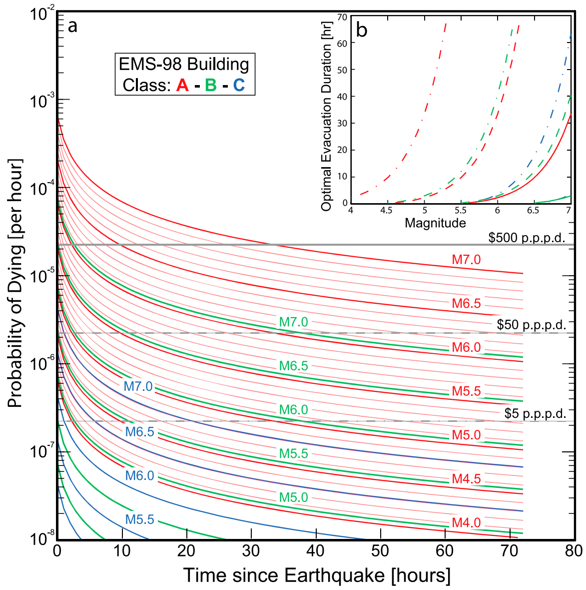

Figure 4. (a) Probability of dying in an "aftershock" for one person living in an EMS-98 class A (red), B (green), or C (blue) building in L'Aquila. An individual earthquake source ("foreshock") is assumed to be in an epicentral distance and depth of 5 km. "Aftershock" and "foreshock" have the same location. "Foreshock" magnitudes are calculated between 4 and 7 (0.1 steps for A, 0.5 steps for B and C). The probability of dying is calculated hourly after the "foreshock" for the following hour. CBA-thresholds are shown in grey. (b) Optimal evacuation duration (intersections between probabilistic loss curves and CBA-thresholds) for different building classes and CBA assumptions.

L'Aquila due to an earthquake between 1 November 2008 and 1 May 2009 for 24 hours time windows, updated after each earthquake or every three hours. The sudden jumps in these curves correspond to the occurrence of potential foreshocks. Due to the increased regional seismicity, the probability is already $3*10^{-5}$ in early February compared to the background seismicity of November until January. The most considerable steps then occur on 30 March, after two events of about M_w4 and on 5 April, in the evening before the destructive mainshock, when a M_w4 and a $M_w4.3$ foreshock occur. It is noteworthy that while the largest foreshocks dominate the probability, the probabilities of numerous small events also lead to noticeable increase in probability. In this case, the probabilistic loss curve never exceeds the threshold of the CBA threshold before the mainshock. Even assuming unrealistically low costs for the evacuation, it is never favourable. The CBA threshold is clearly exceeded after the $M_w6.3$ mainshock, and evacuation of at least the weakest buildings is sensible. Note that in this case, our calculations likely represent at most a lower bound because buildings were damaged by the mainshock, and therefore the risk factor based on building fragility has increased but we haven't accounted for it.

[10] Determining the optimal duration of a mitigation action is another critical and complex task. Earthquake hazard and risk for an individual triggering event decays very rapidly: after one hour, it has decreased already by 40%, after 3hours by 75% and after 9 hours by 90%. Here, we calculate the time-dependent risk and CBA after an initiating earthquake for an individual (Figure 4a). Assuming an initial earthquake of magnitude 5.5 and evacuation costs of \$50/person/day, we can derive that the "optimal" evacuation duration is only a few minutes, even for a poor building (Figure 4b). After an event such as the L'Aquila earthquake, buildings of class A should be abandoned for about six hours, and class B for less than one hour. Consequently, mitigation actions need to be rapid, possibly automatically triggered. If it takes authorities several hours to convene a meeting after a moderate earthquake, the majority of the risk has already passed.

4. Discussion and Conclusion

[11] Certainly, making a decision regarding any loss mitigation action is difficult and involves many dynamic factors such as weather conditions, time of day, size of the city, availability of emergency communication systems and shelters, and preparedness of the population. Nevertheless, the approach presented here can provide valuable input to decision-makers, and we believe that our application of the method to the L'Aquila sequence is the first fully quantitative earthquake risk assessment applied during seismic crises.

[12] Sensitivity analyses indicate that evacuations, to be cost-effective, should emphasize the weakest buildings (thus a subset of buildings of vulnerability class A) and the ones on least stable soil. This hypothesis is also confirmed by the damage pattern of the L'Aquila earthquake. Calibrating the analysis in such a way lowers the CBA threshold because total evacuation costs are lower. This is similar to risk analysis regarding hazards such as floods and avalanches were the risk (and therefore the mitigation actions) varies at a local scale. Thus, smart mitigation strategies of the future target the inhabitants of individual buildings or are more limited actions. For example, evacuating individual, vulnerable buildings with potentially high occupancy (e.g., schools, universities, or churches) or a broad range of less impacting mitigation actions (e.g., pre-positioning emergency response equipment and personal) may be feasible in these circumstances. Costs and losses have to be quantified in each individual case. Such approaches for earthquakes would require a substantial change in how civil protection is organized, communication is distributed and people are trained to respond. Not many people know how vulnerable the building is that they inhabit, but maybe they should just like we should always know were a fire extinguisher can be found. This might increase people's motivation to retrofit their homes.

[13] After an earthquake, seismologists are often asked if and for how long people should abandon their houses. Finding the optimal duration for mitigation actions depends primarily on the mitigation itself, thus lead-time and minimal duration of the chosen mitigation action should be taken into account. STEER provides a framework to answer these important questions.

[14] Although the results presented here are calibrated for the L'Aquila region, a final conclusion of our analysis is that the current understanding of time-dependent earthquake processes is poor; too poor to warrant evacuations in most cases, however, less impacting mitigation actions may be warranted. The lack of more predictive statistical or physics-based models that accurately describe earthquake interaction are the primary obstacle for initiating mitigation actions.

[15] **Acknowledgments.** We would like to acknowledge the help of C. Bonjour, A. Christophersen, G. Trendafiloski, S. Wöhlbier, and J. Zechar to improve the manuscript. We also thank A. Michael for this thoughtful and constructive review. This work was sponsored in part by the Swiss Agency for Development and Cooperation and by EC-Project NERIES contract 026130.

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Auxiliary material for Paper 2009GL042352

ARE SHORT-TERM EVACUATIONS WARRANTED? THE CASE OF THE 2009 L'AQUILA EARTHQUAKE

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SUPPLEMENTARY FIGURE S1
To illustrate the capabilities and limitations of this methodology, we apply it to the L'Aquila Mw6.3 earthquake of 6 April 2009 (Fig. 1). The methodology of STEER (Short-term earthquake risk) is depicted in the supplementary Figure S1.

a) Previous Seismicity: Our focus is on earthquakes that may create losses. The main contribution to elevated probabilities of such earthquakes is due to small to medium-sized earthquakes with magnitudes between 2.5 and 5.5 within the region (Fig. 1 & 3).

b) Aftershock Probability: As the time-dependent rate model, we adopt the probabilistic aftershock model of [Reasenberg and Jones 1994] that is widely used in the seismological community. This aftershock model describes the probability that events are followed by a subsequent larger one, by allowing aftershocks to be larger than the previous earthquakes ([Reasenberg 1999]). This reflects the conservative assumption that all earthquakes are equally able to trigger a larger earthquake. We use region-specific parameter ([Lolli & Gasperini 2003]) to calculate the rate of occurrence based on the seismicity between 1 November 2008 and the 1 May 2009 for a 24 hours time window, updated after each earthquake or every 3 hours. All events are treated as independent; we sum the rate of all events for all magnitude bins. For simplicity, we use each observed hypocenter as the location of the forecasted seismicity.

c) Probabilistic Ground Motion: These forecasted rates, when combined with a predictive ground motion model (PGMM), define a time-dependent probabilistic seismic hazard assessment. To calculate expected intensity of ground motion at all nearby settlements in the L'Aquila case, we follow the approach of the ShakeMap implementation in Italy ([Michelini et al. 2008]). To integrate site amplification, we assume a value of +1.25 intensity units. To verify the loss model, we calculate the expected fatalities of the Mw6.3 L'Aquila earthquake using an estimated site amplification (I(amp) +1.25) and a settlement size dependent building stock for the region of L'Aquila ([Geonames 2008]) (Population of 72,000 inhabitants; distributed in EMS-98 vulnerability classes A (30%), B (30%), C (30%), and D (10%), where A refers to the most vulnerable and F to the most earthquake resistant buildings, [Grunthal, 1998]). The estimated fatalities based on I(amp)=+1.25 of 160 (plausible low), 240 (mean), 355 (plausible high) matches with observed number of fatalities (299 death). Source and directivity effects were not taken into account. We determine the rates of exceeding a given intensity by stacking up the rates at each settlement. Until here, our approach is similar to the STEP maps for California ([Gerstenberger et al. 2005]).

d) Site-specific Loss Estimation: We estimate the losses following the approach implemented in the loss estimation module in QLARM ([Trendafilski et al. 2009]). The building damage is calculated using the European Macroseismic method ([Giovinazzi 2005]) and provides damage grades for building types according to EMS-98 vulnerability classes. This results in a damage probability matrix for particular vulnerability class and seismic intensity. Based on the damage probability matrix, the collapse rates for different vulnerability classes as a function of seismic intensity allows to calculate the percentage among the heavily damaged and destroyed houses. The collapse rates are retrieved from basic information of the World Housing Encyclopedia ([World Housing Encyclopedia 2008]). Knowing the distribution of the damaged buildings and the actual population data ([Geonames 2008]), the number of injured and fatalities is calculated using the casualty matrices derived from casualty rates in [HAZUS 1999] adapted for the vulnerability classes.

e) Probabilistic Loss Curve (PLC): Combining the probabilistic ground motion (Probability of exceeding an intensity level) with the site-specific loss estimation (Losses as a function of intensity level) yields the probabilistic loss curve. This time-dependent probabilistic seismic risk assessment allows risk-based decisions instead of hazard based ones, and would thus allow defining novel loss-based thresholds for mitigation actions. For example, civil protection officials may set the following threshold: We will take mitigation actions if the probability of 100 fatalities reaches one percent for the period of the next 24 hours.

f) Cost-Benefit Analysis: How much risk mitigation can a society afford? To address this question in a quantitative way, we employ a CBA. The optimal policy to perform a mitigation action is when probabilistic risk exceeds the ratio between the costs for mitigation action C and the potential losses L. However, to perform this analysis it is necessary to assign an economic value to both C and L. See [Marzocchi & Woo 2009] for some examples on volcanology. If a mitigation action is initiated, an updated CBA may be performed for the subsequent periods, because the cost for initiating a mitigation action is not necessarily identical to the cost to keep a mitigation action alive.

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Supplementary Figure S1