Project number: 265138
Project name: New methodologies for multi-hazard and multi-risk assessment methods for Europe
Project acronym: MATRIX
Theme: ENV.2010.6.1.3.4
Multi-risk evaluation and mitigation strategies

Start date: 01.10.2010 **End date:** 31.12.2013 (39 months)

Deliverable: D.2.3 – Harmonisation strategy: Report on the strategy for optimal harmonization of single-type risk assessment methodologies for achieving risk comparability.
Version: FINAL-V1
Responsible partner: GFZ
Month due: M38 **Month delivered:** M43

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04.2014

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Dissemination Level		
PU	Public	
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	X
CO	Confidential, only for members of the consortium (including the Commission Services)	

Abstract

As the various hazards and their associated risks that are relevant to Europe have their influence over different spatial and temporal scales, while also physically affecting the human environment differently, it is difficult to make meaningful comparisons between them. The aim of this deliverable is therefore to begin this progress, where the hazards and risks being dealt with by MATRIX, while determined individually without the consideration of interactions, are treated in a harmonised fashion to allow their comparability.

Employing earlier results from the Cologne test case, we combined three risk curves representing annual losses from earthquakes, landslides and earthquakes as presented by Grünthal et al. (2006). We note that such a simple operation (while neglecting the potential interactions between them) is still able to show how only considering the individual risks leads to an underestimation of the total. There are in turn different ways how such results may be presented, for example, risk curves present a picture of the risk situation for a given metric with respect to their probability and potential loss. However, risk matrices (preferred by end-users and stakeholders) allow one to better gauge how a combination of risks leads to a more serious situation by plotting a scenario's movement within a framework outlining "severity" and "frequency".

Comparing the distribution of results (based on ranges of input parameters and models) allows one, for a given return period, to ascertain if a pair of hazard estimates are equivalent. This provides additional information to an end-user/decision maker in that it may assist in establishing guidelines as to how to allocate one's resources.

Finally, there is a need to be aware that only economic losses (as done in this work) are inadequate for a complete loss picture. Likewise, other metrics, such as the proportion of the population with "no shelter" may in fact offer more to responders to disasters. In addition, it must be recognised that natural temporal variability in risk, as seen in the wildfire results for Portugal, contributes to one's uncertainty range and also needs to be acknowledged when comparing risk estimates.

Keywords: Single risk, harmonization

Acknowledgments

The research leading to these results has received funding from the European Commission’s Seventh Framework Programme [FP7/2007-2013] under grant agreement n° 265138 “New Multi-HAzard and MulTi-RIsK Assessment MethodS for Europe” (MATRIX).

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1. Introduction

Although the MATRIX project often speaks about hazard and risk interactions and how the sum of the parts is not necessarily representative of the whole, this by no means excludes the importance of single-type assessments. It is also a fact that the transition from single- to multi-risk assessment represents a process which, in terms of complexity and data requirements, is not negligibly increased (Figure 1a). This transition implies a shift from a "hazard-centred" perspective that characterizes the single-risk assessment, to a "territorial-centred" one. In fact, from a multi-risk perspective, the first element to be defined is the target area of interest, which is in general terms the piece of territory composed of elements at risk that are vulnerable in different ways to various sources of hazards (Carpignano et al., 2009).

The evolution from single-risk to multi-risk analysis consists of three different and complementary elements (Garcia-Aristizabal et al. 2014; Gasparini and Garcia-Aristizabal, submitted): the single-risk assessment (SR); the multi-hazard risk assessment (MHR), and the multi-risk assessment (MR).

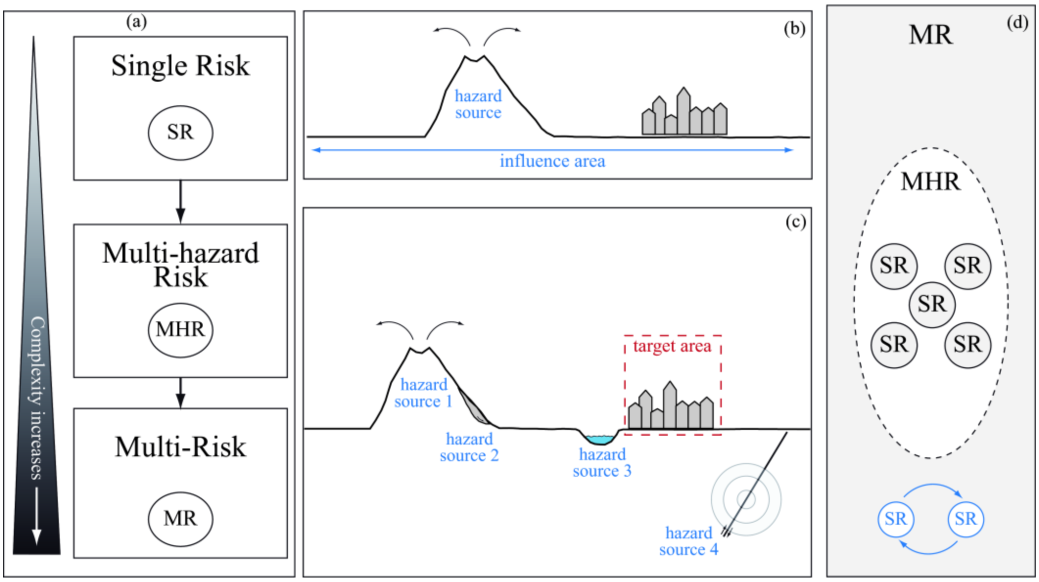

Figure 1: Representation of the transition from the single- to the multi-risk assessment (from Gasparini and Garcia-Aristizabal, submitted).

Error! Reference source not found. represents the transition from the SR to the MR assessment (Figure 1a). The hazard-centred perspective of the SR is represented in **Error! Reference source not found.**b; in this case, the first element of the analysis is generally the hazard source identification and the subsequent definition of the impact area and the assessment of the potential effects. The change towards a territorial perspective is represented in **Error! Reference source**

not found.c. In the MHR, different independent hazard sources affecting a given common area of interest are considered; in this case, the first element of the analysis is the definition of the piece of territory which is the target area for the analysis. The target area must contain the elements at risk that are exposed to adverse events, and are the elements of interest for the loss assessment. Note that this change in perspective is common to both MHR and MR assessments. Once the target area has been identified, the next element of the analysis is the identification of the potential hazard sources that may cause harm to the set of exposed elements in the target area.

Error! Reference source not found.d illustrates how each element in this transition is a subset in the higher levels of the sequence. In fact, a set of SR analyses compose a MHR analysis, and when the MHR assessment is complemented with the analysis of interactions among events, then the MR level is reached. This sequence is, of course, valid if the SR and MHR analyses are done coherently within a multi-risk framework, following some basic (but often not simple) elements of harmonization.

Therefore, a full multi-risk analysis combines both the assessment of different independent risks threatening the same exposed elements (MHR), and the possible interactions produced in potential cascades of events (MR). It implies that all risk need to be harmonized for comparison, and for this reason an issue at mind throughout the MATRIX project is how different types of risk can be meaningfully compared. For example, considering the case of Germany, while 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 Euros) compared to the floods of 2002 (11.6 billion Euros) which caused the deaths of 27 people[1]. It is therefore essential to have some means of comparing the relative importance of different disasters in order to assist decision makers in their prioritizing of mitigation activities, to allow different risks to be summed in order to know the total losses that may be expected over a given period of time, and to be able to present with them, in a useful manner, the accompanying uncertainties.

Resolving this issue is the role of Work package 2 “Single-type risk assessment and comparability”. As the name suggests, this work package is concerned with developing the means by which the different types of independent risk arising from each hazard can be consistently compared and combined to gain a total risk estimate, along with realistic uncertainties that are communicable to end-users and stakeholders. Therefore, the work here concentrates on MHR assessments, whereas interactions and full MR assessments are the scope of the other work packages of MATRIX (namely WP3 and WP5). The first part of WP2 involved identifying the state

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[1] http://www.preventionweb.net/english/countries/statistics/?cid=66

of the art in single-type risk analysis, the results of which are presented in deliverable D2.1 “Single-type risk analysis procedures”. As part of this, for the sake of this project, we defined the risk metric of interest to be (generally) direct losses of residential buildings over annual time and urban spatial scales (as was followed in Work package 7 “’Virtual City’ and test cases”), while recognising that this is simply a first step and that other direct, as well as indirect and less tangible losses, will need to be considered in a truly comprehensive assessment. This point will be raised again later. The second task was concerned with how the uncertainties associated with risk estimates may be identified and presented, which involved defining their different components which we broadly divided between aleatory and epistemic classes of uncertainty. These results were presented in deliverable D2.2 “Uncertainty quantification”.

Finally, this deliverable, D2.3 “Harmonisation strategy”, intends to call upon the results of both of these tasks, and to present means of:

- Combining single-risk estimates to obtain the total risk (without, in these cases, considering the various interactions between hazards and risk).
- Identifying how uncertainties (and their sum) may be applied by, and presented in a meaningful manner to, end-users and stakeholders.

These activities therefore fall under the general heading of “risk harmonisation”. It should be stated that natural hazard and risk research is by no means alone in the problem of harmonisation. Similar concerns have been raised, for example, by Rogelj et al. (2013), who commented that estimating the costs of achieving the goal of limiting global warming to less than 2°C is particularly challenging when considering well known, but poorly quantified, uncertainties and the lack of integration across scientific disciplines.

The following section defines the spatial and temporal scales and metrics of interest to this work. Then, a strategy for combining risk curves to produce a ‘total risk’ curve is presented and applied to the MATRIX test case in Cologne, Germany (see deliverable D7.5 “Cologne test case”). Next, a procedure to compare different risk estimates (and their ranges) and to define those that are different/equivalent is presented and applied again to Cologne. Finally, we consider some other issues related to harmonization and metrics, considering the French West Indies (see deliverable D7.4 “French West Indies test case”) and wildfires in Portugal (see deliverable D4.4 “Social and Economic Vulnerability”). The work presented in this deliverable therefore provides methods for combining and comparing independent risks, which is one of the fundamental elements before proceeding to considering interactions in holistic multi-risk assessments.

2. Temporal/spatial scale definition and metrics

One of the problems when dealing with the comparison and harmonization of risk concerns the spatial and/or temporal scales being dealt with, which in turn are functions of the hazard of concern. Considering spatial scales, different hazards have their own spatial pattern, for example, direct losses from floods are only of a concern to lower-lying areas close to water bodies, and so direct flood losses may be rather localised. By contrast, a major earthquake will affect a much wider area, although again, depending upon geological conditions, the spatial variability in the resulting ground shaking may be significant.

Likewise, considering temporal scales, certain hazards have a degree of regularity, for example, seasonal winter storms, wildfires or hurricanes, while others such as earthquakes and volcanoes need to be considered over much longer periods of time. The problem, however, is that the available time series may not be adequate to gain a proper understanding of what should be expected over a given period, let alone potential extreme events. This may lead to the problem where more familiar events (e.g., hurricanes) are considered, while rarer examples (e.g., earthquakes) are less well accommodated (e.g., the case of older buildings in Kobe, Japan, whose heavy roofs were suitable for seasonal typhoons, but not for infrequent earthquakes, Otani, 1999). Considering the example of Cairns, Australia, the risk associated with a 150 year return period cyclone is much greater than the same return period earthquake, although the maximum feasible earthquake is potentially more damaging than the maximum possible cyclone (Granger, 1999).

Therefore, as stated in the introduction, in this work we have defined the risk metric of interest to be direct losses associated with damage to residential buildings over annual time and urban spatial scales. Our results will usually be expressed in the form of loss per annum versus exceedance probability; however, the use of the risk matrix will also be discussed. Moreover, we will return to this point by discussing the test case of the French West Indies, and the hazard and associated risk of wildfires in Portugal.

3. Combining and comparing risk curves

3.1 Combing single-risk curves

Our objective here is to present a methodology to determine the “total risk” from different independent single risks affecting a common area (i.e., the result of a MHR assessment). This issue is important because when assessing and managing risks over their territory of responsibility, decision-makers rarely have to deal with only one source of risk and therefore they generally are more interested in getting information on what can produce damage and how often it may happen in the area, regardless of the source.

We assume that risk assessments considering *i* independent risk sources threatening a common area have produced *i* independent risk curves. Generally, risk curves represent losses per time unit versus exceedance probabilities. We are interested in quantifying the probability that a given loss value is exceeded, regardless of the risk source exceeding that loss value. This operation can be performed employing the following formulation:

$$P_{tot} = 1 - \prod (1 - P_i) \qquad (1)$$

where P_{tot} is the total annual probability of exceedance of a given risk (expressed as Euros), and P_i is the probability of the exceedance of risk *i* (i.e., here, earthquakes, landslides and floods).

As a demonstrator of the proposed methodology, we use the risk curves derived for Cologne by Grünthal et al. (2006) in order to gain some idea of what the total risk may potentially be. The original three risk curves of Grünthal et al. (2006) describing the situation for earthquakes, floods and windstorms are presented in Figure 2. Following the formulation presented in Eq. 1, these risk curves are combined in all possible ways (i.e., earthquake – flood, earthquake – windstorm, earthquake – flood – windstorm, etc.). Note again that this operation neglects the possible interactions between these hazards (likewise, Grünthal et al., 2006, did not present uncertainties, nor do they consider interactions). Also, because of limitations in the original results, we cannot combine these risks for the entire range of losses covered (i.e., there was insufficient information for the potential losses arising from these hazards to be assessed over the same loss/probability range).

We note that for the loss range over which all hazards have results, the resulting combination of all three curves differs little from combining only the flood and windstorm risks (these being dominant when considering higher probability/lower loss events). However, if for example we were to consider all risk-types for the cases where the losses are of the order of 100 million Euros, we see that considering these together will significantly increase the probability of such a level of loss, from 15 to 35% in 50 years for the individual hazards, to around 75% in 50 years when combined.

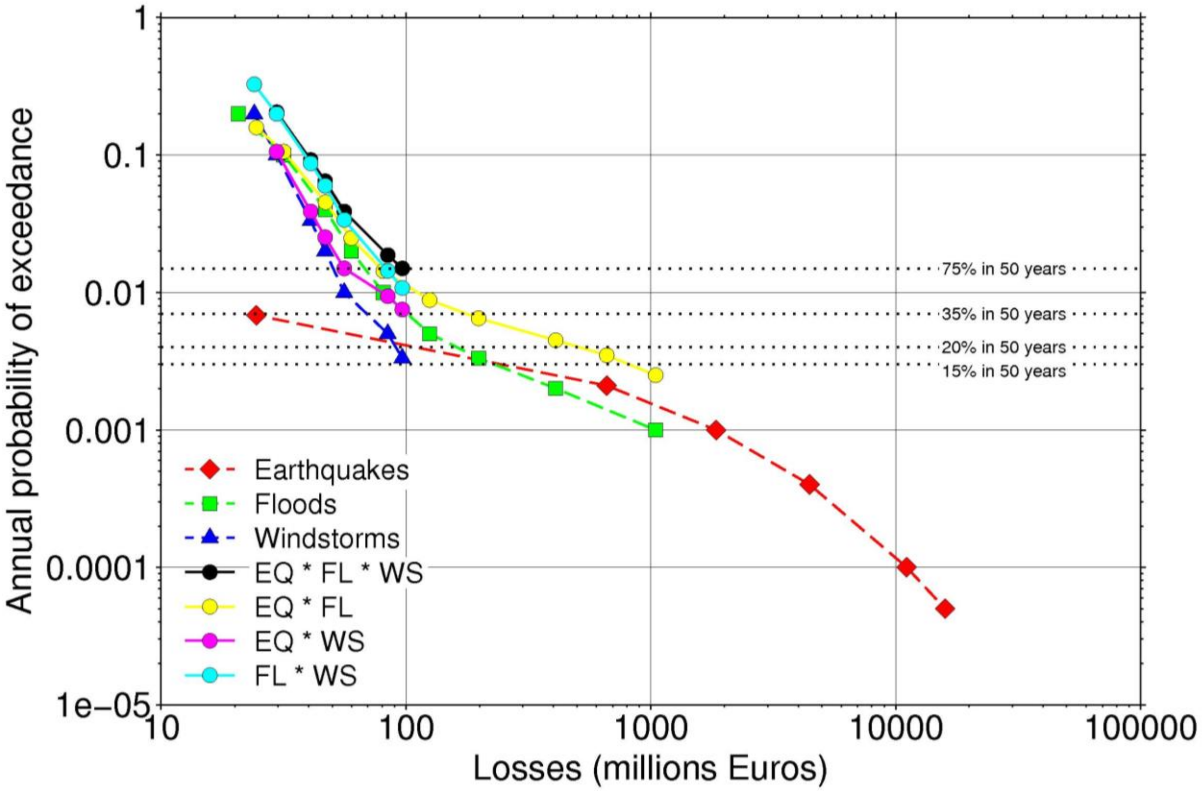

Figure 2: The individual risk curves for the three main hazards (earthquakes – EQ, floods – FL, windstorms – WS) that affect Cologne and their various combinations derived using equation 1. Note that interactions between the different hazards are not considered.

An alternate way of presenting such results (in particular how risk estimates may migrate under different assumptions) is by a risk matrix[2]. In fact, as commented upon in Komendantova et al., (2014), end-users tend to prefer such a format as opposed to the risk curves often used by researchers. Figure 3 shows an example of a risk matrix for Cologne, using some of the estimates of the risk arising from the three hazards shown in Figure 2. Note, we divided the loss and probability ranges in Figure 2 into 5 (to equate them to the way losses - severity and probability – frequency are presented in risk matrices) and the actual estimates are allocated the frequency and severity accordingly.

Included in Figure 3 is the summation of the three risk estimates that give an approximate loss of

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[2] This matrix follows approximately that employed by the German Federal Office of Civil Protection and Disaster Assistance (BBK, http://www.bbk.bund.de/). See also “Risk Mapping and Assessment Guidelines for Disaster Management”, SEC(2010), Brussels, 21.12.2010, European Commission.

100 million Euros. These examples are outlined by the ellipse in the figures, where the result of combining the windstorm (triangle), earthquake (diamond) and flood (square) is shown by the circle. One can see how the total risk has increased by its movement towards the right, in the case of this figure, moving from “Quite likely” to “Likely”. Although “obvious”, and while it must be kept in mind that this figure is only intended for illustrative purposes, one can imagine, based on expert opinion as mentioned above, how the relative distribution of the risks (i.e., the colour scheme) could be altered to better reflect the case at hand. Nonetheless, it illustrates quite well how the risk one must consider migrates when including either individual types, or their summation (and their interactions, as shown by other MATRIX results, e.g., Mignan et al., 2014).

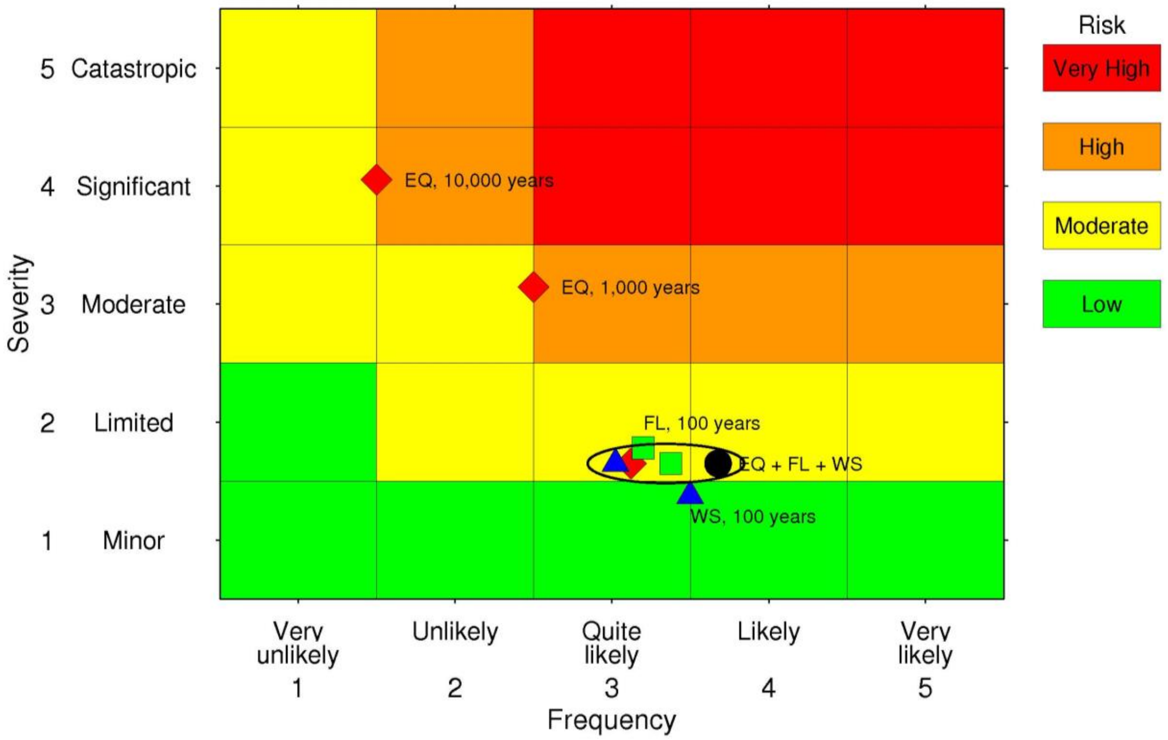

Figure 3: Risk matrix showing how combining the risk associated with individual risks (EQ – earthquake, FL – flood, WS – windstorm, see area) can lead to a significant increase in overall risk. The risk estimates discussed in the text (corresponding to losses of ca. 100 million Euros) are outlined by the ellipse.

3.2 Comparing single-risk estimates

In the following we will employ a very simple means of comparing the risks that may arise from any combination of single-type hazard. The point here is to determine if the risk associated with two given hazards for specific return periods are the same or if they are significantly different. This requires accounting for the uncertainties associated with the risks, since considering, for example, the mean values alone, may give an inaccurate picture. The relevance of this issue is to do with the decision making process, since a clear hierarchy of risks combined with the careful assessment of the cost of mitigation (cost-benefit analyses) may provide a key element to decision-makers for defining the most efficient (given the available resources) mitigation actions.

We will compare for specific return periods the range of results for each risk type newly calculated for the Cologne test case. For the seismic risk, this involved a logic tree approach that considered a range of hazard input parameters and damage and vulnerability models, resulting in 180 estimates per return period (Tyagunov et al., 2013). The flood estimates employed a hybrid probabilistic-deterministic coupled dyke breach/hydrodynamic model (IHAM, Vorogushyn et al., 2010), run in a Monte Carlo simulation. The windstorm risk was found using the Vienna Enhanced Resolution Analysis or VERA tool (Steinacker et al., 2006) and the building damage estimation method of Heneka and Ruck (2008). All three employed the same metric (direct damage, residential buildings) and total costs (see deliverable D7.5 for details).

The test used is the Wilcoxon's test, a distribution free ranking test that asks the specific question "Are the medians of the two distributions the same?" (Barlow, 1989). We compare a range of values for each pair of hazards (earthquake – flood, earthquake – windstorm, flood – windstorm) and apply a null hypothesis (to 0.05) that the question's answer is in the affirmative. The test involves taking 20 random samples from each pair of distributions, applying the Wilcoxon's test, and doing so 10000 times (note, 10000 was chosen by trial and error, with 1000 tests yielding similar results).. This is to reduce the consequence of situations where the random selections of samples are clustered in some way. The return periods we examine are 200, 500 and 1000 years for comparing earthquakes and floods, and 200 and 500 years for floods and windstorms, and windstorms and earthquakes (Figure 4).

Considering first the earthquake distribution, we see that its bimodal character (a product largely of the choice of the ground motion predictive equations, GMPE, see D7.5) immediately adds an additional element of uncertainty as to whether the risks it is compared to are equivalent. Considering the results of the Wilcoxon's test, we note for the 200 year return period (Figure 4a) that earthquakes and floods are not equivalent (in contrast to Grünthal et al., 2006, where they appear very similar), but can be considered comparable for 500 years (Figure 4b, in agreement with Grünthal et al., 2006), although for 1000 years (Figure 4c), a definitive comment cannot be made. For the windstorms and floods (Figure 3d-e), for both the 200 (Figure 4d) and 500 (Figure 4e) years return periods, it is obvious (even without applying this test) that windstorms and floods are not equivalent, with floods being of greater concern in both cases. Finally, for earthquakes and windstorms (Figure 4f-g), for 200 year return period (Figure 4f), these appear to be of equivalent importance, while for 500 years (Figure 4g), this does not appear to be the case (with earthquakes of greater importance), in both cases consistent with Grünthal et al. (2006).

One point that needs to be made here is that these results may possibly change as the range of estimates is refined (i.e., the input parameter and models are better resolved, a point especially obvious for the case of the seismic risk estimates). The second is that even if two hazards appear to be of equal importance, the required mitigating actions may differ significantly. For example, while the 200 years return period earthquakes and windstorms appear to be equivalent, mitigating against earthquake risk would be expected to be more expensive that for windstorms. Again, recalculating the seismic risk using better defined GMPE may alter this picture.

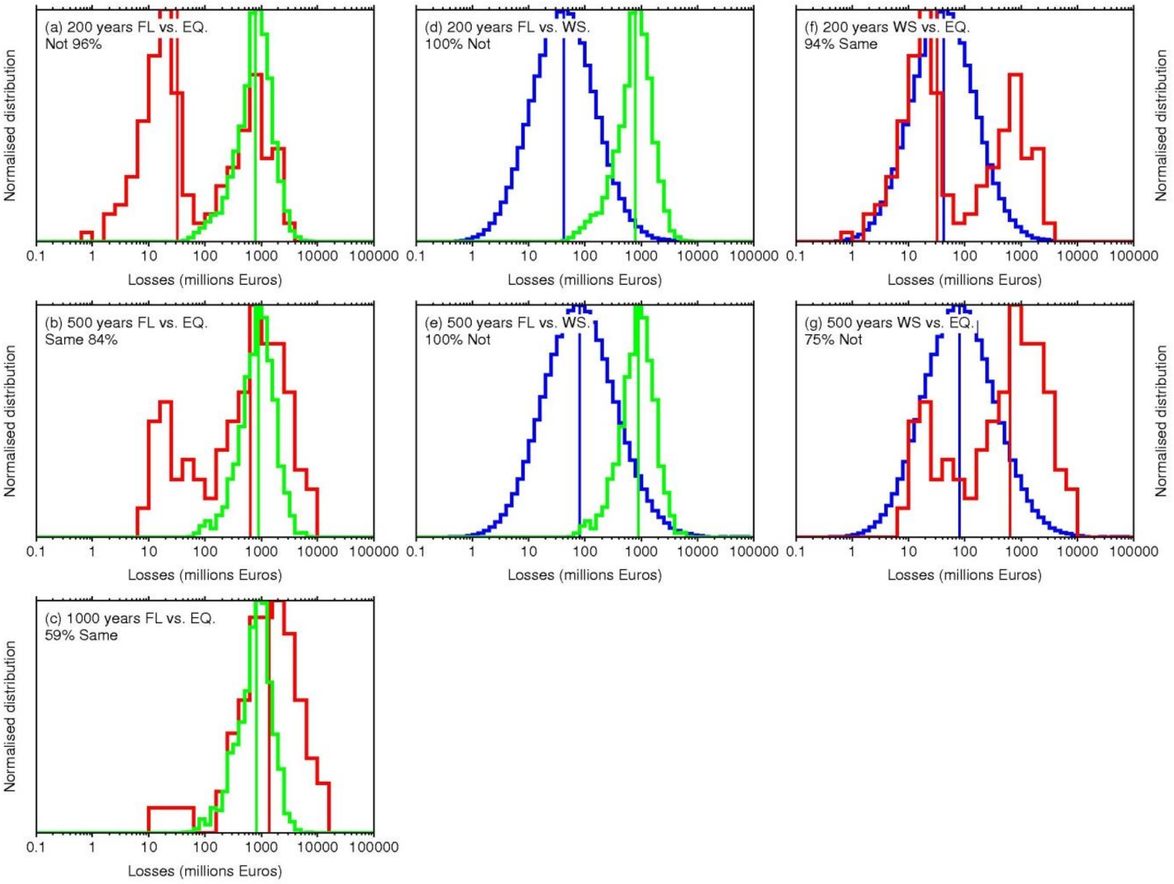

Figure 4: Comparing the distribution of results for each pair of risks. (a-c) Floods (green, FL) and earthquakes (red, EQ) for (a) 200, (b) 500 and (c) 1000 years return periods, (d-e) floods and windstorms (blue, WS) for (d) 200 and (e) 500 years, (f-g) windstorms and earthquakes for (f) 200 and (g) 500 years. The vertical lines of the same colours are the respective medians.

4. Future issues regarding harmonization and common metrics: the examples of the French West Indies and wildfires.

4.1 French West Indies

In this section we expand somewhat on the issue of harmonization and a common metric. Considering first the French West Indies case study (see deliverable D7.4 “French West Indies test case”), difficulties are found when considering the work scale, because the different levels of resolution required were heavily associated with each family of single risks. Table 1 compares the different kinds of input necessary for storm surge and seismic risk assessments. The starting point was the building typology, which was developed for seismic risk assessment (Bertil et al., 2009). This typology was adapted to criteria which are relevant in seismic vulnerability assessment, but building types in storm surge vulnerability are much simpler. On the other hand, the spatial resolution of the seismic risk building database was not enough to undertake the storm surge assessment. For storm surges, and floods in general, the microtopography and the localization of buildings are much more important than for seismic risk scenarios. Multi-vulnerability databases, with one single exposed element associated with different vulnerabilities to different hazards, seem to be an essential first step to improving multi-risk assessments, and may also be considered another step in risk harmonization. Murshed et al. (2007) did more or less the same exercise in Germany and the conclusions are quite similar, that harmonization in vulnerability and economic assessment should be an aim if the final objective is to compare single risks. This again was a factor in the Cologne study, for example, when comparing the results obtained within MATRIX with those from Grünthal et al. (2006), where in MATRIX, as mentioned only direct losses of residential buildings were considered, while in Grünthal et al. (2006), cars and commercial properties were also included. This lead to higher estimates in Grünthal et al. (2006) for more frequent events such as, for example, windstorms, where cars are more likely to be damaged.

Future developments in risk comparisons should be not only in terms of potential direct economic losses, but also in terms of potential personal losses. During the French West Indies study, considering specifically Pointe-à-Pitre, a comparison has been done in terms of “no shelter” or displaced population. The value here is that if one were, for example to consider casualties, then comparing the two hazards, earthquakes and storm surge, would be problematic, given the differences between these in terms of a population being able to be warned, and hence change its behaviour. This example shows that risk comparisons or prioritization only in terms of economic losses can underestimate risk. Viewing at the same time the risk curves that arise from considering both factors appears to be a good way to better compare single risks. Such a comparison in terms of “no shelter” would also be appropriate to other risks, such as volcanos and, as mentioned below, wildfires, and would provide a valuable source of information for disaster response managers.

In an ideal case, indicators about the vulnerability and the assets of the whole economic system should be considered in a multi-risk curve. However, given the complexity (or lack) of actual knowledge about the vulnerability of the various different exposed elements (dwellings, agriculture, fisheries, industry, commercial and public facilities, lifeline infrastructure, etc.) to the different natural hazards, this exercise would be very difficult to conduct completely. If the exercise is limited to the built environment and, more particular, to current buildings, it becomes easier. The problem, however, still remains of the variable weight of damages in current buildings over the whole economic system for different natural hazards (for example, Hurricane Dean in Martinique, where damage to agriculture and fisheries was much higher than the damage to dwellings).

Table 1: Comparison between the required input for storm surge (or floods in general) and seismic risk assessment in terms of scales, spatial resolution and data sources.

Input	Seismic	Storm surge (floods in general)
Vulnerability	Detailed building typology, as a function of structural type & age. Importance of building codes	Very simple building typology, 3 main types of structures. High importance of the number of stories.
Exposed elements location	Number of buildings per district, work at district scale. Census data	Importance of micro topography. Detailed building footprint GIS layer.
€ losses	Transformation from number of buildings per EMS98 damage state	Damage functions as a function of water height. Result directly in loss ratio. Flooded built m^2 & structural damages
Hazard	Intensity or PGA. Resolution depending on local effects map.	Water height. Necessity of high resolution DEM.

4.2 Wildfires

Wildfires could be considered as something of an outsider when considering residential building losses, since, in the Mediterranean, the probability that a household will burn is very low even in an extreme wildfire. The explanation is not only because of its own non-flammable construction materials, but also with human fire extinguishing actions from the household owners, firefighters and civil protection. Several questions about the harmonization of the methodologies were raised between wildfires and other hazards, since the temporal scale is very frequent, the elements at risk are mostly forest, shrub land and agriculture, with a very low expression in terms of burned houses and fatalities. The quantifiable losses are more related to the production of wood, other forest-derived products like cork and pines, and also to CO_2 liberation. These differences therefore suggested to us to only provide a single curve risk for wildfire losses, and not combine them to other hazards, for the time being at least.

In order to create risk curves for the wildfires annual exceedance probability in Portugal, we used the national data of burned area for the time period of 1980 – 2010 and the economic values of losses from the Portuguese National Forest Strategy (AFN, 2006 and the ICNF). The cost values were then ordered and the annual exceedance probability calculated.

To create a model for the risk curve, we carried out 10 Monte-Carlo simulations and also used a global model which was fitted first by an exponential distribution and then a Weibull distribution. The global model presented in Figure 5 was fitted with the exponential distribution, and the curves were based on the upper and lower bounds for the global model using the standard deviation with a 95% interval of confidence. The uncertainty associated with the model in fact not only refers to the statistical process, but also, as shown in Figure 6, by the differences arising between each decade. We found that the Weibull distribution has a better coefficient of determination (R-squared) not only for the global model, but also for the model for each decade, hence this was the one that we consider should be adopted.

While one could imagine combining these risk curves with similar ones related to, for example, floods and earthquakes, despite the concerns raised previously, several similarities between these considerations and those for the French West Indies may be raised. For example, like storm surges, a warning component can be considered with wildfires as human casualties are relatively rare (the tragic losses from, for example, the “Black Saturday” 20089 fires in southeastern Australia being something of an exception). Hence again, the issue of changes in human behaviour need to be considered. However, loss metrics such as “no shelter” may in this case also be useful for analysts and responders alike. In addition, the fact that some of the uncertainty can be assigned to inter-decadal variability reflects how the temporal dimension of risk estimation and the associated comparisons with other risks needs to be considered.

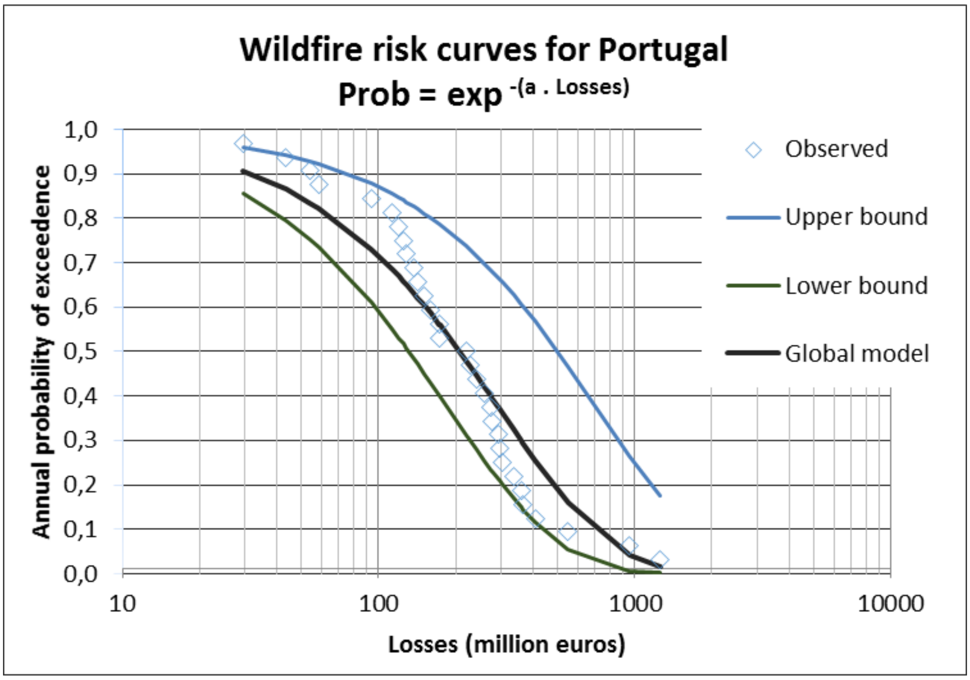

Figure 5: Upper and lower bound calculated for a confidence interval of 95% (using standard deviation).

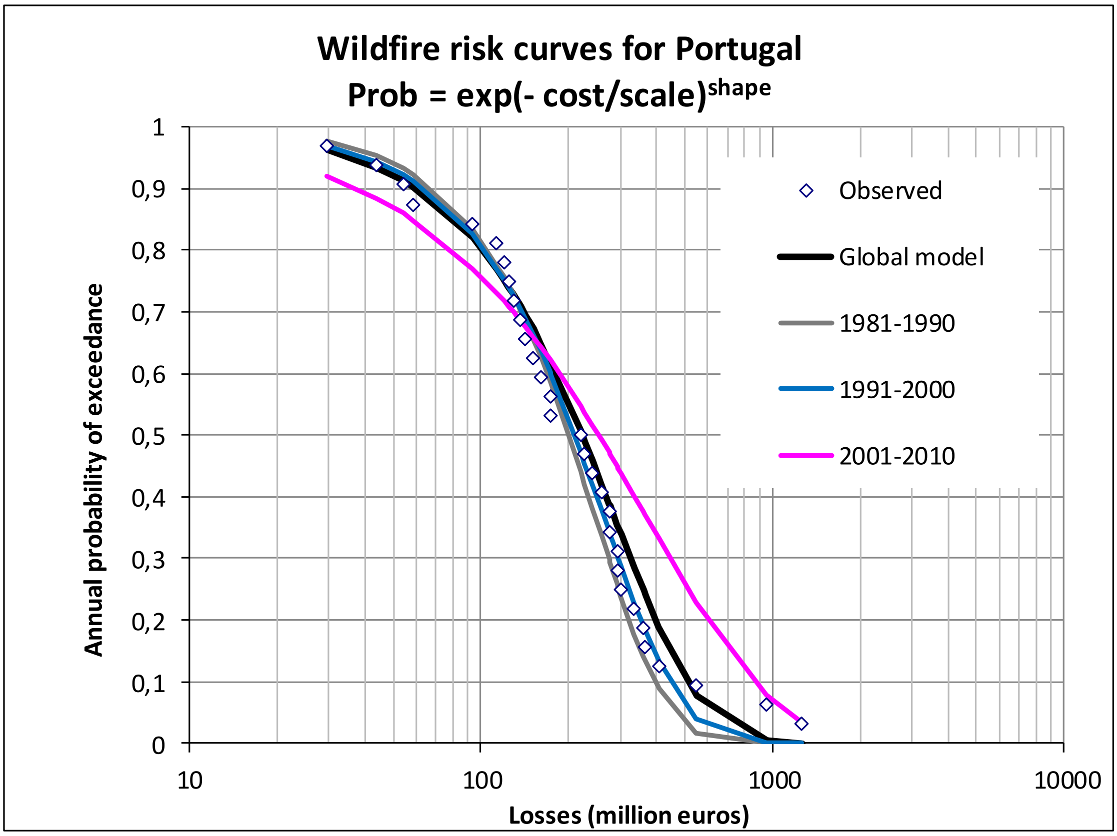

Figure 6: Wildfire risk curves for Portugal with data from the last 30 years fitted with the Weibull distribution. (Global model includes the time series of 1980 to 2010).

5. Conclusions

The aim of this deliverable was to outline methods for harmonizing single-type risk estimates. Such a step is essential before one can meaningfully embark upon a multi-type hazard and risk assessment.

We employed a simple formula (Eq. 1) to combine individual estimates and to show how the total probability for a given level of loss can significant increase. As part of this, we also examined two ways of present risk, in particular how it changes under certain circumstances. The first is the use of risk curves (e.g., Figure 2), which are the probability over a certain time (usually annual) against loss (in our case, direct loss of residential buildings). The other, which is more accepted by end users, is the so-called risk matrix (Figure 3, see also Mignan et al., 2014). The latter plots (in a semi-quantitative manner) severity versus frequency, and is an excellent way to show how combining risk estimates (or including factors such as interactions) moves a given estimate to a higher (or lower) level of concern.

Comparing different risk types for specific return periods may be done using the Wilcoxon's test, provided there is a range of estimates that accommodate the uncertainties in the input parameters and models (Figure 4). Such comparisons then allow one to determine if the consequences of two different hazards are equivalent over a given return period.

There is also a need to consider different forms of losses if one is to have a comprehensive loss assessment, be it single or multi-type. For example, it was identified that not only economic losses but "no shelter" is a useful metric to employ for disaster response in Guadeloupe (and presumably, elsewhere, Table 1). Likewise, considering the time period over which one's estimates is also required, considering general variability, e.g., as shown by the decadal differences in wildfire risk in Portugal (Figures 5 and 6).

All of these points are relevant to the decision-making process, where decision makers can see that they cannot simply treat hazards individually, even without considering interactions. However, if one is comparing two hazard and risk types, the identification of hazards that display a similar level of risk is not the end of the process, as there will then need to be choices made about the allocation of resources for mitigation actions (e.g., the issue of earthquakes and windstorms for Cologne, where for 200 year return periods they are equivalent, but windstorm mitigation would be expected to be less expensive than earthquake. Finally, the actual metric used in risk estimates potentially allows responders some information as to the most appropriate (and immediate) actions.

References

AFN.(2006) Estratégia Florestal Nacional. Autoridade Florestal Nacional. Lisboa

Bertil D., M. Bengoubou-Valérius, J. Péricat, S. Auclair, (2009) Scénarios Départementaux de Risque Sismique en Guadeloupe. Technical Report BRGM/RP-57488-FR.

Carpignano A, Golia E, Di Mauro C, Bouchon S, Nordvik J (2009) A methodological approach for the definition of multi-risk maps at regional level: first application. Journal of Risk Research 12(3-4):513–534, 10.1080/13669870903050269.

Fleming, K., Tyagunov, S., Vorogushyn, S., Kreibich, H., Parolai, S., Muñoz Jimenez, C. and Mahlke, H. (2014) Cologne test case. Deliverable D7.5, New methodologies for multi-hazard and multi-risk assessment methods for Europe (MATRIX project), contract No. 265138.

Garcia-Aristizabal, A., P. Gasparini, and G. Uhinga (2014). Multi-risk assessment as a tool for decision-making. Submitted for publication as a book chapter in a volume of the series ‘Future Cities’ (Springer): “Climate change and urban vulnerability in Africa” (expected publication date: September 2014)

Gasparini P. and A. Garcia-Aristizabal. Seismic risk assessment: Cascading effects (submitted). Book chapter, in: “Encyclopedia of Earthquake Engineering, Section: ‘Seismic risk’ ”, M. Beer, E. Patelli, I. Kougioumtzoglou, I. Siu-Kui Au, Eds (under review).

Granger, K. (1999) Developing an understanding of urban geohazard risk, *Australian Journal of Emergency Management*, Summer 1998/99, pp. 13-14.

Grünthal, G., Thieken, A.H., Schwarz, J., Radtke, K.S., Smolka, A. and Merz, B. (2006) Comparative risk assessments for the city of Cologne – Storms, Floods, Earthquakes, *Natural Hazards*, vol. 38, pp. 21-44.

Heneka, P. and Ruck, B. (2008) A damage model for the assessment of storm damage to buildings, *Engineering Structures*, vol. 30, pp. 3603-3609.

ICNF.(not published) Burned area for Portugal from 1980-2010, Instituto Conservação da Natureza e Florestas (Institute for Nature Conservation and Forests).

Komendantova, N., R. Mrzyglocki, A. Mignan, B. Khazai, F. Wenzel, A. Patt and K. Fleming (2014) Multi-hazard and multi-risk decision support tools as a part of participatory risk governance: feedback from civil protection stakeholders, *International Journal of Disaster Risk Reduction*, vol. 8, pp. 50-67.

Mignan, A., Wiemer S. and Giardini, D. (2014) The Quantification of Low Probability-High Consequences Events: Part I. A Generic Multi-Risk Approach, *Natural Hazards*, doi: 10.1007/s11069-014-1178-4.

Murshed S. M., D. Borst, B. Guse, G. Grünthal, P. Heneka, Th. Hofherr, H. Kreibich, B. Merz, K. Poser, S. Tyagunov, A. H. Thieken (2007). Comparative risk assessment of natural hazards: where do the opportunities lie in catastrophic precaution? 8. Forum DKKV/CEDIM: Disaster Reduction in Climate Change 15./16.10.2007, Karlsruhe University

Otani, S. (1999) Disaster mitigation engineering – The Kobe Earthquake Disaster., presented at the JSPS Seminar on Engineering in Japan at the Royal Society, London, vol., 27 September, 1999.

Rogelj, J., McCollum, D.L., Reisinger, A., Meinhausen, M. and Riahi, K. (2013) Probabilistic cost estimates for climate change mitigation, *Nature*, vol. 493, pp. 79-83, doi: 10.1038/nature11787

Steinacker, R., Ratheiser, M., Bica, B., Chimani, B., Dorninger, M., Gepp, W., Lotteraner, C., Schneider, S. and Tschannett, S. (2006) A mesoscale data analysis and downscaling method over complex terrain. *Monthly Weather Review*, vol. 134, pp. 2758-2771.

Tyagunov, S., Pittore, M., Wieland, M., Parolai, S., Bindi, D., Fleming, K. and Zschau, J. (2013) Uncertainty and sensitivity analyses in seismic risk assessments on the example of Cologne, Germany, Natural Hazards Earth System Science (Discussion), vol. 1, pp. 7285-7332.

Vorogushyn, S., Merz, B., Lindenschmidt, K.-E., Apel, H. (2010), A new methodology for flood hazard assessment considering dike breaches, *Water Resource Research*, vol. 46 (W08541), doi:10.1029/2009WR008475.