Grünthal, G., Thieken, A. H., Schwarz, J., Radtke, K. S., Smolka, A., Merz, B. (2006): Comparative risk assessments for the city of Cologne, Germany - storms, floods, earthquakes. - *Natural Hazards*, *38*, 1-2, p. 21-44.

DOI: http://doi.org/10.1007/s11069-005-8598-0

Natural Hazards (2006) 38: 21-44
DOI 10.1007/s11069-005-8598-0

Comparative Risk Assessments for the City of Cologne – Storms, Floods, Earthquakes

G. GRÜNTHAL[1,*], A. H. THIEKEN[1], J. SCHWARZ[2], K. S. RADTKE[3], A. SMOLKA[4] and B. MERZ[1]

[1] *GeoForschungsZentrum Potsdam, Telegrafenberg, Potsdam, D-14473, Germany;*
[2] *Bauhaus-University Weimar, Geschwister-Scholl-Str. 8, D-99421, Weimar, Germany;*
[3] *University Leipzig, Stephanstr. 3, 04103, Leipzig, Germany;*
[4] *Munich Reinsurance Company, 80791, Munich, Germany*

(Received: 30 March 2004; accepted: 4 July 2004)

Abstract. In this paper a methodology for a multi-risk assessment of an urban area is introduced and performed for the city of Cologne, Germany, considering the natural hazards windstorm, flooding and earthquake. Moreover, sources of the uncertainty in the analysis and future needs for research are identified. For each peril the following analyses were undertaken: hazard assessment, vulnerability assessment and estimation of losses. To compare the three hazard types on a consistent basis, a common economic assessment of exposed assets was developed. This was used to calculate direct economic losses to buildings and their contents. The perils were compared by risk curves showing the exceedence probability of the estimated losses. In Cologne, most of the losses that occur frequently are due to floods and windstorms. For lower return periods (10–200 years) the risk is dominated by floods. For return periods of more than 200 years the highest damage is caused by earthquakes.

1. Introduction

Risk assessments for natural hazards have usually been carried out separately for the various pertinent hazards in the considered regions or cities, without attempting to combine these studies to one holistic risk assessment. There are only a few exceptions: e.g. the UNDRO study (1977) for Manila, the KATANOS report for Switzerland (BZS, 1995), the AGSO Cities project for geohazards in Australian urban communities (e.g. Granger et al., 1999) and the more recent studies for Turrialba, Costa-Rica (van Westen et al., 2002) and Toronto, Canada (Ferrier and Haque, 2003). As demonstrated by Durham (2003), it is, however, such a synoptical view that enables planners and decision-makers to make adequate decisions on risk reduction and loss prevention programs.

The methodological approaches in risk assessment studies range from very coarse indices to elaborate assessments. An example of a coarse index approach is the methodology of Ferrier and Haque (2003). Based on readily available data and expert knowledge about the hazards and their possible effects on the municipality, this method yields a ranking of the different risks in a community and provides guidance to both mitigation and preparedness priorities. Another coarse index was proposed by Munich Re (2003) and also uses available data and expert opinion. At the other end of the spectrum are in-depth assessments which consider the complete risk chain ('triggering natural event – direct impacts on population; built and natural environment – secondary and long-term consequences') by means of complex simulation tools for hazard and vulnerability analyses. Most of them lack, however, the multi-hazard aspect (Davidson, 1999; UN/IDNDR, 2000). One example of a true multi-hazard study is given by Blong (2003) who developed a damage scale for Australia that quantifies the damage to buildings resulting from a range of natural hazards.

This study aims to provide a multi-risk assessment for the city of Cologne, Germany, performed within the DFNK (German Research Network Natural Disasters) project. Cologne was chosen as a demonstration site since there is a huge accumulation of people (1,014,837 inhabitants in 2000) and assets, such as cultural assets, industrial sites (chemical industry, vehicle construction), an important commerce and services sector (including a trade fair) providing nearly 230,000 jobs, several radio and television stations, etc. (Urban Development Authority of Cologne, 2002). Moreover, Cologne is exposed to the three hazard types windstorm, flood and earthquake, representing the most important hazards in Germany.

Storms take a top position in damage caused by natural hazards in Germany (Munich Re, 1999). In particular extratropical cyclones are responsible for about 53% of economic losses. The total insured loss from the series of gales in December 1999 exceeded € 10 billion (Munich Re, 2001). Also flood events are of major concern in Germany with the highest losses of more than € 9 billion in 2002 at the Elbe river. The last severely damaging floods which also affected Cologne occurred in 1993 and 1995 with economic losses of € 530 million and € 280 million, for the whole of Germany. In Cologne, losses amounted to € 77 million in 1993 and € 33 million in 1995 despite similar water levels of 10.63 m and 10.69 m, respectively (Vogt, 1995; Fink et al., 1996). The significant reduction of losses in 1995 was mainly explained by an enhanced risk awareness and a better preparedness of the people at risk – a phenomenon that was also observed in adjacent catchments (Wind et al., 1999).

Whereas windstorms and floods are well known publicly, damaging earthquakes are rather rare in Germany and there is little public awareness of this risk. Nevertheless, and in spite of only moderate event magnitudes, the total losses can be considerable due to the large number and the high values of exposed objects. The 1992 Roermond earthquake (moment magnitude $M_w = 5.3$, local magnitude $M_L = 5.9$), northwest of Cologne killed one and injured 25 people, damaged 7200 buildings and caused losses of € 150 million. Paleoseismologically constrained earthquakes with M_w up to 6.7 (Camelbeeck et al., 2000) would, of course, produce much higher losses, in the order of tens of billions of euro. The frequency of earthquakes is not of concern in the risk management, but their extreme loss potential is.

In order to compare the three hazard types, the following framework is used. The term risk is used to describe the probability that a given loss will occur. Risk encompasses three aspects: hazard, vulnerability and exposed assets (or people). According to this definition the following analysis steps were performed within this study:

1. Hazard assessment, focusing on the probability of occurrence of potentially damaging natural events.
2. Development of an asset inventory, i.e. identifying the values that are exposed and vulnerable to hazard events.
3. Vulnerability assessment, evaluating how exposed assets will suffer by various hazard events.
4. Loss estimation, superimposing value distribution and vulnerability functions and assigning the corresponding scenario event probabilities. In this study only direct monetary losses were considered, i.e. indirect losses as well as intangible damage (casualties, evacuated people etc.) were completely neglected.
5. Synthesis, linking the loss estimates of the different hazard types. Whereas linking losses as such is easy, a true comparison of the hazards is difficult, since different risks may have very different characteristics concerning their impact on the city or their probability of occurrence.

The multi-risk assessment presented in this study differs from the few approaches for multi-risk assessment existing so far, especially in the degree of detail, and partially in the novel approach for vulnerability assessment. In the following sections, the hazard assessment for windstorms, floods and earthquakes is described. The calculation of the assets in Cologne is introduced as a common basis for all these perils. The vulnerability assessment and the loss estimation methods for each hazard type are described. The paper ends with a comparison of the three different risk curves for the city of Cologne as a common risk indicator.

2. Hazard assessment

For each of the three considered perils a hazard assessment was performed focusing on the estimation of the exceedence probabilities of potentially damaging events and effects. At this stage, different hazard types are not comparable with each other since hazards due to windstorms, floods and earthquakes are described by different strength parameters: wind speed, discharge or inundation depth and ground motion or macroseismic intensity, respectively.

2.1. ASSESSMENT OF THE WINDSTORM HAZARD

For studying the storm hazard two kinds of observed wind speed time series are available, gust data and time averaged wind speeds. For the region of Cologne such time series were provided by the German Weather Service (DWD) observed at the DWD station "Köln-Wahn". The first series contains hourly wind speeds, averaged over a sampling period of 10 min. Its length covers 30 years, from 1971 to 2000. The series of the maximum daily 3 s gusts is 45.5 years long, from 1957 to 2002. These two different measures for wind speed are to be compared with data from known damaging events. The question arises, which one is more suitable for the assessment of storm risks. The highest values of the mean wind speed series correspond to the well-known damaging events. The 30 strongest values of the time series belong to dangerous cyclones (Wiebke on March 1, 1990, Herta on February 3, 1990 and a cyclone on November 24, 1984 are the three strongest). The gust series contains strong gusts assigned to the occurrence of disastrous cyclones, but also strong gusts due to local small size events (e.g. the highest value on August 14, 1996 amounts to 38.5 m/s).

Different distribution functions were taken into consideration for the extrapolation of the time series. According to Troen and Petersen (1989) the Weibull distribution estimates extreme values insufficiently. As expected, the Weibull method gave incorrect estimates for the tail of the distribution. Two other functions were tested, i.e. the Schmidt distribution (Schmidt, 1980), which was de-

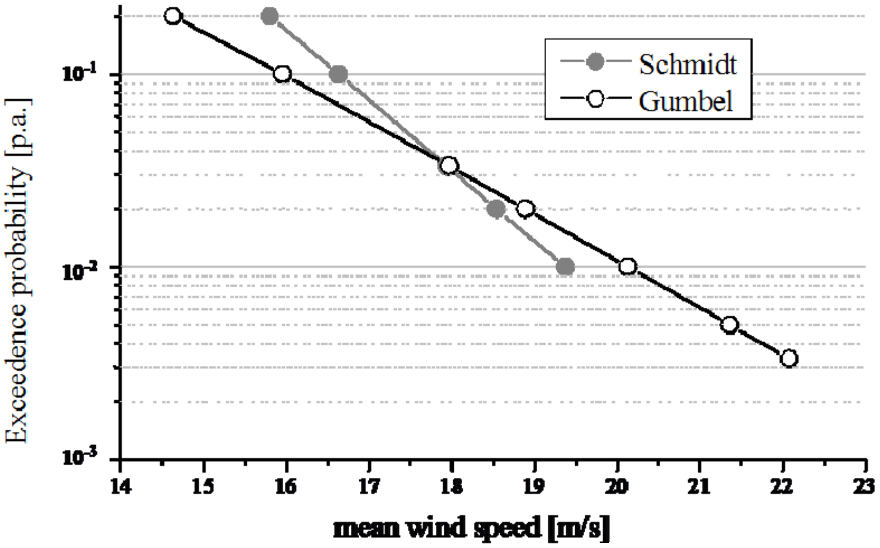

Figure 1. Extrapolated mean wind speeds for selected return periods up to 100 years (following Schmidt) and 300 years (following Gumbel).

veloped especially for wind speeds, and the Gumbel type I distribution (Gumbel, 1958). The accuracy of estimates following Schmidt is sufficient also at the tails. This distribution is valid for sea areas, as well as over land with a flat relief. The extreme values resulting from the Gumbel type I fit only the tail of the distribution sufficiently well. Since this is the important point here, this method was used, too, although its use has clear limitations since it allows infinitely large events and does not consider a physically existing upper bound.

The extrapolation of threshold values of wind speed for some exceedence probabilities is presented in Figure 1. The mean wind speed is presented up to a return period of 300 years (Gumbel method) and alternatively up to 100 years (Schmidt method). The latter is the upper bound of extrapolations suggested by Schmidt. At first glance, both estimations seem to be small, compared for example with mean wind speeds of 26.1 m/s measured during the storm Lothar (26.12.1999) in Karlsruhe. The Cologne region, however, is known for weaker wind speeds in comparison to locations in the open North German lowland. This is due to the protected location of Cologne in the Lower Rhine Embayment (Dütemayer, 2000).

As described above, the mean wind speed was used to develop the loss scenarios. Losses as such, however, are more related to peak gusts than to mean wind speeds (e.g. Munich Re 1993). Therefore, the peak gusts had to be derived from the mean wind speeds. A conventional gust factor G was derived as the quotient of the peak gust and the mean wind speed. The simple model for gustiness at high wind speeds of Wieringa (1973) assesses a median Gust factor depending on available parameters. According to Wieringa the gust factor was calculated as a function of the mean wind speed v_m (averaged over a period $\mathrm{T} = 10$ min), the gust duration t, the roughness length z_0 (a parameter for the effect of surface roughness) and the height above ground z:

$$G(t, T = 10\,\mathrm{min}, z, z_0, v_m) = 1 + \frac{1.42 + 0.3013 \cdot \ln\left(\frac{990}{v_m} - 4\right)}{\ln\left(\frac{z}{z_0}\right)}$$

The duration of the gusts was assumed to be 3 s. The model produces realistic median gust factors between 1.7 and 1.8 for the disastrous cyclones. The mean value observed amounts to 1.86. The maximum of the time series of 18.9 m/s represents the storm Wiebke on March 1, 1990. Peak gusts derived here range between 32.2 m/s and 33.3 m/s, which correspond to the 32 m/s maximum gust observed at the station.

Taking into account the length of the used time series, a reliable estimate for longer return periods than a few hundred years is hardly possible. On the other hand, gust speeds of up to 45–50 m/s were already observed in the North German lowland in the past (Cappel and Emmerich, 1975). In principle, the occurrence of even higher values is possible.

Although the occurrence of damaging tornadoes is possible in Germany (Dotzek, 2001) this event type is not considered here.

2.2. ASSESSMENT OF THE FLOOD HAZARD

The estimation of the flood hazard is based on a flood frequency analysis of the discharge data at the Cologne gauge on the river Rhine. At this gauge a discharge series with reliable daily data from 1880 to 1999 is available. For each hydrological year (from 1st November to 31st October) the maximum discharge was determined. Different distribution functions were adapted to this Annual Maximum Series (AMS): Gumbel type I, Pearson type III, Weibull and Lognormal. The parameters of these distribution functions were estimated by the method of moments (Stedinger et al., 1992). Figure 2 shows the four distribution functions as well as the observed events, whose empirical probabilities were assessed by six different plotting position formulas (Weibull, Gringorden, Cunnane, Median, Blom and Hazen) given in Stedinger et al. (1992). The four distribution functions were then weighted by a Maximum Likelihood method to construct a composite probability distribution function (Wood and Rodríguez-

Iturbe, 1975), which gave the following weights θ_i for the individual distributions: Pearson type III ($\theta_1 = 0.858$), Weibull ($\theta_2 = 0.072$), Lognormal ($\theta_3 = 0.067$), and Gumbel type I ($\theta_4 = 0.003$). The Pearson type III distribution seems to be the best option for this series since it is almost identical with the composite distribution. However, in comparison with the estimates of the German Federal Institute of Hydrology, where multiple annual maximum series and the log-Pearson type III distribution were used, the Pearson type III in combination with the AMS 1880–1999 deliver lower discharge estimates especially for return periods larger than 50 years. The estimates of the German Federal Institute of Hydrology are fairly well represented by the Gumbel type I distribution in Figure 2.

In general, the uncertainty of flood frequency analysis is enormous because sample sizes are limited, the sample types ((multiple) annual maximum series or partial duration series) differ and a variety of distributions and parameter estimation methods are available (e.g. Chbab, 1995). To overcome this problem many countries published guidelines and recommended certain distributions. For example, the log-Pearson type III distribution is the most frequently used distribution in the USA, whereas the generalized extreme value distribution is popular in Great Britain, the Lognormal distribution in China and other distributions in other countries (Singh and Strupczewski, 2002).

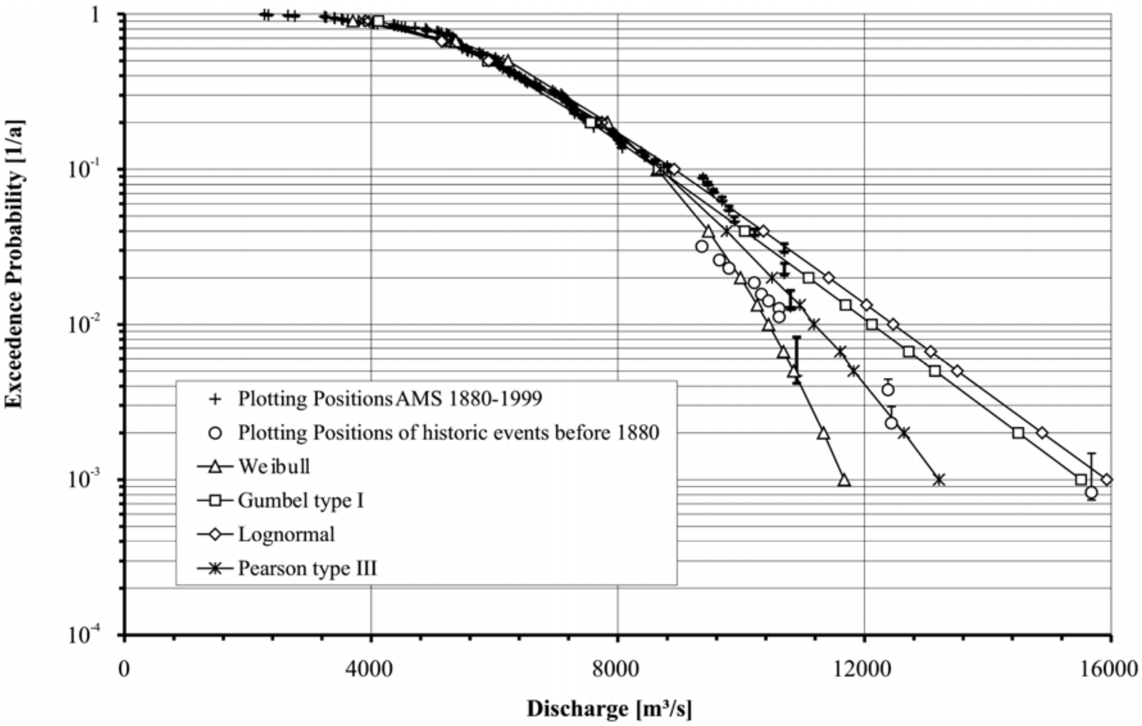

Figure 2. Four possible distributions of discharge at the Cologne gauge based on the annual maximum series from 1880 to 1999 (AMS 1880-1999) and empirical probabilities of observed and historic flood events estimated with different plotting position formulas (cf. text).

The four highest events in the AMS 1880–1999 have the same order of magnitude: 10,700 m^3/s to 10,900 m^3/s (Figure 2). These discharges equal a water level at the Cologne gauge of 10.55–10.66 m. Therefore, it seems that a discharge of around 11,000 m^3/s might serve as an upper bound. However, an analysis of historic flood events in Cologne provided by Krahe (1997) reveals that the extreme floods of 1342, 1374 and 1497 – with water levels and discharge values of 11.53 m (12,435 m^3/s), 13.30 m (15,680 m^3/s) and 11.50 m (12,380 m^3/s), respectively – clearly exceed the largest flood events in AMS 1880–1999. Empirical probabilities of the historic events were estimated by combining the historic events with the AMS 1880–1999 following DVWK (1999). Assuming different plotting position formulas (see above) a return period between 670 and 1350 years was assigned to the largest flood event which occurred in 1374 (Figure 2). It was therefore classified as a 1000-year flood (Figure 2). It has, however, to be emphasised that the discharges of the historic events were obtained with the current rating curve. Owing to morphological and hydraulic changes in the river bed and due to climatic fluctuations during the last centuries, e.g. the Little Ice Age from the 15th to the 18th century, there is some instationarity in the data. Therefore these calculations are fairly uncertain.

For the estimation of flood losses certain discharges have to be converted into water levels and inundation areas. The transformation of discharges into water levels was performed by the rating curve of the Cologne gauge. Inundation scenarios considering the flood protection outlined in Stadt Köln (1996) were provided by MURL (2000) for the water levels 11.30 m, 11.80 m and 12.50 m at the Cologne gauge. Additionally, inundation maps were calculated by interpolating the water levels given at 13 cross sections along the Rhine in Cologne and by intersecting the resulting water surface with a digital elevation model of 50 m grid size. Figure 3 shows a few inundation scenarios. The resolution of the digital elevation model is, however, comparatively coarse. Therefore, uncertainties up to 0.50 m inundation depth might occur. This is especially relevant for water levels below 11.30 m and is a further source of uncertainty which will affect the risk assessment.

2.3. ASSESSMENT OF SEISMIC HAZARD

The Lower Rhine Embayment represents one of the most seismically active areas of Germany. Fairly strong earthquakes have occurred there in the past; e.g. an intensity I = VIII, magnitude $M_L = 6.1$ earthquake on 18 February 1756 near

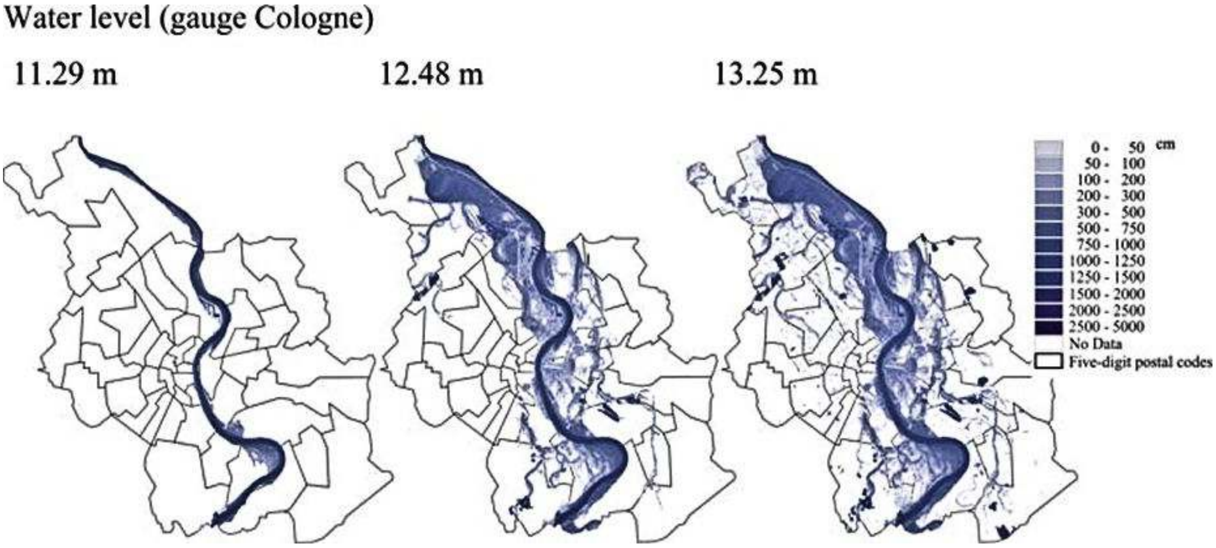

Figure 3. Selected inundation scenarios for Cologne. According to the current rating curve the water levels of 11.30 m, 12.50 m and 13.25 m correspond to a discharge of 12,018 m^3/s, 14,247 m^3/s and 15,677 m^3/s, respectively.

Düren and the $M_L = 5.9$ earthquake 1991 near Roermond/Heinsberg, which had, due to the large focal depth of 20 km, an I = VII only, still causing extensive damage (see Introduction). Cologne lies close to the eastern border of the seismically active area.

The observed seismic record is sufficiently complete since 1250 for intensity VIII and since 1500 for intensity VII (Grünthal et al., 1998). Since the goal of the study is an intensity-based risk assessment, the hazard assessment was performed for this parameter. A harmonized earthquake catalogue covering the entire western Central European area was used (Grünthal and Wahlström, 2003). Seismic source zones based on the seismotectonics of this larger area were taken from Grünthal et al. (1998), while for the Lower Rhine Embayment and the Ardennes 14 smaller seismic source zones were derived on the basis of the detailed neotectonic pattern and tectonic studies (Grünthal and Wahlström, 2006). The catalogue data contain more than 900 earthquakes in all these considered seismic source zones. About 400 events were used to derive the frequency-magnitude parameters for the source zones. Different combinations of the 14 small source zones represent the epistemic uncertainty of the source zonation input for the probabilistic seismic hazard assessment. All the other input parameters were also treated, with their uncertainties, with the logic tree technique. Seismic hazard assessments in terms of intensities were made for the soil conditions of the localities where intensity data points were collected in the past. These are usually the sites of towns, which are located on soft to stiff sedimentary areas in most cases. Cologne, the site of this study, falls into this general

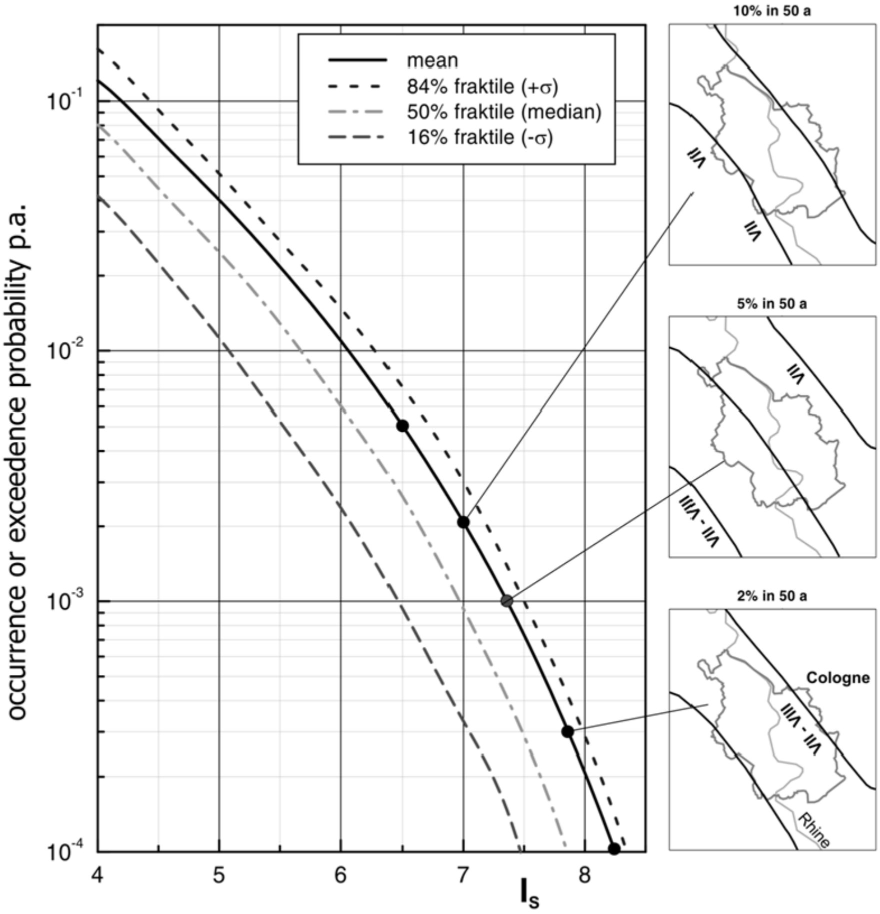

Figure 4. Probabilistic seismic hazard curves for the centre of Cologne in terms of intensities and their fractiles. Basis for the risk assessments are here generally the mean hazard values. Corresponding intensity hazard maps for the city of Cologne are shown as inlay maps for different probability levels.

class of soil conditions.

Intensity-related fractile hazard curves for the centre of Cologne are given in Figure 4. The mean hazard curve, representing the best estimate, is used here for the further procedure regarding loss estimation. Corresponding seismic hazard maps for the area of Cologne for different hazard levels are the basis for the following estimations of seismic losses. Three of these maps are shown in Figure 4.

3. Asset assessment for the city of Cologne

In order to estimate direct losses that might be caused by various hazards, it is necessary to develop an inventory of potentially exposed assets in the area under consideration. For a consistent comparison of different risks, a uniform data base of the assets is essential. Therefore, the aim is to calculate values – here defined as replacement values for the reference year 2000 – for buildings and their contents in different economic sectors, particularly in the sectors of private

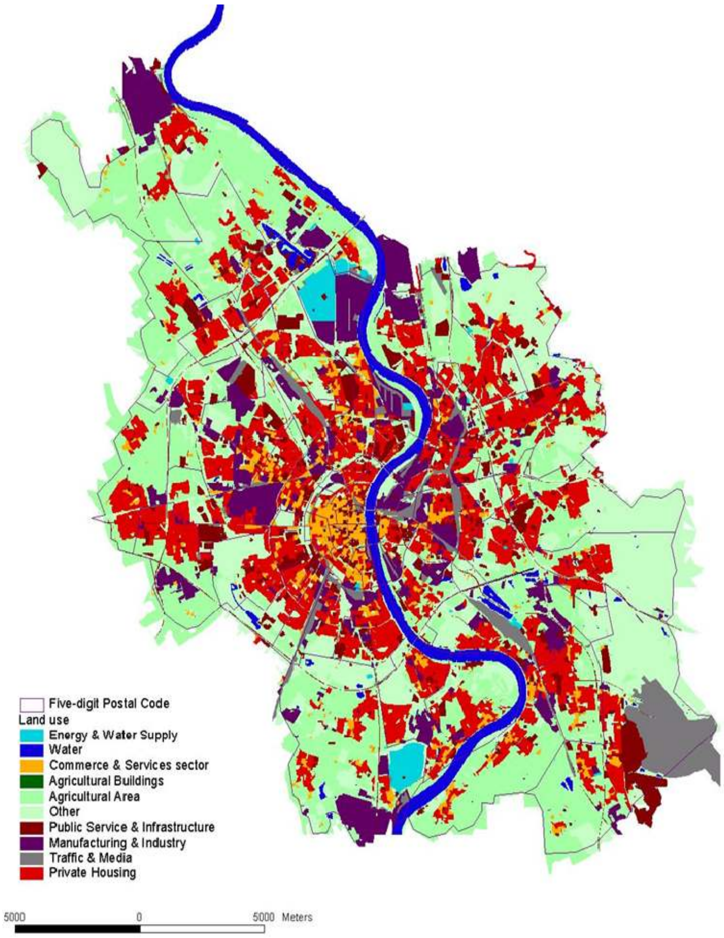

Figure 5. Spatial pattern of Economic Sectors in Cologne according to the land register ATKIS.

housing, commerce and services as well as industry. The values of other economic sectors (energy and water supply, public infrastructure etc.) are also shown in this section in order to demonstrate their contribution to the whole damage potential. As a spatial data base the land register ATKIS, i.e. the German official topographic– cartographic information system, was used.

The assets were estimated by means of the following statistics: On the basis of data on the gross stock of fixed assets in 1997 (Statistical Office North Rhine-Westphalia, 2002, personal communication) and data concerning type and expanse of land uses in North Rhine-Westphalia (MURL, 2000) a unit value per land area [€/m^2] was calculated for all economic sectors that are included in the system of national accounts from 1958. The unit values were scaled to the year 2000 by data on the development of the gross stock of fixed assets in North Rhine-Westphalia (Federal Statistical Office Germany, 2002), i.e. the figures for 1997 were multiplied by 1.0525. As assets are not distributed uniformly throughout the country, but data on the gross stock of fixed assets are only available per federal state, a measure had to be found which accounts for the high concentration of assets in the Cologne region. Therefore, the unit values for North Rhine-Westphalia were adjusted to Cologne using the gross value added per employee. The underlying rationale is that there is a relationship between assets involved in production and value creation: The higher the asset's worth, the higher productivity will be. Gross value added per employee is a productivity measure. In 1996, the average value added per employee throughout Germany was € 50,406 (= 100%). In North Rhine-Westphalia it was € 52,821 (= 105%), and in the city of Cologne it was € 65,010 (= 129%) (Statistical Office Baden-Württemberg, 2000). The unit values for North Rhine-Westphalia were therefore multiplied by 1.23. Since there are no data about the productivity in different parts of Cologne the spatial variation of the assets within the city was neglected in this approach.

The use of the gross stock of fixed assets for asset assessment does not work well for the sector of private housing since the data do not include all private residential buildings. Therefore, an approach based on statistics of the Urban Development Authority of Cologne (2002) and insurance data (GDV, 2003, personal communication) was chosen for this sector: The number of buildings, households and cars in 2000 was each multiplied by the corresponding average insured value in Cologne. By this approach a total value of € 80.25 billion and a mean unit value of 1015 €/m^2 was obtained (Table I).

For loss estimation models, a spatial distribution of the assets is needed. Therefore, the values had to be allocated to object classes within the land register ATKIS. Since there is no exact correspondence between the economic sec-

Table I. Estimation of assets in the city of Cologne on the basis of land use information system ATKIS and unit economic values (Statistical Office North Rhine-Westphalia, 2000) (Reference year: 2000, cf. text).

Economic sector	Area [km^2]	Share of total [%]	Unit economic value [€/m^2]	Total asset in Cologne [billion €]	Share of total [%]
Agricultural area	111.01	26%	-	-	-
Other	100.38	25%	-	-	-
Private housing	79.10	20%	1015	80.25	60%
Manufacturing & Industry	35.30	9%	362	12.79	10%
Public Service & Infrastructure	26.77	7%	467	12.49	9%
Commerce & Services sector	14.25	4%	1179	16.81	13%
Traffic & Communication	17.87	4%	67	1.09	1%
Water	15.27	4%	-	-	-
Energy & Water supply	5.19	1%	1785	9.25	7%
Total	405.14	100%	-	132.68	100%

tors in the national accounts and the ATKIS land use codes, the scheme proposed by MURL (2000) was slightly modified and used to assign ATKIS land use classifications to economic sectors. The resulting spatial pattern of economic sectors in Cologne is shown in Figure 5.

By multiplying the unit value and the area of an object, the economic value of each ATKIS-object was obtained. The object values were then aggregated within five-digit postcodes and for Cologne as a whole. The main results are given in Table 1, the total value amounts to € 133 billion.

Other approaches exist for the estimation of assets. For example, an approach based on the number of inhabitants multiplied by the mean insured values per capita in Germany yields considerably higher values (i.e. an augmentation of 30% for housing and 65% for commerce and industry). Furthermore, data gathered by primary insurers which represent 20% of Cologne’s total portfolio for residential buildings show that the average building value in Cologne is probably higher than the value assumed here. This is due to a higher share of apartment buildings and more valuable town houses. This leads to the conclusion that the values derived with the above described approach represent a rather low estimate of the total values. However, a validation remains difficult. Further data sources should be acquired to better account for the spatial variation of building values within Cologne.

4. Vulnerability assessment and estimation of direct losses

For each of the three natural disasters a set of potentially damaging scenario events was selected. They were related to certain probability levels of the hazard assessments and were applied also for the seismic risk assessments. For these scenarios it was evaluated which assets are exposed to the hazardous events and what the effects are. In the case of damaging earthquakes and windstorms the whole city is affected, as opposed to floods. Monetary direct losses to buildings and contents were then estimated considering only the sectors of private housing, commerce and industry with a total value of € 110 billion (see Table I).

4.1. VULNERABILITY AND LOSS ESTIMATES DUE TO WINDSTORMS

The assessment of expected losses for different return periods was performed using a simple empirical damage function developed by Munich Re (Munich Re, 1993, 2001). It is based on studies of the gust fids of disastrous cyclones like the 1990 storms Daria, Wiebke, Herta and Vivian and the 1999 storms Lothar, Martin and Anatol:

$$\mathrm{LR}(\nu_G) = \begin{cases} \mathrm{LR}\,(80\ \mathrm{km/h}) \cdot \left(\frac{\nu_G}{80\ \mathrm{km/h}}\right)^{\gamma} & \nu_G \geq 80\ \mathrm{km/h} \\ 0 & \nu_G < 80\ \mathrm{km/h} \end{cases}$$

Here, LR(ν_G) is the loss ratio and ν_G the gust wind speed. This equation is valid for speeds above 80 km/h. No significant damages occur in Germany below this value. The analysis of the 1990 data suggests a γ of 3–4. If the 1999 gales are included in the analysis, γ is rather in the range between 4 and 5. No differentiation between coastal area and inland was made, because the data do not support such differences.

The relevant scale of the topography considering storm damage is different from that for flood damage. If the variation of the elevation is lower than 10 m, the difference in damage is not noticed. Therefore, the topography provides no reason to subdivide the area of the city of Cologne into several parts. The damage function used was developed on a 0.1°•0.1° grid, which corresponds to the area of Cologne.

Two estimations were made to take into account the uncertainty of the assessment. For an upper estimate a median roughness length (see Section 2.1) of 0.55 m and a γ of 5 in the vulnerability function was assumed, for a lower estimate a roughness length of 0.45 m and a γ of 4 (see Table II). The exceedence probability for losses up to a return period of 300 years as a mean of a lower and an upper estimate is shown in Figure 8 in comparison with the two other risks.

When applying the wind speed of the maximum event uniformly over the whole city area, the resulting loss ranges from € 39 to € 66 million.

4.2. ESTIMATION OF LOSSES DUE TO INUNDATION

Direct monetary losses due to inundation were estimated by superimposing inundation patterns (Figure 3) with the ATKIS land use cover (Figure 5) which was transformed to a grid with a cell size of 50 m. For each grid cell the inundation depth and the economic sector were determined. As described in Section 3, each economic sector corresponds to a unit economic value. Therefore, the total economic value per grid cell can be calculated easily.

The relative flood loss per grid cell was then estimated by means of stage-damage functions according to MURL (2000). Such a function shows the damage ratio of buildings and contents in dependence on the inundation depth for each economic sector. Monetary flood loss results from the multiplication of the damage ratio by the total economic value per grid cell. Losses per grid cell were aggregated for each economic sector and for Cologne.

For the three inundation scenarios shown in Figure 3, this approach yielded total flood losses of € 157 million, € 3.5 billion and € 5.3 billion, respectively. All in all, flood losses were estimated for 15 inundation scenarios so that a relationship between the water level at the Cologne gauge and the total direct flood losses in the sectors private housing, commerce and industry was constructed. The resulting data, assumed as mean values, are shown in Figure 8.

4.3. ESTIMATION OF LOSSES DUE TO EARTHQUAKES

Neither the earthquake resistance of the building stock in Cologne nor its vulnerability is known. Therefore, a test area with approximately 800 buildings in the city centre was surveyed in detail. Buildings were inspected and identified with respect to their building type and importance category as well as with respect to their structural system (Schwarz et al., 2002a, b). Considering the expected differences in the way that buildings respond to earthquake shaking, including factors like workmanship, state of maintenance etc., the most probable vulnerability class (A, B, C or D) was assigned to each building. Additionally, transitional classes (A–B, B–C or C–D) were introduced (Schwarz et al., 2006). This strictly follows the European Macroseismic Scale EMS-98 (Grünthal, 1998).

It has to be stressed that the building stock in Cologne was affected by severe destruction due to the second world war and its aftermath. The greatest part of the building stock was erected in the past 50 years. Consequently, buildings and construction types of low vulnerability dominate; 80% of the buildings can be assigned to vulnerability class C and less than 14% to vulnerability class B (Figure 6a).

In the sense of geo-statistical extrapolation, the composition of the building stock was applied to the entire city area with consideration of the given age structure of the buildings in the city quarters concerned.

The earthquake scenarios developed in the context of risk studies consider mainly building damage according to the local intensity and corresponding distributions of damage grades for each vulnerability class. Therefore, the differen-

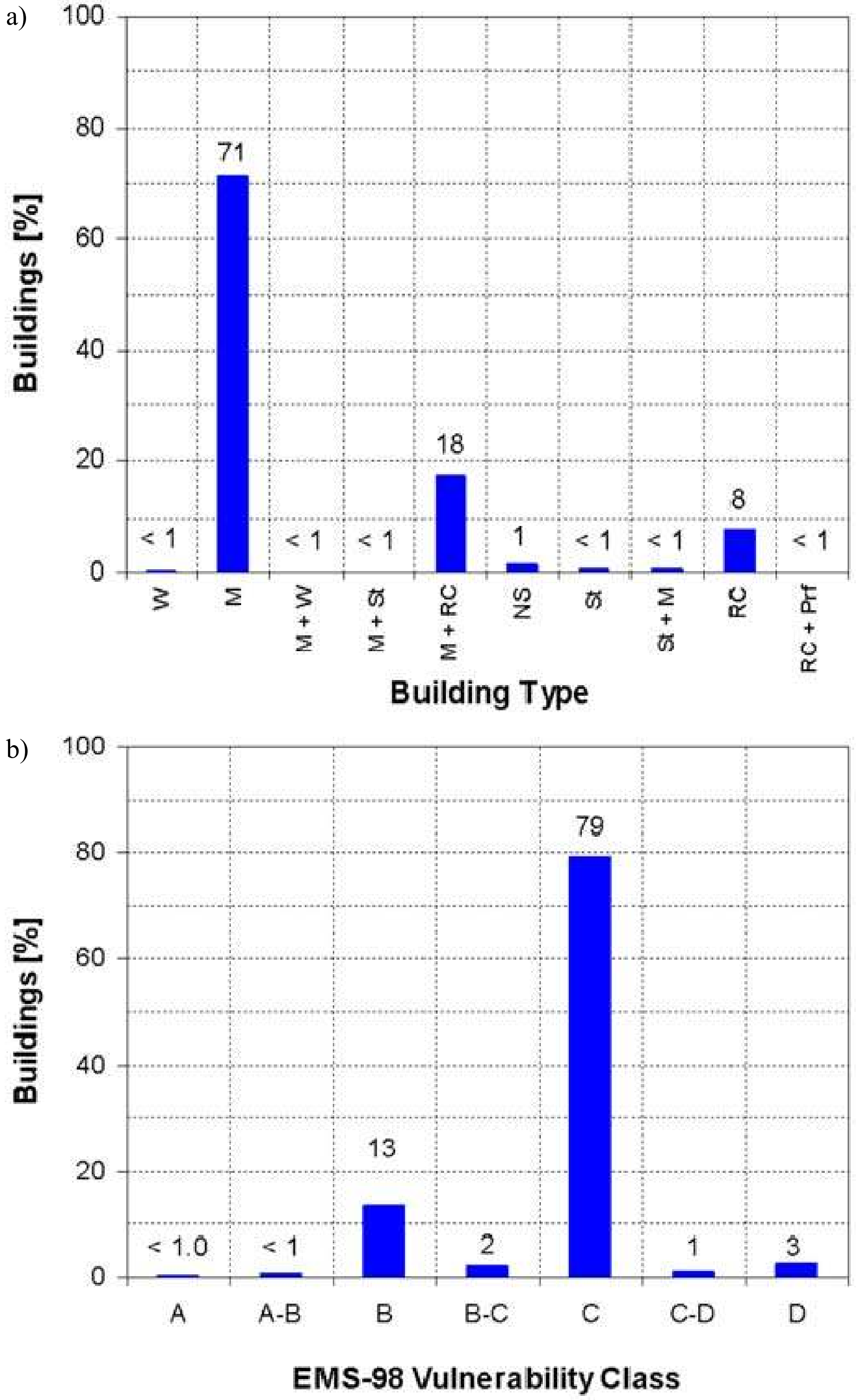

Figure 6. (a) Composition of building types in the study area of Cologne (W: wooden; M: masonry, St: steel, RC: reinforced concrete; NS: natural stone, Prf: Prefabricated). (b) Composition of vulnerability classes (EMS-98) in the study area of Cologne.

ces between building types are transformed into vulnerability classes. For each city district the composition of buildings with respect to their vulnerability classes is extrapolated. For further details of the procedure see Schwarz et al. (2006), where further references are given.

Losses due to earthquakes were estimated on the basis of deterministic scenarios assuming epicentres within the context of historical seismicity (Schwarz et al., 2006). Return periods of intensities were assigned in accordance to Figure 4. For the purpose of the integrated approach within this study, probabilistic intensity hazard maps for the city of Cologne, as given by Figure 4, were applied directly.

Seismic risk maps were prepared for different EMS-intensities. The impact of model assumptions and the step-wise refinement of input variables (like site conditions, building stock or vulnerability functions) on the distribution of expected building damage is considered in more detail by Schwarz et al. (2006). From these investigations it can be concluded that these modifications have an impact on the distribution of damage but are of minor importance for the total loss integrated over the city of Cologne. This is especially true for the effects of site conditions. The fundamental periods of the predominant building types and the instrumentally predicted (and analytically confirmed) site periods are well separated. The estimated damage distributions for the given scenarios are described using the mean grade of damage for each city district.

Within recent case studies a procedure was developed to transform the site-specific description of seismic action (within the period ranges characteristic for the dominant building types) into intensity differences introduced as “Delta-Intensities” (Raschke, 2003). On the basis of those site-specific spectral accelerations calculated in tightly spaced grid elements, the local intensity is differentiated.

On the basis of the results of the site-response-analyses, differences in intensities were determined for each city district depending on the subsoil type. These intensity increments can be understood as correction values for the site intensity and were finally inserted as such into the calculation of the mean damage grades d_m.

For the city of Cologne it seems allowable to assume uniform input values over large areas, minimizing the impact of local site conditions and the scatter of risk assessments. However, it should be stressed that in general, site effects have to be considered by refined 2-or 3-dimensional models. Thus the case of Cologne reflects an exceptional rather than the standard situation. In the scenarios of Figure 7 the influence of local site effects was not considered. Schwarz et al.

Table II. Monetary losses in million € up to a mean return period of 300 years.

Return period	Lower estimation	Upper estimation
5 a	20	29
10 a	24	36
50 a	37	60
100 a	43	60
300 a	70	135

The Schmidt method was used to extrapolate the mean wind speeds up to 100 years mean return period and the Gumbel method for 300 years. For the upper estimate a roughness length of 0.55 m in the gust assessment and a c of 5 in the damage function was assumed; for the lower estimate a roughness length of 0.45 m and an exponent of 4.

(2006) illustrate the variations for specific site conditions as well as the effect of building height. It should be repeated that by this procedure the regional damage distribution of mean damage grades is slightly modified, while the loss over the entire city will be less affected An increase of losses of about 10% was predicted following the approach of locally differentiated intensities.

The assets were taken as given in Figure 5 using a correlation between mean damage grade (d_m) and Mean Damage Ratio (MDR, indicating the loss as percentage of the replacement value). It should be noticed that the scatter around the mean could lead to an underestimation of losses. To clarify the tendency or quantity, further investigations are required starting with a check of available databases from the insurance side.

The correlation is based on the description of damage grades as given in the European Macroseismic Scale EMS-98. The loss is summed up over the city districts. Assuming that within each city district the intensities according to scenario maps are representative, the losses can be expressed in terms of annual probabilities of exceedence corresponding to the mean or another statistical fractile intensity given in Figure 4. By coincidence, probabilistic and deterministic scenarios as presented by Schwarz et al. (2006) indicate only minor differences. Probabilistic results according to Figure 4 and Figure 7 are used for comparing earthquake losses with those of other hazards (storm, flood).

5. The synopsis of natural risks for Cologne

For the comparison of different risks it is a fundamental prerequisite to use a common risk indicator. In this study we agreed to calculate a risk curve for each disaster type. Such a risk curve shows the total direct monetary losses for buildings and contents in the sectors private housing, commerce and industry in Co-

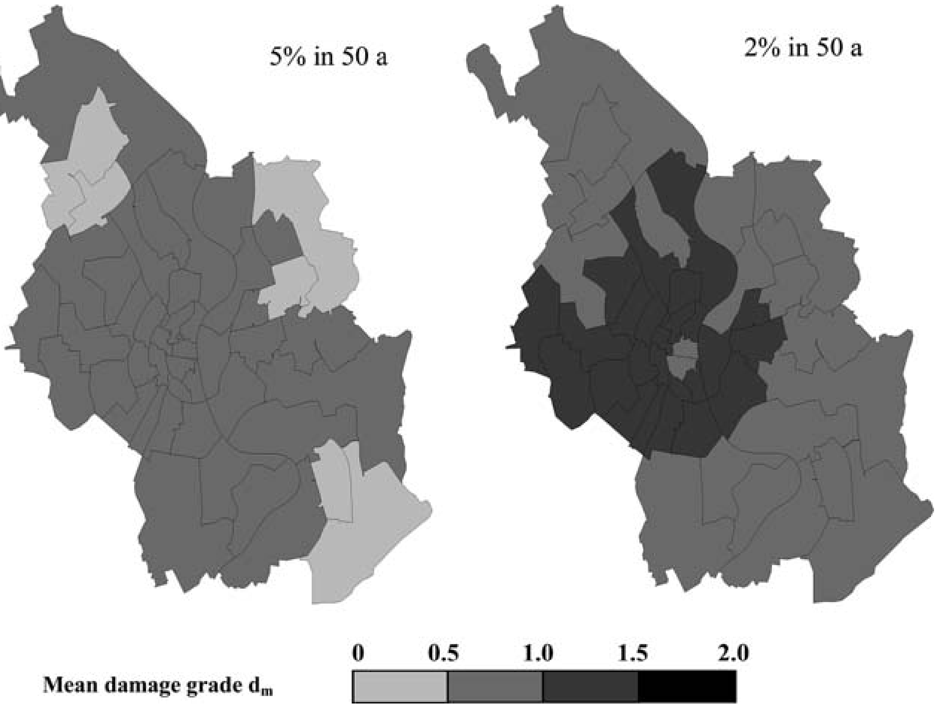

Figure 7. Mean damage grades d_m according to the EMS-98 in postcode-areas of Cologne for two different hazard levels (5% in 50 years, T = 1000 years; 2% in 50 years, T = 2475 years).

logne against their exceedence probability. Different risk curves can be plotted in one graph (Figure 8). This enables the direct quantitative comparison of the risks for the probability ranges which are covered by all three risk curves.

In the case of windstorm risk the curve was calculated as a mean of the lower and upper estimates shown in Table II. A flood risk curve was constructed by combining the exceedence probabilities of discharges according to the Pearson type III distribution, the transformation of discharges into water levels as well as the relationship between water level and direct losses in Cologne. The seismic risk curve was derived from damage scenarios for Cologne according to determined frequency distributions of vulnerability classes in the city, which were associated to certain hazard levels of the corresponding mean hazard curve.

The risk curves in Figure 8 were calculated only for the most probable estimates, i.e. uncertainties were not considered. But the uncertainties can be large. The uncertainties in the estimation of hazards, of assets, of the vulnerability assessments and in the modelling of losses have to be taken into account. This applies, e.g., to the different spatial resolutions used for the three hazards. In the case of Cologne the uncertainty arising from this criterion is relatively, and may be untypically, low due to the uniform topography (with respect to windstorms) and the fairly uniform subsoil conditions within the city (with respect to earthquakes).

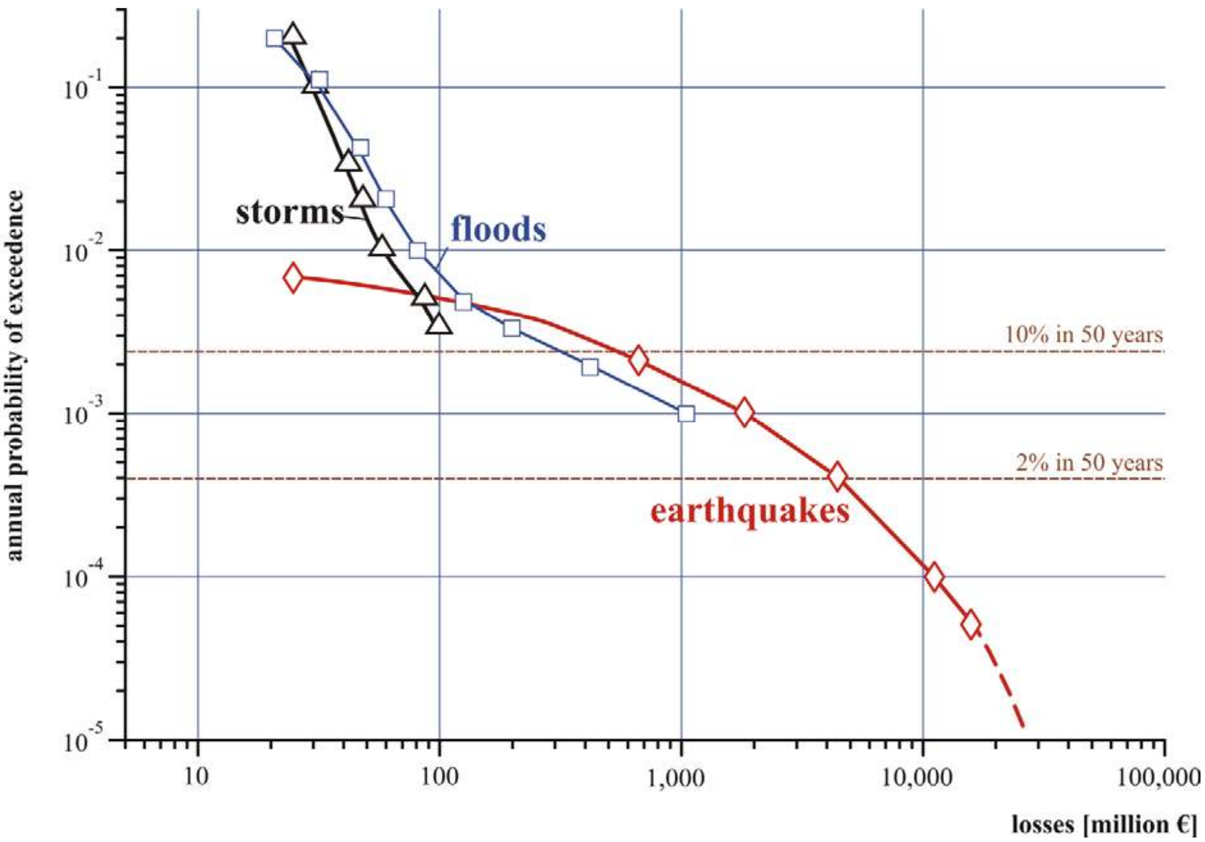

Figure 8. Risk curves of the hazards due to windstorms, floods and earthquakes for the city of Cologne for losses concerning buildings and contents in the sectors private housing, commerce and industry (reference year: 2000).

The uncertainties in the seismic hazard assessment were explicitly calculated (cf. fractiles in Figure 4), while the ranges of different distributions considered for the windstorm hazard and the flood hazard provide a very rough first qualitative impression of their uncertainties (Figures 1 and 2). For the 100-year flood, for example, the flood damage estimate doubles if the Gumbel type I distribution (Figure 2) is assumed. To overcome the uncertainty of the flood frequency analysis it would be necessary to supplement the statistical analysis by hydrologic process understanding and modelling. Thus, special care is required when comparing the risk curves.

Nevertheless, repeated observations in the last years show that for higher exceedence probabilities the risk is clearly dominated by windstorms and floods. Due to the exposed location of Cologne at the River Rhine, the flood risk is prevailing despite the large efforts in flood protection. It should, however, be recognised that the actual damage of frequently occurring floods will be smaller than estimated in this study since only the technical flood protection measures like levees and flood walls were considered in the hazard assessment. The flood events of 1993 and 1995 showed that preparedness of the affected people can considerably reduce the damage (Wind et al., 1999). Effects of early warning, adaptive behaviour, temporal flood barriers, e.g. sandbags, and private emergency and precautionary measures are, however, neglected in the presently applied loss estimation. A better model that accounts for these effects is recently under development.

The flood risk losses are followed by the losses due to the frequent exposure to medium sized windstorms. Cologne itself remained less affected by the strong storms during the last decades. For probability levels smaller than about 5 x 10^{-3} p.a., the course of the flood risk curve shows a drastic increase in losses for decreasing occurrence probabilities due to the failure of the flood defence system. At the probability level of about 5 x 10^{-3} p.a. the earthquake risk curve exceeds that for floods. However, due to the evident uncertainties one can only conclude that earthquakes seem to be of at least equal importance as floods for small exceedence probabilities.

When interpreting the results it must be mentioned that the city of Cologne represents only a minor fraction of the total area affected by the underlying scenario events. This is true for all three natural hazards. For example, only about 12% of the German losses due to the flood events in 1993 and 1995 occurred in Cologne. Whereas windstorm losses for Cologne alone appear comparatively low – even if they were extrapolated to return periods beyond 300 years – they play a very important role from a country-wide perspective due to the high frequency of damage and the large areas affected. In the period 1970–1998, 75% of the economic losses were caused by windstorms, followed by floods with 19% (Munich Re, 1999). The importance of earthquakes comes mainly from their high probable maximum loss potential. Altogether, the risk curves demonstrate such relationships between losses and probabilities fairly well, albeit from a country-wide or a city-related perspective and in the probability ranges where they overlap.

As opposed to the other two natural hazards studied here, the earthquake risk can be assessed with sufficient reliability even for relatively small occurrence and exceedence probabilities. This is due to the distinctly longer observation period for earthquakes, to the availability of paleoseismological indications and geological strain data, which confirm the respective occurrence rates based on hundreds of observed earthquakes, and to well established distribution functions of upper bound earthquake magnitudes (Grünthal and Wahlström, 2006).

Additionally, in Figure 8 the probability level of earthquake building codes (10% occurrence or exceedence within 50 years, corresponding to 475 years mean return period) is depicted as well as the 2% level in 50 years (T=2475).

The latter is increasingly used for risk studies in low seismicity regions and is the hazard level required in the German code for water reservoirs. With regard to the high damage potential of earthquakes, the need for a strict implementation of seismic building codes cannot be denied.

Nevertheless, efforts to mitigate flood and windstorm losses should also be strengthened given their frequent occurrence. The existing hazards as well as available measures of protection and loss reduction should be better communicated to the public.

6. Conclusions

Experiences with decision makers (e.g. disaster management agencies, urban planners, insurers, regional and local authorities) show that they need comprehensive information which includes all relevant hazard types within a region. This case study shows that multi-risk assessments enable the comparison of different risks within an urban area and can reveal the characteristics of different disaster types. Risk curves encompassing the entire range of exceedence probabilities, with direct monetary losses as a risk indicator, provide better and more complete information for disaster mitigation than measures of the expected annual damage (EAD), since EAD is mainly influenced by the losses due to the more frequent events. When using EAD, the damage potential of extreme events with low probabilities is easily ignored. Complete multi-hazard risk curves allow to evaluate the significance of different disaster types better, to raise awareness for the various aspects of disaster mitigation, and to develop tailor-made mitigation strategies.

For concrete planning decisions and emergency strategies, however, even more detailed information is needed. Maps which show the spatial distribution of the hazard intensities, exposed population and values, as well as expected losses due to various disasters in more detail, have to be developed in the future. Furthermore, other hazards should be included in the assessment, if pertinent. Especially, the uncertainties in the whole chain of risk assessment have to be quantified.

Acknowledgements

This study was prepared in the frame of the research project German Research

Network Natural Disasters (DFNK) funded by the German Ministry for Education and Research (project number 01SFR9969/5). The authors are much obliged to Martin Gocht, Water and Finance – Economic Consulting for Water and Environment, Berlin, who contributed data for the asset inventory of Cologne. Data provision from the German Federal Institute of Hydrology, Koblenz, the German Insurance Association (GDV), Berlin and ProAqua, Aachen are gratefully acknowledged.

References

Blong, R.: 2003, A new damage index, *Nat. Hazards* **30**(1), 1–23.

BZS (Bundesamt für Zivilschutz): 1995, KATANOS Katastrophen und Notlagen in der Schweiz – Eine vergleichende Übersicht, Bundesamt für Zivilschutz, Bern.

Camelbeeck, T., Martin, H., Vanneste, K., Meghraoui, M., Verbeeck, K., and Brondeel, M.: 2000, Geomorphic evidence of active faulting in slow deformation areas: The example of the Lower Rhine Embayment, *Proc. Evaluation of the potential for large earthquakes in regions of present day low seismic activity in Europe*, Han-sur-Lesse, Belgium, March 13-17, pp. 31–34.

Cappel, A. and Emmerich, P.: 1975, Zwei Wetterkatastrophen des Jahres 1972: Der Niedersachsen-Orkan und das Gewitterunwetter von Stuttgart, Reports of the German weather service, 135, Offenbach.

Chbab, E. H.: 1995, How extreme were the 1995 flood waves on the rivers Rhine and Meuse?, *Phys. Chem. Earth* **20**(5/6), 455–458.

Davidson, R.: 1999, *An Urban Earthquake Disaster Risk Index*, Stanford University, Stanford, CA.

Dotzek, N.: 2001, Tornadoes in Germany, *Atmos. Res.* **56**(1–4), 233–251.

Durham, K.: 2003, Treating the risks in Cairns, *Nat. Hazards* **30**(2), 251–261.

Dütemayer, D.: 2000, Urban-Orographische Bodenwindsysteme in der städtischen Peripherie Kölns, *Essener Ökologische Schriften*, **12**.

DVWK: 1999, *Statistische Analyse von Hochwasserabflüssen*, Wirtschafts-und Verlags-Ges. Gas und Wasser, Bonn.

Federal Statistical Office Germany: 2002, Gross stock of fixed assets (annual average), 1991 to 2000, http://www.statistik-bw.de/VolkswPreise/ArbeitskreisVGR/tab09.asp (Date of computation: August 2002).

Ferrier, N. and Haque, C. E.: 2003, Hazards risk assessment methodology for emergency managers: A standardized framework for application, *Nat. Hazards* **28**(2/3), 271–290.

Fink, A., Ulbrich, U., and Engel, H.: 1996, Aspects of the January 1995 flood in Germany, *Weather* **51**, 34–39.

Granger, K., Jones, T., Leiba, M., and Scott, G.: 1999, *Community Risks in Cairns: A Multi-Hazard Risk Assessment*, Australian Geological Survey Organisation, Canberra.

Grünthal, G. (ed.): 1998, European Macroseismic Scale 1998 (EMS-98), *Cahiers du Centre Européen de Géodynamique et de Séismologie*, **15**, Luxembourg.

Grünthal, G., Mayer-Rosa, D., and Lenhardt, W. A.: 1998, Abschätzung der Erdbebengefährdung für die D-A-CH-Staaten -Deutschland, Österreich, Schweiz, *Bautechnik* **75**(10), 753–767.

Grünthal, G. and Wahlström, R.: 2003, An Mw based earthquake catalogue for central, northern and northwestern Europe using a hierarchy of magnitude conversions, *J. Seismol* **7**(4), 507–531.

Grünthal, G. and Wahlström, R.: 2006, New Generation of Probabilistic Seismic Hazard Assessment for the Area Cologne/ Aachen Considering the Uncertainties of the Input Data, *Nat. Hazards* **38**, 159–176.

Gumbel, E. J.: 1958, *Statistics of Extremes*, Columbia University Press.

Krahe, P. (1997). Hochwasser und Klimafluktuationen am Rhein seit dem Mittelalter, Hochwasser - Natur im

Überfluß?. In: R. Immendorf (ed.), *Hochwasser -Natur im Überfluß?* (pp. 57–82). Heidelberg: Müller.

Munich Re: 1993, *Winterstürme in Europa – Schadenanalyse 1990 – Schadenpotentiale*, Munich Re.

Munich Re: 1999, *Naturkatastrophen in Deutschland – Schadenerfahrungen und Schadenpotentiale*, Munich Re.

Munich Re: 2001, *Winterstorms in Europe II – Analysis of 1999 losses and loss potentials*, Munich Re.

Munich Re: 2003, *Topics – Annual Review: Natural Catastrophes 2002*. Munich Re Group.

MURL (Ministry of Environment, Regional Planning and Agriculture in North Rhine-Westphalia): 2000, *Potentielle Hochwasserschäden am Rhein in NRW*, Final Report of the Ministry of Environment, Regional Planning and Agriculture in North Rhine-Westphalia.

Raschke, M.: 2003, *Die Korrelation zwischen Erdbebenstärke und Bauwerksschaden und deren Anwendung in der Risikoanalyse*, Ph.D. Thesis, Bauhaus-Universität Weimar.

Schmidt, H.: 1980, Zur Extrapolation empirischer Verteilungen der Windgeschwindigkeit für Standorte im Flachland und auf freier See, *Meteorologische Rundschau* **33**, 129–137.

Schwarz, J., Raschke, M., and Gerstenberger, A.: 2002a, Seismische Schadenspotentiale in deutschen Großstadträumen – Fallstudie Köln, In: Meskouris, K. Hinzen, K.-G. (eds.) *Schutz von Bauten gegen natürliche und technische Erschütterungen*, DGEB-Publikation Nr. 11, 69–83.

Schwarz, J., Raschke, M., and Maiwald, H.: 2002b, Seismic Risk Studies for central Germany on the Basis of the European Macroseismic Scale EMS-98, *Proc. 12th European Conference on Earthquake Engineering*, Elsevier Science LTD., Paper Reference 295.

Schwarz, J., Raschke, M., and Maiwald, H.: 2006, Comparative Seismic Risk Studies for German Earthquake Regions on the Basis of the European Macroseismic Scale EMS-98, *Nat. Hazards* **38**, 259–282.

Singh, V. P. and Strupczewski, W. G.: 2002, On the status of flood frequency, *Hydrol. Processes* **16**, 3737–3740.

Stadt Köln: 1996, *Hochwasserschutzkonzept Köln: Stadt Köln*, Dezernat Bauen und Verkehr, Köln.

Statistical Office Baden-Württemberg: 2000, Volkswirtschaftliche Gesamtrechnung der Länder. Bruttowertschöpfung der kreisfreien Städte und der Landkreise in der Bundesrepublik Deutschland 1980, 1992, 1994 und 1996, Stuttgart, Report 33.

Stedinger, J. R., Vogel, R. M., and Foufoula-Georgiou, E.: 1992, Frequency analysis of extreme events, In: Maidment, D. R. (ed.), *Handbook of Hydrology*, McGraw-Hill Inc., New York, pp. 18.1–18.66.

Troen, I. and Petersen, E. L.: 1989, *European Windatlas*, Risø National Laboratory, Roskilde, Denmark.

UNDRO: 1977, Composite Vulnerability Analysis – A Methodology and Case Study of the Metro Manila Area, Geneva.

UN/IDNDR: 2000, RADIUS: Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disasters, Geneva.

Urban Development Authority of Cologne: 2002, Kölner Strukturdaten 2001, http:// www.stadt-koeln.de/zahlen/index.html (Date of computation: 28.11.2002).

Van Westen, C. J., Montoya, L., and Boerboom, L.: 2002, Multi-Hazard Risk Assessment using GIS in urban areas: A case study for the city of Turrialba, Costa-Rica, In: *Proc. Regional workshop on Best Practise in Disaster Mitigation*, Bali, pp. 120–136.

Vogt, R.: 1995, Hochwasser in Köln, In: *Proc. Mit dem Hochwasser leben*, pp. 48–55.

Wieringa, J.: 1973, Gust factors over open water and built-up country, *Bound-Lay. Meteorol.* **3**, 424–441.

Wind, H. G., Nierop, T. M., Blois, C. J.de, and Kok, J. L.de: 1999, Analysis of flood damages from the 1993 and 1995 Meuse floods, *Water Resour. Res.* **35**(11), 3459–3465.

Wood, E. F. and Rodríguez-Iturbe, I.: 1975, A Bayesian approach to analyzing uncertainty among flood frequency models, *Water Resources Research* **11**(6), 839–843.