**Natural Hazards
and Earth
System Sciences**

Drivers of flood risk change in residential areas

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Abstract. The observed increase of direct flood damage over the last decades may be caused by changes in the meteorological drivers of floods, or by changing land-use patterns and socio-economic developments. It is still widely unknown to which extent these factors will contribute to future flood risk changes.

We survey the change of flood risk in terms of expected annual damage for residential buildings in the lower part of the Mulde River basin (Vereinigte Mulde) between 1990 and 2020 in 10-yr time steps based on measurements and model projections. For this purpose we consider the complete risk chain from climate impact via hydrological and hydraulic modelling to damage and risk estimation. We analyse what drives the changes in flood risk and quantify the contributions of these drivers: flood hazard change due to climate change, land-use change and changes in building values.

We estimate flood risk and building losses based on constant values and based on effective (inflation adjusted) values separately. For constant values, estimated building losses for the most extreme inundation scenario amount to more than 360 million € for all time steps. Based on effective values, damage estimates for the same inundation scenario decrease from 478 million € in 1990 to 361 million € in 2000 and 348 million € in 2020 (maximum land-use scenario). Using constant values, flood risk is 111 % (effective values: 146 %) of the 2000 estimate in 1990 and 121 % (effective values: 115 %) of the 2000 estimate for the maximum land-use scenario in 2020. The quantification of driver contributions reveals that land-use change in the form of urban sprawl in endangered areas is the main driver of flood risk in the study area. Climate induced flood hazard change is important but not a dominant factor of risk change in the study area. With the historical exception of the economic effects in Eastern Germany following the German reunification, value developments only have minor influence on the development of flood risk.

1 Introduction

Losses from natural disasters have dramatically increased during the last few decades, and in terms of economic losses, floods have been the most severe event type (Munich Re, 1997, 2004). It is expected that flood risk will continue to rise in consequence of a combination of climate change (e.g. Kundzewicz et al., 2005) and an increase in vulnerability, e.g. due to increasing flood plain occupancy, value increase in endangered areas and changes in the terrestrial system, e.g. land cover changes and river regulation.

While the concept of climate change and global warming is widely accepted, the impacts on the regional and local scales can be very different and require a closer look. In terms of the increase in flood hazard, recent studies show a mixed picture in Germany and Central Europe. Large scale flood regimes are affected differently by climate induced meteorological changes (Hattermann, 2005). Petrow et al. (2009a, b) analysed the frequency and magnitude of extreme flood events in Germany over the course of 52 yr (1951 to 2002). Positive trends (increase in magnitude and frequency of extreme discharges) could be found for the western, southern and central parts of Germany, while in the northeast changes in flood behaviour are small and not field

significant. Generally, changes in the winter season exceed those in the summer. Other studies (Merz and Blöschl, 2009; Blöschl and Montanari, 2010; Veijalainen et al., 2010, Prud-homme et al., 2010) discuss whether there is any significant increase in flood hazard at all.

Besides the impact of hazard change on flood risk, the accumulation of values in flood prone areas and changes in values are discussed as possible drivers for changes in risk. Indeed, the analysis of Barredo (2009) suggests that the past changes in economic losses are related to the latter two factors.

Land-use changes for the Elbe basin were analysed and land-use projections were developed within the GLOWA-Elbe framework ("Global Change Impacts on the Water Cycle in the Elbe River Basin", a German governmental funded research initiative) described by Hoymann (2010, 2011). These projections are used to analyse future risk developments within this study. Approaches integrating both land-use changes and flood hazard changes were undertaken by Archer et al. (2010), Orr and Carling (2006), De Roo et al. (2003) and Bronstert et al. (2002) and analyse the impact of land-use changes on flood discharges. A broad approach on the national scale that considers a range of flood risk drivers for fluvial and coastal floods was presented by Hall et al. (2003) for England and Wales. It combines quantified risk analysis and also resorts to expert appraisal for judging the influence of risk drivers to project future (2030 to 2100) flood risk under different scenario conditions.

Recent studies by Feyen et al. (2009), Bouwer et al. (2010) and te Linde et al. (2011) focus on both the impact of land-use changes and climate induced flood hazard changes and their influence on flood damage. Te Linde et al. (2011) investigated possible flood risk scenarios along the entire Rhine River and quantified the contribution of climate change and land-use changes to overall risk change. They considered two climate change scenarios, two land-use scenarios and the official flood protection targets of seven sections of the Rhine. An extreme inundation scenario was taken from the International Commission for the Protection of the Rhine "Rhine Atlas" (ICPR, 2001) to calculate potential damage and damage expectations for a number of land-use classes. Their analyses revealed a huge increase in expected annual damage (EAD) ranging from 54 % to 230 % in 2030 compared to 2000, depending on the climate change and land-use scenario. Approximately three-quarters of the increase were attributed to the climate change. These findings diverge from the assessments of the observed trends in economic losses in Europe, where no climate signal was detected (Barredo, 2009). Merz et al. (2010a) identify and describe the types and magnitude of changes in flood risk in Europe and the associated increase of uncertainty and analyse and discuss the implications for flood risk management.

To our best knowledge, no research has so far tried to close the whole risk chain from climate impact via hydrological and hydraulic modelling to damage and risk estimation while also considering building stock and value developments. Our first objective is to set up this model chain as the example of a meso-scale catchment in Germany. Second, we model the development of potential damage in the study area over time and transfer this damage to risk estimates. Third, we analyse which drivers cause the change of flood risk and quantify the contributions of these drivers: flood hazard change (change of the probability of events of a certain magnitude), land-use change (changes in residential area and the associated building stock composition) and changes in building values in terms of reconstruction costs for potentially affected residential buildings.

The paper has the following structure: Sect. 2 presents the study area, followed by Sect. 3 "Data and methods" that first gives an overview of the approach and then presents the data and models used in each step of the risk chain (climate and meteorology – hydrology – hydraulics – land-use and building stock – building values – damage – risk). Intermediate results from all chain links, the results of the damage estimates and risk analysis, and the quantification of the aforementioned influences to overall flood risk are presented and discussed in Sect. 4. Finally, we conclude our analysis and provide an outlook and recommendations for future research.

2 Study area

The study area comprises the lower part of the Mulde catchment downstream of the confluence of Zwickauer Mulde and Freiberger Mulde (Fig. 1). The Mulde River is a sinistral tributary to the Elbe River with a total length of 290 km (including Zwickauer Mulde) and a length of 124 km from the confluence of the main frontal flows (Zwickauer Mulde and Freiberger Mulde) to the Elbe River, the Vereinigte Mulde reach. All main frontal flows originate in the Ore Mountains. The Vereinigte Mulde River is located in the North German Plain and its catchment area is 2054 km^2. Cities located along the Vereinigte Mulde River are Dessau, Bitterfeld, Wolfen, Bad Düben, Wurzen and Eilenburg.

The study area contains 35 municipalities in their administrative borders of the year 2000. It comprises those municipalities which are partly inundated from an extreme event with a return period at gauge Golzern 1 of $T = 1000$ yr (probability as of 2000), corresponding to the maximum inundation scenario (S9) generated for this research. Municipalities that are located in the catchment but are not affected by the maximum scenario (approximately 1000 km^2) are excluded. The total area of the affected municipalities and thus the study area is 1063 km^2, of which about 8.4 % were covered by residential areas in 2000 (Corine Land Cover, 2000; Keil et al., 2005). Because of constraints in hydraulic modelling, no inundation scenarios could be created for the river reach from the gauge at Dessau-Muldebrücke to the Elbe River. This results in moderately underestimating damage and risk for the city of Dessau.
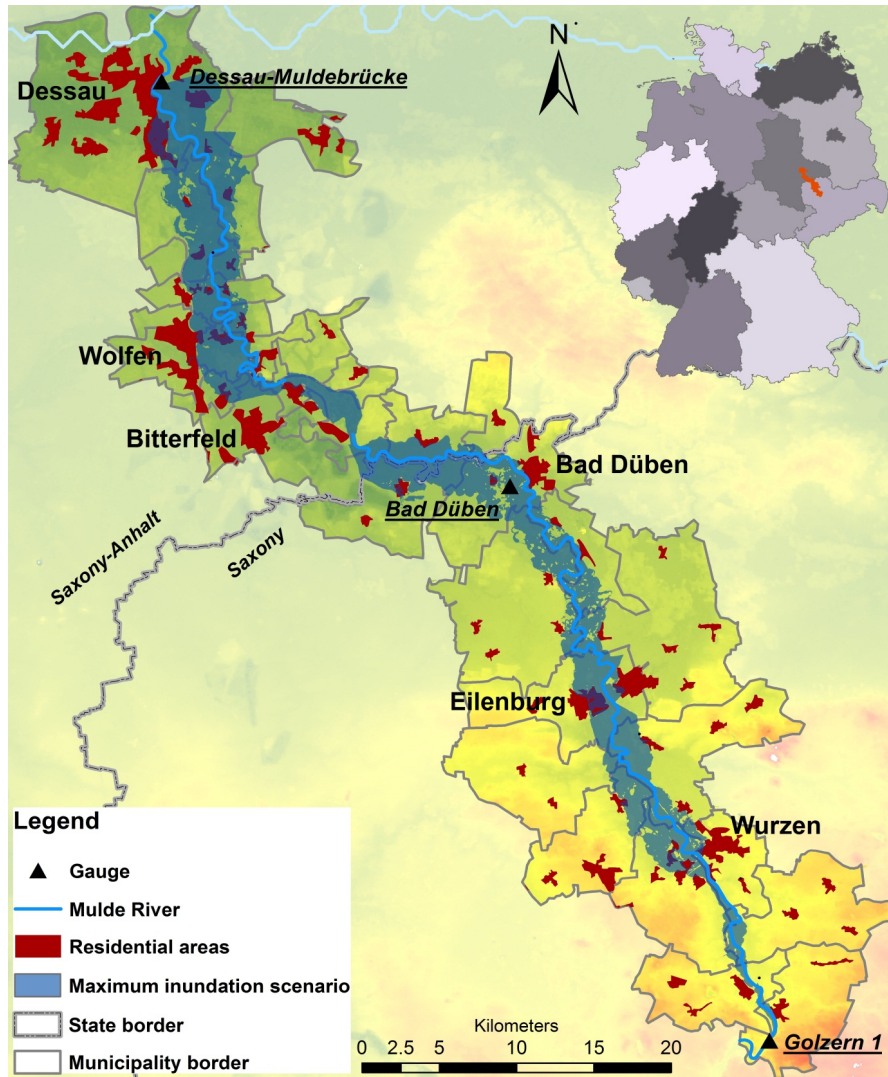
Fig. 1. Study area "Vereinigte Mulde" (municipality borders as of 2000).

The region has undergone major socioeconomic changes since 1990. Due to the economic problems after the reunification of Germany, the population decreased rapidly while, in the same time span, residential areas spread due to changes in the building of new residential structures. Unrestrictive policies and changes in demand resulted in single-family homes being the huge majority of houses built after 1990. This fact, combined with an increase of living space per capita, led to land consuming settlement patterns despite the population decrease. The land-use and building stock projections take this very special development into account.

Flooding of the Mulde River is a common natural hazard in the region. The August 2002 flood in the Elbe basin also affected the study area severely (Haase et al., 2003; Engel, 2004; BfG, 2006; LuG, 2009), causing many dike breaches and damage at other flood protection and river management

structures and massive losses; e.g. residential damage in the city of Eilenburg amounted to 77.12 million € (Apel et al., 2009).

In terms of climate induced flood hazard changes, the Mulde area is located in a transitional zone. The study by Beurton and Thieken (2009) on the regionalisation of flood regimes in Germany indicates that the study area cannot be directly assigned to one of the three major flood regime regions in Germany. Neither can it be regarded as a region with significant trends in flood frequency and magnitude (Petrow and Merz, 2009).

3 Data and methods

The central idea of our approach is to provide analyses on flood risk change and driver contribution based on a complete
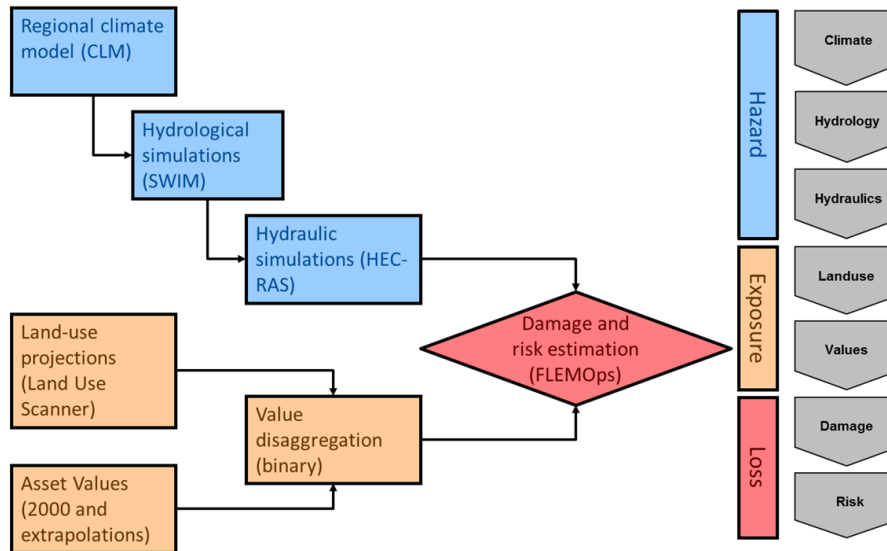
Fig. 2. "Flood Risk Chain" – Chain links and models.

risk chain. This was realized in a model cascade, which accounts for all risk chain links and considers scenarios of climate change, land-use change and asset value development (Fig. 2).

Risk was calculated in terms of expected annual damage (EAD) for 1990, 2000, 2010 and 2020 using sets of damage estimates with consistent scenario assumptions. Changing one parameter at a time, the contribution of flood risk drivers (flood hazard, land-use and building stock, building values) to overall risk change was quantified.

3.1 Quantification of the flood hazard

We defined the flood hazard for four points in time in ten year intervals based on the discharge time series for the preceding 50 yr (e.g. the flood hazard in 1990 is based on the discharge time series 1941 to 1990, see Fig. 3). Discharge data provided the input for inundation modelling and they were also used in the extreme value statistics to calculate flood probabilities. We used daily discharge data for full hydrological years (1st of November to 31st of October). Measured discharge data were used for the time period 1941 to 2000, and simulated discharge data, generated by a hydrological model with climate input based on a future climate scenario, were applied for the time period 2001 to 2020.

Two discharge gauges were used in this study (Fig. 1). Golzern 1, the most upstream gauge in the study area, is used as the reference gauge and as interface to the hydraulic modelling. Uninterrupted discharge measurements are available for 1935, onwards. For the Bad Düben gauge, daily discharge data are available for 1961, onwards.

Discharges corresponding to nine defined return periods (2, 5, 10, 20, 50, 100, 200, 500, 1000 yr) were computed

based on extreme value statistics for Golzern 1 for 2000. These peak flows were used in a hydraulic model to create a set of inundation scenarios. The discharges for the Bad Düben gauge were extracted from these inundation scenarios and return periods were calculated for the Bad Düben based on discharge time series (measured and modelled).

To project the risk changes associated with climate change according to the IPCC A1B emission scenario (A1: very rapid economic growth, global population peaks in mid-century, new technologies; B: balanced use of energy sources, IPCC, 2000), we applied climate data which have been dynamically downscaled from the ECHAM5 General Circulation Model (GCM) using the regional climate model (RCM) COSMO-CLM with a 0.2° horizontal resolution, provided by Deutsches Klimarechenzentrum (German Climate Computing Center – DKRZ 2006, 2007). The downscaled climate data were used to drive the regional hydrological model SWIM, which computes the discharge values at the reference gauge Golzern 1.

SWIM (Krysanova, Wechsung et al., 2000, Krysanova, Müller-Wohlfeil et al., 1998) is a process based semi-distributed hydrological model. For this study it was set up for the Mulde catchment using the following spatial input data: a digital elevation model (DEM; 25 m-DEM from BKG within Germany), land cover data (CLC) and soil data (BUEK, 1000). Observed climate time series based on the DWD station network (data set prepared by PIK using 264 climate stations, Österle et al., 2006) were used as input for model calibration and validation. The time series of meteorological data were interpolated onto a 1 km^2 grid, and aggregated to subcatchment average mean values using universal kriging with elevation for temperature data and the inverse distance weighting method for precipitation, humidity
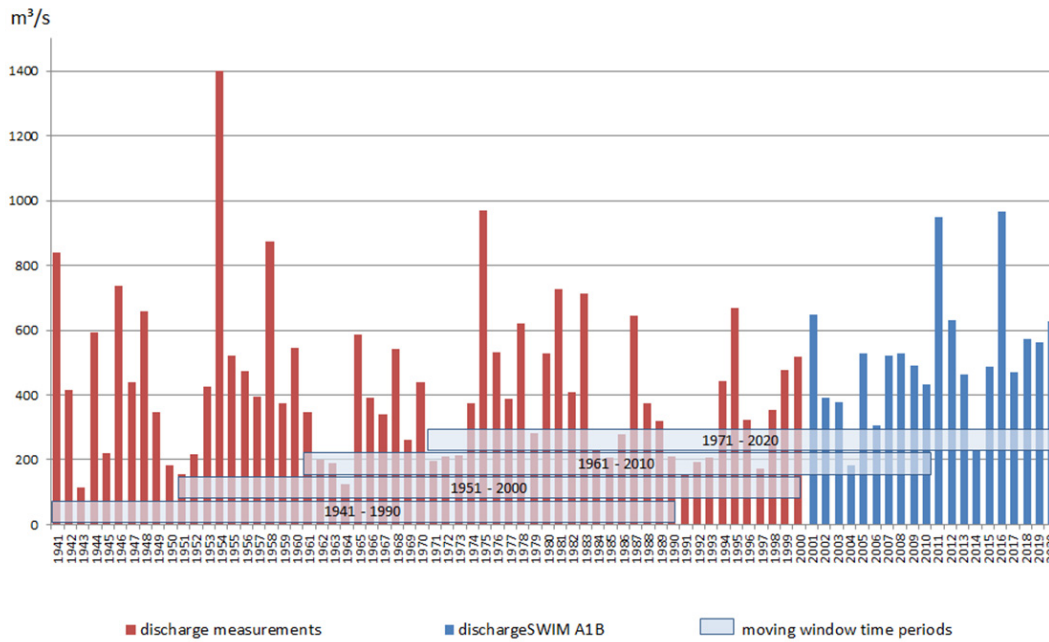
Fig. 3. Golzern 1 – Annual maximum series (AMS) of mean daily discharge 1941 to 2020 and shifting windows for flood hazard analysis.

and radiation. Daily precipitation data were corrected for undercatch errors, depending on wind speed and the aggregation state of the precipitation (Yang et al., 1999). The SWIM model was calibrated automatically using the SCE-UA algorithm (Duan et al., 1992, 1993, 1994) over a period of five years from 1991 to 1995 with one year for model initialization, and the results were further fine-tuned manually. For the calibration period the Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) at Golzern is 0.75 with a bias of 2.4 %; for the validation period (1961 to 2000 excluding 1991 to 1995) these values are 0.83 and -2.3 %. The performance of the model was evaluated visually with respect to daily flows, average and maximum monthly flow regimes, average and maximum annual discharges and flow exceedance curves at more than 20 gauges within the Mulde catchment, but the results cannot be shown here.

In order to generate discharge data for the scenario period 2001 to 2020, the hydrological model was run using the RCM data. These data were also mapped to subcatchments and a bias correction using quantile mapping (Piani et al., 2010) was applied to all climate variables based on the measured climate data interpolated to subcatchments.

To characterize the flood hazard, we computed the extreme value statistics at gauges along the study reach. A set of probability distribution functions was fitted to four 50-yr time series (1941–1990 till 1971–2020), as shown in Fig. 3 for gauge Golzern 1.

The resulting return periods are associated with the last year of each time slice. Since several probability distribution functions may satisfactorily describe the data variabil-

ity, we based our assessment on a composite distribution function approach (Wood and Rodríguez-Iturbe, 1975). The composite function resulted from weighting the distribution functions based on likelihood weights. Flood hazard was expressed as recurrence interval. The probability of each discharge was calculated for 1990, 2000, 2010 and 2020 based on 50 yr discharge time series. Recurrence intervals provided the input for modelling inundation scenarios and were considered in the damage model as one parameter for loss estimation. Finally, they were taken into account to determine flood risk in terms of EAD.

The hydraulic simulations were carried out using the HEC-RAS (USACE, 2010) model setup for the reach between gauges Golzern 1 and Dessau-Muldebrücke. From Golzern 1 to Bad Düben, the model was based on detailed cross-sections provided by LTV (Landestalsperrenverwaltung) Sachsen. In the downstream part of the reach, the cross-sections were extracted from the DEM with 25×25 m horizontal resolution.

The model was calibrated in a steady-state using the flow boundary conditions at Golzern 1, Bad Düben and Priorau gauges and normal depth as the downstream boundary. Modelled water depths from the steady-state run were interpolated and intersected with the DEM25. The resulting water depths at several points were compared with the high water marks and inundation areas from the 2002 flood compiled by DLR (Deutsches Zentrum für Luft- und Raumfahrt) and BKG (Bundesamt für Kartografie und Geodäsie) (Fig. 4). Manning's roughness coefficients were manually adjusted to reduce the RMSE between measured and simulated water
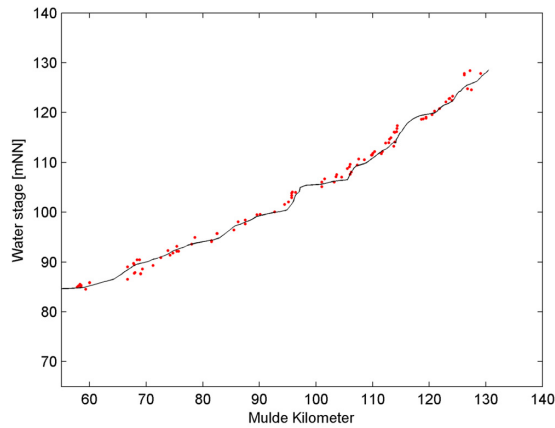
Fig. 4. Water stage profiles along the Mulde – Simulation results from steady-state run (black line) vs. observed values (red dots).

stages and to achieve the best estimations of flood areas, characterised by flood area indices (F1, F2, F3) which are defined as follows:

$$F1 = M1D1 / (M1D1 + M1D0 + M0D1)$$

$$F2 = (M1D1 - M1D0) / (M1D1 + M1D0 + M0D1)$$

$$F3 = (M1D1 - M0D1) / (M1D1 + M1D0 + M0D1)$$

M0D0 denotes the raster cells modelled as dry and observed dry, M0D1 denotes cells modelled as dry and observed as wet, M1D0 denotes cells modelled as wet and observed dry, and M1D1 denotes cells modelled as wet and observed wet.

From 118 high-water marks, 70 points are inundated in the modelling results and 48 are simulated as dry. RMSE for water depths after interpolation and intersection with the DGM25 amounts to 0.66 m.

Flood area indices were computed for two different model domains, which used different roughness parameterisation, and finally for the whole domain:

– The whole modelling domain from gauge Golzern 1 to Dessau-Muldebrücke

– From Golzern 1 to the border with Saxony-Anhalt (Saxony)

– From the border of Saxony to the gauge Dessau-Muldebrücke (Saxony-Anhalt)

The results are summarised in Table 1.

The results for the whole domain can be regarded as satisfactory and compare well with similar studies (Horritt and Bates, 2001, 2002). The model performance for the Saxon part of the reach appeared to be better than the part in

Table 1. Performance statistics of the inundation model in terms of flood area indices (FAI).

FAI/Domain	Whole domain	Saxony	Saxony-Anhalt
F1	0.77	0.85	0.68
F2	0.61	0.8	0.38
F3	0.7	0.75	0.65

Saxony-Anhalt. Manning's roughness values between 0.04 and $0.16 \, \mathrm{m}^{1\,3} \mathrm{s}^{-1}$ were achieved in the calibration process.

Inundation scenarios were derived for return periods of 2, 5, 10, 20, 50, 100, 200, 500 and 1000 yr based on extreme value statistics at Golzern 1 gauge. A typical flood hydrograph was derived from a cluster analysis of the historical flood hydrographs based on the approach of Apel et al. (2006) and upscaled to the selected return periods. The unsteady scenario runs assumed the normal depth as downstream boundary condition. Steady flows corresponding to the initial discharges of the flood hydrographs were used as initial condition. The maximum simulated water stages were intersected with the DEM25 using the HEC-GeoRAS tool to obtain inundation depths.

Flood protection measures are not taken into account due to the lack of consistent information on such structures.

3.2 Exposure

Damage modelling for residential buildings requires information on spatial distribution specific value as well as quality of the building stock.

Our survey used land-use data from CLC1990 and CLC2000 that were published in 2005 (a revised version of CLC1990 is included in the CLC2000 data set). These data were derived from Landsat satellite imagery and provide a consistent land-use classification for Europe (for details, see Keil et al., 2005).

We reclassified CLC data into two classes – residential and non-residential – aggregating class 111 (Continuous urban fabric) and 112 (Discontinuous urban fabric) to residential land-use. All other classes were aggregated to non-residential land-use as we did not assign any residential building values to these classes. Land-use projections for 2020 were taken from Hoymann (2010, 2011) who developed land-use scenarios for the entire Elbe basin. The 2010 projections are an interpolation of year 2000 input data derived from CLC2000 land-use information and year 2020 projections. Hoymann based the projections on calculations of the demand for residential land-use. The allocation of residential land-use was then modelled with the GIS-based Land Use Scanner (LUS) model (Hilferink and Rietveld, 1999; Schotten et al., 2001; Hoymann, 2008) that allocates land-use changes to grid cells using regional claim sets (land-use demand) and suitability maps (current land-use, physical suitability, distance relations, regional spatial

planning, nature protection areas). The LUS application for the Elbe basin assigns land-uses to a 250 m-grid. For this survey we used a derivate of the land-use change scenarios which provide the proportion of expected residential land-use per grid cell. The different land-use change scenarios were based on the IPCC emission scenario storylines A1 (rapid economic growth) and B2 (local environmental sustainability) (IPCC 2000). These global storylines were transferred to the regional developments in the Elbe basin. To consider regional influences, both trajectories were combined with two different land-use policies: maintaining the current (weak) land-use policy (^{0}) and restrictive land-use policy ($^+$) (Hoymann, 2011, details in Hartje et al., 2008). Four residential land-use development scenarios were used in this survey for 2010 and 2020, respectively:

$A1^0$: Globalisation with weak spatial planning policy

$A1^+$: Globalisation with very restrictive spatial planning policy

$B2^0$: Differentiation with weak spatial planning policy

$B2^+$: Differentiation with very restrictive spatial planning policy

To make land-uses comparable for the whole research period, some modifications were conducted on the CLC data: CLC1990 and CLC2000 polygons are intersected with the 250 m-grid from the LUS projections. The proportion of residential land-use in each cell was identified and assigned as cell value to the respective residential land-use grids for 1990 and 2000.

A complete set of building values on the municipality level was created within the CEDIM framework by Kleist et al. (2006) for the year 2000. The cost approach was selected to value buildings and consequently, values were given as reconstruction costs, i.e. the market price of the construction works for restoring a damaged building.

The values were disaggregated, i.e. distributed to the respective land-use units. Thieken et al. (2006) and Wünsch et al. (2009) applied and tested various disaggregation approaches and analysed the influence of these disaggregation schemes on the uncertainty of flood damage estimations. They commended the application of a binary disaggregation approach when using CLC data. The appropriateness of this disaggregation approach was confirmed by our own tests using it for damage estimations in the Saxon parts of the Mulde basin.

The total value of residential buildings for each municipality was taken from Kleist et al. (2006) and this figure was divided by the residential area (m^2) as taken from the land-use information for the year 2000 to get a specific value

per square meter for residential land-use only. These values were then multiplied with the proportion of residential land-use per grid cell resulting in a monetary building stock value for each grid cell. The latter step was done for the 1990 and 2000 land-use information and all 2010 and 2020 land-use scenarios. Damage and risk estimations are comparable for different points of time because the building values per m^2 are constant and, accordingly, the influence of inflation is externalised.

To analyse the influence of building value changes with time, values in terms of reconstruction costs were time adjusted by using official indexed construction prices (Baupreisindex – BPI, DESTATIS, 2010b) for 1990 and 2010 and a linear extrapolation of this index for 2020. The BPI gives the development of construction prices relative to a reference year (for this study the year 2000) and can be interpreted as the inflation of building construction prices. The inherent changes in building values are identified by the inflation-adjustment of time adjusted values with indexed consumer prices (Verbraucherpreisindex – VPI, DESTATIS 2012). The BPI is based on the prices for construction works. These construction works contribute only a small degree to the calculation of the VPI and hence this influence was ignored for our calculations. These adjusted values will be referred to as "effective values" or "effective value changes" in contrast to the "constant values" in the preceding paragraph.

Municipal building stock characteristics were originally derived from a Germany-wide data set for the year 2000 created by INFAS Geodaten in combination with official statistical data about building type and quality. Average building quality per municipality (5 classes, aggregated for use in the applied damage model to only two classes: high quality and medium/low quality, see Thieken et al., 2008) and the composition of residential building stock in terms of percentages of single-family houses, semi-detached/detached and multifamily houses is provided on the municipality level for 2000. Since only a few municipalities in Germany (and none in the study area) had a high average building quality, we assumed that the class affiliation (medium to low average building quality) remains constant for all municipalities in the study area, all points in time and all scenarios.

The composition of residential building stock in Germany in terms of building types was retained by applying a cluster-centre approach (Thieken et al., 2008) based on the share of the three building types in 2000. This resulted in five cluster centres to which all municipalities were assigned. To calculate the building stock composition for the study area in 1990, 2010 and 2020, a linear extrapolation following official statistics about builds and demolitions for each building type at the district level (Landkreise and Kreisfreie Städte) from 1995 to 2004 (DESTATIS 2010a) was used. The linear trend was applied to the reference data from Thieken et al. (2008) on the municipality level for 2000 and extended back to 1990 and forward to 2010 and 2020. We assumed uniform trend behaviour for all municipalities within one district.

The building stock compositions for each municipality and point in time are related to the year 2000 cluster-centres. Cluster "borders" were constructed in a de Finetti diagram (Tri-Plot freeware by Graham and Midgley, 2000) and the direction and magnitude of the changes in building stock composition for each municipality are given.

3.3 Flood damage and flood risk

We used a modified version of the multi-criteria Flood Loss Estimation Model for the private sector (i.e. residential buildings) FLEMOps (Thieken et al., 2008; Elmer et al., 2010) to estimate flood damage to residential buildings. A number of stage damage functions exist (see, e.g. Merz et al., 2010b for a review) and some models provide a number of functions to account for, e.g. different building types or loss sectors, but FLEMOps is the only validated empirical multi-factor damage model for Germany. Contrary to simple stage-damage functions, FLEMOps uses additional parameters such as building type, building quality and flood probability in the damage calculation procedure. The damage modelling process on the meso-scale is given in Fig. 5.

FLEMOps is derived from empirical damage data of 2158 residential loss cases in Germany acquired after floods in 2002, 2005 and 2006 (Thieken et al., 2005; Kreibich and Thieken, 2008). The latest model version FLEMOps+r considers water level, building type and building quality and additionally the effects of flood probability (in terms of recurrence interval), precautionary measures and water contamination (Eq. 1) and is presented and validated in Elmer et al. (2010). However, in this study we ignored the influence of the latter two factors since no reliable methodology is available to model scenarios for precaution and contamination. A plausibility check for this version was undertaken for four Saxon municipalities in the Mulde catchment with more than 300 damaged residential buildings in the 2002 flood event (Eilenburg and Bennewitz in the study area, Grimma just south of the gauge at Golzern and Döbeln at the Freiberger Mulde River). Official damage data were provided by Sächsische Aufbaubank (SAB – Saxon Bank for Development) for the 2002 event. Results from the comparison with modelled damage using the 2002 flood extent information are very satisfactory: an underestimation of just 12 % with estimates for the single municipalities ranging from -32 % to $+12$ % of the official residential damage.

Equation (1) was used to estimate relative building damage D_E for each scenario.

$$D_{E_j} = \left(\frac{\Sigma^{n_j} D_{h_j}}{n_{h_j}} \times \frac{\Sigma^{n_j} D_{tq_j}}{n_{tq_j}} \times \frac{n}{\Sigma^{1_n}} \right) \times \Sigma \frac{D_{pcT_j}}{D_{pcT_j}} \times \frac{1}{n_{pcT_j}} \quad (1)$$

Equation (1) with:

j = (damage) case

D = relative damage (interview information)

D_E = estimated relative damage

h = water level class

t = building type

q = building quality

p = precaution index value (=1)

c = contamination index value (=1)

T = recurrence interval class

pcT = parameter combination (precaution, contamination and recurrence interval) class

n = number of cases

EAD was used as the indicator to describe flood risk (RI). The risk was defined as the probability of an impact times the damage assigned to the magnitude of this impact. The EAD was computed by integrating the area under the risk curve, which is constructed through interpolation of the discrete flood scenarios used in this study (Eq. 2).

$$RI = E\{D\} \approx \sum_{i=1}^{n} D_i \left(\frac{P_i + P_{i+1}}{2} \right) |P_i - P_{i+1}| \quad (2)$$

Equation (2) with:

RI = risk

$E\{D\}$ = damage expectation

i = scenario number

n = number of scenarios

D = damage

D_i = damage scenario

P = probability

P_i = scenario probability

3.4 Quantification of risk change drivers

For the separation and quantification of the contribution of risk influencing factors to overall risk change, the risk influencing parameters (flood hazard associated with climate change, land-use, building values) were changed one-at-a-time. This resulted in three single-driver scenarios, which were compared to the reference scenario.
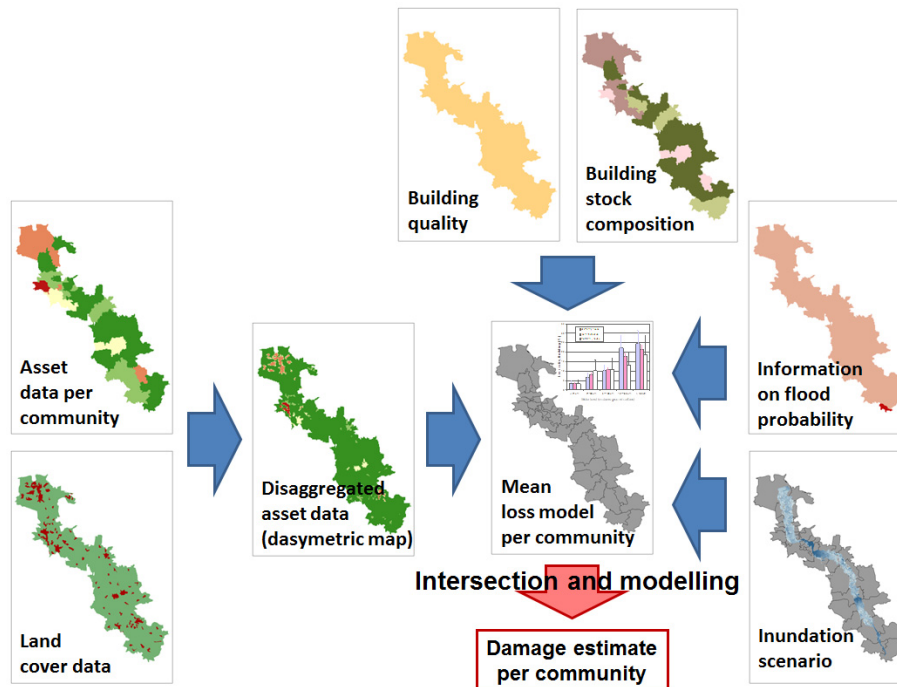
Fig. 5. Steps for meso-scale flood damage estimation with FLEMOps+r.

Table 2. Discharges and flooded area for inundation scenarios S1 to S9.

Scenario	Discharge [m³ s⁻¹]		Inundated area [km²] (Golzern 1 to Dessau-) (Muldebrücke)
	Golzern 1	Bad Düben	
S1	352	324	127
S2	569	515	151
S3	725	659	162
S4	881	802	169
S5	1090	984	178
S6	1251	1118	184
S7	1418	1230	189
S8	1650	1371	194
S9	1842	1462	197

4 Results

4.1 Flood hazard

The peak discharges of the synthetic events are presented in Table 2 and correspond to the recurrence intervals of $T = 2$ (S1), 5 (S2), 10 (S3), 20 (S4), 50 (S5), 100 (S6), 200 (S7), 500 (S8), 1000 (S9) years for Golzern 1 in 2000. Recurrence intervals for other points in time vary (see Fig. 6). Modelled discharges at Bad Düben are smaller for the same scenarios because constant volumes are routed downstream and the hydrographs experience attenuation (Table 2).
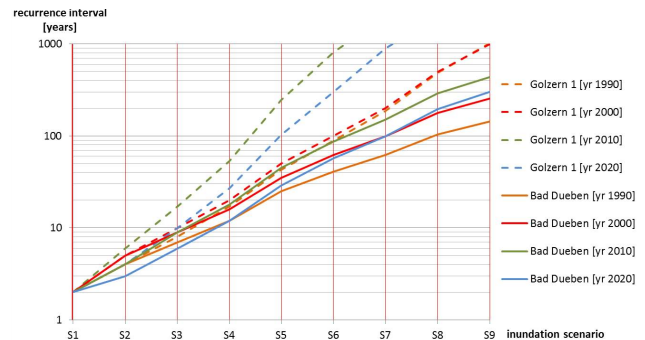

Fig. 6. Recurrence intervals for inundation scenarios at gauges Golzern 1, Bad Düben.

Figure 6 shows the changes of return periods with time for all selected scenarios. The change in time was computed in 10-yr slices as shown in Fig. 3.

The dotted lines give recurrence intervals for Golzern 1, the solid lines for Bad Düben. The calculated flood probabilities show no constant increase or decrease. For the different points in time, flood hazard ranks differently, e.g. the probability of an S2 scenario discharge at the Bad Düben gauge is highest in 2020 and lowest in 2000, while for the S9 scenario discharge the probability ranking is 1990 – 2000 – 2020 – 2010. Single extreme events (e.g. events in the 1950s which are included in the hazard estimation for 1990 but not for 2000) have a dominant influence on hazard estimation and, for short periods of time, will exceed the influence
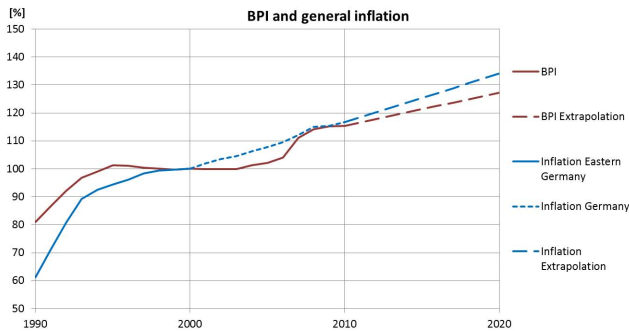
Fig. 7. Construction prices (BPI) and general inflation (VPI) – development and extrapolation to 2020 (base year 2000 = 100 %).

of long term developments. Hence, it might be better to speak of (natural) climate driven hazard variability than hazard change.

Recurrence interval is used as a damage influencing factor in damage modelling. For this purpose, the recurrence intervals are classified (class 1: 1 to 9 yr; class 2: 10 to 99 yr; class 3: >=100 yr), and each gauge catchment in each scenario at every point in time is assigned to one of the three classes (e.g. for 1990, the catchment area of Bad Dueben in scenario S9 is assigned to recurrence interval class 3; see Fig. 6). Between time steps there are only a few changes in recurrence interval class.

4.2 Exposure

Residential land-use corresponding to the CLC classes 111 and 112 covered 7.9 % of the study area in 1990 and 8.4 % in 2000 and shows further increase in the projections for 2010 and 2020. The share of residential land use is given in Table 3 for 1990, 2000 and the extreme projections $B2^+$ and $A1^0$ for 2010 and 2020.

While urban sprawl slows down after 2000, this decrease is twice as high for the "Differentiation scenario" with much stricter land use policy ($B2^+$) than for the "Globalisation scenario" with weak spatial planning policy ($A1^0$).

Effective building values are adjusted for the different points in time by applying the BPI construction price index (DESTATIS, 2010b) and the VPI consumer price index (DESTATIS, 2012). The BPI and VPI development over the past 20 yr can be seen in Fig. 7.

BPI shows periods of stagnation (1995 to 2003) and rapid growth (up to 8 % p.a. – 2007). Overall, there is a positive linear trend that is extrapolated to 2020. The increase of consumer prices in Germany since 2000 is nearly constant and the linear trend for this time span is extrapolated to 2020. Consumer prices for Eastern Germany show a similar pattern from 1994 to 2000. From 1990 to 1993 there is a steep rise in consumer prices following the German reunification. This increase substantially exceeds the rise of building construction costs and thus results in a decrease of effective building
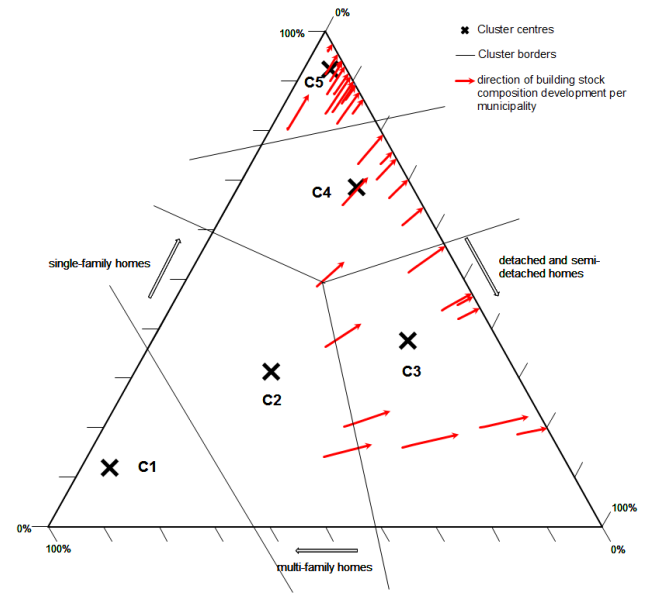

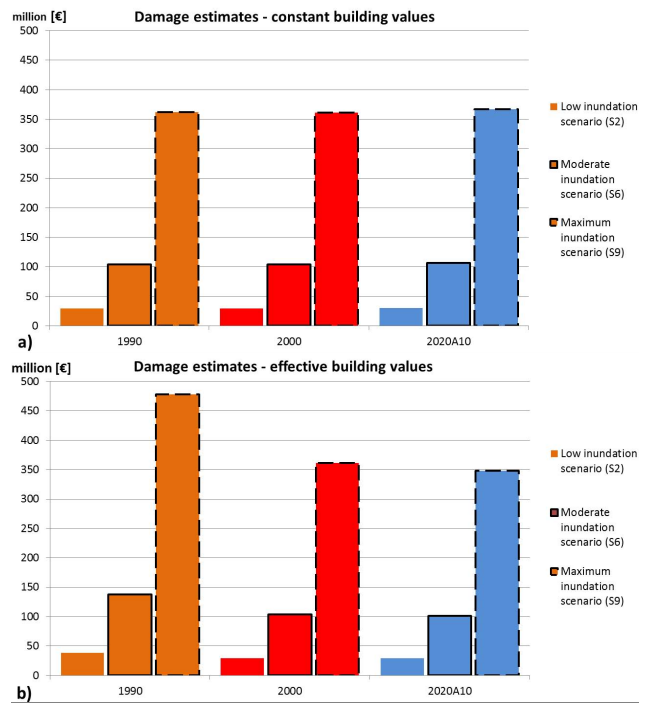**Fig. 8.** Development of building type composition in the study area 1990 to 2020.

Fig. 9. Estimated damage using **(a)** constant building values and **(b)** effective building values for selected inundation scenarios.

values. Effective as well as constant asset values are used in the form of raster maps as input for flood damage modelling.

The composition of the building stock is closely related to land-use change patterns. Urban sprawl is the dominant process of residential development in the Mulde basin

Table 3. Development of residential land-use 1990 to 2020.

Residential Land-Use	1990	2000	2010		2020	
			$B2^+$	$A1^0$	$B2^+$	$A1^0$
% of total area	7.9	8.4	8.5	8.7	8.7	9.1
% of 2000	94.2	100	101.5	103.8	103.2	108.0
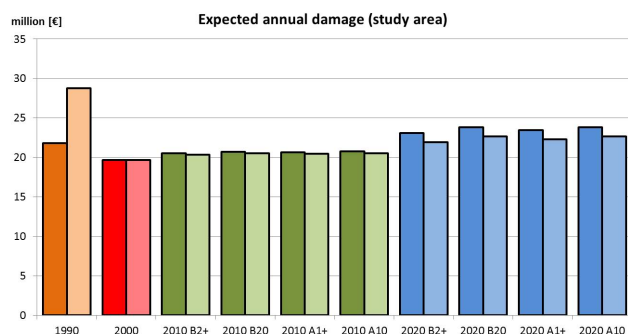
Fig. 10. Flood risk (EAD) development for the study area 1990 to 2020. Dark colours indicate the use of constant values; light colours the use of effective values.

(Hoymann, 2010). This is consistent as new buildings are nearly exclusively of the single-family home type. Figure 8 shows the development of building stock composition in the study area. Each axis of the diagram gives the share of the respective residential building type, summing up to 100 % (in a clockwise direction). Every red arrow represents one municipality in the study area, stating the direction and magnitude of the development from 1990 to 2020. Cluster centres for all German municipalities for the year 2000 are marked by crosses named C1–C5. The building type clusters can be characterised as:

C1 dominated by multi-family homes

C2 mixed (high share of multi-family homes)

C3 mixed (high share of detached and semi-detached homes)

C4 mixed (high share of single-family homes)

C5 dominated by single-family homes

A clear cluster affiliation for each municipality in the study area at every point in time is performed by minimizing the distance to the next cluster centre.

For all municipalities, regardless of original cluster membership, the share of single-family homes rises while the percentage of multi-family homes drops. Shares of detached and semi-detached homes show a slight increase in most and a remarkable increase in some (C2, C3) municipalities.

4.3 Flood damage and flood risk

The maximum estimated flood damage for residential buildings in the study area for the most extreme inundation scenario (S9) is 366.6 million € using constant values ($A1^0$ land use scenario in 2020, Fig. 9a) and 477.8 million € (1990, prices as of 2000) using effective values (Fig. 9b). Damage estimations for the (high probability) inundation scenario S2 are one order of magnitude smaller (see Fig. 9).

While the estimated damage for the study area varies by more than an order of magnitude, depending on the inundation scenario, the relative change of damage over time is nearly constant for all inundation scenarios (constant values, Fig. 9a). The picture is different when effective building values are used: While the changes from 2000 to 2020 ($A1^0$ scenario conditions) are relatively small, damage estimates for 1990 are more than 30 % higher than for 2000 with only minor differences between scenarios. Other scenario conditions ($A1^+$, $B2^0$, $B2^+$) result in similar differences of estimated damage from 2000 to 2020.

The integration of the risk curve over damage estimates for all return periods results in estimations of EAD. Changes in EAD with time (Fig. 10) show an increase from 2000 to 2020 for all scenarios and constant as well as effective values. EAD development from 1990 to 2000 shows decreasing risk for constant (from 21.8 million € to 19.7 million €) as well as for effective values (28.8 million € to 19.7 million €). This huge decrease when using effective values can be attributed to the steep rise of general inflation after 1990 and should be seen as an exceptional economic situation in the historical context.

Different land-use scenarios result in maximum differences of EAD between scenarios of 0.2 million € (or 1 %) for 2010 and 0.7 million € (approximately 4 %) for 2020.

A closer look at the results of the municipality level reveals that the spatial variability of risk in the study area is quite high. It becomes evident that the major cities of Dessau and Eilenburg contribute 2/3 to the total EAD as of 2000. The share distribution shown in Fig. 11 is characteristic for all points in time, which is explained by relatively homogeneous land-use and building stock development.

Small to moderate events with recurrence intervals of up to 20 yr dominate risk expectation, as exemplified in Fig. 12 for the year 2000. This result is in accordance with earlier studies by Merz and others (Merz, 2006; Merz et al., 2010a; Merz and Gocht, 2001). It is important to keep in mind that
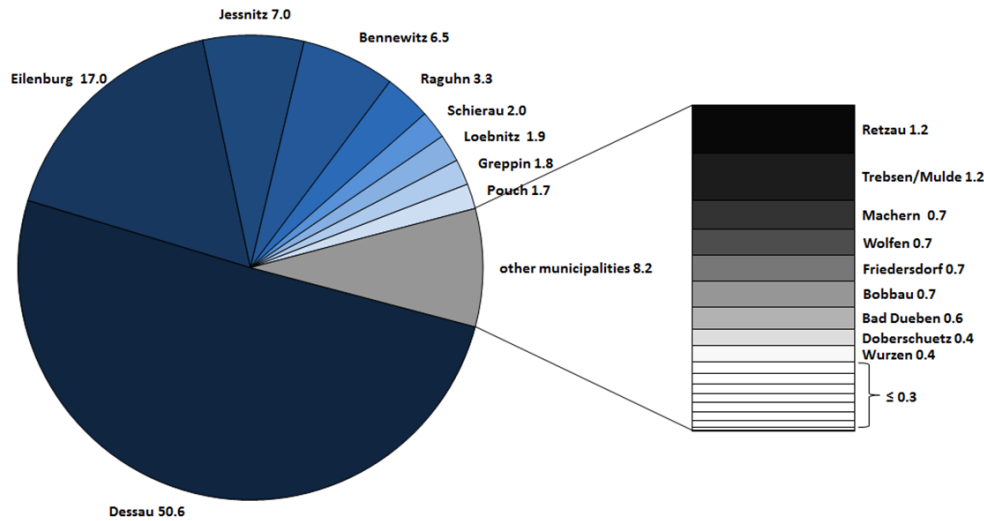
Fig. 11. Contribution of different municipalities to study area EAD as of 2000.

flood protection is omitted in this study. The insertion of protection targets would erase damage caused by floods smaller than the design flood and hence influence the contribution share of events of different magnitude.

On the municipality level, relative risk changes over time vary greatly. Small scale developments, e.g. in land-use change, have significant influence and can lead to strong changes in EAD. Still, the risk change over time in the entire study area is dominated by and hence very similar to the development in the large municipalities.

4.4 Quantification of risk change drivers

Estimating damage and risk in monetary values without adjusting them to a given reference year would give the reconstruction costs – the financial damage – at the time when the damage is realized or the risk is accounted for. But in this concept, inflation is not externalised and thus risk comparisons over time are biased. This can be avoided by using constant values (per unit of area). In this study, constant year 2000 values per m^2 were used for all points in time. Nevertheless, construction price development can differ from general inflation and hence, an effective change of building values with time is possible. To consider the influence of these inherent value changes as a driver of flood risk, we adjusted year 2000 values to 1990, 2010 and 2020 prices by applying the BPI and correct the results for general inflation (VPI). Consequently, the monetary results (damage/risk estimations) are given in € at the prices of the base year 2000. The effective value of residential buildings in the study area decreased rapidly after the introduction of the "Deutsche Mark" in Eastern Germany in 1990 due to special economic effects: The harmonisation of consumer prices in both parts of Germany resulted in high inflation rates in East-

ern Germany until 1993. The increase of building construction prices was much smaller in these years. Since the mid-1990s, the volatility of the BPI was still higher than that of general inflation but both show similar trend behaviour (see Fig. 7).

Very few areas changed from residential use to other land-use types in the time frame of our study. All significant changes were settlement expansions, predominantly into prior agricultural areas. This expansion was a highly homogenous process. Demand and supply of living space changed abruptly in 1989/1990 in Eastern Germany and since then, single-family houses make up more than 90 % of new residential buildings in the study area. As the FLEMOps+r damage model considers differences in relative damage due to building types, the relation between land-use increase and increase of (estimated) damage is not linear.

The moving window approach to derive gauge specific flood hazard and its change by applying extreme value analyses and the fact that no significant trends are detected for extreme discharges in the study area is reflected in the hazard specific risk estimates: There is no steady increase with time.

The separation of influences on overall risk change shows major differences in the contribution of the three drivers to risk increase (Table 4). Based only on the development of effective values, risk in 1990 is 132 % of the risk in 2000. The further decrease is small: Starting in 2000, the decrease is 1 % to 2010 and 5 % to 2020 for our test case.

Climate induced hazard change leads to changes in damage risk of 17 % maximum from 2000 to 2020. But the hazard shows strong fluctuations. As stated before, climate change and flood hazard change analyses from earlier studies showed no or minor changes for the region and these findings are affirmed here. Hence, the influence of climate change on
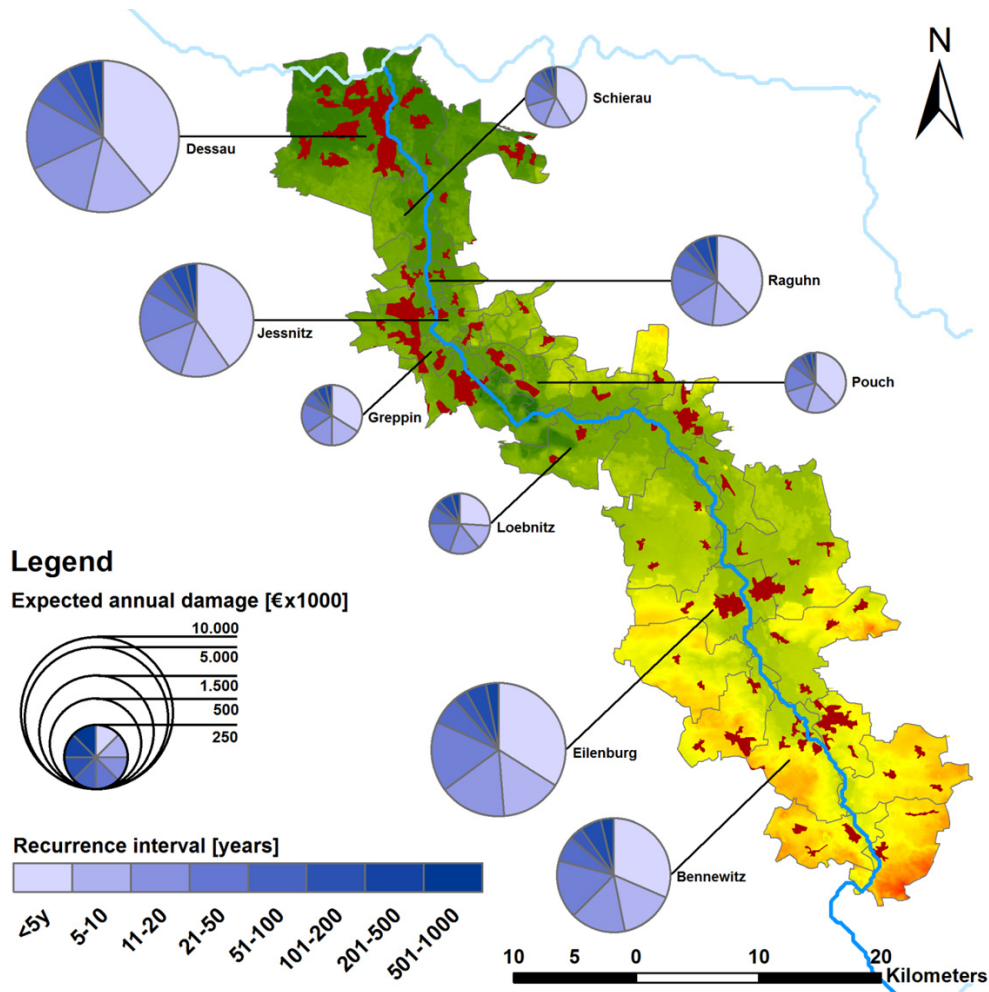
Fig. 12. Contribution of event magnitude to EAD in 2000 for the most affected municipalities.

risk development cannot be interpreted for this region, but the flood hazard fluctuations give an impression of the magnitude of the influence of climate – or better flooding – variability.

The third type of development considered in this analysis was changes in land use and building stock composition. With this parameter as single influence risk in 2000 is 20 % higher than 1990 and increases by a maximum of 32 % (A1[0]-scenario) from 2000 to 2020. This parameter can be influenced by regional and national (land-use) policies. The maximum risk increase of 21 % (constant values) or 15 % (effective values) can be lowered by up to 4 percentage points (2000 to 2020) when applying strict regulations to the development of residential areas ([+]-scenarios).

5 Conclusions

In this study we established a flood risk chain from climate influences on meteorology over hydrological and hydraulic modelling to damage and risk estimations, using measured data and state-of-the-art modelling approaches. The results show high flood risk in the area and an increase of this risk for residential buildings from 2000 to 2020. When using constant building values, a slight decrease of flood risk is found from 1990 to 2000 that can be attributed to a decrease in the flood hazard. Based on effective values, there is a distinct reduction of EAD for this time frame.

The spatial risk distribution and the risk contribution of events of different probability show that risk for the study area is dominated by the residential areas of the major cities. Frequent events with recurrence intervals up to approximately 50 yr cause more than 80 % of the annually expected damage.

Attribution of risk changes to single drivers showed that the expansion of residential areas is the main driver of flood risk in the study area. Consequently, the potential influence of local and regional land-use policies is substantial and could contribute significantly to short-term and/or medium-term risk mitigation: As for land-use scenarios that assume

Table 4. Overall risk change compared to single parameter risk change for the study area.

Year/ Scenario	Expected annual damage				
	Hazard	Land use and building type	All (constant values)	Effective building value	All (effective building value included)
1990	21.897.442 € 111 %	15.848.608 € 80 %	21.788.503 € 111 %	26.009.414 € 132 %	28.781.278 € 146 %
2000	19.690.098 € 100 %	19.690.098 € 100 %	19.690.098 € 100 %	19.690.098 € 100 %	19.690.098 € 100 %
2010 A1^0	20.443.715 € 104 %	23.074.321 € 117 %	20.754.312 € 105 %	19.467.214 € 99 %	20.523.674 € 104 %
2010 A1$^+$	20.443.715 € 104 %	22.981.878 € 117 %	20.673.118 € 105 %	19.467.214 € 99 %	20.443.381 € 104 %
2010 B2^0	20.443.715 € 104 %	23.054.057 € 117 %	20.734.970 € 105 %	19.467.214 € 99 %	20.504.546 € 104 %
2010 B2$^+$	20.443.715 € 104 %	22.846.038 € 116 %	20.550.287 € 104 %	19.467.214 € 99 %	20.321.916 € 103 %
2020 A1^0	23.113.710 € 117 %	25.922.105 € 132 %	23.841.090 € 121 %	18.713.324 € 95 %	22.658.396 € 115 %
2020 A1$^+$	23.113.710 € 117 %	25.453.723 € 129 %	23.436.873 € 119 %	18.713.324 € 95 %	22.274.231 € 113 %
2020 B2^0	23.113.710 € 117 %	25.901.276 € 132 %	23.817.529 € 121 %	18.713.324 € 95 %	22.636.004 € 115 %
2020 B2$^+$	23.113.710 € 117 %	25.051.534 € 127 %	23.069.287 € 117 %	18.713.324 € 95 %	21.924.880 € 111 %

strict land-use policies ($^+$-scenarios), the risk increase is considerably limited.

Climate induced flood hazard change is also an important but not a dominant factor of risk change in the study area. However, for a detailed analysis of hazard change, the study period might be quite short, and in the long term, global warming might change the flood regime in northeastern Germany in a way not accounted for in our analysis.

The influence of effective value development must be interpreted with caution: The overall influence of effective value changes appears to be weak. Construction price and consumer price indexes show concurring trend behaviour since the mid-90s and differences can be explained by the higher volatility of construction prices as they are more influenced by economic cycles than general inflation. The distinct reduction of EAD from 1990 to 2000 is caused mainly by value changes. This is an effect of historically exceptional economic developments in Eastern Germany in the early 1990s. The benefit of using effective values in future research seems questionable, at least if damage (and building value) is defined as reconstruction costs, i.e. the cost approach is selected to value residential buildings. Using real estate market prices as building values, i.e. the sales comparison approach, might result in different recommendations.

Some more points should be accounted for in future research: Protection measures were not considered in this study due to a lack of data. Protection structures like dams reduce the influence of high-probability flood events on flood risk. This has implications for risk comparison. Flood hazard does not change evenly over time for the entire range of event probabilities (see Fig. 6). Relative risk change from time to time that considers the whole range of event probabilities is different from relative risk change when high probabilities are omitted. If available, such data should be included to make flood risk assessment more realistic. Official statistics will probably take a large step forward in data quality in terms of up-to-dateness and accuracy after the 2011 census in Germany. Current approaches and data sets (e.g. building stock) should be checked and updated accordingly. For the study period, our risk estimation concentrated on residential buildings as an indicator for flood risk. A comprehensive risk assessment should include all economic sectors. We used the best available data and models, but an ensemble approach would allow for better estimation of the inherent uncertainties of the model chain. Finally, expanding the approach to the macro-, i.e. national, scale would enable the calculation of trans-basin flood risk and hence the overall flood risk associated with large scale events.

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