



# A spatiotemporal multi-hazard exposure assessment based on property data

S. Fuchs<sup>1</sup>, M. Keiler<sup>2</sup>, and A. Zischg<sup>2,3</sup>

<sup>1</sup>University of Natural Resources and Life Sciences, Institute of Mountain Risk Engineering, Vienna, Austria

<sup>2</sup>University of Bern, Institute of Geography, Bern, Switzerland

<sup>3</sup>University of Bern, Oeschger Centre for Climate Change Research, Mobiliar Lab for Natural Risks, Bern, Switzerland

Correspondence to: S. Fuchs (sven.fuchs@boku.ac.at)

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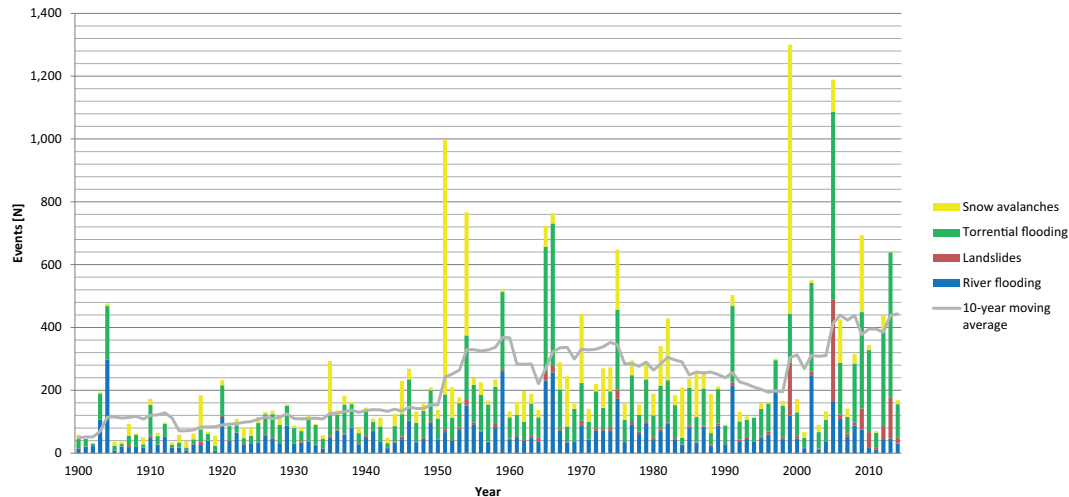
**Abstract.** The paper presents a nation-wide spatially explicit object-based assessment of buildings and citizens exposed to natural hazards in Austria, including river flooding, torrential flooding, and snow avalanches. The assessment was based on two different data sets, (a) hazard information providing input to the exposure of elements at risk, and (b) information on the building stock combined from different spatial data available on the national level. Hazard information was compiled from two different sources. For torrential flooding and snow avalanches available local-scale hazard maps were used, and for river flooding the results of the countrywide flood modelling eHORA were available. Information on the building stock contained information on the location and size of each building, as well as on the building category and the construction period. Additional information related to the individual floors, such as their height and net area, main purpose and configuration, was included for each property. Moreover, this data set has an interface to the population register and allowed, therefore, for retrieving the number of primary residents for each building. With the exception of sacral buildings, an economic module was used to compute the monetary value of buildings using (a) the information of the building register such as building type, number of storeys and utilisation, and (b) regionally averaged construction costs.

It is shown that the repeatedly stated assumption of increasing exposure due to continued population growth and related increase in assets has to be carefully evaluated by the local development of building stock. While some regions have shown a clearly above-average increase in assets, other regions were characterised by a below-average development. This mirrors the topography of the country, but also the dif-

ferent economic activities. While hotels and hostels are extraordinarily prone to torrential flooding, commercial buildings as well as buildings used for recreational purposes are considerably exposed to river flooding. Residential buildings have shown an average exposure, compared to the number of buildings of this type in the overall building stock. In sum, around 5 % of all buildings are exposed to torrential flooding, and around 9 % to river flooding, with around 1 % of the buildings stock being multi-exposed. The temporal assessment of exposure has shown considerable differences in the dynamics of exposure to different hazard categories in comparison to the overall property stock. In conclusion, the presented object-based assessment is an important and suitable tool for nation-wide exposure assessment and may be used in operational risk management.

## 1 Introduction

World-wide data on natural disasters suggest an increasing number of reported events, of people affected and economic losses, but – in the most-developed countries – a decreasing number of reported fatalities since around 1900 (e.g. CRED, 2014; Munich Re, 2014). Regional analyses supplement these global data, but these regional data are not easily available because they are often not collected in global databases due to relatively low event magnitudes only affecting society on a regional or even local scale (United Nations, 2013). A review of Fuchs et al. (2013) has shown that overall conclusions on the dynamics of natural hazards, including



**Figure 1.** Annual number of documented natural hazards causing losses in Austria. Data source: Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management, 12/2014.

floods, landslides and snow avalanches, may be challenging due to the inherent complexity behind data.

Focusing on mountain regions, an increase in hazardous events and associated losses is repeatedly claimed (a) as a result of increasing exposure of elements at risk (Mazzorana et al., 2009; Preston, 2013), (b) due to natural fluctuations in flood frequencies (Schmocker-Fackel and Naef, 2010), and (c) due to the effects of climate change (e.g. Huggel et al., 2012; Korup et al., 2012). In Fig. 1, the annual number of natural hazards triggering losses in the Eastern European Alps (Republic of Austria) is shown. The underlying event documentation focused on different types of hazards but no further detailed information on individual losses or loss pattern is provided. The data for the period 1900–2014 describes snow avalanches, torrential flooding, landslides and river flooding, as well as the 10 years moving average of the total number per year. While between 1900 and 1959 an increase in the annual number of hazard events of around a factor of four can be concluded – presumably also due to an improved event observation – between 1960 and 1964 a decrease of around 50 % is traceable, followed by an increase due to the excessive events in 1965 and 1966. Since then, the 10 years moving average is steadily decreasing again, which is in line with the increasing efforts into technical mitigation measures since the mid-1960s (Fuchs, 2009; Holub and Fuchs, 2009). Due to the high number of hazard events in 1999, 2002, 2005 and 2009, however, the curve is again increasing to around 440 events per year. During the period of investigation, specific years with an above-average occurrence of individual hazard types can be traced as for example snow avalanches in 1951, 1954, 1999 and 2009, torrential flooding in 1965, 1966, 2005 and 2013, and river flooding in 1904, 1959, 1966 and 2002. The trend reported in Fig. 1 is in clear contrast to the trends repeatedly presented for

world-wide data and indicating an exponential increase in the number of events since the 1950s (e.g. Keiler, 2013). Apart from hazard dynamics (the natural frequency and magnitude of events), decreasing dynamics in mountain hazard losses may result from (a) increased efforts into technical mitigation (Keiler et al., 2012), (b) an increased awareness of threats being consequently considered in land-use planning (Wöhler-Alge, 2013; Thaler, 2014), both leading to less exposure, and (c) a decline in vulnerability (Fuchs et al., 2007; Jongman et al., 2015) which will not be further considered in the following sections. Apart from the ongoing discussion of the effects of climate change influencing the hazard trigger (e.g. Auer et al., 2007; Keiler et al., 2010; Lung et al., 2013), the effects of dynamics in exposure have so far not been sufficiently studied in the context of a possible influence on dynamics of damaging events suggested by Fig. 1. Since spatially explicit data on the dynamics of exposure remained fragmentary, data on the temporal dynamics of natural hazard events resulted in misleading conclusions with respect to the underlying causes and effects (Pielke Jr., 2007), and studies on dynamics in loss data may therefore have over-emphasized the effects of climate change (Barredo, 2009).

Focusing on exposure, the effectiveness of natural hazard risk management depends on the availability of data and in particular an accurate assessment of elements at risk (Jongman et al., 2014), which also requires a temporal and spatial assessment of their dynamics. It has been repeatedly claimed with respect to flood hazards in Europe that the main driver of increases in observed losses over the past decades is increased physical and economic exposure (Bouwer, 2013; Hallegatte et al., 2013; Jongman et al., 2014). Until now, however, in mountain regions of Europe such conclusions remain fragmentary since property data have only been available on the local scale as a result of individual case stud-

ies. These – often conceptual – studies related to the temporal dynamics of exposure to multiple types of mountain hazards include both the long-term and the short-term evolution. Long-term changes were found to be a result from the significant increase in numbers and values of properties endangered by natural hazard processes, and can be observed in both rural and urban mountain areas of Europe (Keiler, 2004; Fuchs et al., 2005; Keiler et al., 2006a; Shnyparkov et al., 2012). Short-term fluctuations in elements at risk supplemented the underlying long-term trend, in particular with respect to temporary variations of people in hazard-prone areas and of vehicles on the road network (Fuchs and Bründl, 2005; Keiler et al., 2005; Zischg et al., 2005). These results suggest that the spatial occurrence of losses is not so much dependent on the occurrence of specifically large events with high hazard magnitudes but more a result of an increased number of elements at risk in endangered areas (Fuchs et al., 2012). Most of the recent works, however, rely on local object-based studies (Zischg et al., 2004; Fuchs et al., 2012) or aggregated land use data (Bouwer et al., 2010; de Moel et al., 2011; Cammerer et al., 2013), leading to substantial uncertainties if up-scaled to a larger spatial entity (de Moel and Aerts, 2011; Jongman et al., 2012a). Because of the limited data availability, comprehensive object-based and therefore spatially explicit analyses have thus not been extended beyond the local or regional level (Kienberger et al., 2009; Huttenlau et al., 2010; Zischg et al., 2013), and studies focusing on the national level in mountain regions using such data remain fragmentary (Fuchs et al., 2013).

To contribute to this gap, we show how detailed property level data can be used to improve the understanding of trends in hazard exposure on a national level. We will explicitly focus on dynamics in elements at risk, neglecting (a) any changes in the process dynamics due to underlying changes in the natural system including the effects of climate change, (b) any shifts in exposure due to the implementation of technical mitigation measures, and (c) any changes in vulnerability. This allows for the assessment of dynamics in property exposure, and will provide insights elements at risk may have on changing risk in mountain environments leaving other risk-contributing factors constant.

## 2 Methods

This study is based on two different data sets, (a) hazard information providing input to the exposure of elements at risk, and (b) information on the building stock combined from different spatial data available on the national level. We consider hazard information for river flooding, torrential flooding including debris flows, and snow avalanches since these hazard types are responsible for the majority of damages in the European Alps (Sinabell and Url, 2007; Hilker et al., 2009). In the following, the composition and preparation of data sets is described.

### 2.1 Hazard information

Two different sources provide the base for compiling hazard information. For mountain hazards accessible local-scale hazard maps are used, and for river flooding the results of a nation-wide flood modelling are available. This combination of data sets was necessary because (a) for mountain hazards, no nation-wide modelling is available in Austria and (b) for river flooding, no nation-wide compilation of hazard maps exists in contrast to mountain hazards due to the fact that river flooding lies within the competency of the individual Federal States.

In Austria, the method for hazard mapping is regulated by a national legal act (Republik Österreich, 1975) and an associated decree (Republik Österreich, 1976). The implementation of these regulations is assigned to the Federal Ministry of Agriculture, Forestry, Environment and Water Management (BMLFUW) and administrated by the governmental departments of the Austrian Service for Torrent and Avalanche Control (WLV). Since the mid-1970s, these governmental departments have been progressively compiling hazard maps for the communities affected by mountain hazards based on available data and information on hazards as well as modelling exercises (Holub and Fuchs, 2009). These hazard maps are mostly compiled on a detailed local scale of 1:2000 to 1:10000 in order to decide whether or not individual plots are affected by the different hazard types. Hazard maps usually refer to individual catchments within individual communities, and depict the area affected by a design event with a return period of 1 in 150 years. So far, 92 % of all communities with an obligation for hazard mapping in Austria do have a legally valid hazard map. According to the Decree on Hazard Zoning (Republik Österreich, 1976), red hazard zones indicate those areas where the permanent utilisation for settlement and traffic purposes due to the exposure to the design event is not possible or only possible with extraordinary efforts for mitigation measures. Already existing buildings in these areas are not allowed to be expanded or to be used for other purposes than the existing one. Yellow hazard zones indicate those areas where a permanent utilisation for settlement and traffic purposes is impaired by the design event. Red and yellow hazard zones of different catchments and multiple hazard types may overlap, and as a result elements at risk may be exposed to more than one hazard type (multi-exposure, Kappes et al., 2012a, b). While in some catchments there may be a temporal differentiation of processes affecting the same elements at risk (snow avalanches during winter and torrential processes in summer), in other catchments there may be a temporal overlap of different processes occurring in the same period of time (debris flows from the tributary and flooding in the receiving channel), both affecting the same elements at risk. The available red and yellow hazard zones were provided digitally by the Austrian Federal Ministry of Agriculture, Forestry, Envi-

ronment and Water Management in March 2013 in order to select exposed property.

For river flooding data from the digital eHORA platform (<http://www.hochwasserrisiko.at/>) was used. This platform provides information on the flooding extent using web-GIS techniques, and has been jointly implemented by the Federal Ministry of Agriculture, Forestry, Environment and Water Management and the Austrian Insurance Association in terms of a public-private partnership on more than 25 000 of a total of 39 300 river kilometres (Stiefelmeyer and Hlatky, 2008). By using a hydrological model probabilistic runoff data for a 1 in 30, 100, and 300 year event was computed and converted into water levels and flood zones based on a nationwide DEM and a digital slope model. Following an ongoing discussion on the harmonisation of hazard mapping in Austria (Rudolf-Miklau and Sereinig, 2009), the 1 in 100 year event was provided by the Austrian Insurance Association in terms of a vector representation of flood plain boundaries and taken for our analysis.

## 2.2 Data on the building stock

Since the implementation of the Federal Law related to the Building Register (Republik Österreich, 2009), municipalities in Austria are responsible for the collection and digital processing of specified information related to the entire building stock. This information is centrally stored in a database and contains information on the location and size of each building, as well as on the building category and the construction period (1919–2000) and year of construction (since 2001), respectively (Statistik Austria, 2012). The latter information is related to the existing building stock. However, even though a building will be destroyed, the information and property attributes will be archived in the database and can be separately queried in order to provide a full overview on the construction history. Additional information related to the individual floors, such as their height and net area, main purpose and configuration, is included for each property. Moreover, this data set has an interface to the population register and allows, therefore, for retrieving the number of primary residents per accommodation unit for each building. Because this information contains  $x$  and  $y$  coordinates based on the address it can be processed within a GIS environment. Each building is characterized by the main use, which is assessed by the net area of used space for different purposes of every floor. If a minimum 50 % of the total net area of the building is for residential purpose, the building is characterized as a residential building. If the total sum of net areas for residential use is below 50 %, the main use is derived from the use with the largest total net area. If the net area of different types of use is the same, the main use is hierarchically classified in decreasing order by (1) hostels and hotels, (2) office buildings, (3) commercial buildings, (4) communication and transportation buildings, (5) industrial buildings, (6) buildings for cultural activities

and leisure, (7) agricultural buildings, (8) sacral buildings. Building categories were taken from the classification within the data set (Statistik Austria, 2012). Since the amendment of the respective law (Republik Österreich, 2013) the data may be used by the Federal administration for research purposes, and as such the information was made available through the Federal Ministry of Agriculture, Forestry, Environment and Water Management.

## 2.3 Exposure analysis

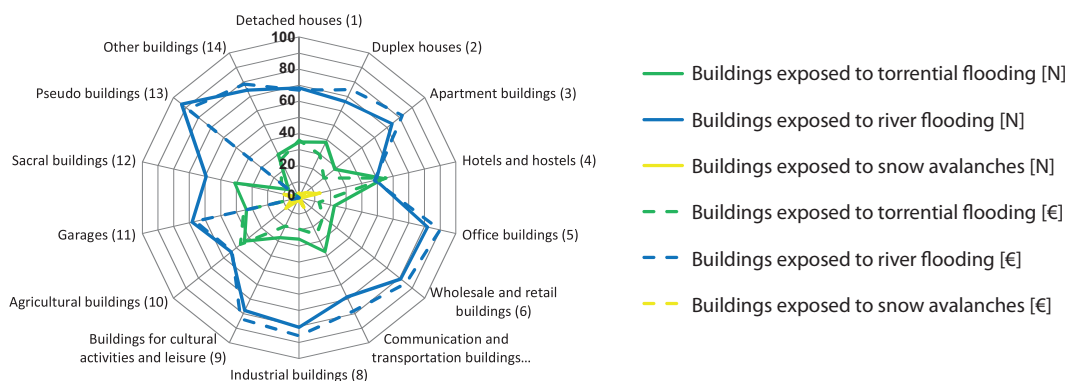
In exposure analysis, the building data set was intersected with the hazard information. The hazard information was represented as polygon, and the address location in terms of  $x$  and  $y$  coordinates by a point. A relational database composed from different modules was created.

With the exception of sacral buildings, an economic module was used to compute the monetary value of buildings using (a) the information of the building register such as building type, number of storeys and utilisation, and (b) regionally averaged construction costs following a method outlined in Fuchs and Zischg (2013) based on Keiler et al. (2006b) and Kranewitter (2002). The construction costs were based on replacement values instead of market values following general insurance principles (Fuchs and McAlpin, 2005), and were adjusted to inflation using the respective index of construction costs (Statistik Austria, 2013).

An exposition module was applied to connect the spatially defined information from the building register ( $x$  and  $y$  coordinates) to the hazard information in order to achieve information whether or not a building is exposed. In this step, an auxiliary data set on the building footprint of every building retrieved from the digital cadastral map was used to test whether or not the spatial location of a building corresponds to the point information of the digital building register and to assign the information of the hazard map to the address points. If the location of the  $x$  and  $y$  coordinates of the building did not match exactly with the location of the building, they were snapped to the border of the nearest building footprint available within a distance of  $\leq 15$  m around a polygon. Address information inside a polygon or in a distance exceeding 15 m were not changed, the first was included in the analyses as point information, the latter was excluded due to missing preciseness in geographic location. Assuming that hazards may damage buildings also if just parts are affected, an intersection between the building footprint and the hazard information was made. Thereby, any building was computed as being part of the highest hazard intensity level it was intersecting with.

Using information of the population register, the number of exposed citizens (principal residences) was calculated on the level of individual buildings.

The spatial and temporal analyses were relying on the information in the digital building register, i.e. on the construction period and construction year, respectively. As a result,



**Figure 2.** Radar chart of exposure (percentage of numbers and reconstruction values) to river flooding, torrential flooding and snow avalanches for different building categories.

the analysis of the dynamics of elements at risk is based on present-day monetary values and actual numbers of citizens, and can neither be used to deduce the historical composition of society, nor the historical value distribution. However, this approach can be used to indicate the temporal and spatial dynamics beyond the economic development in the country, and may therefore serve as a proxy for the absolute development of exposure.

### 3 Results

In the following sections results from the analyses are presented, focusing on the number of exposed buildings and citizens. Both the spatial and temporal analyses resulted in considerable heterogeneities among the communities and among different building categories. In Sect. 3.1 the results of the spatial analysis are provided, and in Sect. 3.2 the results of the temporal analysis are presented.

#### 3.1 Results of spatial analysis

In Austria, 2 399 500 buildings are located, 319 026 of which (13.3 %) are exposed to natural hazards (Table 1). Of these almost 2.4 million buildings, 9 % (219 359) are exposed to river flooding, and 5 % to mountain hazards (torrential flooding 111 673 and snow avalanches 9009). Altogether, 298 248 buildings (93.5 % of exposed buildings and 12.4 % of the entire building stock in Austria) are exposed to one hazard type, and 20 778 buildings (6.5 % of exposed buildings and 0.9 % of the entire building stock in Austria) are exposed to more than one hazard type: 18 089 buildings are exposed to river and torrential flooding, 2595 to torrential flooding and snow avalanches, 568 to snow avalanches and river flooding, and 237 to river and torrential flooding as well as snow avalanches.

Citizens exposed were defined as primary residents according to the compulsory residency registration. When comparing the building stock with the number of primary resi-

dents, a slightly higher percentage (9.7 % versus 9.1 %) of citizens is exposed to river flooding, while to mountain hazards, a lower percentage (5.0 % versus 4.3 %) is affected. In total, 1 125 601 citizens are exposed to natural hazards, 1 058 594 (94.0 % of the exposed residents and 13.3 % of the entire population) to one type of hazard and 67 007 (5.95 % of the exposed residents and 0.8 % of the entire population) to more than one hazard type (Table 2).

Analysing the data set according to the type of building, a considerable part of the building stock is composed from residential buildings (category 1–3), but also a high number of hotels (category 4) and commercial buildings (category 5–8) is exposed (Table 3):

- a total of 2 056 322 residential buildings represent 85.7 % of the entire buildings stock in the country, but only 12.62 % of them (259 687) are exposed;
- a total of 140 470 commercial buildings represent 5.86 % of the entire buildings stock in the country, and 21.06 % of them (29,593) are exposed;
- a total of 37 272 hotels and hostels represent 1.55 % of the entire buildings stock in the country, and 23.04 % of them (8589) are exposed.

Analysing Fig. 2 it becomes evident that – with the exception of hostels and hotels – the percentage of buildings exposed to torrential flooding is below the percentage of buildings exposed to river flooding. A relatively high share of buildings from the category of residential buildings and commercial buildings is exposed to river flooding, whereas apart from hostels and hotels a considerable percentage of sacral buildings and agricultural buildings is exposed within the hazard type of torrential flooding. The percentage of hotels exposed to torrential flooding is even higher than the percentage of hotels exposed to flooding, which is exceptional: the other building categories exposed to torrential hazards fall relatively below the river flooding exposure. Only a minority of buildings is exposed to snow avalanches. Moreover,

**Table 1.** Information on non-exposed buildings and buildings exposed to river flooding, torrential flooding and snow avalanches, aggregated on the level of Federal States in Austria. Additionally, information on multi-exposed buildings is given.

Federal state	Buildings [N]	Non-exposed buildings [N]	Exposed buildings [N]	Exposed buildings [%]	Single exposure						Multi-exposure			
					River flooding [N]	Torrential flooding [N]	Snow avalanches [N]	River flooding and torrential flooding [N]	Torrential flooding and snow avalanches [N]	River flooding and snow avalanches [N]	Torrential flooding, river flooding and snow avalanches [N]			
Burgenland	133 482	123 905	9577	7.2	9439	140	0	2	0	0	0	0	0	
Carinthia	185 693	161 782	23 911	12.9	17 012	8466	188	1660	95	10	10	10	10	
Lower Austria	648 693	569 085	79 608	12.3	73 239	8381	6	2018	0	0	0	0	0	
Upper Austria	425 718	378 307	47 411	11.1	37 836	12 471	137	2950	22	71	10	10	10	
Salzburg	139 377	99 662	39 715	28.5	20 360	23 800	594	4684	319	128	92	92	92	
Styria	381 484	331 065	50 419	13.2	27 953	25 695	460	3530	130	52	23	23	23	
Tyrol	192 381	141 735	50 646	26.3	25 635	24 631	4465	2975	924	276	90	90	90	
Vorarlberg	106 098	91 910	14 188	13.4	4334	8089	3159	270	1105	31	12	12	12	
Vienna	186 574	183 023	3551	1.9	3551	0	0	0	0	0	0	0	0	
Sum	2 399 500	2 080 474	319 026	13.3	219 359	111 673	9009	18 089	2595	568	237	237	237	

**Table 2.** Information on non-exposed principal residents and principal residents exposed to river flooding, torrential flooding, and snow avalanches, aggregated on the level of Federal States in Austria. Additionally, information on multi-exposure is given.

Federal state	Single exposure					Multi-exposure				
	Principal residents [N]	Non-exposed residents [N]	Exposed residents [N]	Exposed residents [%]	River flooding [N]	Torrential flooding [N]	Snow avalanches [N]	River flooding and torrential flooding [N]	Torrential flooding and snow avalanches [N]	Torrential flooding, river flooding and snow avalanches [N]
Burgenland	284 735	267 378	17 357	6.1	17 092	266	0	0	0	0
Carinthia	556 248	478 721	77 527	13.9	58 784	23 057	367	4478	203	20
Lower Austria	1 621 951	1 393 880	228 071	14.1	212 713	21 155	9	5806	0	0
Upper Austria	1 422 853	1 257 724	165 129	11.6	137 850	38 117	307	10 917	57	199
Salzburg	535 671	356 248	179 423	33.5	111 614	85 265	1621	18 008	969	424
Styria	1 212 345	1 044 934	167 411	13.8	105 888	70 219	913	9296	249	115
Tyrol	719 304	495 781	223 523	31.1	144 072	80 218	13 376	10 901	2542	918
Vorarlberg	373 566	328 682	44 884	12.0	16 363	24 749	6976	848	2318	56
Vienna	1 759 940	1 737 664	22 276	1.3	22 276	0	0	0	0	0
Sum	8 486 613	7 361 012	1 125 601	13.3	826 652	343 046	23 569	60 255	6338	1732

**Table 3.** Buildings exposed to natural hazards according to different building categories. Building category 13 (pseudo buildings) includes mobile and temporary accommodation facilities such as mobile homes and barracks if persons are living there, and building category 14 includes all other buildings not included in categories 1–13 (Statistik Austria, 2012).

Building categories	Buildings [N]	Buildings [%]	Single exposure										Multi-exposure				
			Non-exposed buildings [N]	Exposed buildings [N]	Exposed buildings [%]	River flooding [N]	Torrential flooding [N]	Snow avalanches [N]	River flooding and torrential flooding [N]	Torrential flooding and snow avalanches [N]	River flooding and snow avalanches [N]	Torrential flooding, river flooding and snow avalanches [N]					
Detached houses (1)	1 510 151	62.94	1 335 938	174 213	11.54	119 189	60 424	4607	8600	1280	221	94					
Duplex houses (2)	542 118	22.59	457 359	84 759	15.63	56 195	32 477	2308	5421	681	177	58					
Apartment buildings (3)	4053	0.17	3338	715	17.64	528	204	38	37	18	3	3					
Hotels and hostels (4)	37 272	1.55	28 683	8589	23.04	4217	4622	994	895	302	82	35					
Office buildings (5)	31 420	1.31	25 551	5869	18.68	4815	1325	63	315	17	5	3					
Wholesale and retail buildings (6)	32 583	1.36	25 646	6937	21.29	5612	1761	73	481	25	5	2					
Communication and transportation buildings (7)	4319	0.18	3525	794	18.38	544	295	53	73	24	9	8					
Industrial buildings (8)	72 148	3.01	56 155	15 993	22.17	12 874	4113	248	1139	86	30	13					
Buildings for cultural activities and leisure (9)	21 082	0.88	17 041	4041	19.17	3142	1113	90	264	35	11	6					
Agricultural buildings (10)	18 496	0.77	17 341	1155	6.24	624	501	121	66	24	4	3					
Garages (11)	48 819	2.03	43 412	5407	11.08	3686	1811	136	193	31	5	3					
Sacral buildings (12)	4384	0.18	3896	488	11.13	289	200	47	33	15	2	2					
Pseudo buildings (13)	4 536	0.19	3 683	853	18.81	797	71	3	18	0	0	0					
Other buildings (14)	68 119	2.84	58 906	9213	13.52	6847	2756	228	554	57	14	7					
Sum	2 399 500	100	2 080 474	319 026	13.30	219 359	111 673	9009	18 089	2595	568	237					



it can be deduced from Fig. 2 that the exposed values are higher for buildings exposed to river flooding in almost all building categories, and lower for buildings exposed to torrential flooding. The exception is again within the group of hostels and hotels, as well as agricultural buildings, garages, pseudo buildings and detached houses. Sacral buildings were not considered during economic analysis.

If queried spatially on a municipal level, considerable differences would manifest throughout the country, as shown in Fig. 3 by using a bipolar representation. The reference for Fig. 3 (left column panels) was the number of buildings which are affected by the respective hazard. Communities with no hazard data available are shown in grey colours and were not considered during the set of computations. The reference for Fig. 3 (right column panels) was the number of primary residents exposed to the respective hazard, and again grey colours show communities which were not considered because of missing hazard information.

- Regarding snow avalanches, the mean number of exposed buildings is 30.4 per municipality focusing on avalanche-prone municipalities, and the mean number of exposed principal residents is 79.6. The highest exposure is found in those municipalities next to the main chain of the Alps in western Austria (Federal States of Vorarlberg and Tyrol).
- The mean number of buildings exposed to torrential processes is 87.7 per municipality focusing on torrent-prone municipalities, and the mean number of exposed principal residents is 269.3. Apart from some outliers the highest exposure can be found in the Federal State of Salzburg as well as in municipalities of adjacent Federal States.
- River flooding is a threat to almost the entire country, and a mean number of 97.1 buildings is exposed per municipality. Due to the considerable number of buildings exposed to river flooding in the larger Vienna agglomeration, the highest exposure can be found in this area. Moreover, communities along the larger rivers show an above-average exposure. The mean number of exposed principal residents is 365.9 per municipality.

To summarise the nation-wide spatial assessment, around 13 % of the entire building stock and 13 % of the principal residents are exposed to the considered natural hazard scenarios in Austria, while considerable regional differences are manifested: While in the Federal States of Salzburg and Tyrol, 28.5 and 26.3 % of the entire building stock as well as 33.5 and 31.1 % of the residents are exposed, in Vienna it is only 1.9 and 1.3 %. While only around 5 % of all buildings and 4.3 % of the residents in Austria are exposed to mountain hazards (torrential flooding and snow avalanches), around 9 % of all buildings and almost 10 % of the residents are exposed to river flooding. Above-average exposure to mountain

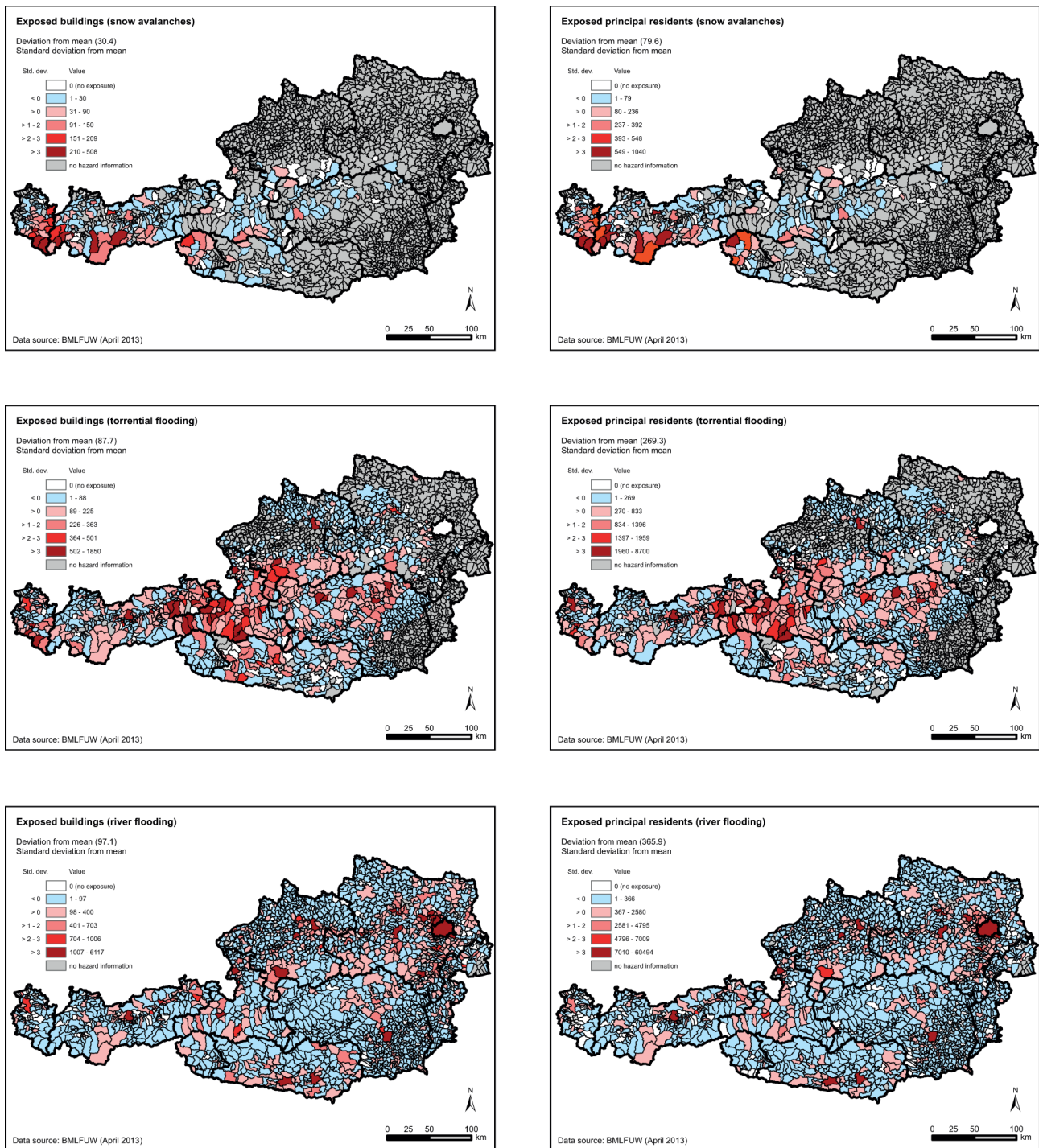
hazards can be found in the Federal States of Salzburg, Tyrol and Vorarlberg, and buildings in Salzburg, Tyrol and Lower Austria are exceptionally prone to river flooding (Tables 1 and 2). Almost 1 % of the entire properties and 0.8 % of the residents have to be classified as being multi-exposed, which is, according to the topography of the country, a very low value.

### 3.2 Results of temporal analysis

In Fig. 4 the temporal analysis of the building stock in Austria is presented. There is evidence that the absolute number of buildings exposed to individual hazard types steadily increases in the country, which means that over the study period there were no exceptional construction activities traceable in either flood-prone areas or areas prone to torrential hazards (Fig. 4a). In contrast, a considerable increase of non-exposed buildings is evident for the period since the 1950s. Additionally, it can clearly be shown that exposure to snow avalanches is relatively low compared to other hazard categories, even if individual events occurred leading to considerable economic losses in recent decades (Fuchs et al., 2013). Since 1919, the total number of properties in Austria has increased by 643 % from 373 067 to 2 399 500 buildings. For 4.25 % of buildings, however, a year of construction was missing in the data and they were therefore excluded from further analysis. The total number of properties exposed to river flooding has increased by 650 % from 33 697 to 219 359 buildings (4.16 % excluded due to missing information on the year of construction). The total number of properties exposed to torrential flooding has risen by 594 % from 18 797 to 111 673 buildings (3.35 % excluded due to missing information on the year of construction). The total number of properties exposed to snow avalanches has risen by 433 % from 2081 to 9009 buildings (2.9 % excluded due to missing information on the year of construction). Based on absolute figures it has to be concluded that the growth rate is almost the same for buildings exposed to river flooding and non-exposed buildings, whereas for torrential flooding the growth rate is slightly lower and for snow avalanches the rate is considerably lower.

In Fig. 4b, the growth rate is shown for the building stock exposed to torrential and river flooding as well as snow avalanches, based on the respective construction period 1919–2012. Additionally, the growth rate of the overall building stock is provided. While the growth rate of the buildings exposed to river flooding is above the overall growth rate over the entire time period, the growth rate of buildings exposed to torrential flooding is below this rate for the period prior to 1960 and after 1980. For the period 1960–1980, both rates are almost the same. The growth rate of buildings exposed to snow avalanches is clearly below over the entire time span.

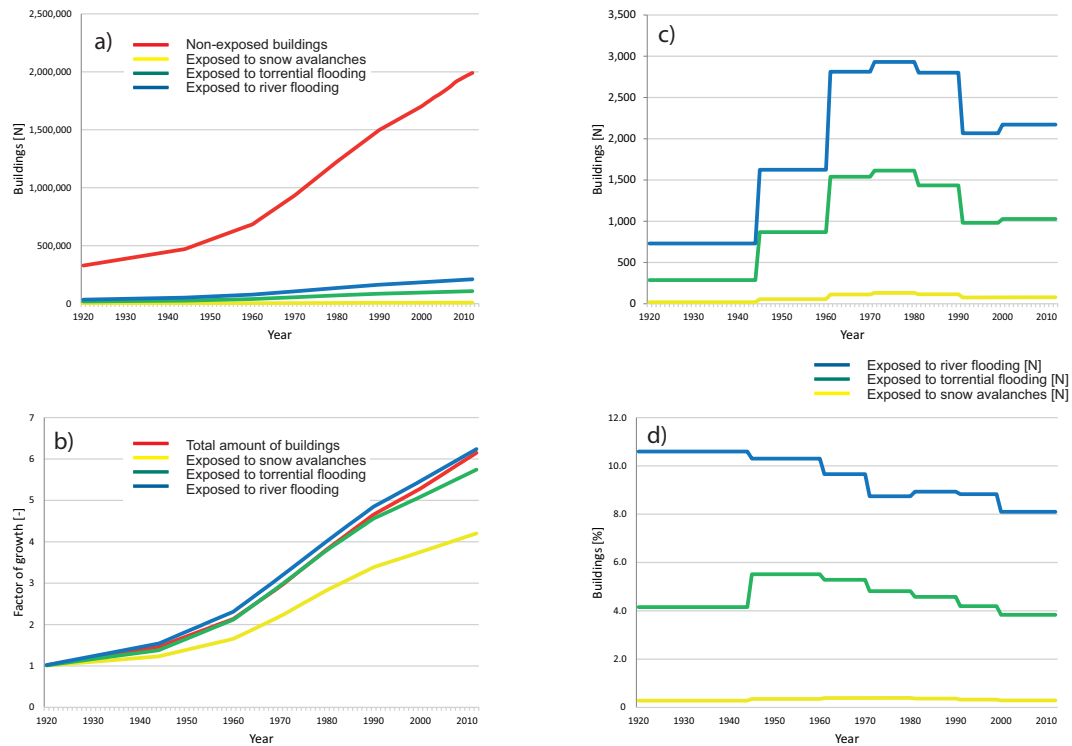
In Fig. 4c, the average annual number of newly constructed buildings is shown for the different hazard cate-



**Figure 3.** Number of buildings and primary residents exposed to snow avalanches, torrential flooding and river flooding in Austria, shown as deviation from mean.

gories. Until the 1970s, this number has risen remarkably and since then, the number of new constructions is decreasing. Since 2000, however, there is again a slight increase detectable. What is evident, however, that the curves for river flooding and torrential flooding follow the same pattern over

the study period. The annual growth was lowest in the period 1919–1944 (snow avalanches: 19, torrential flooding: 286, river flooding: 731 new buildings per year, for comparison annual growth for the entire building stock: 6894 buildings per year) and highest in the period 1971–1980 (snow

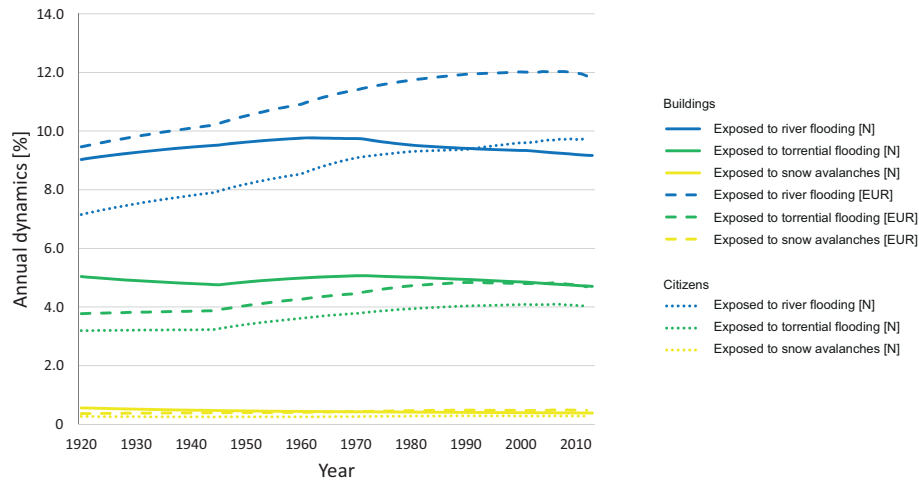


**Figure 4.** Temporal development of building stock in Austria. In (a) the cumulative absolute increase in the number of buildings is shown for non-exposed buildings and buildings exposed to snow avalanches, torrential as well as river flooding. In (b) the relative increase of the building stock is shown for the total number of buildings and buildings exposed to snow avalanches, torrential as well as river flooding, 1919 = 1. In (c) the average annual number of newly constructed buildings is shown for buildings exposed to snow avalanches, torrential as well as river flooding. In (d) the annual number of newly constructed exposed buildings versus the total number of newly-constructed buildings is shown for buildings exposed to snow avalanches, torrential as well as river flooding.

avalanches: 132, torrential flooding: 1614, river flooding: 2931 new buildings per year, for comparison annual growth for the entire building stock: 33 515 buildings per year). Currently, 78 buildings are constructed each year in avalanche-prone areas, 1028 in areas prone to torrential flooding, and 2172 in areas prone to river flooding, while 26 814 buildings are constructed annually throughout the country.

If these data are related to the annual construction activities only, neglecting the high number of already existing buildings, a reverse trend becomes obvious (Fig. 4d): the annual number of newly constructed exposed buildings versus the total number of newly constructed buildings regardless of the exposure is decreasing since the 1940s, but with different rates. The only exception is a decade of 1981–1990, where the percentage of buildings exposed to river flooding is slightly increasing, and the period between 1919–1944 and 1945–1960 with an increase from 4.2 to 5.5 % for torrential flooding. For river flooding, the percentage of new development in exposed areas decreased from 10.6 to 8.1 % for the period under investigation, while for torrential flooding the decrease is from 4.2 to 3.8 %. For snow avalanches, the percentage is within a range of 0.3–0.4 % only.

The results of a cumulative analysis including the entire building stock and focusing on inter-annual changes in the construction activity between exposed buildings and the total building stock are shown in Fig. 5 by the relation between annual dynamics in new constructions per year against the respective entire building stock at each time step. Because of the relatively low number of exposed buildings in the country (cf. Table 1), the resulting percentage is low. For river flooding, a slight increase in the share of elements at risk exposed from 9 to 9.8 % is detectable until the 1960s and since then a slight decrease to 9.2 % can be proven. In contrast, with respect to torrential flooding, the percentage of share of elements at risk is slightly decreasing from 5 to 4.8 % for the period 1919–1944, subsequently increasing to 5.1 % until 1970, and decreasing again to 4.7 %. For snow avalanches, the values are slightly decreasing over the entire period under investigation from 0.6 to 0.4 %. The buildings exposed to river flooding and torrential flooding are increasing in value compared to the non-exposed buildings, in particular during the period 1944–1990. The number of residents exposed is following a similar increase than the value of buildings from 7.2 to 9.7 % for river flooding. For torrential flooding, the increase is from 3.2 to 4.0 %, whereas since 1980 this rate



**Figure 5.** Relation between exposed buildings and residents and the total building stock and total number of residents. The numbers are based on average annual construction activities based on the available construction periods.

is almost constant around 4 %. The increase of residents exposed to snow avalanches is constant with a factor of 0.3 %. The overall dynamics, however, are within percent range.

#### 4 Discussion

Whereas so far a general increase in the building stock could only be proven for selected case studies if data are analysed object-based (Keiler, 2004) or aggregated in terms of land-use classes (Cammerer and Thieken, 2013), the presented results provide more diversified insights in exposure. To give an example, previous studies with respect to exposure concluded that in some villages the property has increased above-average compared to the regional-scale development (Keiler 2004; Fuchs and Bründl, 2005). Taking the findings presented above it was shown that hazard-dependent above- and below-average dynamics are evident throughout the country both for the number of buildings and citizens. In some rural test sites, the total number of endangered buildings had been reported to having increased by a factor of approximately 2.5 since 1950, most of this increase being due to the category of accommodation facilities, such as hotels and guest houses (Keiler et al., 2006a) and residential buildings (Fuchs et al., 2005). By means of the nation-wide building register it was shown that the exposure of different building categories – as well as citizens exposed – is variable in dependence on the hazard type. Cammerer and Thieken (2013) concluded with respect to a possible future development of exposure until 2030 that if built-up areas expand along the valley bottom in the neighbourhood to existing settlements, a considerable increase in exposure will result. However, these projected changes in areas at risk vary strongly between the individual land-use scenarios applied (Cammerer and Thieken, 2013). By extrapolation of the temporal dynamics it can be shown that if a further development

of construction activity in Austria following the numbers of the period 1919–2012 is assumed, a continued increase of buildings exposed to river flooding of 2 % per year – compared to the entire building stock – would result in a number of 530 000 exposed buildings until 2100 (increase of 2.5 compared to 2012 which would be 8.1 % of the entire building stock in 2100). If new constructions would be banned immediately in areas exposed to flooding and the annual growth rate of the new constructions is assumed as 2 %, in the year 2100 still 3.4 % of the entire building stock would be exposed to river flooding, and 1.7 % to torrential flooding. This shows the considerable time lag as a result of previous land-use decisions and therefore clearly highlights the importance of risk management actions in terms of structural prevention measures.

Most communities with an extraordinary share of buildings prone to mountain hazards are located in the mountainous part of Austria, communities with an above-average exposure to river flooding are cities or centred on agglomerations in the alpine foreland. Given the economic structural change from the primary to the tertiary sector within the country, a high number of hotels is located in mountain tourist-spots, which explains the high exposure to mountain hazards. In turn, in regions with an emphasis on the secondary sector, a considerable share of commercial buildings, which are usually space-requiring, is located in flood plains of larger rivers or – historically grown – along mountain torrents because of the demand for hydropower. The category of buildings for cultural activities also requires space, and is therefore also often located in the flood plains. These areas were traditionally also used for agricultural purposes, which explains the above-average presence of agricultural buildings in these areas. Hence, since information on the building stock became increasingly available throughout Europe (e.g. Jongman et al., 2012b), more accurate information on

values exposed can be obtained contributing to strategic hazard and risk management (Mazzorana et al., 2009, 2012). Moreover, the results allow for adjusting adaptation strategies (Rojas et al., 2013). Small-scale differences in exposure can be precisely shown, which allows for more differentiated management strategies such as increasing community awareness (Fuchs et al., 2009; Meyer et al., 2012), implementing local structural protection (Holub et al., 2012) or fostering tailored insurance solutions (Paudel et al., 2013; Carina et al., 2014). Future investments into risk management are encouraged in particular for those communities with an above-average exposure to individual hazard types. As a result, public investments in mitigation measures can be targeted at regions with higher values at risk, which follows the axiom of spending public funding with the highest return of investments (Meyer et al., 2013).

The results also proved that the number of documented hazard events as shown in Fig. 1 should not directly be used to assess the development of losses and exposure: while the overall stock of exposed buildings as well as the non-exposed buildings increased by a factor of 2.3 between 1960 and 2000, the number of damaging hazard events was almost decreased by 50%. With respect to the annual growth rate of non-exposed and exposed buildings, the total building stock as well as the buildings exposed to river flooding and torrential flooding show similar characteristics and a rate of around a factor of six. The buildings exposed to snow avalanches again have a below-average rate (around 4.2). The total number of new constructions, in contrast, increased since 1944 and culminated in the period 1971–1980 followed by a sharp decrease and an additional increase since 2000 (Fig. 4c). As such, factors other than exposure may be responsible for temporal dynamics of natural hazard loss, such as (a) changes in the natural process activity resulting from the effects of climate change, and (b) the implementation of technical mitigation measures leading to less exposure or vulnerability. These factors were explicitly neglected during the present study in order to get the signal of dynamics in peril exposure in mountain environments.

Comparing the ratio between new constructions and the existing building stock (Fig. 5) and the annual ratio of new constructions inside hazard-prone areas and the total new constructions (Fig. 4d), a time lag between actual planning decisions and their effects on exposure becomes evident. While the ratio of buildings exposed to river flooding compared to the cumulative development of buildings stock is increasing until the 1960s, the ratio of annual constructions inside endangered areas is already decreasing starting with 1945 due to the relatively higher number of non-exposed buildings in Austria (almost 87% of the entire stock). With the exception of the decade 1981–1990, where a slight increase in this annual ratio is detectable, both the annual ratio of exposed to non-exposed buildings and the ratio between exposed buildings and the entire stock is decreasing. This may be interpreted as success of land-use planning activi-

ties (namely hazard mapping and the related ban of new constructions inside red hazard zones), even if a clear relation between new constructions and the implementation of hazard maps cannot be deduced. Because fewer buildings are exposed to torrential flooding, this pattern cannot be followed in this category of exposure: for torrential flooding both the annually constructed number of buildings exposed compared to the entire building stock (Fig. 5) and the annual number of constructions inside endangered areas (Fig. 4d) is decreasing until 1944, followed by an increase until 1970 and 1960, respectively. Since then, both ratios are continuously decreasing. This clearly shows the dependency of success in land-use planning on the initial situation, and in turn reveals the challenge in exposure in a different light: even if the ratio of annual new development inside and outside endangered areas is decreasing, the effects will be unveiled decades later. More precisely, the fewer buildings are exposed in comparison to the entire buildings stock, the longer land-use regulations enacted today will take to show success.

Nevertheless, some limitations of the data have to be addressed. While this study relies on a building inventory providing detailed information on the characteristics and types of the current building functionality, dimension and residents, historical information on the population composition as well as information on former population registers would enhance the significance of the results with respect to exposed citizens. Furthermore, exposure analysis is only possible for those buildings where information in the building register is available. Minor auxiliary buildings and remote agricultural buildings without addresses are not considered. Furthermore, around 8% of the communities with an obligation for hazard mapping is not considered because of missing hazard information – the mandatory hazard map has not yet been compiled and set effective in law, respectively. Despite these limitations, the results demonstrate advantages in comparison to local-scale case studies, and provide valuable information for decisions in natural hazard mitigation.

## 5 Conclusions

A detailed and spatially explicit object-based assessment of buildings exposed to natural hazards in Austria was undertaken, including elements at risk to river flooding, torrential flooding, and snow avalanches. While some regions have shown a clearly above-average increase in assets, other regions were characterised by a below-average development. This mirrors the topography of the country, but also the different economic activities: as such, hotels and hostels were found to be extraordinarily prone to mountain hazards, and commercial buildings as well as buildings used for recreational purposes to river flooding. Residential buildings have shown an average exposure, compared to the number of buildings of this type in the overall building stock.

In conclusion, a nation-wide and object-based assessment has advantages compared to the traditional approaches based on individual case studies: exposure to natural hazards is heterogeneous, and follows small-scale patterns which cannot necessarily be satisfyingly modelled by only assessing one hazard type within a specific local environment. The accuracy of such information may be used – together with down-scaled climate projections and combined with appropriate hazard models – to provide valuable risk estimates on a national scale. As a result, such approaches may also be valuable for the implementation of the European Floods Directive. The presented method together with the results may be used for similar assessments focusing on hazards other than those covered by the Directive, and may enable for a more precise overview on exposure and possible losses. This may link the development of risk to socio-economic development indicators, and improve available risk management options facing the challenge of global environmental change.

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