Communicating Time-Varying Seismic Risk during an Earthquake Sequence

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1 Communicating time-varying seismic 2 risk during an earthquake sequence

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5 1 Introduction

6 From a geological perspective, big earthquakes happen steadily; but from a human per-
7 spective, they are very rare and recurrences may be separated by several generations.
8 Therefore, society easily loses its awareness of the omnipresent seismic hazard. How-
9 ever, this state of unawareness rapidly changes when people feel an earthquake or a
10 swarm of earthquakes; the public will demand expert advice on future developments
11 and on how to cope with the situation. The 2009 L'Aquila quake demonstrated how risk
12 communication in such a situation can be sensitive [Wolman 2014; Jordan 2013]. The
13 ensuing prosecution of the involved scientists and engineers also made one thing clear:
14 that probabilities, especially the small ones of rare events, are difficult to understand—
15 not only for the public. Ultimately, this case highlighted the importance of public com-
16 munication and the clear delineation of roles and responsibilities, and it pushed the use
17 of scientific methods to drive alternative risk mitigation strategies. For instance, van
18 Stiphout et al. [2010] suggested an approach for objective short-term evacuation deci-

19 sions: probabilistic risk forecasting combined with cost–benefit analysis.

20 Compared to Italy, Switzerland has low seismic hazard, but Switzerland has expe-
21 rienced major earthquakes with estimated magnitudes of $M > 6$: 1295 in Churwalden,
22 1356 in Basel, and 1855 in Visp [Fäh et al. 2011]. Earthquake risk is in fact the dominant
23 natural hazard in Switzerland; although disastrous events are infrequent, loss estimates
24 of a repeat of a 1356 $M_w = 6.7$ Basel earthquake exceed 100 billion CHF (Swiss Francs).
25 In 2012, the *Swiss Federal Office for Civil Protection* simulated a repeat of this event in
26 a scenario exercise called SEISMO-12 [BABS 2012]. Several organizations, officials, and
27 civil servants practiced the response to what is considered to be the worst type of natural
28 disaster that can occur in this region. Knowing how to react in case of emergency and
29 recalling the potential threat not only make one aware of the risk, but this knowledge
30 and awareness will contribute to risk reduction.

31 In this article, we also seek to contribute to risk reduction, but in a different way.
32 Suppose that a region encounters a period of increased seismic activity, and we want
33 to make predictive statements about potential earthquake *consequences* on a short time
34 scale: the corresponding increase in seismic risk of the population. Fig. 1 puts the terms
35 “*earthquakes*,” “*seismic risk*,” and “*mitigation actions*” into context and compares long-
36 term with short-term mitigation actions. Assessing short-term seismic risk is a natu-
37 ral extension of *operational earthquake forecasting* (OEF), which has been discussed
38 extensively in these pages [Jordan and Jones 2010; Jordan et al. 2014; Jordan 2013;
39 Kossobokov et al. 2015; Marzocchi et al. 2014; Wang and Rogers 2014] and elsewhere
40 [Jordan et al. 2011; Woo and Marzocchi 2014]. OEF aims to link earthquake forecast-
41 ing and risk management [Woo 2010], assist decision makers, and help prepare for a
42 potential disaster. After a large earthquake, OEF can be useful because aftershocks may
43 impact rescue and recovery efforts. One of the primary challenges in OEF is that fore-
44 cast probabilities of damaging events typically remain very low, making it difficult to
45 advise the public. Since these obstacles are not an excuse to neglect scientific research
46 on short-term earthquake advisories, van Stiphout et al. [2010] introduced a cost–benefit
47 analysis that considers forecast probabilities as information for making evacuation de-
48 cisions by quantifying the risk in terms of human losses. A real-time probabilistic loss

49 forecast currently running in Italy was just published by *Iervolino et al. [2015]*, how-
50 ever missing the cost–benefit component as in van *Stiphout et al. [2010]*. We believe
51 that cost–benefit analysis adds value beyond making probabilistic forecasts: it provides
52 objective statements that may justify mitigation actions (e. g., evacuations).

53 In this article, we apply the approach of van *Stiphout et al. [2010]* to the synthetic
54 earthquake sequence that drove the SEISMO-12 scenario. In doing so, we extend the
55 risk forecast by adding spatial information: a refined seismicity model provides a spatial
56 rate forecast, and detailed settlement data provides district-wise exposure information.
57 As a further improvement, we extend the cost–benefit analysis: rather than a binary
58 recommendation to act or not act, we suggest using alarm levels to communicate the
59 risk. The advantage of alarm levels is that they can be connected with specified actions,
60 be a guide for those affected, and be updated depending on the warranted measures
61 [*Newhall 2000*]. To be clear, as seismologists we don’t want to communicate decisions;
62 we want to *support* authorities to make the right decisions.

63 According to van *Stiphout et al. [2010]*, a regional evacuation would not have been
64 justified before the L’Aquila mainshock. In this article, we want to explore whether
65 high-resolution exposure data and spatially-varying risk forecasts could justify small-
66 scale evacuations, or certain low-cost mitigation measures. It is assumed that during the
67 historic Basel sequence most of the 7,000 inhabitants fled the city because of foreshocks
68 [*Gisler et al. 2008*]. They escaped because no one knew what would follow. Today, we
69 still do not know, but we can quantify the risk for higher consequences depending on the
70 event magnitude. We want to use this ability and address the question: How long should
71 an evacuation last? Particularly, we search for a way to present such science-based
72 justifications.

73 2 Method

74 Before making any statements about justified actions, we need to forecast the conse-
75 quences that future earthquakes have on the population—seismic loss, a specific form
76 of seismic risk. The risk is assessed by connecting all the *potential* losses with the prob-

ability of these losses. Potential losses are a function of shaking level; in turn, the probability of reaching a shaking level is expressed by the seismic hazard and typically varies in time. Following this principle—once aware of the potential (time-invariant) losses—we forecast the seismic hazard at various shaking levels to assess the time-varying risk in terms of fatalities.

To estimate the potential losses at a given shaking intensity, we adopt the loss estimation procedure of QLARM [Trendafiloski and Wyss 2009], a tool used to quantify losses after disastrous events [Wyss 2004], or to model deterministic scenarios [Wyss and Kästli 2007]. QLARM estimates fatalities, F , as a function of shaking intensity, I , according to

$$F(I) = \left(\sum_{n=0}^5 \sum_{j=A}^F \Pr(C_5|D_n) \Pr(D_n|V_j) \Pr(V_j|I) \right) \cdot N,$$

where V_j represents the buildings' vulnerability as defined by Giovinazzi and Lagomarsino [2004] based on EMS-98 (European Macroseismic Scale, Grünthal [1998]); and the empirical relations, $\Pr(C_5|D_n)$, translate the buildings' damage states, D_n , to the fraction of people dying, C_5 . This fraction is multiplied by the population, N , to yield an estimate of the number of fatalities, $F(I)$.

Based on information of the seismic sequence, E , an earthquake occurrence model produces a seismicity rate forecast, $\vec{\lambda}$, for any future period. We use the *Short-Term Earthquake Probability* model (STEP, Gerstenberger et al. [2005]) which extends the “RJ” model (Reasenber and Jones [1989], used by van Stiphout et al. [2010]) by modeling the spatial clustering of aftershocks—the RJ model has no spatial component. STEP uses the aftershock distribution to estimate a synthetic fault, and forecast rates are smoothed along this fault. A ground motion model converts the STEP rate forecast $\vec{\lambda}$ into probabilities of *exceeding* distinct shaking levels I :

$$P(> I|E) = \Pr(> I|\vec{\lambda}) \Pr(\vec{\lambda}|E)$$

(i. e. EMS-98 intensities [Grünthal 1998]), and we obtain a probabilistic hazard forecast [Wiemer 2000] that is complemented by the background, or long-term, hazard.

101 With the loss estimation $F(I)$ and the short-term hazard $P(>I|E)$ issued for the same
 102 shaking levels I , we construct a so-called *loss exceedance curve* [Crowley and Bommer
 103 2006], or *probabilistic loss curve* (PLC) [van Stiphout et al. 2010]. The PLC can be
 104 understood as a function of the continuous potential loss, in our case the potential fatal-
 105 ities $F(I)$ linked to the corresponding probabilities from the hazard forecast (for distinct
 106 intensity levels I). Stated differently, the PLC is the survival function of the loss ran-
 107 dom variable and enables us different expressions of the risk, e. g., the chance for more
 108 than one fatality, the expected fatalities using its integral [Muldowney et al. 2012], or the
 109 individual risk of dying.

110 Approaching the decision problem of evacuating or not requires an agreement of 1) a
 111 practical risk threshold and 2) whether this level refers to the societal or individual risk.
 112 We compare costs of an evacuation with its benefits to find this level, the so-called cost-
 113 benefit threshold; a trade-off analysis in the sense that the expected costs are minimized
 114 [Marzocchi and Woo 2009]. For instance, an evacuation is preferable if its costs are
 115 exceeded by the expected loss; then, the benefit is a monetary equivalent for saved hu-
 116 man lives. Our threshold refers to the individual risk by normalizing with the population
 117 number. Such an *economic* perspective of risk might be adequate for decision makers,
 118 but not for an individual because everyone is treated equal. Nevertheless, for simplicity,
 119 we maintain this principle and regard our approach as decision support. To facilitate
 120 communication of the seismic risk, we propose a traffic-light system that correlates with
 121 the cost-effectiveness: the ratio between current risk and cost-benefit threshold deter-
 122 mines the alarm level (and corresponding color). To be more specific, the red alarm
 123 level is reached when the risk exceeds the threshold; the alarm is dark-red when the risk
 124 exceeds 200 % of the threshold; for the dark-red orange, yellow, and light-green alarms,
 125 these ratios are 83 %, 66 %, and 50 %, respectively.

126 3 Models and Data

127 Our colleague J. Wössner created the synthetic earthquake catalog that was used for the
 128 SEISMO-12 scenario exercise (see Data and Resources section): he generated a catalog

129 using *Hainzl et al. [2008]*’s ETAS (Epidemic Type Aftershock Sequence) simulation
 130 code and manually added several “foreshocks” and a few larger “aftershocks” (J. Wöss-
 131 ner, personal communication). The synthetic earthquakes (Figure 2) ought to match the
 132 15–20 km long Basel-Reinach fault south of the city of Basel [*Meghraoui et al. 2001*;
 133 *Fäh et al. 2009*]*—*one of many fault systems in this region. We included the many
 134 smaller events (down to M1.0) to enable fault estimation. Since we know very little
 135 about the aftershock behavior of large Swiss earthquakes ($M > 6.0$), we used seismicity
 136 parameters of Italy as determined by *Wössner et al. [2010]* and assumed a maximum
 137 possible magnitude of 7.5. STEP requires a spatial estimate of the background seismic-
 138 ity rate; for this study, we used a synthetic earthquake catalog of Switzerland generated
 139 by *Wiemer et al. [2009]*. These rates also control the background *hazard* which is added
 140 to the hazard forecast. To calculate hazard, we applied the ground motion model of
 141 *Cauzzi et al. [2014]* (stress drop $\Delta\sigma = 60\text{bar}$) which is based on a stochastic simulation
 142 of ground motion [*Edwards and Fäh 2013*] using parameters for Switzerland. We con-
 143 verted the predicted peak ground velocity (PGV) into macroseismic intensity using the
 144 approach of *Faenza and Michelini [2010]*, who based their regression on Italian data.
 145 We also added regional site amplifications [*Kästli and Fäh 2008*; Appendix D-1 of *Fäh*
 146 *et al. 2011*] which range between 0 and 1.05 intensity units in the study region (with a
 147 mean of 0.46).

148 We used relatively high-resolution settlement data in our analysis: *Baisch et al. [2009]*
 149 published the population and building inventory for each of the 19 Basel quarters and
 150 60 surrounding municipalities. Hereafter, we refer to these 79 regional subdivisions as
 151 ‘locales’. The building dataset contains only residential units distributed in modified
 152 Risk-UE building classes which we translated to EMS-98 vulnerability classes [*Grün-
 153 thal 1998*]. To do this, we used vulnerability indices proposed by [*Giovinazzi and Lago-
 154 marsino 2004*] and mapped each Risk-UE class to the most probable EMS-98 class.
 155 These indices are used to construct a (semi-empirical) vulnerability model [*Giovinazzi
 156 and Lagomarsino 2004*]*—*a relationship between seismic hazard and the probability of
 157 experiencing certain damage states*—*to conform with the casualty model and to have
 158 a better understanding of the vulnerability of the region (Figure 3). Because the dis-

159 tribution of people among the different vulnerability classes is not given, we make the
160 simplifying assumption that it matches the distribution of vulnerability classes itself. In
161 other words, if 20 % of a district’s buildings belong to vulnerability class B, we assume
162 that 20 % of the district’s inhabitants are in class B buildings. We replace the casualty
163 model used by van *Stiphout* et al. [2010], which translates building damage into casualty
164 degrees, with a model proposed by *Zuccaro* and *Cacace* [2011] for Italy and consider a
165 constant building occupancy of 80 %. Although we only have residential building data,
166 we regard them as a vulnerability indicator for all buildings—thus, our assumption is
167 that on average 80 % of the people are always present in the buildings.

168 4 Results

169 Figure 4a illustrates that STEP uses the spatial distribution of events to refine the fore-
170 cast: once the initially-circular aftershock zone contains 100 aftershocks above the mag-
171 nitude of completeness, STEP models the fault and transitions from an isotropic smooth-
172 ing to a fault-based smoothing—this happens two hours after the mainshock. We trans-
173 lated the forecast seismicity rates to hazard: the forecast probability of exceeding EMS
174 intensity VI (“slightly damaging”) in the next 24 hours after the mainshock reached 0.67
175 as a mean value for the whole region; seven days later, the mean exceedance probability
176 had dropped to 0.10. In the following, our forecast length stays fixed at 24 hours. The
177 seismicity forecast rates change continuously during the sequence (Figure 5, gray line);
178 the rates influence the hazard exceedance probabilities and subsequently the risk prob-
179 abilities (dotted, dashed, and solid curve). Since the curves follow the same trend, the
180 figure emphasizes the connection between the seismicity forecast and the risk forecast:
181 they 1) increase gradually with every larger earthquake (black circles—actually, these
182 will, in retrospect, be recognized as foreshocks), 2) peak as the mainshock occurs, and
183 3) finally decay smoothly. The fluctuation in the risk curves shortly after the M6.6 event
184 results from an unstable fault estimation due to using only the few events available at that
185 time; the second peak after about 4 days results from a second aftershock zone modeled
186 by STEP that produces its own aftershock rates in a smaller area northwest of the main

187 fault (see Figure 4a, bottom right, and largest gray circle in Figure 2). After 10 days, our
 188 simulated sequence is truncated and the forecast probabilities and rates reach the back-
 189 ground level after about 1000 years, assuming no other sequence happens in the region.
 190 The risk information shown in Figure 5 follows from combining the hazard forecast with
 191 the loss estimation using loss exceedance curves (e. g., Figure 6) at a time: for both sub-
 192 regions (dashed and dotted curve) and the whole region (top black curve), we convolved
 193 the loss curves of all corresponding locales to determine a total loss exceedance curve
 194 that represents the regional view of risk. To understand the influence of the mainshock
 195 magnitude, we varied its size in Figure 6. Loss exceedance curves allow risk statements
 196 in various terms: for instance, the integral of each curve equals the expected number of
 197 fatalities, $E[F]$, for the next day. Furthermore, dividing $E[F]$ by the population number
 198 yields the probability of an individual dying, P_{indv} , during this forecast period. Since we
 199 separated the locales of the city of Basel from the surrounding region, we see in Figure
 200 5 that an individual is at higher risk (twice as high) in the urban area than in the rural
 201 area. Although only 30 % of the population in the region lives in the city of Basel, this
 202 subregion accounts for almost half of the losses (in terms of expected fatalities, see Fig-
 203 ure 7a). This uneven distribution of losses can be explained by 1) the higher percentage
 204 of older (read: more vulnerable) masonry buildings in the urban area, and 2) the urban
 205 area is, on average, closer to the estimated fault zone.

206 One minute before the mainshock, the sum of $E[F]$ among all locales is 5 fatalities,
 207 and the mean of P_{indv} is about 1.1×10^{-5} (see Figure 5); P_{indv} for someone in a vul-
 208 nerable building (EMS class B) is about 3.7×10^{-5} . To see these probabilities from
 209 another point of view: they lie roughly on the same level as a Swiss resident dying due
 210 to any cause of death in any 24 h period (2.6×10^{-5} , [Bundesamt für Statistik 2011]).
 211 One minute after the M6.6, the values are 434 fatalities and 10^{-3} (0.1%), respectively—
 212 ignoring the effects of the mainshock. The “background” probability—before the whole
 213 sequence—is 2.2×10^{-8} (see Figure 5), similar to the probability of dying from AIDS
 214 in Switzerland in any 24 h period (2.4×10^{-9} , [Bundesamt für Statistik 2011]).

215 For comparison, we used the single M6.6 event for a deterministic loss calculation
 216 using a ShakeMap-type hazard expression as input for the loss estimation (maximum

intensity of 8.7). The expected number of fatalities for the whole region was 683 (with a range between 400 and 1128—using the plausible uncertainty bounds due to the fuzzy definition of the buildings' vulnerability index, see *Giovinazzi and Lagomarsino* [2004]). The fatality number for the city of Basel is 378 (231–604), and for the surrounding region 305 (169–524), respectively. The fatality range for the city of Basel is comparable a scenario loss estimation done by *Wyss and Kästli* [2007]: 250–600 for a M6.5 with 15 km distance to Basel.

Another way of expressing the probabilistic risk is to directly extract a value from the loss exceedance curve: for the whole region the probability to exceed 10 fatalities in the first 24 h after the mainshock is 100 % (before the mainshock this chance is 9 %). Likewise, there is a 99.7 % chance that more than 100 fatalities will occur in the first 24 h (0.9 % before the mainshock). Note that reported numbers are certainly overestimates since we assume that the exposure does not change in time. Figure 7a demonstrates an alternative risk statement using a single value from the loss exceedance curve of each locale: it maps the fatalities to be exceeded with a fixed probability. These values deliver a spatial and relative impression of the risk.

To make use of probabilistic statements for decision making and facilitate their interpretation, we apply a cost–benefit analysis and determine if the current risk level justifies evacuations. In contrast to van *Stiphout* et al. [2010], we considered the mitigation action for *all* EMS-98 vulnerability classes and not just the most vulnerable class. We assume the value of a human life in Switzerland to be 10 million CHF; the social-economic cost of evacuating a person per day was set to 1,000 CHF. The actual values that decision makers or risk managers might use are not easy to discover; to get an idea of involved costs in Switzerland, we refer to both a risk evaluation of natural hazards [*PLANAT* 2004] and a cost–benefit analysis of avalanche risk [*Bründl* et al. 2006]. The cost–benefit ratio is the probability threshold representing the upper risk limit the government should tolerate without taking action; in our case it is 10^{-4} as shown in Figure 5 (red line). One minute before the mainshock, the individual risk to die lies one order of magnitude below the threshold (1.1×10^{-5}). Thus, a widespread evacuation would only be cost-effective if the threshold amounts a tenth of its former value (e.g., human

247 life worth 20 million and daily costs of 200)—or, if the evacuation should address only
248 inhabitants of the most vulnerable class B, about a third of its former value. One minute
249 after the mainshock, the cost–benefit threshold is exceeded in every locale and remains
250 so in many locales 3 days later (see Figure 7b).

251 We can forecast when the risk will fall below the threshold again (Figure 8), which
252 tells us, prospectively, the optimal evacuation duration at the very moment. The individ-
253 ual risk decays rapidly—67 % of the initial risk is gone after 1 day, 88 % after 3 days,
254 and 92 % after a week. The risk is strongly influenced by the vulnerability class; and
255 class E would not be cost-effective to evacuate at all.

256 We extend the idea of providing spatial evacuation decisions and demonstrate the ef-
257 fect of the magnitude on the cost-effectiveness of evacuations in Figure 9. We consider
258 a generic scenario with the earthquake placed in the middle of the region of interest.
259 (Hence, the scenario’s event location differs from SEISMO-12.) For this particular set-
260 ting, it requires at least a M5.4 event to exceed the thresholds (not shown: alarm level
261 4 in the inner districts of Basel). Because we don’t know where the next damaging
262 earthquake in this region will be, or how big it will be, we could pre-calculate scenarios
263 with varying magnitude and location. Then, we could immediately provide a suitable
264 recommendation based on our current knowledge. Note that although the mainshock lo-
265 cation is not directly beneath the center of Basel City, the inner city reaches high alarm
266 levels soonest (because of the relatively high vulnerability). In addition to a graphical
267 representation of the four scenarios, Table 1 echoes the “optimal” evacuation duration
268 for the whole region, or for treating the two regions ‘City of Basel’ and the ‘Surrounding
269 region’ as separate “targets” of an alarm call. Table 1 indicates the benefit of increasing
270 the spatial resolution: we find a longer evacuation duration for higher-risk areas—in this
271 case the city of Basel. A similar “optimization” effect can be observed when further re-
272 fining the evacuation on specific vulnerability classes—then resulting in greatly varying
273 evacuation durations.

5 Discussion and Conclusion

Our work addresses one of the nightmare scenarios of both seismologists and civil defense officials: what actions should one recommend after a moderate earthquake of magnitude 4.5–5.5? Such an event would likely cause very limited damage, but the chance of a larger event to follow in the next 7 days is about 2–4 %, and the risk would be a factor of 100–1000 above the background (Figure 5). The chance of a catastrophic event of magnitude 6.5, however, remains small ($\sim 0.5\%$). In Basel, there is the additional piece of evidence that the 1356 earthquake did indeed have a foreshock sequence that lasted a few hours and included a magnitude 5.4 event [Fäh et al. 2011]. We note, however, that a large fraction of damaging earthquakes will occur without any foreshocks (e. g., see Agnew and Jones [1991] for California). Because the risk decays very rapidly after a potential foreshock, decisions need to be made very quickly. As the events of the L’Aquila earthquake have shown, these decisions can disrupt society and be challenged in court. This study is an attempt to outline a rational, defensible baseline for decision making.

Current short-term forecasting models—the basis of our risk assessment—are not particularly skillful at forecasting large events. To facilitate the interpretation of the rather small probabilities that result from these models, we applied a trade-off analysis from an economic perspective: comparing the seismic risk with the costs for preventing loss of lives. Whether an evacuation can be justified before a possibly impending mainshock depends primarily on the size of the foreshocks, if they should occur. For this reason, we explored evacuation justifications for different magnitudes. In our case, with a M5.1 foreshock, we found that a large-scale evacuation is not justified at any time before the M6.6 mainshock. It is not even cost-effective to evacuate only the most vulnerable buildings. However, assuming an event of magnitude 5.5, evacuations of the central part of the city for 6–12 hours would indeed be justified (Figure 9). After a magnitude 6.0 event, cost-benefit analysis recommends that the inner city should be evacuated for several days, and also surrounding areas should be evacuated for more than 12 hours.

After a magnitude 6.6, the situation is quite different: the probability for an individual

303 to die within the next 24 hours becomes 4 orders of magnitude higher than the long-term
304 average. Although the absolute value remains at about one per mille, our analysis rec-
305 ommends evacuation in all locales for at least 24 hours. At later times, alarm levels vary
306 throughout the region. However, we note that after a major damaging event, additional
307 constraints on building use will rapidly be dominant in decision making.

308 Our findings stand in contradiction to current established procedures in Switzerland
309 and elsewhere. After a M5.5 or M6.0 event, there are so far no plans to evacuate build-
310 ings. Therefore, our findings should inspire discussions with civil defense authorities
311 and decisions makers on what to do following such an event.

312 In this article, we propose a color-coded earthquake alarm level, based on the cost-
313 benefit level of action to be taken (e. g., Figure 8). Our particular mapping of risk to
314 colors is arbitrary, but has several benefits: The earthquake alarm level

- 315 • is easily communicated and widely used in other scientific communities;
- 316 • is a result of a probabilistic approach that accounts for uncertainties and makes
317 use of all available information on hazard and vulnerability; the alarm level itself
318 is a concise summary of this process and is easier to interpret than, say, foreshock
319 probabilities;
- 320 • can be computed automatically, which is critical for real-time decision making;
321 and
- 322 • is fully reproducible.

323 We suggest that the use of an alarm level based on cost-benefit analysis would be a
324 substantial enhancement for communication of time-dependent seismic hazard and risk
325 information.

326 Locale-specific mitigation actions improve cost-effectiveness relative to regional ac-
327 tions. Passing alarm calls to specific building types would be even better, but impractical
328 at this point. Although our method permits such detailed analysis, it seems unlikely that
329 evacuation recommendations would be conditional on building and site class, as most
330 people do not know their building's characteristics. For this reason, effort should be put

331 into for example improving the emergency system, educating the people, and gathering
332 better building information (e. g., considering building monitoring using smart devices).

333 The presented method can be applied to other regions, provided there is a good
334 understanding—or at least particular simplifying assumptions—about the regional 1)
335 aftershock behavior, 2) ground-motion attenuation, 3) inventory data of buildings, 4)
336 population distribution, and 5) definition of the cost–benefit threshold. Nevertheless, we
337 made simplified assumptions and note that our method and analysis could be improved
338 in future studies. For example, more efforts are needed to calibrate and validate, e. g.,
339 economical values, alarm levels, or the forecasting model. In this study, we did not ac-
340 count for progressive damage—the building stock and population distribution (and its
341 number) were taken as constants throughout the crisis. Therefore, our results for the
342 time after the mainshock (e. g., evacuation durations) are based on the (certainly incor-
343 rect) assumption that the mainshock did not alter the inventory. We also neglected many
344 uncertainties, based on simplified assumptions (e. g., that all residents would behave the
345 same) or limited data availability (e. g., no individual building response to shaking), and
346 these uncertainties may not be reduced in the near future. Despite these limitations, our
347 loss forecasting approach demonstrates that available data and models can be combined
348 to add value to risk communication. We also note that our method is modular: elements
349 can be exchanged and improved by new insights or by ensemble, or hybrid, forecast
350 models [*Rhoades and Gerstenberger 2009; Marzocchi et al. 2012; Shebalin et al. 2014;*
351 *Rhoades 2013; Rhoades et al. 2014*] and a suite of hazard models [*Atkinson et al. 2014;*
352 *Scherbaum et al. 2009*]*—which also help to represent uncertainties. Vulnerability mod-*
353 *els (i. e. empirical and analytical fragility curves) can also form ensembles: for example*
354 *using a rating scheme based on the models’ reliability [Rossetto et al. 2014; Porter et al.*
355 *2012] to derive a mean fragility curve from a selection out of a large pool of available*
356 *fragility curves.*

357 The considered earthquake scenario only approximates the historic 1356 event; no-
358 body knows how well it approximates the next earthquake. But we think that our spatial
359 risk estimates give at least a conditional indication of the relative seismic risk among
360 the localities, perhaps already making officials aware of “weak points.” In addition,

361 even uncalibrated alarm levels should correlate with the gravity of the situation, which
362 identifies localities that are most in need of help, e. g., to prioritize rescue teams and to
363 allocate resources.

364 If a large event happens soon, we could provide supportive information. But it re-
365 mains unclear how we should communicate scientific findings to benefit society and en-
366 hance civil protection. Based on the assessed risk, we need to make the right decision—a
367 choice among alternatives [Fischhoff et al. 1981]. A cost–benefit analysis is one way
368 to find a “safe” level. Although the decision makers will assign the values of the cost–
369 benefit analysis [Marzocchi and Woo 2009], the right choice depends on values and
370 beliefs of individuals [Fischhoff et al. 1981], who perceive risk in their own way. There
371 can be no sole parameter, and it appears that finding a risk threshold challenges us
372 as much as risk assessment itself. Therefore, Woo and Marzocchi [2014]’s suggestion
373 seems reasonable: “provide different warnings to the public without imposing any spe-
374 cific mitigation action”; essentially “‘nudging’ people to adopt their own mitigation
375 strategy.” Cost–benefit analysis may not only be useful *during* an earthquake crisis, but
376 also (far) in advance: (1) to justify seismic retrofit measures of buildings and facilities
377 [Woo 2010] and (2) to justify any numerous low-cost measures like securing the house-
378 hold against shaking-induced threat of falling objects, staying alert or moving to a safer
379 place even after a minor earthquake, and, last but not least, occasionally reminding the
380 public to be more seismically aware [Woo 2010; Woo and Marzocchi 2014]).

381 The ability to forecast short-term seismic risk anytime and anywhere is the first step
382 of personal decision making and these findings should help to raise risk awareness.
383 Alarm levels that vary in space and time may be valuable to decision makers, authorities,
384 engineers, and even the public. Nevertheless, low probabilities, high uncertainties, and
385 middling data quality limit the utility of forecasting. It follows that forecasting risk is
386 not an easy task; even more so if the forecasts drive decisions and risk communication.

387 Data and Resources

388 We used MATLAB to produce our code and most of the plots; some plots were made us-
389 ing the Generic Mapping Tools (www.soest.hawaii.edu/gmt; *Wessel and Smith* [1998]).
390 The synthetic catalog is available as ZMAP-format in the electronic supplement to this
391 article. We modified the original STEP code that was provided by Matthew C. Ger-
392 stenberger in JAVA programming language [*Gerstenberger* 2006] implemented within
393 OpenSHA [*Field et al.* 2003]. To give each locale a spatial representation, we used
394 Swiss boundary data from the *Federal Agency for Statistics* [*Bundesamt für Statistik*
395 2009], and for the remaining municipalities we extracted boundaries from the Open-
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References

- Agnew, D. C. and L. M. Jones (1991). “Prediction probabilities from foreshocks”. In: *Journal of Geophysical Research* 96.B7, p. 11959. URL: <http://doi.wiley.com/10.1029/91JB00191>.
- Atkinson, G. M., J. J. Bommer, and N. a. Abrahamson (2014). “Alternative Approaches to Modeling Epistemic Uncertainty in Ground Motions in Probabilistic Seismic-Hazard Analysis”. In: *Seismological Research Letters* 85.6, pp. 1141–1144. URL: <http://srl.geoscienceworld.org/cgi/doi/10.1785/0220140120>.
- BABS (2012). *Internationale Erdbebenübung SEISMO 12: Harte Arbeit für Führungsstäbe*. {Media information. Bundesamt für Bevölkerungsschutz}. URL: <http://www.bevoelkerungsschutz.admin.ch/internet/bs/de/home/dokumente/news/detail.44499.nsb.html>.
- Baisch, S. et al. (2009). *SERIANEX - Deep Heat Mining Basel*. Tech. rep.
- Bründl, M., M. McAlpin, U. Gruber, and S. Fuchs (2006). “Application of the marginal cost-approach and cost-benefit analysis to measures for avalanche risk reduction—A case study from Davos, Switzerland”. In: *RISK21-Coping with Risks due to Natural Hazards in the 21st Century*. Taylor & Francis, pp. 155–168. URL: <http://www.crcnetbase.com/doi/abs/10.1201/9780203963562.ch16>.
- Bundesamt für Statistik (2009). *Generalisierte Gemeindegrenzen, Stufe 3: Geodaten*. URL: http://www.bfs.admin.ch/bfs/portal/de/index/dienstleistungen/geostat/datenbeschreibung/generalisierte_gemeindegrenzen.html.
- Bundesamt für Statistik (2011). *Todesfälle: Anzahl, Entwicklung und Ursachen. Sterbeziffern für 30 wichtige Todesursachen nach Geschlecht*. Neuchâtel. URL: <http://www.bfs.admin.ch/bfs/portal/de/index/themen/14/02/04/key/01.html> (visited on 03/03/2014).
- Cauzzi, C., B. Edwards, D. Fah, J. Clinton, S. Wiemer, P. Kastli, G. Cua, and D. Giardini (2014). “New predictive equations and site amplification estimates for the next-generation Swiss ShakeMaps”. In: *Geophysical Journal International* 200.1, pp. 421–438. URL: <http://gji.oxfordjournals.org/cgi/doi/10.1093/gji/ggu404>.
- Crowley, H. and J. J. Bommer (2006). “Modelling Seismic Hazard in Earthquake Loss Models with Spatially Distributed Exposure”. In: *Bulletin of Earthquake Engineering* 4.3, pp. 249–273. URL: <http://www.springerlink.com/index/10.1007/s10518-006-9009-y>.

- 442 Edwards, B. and D. Fäh (2013). “A Stochastic Ground-Motion Model for Switzerland”. In: *Bul-*
 443 *letin of the Seismological Society of America* 103.1, pp. 78–98. URL: [http://www.bssaonline.](http://www.bssaonline.org/cgi/doi/10.1785/0120110331)
 444 [org/cgi/doi/10.1785/0120110331](http://www.bssaonline.org/cgi/doi/10.1785/0120110331).
- 445 Faenza, L. and A. Michelini (2010). “Regression analysis of MCS intensity and ground motion
 446 parameters in Italy and its application in ShakeMap”. In: *Geophysical Journal International*
 447 180.3, pp. 1138–1152. URL: <http://doi.wiley.com/10.1111/j.1365-246X.2009.04467.x>.
- 448 Fäh, D. et al. (2009). “The 1356 Basel earthquake: an interdisciplinary revision”. In: *Geophysical*
 449 *Journal International* 178.1, pp. 351–374. URL: [http://gji.oxfordjournals.org/cgi/doi/10.1111/](http://gji.oxfordjournals.org/cgi/doi/10.1111/j.1365-246X.2009.04130.x)
 450 [j.1365-246X.2009.04130.x](http://gji.oxfordjournals.org/cgi/doi/10.1111/j.1365-246X.2009.04130.x).
- 451 Fäh, D. et al. (2011). *ECOS-09 Earthquake Catalogue of Switzerland. Release 2011. Report and*
 452 *Database. 17.04.2011*. Tech. rep. Swiss Seismological Service, ETH Zürich.
- 453 Field, E. H., T. H. Jordan, and C. A. Cornell (2003). “OpenSHA: A developing community-
 454 modeling environment for seismic hazard analysis”. In: *Seismological Research Letters* 74.4,
 455 pp. 406–419. URL: <http://srl.geoscienceworld.org/content/74/4/406.short>.
- 456 Fischhoff, B., S. Lichtenstein, and P. Slovic (1981). *Acceptable Risk*. Cambridge University
 457 Press.
- 458 Gerstenberger, M. C. (2006). *STEP: Further Development of Short-Term Earthquake Probabili-*
 459 *ties Codes and Statistical Tests of Forecasts*. Tech. rep. Institute of Geological & Nuclear Sci-
 460 ences (GNS). URL: <http://earthquake.usgs.gov/research/external/reports/06HQGR0141.pdf>.
- 461 Gerstenberger, M. C., S. Wiemer, L. M. Jones, and P. A. Reasenberg (2005). “Real-time forecasts
 462 of tomorrow’s earthquakes in California.” In: *Nature* 435.7040, pp. 328–331. URL: [http://](http://www.ncbi.nlm.nih.gov/pubmed/15902254)
 463 www.ncbi.nlm.nih.gov/pubmed/15902254.
- 464 Giovinazzi, S. and S. Lagomarsino (2004). “A macroseismic method for the vulnerability assess-
 465 ment of buildings”. In: *Proc. of 13th World Conference on Earthquake Engineering, Paper No.*
 466 *896*. 896. Vancouver, Canada. URL: http://www.iitk.ac.in/nicee/wcee/article/13_896.pdf.
- 467 Gisler, M., D. Fäh, and D. Giardini (2008). *Nachbeben - Eine Geschichte der Erdbeben in der*
 468 *Schweiz*. 1st ed. Bern: Haupt Verlag, p. 187.
- 469 Grünthal, G. (1998). *European Macroseismic Scale 1998*. Tech. rep. Luxembourg: European
 470 Seismological Commission. URL: [http://www.gfz-potsdam.de/portal/gfz/Struktur/Departments/](http://www.gfz-potsdam.de/portal/gfz/Struktur/Departments/Department+2/sec26/resources/documents/PDF/EMS-98_Original_englisch_pdf)
 471 [Department+2/sec26/resources/documents/PDF/EMS-98_Original_englisch_pdf](http://www.gfz-potsdam.de/portal/gfz/Struktur/Departments/Department+2/sec26/resources/documents/PDF/EMS-98_Original_englisch_pdf).
- 472 Hainzl, S., A. Christophersen, and B. Enescu (2008). “Impact of Earthquake Rupture Extensions
 473 on Parameter Estimations of Point-Process Models”. In: *Bulletin of the Seismological Soci-*

474 *ety of America* 98.4, pp. 2066–2072. URL: <http://www.bssaonline.org/cgi/doi/10.1785/>
 475 0120070256.

476 Iervolino, I., E. Chioccarelli, M. Giorgio, W. Marzocchi, G. Zuccaro, M. Dolce, and G. Manfredi
 477 (2015). “Operational (Short-Term) Earthquake Loss Forecasting in Italy”. In: *Bulletin of the*
 478 *Seismological Society of America* 105.4, pp. 2286–2298. URL: [http://www.bssaonline.org/](http://www.bssaonline.org/lookup/doi/10.1785/0120140344)
 479 [lookup/doi/10.1785/0120140344](http://www.bssaonline.org/lookup/doi/10.1785/0120140344).

480 Jordan, T. H. (2013). “Lessons of L’Aquila for Operational Earthquake Forecasting”. In: *Seis-*
 481 *mological Research Letters* 84.1, pp. 4–7. URL: [http://srl.geoscienceworld.org/cgi/doi/10.](http://srl.geoscienceworld.org/cgi/doi/10.1785/0220120167)
 482 [1785/0220120167](http://srl.geoscienceworld.org/cgi/doi/10.1785/0220120167).

483 Jordan, T. H. and L. M. Jones (2010). “Operational Earthquake Forecasting: Some Thoughts
 484 on Why and How”. In: *Seismological Research Letters* 81.4, pp. 571–574. URL: [http://srl.](http://srl.geoscienceworld.org/cgi/doi/10.1785/gssrl.81.4.571)
 485 [geoscienceworld.org/cgi/doi/10.1785/gssrl.81.4.571](http://srl.geoscienceworld.org/cgi/doi/10.1785/gssrl.81.4.571).

486 Jordan, T. H., W. Marzocchi, a. J. Michael, and M. C. Gerstenberger (2014). “Operational Earth-
 487 quake Forecasting Can Enhance Earthquake Preparedness”. In: *Seismological Research Let-*
 488 *ters* 85.5, pp. 955–959. URL: <http://srl.geoscienceworld.org/cgi/doi/10.1785/0220140143>.

489 Jordan, T. H., Y.-T. Chen, P. Gasparini, R. Madariaga, I. Main, W. Marzocchi, G. Papadopoulos,
 490 G. Sobolev, K. Yamaoka, and J. Zschau (2011). *Operational Earthquake Forecasting: State*
 491 *of Knowledge and Guidelines for Implementation*. Tech. rep. May. International Commission
 492 on Earthquake Forecasting for Civil Protection (ICEF). URL: [http://www.annalsofgeophysics.](http://www.annalsofgeophysics.eu/index.php/annals/article/view/5350)
 493 [eu/index.php/annals/article/view/5350](http://www.annalsofgeophysics.eu/index.php/annals/article/view/5350).

494 Kästli, P. and D. Fäh (2008). *Site amplification factors for intensity attenuation; a case study for*
 495 *Switzerland*. Appendix D-1 of ECOS-09. Swiss Seismological Service, ETH Zürich, pp. 1–
 496 39. URL: http://www.seismo.ethz.ch/static/ecos-09/Appendix/Appendix_D.pdf.

497 Kossobokov, V. G., A. Peresan, and G. F. Panza (2015). “On Operational Earthquake Forecast
 498 and Prediction Problems”. In: *Seismological Research Letters* 86.2, pp. 287–290. URL: [http:](http://srl.geoscienceworld.org/cgi/doi/10.1785/0220140202)
 499 [//srl.geoscienceworld.org/cgi/doi/10.1785/0220140202](http://srl.geoscienceworld.org/cgi/doi/10.1785/0220140202).

500 Marzocchi, W., a. M. Lombardi, and E. Casarotti (2014). “The Establishment of an Operational
 501 Earthquake Forecasting System in Italy”. In: *Seismological Research Letters* 85.5, pp. 961–
 502 969. URL: <http://srl.geoscienceworld.org/cgi/doi/10.1785/0220130219>.

503 Marzocchi, W. and G. Woo (2009). “Principles of volcanic risk metrics: Theory and the case
 504 study of Mount Vesuvius and Campi Flegrei, Italy”. In: *Journal of Geophysical Research*
 505 114.B3, B03213. URL: <http://doi.wiley.com/10.1029/2008JB005908>.

506 Marzocchi, W., J. D. Zechar, and T. H. Jordan (2012). “Bayesian Forecast Evaluation and En-
507 semble Earthquake Forecasting”. In: *Bulletin of the Seismological Society of America* 102.6,
508 pp. 2574–2584. URL: <http://www.bssaonline.org/cgi/doi/10.1785/0120110327>.

509 Meghraoui, M., B. Delouis, M. Ferry, D. Giardini, P. Huggenberger, I. Spottke, and M. Granet
510 (2001). “Active normal faulting in the upper Rhine graben and paleoseismic identification
511 of the 1356 Basel earthquake.” In: *Science (New York, N.Y.)* 293.5537, pp. 2070–2073. URL:
512 <http://www.ncbi.nlm.nih.gov/pubmed/11557888>.

513 Muldowney, P., K. M. Ostaszewski, and W. Wojdowski (2012). “The Darth Vader Rule”. In:
514 *Tatra Mountains Mathematical Publications* 52, pp. 53–63.

515 Newhall, C. G. (2000). “Volcano warnings”. In: *Encyclopaedia of volcanoes, Academic, New*
516 *York*. URL: [http://scholar.google.com/scholar?hl=en%5C&btnG=Search%5C&q=intitle:](http://scholar.google.com/scholar?hl=en%5C&btnG=Search%5C&q=intitle:Volcano+warnings%5C#0)
517 [Volcano+warnings%5C#0](http://scholar.google.com/scholar?hl=en%5C&btnG=Search%5C&q=intitle:Volcano+warnings%5C#0).

518 PLANAT (2004). *Strategien Naturgefahren Schweiz - Synthesebericht*. Tech. rep. Biel.

519 Porter, K. A., K. Farokhnia, I. H. Cho, D. Grant, K. Jaiswal, and D. Wald (2012). “Global Vul-
520 nerability Estimation Methods for the Global Earthquake Model”. In: 4504, pp. 24–28.

521 Reasenbergs, P. A. and L. M. Jones (1989). “Earthquake hazard after a mainshock in california.”
522 In: *Science (New York, N.Y.)* 243.4895, pp. 1173–1176. URL: [https://www.sciencemag.org/](https://www.sciencemag.org/content/243/4895/1173.abstract)
523 [content/243/4895/1173.abstract](https://www.sciencemag.org/content/243/4895/1173.abstract).

524 Rhoades, D. a. (2013). “Mixture Models for Improved Earthquake Forecasting with Short-to-
525 Medium Time Horizons”. In: *Bulletin of the Seismological Society of America* 103.4, pp. 2203–
526 2215. URL: <http://www.bssaonline.org/cgi/doi/10.1785/0120120233>.

527 Rhoades, D. a. and M. C. Gerstenberger (2009). “Mixture Models for Improved Short-Term
528 Earthquake Forecasting”. In: *Bulletin of the Seismological Society of America* 99.2A, pp. 636–
529 646. URL: <http://www.bssaonline.org/cgi/doi/10.1785/0120080063>.

530 Rhoades, D. a., M. C. Gerstenberger, A. Christophersen, J. D. Zechar, D. Schorlemmer, M. J.
531 Werner, and T. H. Jordan (2014). “Regional Earthquake Likelihood Models II: Information
532 Gains of Multiplicative Hybrids”. In: *Bulletin of the Seismological Society of America* 104.6.
533 URL: <http://www.bssaonline.org/cgi/doi/10.1785/0120140035>.

534 Rossetto, T., D. D’Ayala, I. Ioannou, and A. Meslem (2014). “Evaluation of Existing Fragility
535 Curves”. In: *SYNER-G: Typology Definition and Fragility Functions for Physical Elements at*
536 *Seismic Risk*. Ed. by K. Pitilakis, H. Crowley, and A. Kaynia. Dordrecht Heidelberg New York

537 London: Springer Netherlands. Chap. 3, pp. 47–93. URL: [http://link.springer.com/chapter/10.](http://link.springer.com/chapter/10.1007/978-94-007-7872-6_3)
538 1007/978-94-007-7872-6_3.

539 Scherbaum, F., E. Delavaud, and C. Riggelsen (2009). “Model Selection in Seismic Hazard
540 Analysis: An Information-Theoretic Perspective”. In: *Bulletin of the Seismological Society of*
541 *America* 99.6, pp. 3234–3247. URL: <http://www.bssaonline.org/cgi/doi/10.1785/0120080347>.

542 Shebalin, P. N., C. Narteau, J. Zechar, and M. Holschneider (2014). “Combining earthquake
543 forecasts using differential probability gains”. In: *Earth, Planets and Space* 66.1, p. 37. URL:
544 <http://www.earth-planets-space.com/content/66/1/37>.

545 Trendafiloski, G. and M. Wyss (2009). “Loss estimation module in the second generation soft-
546 ware QLARM”. In: *Second International Workshop on Disaster Casualties*. June. University
547 of Cambridge, UK.

548 Van Stiphout, T., S. Wiemer, and W. Marzocchi (2010). “Are short-term evacuations warranted?
549 Case of the 2009 L’Aquila earthquake”. In: *Geophysical Research Letters* 37.6, pp. 1–5. URL:
550 <http://onlinelibrary.wiley.com/doi/10.1029/2009GL042352/abstract>.

551 Wang, K. and G. C. Rogers (2014). “Earthquake Preparedness Should Not Fluctuate on a Daily
552 or Weekly Basis”. In: *Seismological Research Letters* 85.3, pp. 569–571. URL: [http://srl.](http://srl.geoscienceworld.org/cgi/doi/10.1785/0220130195)
553 [geoscienceworld.org/cgi/doi/10.1785/0220130195](http://srl.geoscienceworld.org/cgi/doi/10.1785/0220130195).

554 Wessel, P. and W. H. F. Smith (1998). “New, improved version of generic mapping tools re-
555 leased”. In: *Eos, Transactions American Geophysical Union* 79.47, pp. 579–579.

556 Wiemer, S. (2000). “Introducing probabilistic aftershock hazard mapping”. In: *Geophysical Re-*
557 *search Letters* 27.20, pp. 3405–3408. URL: <http://doi.wiley.com/10.1029/2000GL011479>.

558 Wiemer, S., D. Giardini, D. Fäh, N. Deichmann, and S. Sellami (2009). “Probabilistic seismic
559 hazard assessment of Switzerland: best estimates and uncertainties”. In: *Journal of Seismology*
560 13.4, pp. 449–478. URL: <http://www.springerlink.com/index/10.1007/s10950-008-9138-7>.

561 Wolman, D. (2014). *The Aftershocks*. <https://medium.com/matter/the-aftershocks-7966d0cdec66>.
562 URL: <https://medium.com/matter/the-aftershocks-7966d0cdec66>.

563 Woo, G. (2010). “Operational Earthquake Forecasting and Risk Management”. In: *Seismological*
564 *Research Letters* 81.5, pp. 778–782. URL: [http://srl.geoscienceworld.org/cgi/doi/10.1785/](http://srl.geoscienceworld.org/cgi/doi/10.1785/gssrl.81.5.778)
565 [gssrl.81.5.778](http://srl.geoscienceworld.org/cgi/doi/10.1785/gssrl.81.5.778).

566 Woo, G. and W. Marzocchi (2014). “Operational earthquake forecasting and decision-making”.
567 In: *Early Warning for Geological Disasters*. Ed. by F. Wenzel and J. Zschau. Springer Berlin

568 Heidelberg, pp. 353–367. URL: [http://link.springer.com/chapter/10.1007/978-3-642-12233-](http://link.springer.com/chapter/10.1007/978-3-642-12233-0_18)
569 0_18.

570 Wössner, J., A. Christophersen, J. D. Zechar, and D. Monelli (2010). “Building self-consistent,
571 short-term earthquake probability (STEP) models: improved strategies and calibration proce-
572 dures”. In: *Annals of Geophysics* 53.3, pp. 141–153.

573 Wyss, M. (2004). “Real-time prediction of earthquake casualties”. In: *Disasters and Society –*
574 *From Hazard Assessment to Risk Reduction*. Univ. Karlsruhe, pp. 165–173. URL: [http://www.](http://www.wapmerr.org/publication/Loss_prediction_Wyss_Karlsruhe.pdf)
575 [wapmerr.org/publication/Loss_prediction_Wyss_Karlsruhe.pdf](http://www.wapmerr.org/publication/Loss_prediction_Wyss_Karlsruhe.pdf).

576 Wyss, M. and P. Kästli (2007). *Estimates of Regional Losses in Case of a Repeat of the 1356*
577 *Basel Earthquake*. Tech. rep. August. URL: [http://www.wapmerr.org/publication/Basel1356Losses_](http://www.wapmerr.org/publication/Basel1356Losses_WAPMERR.pdf)
578 [WAPMERR.pdf](http://www.wapmerr.org/publication/Basel1356Losses_WAPMERR.pdf).

579 Zuccaro, G. and F. Cacace (2011). “Seismic Casualty Evaluation: The Italian Model, an Appli-
580 cation to the L’Aquila 2009 Event”. In: *Human Casualties in Earthquakes*. Ed. by R. Spence,
581 E. So, and C. Scawthorn. Dordrecht: Springer Netherlands. Chap. 12, pp. 171–184. URL:
582 http://link.springer.com/content/pdf/10.1007/978-90-481-9455-1_9.pdf.

Figure 1: Schematic overview of the components of risk and where mitigation actions may be taken. The right part (short-term mitigation) is the focus of this present article. The figure also emphasizes that the terms *hazard* and *risk* are not interchangeable in seismology.

Figure 2: Simulated earthquake sequence for a M6.6 mainshock in space (top) and time (bottom). In addition to an ETAS simulation (open circles), several events were added manually: foreshocks (black circles) and aftershocks (gray circles).

Figure 3: Map-view of processed building inventory information for all 79 locales: we converted the original data set to EMS-98 *vulnerability classes* to serve as input for the loss estimation. The map reveals varying vulnerability distributions (only classes B–E present); the area of each pie chart is proportional to the number of buildings. The city of Basel is contoured with a black line.

Figure 4: 24-hour forecasts for the Basel region using earthquake data available at the specified time. **a)** Rate forecasts, showing the number of M3+ earthquakes that STEP forecasts in each bin over the next 24-hour period. The model estimated a fault after 100 aftershocks (not illustrated); 598 aftershocks occurred 24 hours after the M6.6 (large image). **b)** Short-term hazard forecasts. We use PSHA to convert the forecast rates into the probability of exceeding various EMS intensities within the next 24 hours. EMS VI was chosen as an example; the scattering results from site amplification data.

Figure 5: Time-varying risk probabilities (dotted, dashed, and solid curve) and seismicity rate (gray curve, right axis) using information available at that time (i. e. retrospective). The risk curves indicate the probability that any inhabitant will die in the next 24 hours, separated for the city of Basel (dotted curve), the surrounding region (dashed curve), and the whole region (solid curve). While (a) depicts the sudden risk increase due to the foreshock sequence and the mainshock, (b) illustrates the subsequent risk decay logarithmic in time. Subfigure (a) further shows the risk threshold of the cost-benefit analysis (thick black line). To track the seismicity during this time, stems in (c) and (d) represent earthquakes with the same gray shading as in Figure 2.

Figure 6: A probabilistic loss curve (PLC) represents the survival function of the fatality number, a loss random variable, and expresses the probability of exceeding certain losses. The five PLCs (solid black) display the daily risk for the whole region immediately after the corresponding magnitude. The M6.6 is the scenario earthquake considered in this study; for the other curves, we set the mainshock magnitude accordingly. Regional PLCs (dashed and dotted curve) correspond to the M6.6 event.

Figure 7: **a)** Spatial 24-hour time-varying loss forecast for each locale one minute after the M6.6 (white star). The mapped fatality number will not be exceeded with 90 % probability in 24 hours; the values in the lower right give a regional fatality number determined by convolving loss curves of corresponding locales (and is thus not the sum among the locales). **b)** Cost–benefit map with proposed alarm levels three days after the M6.6, indicating the cost-effectiveness of evacuating the complete locality (all vulnerability classes) for the following day. For the time one minute after the M6.6, the map would be completely dark red (compare to Figure 9). The alarm levels are proportional to the ratio between the individual probability dying and the threshold (see Figure 8); e. g., red color denotes threshold exceedance, dark red at least by 100 %.

Figure 8: Prospective forecast of the individual probability of dying (within 24 hours) as issued right after the mainshock for the city of Basel (white), the surrounding region (gray), and the whole region (black)—separated by EMS vulnerability class (see legend). This plot allows us to explore the optimal evacuation duration: as long as the probability exceeds the predefined cost–benefit threshold (red line), an evacuation is justified for that vulnerability class for the next 24 hours. The Figure illustrates how we proposed our alarm-level scale (as used in Figure 7b and 9); it depends on the ratio between probability and threshold.

Figure 9: Cost–benefit results for four different scenarios of varying magnitude (which differ in location compared to the SEISMO-12 exercise). For each scenario, the map displays proposed alarm levels. For six selected locales, we forecast—immediately after the respective event—the prospective alarm levels in time. These should give an idea of how long each locale can remain evacuated in a cost-effective way: the optimal evacuation would last as long as the alarm is red or dark-red. Note that the graph is non-linear as indicated by the dashed line: the last 6 days were contracted relative to the first 24 h and were made transparent.

Table 1: Cost-effective (i. e. “optimal”) evacuation durations for different magnitudes of a scenario earthquake as placed as in Fig. 9; considering (1) different regions, and (2) different vulnerability classes for evacuation. Note that even for a true event, these evacuations times would be only a first guess, because the forecast model will learn from the ongoing sequence over time; evacuation times then could be revised regularly. Also note that the scenario earthquake’s location differs from the SEISMO-12 scenario as used before.

Magnitude	Whole region				City of Basel				Surrounding region			
	B	B+C	C	Σ	B	B+C	C	Σ	B	B+C	C	Σ
6.5	436 h	180 h	72 h	108 h	520 h	300 h	108 h	204 h	344 h	124 h	60 h	88 h
6.0	84 h	29 h	7 h	14 h	104 h	55 h	14 h	34 h	62 h	16 h	5 h	6 h
5.5	8 h	—	—	—	11 h	3 h	—	—	4 h	—	—	—
5.0	—	—	—	—	—	—	—	—	—	—	—	—

”—” means that an evacuation is *not* cost-effective according to the assumed criteria