

# Harmonizing and comparing single-type natural hazard risk estimations

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## ABSTRACT

Single-type hazard and risk assessment is the usual framework followed by disaster risk reduction (DRR) practitioners. There is therefore a need to present and compare the results arising from different hazard and risk types. Here we describe a simple method for combining risk curves arising from different hazard types in order to gain a first impression of the total risk. We show how the resulting total (and individual) risk estimates can be examined and compared using so-called risk matrices, a format preferred by some DRR practitioners. We apply this approach to Cologne, Germany, which is subject to floods, windstorms and earthquakes. We then use a new series of risk calculations that consider epistemic uncertainty. The Mann-Whitney test is applied to determine if the losses arising from pairs of hazards are comparable for a given return period. This benefits decision makers as it allows a ranking of hazards with respect to expected damage. Such a comparison would assist planners in the allocation of resources towards the most efficient mitigation actions. However, the results are dependent upon the distribution of estimates (i.e., level of uncertainty), which is in turn a function of our state of knowledge.

## 1. Introduction

Although there is an increasing awareness of the importance of the potential interactions that arise between different hazard types and their associated risks, there is still a need for robust and meaningful comparisons between the risks arising from individual hazard types occurring in the same area [Kappes et al. 2012, Marzocchi et al. 2012]. The reason for this is partly due to the importance of single-type risks to stakeholders and decision makers owing to their relative ease of use, the different competencies in risk management (e.g., water boards are often only responsible for floods, not other

hazards) and the (single-risk) mandate that authorities are usually assigned [e.g., Komendantova et al. 2014].

Therefore, while the single-type approach for natural hazard and risk assessment (i.e., individual types are treated separately, without considering how different hazards may interact with each other at the various levels of the risk assessment chain) is still the general one followed by the disaster risk reduction (DRR) community [e.g., Kreibich et al. 2014], it often lacks a common framework allowing for the comparability of quantitative risk assessments, both in terms of comparable spatial and temporal scales, and with respect to the metrics being employed. In addition, while several attempts have been made to provide a more holistic view in terms of comparing natural hazard risk curves [e.g., Grünthal et al. 2006, Schmidt-Thomé et al. 2006, Garcia-Aristizabal et al. 2015], the issue of uncertainties has not usually been considered. These points therefore lead to a number of concerns.

Consider first the issue of what should be employed as the most appropriate risk metric (a matter of “comparing apples with apples”). Such a metric must allow losses from different types of disaster to be meaningfully compared, assisting both responders to disasters and those involved in longer-term planning. For example, in the case of Germany, although the summer 2003 heat wave resulted in the highest number of deaths from an extreme natural event for the period 1980-2010 (9,355 people), the associated economic losses were relatively low (€ 1.65 billion) compared to the floods of 2002 (€ 11.6 billion) which caused the deaths

of 27 people (PreventionWeb website, [www.preventionweb.net/english/countries/statistics/?cid=66](http://www.preventionweb.net/english/countries/statistics/?cid=66)). Similarly, comparing numbers of casualties arising from, for example, an earthquake and a hurricane, neglects how there is a greater capacity for early warning (hence the undertaking of mitigating actions) for the latter than for the former, leading to the suggestion that the numbers of people lacking shelter as a result of the event may be a more useful metric [Monfort and Lecacheux 2013].

The next question deals with the spatial and/or temporal scales being dealt with, each of which depends upon the hazard of concern. Considering spatial scales, different hazards have their own spatial pattern, for example, direct losses from floods are generally restricted to lower-lying areas close to water bodies, and so a flood may be rather localized, although in larger events, the extent of direct damage may be considerable (e.g., Germany, 2002, 2013, Thailand, 2011). By contrast, the area affected by an earthquake is not limited by such factors and primarily depends upon the event's magnitude, although again, depending upon geological conditions, there may be considerable spatial variability in the resulting ground shaking [e.g., Parolai et al. 2007]. With regards to temporal scales, certain hazards display a degree of regularity, for example, seasonal winter storms or hurricanes, while others, such as earthquakes and volcanoes, follow less regular patterns or exhibit longer return periods and thus, must be considered over much longer times. This in turn leads to the difficulties in dealing with how to prioritize high probability/lower damage *versus* low probability/high damage events. However, a serious associated problem is that historical records may not be adequate to gain a proper understanding of what can be expected over a given time period, let alone potential extreme events. This may lead to the case where more familiar events (e.g., hurricanes) are accommodated, while rarer ones (e.g., earthquakes) are neglected, as was the case for older buildings in Kobe, Japan, whose heavy roofs were suitable for seasonal typhoons, but not for less-frequent earthquakes [Otani 1999].

As mentioned above, individual hazards and risks are generally treated separately, leading to the possibility of underestimating the total risk an area may be threatened by. Hence, there is the need to be able to combine the risk estimates associated with each hazard, while presenting uncertainties in a meaningful manner. This capacity is essential in that it allows an understanding of the relative importance of different hazards and risks in order to assist decision makers in their prioritizing of mitigation activities, especially given the frequent lack of resources available. Associated with these issues is the need for a robust understanding of

the associated uncertainties themselves, not only their actual magnitudes, but their nature when one considers them as being either aleatory, i.e., inherent in the system under consideration, or epistemic, i.e., related to our lack of knowledge about the processes involved.

In this paper, we propose a framework that allows the estimation of the total risk arising from multiple independent hazards affecting an area that also allows for risk comparability, while considering uncertainties. It is worth noting that the approach presented in this work does not take into account hazard and risk interactions, which would require a much more in-depth multi-risk analyses [see e.g., Garcia-Aristizabal et al. 2015, Liu et al. 2015]. We generally consider risk in the form of loss estimates from damaged/destroyed residential buildings over annual time scales and urban spatial scales, expressed as expected loss *per annum* (in Euros) *versus* probability of exceedance. The test case is the city of Cologne, the fourth-largest city in Germany (1,036 million inhabitants, 2011; Statistisches Jahrbuch [2012]) and a major industrial, financial, and cultural center. It is also an important transport hub, including one of the largest inland ports in Europe and a critical segment in east-west transport across Europe. Although the level of natural hazard risk in Cologne is relatively low compared to many parts of the world, it is still under threat from three major hazard types: earthquakes, windstorms and floods, which are the most important hazards in Germany [Grünthal et al. 2006, Kreibich et al. 2014]. There is also the potential for interactions at various levels of the risk assessment chain, in particular, earthquakes affecting flood defenses and hence increasing flood risk [Fleming et al. 2014].

Cologne has been a test case for a number of research programs dealing with hazard and risk (e.g., DFNK - German Research Network Natural Disasters, MATRIX - New Multi-Hazard and Multi-RISK Assessment MethodS for Europe, SENSUM - Framework to integrate Space-based and in-situ SENSing for dynamic vUlnerability and recovery Monitoring). Specifically, the work presented here is part of the MATRIX project, which focused on multi-type hazard and risk assessment, including interactions at all levels of the disaster risk chain [e.g., Garcia-Aristizabal et al. 2013] and different forms of loss, i.e., direct *versus* indirect, and tangible *versus* intangible losses, as well as issues related to personal and institutional biases in decision-making within multi-risk environments. However, it by no means ignored the importance of single-type risk assessment and the issues just discussed [Parolai et al. 2014].

In the following section we present a method for combining risk estimates leading to the harmonized comparison of natural hazard risk curves. Such results

may be presented using the so-called risk matrix, a table where one dimension represents frequency, probability, etc. of an event, while the other dimension categorizes the event’s consequences, impact, etc. [e.g., Cook 2008, Cox 2008]. Risk matrices are a commonly used form for quantitative and qualitative representation of risks (e.g., the German Federal Office of Civil Protection and Disaster Assistance; BBK [2011]) and were included in the European Commission’s guidelines for risk mapping [EC 2010]. This is followed by a discussion that describes the use of the Mann-Whitney test (also known as Wilcoxon-Mann-Whitney, or U-test; Barlow [1989]). The Mann-Whitney test is a non-parametric test of the null hypothesis that two samples come from the same population (in our case, the samples are from different sources of loss estimates) against an alternative hypothesis that one population tends to have larger values than the other. We employ it to compare the range of risk estimates from different hazards for specific return periods; these ranges in risk estimates arise when considering uncertainties in the input parameters and models. We conclude with a discussion of the steps still required and the consequences such efforts may have on DRR decision making.

**2. Combining single-type risks**

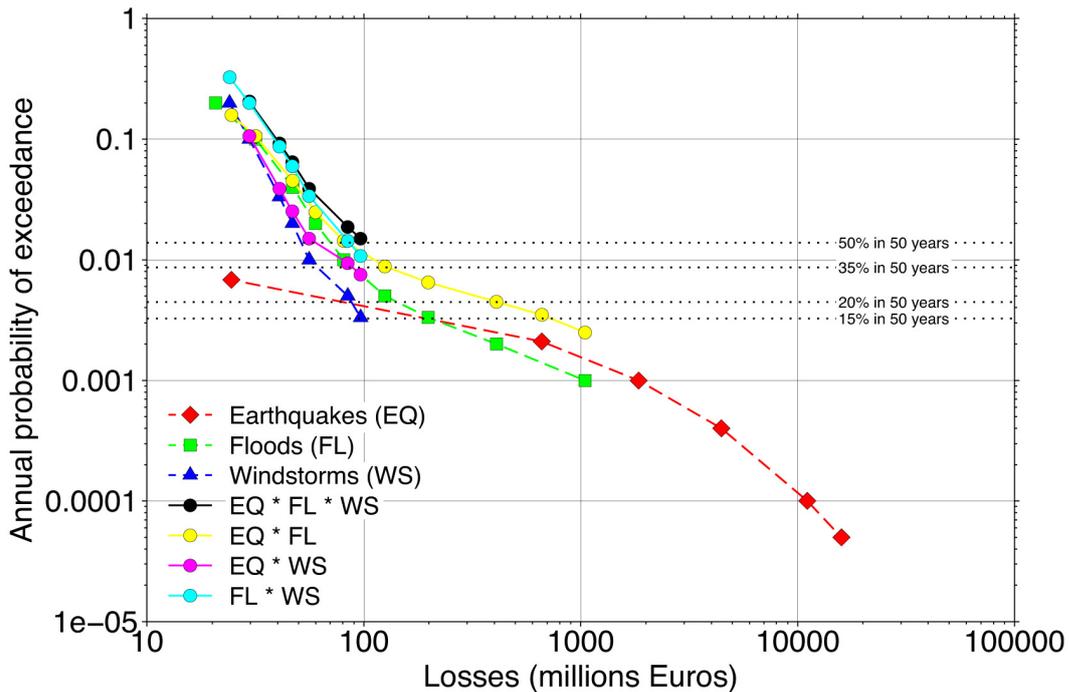
Decision makers often have to deal with the effects of more than one type of risk. For this reason, providing them with information about the likelihood of a given loss value independent of its cause may be an im-

portant piece of data for planning purposes. Therefore, considering the results of independent, non-interacting single-type risk assessments, we are interested in calculating a “total risk” curve relating the exceedance probability of a given loss value, independent of the risk source (or sources) causing it. If  $P_i(L_j)$  is the probability of exceedance of the  $j^{th}$  loss *per annum* ( $L_j$ ) for the  $i^{th}$  risk source (e.g., earthquakes, floods, landslides, etc.), then the total annual exceedance probability curve can be calculated as:

$$P(L_j)_{tot} = 1 - \prod (1 - P_i(L_j)) \tag{1}$$

which is valid for  $i$  independent single-type risk sources (i.e., neglecting possible risk interactions). We apply this approach to the risk curves obtained by Grünthal et al. [2006], which represent the annual probability of the exceedance of direct loss for each of the three hazards mentioned in the introduction. The exposed elements considered are buildings and contents in the sectors of private housing, commerce and industry, relative to the year 2000. The curves were shown only for the most probable estimates, meaning that uncertainties were not taken into account in the risk comparisons, nor the potential interactions between the different hazards, e.g., the flood estimates do not consider the failure of river dikes.

Figure 1 shows the three risk curves of Grünthal et al. [2006] for earthquakes, floods and windstorms, along with each of the possible combinations among them



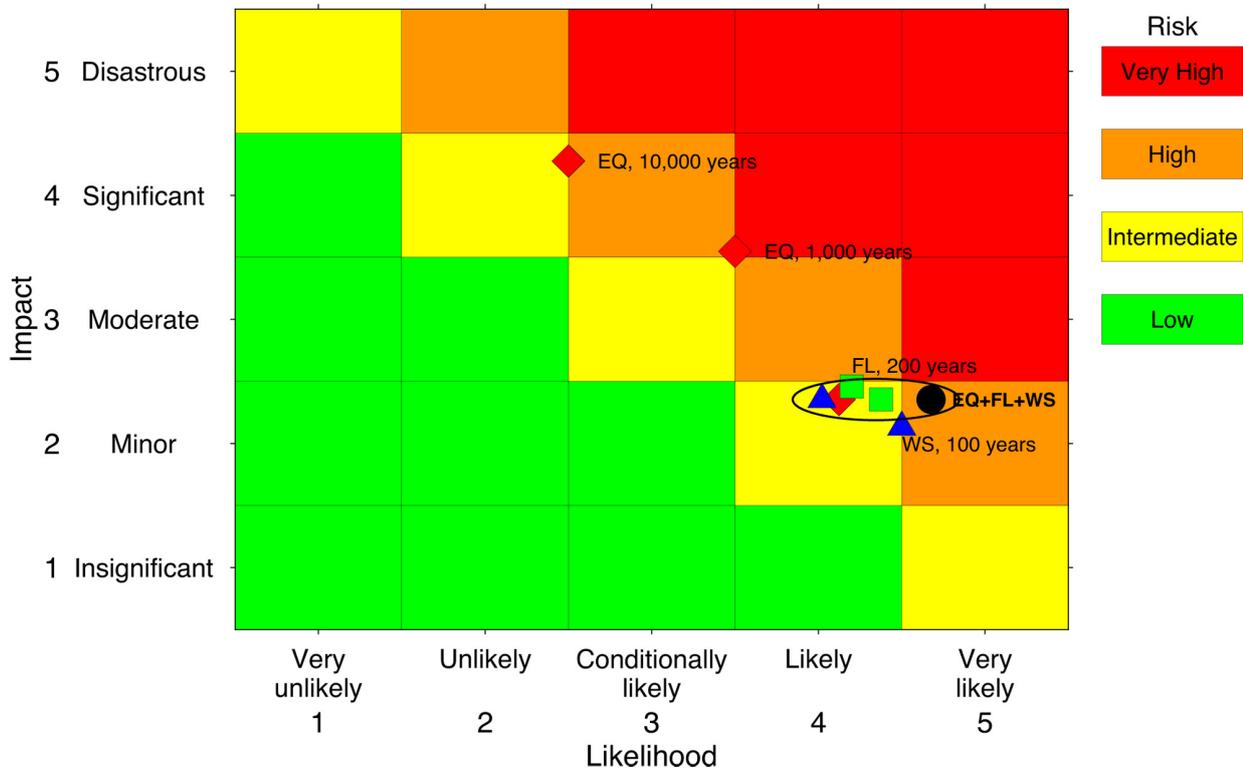
**Figure 1.** The individual risk curves for the three main hazards (earthquakes - EQ, floods - FL, windstorms - WS) that affect Cologne, as presented by Grünthal et al. [2006], and their various combinations derived using Equation (1).

according to Equation (1). Note the original values from Grünthal et al. [2006] were losses found for a series of probabilities. We took these and, from the loss estimates themselves, interpolated where necessary in order to find the resulting probability for all three hazards together exceeding a given loss. It is notable, although expected, that for the loss-range over which all hazards have results, the resulting combination of the three curves differs little from combining only floods and windstorms, which are the dominant risks for higher probability/low loss events. However, if, for example, we consider all risk-types for the cases of losses of the order of €100 million and combine them, the resulting curve indicates a greatly enhanced probability, from 15 to 35% in 50 years for the individual hazards, to over 50% in 50 years when combined, all the more important when one considers that potential interactions are still not considered.

Now we present such changes in risk by means of a risk matrix. Figure 2 shows an example of a risk matrix for Cologne using some of the estimates arising from the three hazards discussed in Figure 1. The ranges of Impacts (here economic losses, but such a format can be used for other forms of losses such as casualties) and Likelihoods (annual probabilities of exceedance)

have been divided into five categories over a logarithmic scale. For the likelihood, we employed the ranges presented in BBK [2011] and shown in Table 1, where the probabilities range from  $\leq 0.1$ /year for the upper range of very likely to  $\leq 0.00001$ /year for the upper limit of very unlikely. For the Impact, we adopted a similar form, with Insignificant having a lower bound of  $\geq \text{€}1$  million and Disastrous being  $\geq \text{€}10$  billion (see Figure 1 of BBK [2011]). It should be pointed out, however, that we use these bounding values for only illustrative reasons and that different limits may be set based on more extensive expert judgment. Similarly, we use the same color ranking of risk (expressed as Likelihood x Impact) as presented in BBK [2011], although we have modified slightly the actual distribution of the colors, recognizing, however, that according to some authors [e.g., Cox 2008], the color distribution itself should be modified (again, this exercise is for illustrative purposes). For this case, considering earthquakes, it is easily recognizable how the impact is *Significant* for events with recurrence periods of 10,000, bordering between *Significant* and *Moderate* for 1,000 years, and *Minor* for those with return periods of the order of 100's years.

To show how the situation changes when we consider the combining of risk estimates, we present in



**Figure 2.** Risk matrix (exploiting the values presented in Figure 1) showing how combining the risk associated with individual perils (EQ - earthquake, FL - flood, WS - windstorm) can lead to a significantly higher probability of exceeding a given level of loss (EQ+FL+WS). The individual and combined risk estimates outlined by the ellipse correspond to the annual exceedance of losses of  $\approx 100$  million, hence why they are all along the same Impact row. The ranges for the different classifications are presented in Table 1. The color scheme is derived from that used by BBK [2011].

| Value | Likelihood classification | Annual probability | Expected return period | Impact classification | Lower value ( $\times 10^6$ euros) |
|-------|---------------------------|--------------------|------------------------|-----------------------|------------------------------------|
| 5     | Very likely               | $\leq 0.1$         | 10                     | Disastrous            | 10,000                             |
| 4     | Likely                    | $\leq 0.01$        | 100                    | Significant           | 1,000                              |
| 3     | Conditionally likely      | $\leq 0.001$       | 1,000                  | Moderate              | 100                                |
| 2     | Unlikely                  | $\leq 0.0001$      | 10,000                 | Minor                 | 10                                 |
| 1     | Very unlikely             | $\leq 0.00001$     | 100,000                | Insignificant         | 1                                  |

**Table 1.** The bounding limits for the risk matrix presented in Figure 2 (for the likelihood, see Table 3 in BBK [2011], for the terms of likelihood and impact, see Figure 1, BBK [2011]).

Figure 2 the combination of the three risks probabilities that give an approximate loss of €100 million/annum. These examples are outlined by the ellipse, where the result of combining the windstorm (triangle), earthquake (diamond) and flood (square) is shown by the circle. As we are looking at the likelihood of occurrence here, all values have the same Impact, i.e., aligned along the same Y-axis value, hence they only vary in their location along the Likelihood or X-axis. It can be seen how the total risk has moved towards the right from “Likely” to “Very likely”. One therefore can see how this form of presentation allows changes in risk to be identified, at a qualitative level, when considering different factors. In other words, it allows a ready means of presenting how the consideration (or otherwise) of different hazard combinations, as well as their interactions, may be seen and understood [e.g., Mignan et al. 2014]. One can also imagine how, based on expert opinion, the relative distribution of the risk color scheme and boundaries between the Impact and Likelihood classifications may be altered to better reflect the case at hand.

### 3. Prioritization of risk considering uncertainties

In this section, we make use of a series of risk estimates that take into account uncertainties for the natural hazards relevant to Cologne. For each peril, the same metric is used, that is direct damage to residential buildings, and the same total costs (which differ from those of Grünthal et al. [2006], who also considered commercial buildings and other items). The value of the exposed assets was derived by considering commercial geomarketing data provided by infas geodat [INFAS 2010]. Note that we did not use the results outlined below for the previous exercise, since for flood risk, estimates for only three return periods were available. We also note that the following are not intended to replace the previous results, but are meant to demonstrate our framework for allowing a quantitative comparison between hazard and risk types.

For the seismic risk, the estimates were obtained using a logic tree approach that considers a range of input parameters for the hazard [e.g., Grünthal et al.

2010, Crowley et al. 2011a, 2011b], exposure, vulnerability [e.g., Tyagunov et al. 2006, INFAS 2010, Wieland et al. 2012] and loss components (e.g., EMS-98; Hwang et al. [1994]), representing different models and sources of information (see for details Tyagunov et al. [2014]). In the end we obtained a family of 180 seismic risk curves, representing the risk in terms of probable monetary losses ranging from millions to billions of euros. What is important to note is that the calculated risk estimates show considerable uncertainties. The observed large spread can be explained by our assigning of equal weights to the different (both the regional and adapted) models used in the risk calculations. Furthermore, comparing the uncertainty distribution for different return periods, one can observe the bimodal shape of the distribution, which is due to the fact that some of the used models neglected the contribution of small earthquake magnitudes. That is why the bimodality is especially distinct at lower hazard levels/shorter return periods, while for larger earthquakes/longer return periods the models give closer risk estimates and therefore the spread appears to lessen.

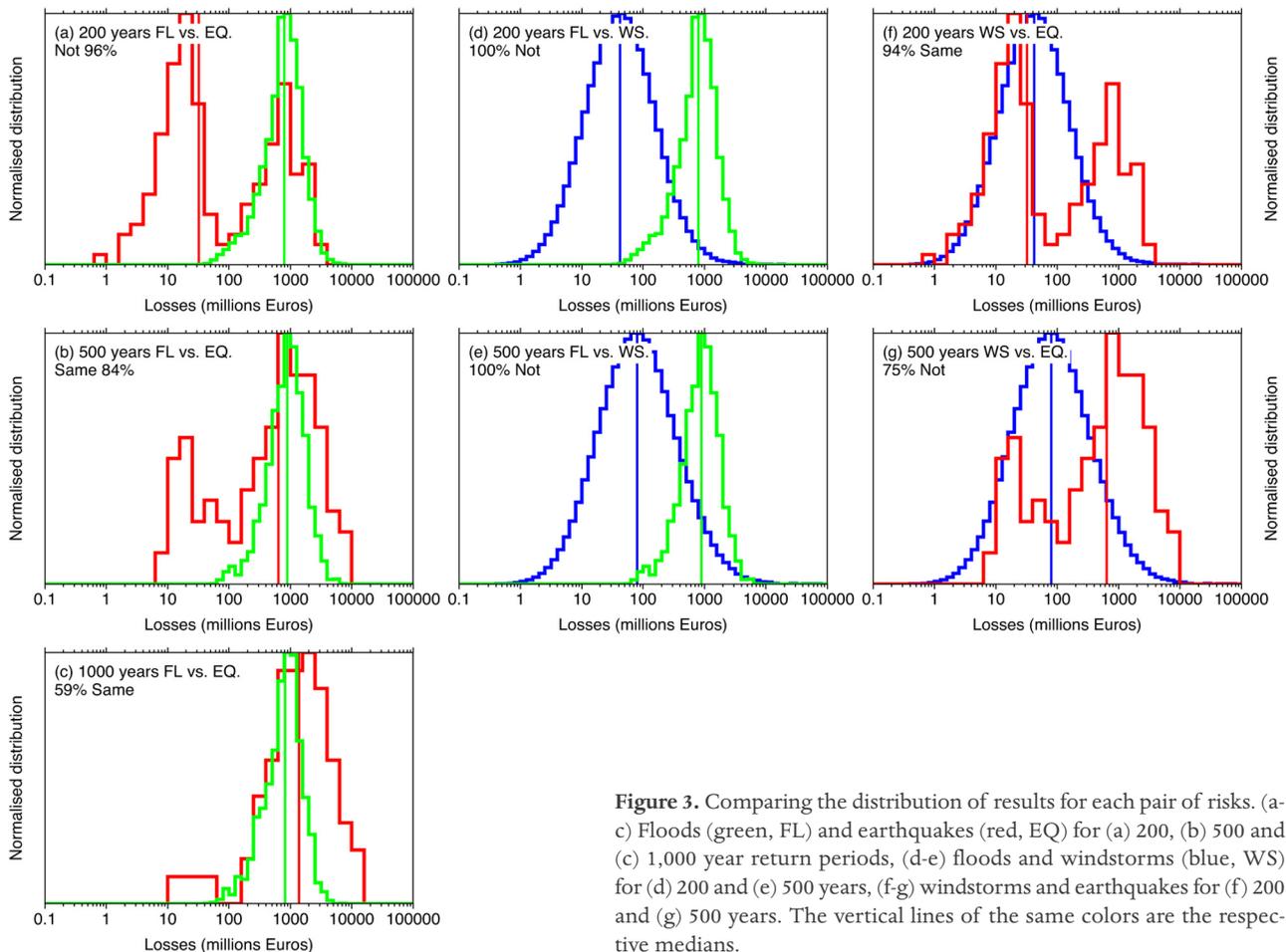
The flood risk was derived using a coupled hybrid probabilistic-deterministic dike breach-hydrodynamic model IHAM [Vorogushyn et al. 2010]. The model was setup for the Rhine reach between river gauges Andernach and Düsseldorf, including a total of 123 river kilometers with the target area of Cologne located in the middle of the reach. The IHAM model was run in a Monte Carlo simulation for scenarios with return periods of 200, 500 and 1,000 years, resulting in a set of about 1,000 inundation patterns for each return period. Based on these inundation scenarios, economic damages to residential buildings were estimated using seven flood damage models to reflect the uncertainty associated with different damage model structures. These are four stage-damage curves [MURL 2000, HYDROTEC 2001, 2002, ICPR 2001, Merz et al. 2013], multi-parameter flood loss estimation models (FLEMOPs, Thieken et al. [2008]; FLEMOPs+r, Elmer et al. [2010]) and the decision tree-based model RT2 [Merz et al. 2013]. Besides the damage model structure uncertainty, uncertainty

associated with flood hydrograph and dike breach processes was also taken into account.

The windstorm risk estimates employed the Vienna Enhanced Resolution Analysis or VERA tool [Steinacker et al. 2006]. The VERA analysis provided gridded data of the 10 minutes mean wind for the area of Cologne for a time period of 35 years (1971 to 2005). To estimate statistical uncertainty, a scheme was used that includes Monte Carlo simulation methods. As a result, a number of hazard and risk curves were produced (some 9,000,000 in this case), allowing a range in the overall uncertainty to be derived. The building damage estimation method of Heneka and Ruck [2008] was employed, where the monetary damage to buildings is proportional to gust wind speed, and the amount of damage is a function of the relative wind (i.e., the ratio of maximum wind gust speed during the event and the wind gust speed of a 50 year return period event). The losses are based on the reconstruction costs of residential buildings using the disaggregated data developed for the flood risk and the same totals as in the other hazards (see also Heneka and Hofherr [2011]).

The objective of this comparative risk assessment is to assess if the losses arising from two independent typologies of hazards for a specific return period are

significantly different. For this, we use the distribution-free ranking Mann-Whitney test mentioned above [e.g., Barlow 1989]. This involves testing a null hypothesis asserting that two variables have the same probability distribution against an alternative hypothesis that one population tends to have larger values than the other [e.g., Hollander and Wolfe 1999]. This test has been used in a variety of hazard and risk related studies, for example, temporal changes in wildfires [Salis et al. 2014] and inter-regional comparisons with respect to meteorological hazards [Bommer and Senkbeil 2010]. Since in our cases the population distributions might not be normal for the different hazard types, we decided to repeat the test 10,000 times by resampling randomly each population (the number of tests was found by trial and error, in fact, the results differ little if only 1,000 tests were used). This is to reduce the consequence of situations where the random selections of samples are clustered in some way. The results are analyzed in term of the frequency of rejecting the null-hypothesis. We consider each pair of hazards (earthquake - flood, earthquake - windstorm, flood - windstorm) for the return periods 200, 500 and 1,000 years when comparing earthquakes and floods, and 200 and 500 years for floods and windstorms, and windstorms and earthquakes (Figure 3).



**Figure 3.** Comparing the distribution of results for each pair of risks. (a-c) Floods (green, FL) and earthquakes (red, EQ) for (a) 200, (b) 500 and (c) 1,000 year return periods, (d-e) floods and windstorms (blue, WS) for (d) 200 and (e) 500 years, (f-g) windstorms and earthquakes for (f) 200 and (g) 500 years. The vertical lines of the same colors are the respective medians.

Considering first the earthquake loss distribution, we immediately note its tendency to have a bimodal character, especially for shorter return periods (see above and Tyagunov et al. [2014]). This is an example of how an unreliable comparison may arise if we simply considered the resulting medians or averages of two distributions of risks. This is the added value of propagating uncertainties arising in the risk assessment process up to the resulting risk curve, as done in this work. To objectively compare risk curves obtained for different phenomena taking into account uncertainties, we confront the variability of these risk curves at different return periods (Figure 3). In practice, we extract “slices” at different return periods and compare the resulting distributions in order to define if they are significantly different or not. From the results of the Mann-Whitney test comparing earthquake and flood loss distributions at different return periods, we observe that for the 200 year return period (Figure 3a), the null-hypothesis is rejected, i.e., the two distributions are different. For the 500 and 1,000 years return periods (Figure 3b and 3c, respectively), the null-hypothesis cannot be rejected and therefore these distributions can be considered to be comparable. These results indicate that when considering loss levels expected with a 200 return period, the losses tend to be higher for floods with respect to earthquakes; conversely, for longer return periods (i.e., 500 and 1,000 years), the losses from earthquakes and floods in this area are of the same order of magnitude. On the other hand, comparing the losses caused by windstorms and floods for both the 200 (Figure 3d) and 500 (Figure 3e) years return periods, the distributions can be considered as being significantly different, with floods of greater concern in both cases. Finally, comparing losses caused by earthquakes and windstorms (Figure 3f-g), these appear for the 200 year return period (Figure 3f) to be comparable, while for 500 years (Figure 3g), this does not appear to be the case (with higher losses expected from earthquakes).

#### 4. Conclusions

A simple method for combining different independent single-risk curves to derive a total exceedance probability loss curve, along with a means of graphically showing how total risk changes as one combines the individual components (namely the risk matrix) is demonstrated for the case of Cologne. As other authors have demonstrated [e.g., Komendantova et al. 2014, Mignan et al. 2014], risk matrices are also useful in showing how total risk varies when interactions are considered, providing a bridge between the qualitative analysis commonly used by the DRR practitioners and the quantitative assessment provided by the scientific

community. However, some authors have expressed reservations as to the accuracy of the value of such schemes as risk matrices [e.g., Cox 2008] and so care must be made when employing this method of presentation of results.

A means of assessing the significance in the differences (or similarities) between pairs of risk types when considering a range of plausible values for a given return period was examined. In a rigorous quantitative context, the approach considers the uncertainties taken into account in the assessment of the single risks. Such an exercise may be of benefit to the decision making process, whereby if the risks associated with two types of hazard are statistically significantly comparable (i.e., they have a similar likelihood of inflicting the same amount of damage), then the required risk management schemes may need to consider both of them for cost/benefit analyses, or at least help decision makers when deciding on how to allocate resources. For example, while the losses for two different hazards may be of the same order of magnitude for a given return period, it is possible that implementing mitigation actions for one may be much more expensive than for the other.

It also shows that one needs to accommodate uncertainties, since as commented above (and suggested by the earthquake risk results' distribution) simply using, for example, average curves, may yield misleading conclusions about the relative importance of a given combination of hazard types. However, it is also important to note that the actual results for the test case would vary as the range of employed input models and parameters are updated (i.e., the epistemic uncertainty is refined as our knowledge improves). There is also the point that the extent of the uncertainties may (or rather should) influence decision making, as a wide uncertainty range may suggest both serious and negligible consequences. Still, the presented approach potentially allows the combination and comparison of updated risk estimates in an effective way using the proposed framework.

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