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Project data

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Executive Summary

Worldwide, one third of the economic losses caused by natural hazards are determined by floods. Flood damage increased significantly in the last decades and is expected to rise further in several regions of the world due to altered flood frequencies in consequence of global climate change and shifts in vulnerability. In order to encounter rising flood losses in the future it is necessary to reduce them to an acceptable level by an adapted and sustainable risk management.

The FloodTimeS project meets the demand of a modern risk-based natural hazard management and has moved towards a future-oriented management of climate change induced effects on human-environment systems. On the one hand, the project aimed at examining the impacts of climate change on the frequency-magnitude relationship of floods thus quantifying the hazard potential for the 21st century. On the other hand, shifts in the damage potential were investigated and quantified, particularly for the settlements along the Lech river reaches in the region of Reutte, Tyrol, Austria. As main outcome it was aimed at generating flood risk time series for the next decades which might be used as a basis for recommendations on appropriate adaptation measures.

Following the definition of risk, meteorological, hydrological and hydraulic investigations to define flood hazard and the estimation of flood impacts (i.e. the flood damage) to quantify vulnerability have to be carried out to determine current and future flood risk. In FloodTimeS, the flood hazard analysis integrated i) downscaling of global circulation model results, ii) hydrological modelling, iii) flood frequency analysis, and iv) hydraulic modelling to assess changes in inundated areas. The socio-economic investigations consisted of i) land use modelling, ii) identifying flood exposed assets at risk, and iii) assessing the vulnerability to quantify changes in the damage potential. Finally, flood probabilities and vulnerability assessments were combined to risk estimates for present and future conditions.

The main findings of the project are that changes in flood risk in the near future (i.e. in 2030) are relatively low compared to 2006. Only if strong urbanization takes place associated with economic growth, flood risk will increase remarkably. The impact of climate change on the flood hazard and further on flood risk is slight or negligible compared to the contribution of potential land use changes in the near future, i.e. by 2030.

The project FloodTimeS started in November 2009 and ended in January 2013. During the project period, seven papers in international peer-reviewed journals as well as six other papers were published. In addition, one PhD was finished in September 2012 and a second PhD will follow in 2013. Furthermore, two international workshops were organised and performed by the project consortium. Altogether, the main aims of the project were achieved and the project has contributed to international networking and recognition of research in Austria.

1 Introduction and objectives of the project

Initial situation and motivation

Worldwide, the number of big natural disasters at least doubled during the last 50 years, while in the same time period the resulting damages increased by factor eight (Munich Re 2008). Of all natural hazards, floods are responsible for the largest economic losses worldwide (Munich Re 1997; 2004). In Austria, the flood events in August 2002 and 2005 caused damage of 2445 Million Euro and 515 Million Euro, respectively (Munich Re 2007). Further increases in losses are expected. A weakening of the increasing trend of flood losses can only be achieved with a significantly improved risk management.

In this context, flood risk is defined as the product of hazard, i.e. the physical and statistical aspects of the flooding process (e.g. return period of the flood, extent and depth of inundation), and vulnerability, i.e. the exposure of people and assets to floods and the susceptibility of the elements at risk to suffer from flood damage (e.g. Mileti 1999; Merz & Thieken 2004). In risk analyses with a technical focus, vulnerability comprises two elements (Merz & Thieken 2004; Kron 2005): 1) the asset values at risk: the buildings, infrastructures, humans etc. that are exposed to the flood hazard; and 2) the susceptibility (vulnerability) of the exposed structures, e.g. the lack of resistance to damaging/destructive forces. Thus flood risk can be defined as: Risk = Hazard x Values at Risk x Vulnerability. Changes in flood risks can hence be attributed to – but can also be governed by – changes in the flood hazard, elements at risk (exposure) or their susceptibility to flooding.

One important factor for increasing losses is the ongoing settlement and economic development leading to a continuous increase in assets in flood-prone areas. In developing countries, this trend is due to population growth, but it is also due to comparatively low prices for building land, good transport infrastructure and the relatively high proximity to cities in industrialised countries. For instance, communities with more than 5000 citizens are twice as often located at rivers as in the total area of Germany (Borchert 1992). Therefore, urban and spatial planning are crucial for the development of the flood risk (White & Howe 2002; Petrow et al. 2006).

In several regions, climate change may contribute to an increase in flood losses due to an augmentation of flood frequencies and magnitudes. However, the impact of climate change differs from catchment to catchment (Smith 1999; Schreider et al. 2000; Hall et al. 2005). Recently, results for Austria were published by Blöschl et al. (2011). Due to the complexity of regional changes in meteorology and hydrology projections of changes in flooding are of low confidence (IPCC 2012). Even with regard to observed changes in the magnitude and frequency of floods, IPCC (2012) finds limited to medium evidence at regional scales due to limited flood records and confounding effects of changes in land use and engineering. In fact, human-induced changes in land use have also been identified to play a key role in flood risk development (e.g. Hall et al. 2006; Feyen et al. 2009; Merz et al. 2010a). However, climate impact studies on flooding that also include vulnerability and risk aspects are still rare. Therefore, the FloodTimeS-project aimed at investigating changes in flood risk due to climate as well as socioeconomic changes in an alpine environment.

Project goals

In the perspective of the catastrophic floods in 1999, 2002 and 2005, a considerable increase in both the hazard and damage potential of natural events has become apparent also in the Alpine Space (BMLFUW 2006; Stötter 2007). The new challenges have to oppose an adapted and sustainable risk management and have to reduce future damages to an acceptable level. As a consequence, the master goals of the project FloodTimeS were:

- to examine the impacts of climate change on frequency and magnitude relationship of floods thus quantifying the hazard potential for the 21st century,

- to investigate and quantify shifts in the damage potential particularly the development of settlement along river reaches and
- to develop risk time series for the next decades.

In this project, a risk analysis with a focus of changing climatic and land-use conditions was carried out. With regard to the flood hazard, research focussed on meteorological and hydrological parameters and their influence on the relationship of flood frequencies (return periods) and magnitude of events (intensities). With respect to vulnerability and damage the development of the number of people living in affected areas and the growth in extent and value of flood-exposed settlements and infrastructure were of interest as these factors have mainly been responsible for the recent increase in losses from natural disasters (Kron 2005).

A pressing aim of this study was to minimize the risk to be expected by giving recommendations for appropriate adaptation to policy-makers, administrations, and other stakeholders. Therefore, this study was meant to contribute to efforts that have been made to maintain the European Alps as living space and economic area – also in times of global climate change.

In what follows, first the methodological approach of the project and the study area are introduced (Chapter 2). Then the project contents and results are summarized per work package (Chapter 3). Finally conclusions and recommendations are presented in Chapter 4. At the end of the report a list of references and of dissemination activities of the FloodTimeS-project can be found.

2 Methodological Approach and Study Area

The study was designed as a pilot project for flood risk analyses in the perspective of climate and land use change. Following the above-mentioned definition of risk, meteorological, hydrological and hydraulic investigations to quantify the hazard and the estimation of flood impacts to characterise vulnerability were undertaken separately as illustrated in Figure 1.

The flood hazard analysis integrated:

i. downscaling of global circulation model results by the Expanded Downscaling (EDS) technique introduced by Bürger (1996),
ii. hydrological modelling with the conceptual semi-distributed rainfall–runoff model HQsim,
iii. flood frequency analysis by the GEV distribution, and
iv. hydraulic modelling to assess changes in inundated areas by the two-dimensional model Hydro_AS-2D (Nujic 2003).

The socio-economic investigations consisted of:

v. land use modelling with the explicit model Dyna-CLUE (Verburg & Overmars 2009),
vi. identifying flood exposed assets at risk by GIS analyses, and
vii. assessing the vulnerability to quantify changes in the damage potential by using different stage-damage curves.

Finally, flood probabilities and vulnerability assessments were combined to risk estimates for present and future conditions. Details on the methods are given in chapter 3.

Investigation area

As investigation area, the upper part of the catchment area of the river Lech with particular emphasis on the area around Reutte in Tyrol, Austria, was chosen. The catchment has an area of about 1000 km² and covers around one quarter of the whole Lech watershed up to Marxheim in Germany (see Figure 2).

The catchment is characterized by a nivo-pluvial runoff regime, with a minimum runoff observed during winter and a maximum runoff in late spring and summer. Long-term mean daily runoff at the outlet gauge at Lechaschau is approximately 45 m³/s. Major floods can be caused either by a combination of snow melt and heavy rainfall or by heavy rainfall alone. Altitude ranges from 838 m a.s.l. at the outlet of the basin to 3038 m a.s.l. at the highest mountain peak.

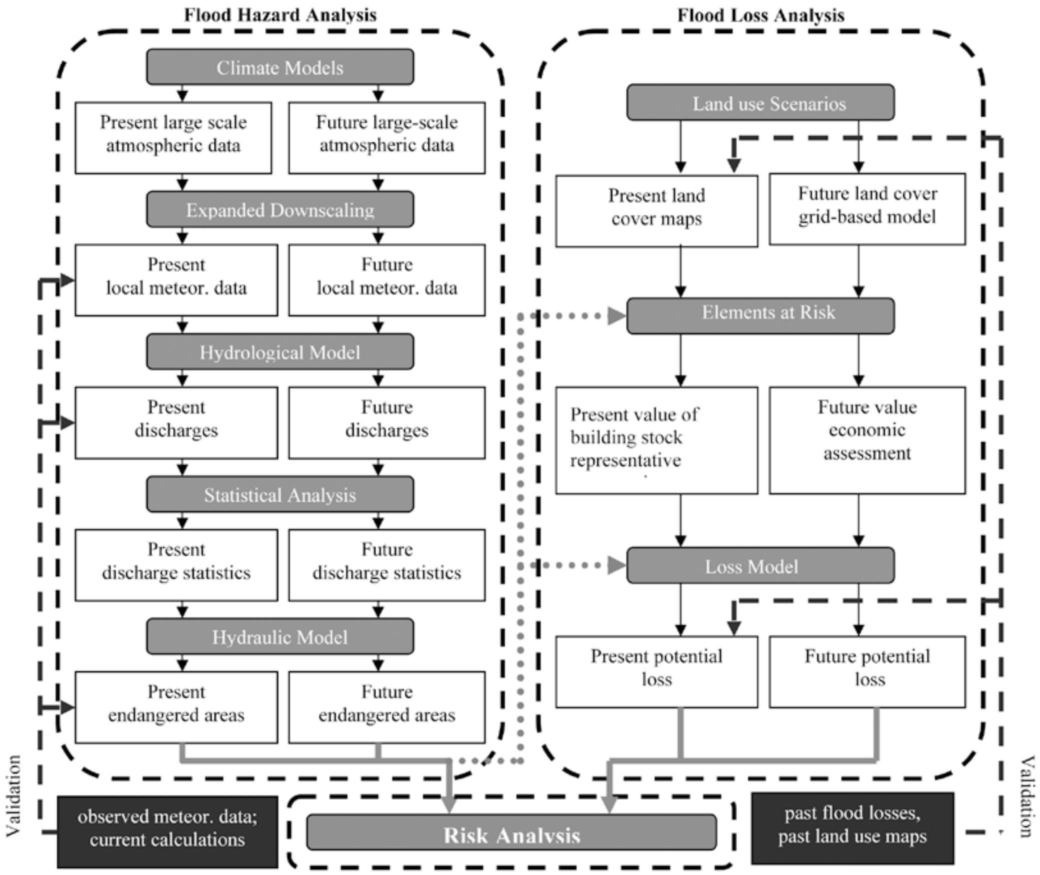

Figure 1: Methodological steps in FloodTimeS.

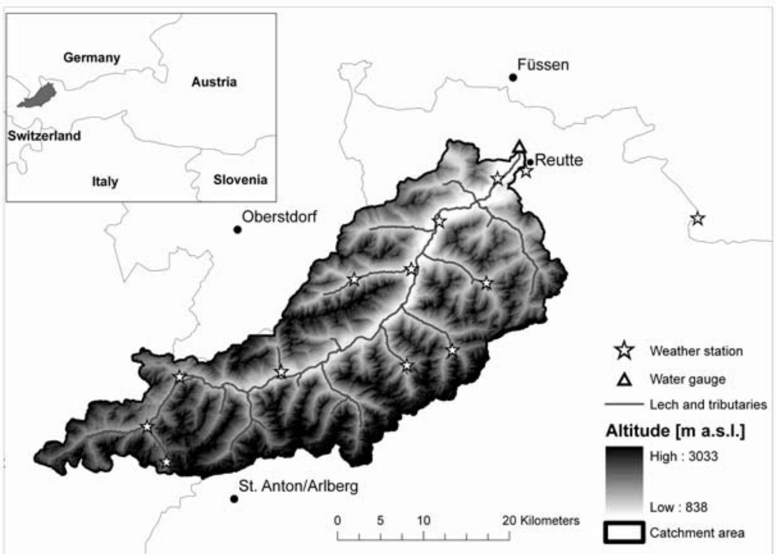

Figure 2: Map of the Lech watershed, showing the location of weather stations and the location of the water gauge.

3 Contents and results of the project

The following sections summarise the main results of the FloodTimeS-project, following the structure presented in Figure 1.

Climate change scenarios (Work package 1.1)

The aim of this work package was to derive climate change scenarios for the gauging stations in the study area shown in Figure 2. Therefore, the output of global circulation models was downscaled to a finer spatial resolution, with a special focus on reproducing extreme weather events. In order to assess and to reduce possible uncertainties involved in the climate projections a set of different climate models and scenarios was used.

In the FloodTimeS-project, the Expanded Downscaling (EDS) technique, introduced by Bürger (1996) was applied. EDS is a statistical downscaling technique which belongs to the group of regression methods. Thereby, a linear function between the large-scale variables x ('predictors') and the local-scale variables y ('predictands') is established. EDS is largely based on the concept of a multiple linear regression (MLR), which is frequently applied in statistical downscaling of GCM output (e.g. Maraun et al. 2010). However, the least-squares criterion of MLR significantly reduces the variability of local climate variables. Therefore, Bürger (1996) modified this concept in order to better simulate climate extremes. A side condition was added to the MLR definition which expresses the preservation of the local covariance. A full description of the EDS model is given in Bürger et al. (2009).

Figure 3 gives an example of the performance of the EDS model in the complex Lech basin. In general, observed precipitation is reproduced fairly well by the EDS model, which is driven with reanalysis data (ECMWF-interim data). Based on the period from 1989 to 2005, the correlation coefficient between observed and simulated time series is 0.78 for areal average precipitation.

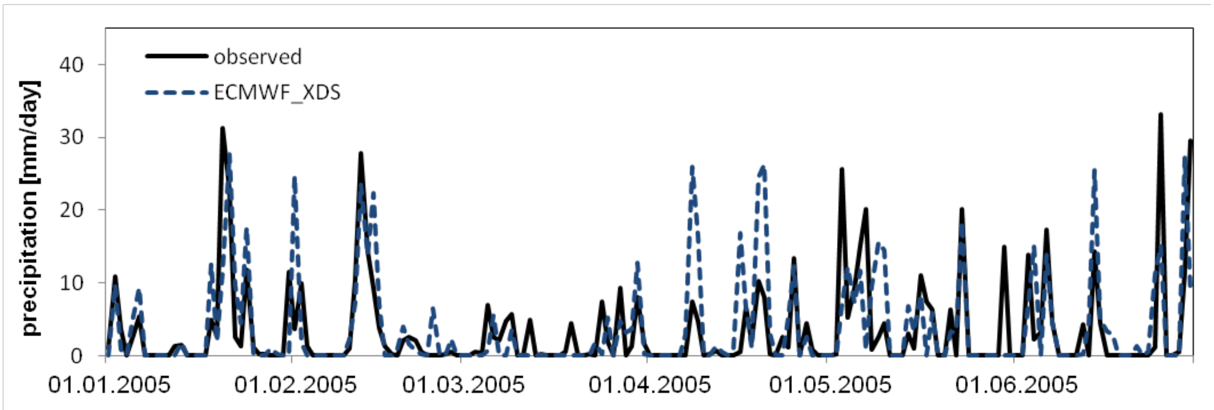

Figure 3: Observed and statistically downscaled precipitation at station 101113 (Lech village) from 01.01.2005 to 30.06.2005. The EDS model is forced using ECMWF reanalysis data (denoted by ECMWF_XDS).

Beside the ECMWF-interim data, which was used to calibrate and validate the EDS model, the output of two GCMs, i.e. EH5OM and HadGEM2, was downscaled to a finer spatial resolution. The EH5OM simulation run was based on the A2-scenario as defined in the Special Report on Emission Scenarios (SRES), while the HadGEM2 simulation run was forced by the A1B-scenario. Three ensemble integrations of the EH5OM model for the control run and the future scenario were used. The HadGEM2 simulations included one simulation for the control run and three ensemble integrations for the future scenario. The ensemble members of each GCM were treated as one 90-yr experiment for the present and future scenario.

In general, downscaling precipitation extremes is a challenging task and is subject to large uncertainty. Recently, several investigations have reported large model biases when focusing on precipitation extremes (e.g. Smiatek et al. 2009). The results of this investigation showed that the EDS model performed very well in reproducing observed precipitation extremes. The biases of all simulations are within an acceptable range, even for rare events, e.g. that one with a 20-year return period. Thus the downscaled meteorological data served as input data for the hydrological model and provided a better understanding of the complex climate change on a regional scale (WP 1.2).

Hydrologic modelling (Work package 1.2)

The meteorological input data, i.e. temperature and precipitation, of the baseline and the future scenarios were to be transformed into discharge series by hydrological modelling. The hydrological model HQsim was used to simulate the hydrological behaviour of the Lech basin. HQsim is a conceptual semi-distributed rainfall–runoff model which was specially designed for the simulation of runoff in mountainous watersheds. The model is largely based on the water balance model BROOK, developed by Federer & Lash (1978). Details of the model are reported in Dobler & Pappenberger (2012).

In a first step, a sensitivity analysis was performed with the HQsim model. Sensitivity analysis is an important tool i) to better understand how these complex models work, ii) to verify the model structure, and iii) to determine the key parameters which exhibit major influence on the simulation results (Sieber & Uhlenbrook 2005; Manache & Melching 2008). The latter is of particular interest in order to reduce the dimensionality of the parameter space, which is important for a variety of applications, such as model calibration, parameter estimation or uncertainty assessment in order to identify the most important parameters of the complex model. In this study, three different sensitivity analysis techniques were applied, namely i) Regional Sensitivity Analysis (RSA), ii) Morris analysis and iii) State Dependent Parameter (SDP) Modelling.

Generally, the results show that parameters affecting snow melt and processes in the unsaturated soil zone are of high significance in the analysed Lech catchment. The parameter meltfunc_max, which defines the maximum degree-day factor, was found to be of particular importance. While parameters affecting snow melt show clear temporal patterns in the sensitivity throughout the year, the importance of parameters affecting processes in the unsaturated soil zone do not vary in importance throughout the whole year. These findings considerably helped to improve the model calibration.

In a next step, the HQsim model was calibrated and validated based on observed meteorological and hydrological data. A classical split-sample test was applied to divide the time series from 1989 to 2005 into a calibration (1989 to 2000) and a validation (2001 to 2005) period. It should be noted that the chosen periods are identical to those used for calibrating and validating the EDS model (WP 1.1).

Figure 4 gives an example of the performance of the HQsim model for one year in the validation period. Generally, a good agreement between observed and simulated runoff data is obtained. The hydrological simulations reveal slight weaknesses in the simulation of flood peaks during winter. However, as these events are usually small to medium flood events in comparison to summer floods, they may not cause large damages. Hence, their influence on the estimation of flood risk is limited. The Nash-Sutcliffe efficiency (NSE) criterion, which is used to quantify the model performance, is 0.86 for the period from 1989 to 2005, indicating that the model performs well in this complex Alpine watershed.

Finally, the performance of the modelling chain consisting of the EDS and HQsim models was tested in reproducing observed runoff data. Figure 5 illustrates the performance of HQsim model forced with downscaled ECMWF data for one year in the validation period. It can be seen that the modelling chain captures hydrological processes well with a NSE coefficient of 0.73 for the calibration and validation period.

The performance of the HQsim simulation driven with downscaled reanalyses data shows slight weaknesses when focusing on very extreme floods, such as those in 1999 and 2005, which had return periods of multiple centuries. This is mainly due to the relatively short calibration and validation period used in this study, which creates considerable uncertainty for events with high return periods. However, longer periods of high-quality reanalysis data such as ERA-interim data were not available.

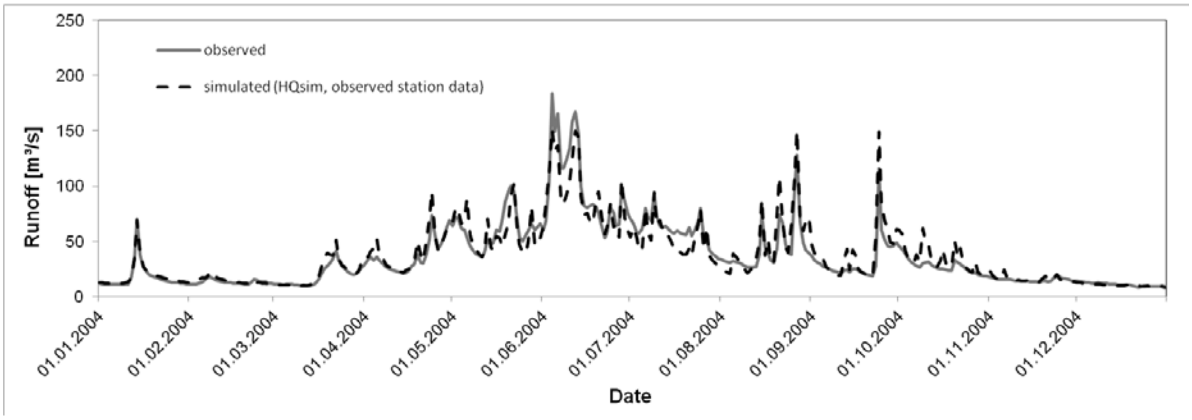

Figure 4: Runoff performance of the HQsim model for the year 2004.

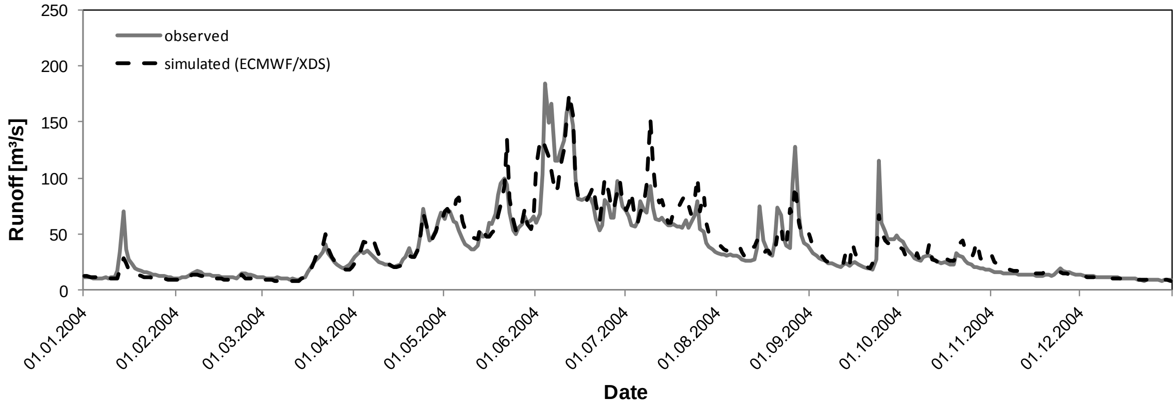

Figure 5: Runoff performance of the HQsim model driven by downscaled ECMWF reanalysis data for the year 2004.

In a last step, the downscaled output of the two GCMs, i.e. EH5OM and HadGEM2 (see above), was used to force the hydrological model in order to obtain runoff series for present and future climate conditions.

Statistical Analysis (Work package 1.3)

The objective of this work package was to estimate the frequency (return period) and magnitude (intensity) relationship of floods by fitting various functions to the data and selecting those which will be able to describe the observed floods in best possible way.

Estimating the frequency of extreme floods is a key element, but also a major challenge in flood risk analysis. A robust estimation of extreme events requires long flood records in order to reliably extrapolate long return periods (e.g. Merz & Thieken 2009). However, in Alpine catchments long-term measurements are often missing. This hampers the application of flood frequency analysis when observed runoff data has to be used as input. As a first step, the Generalized Extreme Value (GEV) distribution was applied to different annual maximum discharge series derived from discharge measurements at the gauge Lechaschau. In order to reduce uncertainty, information on historic flood events was included by using the procedure of DVWK (1999), i.e. the data gap between the historical event in 1910 and the beginning of continuous measurements in 1971 are filled several times with observed flood discharges that fall below the discharge attributed to the historical event. This is based on the assumption that in the data gap the statistical characteristics of the observed time series are also valid (Merz & Thieken 2009).

When fitting the Generalized Extreme Value (GEV) distribution to the annual maximum discharge series of two different time slices of the water gauge in Lechaschau near Reutte - 1971 to 1998 and 1971 to 2008, respectively -, a wide range of uncertainty is obtained as shown in Figure 6. The occurrence of several severe floods from 1999 to 2008 decisively changes the distribution function. Therefore, Merz & Blöschl (2008) suggested expanding this traditional concept by including temporal, spatial and causal information. In this project, historical data were included in order to get more robust estimations. For this, runoff records downstream of Lechaschau/Reutte, i.e. at the water gauge in Füssen (Germany), were used. Here, data are available since 1901; since 1954 measurements are, however, influenced by backwater effects. Therefore, data were only used to identify strong historic flood events.

The time series at Füssen revealed that a flood with similar intensity like the one in 1999 occurred in 1910. This historical event is also confirmed by Meier (2002) for the Upper Lech Valley. This event was thus included in the flood frequency analysis at the gauge Lechaschau by using the procedure of DVWK (1999). Table 1 summarizes the estimates of the return periods of the flood event of 2005 that had a peak discharge of 943 m^3/s at the gauge Lechaschau.

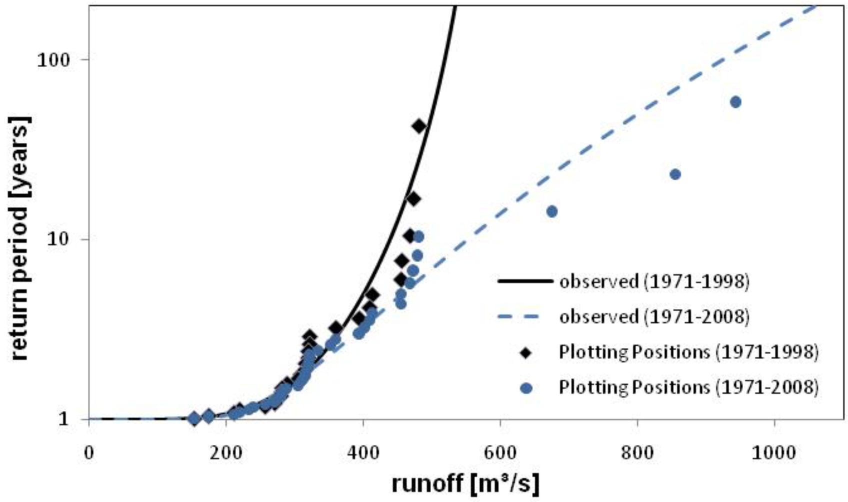

Figure 6: Flood frequency analysis for different time slices of the water gauge in Lechaschau.

Table 1: Estimation of return periods and floods at the water gauge in Lechaschau.

Used time series	Return period of the flood 2005 [years]
1971-1998	>> 1000
1971-2008	~ 110
1971-2008 with historic flood records	~ 330

Table 2: Changes in the flood probabilities between the control and scenario simulations, based on two GCMs, i.e. EH5OM (A2) and HadGEM2 (A1B).

	Return period	EH5OM (A2)	HadGEM2 (A1B)
HQ30	30	-3.9 %	-8.4 %
HQ100	100	-0.2 %	-8.0 %
HQ200	200	+3.4 %	-7.6 %
HQ300	300	+5.9 %	-7.6 %

Further, it was assumed that the two curves shown in Figure 6 can be regarded as an envelope of the "real" flood frequency distribution at the gauge Lechaschau, since the series of the time period 1971 to 1998 contains comparatively low flood discharges, while the series from 1971 to 2008 contains three severe flood events. Considering this, Table 1 illustrates that the inclusion of historical information significantly improves the estimation of events with higher return periods.

In a next step, the GEV distribution was applied to the annual maximum discharge series of both the control and scenario simulations produced in WP1.2. Relative changes in the flood probabilities between the control and scenario simulations were calculated and the changes were applied to the series with historic flood records. Table 2 shows the calculated change factors for the different flood return periods.

Hydraulic modelling (Work package 1.4)

Hydraulic modelling is an important component for flood risk analyses since it transforms the observed or simulated discharge (WP 1.3) into inundation extent and depths along a river reach. In FloodTimeS it was intended to perform hydraulic simulations for the area of Reutte, which is the most important settlement area in the investigation region. For that a variety of models exist, ranging from simple interpolation methods to more complex and spatially detailed models such as 1D-, 2D- or a coupling of 1D/2D-models (e.g. Aronica et al. 1998; Bates & de Roo 2000; Apel et al. 2009). In FloodTimeS, the two-dimensional model Hydro_AS-2D (Nujic 2003) was applied. This model has been applied as a standard system for flood routing in Bavaria, Germany, the neighbouring region to our study area (Dorner et al. 2008) and also for hydraulic scenarios in an Alpine foreland river in Austria (e.g. Neuhold 2013).

The model was originally developed for dam break and flood wave propagation, but is increasingly used for the two-dimensional stream and discharge simulation for river flooding analysis (Noack & Yörük 2008). The spatial discretization is based on the Finite-volume method, whereas the temporal discretization is solved by the Runge-Kutta method (for more details see Nujic 2003). Thus 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 & Yörük 2008) for the generation of the mesh.

Pre- and post-processing of the two- and three-dimensional finite elements was carried out by means of the Surface-water Modelling Solution Software (SMS) from Aquaveo™ (http://www.aquaveo.com). Thereby a mesh of the river channel (length: ~10 km) with its levees was derived integrating 40 cross section profiles of the Lech River and laser scanning data (1 m) from the Tyrolean government. Outside of the levees a flood plain model was built by means of the same laser scanning data (1 m) and the official building map. Thus a simulation grid could be derived by a combination of the river channel model and the flood plain model. In order to reduce the computational resources resulting of the huge amount of computational nodes at each time step refinements of the mesh were carried out by thinning out the node density in flat areas and deleting the nodes within building areas (see Figure 7).

Furthermore, hydraulic relevant structures like bridges, e.g. between Lechaschau and Reutte, and structural protection measures, e.g. flood walls at Lechaschau, were considered in the terrain model.

For the calibration of the flood event in 2005 the structural measures were adapted to the real situation at that time. However, the hydraulic simulations for the present flood scenarios (after 2005) as well as for the future scenarios considered the most recent flood control measures, e.g. heightening of the dikes after flooding in 2005.

Roughness coefficients for the flood plain were derived for different land use classes of the current land use map from the government and for different parts of the river channel according to the Manning/Strickler formula. The hydrologic boundary conditions were adjusted for the inlet discharge according to the discharge at the gauge Lechaschau (WP 1.2 and WP 1.3) located close to the district capital Reutte.

The two-dimensional simulations were performed with the peak discharge observed in August 2005 (for model validation) and subsequently with peak discharges that correspond to different recurrence intervals for the present or the future situation as outlined in WP 1.3. For all simulations, the flood wave observed in August 2005 was used and scaled by the peak discharge that corresponds to the scenario under study.

The resulting simulated maximum water depths (in m above ground surface) and water levels (in m above sea level) were provided as 1 m grid. For the intersection with the asset values (see WP 2.2) and the assessment of flood damage (WP 2.3) the maximum water depths were aggregated on a cell size of 10 m by using the mean of the input cells.

Figure 7: Mesh of the river channel and the flood plain considering building delineations for an improved simulation of the flow characteristics.

The validation of the simulated water depths and inundation area was carried out by means of the flood event in August 2005. From that event, observed water marks were acquired from the engineering office 'DonauConsult' (http://www.donauconsult.at). The water marks were recorded one month after the flood by means of levelling of flood level marked stones, bridges or buildings (DonauConsult, personal communication in 06/2011). As an approximate reference for the accuracy of the flood extent we used the mapped flood extent of Ebner et al. (2007) in the south of the study area, i.e. around the municipalities of Höfen and Ehenbichl (Figure 8). However, the mapped flood boundary based on oblique aerial photos taken by the Austrian Armed Force during the flood event in August 2005 has some shortcomings in the flood affected areas in Tyrol as it is, for instance, not available for the northern part of the study area, where the largest inundation occurred. Furthermore, the photos were recorded two days after the peak discharge. As a consequence, it was difficult to map the exact maximum flood extent (for details see Ebner et al. 2007).

The water depths of 2005 were compared by the deviations between the recorded water marks and the simulated depths with different error measures (Table 3), whereas the flood extent was validated by means of the "Flood Area Index", which is one of the most recommended measures in the literature (e.g. Apel et al. 2009; Mason et al. 2009; Dung et al. 2011). This binary pixel-wise comparison method of observed and modelled flood extents is derived from the ratio between the "correctly" simulated pixels to the intersection area of modelled and observed inundation area (e.g. Apel et al. 2009).

The error statistics for the simulated flood event in 2005 show, that the deviations between the modelled and the observed water depths are small (Table 3). Both for the simulation "22a" (dike heights as in 2005) as well as for the simulation "23a" (dike heights as in 2005 and dikes were artificially opened at two breach locations at the municipality of Pflach as described in Kröll 2007) the errors of the inundation depths are slight with a bias of only 0.31 m or a Root Mean Squared Error (RMSE) of 0.51 m. The Flood Area Index may appear not sufficient (0.84), but should not be overestimated due to the reasons given above. Instead it should be seen as a rough indicator for the modelled flood extent particularly as this measure itself has some deficiencies regarding the bias towards large inundation extents (Dung et al. 2011).

In Figure 8, the water marks and mapped flood extent as well as the flood area of simulation “23a” is exemplarily illustrated for the southern part of the study area. Due to the observed dike breaches at the community of Pflach, we consider the scenario “23a” more reliable than “22a” even if its better performance (larger simulated flood extent at this area) could not been validated quantitatively because of missing recorded water marks and a mapped flood extent in this part of the study area.

After the successful validation of the hydraulic model in the study area, different scenarios were calculated for the present as well as for the future situation with the most recent structural protection measures. Thereby four different recurrence intervals were considered (30-year, 100-year, 200-year and 300-year) as well as two different global climate models (with the emission scenarios A1B and A2, see WP 1.1) for the situation in the year 2030 assuming the changes in the peak discharges that are listed in Table 2. The simulated flood extents were further used in WP 2.2 for the identification of the buildings at risk for different points in time, whereas the simulated inundation depths are an important input for the flood damage modelling in WP 2.3 and the risk analysis in WP 3.

Table 3: Error statistics for two simulations of the flood event in 2005 at eight water marks (see Figure 6); the flood area index was calculated for the southern part of the study area (DEM: digital elevation model, 22a: dike heights as in 2005, 23a: dike heights as in 2005 and dikes were artificially opened at two breach locations at the municipality of Pflach as described in Kröll (2007)).

DEM	Bias (m)	Mean absolute error (m)	Root mean square error (m)	Flood Area Index (-)
22a	0.31	0.38	0.51	0.84
23a	0.31	0.38	0.51	0.84

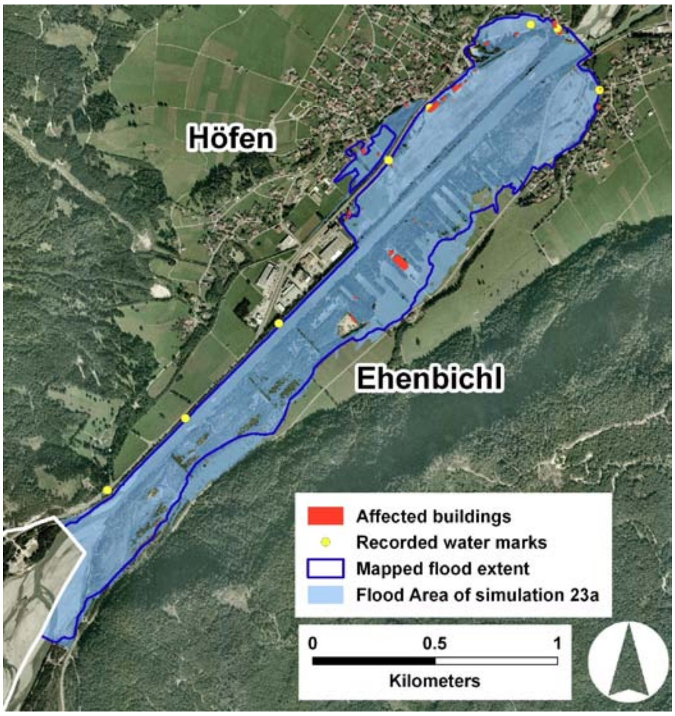

Figure 8: Comparison of the water marks and the flood extent of 2005 with the simulation scenario “23a” in the southern part of the study area.

Land-use scenarios (Work package 2.1)

The work package 2.1 aimed at developing or adopting a GIS-based algorithm that is capable of generating realistic land use change at the local to regional scale, particularly settlement areas in the city of Reutte. Among the variety of land use models the spatially explicit land use model CLUE-S (Verburg et al. 2002), in particular its newer and adapted version Dyna-CLUE (Verburg & Overmars 2009) was applied to simulate future land use patterns in the area of Reutte. The CLUE models have already been used in a wide range of studies before (e.g. Trisurat et al. 2010; Verburg & Veldkamp 2004; Verburg et al. 2008). Among these, case studies were also carried out in an alpine region, e.g. in the framework of the ClimChAlp project (http://www.climchalp.org), where land use scenarios for the Italian Alps were generated, or in other mountainous regions like in Vietnam (Castella & Verburg 2007). Hence, it was expected that the model delivers usable results for the study area of the FloodTimeS-project.

The newer version Dyna-CLUE (Verburg & Overmars 2009) combines the top-down allocation of land use change to grid cells with a bottom-up determination of conversions for specific land use transitions. The spatially explicit allocation module allocates the regional level demands to individual grid cells until the demand has been consumed by an iterative procedure, in which the allocated area of the individual land use types is compared with the claimed area.

A substantial prerequisite for all land use models is the available land use/cover information, which is provided by 'real world' land use maps at a certain point in time. As existing land use/cover databases like CORINE or PELCOM provide only coarse information, which is characterized by substantial over- and underestimations of several land use/cover classes (e.g. Bach et al. 2006), we derived for this local study a land use dataset of the year 2006 based on the visual interpretation of digital colour orthophotos from an aerial survey in 2005/2006. In total, nine land use classes were derived and converted into a raster format (50 m) (see Figure 9b). Furthermore, a second land use dataset valid for the year 1971 was derived (see Figure 9a) in order to analyse the historical land use changes and also the observed settlement agglomerations in flood-prone areas (WP 2.2). The data bases for this land use pattern were digital panchromatic orthophotos surveyed in 1971.

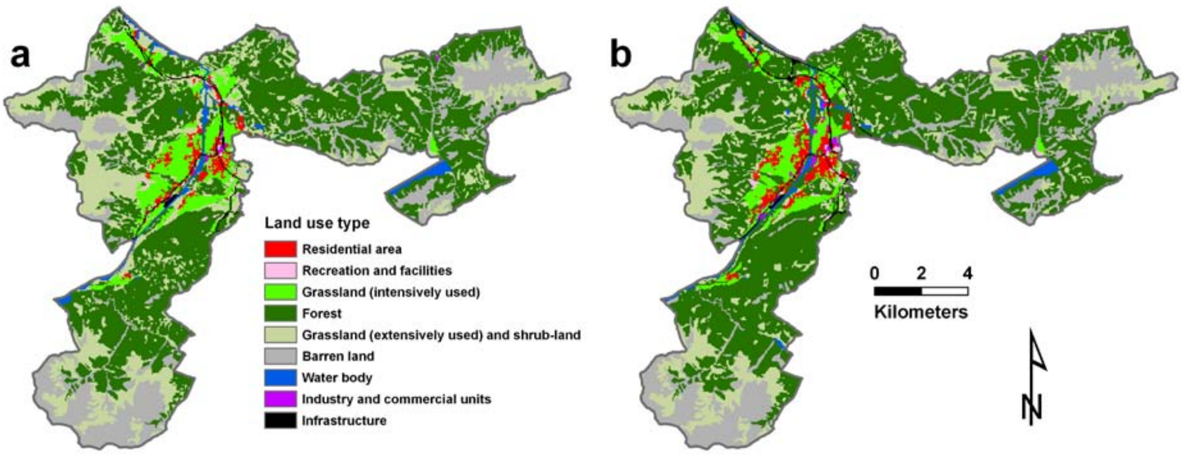

Figure 9: Land use pattern in 1971 (a) and land use pattern in 2006 (b).

On the basis of the land use dataset of 2006 a model calibration of Dyna-CLUE was carried out. Thereby, a variety of potential land use drivers were selected and entered in the statistical model (i.e. logistic regression) to explain the spatial distribution of certain land use types. These land use drivers are of socio-economic (e.g. population density) or biophysical (e.g. climate, topography) origin. Additional influencing factors are accessibility parameters (e.g. distance to town centre or street) as well as neighbourhood interactions. For indicating the goodness of fit of the logistic regression model the relative operating characteristic (ROC) method (Swets 1988) was used, which provides a measure that resembles the use of the R^2 statistic in linear regression analysis. The results of this measure indicate that the selected logistic models are acceptable for using the established relations in the land use change model. Particularly for the urban land use classes, like residential areas, as well as for industrial and commercial units, the threshold value of 0.9 was exceeded, which is highly relevant to the development of flood exposure and flood damage (see WP 2.2 and WP 2.3).

For the future scenario generation the land use demand of the different land use types had to be assessed. Common approaches are for example the extrapolation of the recent land use trend into the near future (e.g. Pontius & Malanson 2005), simple demand models (e.g. Sohl et al. 2007) or participatory approaches (e.g. Tappeiner et al. 2008). In this study, the four spatial planning scenarios for Austria until 2030, published by the Austrian Conference on Spatial Planning (ÖROK), were used. The four integrated spatial development scenarios (for details see ÖROK 2008) of the ÖROK are based on a participatory approach calling for the input of multiple stakeholders, and they are not constrained by existing policies (Williams et al. 2009). Furthermore, spatial policies were included in the scenario generation until 2030 as they may constrain or prefer specific developments in designated areas (e.g., White & Howe 2002; Holub & Fuchs 2009).

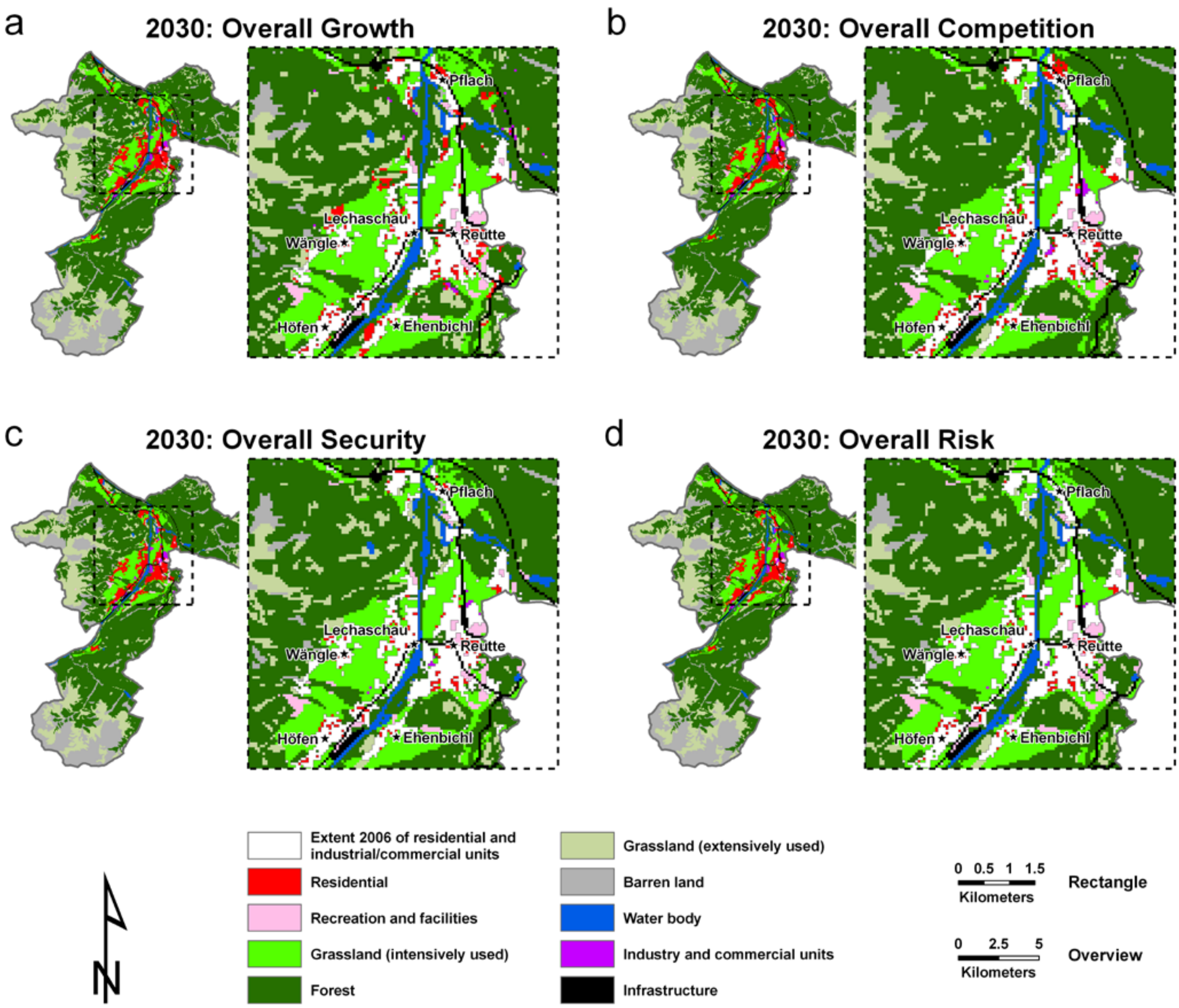

Figure 10: Land use pattern in 2030 for the basin of Reutte with rectangle of the settlement area based on current spatial policy and the storylines a) Overall Growth, b) Overall Competition, c) Overall Security and d) Overall Risk (note: Extent of residential and industrial/commercial units in 2006 are displayed in white colour)

The four different scenarios of 2030 illustrated in Figure 10 are based on national projections and current spatial policy and reveal a wide range of potential land use trends. The simulated land use changes between 2007 and 2030 are not as intensive as in the historic time span, but still notable – depending on the assumed scenario of land use change. Concerning the urban land use types, the historical annual growth rate of residential areas, for instance, is not more than one and a half times higher than in the strongest urbanization scenario 'Overall Growth'. However, in comparison with the weakest urbanization scenario 'Overall Risk', the factor amounts to 5.7. In case of industrial and commercial units, the observed mean annual growth rate is even more intense than for residential areas.

Further results of the investigations on future land use projections were presented in Cammerer et al. (2012) or in Cammerer & Thieken (2013), where the future trends are compared with the historical land use changes.

Elements at risk (Work package 2.2)

In this work package all elements in the investigation area Reutte that are potentially at risk of being flooded were to be evaluated on an economic basis that means a representative monetary value has to be assigned to each structure. In general, assets can be divided in monetary, tangible and intangible assets, whereas only tangible assets are usually of interest for damage assessment studies (Meyer 2005). Furthermore, the assessment concept has to be defined, i.e. the usage of replacement values or depreciated values (Meyer 2005; Messner et al. 2007; Merz et al. 2010b). In this study replacement values were applied, which assume that damaged properties (or damaged parts of a property) will be replaced by new, similar items.

As a basis, we used the aggregated replacement values for each municipality in the investigation area presented in the study of Huttenlau & Stötter (2008). In that study replacement values for the year 2006 were divided up in six functional classes (residential, mixed usage, agriculture, open land, industry and commerce, tourism). After assigning all land use types of our study (see WP 2.1) to their functional classes, specific values (€/m²) for residential buildings and household contents could be derived by dividing the aggregated values by the residential area of each municipality in 2006. For all subsequent analyses an average replacement value for buildings (€ 279 per m²) and contents (€ 89 per m²) was used for the whole study area. Moreover, the upper and lower specific replacement values were applied to illustrate the uncertainty of asset estimation (see Cammerer & Thieken 2013).

The asset values for the future land use scenarios (see WP 2.1) were estimated by means of two different concepts. On the one hand, for each scenario and all points in time 'constant values', i.e. asset values at constant prices of the reference year 2006, were assigned to all grid cells occupied by residential area to discount for inflation. On the other hand, 'adjusted values' were calculated to account for changes in the economic values itself, which is often neglected in many risk assessments for the future (e.g. Feyen et al. 2009; te Linde et al. 2011). As pointed out by Bouwer (2012), the total increase in asset values consists of new assets due to land use change (e.g. new residential areas) as well as appreciation of existing values by technical innovation, improvement or maintenance and repair. Therefore, we introduced an additional correction factor by means of the Gross Domestic Product (GDP) as an approximate indicator of the value development over time (e.g. Bouwer et al. 2010; de Moel et al. 2011). The mean annual average growth rate of the GDP was also published within the ÖROK scenarios (ÖROK 2008) and could therefore be surcharged by means of a correction factor. Since economic growth is already partly covered by the expansion of built-up areas (as simulated by the land use model), the GDP has to be further corrected by relative changes of allocated built-up area according to the approach of Bouwer et al. (2010). Thus all grid cells occupied by residential area in the different land use scenarios obtain an 'adjusted' specific replacement value for buildings and inventory, expressed for the reference year 2006 (for details see Cammerer & Thieken 2013).

For deriving assets at risk, the total asset values (separated into values for buildings and contents) for each point in time and for both concepts, i.e. 'constant values' and 'adjusted values', were intersected with the four different inundation scenarios, i.e. the 30-, 100-, 200- and 300-year flood, provided by WP 1.4. Additionally, also the potential changes of flood exposed residential areas in the flood plain of 2005 were analyzed, which is described in detail by Cammerer et al. (2012).

To filter out the effect of the development of the values at risk from potential changes in the flood hazard (and consequently changes in the inundation area) only the inundation scenarios for the current situation, i.e. without any impacts of climate change, were applied. The results of the historic and potential future development in the assets at risk are shown exemplarily by the total buildings values in the four inundation scenarios for different points in time (Figure 11).

When the building values at risk are compared with the replacement values of 2006 (‘constant values’) considerable changes in the historic time span (1971 to 2006) can be detected. In this period of 35 years, an annual growth rate of more than ~ 2.2 % was observed in all four inundation scenarios.

In the simulated period (2007 to 2030), the asset value development depends very much on the selected land use scenario. In the two rather moderate land use scenarios ‘Overall Risk’ and ‘Overall Security’ the flood-exposed building values are almost constant until 2030 in comparison to the year 2006. In the scenario ‘Overall Competition’, however, the building values grow slightly in the potential inundation areas (0.2 to 0.4 % per year) between 2007 and 2030. Only in the most extreme urbanization scenario ‘Overall Growth’ the annual growth rate jumps up remarkably, which is even higher (i.e. 5.8 to 7.7 %) than in the historical period in the four inundation scenarios.

When the residential building values at risk are corrected by means of the real GDP (‘adjusted values’), both for 1971 and for the four scenarios for 2030, the relative changes in the flood exposed building values are considerably larger due to the consideration of the economic development in this period (Figure 11b). Thus the historical changes between 1971 and 2006 already account for ~ 4.5 % per year in the areas at risk. Between 2007 and 2030 the range of the annual growth rate of the building values at risk is estimated to be between ~ 1 % (‘Overall Risk’) and ~ 2 % (‘Overall Security’) in the two moderate land use scenarios. For the scenario ‘Overall Competition’, an annual increase of 3.5 to 4.1 % of the building values was derived. In the strongest land use and economic growth scenario ‘Overall Growth’, the annual increase even amounts to 11.7 % and 14.8 %.

The absolute changes with regard to household contents are, of course, less than for buildings, but the relative changes in the ‘constant values’ as well as in the ‘adjusted values’ are nearly equal. However, the application of minimum or maximum specific replacement value for all municipalities instead of an average value (see ranges in Figure 11) shows that the total building values (and also household content values) at risk may be subjected to considerable uncertainties.

The investigation of the asset values at risk reveals a remarkable increase in residential building and content values within the present flood zones. For the future a further growth of asset values in the flood-prone areas can only be detected for the strongest land use scenarios. However, an additional consideration of economic growth (‘adjusted values’) leads to a further and clear rise in the assets at risk, particularly in the projected time span (2007 to 2030) and the strongest urbanization and economic growth scenarios. In these estimates, however, also the asset depreciation should be considered to better account for the expenditure (e.g. technical improvement) of the Gross Domestic Product (GDP), which was used as surrogate measure for the economic growth. Moreover, the usage of national projections and national historical records of the GDP instead of regional measures might lead to notably different results. Nevertheless, for such a long time span, it was not possible to get this measure on a regional scale for the historic and the projected period.

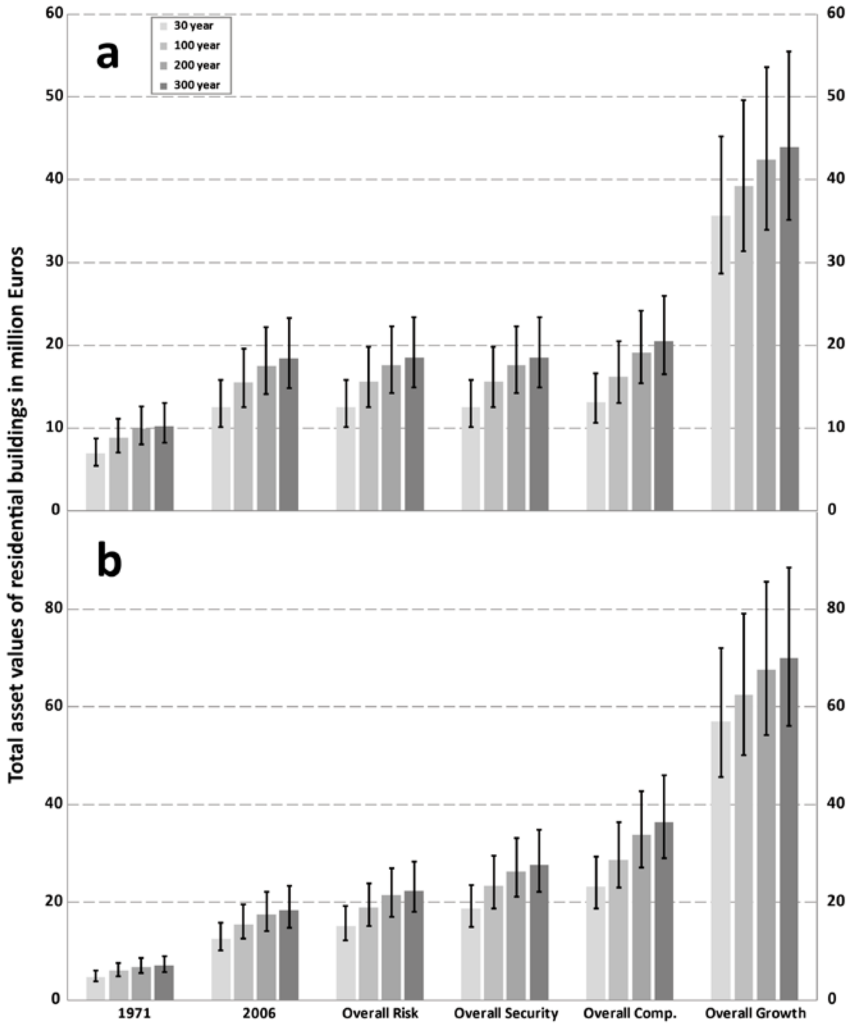

Figure 11: Total asset values with range (by using minimum and maximum specific values) for residential buildings in million Euros and 'constant values' (a) and 'adjusted values' (b) for different points in time within the four inundation areas assigned to the 30-, 100-, 200- and 300-year flood, respectively

Loss modelling (Work package 2.3)

Flood losses are commonly classified in direct and indirect damage (e.g. Smith & Ward 1998; Merz et al. 2010b). While direct flood damage results from the physical contact of water with property, humans etc., indirect damage like production loss or cost of emergency service occur outside the flooded area, but are induced by the same flood event (Merz et al. 2010b). In this study, we limit the estimation of flood losses to direct, structural flood damage on buildings with a focus on residential areas. Potential flood losses were to be estimated for the present as well as for future climate and land use scenarios. For this, the inundation scenarios provided by WP 1.4 and the land use scenarios with an assigned asset value created in WP 2.1 and WP 2.2 were combined with a flood loss model.

Commonly, damage estimations are carried out by means of depth-damage functions which are internationally accepted as a standard approach (Smith 1994). Furthermore, these functions are differentiated between a relative approach which requires the values of the elements at risk and an absolute approach which has the disadvantage of re-calibration due to shifts in the underlying property values (see Merz et al. 2010b for an overview). Because of its simplicity and better transferability to other regions (Merz et al. 2010b), this study uses relative damage functions by integrating the values of the objects at risk, which were already estimated in WP 2.2, and empirical loss data.

To derive empirical damage functions flood loss data have to be collected in the aftermath of a flood event in contrast to synthetic functions, where flood losses are assessed by means of what-if analyses (Merz et al. 2010b; Thieken et al. 2010). In Austria, however, flood loss data of past events have hardly been collected or do not contain the relevant information to relate the flood losses to a certain water depths (e.g. Habersack et al. 2004). Flood loss data are generally collected in the frame of compensation payments by the Austrian disaster funds. Since the single federal states proceed differently in the collection of the data, the quality of the official loss data varies strongly and often enables no separation between different damaged objects (e.g. residential buildings, industry etc.) or damage to the building structures and their contents.

Due to these deficiencies we relied on comprehensive flood loss data which were collected in the aftermath of recent flood events in Central Europe in 2002, 2005 and 2006. Thereby two surveys with computer-aided telephone interviews were carried out in flood affected private households in Germany to collect flood losses on residential buildings and household contents as well as potential flood damage influencing factors like water level, flood duration, contamination, precautionary and emergency measures (for a more detailed description of these campaigns see Thieken et al. 2005, 2007; Kreibich & Thieken 2009). From these two datasets only the flood affected households which are located in the federal state of Bavaria were extracted (n = 766), as Bavaria is very close to the study area in Tyrol and is supposed to have similar building characteristics and damage characteristics.

In total, 475 of 766 cases contained the information about the damage on buildings, which were indexed to the reference year 2006 and were used to derive the loss ratio, i.e. the relative damage. For that, the indexed total values of buildings (replacement costs) are required which is described in detail by Thieken et al. (2005) or Elmer et al. (2010). As not all interviews contained sufficient information for the calculation of the damage ratio for buildings, these relative losses could only be calculated for 420 cases (building ratio).

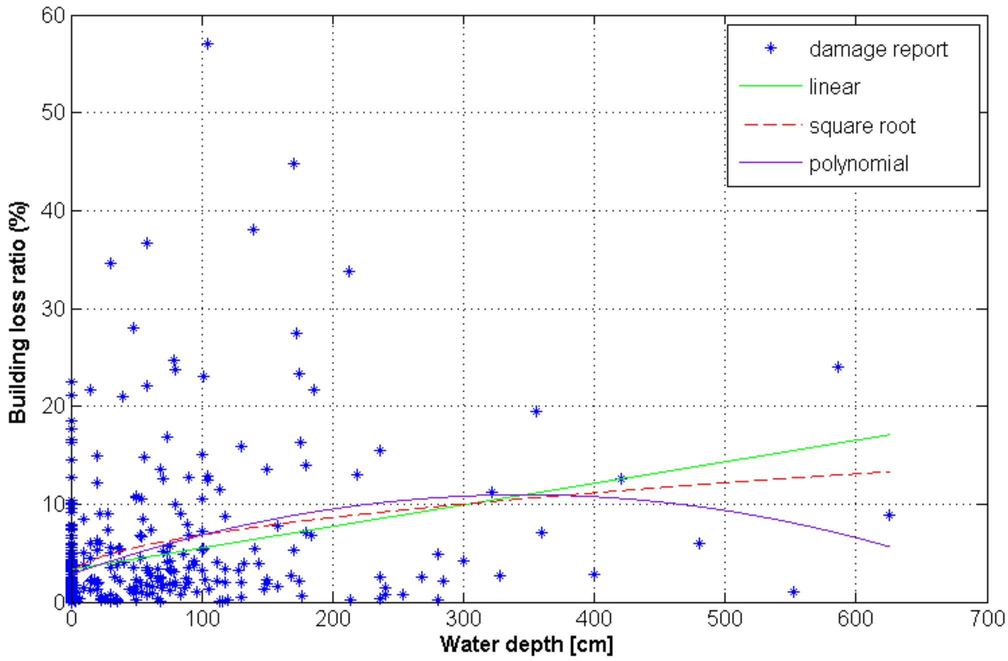

Figure 12: Residential building loss ratios (in %) with corresponding water depths (in cm) surveyed in Bavaria (Germany) and derived depth-damage functions.

Based on this dataset of Bavarian residential buildings, we derived a linear, a square-root as well as a polynomial stage-damage function (Figure 12), which are often suggested in flood loss estimation (e.g. Büchele et al. 2006; Kreibich & Thieken 2008; Elmer et al. 2010). Additionally, we used three typically used depth-damage functions for the residential sector in Germany. These are the two empirical approaches of MURL (2000) and Hydrotec (2002) as well as the empirical-synthetical approach of ICPR/IKSR (2001). While the previous two functions were derived from the German flood damage data base HOWAS (Merz et al. 2004), the latter function uses additionally some synthetic data (Merz et al. 2010b). All three approaches include additional "expert knowledge".

The building loss ratios, which are calculated for all six functions depending on the water depth, are finally multiplied with the specific asset value in the corresponding grid cell.

In order to validate model performance and therefore the reliability of the six depth-damage functions, observed flood loss data of a past event in the study area were required. Furthermore, the actual maximum water depths of this event have to be taken into account to reproduce the observed flood characteristics. For that, we used the simulated maximum water depths of the flood event in August 2005 that were provided by WP 1.4.

Moreover, we acquired anonymized loss data of the flood event in 2005 from the Tyrolean government for the study area. Since the loss data for the private sector were not separated to damage to buildings and household contents it was assumed that 30 % of the total loss claim refers to household contents in cases where both damage types occurred (which was indicated per single loss report). This assumption is underpinned by the standardized valuation for flood losses on residential buildings of the federal state of Lower Austria (Amt der NÖ Landesregierung 2012), where the average content damage of residential buildings accounts to around 30 % of the total flood loss.

For the comparison of the flood loss estimates using building values of the year 2006 (see WP 2.2) the anonymized and separated loss data on buildings were normalized to the reference year 2006 by means of the construction cost index of Statistics Austria (2013). Lastly, a resampling of all loss records was carried out by means of a bootstrapping method to obtain a 95 % confidence interval (2.5th and 97.5th percentile) of the total building loss in the study area. Thus it is possible to evaluate the performance of the derived and conventional depth-damage functions not only in regard to the total aggregated building losses in the study area (~ 2 Mill. Euro), but also regarding to the bootstrap confidence interval as suggested by Thieken et al. (2008).

The flood loss model validation for the flood event in August 2005 was carried out for the two hydraulic simulations based on the DEMs "22a" and "23a", which showed similar error statistics (see WP 1.4). For these two simulation runs, the six functions were applied using the average replacement values for buildings in 2006 (€ 279 per m²) as well as the upper and lower specific replacement values to account for uncertainty in the asset estimation (see WP 2.2.).

As can be seen in Figure 13 and Table 4 the derived depth-damage functions from the Bavarian loss records perform considerably better than the common functions used in Germany. Only the standard function of ICPR/IKSR (2001) achieves good results when all the models are evaluated by means of the 95 % bootstrap confidence interval (Figure 13 and Table 4). The most accurate estimation in the simulation run "22a" is achieved by the square root function (deviation of ~ 180 k€), whereas the linear function performs better in run "23a" (deviation of ~ 119 k€). In contrast, the functions of Hydrotec (2002) and MURL (2000) turned out to be not suitable due to considerable overestimation or underestimation of the flood losses in 2005. Therefore, only the three derived damage functions and the function of ICPR/IKSR (2001) were further used for the simulation of flood losses on buildings.

For the estimation of potential present and future flood losses, the asset values of WP 2.2 were referred to different points in time by "constant values" and "adjusted values" (see above) and were combined with the various flood scenarios from WP 1.4. This synthesis of the flood hazard and the flood vulnerability in the area of Reutte is described in WP 3.

Table 4: Comparison of the loss estimates for six different stage-damage functions with the observed flood damage (confidence interval) on residential buildings for the flood event of August 2005.

Stage-damage curve	Simulation run "22a" Estimated losses (k€)	Simulation run "22a" Within 95 % Confidence Interval	Simulation run "23a" Estimated losses (k€)	Simulation run "23a" Within 95 % Confidence Interval
MURL (2000)	608	×	842	×
ICPR/IKSR (2001)	1,736	✓	2,553	✓
Hydrotec (2002)	7,133	×	9,094	×
linear	1,498	✓	1,877	✓
square root	1,817	✓	2,241	✓
polynomial	2,266	✓	2,971	✓

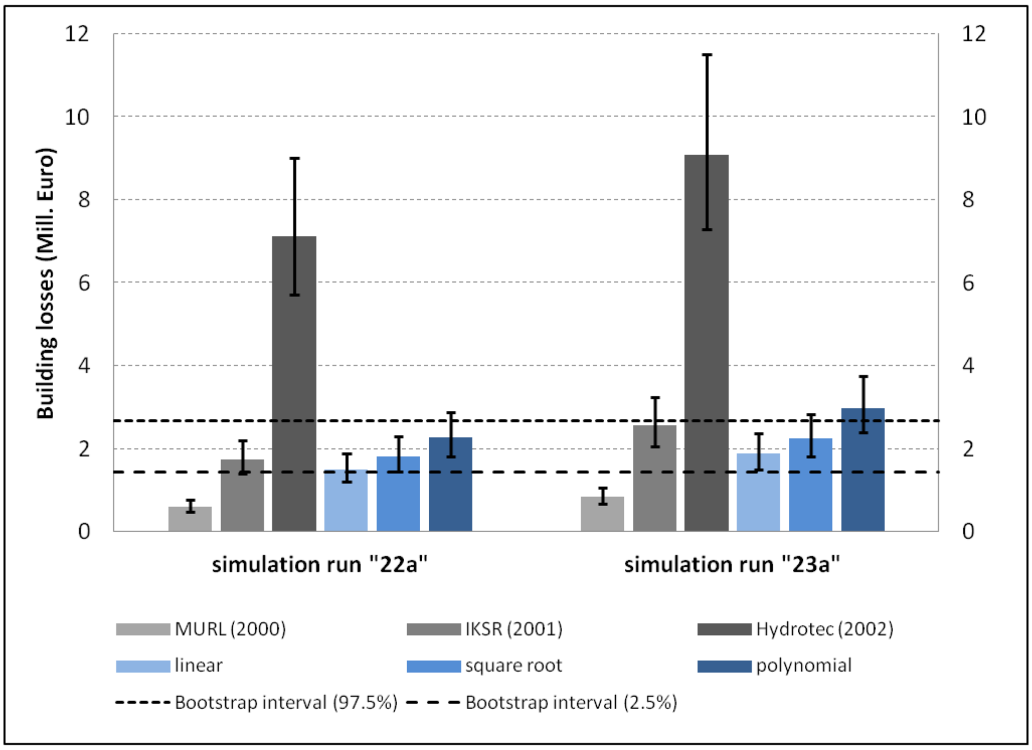

Figure 13: Flood loss model estimates for the two hydraulic simulation runs "22a" and "23a" for the flood event of August 2005 with mean and min/max (error bars) specific asset values of 2006.

Risk analysis (Work package 3)

Typically, flood risk is defined as the product of hazard, i.e. the physical and statistical aspects of the flooding process (e.g. return period of the flood, extent and depth of inundation), and vulnerability (e.g. asset values at risk and their susceptibility to flooding) (e.g. Merz & Thieken 2004). Human-induced changes in land use as well as climate change impacts on hydrological processes have been identified to play a key role in flood risk analysis (e.g. Hall et al. 2006; Feyen et al. 2009; Merz et al. 2010a). Thus, future-orientated flood risk assessments have to take into account the impacts of economic development, climate and land use change. However, only a few attempts have been made so far to assess flood risk by integrating possible future changes in both climate and socio-economic development (e.g. Hall et al. 2005; te Linde et al. 2011). In this study, changes in land use and climate were therefore integrated in the future-orientated flood risk analysis. This work package unites and synthesizes thereby the results which were obtained by to the combination of climate change impacts, land use changes as well as economic development as illustrated in Figure 1.

As described in WP 1.4, four different inundation scenarios, i.e. the 30-year, 100-year, 200-year and 300-year flood, were estimated for different points in time, i.e. in 2006 and in 2030, considering current structural protection measures and two different climate change scenarios based on the EH5OM modelling results with the A2-scenario and on HadGEM2 simulation results with the A1B-scenario, respectively, for the future situation in 2030. These hydraulic scenarios were further related to the corresponding land use pattern in 2006 and 2030, where four land use scenarios were considered. Thereby, the assigned asset values for residential areas in the future, i.e. in 2030, were based on 'constant values' (i.e. asset values at constant prices of reference year 2006) as well as on 'adjusted values' (i.e. asset values adjusted by Gross Domestic Product (GDP) increase at constant prices of reference year 2006; see WP 2.2). Furthermore, the asset values for the present and future situation were divided in mean specific values as well as minimum and maximum specific values to account for uncertainty in the asset estimation (see Cammerer & Thieken 2013). The estimation of flood losses further (WP 2.3) combines these exposed asset values with the water depths of the hydraulic simulation by means of four stage-damage functions that were successfully validated for the flood event in 2005 (WP 2.3).

Due to the variety of scenarios that were considered in each step of the model chain, a variety of damage estimates is obtained for each flood recurrence interval and assessment concept. Absolute damage estimates are exemplarily shown for the most intense flood event, i.e. the 300-year flood, in Figure 14. Thereby the residential building values are based on 'constant values' (Figure 14a) and 'adjusted values' (Figure 14b) including also the range of the specific asset values to estimate the flood damage by means of all four depth-damage functions (i.e. ICPR/IKSR, linear, square root, polynomial).

From Figure 14a and Table 5 it can be seen that potential damage on residential buildings grows only slightly between 2006 and 2030, when constant values are applied – except for the case of the strong urbanization scenario 'Overall Growth'. Furthermore, loss estimates based on the climate scenario 'HADGEM2' (A1B) are lower than estimates based on 'EH5OM' (A2).

Table 5: Relative differences (in %) of potential flood losses in residential areas between 2006 and 2030 for all four recurrence intervals depending on different land use and climate scenarios as well as on the linear depth-damage function and constant values (left) or adjusted values (right, in paranthesis).

Scenarios		**Recurrence interval**			
Land use	Climate	30-year	100-year	200-year	300-year
Overall Risk	HADGEM2 (A1B)	-7 (13)	-8 (11)	-11 (8)	-8 (11)
Overall Risk	EH5OM (A2)	-4 (17)	0 (22)	4 (26)	12 (36)
Overall Security	HADGEM2 (A1B)	-7 (39)	-8 (37)	-11 (32)	-8 (37)
Overall Security	EH5OM (A2)	-4 (44)	0 (50)	4 (55)	14 (70)
Overall Compet.	HADGEM2 (A1B)	-2 (72)	-5 (69)	-6 (66)	-2 (73)
Overall Compet.	EH5OM (A2)	1 (78)	4 (84)	13 (100)	24 (119)
Overall Growth	HADGEM2 (A1B)	201 (381)	172 (334)	155 (306)	152 (301)
Overall Growth	EH5OM (A2)	211 (395)	187 (358)	183 (351)	188 (360)

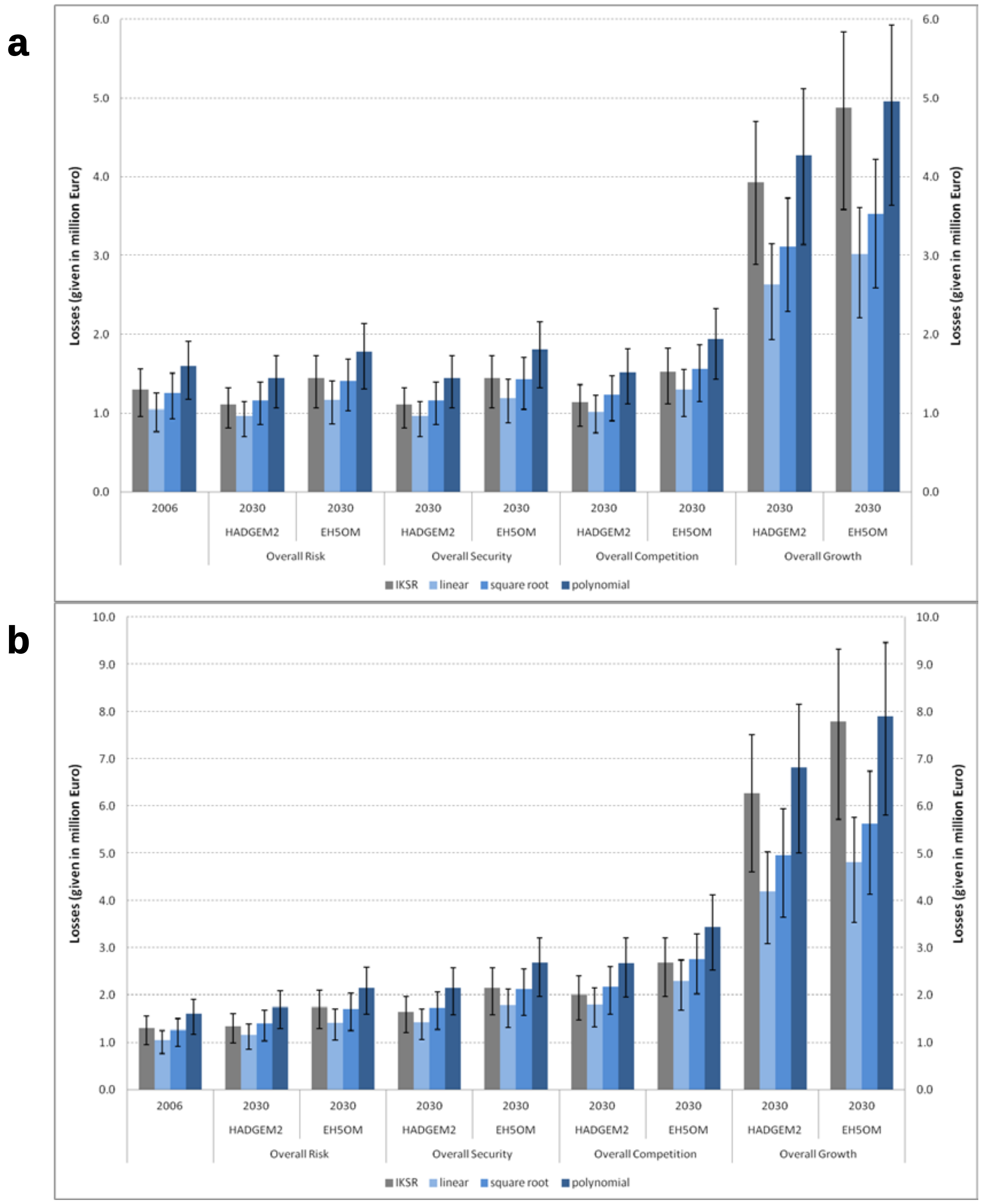

Figure 14: Estimated flood losses for residential areas based on mean ‘constant values’ (a) and ‘adjusted values’ (b) (with range by using minimum and maximum specific values) and four different depth-damage functions for a 300-year flood in 2006 and in 2030 (considering two different global climate models and four land use scenarios).

For example, potential losses of the land use scenario ‘Overall Competition’ assessed by the most accurate loss function (linear) are 24 % higher (EH5OM) in comparison to the potential losses in 2006 than the estimates results of ‘HADGEM2’ (-2 %) (Table 5 and Figure 14a). In the strongest urbanization scenario, however, the differences of both climate scenarios to 2006 are considerable, amounting to 188 % and 152 %, respectively (Table 5).

When all loss estimates are based on ‘adjusted values’ (Figure 14b and Table 5), the increase between 2006 and 2030 is stronger due to the consideration of the economic development. Then potential losses of the weakest urbanization scenario 'Overall Risk' are higher for both climate scenarios than in 2006. For the linear loss function the estimates yield in 36 % (HADGEM2-A2) or 11 % (EH5OM-A1B) higher potential damage to buildings than in 2006 (Table 5 and Figure 14b). For the more intense urbanization scenarios 'Overall Competition' and 'Overall Growth' the relative increase in damage even amounts to 119 % and 73 % or 360 % and 301 % for both climate scenarios, respectively (Table 5).

Nevertheless, from both figures it is apparent that all damage estimates are associated with a relatively high uncertainty resulting from the range of specific asset values (see WP 2.2), the different loss functions (see WP 2.3) as well as the climate scenarios (WP 1.1). Thus the variation of absolute damage estimates is especially high when the strongest urbanization and economic development scenarios are taken into account.

Figure 14 and Table 5 indicate that especially the effects of land use change and economic development are responsible for the potential increase in losses to residential buildings in the future. While the application of two different climate models (HADGEM2, EH5OM) results in rather low differences of the loss estimates, the use of different land use scenarios in combination with associated economic development has a tremendous effect on the loss models outcome.

In order to separate the contribution of the single effects, i.e. climate change, land use change and economic development, on future flood risk, we combined the most contrasting land use scenarios ('Overall Risk' and 'Overall Growth') with the present flood hazard to isolate the full range of potential effects from land use changes on flood risk. On the one hand, this was done by means of 'constant values' to separate land use change effects only. On the other hand, these calculations were additionally performed assuming 'adjusted values' to separate the effect of economic development. For the estimation of the contribution of climate change, in contrast, we combined the outcome of the two climate models (HADGEM2, EH5OM) with the current land use pattern, i.e. in 2006. Thus we derived the potential range of changes in flood risk when the most conservative scenarios are applied (Figure 15a) and when the most extreme scenarios are used (Figure 15b). In Figure 15 all loss calculations are carried out by means of the linear damage function and the mean specific asset values. Therefore, the range of asset estimates and flood loss functions is neglected in this figure.

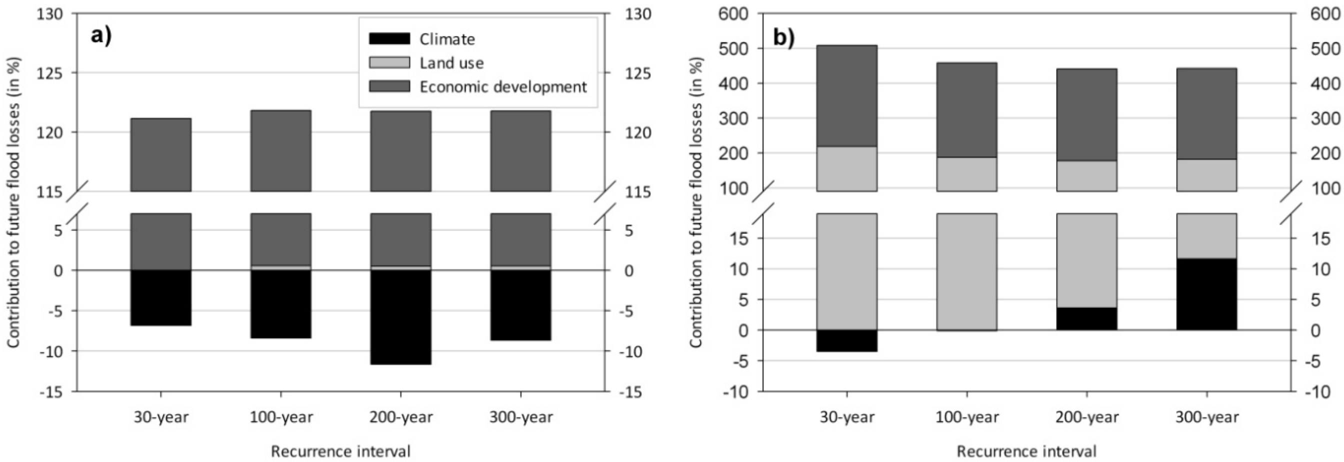

Figure 15: Relative contribution of the single effects of changes in climate, land use and economic development on future flood risk based on very conservative assumptions (a) and more extreme scenarios (b). Note: The y-axes have different scales within and between both figures

As illustrated in Figure 15, the relative isolated impact of climate change until 2030 on flood risk is very small (Figure 15b) or even negative (Figure 15a). According to Dobler et al. (2012) changes in the flood hazard due to climate change is assumed to occur towards the end of the 21st century. Until 2030, impacts of climate change on flooding may be masked by the large uncertainty in the underlying different climate models. In contrast, land use change can contribute considerably to future flood risk when the strongest urbanization scenario is assumed

(Figure 15b). In combination with the economic development, which has a nearly similar relative effect, the cumulative impact on flood risk may be remarkable, e.g. an increase of 459 % in case of a 100-year flood compared to 2006. However, in case of the conservative land use scenario 'Overall Risk' only the effect of economic development on the underlying asset values sticks out while the contribution of land use is almost negligible and the influence of the climate model even negative (Figure 15a).

4 Conclusions and recommendations

Data and knowledge on climate change impacts on flood risks as well as on the costs of appropriate adaptation are currently not transparently available (Hall et al., 2012). It was the aim of the FloodTimeS-project to partly fill this gap by using the alpine Lech catchment as an example. As risk includes aspects of flood hazard as well as vulnerability, the modelling approach within FloodTimeS was tripartite: first, the project aimed at examining the impacts of climate change on the frequency-magnitude relationship of floods. Secondly, shifts in damage potential due to land use changes and economic development were to be investigated and quantified. Finally, it was aimed at generating flood risk time series for the next decades which might be used to derive recommendations on appropriate adaptation measures.

To reliably assess future flood risks, complex model chains have to be applied, including the linkage of global circulation modelling results with downscaling methods and hydrological models as well as frequency analysis, hydraulic modelling and damage estimation. Furthermore, land use changes, associated socio-economic developments and asset values have to be considered in damage and risk estimation. The model chain aspired by the FloodTimeS-consortium is illustrated in Figure 1. The description of the project results demonstrates that the FloodTimeS-project successfully established and applied all elements of this complex model chain. Therefore, the main aims of the projects were achieved, although some drawbacks of the used methods and limitations of the results still remain.

To begin with, downscaling precipitation extremes is a challenging task and is subject to large uncertainty, especially in mountainous areas. The results of our investigation showed that the Expanded Downscaling model (EDS) performed very well in reproducing observed precipitation extremes. Although the calibration period of the downscaling model was rather short (i.e. from 1989 to 2000) and was hence expected to create considerable uncertainty for precipitation events with return periods larger than this, the biases of all simulations are within an acceptable range, even for rare events, e.g. events with a return period of 20 years. In summary, EDS is a valuable tool to study the effects of climate change on precipitation extremes on local, even mountainous scales. Model calibration and validation could be further improved by longer periods of ERA-interim data.

The downscaled precipitation and temperature time series were further used as input data for the conceptual semi-distributed rainfall–runoff model HQsim. Before running the model with these input data, investigations with different sensitivity analysis techniques were found to improve the understanding of the HQsim model and helped to accelerate its calibration and consecutive applications.

In general, a good agreement between observed and simulated runoff data was obtained. In the validation period from 1989 to 2005, the Nash-Sutcliffe efficiency amounted to 0.86 with observed climate data and to 0.73 when downscaled ECMWF data were used as model input. However, the hydrological simulations revealed slight weaknesses in the simulation of flood peaks during winter. Since these events are usually small to medium flood events in comparison to summer floods in the study area, they may, however, not cause large damages. Hence, their influence on the estimation of overall flood risk was assumed to be limited. Therefore, efforts to further improve model performance were neglected.

Furthermore, the performance of the HQsim simulation driven with downscaled reanalyses data showed slight weaknesses when focusing on very extreme floods, such as those that occurred in 1999 and 2005. This is mainly due to the relatively short calibration and validation period used in this study, which implies the model behaviour does not cover the totally possible natural variability and thus creates considerable uncertainty for events with high return periods. As already mentioned, longer periods of high-quality reanalysis data such as ERA-interim data would be helpful to overcome this problem in the future.

Discharge time series were then used to derive a flood frequency distribution. For this, the Generalized Extreme Value (GEV) distribution was applied to different annual maximum discharge series derived from observed discharges at the gauge Lechaschau. Since the occurrence of several severe floods between 1999 and 2005 decisively changed the distribution function, data on historic flood events were included to get a more robust frequency distribution. Although this approach considerably helped to improve flood frequency estimations, questions concerning the stationarity of discharge data are still open: the benefits of enlarging the time series may result in the drawback that the time series may not be representative for the present conditions (Merz & Thieken 2009).

Different approaches how to include climate change in flood frequency distributions can be found in the literature (compare e.g. te Linde et al. 2011, Elmer et al. 2012). Since discharge time series that result from the model chain “emission scenario (A2, A1B) – GCM (EH5OM, HadGEM2) – Downscaling (EDS) – hydrological model (HQsim)” must not be seamlessly combined with observed discharge series, the relative changes in the flood probabilities between the control (1971-2000) and scenario (2016-2045) simulations were calculated (see Table 2) in FloodTimeS. These changes were then added to the peak flows that were derived for certain return periods from the observed data (1971-2008 including historic events). By this way, flood frequencies and peak flows for a future time period representing the year 2030 could be reliably derived and used in the hydraulic simulation. The year 2030 was chosen in order to be consistent with the investigations on land use developments, but the approach could be applied to any other period up to 2100.

In order to transform peak discharges into inundation areas and depths, the two-dimensional model Hydro_AS-2D was implemented in the region of Reutte, which is the most important settlement area in the study region. The hydrodynamic model was capable of simulating the most recent flood event in 2005 with acceptable quality, although data on cross-sections and structural protection measures remained incomplete and hampered scenario development. Therefore, effects of adaptation by retrofitting structural protection measures could not be investigated in detail. Nevertheless, various flood scenarios were simulated for different recurrence intervals (30-, 100-, 200-, 300-year flood) for the present (i.e. in 2006) as well as for the future situation in 2030 considering two different climate change scenarios and the most recent structural protection measures. With this step, the flood hazard analysis was completed. Inundation scenarios could further be used for exposure analysis and damage estimation.

In order to not only account for impacts of climate change, the FloodTimeS-project made considerable efforts to simulate further land use changes. For this, the spatially explicit land use model CLUE-S, in particular its newer and adapted version Dyna-CLUE, was applied to the region of Reutte including spatial policies, e.g. area zoning plans and hazard zones, and taking four different national spatial planning scenarios of the ÖROK as basis for the quantitative land use demand. With this approach, explicit land use simulations with a spatial resolution of 50 m were conducted until the year 2030. Due to limitations of assumptions and data, it was not possible (nor reasonable) to simulate land use change beyond 2030 at this local scale – in contrast to the flood hazard analysis that could be performed until 2100 due the availability of GCM results.

Another difficulty is the missing validation of the land use model due to the lack of further land use data sets and other input data. Although the applied land use model was validated successfully in many case studies worldwide (e.g. Pontius et al. 2008), the validation is, of course, site-specific as the model can behave differently in other settings (Pontius et al. 2008). Like in our study, the lack of consistent data over a longer period hinders a proper validation in most land use change studies (e.g. Verburg et al. 2008). Therefore, and in order to be consistent with the time frame of observed discharges, historical land use change rates between 1970 and 2006 were determined additionally and revealed that past changes were higher than the projected future scenarios. In spite of this, the risk analyses revealed that in the near future, i.e. up to 2030, the projected land use changes increase flood risk more than climate change (see Figure 14).

Another important driver for future flood risk is economic development (see Figure 14) that was considered in FloodTimeS by two approaches ('constant values' and 'adjusted values'). The investigation of the asset values at risk revealed a remarkable increase in residential building and content values within the present flood zones. For the future a further growth of asset values in the flood-prone areas were detected for the strongest land use scenarios. However, an additional consideration of economic growth ('adjusted values') led to a further and clear rise in the assets at risk, particularly in the projected time span (2007-2030) and the strongest urbanization and economic growth scenarios.

Although the approaches taken are state-of-the-art, it has to be emphasised that this part could be further improved. For example, asset appreciation is included by the gross domestic product (GDP), which was used as surrogate measure for the economic growth in the different scenarios. However, also asset depreciation should be considered to better account for the expenditure (e.g. for technical improvements) of the GDP. Another drawback arises from the usage of national projections and national historical records of the GDP instead of regional data which may differ notably. It was, however, impossible to get GDP data on the regional scale for the historic as well as the projected time period.

The damage estimation was restricted to damage to residential buildings. Due to the coarse data of the land use scenarios and asset estimation, damage modelling was performed on the meso-scale, not on a building-specific micro-scale. Initially, six damage functions were considered. Two of them were ruled out using the reported damage the 2005 flood and a bootstrap approach (Table 4). By this approach, it could be shown that damage functions derived from real flood loss data in Bavaria (Germany), where building characteristics and flood processes are similar to the study area, outperformed most of the commonly applied depth-damage functions that were not adapted to the region under study. Therefore, the adapted functions were used for the assessment of potential residential losses for the present and future inundation scenarios. It is assumed that damage estimation could be even more reliable if loss data from the study area was available. This hypothesis will be tested systematically in future research.

Finally, all elements of the model chain were combined in a risk analysis. Originally, it was intended to derive flood risk time series for different time slices (e.g. 1970 to 1999, 2010 to 2029 etc.). However, due to data limitations it was impossible to assign and separate the effects of each risk driver (land use etc.) continuously from 1970 to 2030 or even 2100 or even for several time slices. Therefore, only potential changes in flood risk between the present situation (around 2006) and the near future (around 2030) was assessed. Furthermore, the isolated contribution of the single risk drivers was derived for the future scenarios.

Altogether, changes in flood risk in the near future, i.e. by 2030, are relatively low compared to the reference year 2006. Only if strong urbanization took place associated with economic growth, the assets at risk would increase remarkably. This illustrates that in our study area the effects of climate change on the flood hazard and further on flood risk is slight or negligible compared to the contribution of potential land use changes in the near future, i.e. by 2030. This finding implies that stakeholders should carefully watch and govern land use development in settlements of the Lech catchment. Recommendations for further adaptation – other than weak measures such as risk awareness building and communication – are currently difficult to derive with certainty from the project results.

Nevertheless, the work of the project is valuable. The complex model chain was successfully and consistently established in the study area and can be now used to simulate different adaptation and flood management options. For example, effects for spatial policies and structural protection measure could be investigated systematically. In future, also the damage reducing effects of private precautionary measures that are currently not well developed in the region could be incorporated in the damage model and regarded as adaptation strategy. Ideally, such investigations should be performed in a participatory framework, i.e. regional and local stakeholders can influence the selection of scenarios and adaptation options. A collaborative modelling platform, as presented by Evers et al. (2012), could facilitate this research. The scenarios and simulations that were already performed in FloodTimeS could be used as a starting point for such an exercise.

Although the model chain is regarded to be of good quality and reliability, since a lot of efforts were made to calibrate and validate all elements of the model chain, the overall uncertainty of the model results might still be high, but currently unknown and should be a topic for further research.

The project FloodTimeS started in November 2009 and ended in January 2013. During the project period, seven papers in international peer-reviewed journals as well as six other papers were published – a great share of them are co-authored by scientists from Canada, Germany, the Netherlands and the UK. In addition, one PhD was finished in September 2012 and a second PhD will follow in 2013. Furthermore, two international workshops were organised and performed by the project consortium. Therefore, the FloodTimeS-project also considerably contributed to international networking and recognition of research in Austria as it was intended by the Austrian Climate Research Program.

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Publications and Dissemination activities of the FloodTimeS-project

Project workshops

2011

Workshop „Extreme Hochwasserereignisse und statistische Analysen", 31.05.2011-01.06.2011. Innsbruck, Austria, with nine presentations and 25 participants from Austria, Germany and Switzerland.

2012

Workshop „Challenges for assessing future flood losses", 22.03.2012-23.03.2012. Innsbruck, Austria, with nine presentations and 27 participants from Austria, Germany, Italy, Indonesia, the Netherlands and Romania.

Oral presentations

2010

Dobler, C., Cammerer, H., Thieken, A., Schöberl, F., Stötter, J., Bronstert, A.: FloodTimeS: Entwicklung von Hochwasser-Risiko-Zeitreihen für das 21. Jahrhundert. 11. Österreichischer Klimatag, 11.03.2010-12.03.2010. Wien

Dobler, C.: Klima-Ensemble-Projektionen zur Abschätzung zukünftiger Abflüsse in einem alpinen Einzugsgebiet. Tag der Hydrologie 2010. 25.03.2010-26.03.2010. Braunschweig

2011

Dobler, C..: Assessment of climate change impacts on flood hazard potential in an Alpine watershed. EGU 2011, 03.04.2011-08.04.2011. Vienna, Austria.

Cammerer, H., Thieken, A.: Flood loss reduction due to private precaution. UFRIM 2011, 21.09.2011-23.09.2011. Graz, Austria.

Dobler, C., Stötter, J.: Assessing the Impacts of Climate Change on Flood Frequency in an Alpine watershed. Managing Alpine Future II, 21.11.2011–23.11.2011. Innsbruck, Austria.

Thieken, A.: Analysing changes in flood risks in an alpine catchment. Managing Alpine Future II, International Conference, 21.11.2011–23.11.2011, Innsbruck, Austria

2012

Cammerer, H., Thieken, A.: Spatio-temporal dynamics in the flood exposure due to land use changes. EGU 2012, 22.04.2012-27.04.2012. Vienna, Austria

Dobler, C., Cammerer, H., Lammel, J., Thieken, A., Schöberl, F. & Stötter, J.: Modellierung des zukünftigen Hochwasserrisikos in einem alpinen Einzugsgebiet. 13. Österreichischer Klimatag, 14.06.2012-15.06.2012. Vienna, Austria.

Poster presentations

2010

Dobler, C.: Climate-ensemble projections for the investigation of possible changes in runoff in an Alpine watershed. EGU General Assembly 2010, Vienna, 02.05.2010-07.05.2010.

2011

Cammerer, H., Thieken, A.: Konzepte zur Abschätzung von künftigen Hochwasserschäden an Wohngebäuden. Tag der Hydrologie 2011, 24.03.2011-25.03.2011. Vienna, Austria.

Cammerer, H., Thieken, A.: Land use scenarios for flood risk analyses. EGU General Assembly 2011, 03.04.2011-08.04.2011. Vienna, Austria.

Cammerer, H., Thieken, A..: Flood loss reduction due to private precaution. UFRIM 2011. 21.09.2011-23.09.2011. Graz, Austria.

2012

Cammerer, H., Thieken, A.: Spatio-temporal dynamics in the flood exposure due to land use changes. EGU 2012, 22.04.2012-27.04.2012. Vienna, Austria

Dobler, C.: Downscaling precipitation extremes in a complex Alpine catchment. EGU 2012. 22.04.2012-27.04.2012. Vienna, Austria.

Cammerer, H., Thieken, A.: Temporal variability of the flood damage potential due to land use changes in the Alpine Lech Valley. FLOODrisk 2012. 20.11.2012-22.11.2012. Rotterdam, the Netherlands.

Paper (peer-reviewed)

2010

Dobler, C., Stötter, J., Schöberl, F. (2010) Assessment of climate change impacts on the hydrology of the Lech Valley in northern Alps. - Journal of Water and Climate Change 1 (3): 207-218, DOI: 10.2166/wcc.2010.122.

2012

Dobler, C., Bürger, G., Stötter, J. (2012): Assessment of climate change impacts on flood hazard potential in an Alpine watershed. - Journal of Hydrology 460: 29-39, DOI: 10.1016/j.jhydrol.2012.06.027.

Dobler, C., Hagemann, S., Wilby, RL., Stötter, J. (2012): Quantifying different sources of uncertainty in hydrological projections in an Alpine watershed. - Hydrology and Earth System Sciences 16, 4343-4360, DOI: 10.5194/hess-16-4343-2012.

2013

Dobler, C., Bürger, G., Stötter, J. (2013): Simulating future precipitation extremes in complex Alpine catchment. - Natural Hazards and Earth System Sciences 13, 263-277, DOI: 10.5194/nhess-13-263-2013.

Online first/in press

Cammerer, H., Thieken, A.H., Verburg, P.: Spatio-temporal dynamics in the flood exposure due to land use changes in the Alpine Lech Valley in Tyrol (Austria). – Natural Hazards, online first (17 July 2012), DOI: 10.1007/s11069-012-0280-8.

Dobler, C., Pappenberger, F.: Global sensitivity analysis for a complex hydrological model applied in an Alpine watershed. – Hydrological Processes, online first (26 September 2012), DOI: 10.1002/hyp.9520.

Cammerer, H., Thieken, A.H.: Historical development and future outlook of the flood damage potential of residential areas in the Alpine Lech Valley between 1971 and 2030. – Regional Environmental Change, online first (25 January 2013), DOI: 10.1007/s10113-013-0407-9.

Paper (other)

2010

Dobler, C. (2010): Possible Changes in Flood Frequency in an Alpine Catchment. In: Dölemeyer A, Zimmer J, Tetzlaff G [eds.]: Risk and Planet Earth. Vulnerability, Natural Hazards, Integrated Adaptation Strategies. Schweizerbart, Leipzig, p 88-94.

Dobler, C. (2010): Klima-Ensemble-Projektionen zur Abschätzung zukünftiger Abflüsse in einem alpinen Einzugsgebiet. In: Meon, G. [ed.]: Nachhaltige Wasserwirtschaft durch Integration von Hydrologie, Hydraulik, Gewässerschutz und Ökonomie. Forum für Hydrologie und Wasserwirtschaft 29. 10. p. 17-24.

2011

Cammerer, H., Thieken A.H. (2011): Flood Loss Reduction due to Private Precaution. In: Urban Flood Risk Management. Approaches to enhance resilience of communities (G. Zenz & R. Hornich, eds.). Proceedings of the International Symposium UFRIM, Graz, 21-23 September 2011, p. 381-386.

Dobler, C. (2011): Assessment of climate change impacts on floods in an Alpine catchment. In: Managing Alpine Future II - Inspire and drive sustainable mountain regions (A. Borsdorf, J. Stötter & E. Veulliet, eds.). Proceedings of the Innsbruck Conference, November 21-23, 2011. (IGF-Forschungsberichte 4). Verlag der Österreichischen Akademie der Wissenschaften: Wien. ISBN: 978-3-7001-7153-3, p. 134-142.

Thieken, A.H., H. Cammerer, C. Pfurtscheller (2011): Risk management, adaptation and monetary aspects. In: Flood Hazards: Impacts and Responses for the Built Environment (J. Lamond, C. Booth, F. Hammond, D. Proverbs, eds.), CRC Press, Taylor & Francis Group, ISBN: 978-1-4398-2625-6; DOI: 10.1201/b11050-17, Chapter 13, p. 177-190.

Thieken A.H., Cammerer H., Dobler C., Lammel J., Bronstert A., Stötter J., Schöberl F. (2011): Analysing changes in flood risks in an alpine catchment. In: Managing Alpine Future II - Inspire and drive sustainable mountain regions (A. Borsdorf, J. Stötter & E. Veulliet, eds.). Proceedings of the Innsbruck Conference, November 21-23, 2011. (IGF-Forschungsberichte 4). Verlag der Österreichischen Akademie der Wissenschaften: Wien. ISBN: 978-3-7001-7153-3, p. 97-106.

PhD-theses

Dobler, C. (2012): Simulating the hydrological response of the Alpine river Lech to climate change – Downscaling climate change scenarios, modelling their hydrological impacts and addressing uncertainties in the model projections. University of Innsbruck (examination passed on 17 September 2012).

Cammerer, H. (2013): Assessing changes in flood risk for the Alpine Lech Valley (Tyrol). University of Innsbruck (ongoing).