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Discussions

Adaptability and transferability of flood loss functions in residential areas

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Abstract

Flood loss modeling is an important component within flood risk assessments. Traditionally, stage-damage functions are used for the estimation of direct monetary damage to buildings. Although it is known that such functions are governed by large uncertainties, they are commonly applied – even in different geographical regions – without further validation, mainly due to the lack of data. Until now, little research has been done to investigate the applicability and transferability of such damage models to other regions. In this study, the last severe flood event in the Austrian Lech Valley in 2005 was simulated to test the performance of various damage functions for the residential sector. In addition to common stage-damage curves, new functions were derived from empirical flood loss data collected in the aftermath of recent flood events in the neighboring Germany. Furthermore, a multi-parameter flood loss model for the residential sector was adapted to the study area and also evaluated by official damage data. The analysis reveals that flood loss functions derived from related and homogenous regions perform considerably better than those from more heterogeneous datasets. To illustrate the effect of model choice on the resulting uncertainty of damage estimates, the current flood risk for residential areas was assessed. In case of extreme events like the 300 yr flood, for example, the range of losses to residential buildings between the highest and the lowest estimates amounts to a factor of 18, in contrast to properly validated models with a factor of 2.3. Even if the risk analysis is only performed for residential areas, more attention should be paid to flood loss assessments in future. To increase the reliability of damage modeling, more loss data for model development and validation are needed.

1 Introduction

Flood damage assessment attracts growing attention in recent years as its consideration in frame of flood risk analysis is still new and immature (Büchele et al., 2006; Merz et al., 2010). Besides the interest within the scientific community, the need of flood loss estimations ranges from decisions on loss compensations by disaster funds and financial appraisals of the (re-)insurance sector to risk maps required by legislation like the Floods Directive 2007/60/EC and evaluation of risk reduction projects (Dutta et al., 2003; Downton and Pielke, 2005; Merz et al., 2010; Jongman et al., 2012; Meyer et al., 2013). The European Floods Directive 2007/60/EC, for instance, requires for all European member states flood hazard and flood risk maps at the river basin scale in areas of significant flood risk (EC, 2007). Flood risk considers usually the hazard characterized by the probability and intensity of certain flood events and the associated potential consequences (EC, 2007). However, a majority of the member states has until recently only few or no flood risk maps that include information on the consequences of potential floods (de Moel et al., 2009).

Flood consequences are generally measured by the exposure of elements at risk and their vulnerability, often expressed in monetary terms (Thywissen, 2006). Mostly, only the hazard side is depicted, i.e. the flood extent or the potential flood depths (de Moel et al., 2009), which reflects the continuous stronger attention of the hazard side in flood risk analysis (Freni et al., 2010; Merz et al., 2010; de Moel et al., 2012). While much effort is done to improve the hazard estimation leading to more accurate and more reliable models, the estimation of flood damage is still crude and affected by large uncertainties (Merz et al., 2004; Egorova et al., 2008; Freni et al., 2010; de Moel and Aerts, 2011; Meyer et al., 2013).

Until now, there is no standard procedure to determine the flood impact (Oliveri and Santoro, 2000; Nicholas et al., 2001; Luino et al., 2009) resulting in a wide range of flood damage models with substantial differences in their underlying approaches (Merz et al., 2010; Papathoma-Köhle et al., 2011; Jongman et al., 2012; Meyer et al., 2013).

Generally, flood damage can be classified in direct and indirect damage (Smith and Ward, 1998; Merz et al., 2010). Direct damage like loss of life or devastation of buildings and infrastructure comprise those which are caused by the direct physical contact of the flood water with economic assets, humans or any other object (Smith and Ward, 1998). Indirect costs like production loss or cost of emergency service, in contrast, occur outside the inundated area, but are induced by the direct impact of the flood event (Cochrane, 2004; Meyer et al., 2013). Both types can be further differentiated in tangible and intangible damage, depending on whether they can be monetized or not (Smith and Ward, 1998). More recently, also losses due to business interruption, occurring in areas directly affected by the flood as well as costs of risk mitigation are included as separate sub-category within loss assessments of natural hazards (for a comprehensive overview see Meyer et al., 2013).

As the quantification of indirect losses is still problematic, usually only direct tangible losses are estimated (Cochrane, 2004; Meyer et al., 2013). For direct losses, susceptibility functions are commonly applied, which relate hazard parameter(s) like water depth with the resulting economic damage of a certain object at risk, e.g. residential buildings (Merz et al., 2010; Papathoma-Köhle et al., 2011; Meyer et al., 2013). These susceptibility functions vary nevertheless, when different economic sectors like residential properties, commercial units or agriculture are taken into account. But even by attributing elements at risk to the same economic sector with comparable susceptibility characteristics, flood damage data still contain a large variability (e.g. Merz et al., 2004; Kang et al., 2005; Freni et al., 2010; Pistrika and Jonkman, 2010). As outlined by Thieken et al. (2005) flood damage is controlled by a variety of influencing factors which can generally be differentiated into impact parameters (like water depth, flood duration, flow velocity, contamination) and resistance parameters (like building characteristics, private precaution, emergency measures).

Although it is known that different processes and characteristics of a flood event govern flood damage (e.g. Kelman and Spence, 2004; Schwarz et al., 2005; Thieken et al., 2005; Merz et al., 2010) the majority of damage estimations apply simple depth-damage functions (Luino et al., 2009; Merz et al., 2010; Meyer et al., 2013) as it is internationally accepted as standard approach for assessing direct urban damage (Smith, 1994). According to Papathoma-Köhle et al. (2011) the usage of stage-damage functions can be dated back to the seminal paper of White (1945), who linked the water level to relative (i.e. the loss ratio) or total (i.e. in monetary values) damage. Since then, flood damage assessment methods were developed in many countries with different complexity and purposes. Most of them use, in fact, still inundation depth as the main impact parameter (see e.g. Merz et al., 2010; Jongman et al., 2012 for an overview), but some models also integrate additional parameters like flow velocity (e.g. Schwarz and Maiwald, 2007; Kreibich et al., 2009; Pistrika and Jonkman, 2010), contamination (e.g. Kreibich and Thieken, 2008; Thieken et al., 2008; Prettenthaler et al., 2010), the duration of flooding (e.g. Dutta et al., 2003; Penning-Rowsell et al., 2005) or the recurrence interval (e.g. Elmer et al., 2010). With regard to the consideration of different resistance parameters, the majority of damage models differentiates between the use or type of building (e.g. Oliveri and Santoro, 2000; Dutta et al., 2003; Kang et al., 2005; Büchele et al., 2006; Schwarz and Maiwald, 2007; Kreibich and Thieken, 2008; Thieken et al., 2008). Few models also take additional parameters like precautionary behavior (e.g. Büchele et al., 2006; Kreibich and Thieken, 2008; Thieken et al., 2008) or the early warning time (e.g. Penning-Rowsell et al., 2005) into account. Only recently, data mining approaches have been successfully applied to derive more sophisticated damage models (Merz et al., 2013).

Nevertheless, most of the damage models have in common that they have been derived for a certain geographical area. Due to specific regional building characteristics and further specific relationships between losses to buildings and flood impact factors reliable model application is assumed to be restricted to its region of origin (Oliveri and Santoro, 2000; Kang et al., 2005; Luino et al., 2009; Merz et al., 2010; Papathoma-Köhle et al., 2011). Since the building types and quality of buildings differ in other parts of the world, these models cannot be easily transferred to other regions without any model adaptation and validation (Merz et al., 2010; Papathoma-Köhle et al., 2011; Meyer et al., 2013). The evaluation of the flood loss model performance is, however, hardly investigated due to the lack of reliable real damage data (Thieken et al., 2008; Merz et al., 2010; Jongman et al., 2012; Meyer et al., 2013).

In general, the associated uncertainty of damage estimates arises from the development of the damage curves, the underlying asset values as well as the applied methodological framework, i.e. the spatial scale, cost basis or damage-function type (Merz et al., 2010; de Moel and Aerts, 2011; de Moel et al., 2012; Jongman et al., 2012). According to Apel et al. (2009) and de Moel and Aerts (2011), the largest impact on damage estimation is caused by the shape of the applied depth-damage curve as well as the associated asset values, while the accuracy of the hydraulic input is of minor importance. Although uncertainty in flood damage modeling has to be reduced to make the results more reliable and the models more confident, research on model validation and transferability is still rare (Thieken et al., 2008; Merz et al., 2010; Papathoma-Köhle et al., 2011; Jongman et al., 2012; Meyer et al., 2013). To our knowledge, only few studies have performed a flood loss model validation like in the work of Thieken et al. (2008), Apel et al. (2009), Wuensch et al. (2009), Seifert et al. (2010) or Jongman et al. (2012). Others relied on model intercomparisons (e.g. Bubeck et al., 2011).

This study aims therefore at investigating the transferability and validation of flood damage models to an Austrian region, which is introduced in Sect. 2.1. Thereby commonly applied as well as newly derived depth-damage functions for the residential sector are used to estimate direct damage to buildings that was observed during the latest flood event in August 2005. Additionally, the multi-parameter flood loss model FLEMO (Thieken et al., 2008) is adapted to this study area to test its applicability and transferability to another geographical region.

The test protocol followed the assumption that damage estimates are more reliable if the basic data from which the damage function/model are derived, are closer (in the sense of more similar building and flood characteristics) to the region under study. For this, two data sets – a heterogeneous data set from Germany and a more homogeneous data set from the adjacent German federal state of Bavaria – were used to derive damage models. The performance of the various damage estimates was judged by means of official loss data from the government and hydraulic simulations of the flood event in 2005.

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Finally, potential flood losses for different recurrence intervals and present hydraulic conditions are calculated by means of plausible, i.e. successfully validated, flood loss models and all loss models (including the not successfully validated models), to explore how uncertainty of flood risk assessments can be reduced by proper model selection.

2 Data and methods

2.1 Study area and flood event in 2005

The study area is the Alpine Lech catchment in the north-western part of Austria, mainly located in the federal state of Tyrol (Fig. 1). This watershed has a size of 1000 km^2 up to the gauge Lechaschau (Dobler et al., 2010), close to the district capital Reutte and near the border to Germany. In the mountain basin of Reutte the flat valley bottom has its largest extent within the Austrian Lech catchment. There, most of the workplaces are provided in the service sector and in the industrial sector, as the agricultural sector decreased remarkably in the last decades (Amt der Tiroler Landesregierung, 2008). Residential areas have expanded strongly, e.g. by 60 % between 1971 and 2006, mainly at the expense of intensively used grassland (Cammerer and Thieken, 2013). In the same period (1971–2006), the population in the seven investigated riparian municipalities of the Lech River grew intensively, e.g. by 62 % between 1971 and 2006 in the municipality of Pflach (for more details see Cammerer et al., 2012). This study is also limited to the analysis of these seven municipalities in the mountain basin of Reutte.

The Lech River, a tributary of the Danube River, affected this settlement area several times by severe flooding in the recent past (Kröll, 2007; Cammerer and Thieken, 2013). Especially the flood events in 1999 and 2005 led to large inundations and flood losses despite various structural flood protection measures (Cammerer and Thieken, 2013). While the monthly average discharge between 1971 and 2000 at the gauge Lechaschau amounted to 45 $m^3 s^{-1}$ (Dobler et al., 2010), the peak flows of 1999 and 2005 reached 855 $m^3 s^{-1}$ and 943 $m^3 s^{-1}$, respectively (Cammerer and Thieken, 2013).

The last flood event in August 2005 with an estimated return period of 330 yr at this gauge (Thieken et al., 2011) particularly hit the municipalities of Pflach and Höfen in the study area since overtopping and breaches of embankments caused rapid flooding with large water depths (Kröll, 2007). This flood event was triggered by a Vb-similar weather pattern with prolonged intensive rainfall combined with already saturated soil leading to high discharges at many Tyrolean gauges (Amt der Tiroler Landesregierung, 2005). For the whole federal state of Tyrol direct losses of € 410 million were estimated (Amt der Tiroler Landesregierung, 2006).

2.2 Simulation of the flood event in 2005

In order to investigate the applicability and transferability of different loss functions to the Austrian study area the flood event and observed damage in 2005 in private households was simulated. For that, a variety of relative damage functions, which are further explained in Sect. 2.3.2, were applied based on the asset values for the residential sector and additional information for the extended models (Sect. 2.2.3) as well as the simulated maximum water depths of the event in August 2005 (Sect. 2.2.1). The outcome of each function is finally validated by means of official flood loss data (Sect. 2.2.2).

2.2.1 Flood hazard information

Besides the determination of residential properties relative damage functions require also information about the flood hazard to relate damage to property with the characteristics of inundation. For the simulation of the maximum water depths of the flood event in August 2005 we performed a hydrodynamic-numeric modeling by means of the two-dimensional model Hydro_AS-2D (Nujic, 2003). Originally developed for dike break and flood wave propagation the model is increasingly used for river flood analysis (Noack and Yörük, 2008) and is applied as a standard system for flood routing in the neighboring federal state of Bavaria (Germany). While the spatial discretization is based on the finite-volume method, the temporal discretization is solved by the

Runge–Kutta method (for details see Nujic, 2003). The model has the advantage that linear triangular and quadrangular elements can be used with different spatial resolution in order to consider discharge relevant structures like dikes, streets etc. (e.g. Noack and Yörük, 2008). The mesh with a length of approx. 10 km consists of a river channel model integrating 40 cross section profiles and a flood plain model based on laser scanning data with a spatial resolution of 1 m. Hydraulic relevant structures like bridges or structural flood protection measures, e.g. the flood wall that protects the municipality of Lechaschau, were also considered in the terrain model. The simulation of the flood event in 2005 was carried out by adapting the structural protection measures to the situation before the flood in 2005. The hydrologic boundary conditions were adjusted for the inlet discharge according to the discharge at the gauge Lechaschau. Finally, the two-dimensional simulations were performed with the flood wave observed in August 2005.

In order to assess the model performance, the simulated water depths were compared with (11) observed water marks acquired from the engineering office "Donau-Consult" (http://www.donauconsult.at) recorded one month after the flood by means of leveling of flood level marked stones, bridges or buildings (DonauConsult, personal communication in June 2011). It has to be noticed that two measurements out of all 13 georeferenced recorded water marks were assumed to be erroneous as their georeferenced locations did not agree with the corresponding verbal description of their location. Due to this supposed shift in the coordinates, both marks were left out. In addition to the water marks, the flood extent was compared with the flood extent mapped by Ebner et al. (2007) in the southern part of the study area, which is based on oblique aerial photos taken by the Austrian Armed Force during the flood event in August 2005. Since the aerial photos were recorded two days after the peak discharge and were not available for the northern part of the study area, the mapped extent has, however, some shortcomings as quality criterion and therefore serves only as a rough estimate. While the model validation was performed by means of the simulated water levels (in m a.s.l.) on a 1 m grid, the corresponding water depths (in m above ground surface) were aggregated on a cell size of 10 m by using the mean of the input cells for the intersection with the asset values (10 m cell size) in frame of the damage modeling.

For the flood event in 2005 two hydraulic simulation runs were considered. Since in 2005 levee failures occurred in the community of Pflach (Kröll, 2007), the dikes were artificially opened at two breach locations in the simulation run *"23a"*. In the simulation run *"22a"*, in contrast, no dike breach location was included in the terrain model leading solely to overtopping effects in this area. In addition to the two simulation runs for the 2005-flood, further hydrodynamic simulations were carried out for discharges that represent the current statistical flood return period of 30, 100, 200 and 300 yr. In these simulations, the recent improvements of the structural protection measures were already considered, e.g. heightening of the levees at the community of Pflach. Therefore, the flood extents for the 300 yr flood are smaller than in 2005 (data not shown).

2.2.2 Official flood loss data of 2005

In Austria, loss data of flood events are generally collected in frame of the loss compensation by the national Disaster Fund (*Katastrophenfonds*), which was established in 1966 in the aftermath of a series of natural disasters in the Austrian Alps and revised in 1996 (Habersack et al., 2004; Holub and Fuchs, 2009). Thereby the single federal states are responsible for the data collection and loss compensations for private households and companies due to natural hazards. This is one of the main tasks of this fund apart from the financial support for the construction and maintenance of structural flood and avalanche defense measures (Holub and Fuchs, 2009). As the responsibility of the financial support in frame of the disaster fund is assigned to the single federal states, different approaches exist for loss compensation and loss recording (Habersack et al., 2004). In some federal states, losses are not explicitly documented with regard to the damaging process (flood, debris flow etc.), the object at risk (e.g. residential building or industry), or the damage to building and household contents, for instance (Habersack et al., 2004). Likewise, each federal state has its own guidelines which determine the extent and content of the financial assistance (Habersack et al., 2004). In Tyrol, for example, an average loss compensation of 20 % of the total damage to buildings and contents can be received by the affected parties (Habersack et al., 2004) as long as no insurance indemnities were paid out which are subtracted before loss is compensated by the disaster fund (Habersack et al., 2004; Holub and Fuchs, 2009). Furthermore, the loss compensation in Tyrol requires bills and vouchers for payments which is controlled and handled by the commission for elemental property damage at the Tyrolean government (Habersack et al., 2004).

For this study, anonymized loss data for the seven investigated municipalities in the area of Reutte were provided by the Tyrolean government. At first, these data were shaped to our usage by extracting only the loss reports where damage could be traced back due to a flood and where only residential buildings (and household contents) were affected. However, some flood loss reports could not be divided into structural damage to buildings and damage to household contents since both types were affected and only an aggregated loss was recorded. We assumed that in case of such a cumulative damage the share of damage to household contents amounted to 30 % of the total loss. This value was taken from the loss documentation guidelines of the federal state of Lower Austria (Amt der NÖ Landesregierung, 2012).

To compare the observed damage to buildings (1.9 k€; $n = 70$ cases) with the flood loss model estimates using building values of the year 2006 (Sect. 2.2.3) the anonymized and separated building loss data were indexed to the reference year 2006 by means of the construction cost index of Statistics Austria (2013a). Lastly, a resampling of all loss records was carried out by means of bootstrapping with 10 000 simulated random samples which were drawn by replacement from the loss records. The 2.5th and 97.5th percentile of the total building loss as well as the mean (and median) total damage of these samples were used to obtain a 95 % confidence interval of the observed losses. Following the work of Thieken et al. (2008), loss estimates that fall within the 95 % interval of the resampled data were assumed to be acceptable, whereas others can be rejected. By this approach it is possible to evaluate the performance and transferability of the applied damage models.

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2.2.3 Asset values and additional data for the extended models

Asset values are an important prerequisite when flood losses are calculated on the basis of relative damage functions (Wuensch et al., 2009; Merz et al., 2010). Depending on the scale of investigation, single object values (micro-scale) or aggregated information (meso- and macro-scale), like on municipality level, are required (Wuensch et al., 2009). To bridge the gap between explicit hazard data like water depths and coarse information of the asset values (e.g. municipality or district level) a disaggregation has to be performed (e.g. Thieken et al., 2006; Wuensch et al., 2009). Therefore, ancillary information with a higher resolution like land use data are commonly applied to transfer the aggregated (municipal) values to a higher spatial resolution (Merz et al., 2010).

In this study, we rely on a land use map of 2006 for attributing aggregated asset values to residential areas. This land use map was derived on the basis of the visual interpretation of true color orthophotographs (RGB) provided by the Tyrolean government. The land use data set of 2006, applied in previous studies of Cammerer et al. (2012) and Cammerer and Thieken (2013), differentiates between nine land use classes on a spatial resolution of 50 m. For the estimation of the asset values of residential areas we assigned aggregated replacement values of 2006 provided by Huttenlau and Stötter (2008) to the land use type "residential area" of Cammerer et al. (2012). Thereby the aggregated replacement values of buildings on the municipal level were divided by the residential area of each municipality of the land use map 2006 to obtain specific replacement values (€ m^{-2}). For the damage estimation we used an average replacement value for residential buildings of € 279 per m^2 for the whole study area. Furthermore, the minimum (€ 224) and maximum (€ 353) specific replacement value was used to account for uncertainty in sense of valid parallel models (Merz and Thieken, 2009). Further details of the asset estimation are specified in Cammerer and Thieken (2013).

2.3 Derivation and adaptation of the flood loss models to the study area

2.3.1 Data basis for the flood loss functions

Since more detailed flood loss data of past events have hardly been collected in Austria or do not contain the relevant information to relate the flood losses to a certain water depth (Habersack et al., 2004), we used a comprehensive flood loss data base from Germany as a basis for the derivation of various flood loss functions and the multi-parameter loss model. These loss data were collected in the aftermath of flood events in Central Europe in 2002, 2005 and 2006 affecting the catchments of the rivers Elbe and Danube. Thereby two surveys with computer-aided telephone interviews were carried out in flood-affected private households in Germany. In the first campaign in 2003, 1697 private households in the German federal states of Bavaria, Saxony and Saxony-Anhalt, which were affected by flooding in August 2002, were interviewed. In frame of this survey, flood losses on residential buildings and household contents were recorded as well as potential flood damage influencing factors like water level, flood duration, contamination, precautionary and emergency measures (for a more detailed description of this campaign see Thieken et al., 2005, 2007). At the end of 2006, a similar campaign was conducted among 461 private households which were hit by floods in Bavaria in August 2005 or along the Elbe in March/April 2006 (for more details see Kreibich and Thieken, 2009).

From this database with a total of $n = 2158$ cases we first calculated the building loss ratios, i.e. the relative damage. For this, the absolute damage to buildings was indexed to the reference year 2006. In addition, the indexed total value of buildings (replacement costs) was calculated as described in detail by Thieken et al. (2005) and Elmer et al. (2010). As not all interviews contained sufficient information for the calculation of the loss ratio for residential buildings these relative losses were only available for 1121 cases. From this data set we considered two subsets which were further used for the model development: the first dataset *"surveys_GER"* comprises all cases from both surveys, in which damage ratios were available; this heterogeneous subset contained

1121 cases. The second dataset *"surveys_BY"* is constrained to the cases from the federal state of Bavaria resulting in 415 flood affected households with loss ratios. Due to the adjacent location of Bavaria to our study area, we hypothesize that the derived loss functions of this subset may yield in more reliable estimates because of assumable similar building characteristics and damage patterns than functions derived from data of more dissimilar and heterogeneous regions. This is supported by findings from e.g. Oliveri and Santoro (2000), Dutta et al. (2003) and Kang et al. (2005).

2.3.2 Derivation of the flood loss models

Since relative stage-damage curves have the advantage of a better transferability in space and time (Oliveri and Santoro, 2000; Merz et al., 2010) we follow a relative (empirical) approach in this study. On the one hand, we use three simple relative stage-damage functions already elaborated in previous studies in Germany, i.e. MURL (2000), ICPR (2001) and Hydrotec (2002). In the first model the loss ratio of residential buildings is calculated by the linear function $y = 0.02 \cdot x$, where x is the water depth in meter and y the loss ratio (MURL, 2000). In case of water levels higher than 5 m, the damage ratio is set to 10 % (MURL, 2000). The second model (ICPR, 2001) describes the resulting loss ratio by the function $y = (2x^2 + 2x)/100$ which was derived empirically from the German flood damage data base HOWAS, similarly to the previous function. The last function of Hydrotec (2002) uses additionally some synthetical what-if data as a basis to derive the relative loss by the function $y = (27\sqrt{x})/100$.

On the other hand, we used newly derived damage functions in accordance to our test protocol assuming that loss estimates perform better if the underlying models are derived from related and geographical more adjacent areas. Like in the previous functions, we also used a linear, square root and polynomial stage damage curve which is often suggested in flood loss estimation (e.g. Büchele et al., 2006; Kreibich and Thieken, 2008; Elmer et al., 2010). As contamination seems to affect flood losses decisively (e.g. Nicholas et al., 2001; Kelman and Spence, 2004; Kreibich et al., 2005; Penning-Rowsell et al., 2005; Thieken et al., 2005, 2007; Kreibich and Thieken, 2008) and its consideration yields in more accurate loss estimations (e.g. Thieken et al., 2008; Prettenthaler et al., 2010), we separated these functions regarding contamination of flood water in an additional stage. As a data basis for the derivation of the six stage-damage functions (with and without consideration of contamination) we used the two datasets *"surveys_GER"* and *"surveys_BY"* that were introduced in Sect. 2.3.1.

Lastly, the multi-factorial flood loss model FLEMO (Thieken et al., 2008) was adapted to the Austrian study area. This empirical model was originally developed on the basis of collected flood loss data in the aftermath of the flood event in 2002 in Germany. In its basic stage it assesses the direct monetary damage to residential buildings by differentiating between five classes of water depth, three residential building types and two building qualities (Büchele et al., 2006; Thieken et al., 2008). In an extended model stage (FLEMO+) three classes of contamination and three classes of private precaution are additionally included. The model is applicable on the micro-scale, i.e. on the object level, as well as on the meso-scale, i.e. on homogeneous land use units. For both scales it was successfully validated (Thieken et al., 2008) and applied or modified in different studies (e.g. Kreibich and Thieken, 2008; Apel et al., 2009; Merz and Thieken, 2009; Wuensch et al., 2009; Elmer et al., 2010; Kreibich et al., 2011; Merz et al., 2013).

In this study, FLEMO is applied on the meso-scale by modifying the required input parameters to the Austrian study area. This adapted model is called FLEMO_{AT} and $\text{FLEMO}_{\text{AT+}}$ in what follows. In Austria, the *building type* is not classifiable in one-family, (semi-)detached or multifamily house when referring to the official statistical data (Statistics Austria, 2013b). Thus a new classification scheme for the adapted model version was introduced which is based on the official statistical data for Austria. Thereby the building type is differentiated between one family houses, two family houses and multifamily houses (i.e. more than two families/apartments within one building).

The *building quality* in Austria is differentiated in four classes (Statistics Austria, 2013b) and is adapted to the two different classes applied in Germany, i.e. low/medium quality and high quality, by assigning the lower three building quality categories

(*Ausstattungskategorie der Wohnungen B–D*) to low/medium quality and the highest category (*Ausstattungskategorie der Wohnungen A*) to high building quality.

The level of *private precaution* and *contamination* for the extended model stage $FLEMO_{AT+}$ could not be realized as detailed as in the original model version of Thieken et al. (2008). In the Austrian model version, only four combinations of contamination (yes/no) and precaution (yes/no) are differentiated. Contamination is the fact that private households were affected by contamination of the flood water due to sewage, chemicals, oil and/or petrol. Precaution was assumed to be in place when households implemented "flood adapted building use" (i.e. the cost-extensively usage of flood-prone storeys) and/or "flood adapted interior fitting" (i.e. the usage of water-repellant materials such as tile floor instead of parquet or movable furniture in affected storey, for example) before the flood event since these two building precautionary measures turned out to be very effective (for details see Kreibich et al., 2005; Cammerer and Thieken, 2011). The derivation of the loss functions (basic model stage) and the scaling factors (Büchele et al., 2006) (for the extended model stage) are finally performed for both datasets *"surveys_GER"* and *"surveys_BY"*, separately.

For the extended damage functions (consideration of contamination) as well as for the adapted model $FLEMO_{AT+}$ information about contamination and private precaution was gathered by means of the study of Raschky et al. (2009). Thereby 218 interviews in private households in the Austrian federal states of Tyrol and Vorarlberg were carried out in the aftermath of the flood event in 2005 in order to compare different risk transfer systems of three Alpine regions being affected of this large flood event (Grisons (Switzerland), Tyrol (Austria) and Bavaria (Germany)). Among various questions, also the level of private precaution and contamination was questioned. While all households did response to questions concerning their precautionary behavior, less people provided information on the level of contamination, since only 72 of all surveyed households were actually affected by the flood in 2005 (Raschky et al., 2009). Nevertheless, this information enabled a determination of contamination occurrence and precaution in private households in the district of Reutte.

An important prerequisite for the derivation of the loss functions is that the building loss ratios between the single subclasses, for example between both contamination types, differ significantly. Statistical differences between two independent subclasses were tested by the Mann–Whitney-U-Test and by the Kruskal–Wallis-H-Test for three subclasses and more. In case that the subclasses differ significantly ($p < 0.05$) the corresponding loss ratios are derived for each subclass. Otherwise, this variable is not considered as input parameter in the adapted flood loss models. Furthermore, all stage-damage curves were calculated based on the water level above ground surface by setting water levels below ground surface (cases where only the basement was affected) to zero.

The final damage estimation is done on a raster basis. First, the asset map is intersected with the hydraulic scenario which results in the potentially affected assets. Then the loss ratio is determined per grid cell and finally multiplied with the asset value of the corresponding raster cell to obtain the absolute monetary damage to residential buildings. Grid estimates are summarized per municipality and finally for the whole event.

3 Results

3.1 Validation of the hydraulic simulations

The validation of the hydraulic modeling was carried out by means of the recorded water marks and the mapped flood extent of the flood in 2005. The deviations between eleven recorded and georeferenced watermarks (Fig. 2) and the simulated maximum water levels at these points are small; they are summarized by different error statistics in Table 1. The bias amounts only to 0.31 m in both simulation runs which is slightly larger when the mean absolute error (MAE) is used. With respect to the root mean square error (RMSE), which emphasizes larger deviations, the total error in both runs is also acceptable (0.51 m). The error statistics at the eleven compared water marks indicate a reasonable fit of the hydraulic model.

As a quality measure for the modeled flood extent we calculated the "Flood Area Index" (Table 1), which is one of the most recommended measures in the literature (e.g. Apel et al., 2009; Dung et al., 2011). Since the mapped flood extent is only available for the southern part of the study area (Fig. 2b) and not for the northern part (Fig. 2a) where the largest inundation occurred, this measure has, however, only a limited explanatory power. Furthermore, the rather low value of 84 % (Table 1) which seems to be insufficient can be refuted due to the shortcomings of the mapping procedure (like record of the aerial photos two days after the flood peak) outlined by Ebner et al. (2007). Nevertheless, this index gives a rough estimate that both simulation runs may hit the observed flood extent well with little differences in the outlines of the flood extent (Fig. 2b, red circles). Although it was not possible to compare both simulation runs quantitatively in the northern part at the community of Pflach where the two runs differ distinctly (Fig. 2a, red circle), we conclude that simulation run *"23a"* is more plausible due to the consideration of the dike breaches. Nevertheless, we use both simulation runs for the further analysis as the quantitative validation results are equal.

Regarding the distributions of the inundation depths within residential areas (Fig. 3), the two simulation runs differ particularly in the range of lower (0.5–0.8 m) and higher (2.2–3.0 m) water depths. The larger share of higher water depths in simulation *"23a"* results from the dike breach locations where larger parts of residential area were flooded (Fig. 2a). Therefore the distribution of run *"22a"* shifts to a higher share of lower water depths which will consequently affect the damage estimates of both runs.

3.2 Statistical analysis of the flood losses and the derived loss functions

The statistical analysis of the two datasets *"surveys_GER"* and *"surveys_BY"* reveals that, in general, the variation and the mean average of the loss ratios in private households of the mixed subset *"surveys_GER"* is larger compared to the Bavarian subset *"surveys_BY"* (Table 2). This may be explained by the larger heterogeneity of the

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German-wide dataset, collected in different geographical regions and from various flood events. As pointed out by Thieken et al. (2005) specific building characteristics, for instance, may affect the specific relationships between losses to buildings and flood impact factors leading to a large variation of damage data in more heterogeneous regions (Luino et al., 2009; Merz et al., 2010). This assumption is also reflected by our results. When the flood losses are subdivided into different water levels, the loss ratios between the five water level classes applied in $FLEMO_{AT}$ differ significantly in both datasets. As expected, mean damage to buildings increases with rising water levels, since water depth is identified as the most dominant influencing factor on flood damage (Thieken et al., 2005). The variation within the single water level classes is, however, again higher in the larger subset, particularly above a water depth of 1 m (Table 2). Loss ratios between the three building types are also significantly different in both subsets, especially in case of one-family houses which have, however, the highest share in the study area (60 %). The building quality, in contrast, shows no significant differences in the loss ratios of both subsets. Consequently, this input parameter is discarded in the adapted model $FLEMO_{AT}$.

The loss characteristics differentiated by contamination again underpins the importance of considering the effect of contamination to building damage. Both subsets show that in case of contamination flood loss differs significantly and are therefore considered in the more simple stage-damage functions as an additional influencing factor. The benefit of private precaution is also illustrated in Table 2. When one or both of the mitigation measures "flood adapted building use" and/or "flood adapted interior fitting" is implemented, the loss ratios of buildings are significantly lower in both subsets justifying once more the great influence of building precautionary behavior. From all loss characteristics shown in Table 2 it can be concluded that the variation of the different loss ratios within the single subsets are notably larger in the dataset that was collected in more distributed regions than in the rather regional dataset from Bavaria. Nevertheless, there is also a spatial limit regarding more homogeneous samples from smaller regions for deriving depth-damage functions. As discussed by Chang et al. (2008)

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spatial autocorrelation influences considerably the relationship between flood depth and resulting damage in small sample areas. Thus it can be assumed that both a large region as well as too small areas may lead to notable variations in the damage data particularly when only flood depth is considered as main influencing parameter. A subsequent differentiation of the Bavarian subset *"surveys_BY"* into the same flood event of 2005 (data not shown) did not reduce the variation of the damage data furthermore. This finding is, however, not statistically robust due to the small sample sizes in the smaller subclasses. Therefore the statistical analysis and derivation of the flood loss functions is also a compromise between the data availability and the resulting model performance.

The different loss functions derived from both subsets are shown in Fig. 4. This figure illustrates the range of the damage functions, particularly for the whole dataset (Fig. 4a). However, even in such a heterogeneous dataset the newly derived functions lie in closer proximity than the three common stage-damage functions of MURL (2000), ICPR (2001) and Hydrotec (2002), which were derived from the more comprehensive HOWAS flood loss database and expert judgment (Merz et al., 2004). These deviations do not only lead to a larger range of the following damage estimates, but also demonstrate (1) the need to derive functions from more homogeneous data that better reflect characteristics of the region under study and (2) the importance to include more factors than only water level explaining flood damage. From the derived functions the polynomial functions increase strongest in both datasets, while the remaining functions lie close together, especially in the Bavarian subset. Figure 4 also shows the impact of contamination as all functions increase steeper when this factor is included.

In order to account for the local characteristics of contamination and precaution in the study area the proportion of these influencing factors were derived from the Tyrolean survey. The analysis reveals that most of the households (71 %) in the district of Reutte were not affected by contamination which is slightly higher than in the whole federal state of Tyrol (68 %) in 2005. The share of households which did not perform one or both of the very effective building precautionary measures "flood adapted building use"

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and/or “flood adapted interior fitting” amounts to 80 %, but is a little bit lower than in the whole federal state (85 %). The proportion of contamination is finally considered for weighting the extended functions to calculate the total damage on residential buildings in the study area. For the extended model $FLEMO_{AT+}$ the proportions of precaution within the contamination classes were used to multiply the total loss of $FLEMO_{AT}$ with the derived scaling factors (Table 3).

3.3 Comparison of the modeled flood damage with the observed loss

The overall reported flood loss to buildings in the residential sector in 2005 (indexed to 2006) amounted to 1904 k€ and 1885 k€ (mean and median of the 10 000 bootstrap samples), respectively, whereby the 95 % confidence interval ranges from 1429 k€ (2.5th percentile) to 2662 k€ (97.5th percentile). In comparison to the long-term average damage to buildings for whole Austria (based on the analysis of all flood events between 1991 and 2003) amounting to 21 k€ (Habersack et al., 2004), the indexed average damage of buildings (of the 10 000 bootstrap samples) in 2005 in the study area amounts to 28.5 k€ (std.dev.: 4.4 k€) which is marginally higher due to the extreme hydrological impact of the flood event in 2005.

The performance of all flood loss models to estimate the total damage of the 2005-event is summarized in Table 4 assuming the mean specific asset values and the water depths of both simulation runs. Out of the three commonly applied stage-damage functions only the loss function of ICPR (2001) lies within the confidence interval, independent of the simulation run (Table 4, Fig. 5). While the results of MURL (2000) underestimate the observed flood loss in both runs clearly, the calculations based on Hydrotec (2002) overestimate the observed loss considerably. For the simulation run *“23a”*, for instance, the latter provides 4.6 times higher damage to buildings than reported. Even if the full range of the underlying asset values is applied, none of these two functions is within the confidence interval in one of the two simulation runs. Some of these functions were already used in different geographical regions before like in the German federal states of Saxony (Schwarz et al., 2005; Thieken et al., 2008) and

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Baden-Wuerttemberg (Thieken et al., 2008; Apel et al., 2009; Merz and Thieken, 2009) but it has also been reported that these models tend to under- or overestimate observed damage to buildings (e.g. Schwarz et al., 2005; Thieken et al., 2008; Apel et al., 2009).

With regard to the newly derived loss models, the pattern is very different. Table 4 illustrates that none of the functions derived from the whole dataset *"surveys_GER"* is able to reproduce reliable loss estimates in the study area. Only when the full range of the specific asset values is taken into account, three functions (linear, linear (co.), square root (co.)) fall within the confidence interval when assuming the minimum specific asset value as a basis (data not shown). However, this is only valid for simulation run *"22a"*, which is supposed to underestimate the flood extent in the area of Pflach (see Sect. 3.1). The best estimate based on the dataset *"surveys_GER"* and run *"23a"* is obtained by the linear function which considers also the effect of contamination in the study area. Even if the estimate for run *"23a"* is outside of the confidence interval, the overestimation amounts only to a factor of 1.5 when the minimum specific asset value is applied. In case of the adapted multi-factorial loss model $FLEMO_{AT}$ the overestimation is a little bit higher (factor of 2). However, when contamination and the precautionary behavior are taken into account ($FLEMO_{AT+}$), the estimates are marginally better (overestimation factor of ~ 1.7) for this run and the lowest specific asset values.

From Table 4 it is further apparent that those loss functions which are derived from the Bavarian dataset *"surveys_BY"* achieve clearly better results than those from the larger, but mixed dataset. Both for simulation run *"22a"* and for run *"23a"* almost all derived functions estimate the reported loss well except for the polynomial function in case of run *"23a"*. The latter is outside the confidence interval, but is only ~ 1.4 times higher than the reported loss. However, when the full range of the asset values are applied (Fig. 5), this function is also within this range when assuming the minimum asset values as input data. From Fig. 5 it can further be seen that three functions (linear, linear (co.), square root (co.)) are completely in the validation range independent of the applied asset values in the simulation run *"23a"*. For the simulation run *"22a"* even the half of the derived functions, i.e. square root (co.), polynomial (co.) and both FLEMO models, lies within this interval when the full range of the asset values is considered (Fig. 5). The most accurate functions for run *"22a"* are the $FLEMO_{AT}$ (only 0.7 % higher estimates than the mean total loss) and the linear functions (only 0.1 % higher estimates than the median total loss) when the mean and the maximum specific asset values are applied. In case of the more reliable simulation run *"23a"*, the polynomial function which considers the effect of contamination and which is based on the minimum specific asset values achieves the best result by underestimating the reported loss by only −1.1 % (mean total damage) and −0.1 % (median total damage), respectively. Only slightly larger is the deviation of the $FLEMO_{AT}$ model (also based on the minimum specific asset value), which overestimates the mean total damage by 1.2 % and the median total damage by 2.2 % in this simulation run.

The validation procedure strongly illustrates the importance of the site specific evaluation of flood loss models. Using the reported flood loss as a quality criterion, it becomes apparent that general loss functions are hardly applicable in our study area. Only the function of ICPR (2001) proved to be reliable at this site and can therefore be recommended for further loss estimations in this area. The derivation of simple stage-damage functions shows that loss data collected in a neighboring region with assumable similar building characteristics and loss figures yields remarkably better results than (more) data from heterogeneous regions. This is in line with prior statements (e.g. Oliveri and Santoro, 2000; Kang et al., 2005; Luino et al., 2009) that loss functions should only be applied in related regions with similar depth–damage relationships.

Nevertheless, also the uncertainty of the underlying asset values has to be taken into account when loss estimates are evaluated (e.g. Egorova et al., 2008; de Moel and Aerts, 2011). In fact, most of the damage functions worked well with the mean asset values, but some of them achieved only good results with the full range of asset values. Therefore we recommend the usage of not only one (mean) property value as also this important component is associated with uncertainty (Egorova et al., 2008; de Moel and Aerts, 2011). In this context, it has also to be noticed that stage-damage

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curves which just miss the confidence interval should not generally be discarded as also the reported loss may be affected by uncertainties, even if we aggregated the observed damage to the whole study areas as recommended by Downton and Pielke (2005).

3.4 Current flood risk estimates for residential areas

In a last step, the current flood risk for residential areas was assessed for the seven investigated municipalities in the area of Reutte. Thereby four inundation scenarios were generated for the recurrence intervals $T = 30$, 100, 200 and 300 yr by considering the most recent structural protection measures erected in the aftermath of 2005. However, these simulations do no more comprise dike breach scenarios as it is assumed that the latest improvements of the levees in the municipality of Pflach, for example, allow no more failures in future. Thus the potential inundation areas are smaller (data not shown) leading to presumably lower potential damage on residential buildings for the 300 yr flood in comparison to the flood of 2005.

To demonstrate the wide range of flood risk curves obtained from different damage functions and asset values all possible 57 specific model combinations are shown in Fig. 6. However, as shown before, a large part of the functions is not plausible for this study area. Particularly the functions derived from the mixed dataset *"surveys_GER"* are hardly applicable. In sum, 28 models can therefore be discarded contributing to a large uncertainty in the flood risk estimates (Fig. 6). For the 300 yr flood, for example, the range differs by € 5.9 million, which corresponds to a factor of ~ 18 between the highest and the lowest estimate. In contrast, the uncertainty is considerably reduced when only plausible models, which were successfully validated for the 2005 event in the study area, are employed. The range of these remaining 29 models is then reduced to only € 1.0 million corresponding to a factor of 2.3 between the estimates of the highest and the lowest plausible models for this return period.

The best estimated risk curves are also shown in Fig. 6, derived from the most accurate model combinations of the two simulation runs *"22a"* and *"23a"* (see above).

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The maximum range of these specific combinations is only € 0.3 million (factor of 1.3) and illustrates the remaining deviation between the most accurate models as far as two hydraulic simulation runs are applied for the flood loss model validation. However, for a complete assessment of the associated uncertainty for flood risk curves also the uncertainty of the flood frequency estimates has to be taken into account (e.g. Merz and Thieken, 2009).

Nevertheless, the focus of this study was not to evaluate the uncertainty of flood risk curves, but to demonstrate how large only the absolute contribution might be when non-plausible loss models are used to quantify damage for a given sector. Thereby the large range of different damage functions and diverging asset values became apparent when flood risk curves are calculated. Future research should consequently be aware of the associated uncertainty in case of loss estimations which cannot be validated in the corresponding study areas due to the lack of real damage data.

4 Conclusions

Depth-damage functions are the international standard to assess direct flood losses in urban areas. While much effort is done to improve the flood hazard assessment by more complex hydraulic models, better elevation data or detailed flood frequency analysis, flood loss assessment still attracts less attention within the field of flood risk analysis. However, previous studies have shown that the uncertainty of flood damage estimates may be considerable and can further largely contribute to the overall uncertainty of flood risk assessments. Besides the simplicity of stage-damage functions neglecting other important damage influencing parameters, such functions are often used in different geographical regions without evaluating their performance, mostly due to the lack of real damage data from the study area. Few studies already pointed out that attention has to be paid when depth-damage functions are applied in heterogonous regions, where the specific relationships between losses to buildings and flood impact

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factors might be significantly different. However, such investigations have hardly been performed until now.

This study aimed therefore at investigating the applicability and transferability of different flood loss functions to other geographical regions. Thereby, three common stage-damage functions were used which were derived from a large German flood loss database. Furthermore new, empirically-based functions were derived from comprehensive surveys carried out in the aftermath of severe floods in Germany. This dataset was split in two subsets with all loss data from different regions, on the one hand. The second subset, on the other hand, comprises only loss data which were collected in a more related and homogeneous region, i.e. the federal state of Bavaria (Germany), which is very close to the Austrian study area with presumably similar building and loss characteristics and hence flood loss relationships. Additionally, also a multi-factorial flood loss model was adapted to this study area derived from these two subsets. This model considers also building characteristics and contamination as well as precautionary behavior performing well in previously investigated study areas in Germany.

In accordance with the hypothesis that more homogenous regions might have quite identical relationships between flood losses and impact parameters this study clearly showed that those loss functions performed significantly better than those which are derived from a very heterogeneous sample. Although the well-performing functions are also connected with marginal uncertainties, their range could be reduced remarkably in contrast to the functions from the other subset or even from another flood loss database with mixed loss reports. The importance of this uncertainty bound becomes apparent when a flood risk analysis was carried out. There, the estimates of the non-plausible models differ by a factor of 18 between the highest and lowest loss calculation. In contrast, the uncertainty range of the successfully validated models is reduced to a factor of 2.3. Even if the risk was only estimated for residential areas it should become more evident how large uncertainties of single methodological steps like the damage modeling within risk analysis might be.

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Due to these findings we encourage future research not only to be aware of the problematic applicability and transferability of flood loss models in different geographical regions. Instead more systematic flood loss data collection is needed to adapt and validate flood loss models in other study areas since they are often used in risk analysis, regardless of their associated uncertainties.

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Table 1. Error statistics for two simulation runs of the flood event in 2005. Note: the "Flood area index" was only calculated for the southern part of the study area (DEM *"22a"*: dike heights as in 2005; DEM *"23a"*: dike heights as in 2005 but artificially opened at two breach locations at the municipality of Pflach as described by Kröll, 2007).

Digital elevation model (DEM)	Bias (m)	Mean absolute error (m)	Root mean square error (m)	Flood area index (%)
22a	0.31	0.38	0.51	83.8
23a	0.31	0.38	0.51	83.8

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Table 2. Statistical characteristics of the flood damage ratios of the two subsets (*"surveys_GER"*[a] and *"surveys_BY"*[b]) and differentiated between the factors considered in the flood loss functions.

Factor	*n*	25 %-ile	50 %-ile (mean)	75 %-ile	*n*	25 %-ile	50 %-ile (mean)	75 %-ile
	surveys_GER				*surveys_BY*			
All loss reports	1135	1.5	5.1 (11.1)	15.4	420	0.5	1.9 (4.4)	5.2
Water Level	(*)				(*)			
< 21 cm	439	0.4	1.5 (3.4)	3.9	247	0.3	1.2 (2.6)	3.1
21–60 cm	137	2.0	5.1 (8.4)	10.5	52	0.9	3.4 (6.1)	7.2
61–100 cm	131	2.9	5.7 (9.5)	12.7	49	1.9	3.5 (5.6)	7.3
101–150 cm	151	6.3	13.6 (17.8)	25.7	29	1.9	3.4 (8.3)	12.0
> 150 cm	263	8.6	17.9 (22.4)	31.5	38	1.9	5.6 (9.5)	14.3
Building type	(*)				(*)			
One-family houses	654	1.7	6.0 (12.4)	19.4	230	0.8	2.1 (5.1)	5.9
Two-family houses	294	1.3	4.3 (9.6)	12.5	117	0.4	1.5 (3.8)	4.2
Multi-family houses	186	1.1	3.9 (8.9)	10.5	73	0.3	1.3 (3.1)	4.2
Building quality								
High quality	1062	1.5	5.1 (11.2)	15.4	388	0.5	1.8 (4.4)	5.1
Low/medium quality	66	0.7	3.3 (9.0)	15.7	28	0.4	2.1 (5.1)	8.4
Contamination	(*)				(*)			
None	546	0.6	2.1 (6.2)	6.6	279	0.3	1.4 (3.2)	3.8
Yes	579	3.6	10.9 (15.7)	22.4	139	1.4	3.5 (6.8)	8.5
Private precaution[c]	(*)				(*)			
None	868	2.0	6.9 (12.8)	18.3	281	0.6	2.1 (5.1)	6.0
Yes	265	0.5	1.9 (5.4)	5.7	137	0.4	1.3 (3.0)	3.5

[a] Subset comprises all cases from both surveys carried out in Germany.
[b] Subset is constrained to the interviews collected in the federal state of Bavaria.
[c] Precaution is the fact when households implemented "flood adapted building use" and/or "flood adapted interior fitting".
Note: (*) differences in the subsets are significant on a 0.05-level.

Table 3. Derived scaling factors for building losses due to private precaution and contamination. Factors for the extended loss model $FLEMO_{AT+}$ are differentiated between the two subsets *"surveys_GER"* and *"surveys_BY"*.

	surveys_GER	*surveys_BY*
No contamination, no precaution	0.90	0.88
No contamination, good precaution	0.44	0.48
Contamination, no precaution	1.33	1.53
Contamination, good precaution	0.81	0.90

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Table 4. Comparison of different loss estimates with the observed flood damage (95 % confidence interval) on residential buildings for the flood event of August 2005 (✓ and × means that estimate lies within or outside the interval, respectively). Note: For the loss estimates only mean specific asset values are taken into account here.

Dataset	Damage function	Simulation run *22a* Estimated losses (in k€)	Simulation run *22a* Within 95 % interval	Simulation run *23a* Estimated losses (in k€)	Simulation run *23a* Within 95 % interval
HOWAS	MURL (2000)	608	×	842	×
	ICPR (2001)	1736	✓	2553	✓
	Hydrotec (2002)	7133	×	9094	×
surveys_GER	linear	3114	×	4264	×
	square root	3807	×	4776	×
	polynomial	4509	×	6042	×
	$FLEMO_{AT}$	3778	×	4887	×
	linear (co.)	2903	×	3718	×
	square root (co.)	3314	×	4142	×
	polynomial (co.)	4122	×	5506	×
	$FLEMO_{AT+}$	3342	×	4322	×
surveys_BY	linear	1560	✓	1963	✓
	square root	1819	✓	2244	✓
	polynomial	2181	✓	2854	×
	$FLEMO_{AT}$	2005	✓	2510	✓
	linear (co.)	1471	✓	1836	✓
	square root (co.)	1678	✓	2060	✓
	polynomial (co.)	1898	✓	2454	✓
	$FLEMO_{AT+}$	1872	✓	2343	✓

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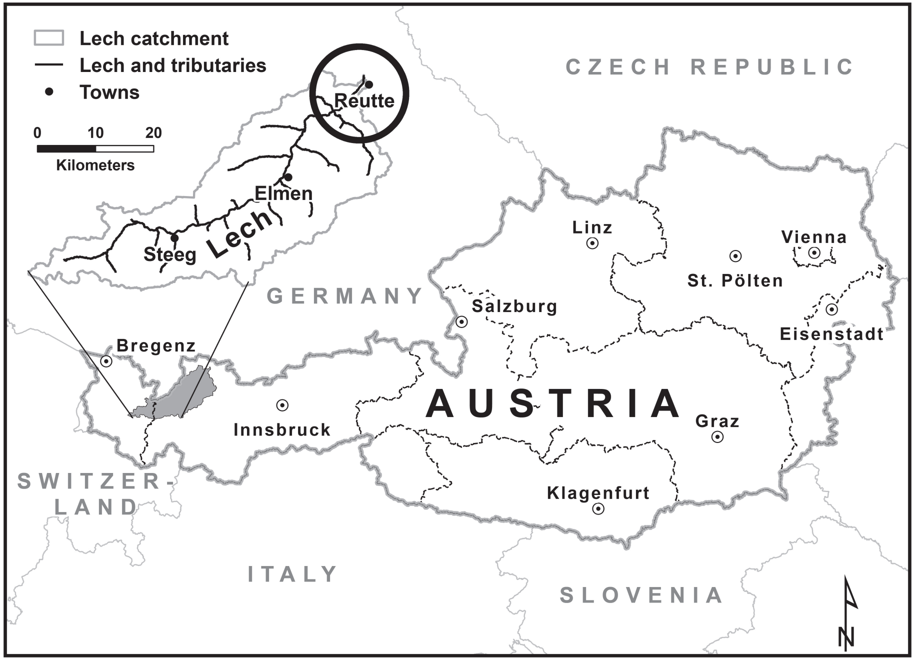

Fig. 1. Geographical overview of the study area in Austria.

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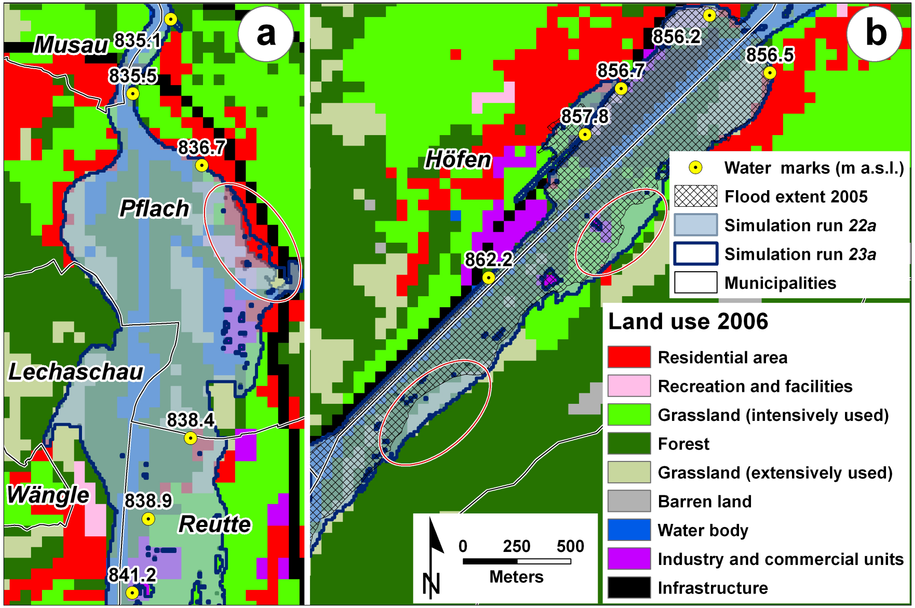

Fig. 2. Comparison of the water marks and the flood extent of 2005 with the two simulation runs *"22a"* and *"23a"* in the northern **(a)** and in the southern part **(b)** of the study area. The red circle in **(a)** illustrates the location of the difference in the flood extents at the community of Pflach between both runs. The red circles in **(b)** display the differences between the observed and modeled flood extents in the southern study area.

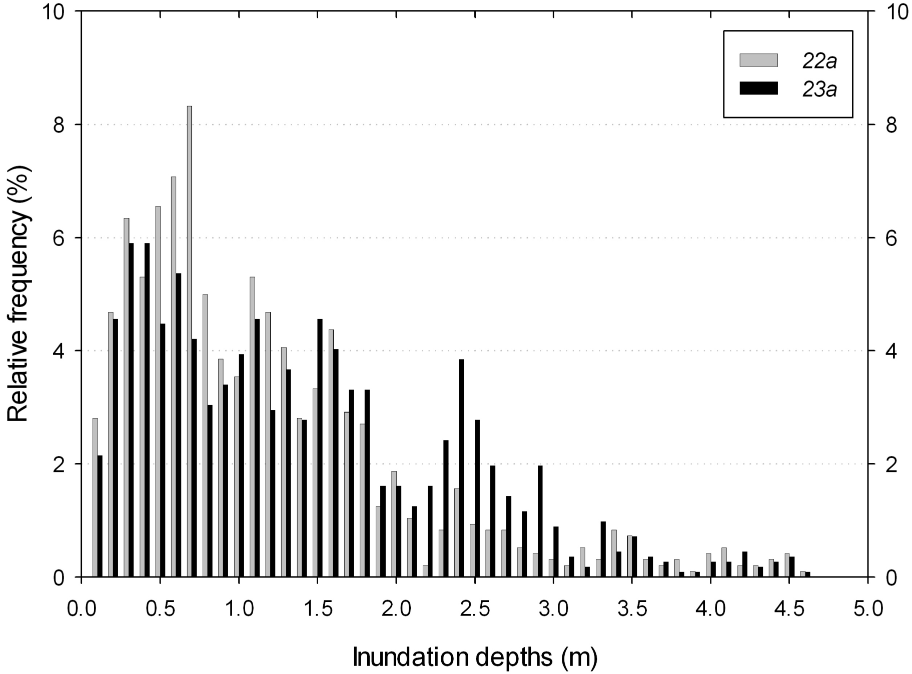

Fig. 3. Relative frequencies of the water depths (within a 10 cm interval) in 2005 for the two simulation runs *"22a"* and *"23a"*. Note: only inundated grid cells within residential areas are analyzed in this histogram.

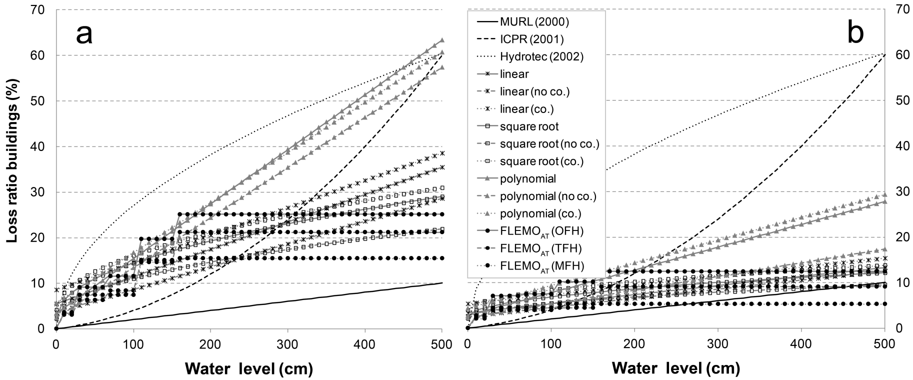

Fig. 4. Common stage-damage functions and newly derived ones from the mixed dataset *"surveys_GER"* **(a)** and from the Bavarian subset *"surveys_BY"* **(b)**. Functions with "co." and "no co." in parenthesis differentiate further between contamination and no contamination, respectively. $FLEMO_{AT}$ curves are shown for one-family (OFH), two-family (TFH) and multifamily (MFH) houses.

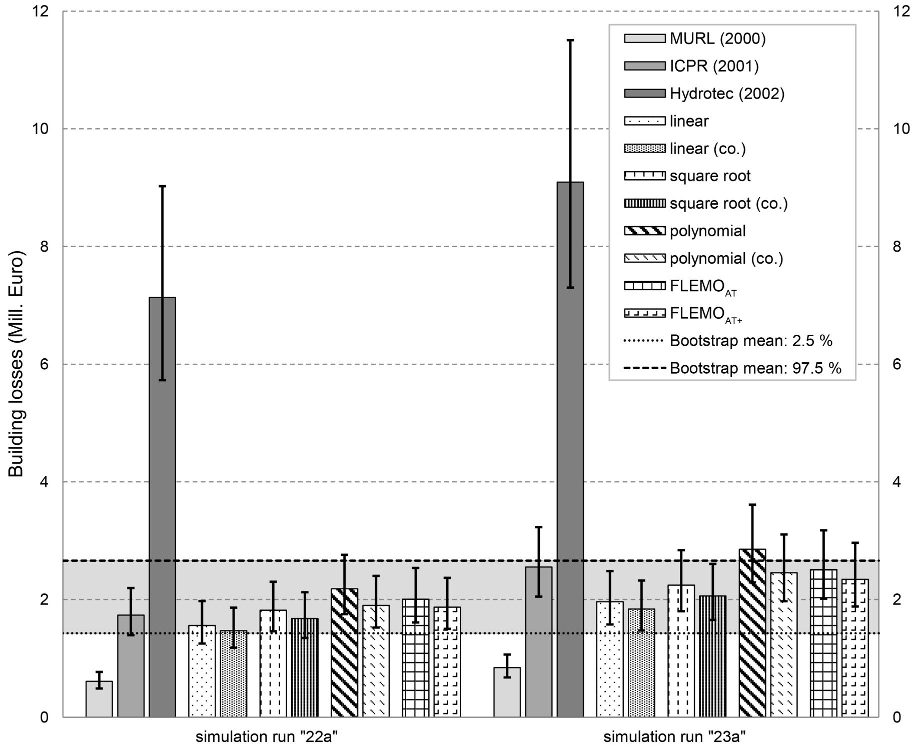

Fig. 5. Flood loss model estimations with error bars (due to the range of underlying asset values) for the flood event in August 2005 for the two hydraulic simulation runs *"22a"* and *"23a"* by means of the loss functions derived from the Bavarian subset *"surveys_BY"*. Loss estimates of the three standard functions (MURL, 2000; ICPR, 2001; Hydrotec, 2002) are also plotted here. The confidence interval that was derived from reported losses by bootstrapping is highlighted in light grey.

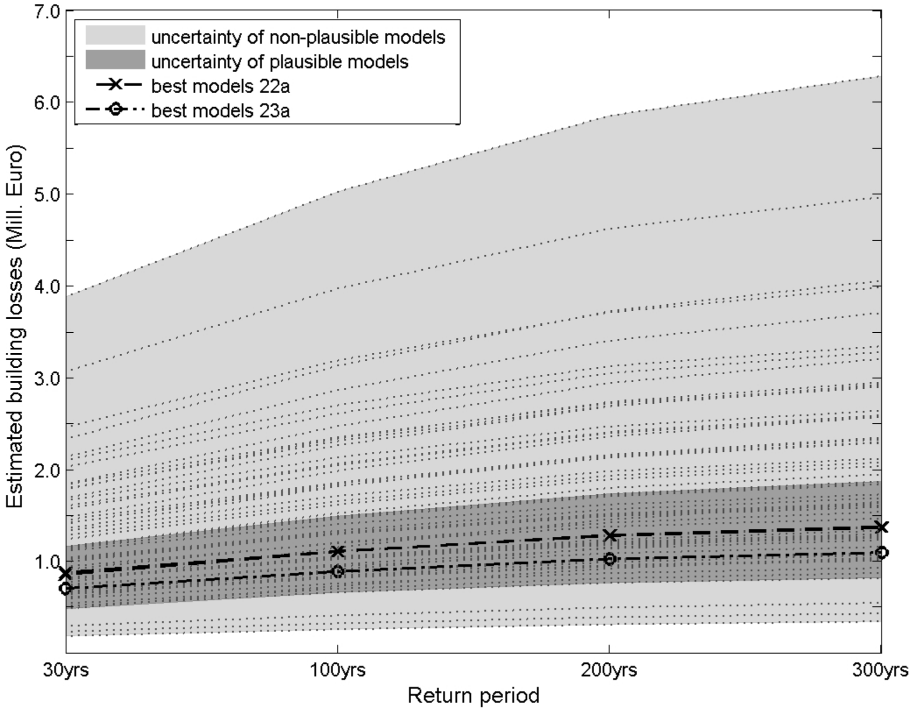

Fig. 6. Current risk curve for residential areas with associated uncertainty bounds based on the range of 29 plausible models, i.e. successfully validated models, and based on the range of 28 additional, non-plausible loss models. The most accurate functions (i.e. the smallest deviation to the observed loss) in case of the hydraulic simulation runs *"22a"* and *"23a"* for 2005 are shown in dotted lines.

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