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ORIGINAL PAPER

Spatiotemporal dynamics: the need for an innovative approach in mountain hazard risk management

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Abstract Starting with an overview on losses due to mountain hazards in the Russian Federation and the European Alps, the question is raised why a substantial number of events still are recorded—despite considerable efforts in hazard mitigation and risk reduction. The main reason for this paradox lies in a missing dynamic risk-based approach, and it is shown that these dynamics have different roots: firstly, neglecting climate change and systems dynamics, the development of hazard scenarios is based on the static approach of design events. Secondly, due to economic development and population dynamics, the elements at risk exposed are subject to spatial and temporal changes. These issues are discussed with respect to temporal and spatial demands. As a result, it is shown how risk is dynamic on a long-term and short-term scale, which has to be acknowledged in the risk concept if this concept is targeted at a sustainable development of mountain regions. A conceptual model is presented that can be used for dynamical risk assessment, and it is shown by different management strategies how this model may be converted into practice. Furthermore, the interconnectedness and interaction between hazard and risk are addressed in order to enhance prevention, the level of protection and the degree of preparedness.

Keywords Mountain hazards · Risk assessment · Space · Time · Risk management

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1 Introduction

Comprehensive databases on disasters due to natural hazards present worldwide trends which can be summarised by an increasing number of reported events, of people affected and economic losses, but a decreasing number of reported fatalities in the last decades (IFRCRCS 2005; Munich Re 2011; Swiss Re 2011; CRED 2012).

Acknowledging these threats for decades, international action such as the International Decade for Natural Disaster Reduction (IDNDR, United Nations General Assembly 1989) and its successor, the International Strategy for Disaster Reduction (ISDR, United Nations General Assembly 2000) was taken not only with a particular focus on developing countries, but also with respect to most developed countries. The primary focus of disaster risk reduction was shifted from hazards and their physical consequences to the processes involved in the physical and socio-economic dimensions of risk and a wider understanding, assessment and management of risk induced by natural hazards. This highlighted the integration of approaches to risk reduction into a broader context between natural sciences and social sciences.

The concept of risk has become a focal topic of many scientific and professional disciplines as well as practical actions. Consequently, a broad range of conceptualisations of the term exist that show, nevertheless, as lowest common denominator the combination of the likelihood that an undesirable state of reality may occur as a result of natural events or human activities (Kates and Kasperson 1983). Undesirable states of reality are linked to damage, loss or similar negative, and thus adversely evaluated effects to those attributes valued by mankind (Crozier and Glade 2005). The definition of risk, therefore, contains three elements: (1) outcomes that have an impact upon what humans value; (2) a likelihood of occurrence and (3) a specific context in which the risk may materialise (Renn 2008). Thus, risk may be defined as the potential loss to an exposed system, resulting from the convolution of hazard and consequences at a certain site and during a certain period of time (Cardona 2004). The system modelled is a single cross section of space and time: an area with a relatively homogeneous expectation of a single hazard and a duration in time appropriate to the temporal character of the natural events and the related human activity (Kates 1971).

In the perspective of natural sciences, this relationship is regularly expressed by the risk equation (Eq. 1), which with respect to natural hazards is conceptualised by a quantifying function of the probability of occurrence of a hazard scenario (p_{Si}) and the related consequences on objects at risk exposed (c_{Oj}).

$$R_{i,j} = f(p_{\mathrm{Si}},\ c_{\mathrm{Oj}}) \tag{1}$$

The consequences can be further quantified by the elements at risk and their extent of damage and specified by the individual value of elements j at risk (A_{Oj}), the related vulnerability in dependence on scenario i ($v_{\mathrm{Oj,\ Si}}$), and the probability of exposure ($p_{\mathrm{Oj,Si}}$) of elements j to the scenario i (Eq. 2).

$$R_{i,j} = f(p_{\mathrm{Si}},\ A_{\mathrm{Oj}},\ v_{\mathrm{Oj,Si}},\ p_{\mathrm{Oj,Si}}) \tag{2}$$

This quantitative definition of risk provides the framework for probabilistic risk assessment and has its roots in both technical risk analyses and actuarial analyses.

The main challenge of risk assessment is rooted in the connected system dynamics driven by both geophysical and social forces: Applying the concept of risk will provide an individual number, regularly expressed in monetary units as expected degree of loss, if the underlying hazard scenario will occur (e.g. Fuchs et al. 2004; Penning-Rowsell et al. 2005; Fell et al. 2008). Even if this information is an important milestone for the development of tailored management solutions (Holub and Fuchs 2009; Holub et al. 2012), the risk concept poses several challenges because of the inherent static approach. On the one hand, the calculation of risk is based on the prevailing system conditions, namely on numbers of elements at risk exposed and their valuation, the current land-use regulations, etc. (Fuchs et al. 2005, 2006; Keiler et al. 2004, 2006). On the other hand, the hazard scenarios these elements at risk are exposed to are developed based on frequency–magnitude relationships of the natural processes investigated. It is broadly accepted, however, that natural processes are subject to dynamics due to the variations of the triggering factors resulting from climate change (e.g. Beniston et al. 2007; Keiler et al. 2010; Field et al. 2012), which may alter existing frequency–magnitude relationships for hazard scenarios (Kron 2003). Furthermore, there is a connectivity between different hazardous processes and different elements at risk exposed (Keiler 2011). As a result, short-term as well as long-term dynamics of hazard processes have to be acknowledged (Zischg et al. 2005a; Sattler et al. 2011).

Additionally, the social system and therefore land use, elements at risk exposed and vulnerability are not constant over time and with respect to the spatial entities (Keiler et al. 2004; Fuchs et al. 2005, 2006; Keiler et al. 2006; Fuchs and Keiler 2008; Elmer et al. 2012). Consequently, there is a strong need to include these dynamics into the risk concept (Bouwer et al. 2010), which was also on main result from the Floodsite project (Priest 2009).

Nevertheless, identifying and analysing these dynamics of risk is still a challenge in natural hazard risk research. In the subsequent sections, we will show how these dynamics influence the risk level with respect to different temporal and spatial dimensions, why a dynamical approach is important with respect to applied natural hazard mitigation, how such information may be implemented in the risk management approach, and how this approach might enhance our understanding of the dynamics of natural hazard risk. We will focus on mountain hazards and risk as a result of case studies that have been conducted in the European Alps and in mountain regions of the Russian Federation since mountain regions provide a significant proportion of human settlements and areas used for economic purpose and recreation (Ives et al. 1997; Price 1999; Nordregio 2004). Mountain regions are exceedingly prone to changing environmental conditions (Slaymaker et al. 2009). Thereby, mountain geosystems are not exceptionally fragile but they show a greater range of susceptibility to disturbance than many other landscapes (Slaymaker and Embleton-Hamann 2009), and as a consequence, global changes of important magnitude, in particular climate and land-use change, are already taking place (Parry et al. 2007; Solomon et al. 2007).

2 Losses due to mountain hazards

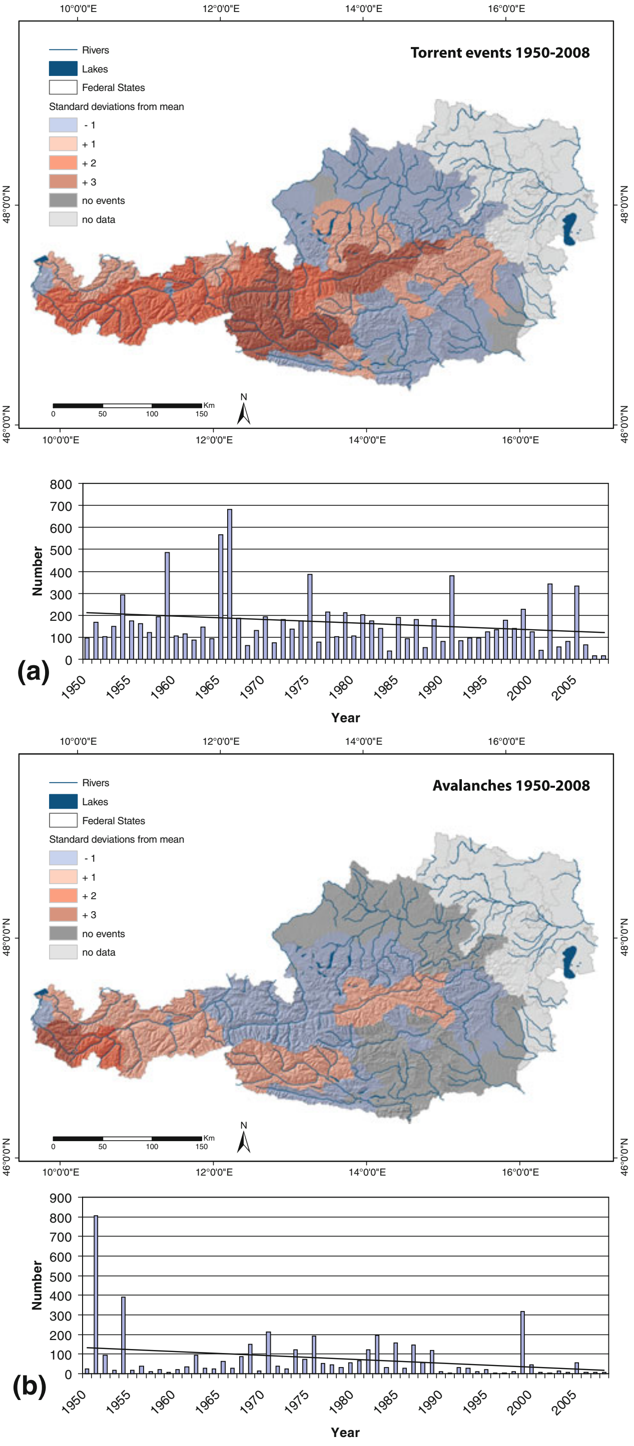
Data on hazardous events and associated losses for European mountain regions seem to be quite well documented, particularly for Italy, Switzerland and Austria. Within the Russian Federation, in contrast, data are by far less well available, in particular with respect to quantifying numbers of losses. However, as a result of duplicities in research efforts and administrative responsibilities, several bibliographies and databases concerning hazard inventories exist, which makes a comparison and assessment challenging. Nevertheless, apart from the resulting inconsistency and incompleteness of individual inventories (which has already been reported with respect to mountain regions by Eisbacher and Clague (1984) and by Alger and Brabb (2001)), the general development of losses can be concluded and an overall conclusion for possible future needs can be drawn.

- For the Republic of Italy, data related to landslide occurrence focusing on fatalities due to landslide-type events had been analysed by Guzzetti (2000), Calcaterra and Parise (2001), Guzzetti and Tonelli (2004) and Guzzetti et al. (2005). Additionally, Catenacci (1992) estimated that at least 2,447 lives were lost in the period 1945–1990, while Guzzetti (2000) reported almost 10,000 fatalities due to landslides (including debris flows) in Italy, and a total of 50,593 harmed people due to landslides and flooding in the last 725 years (Guzzetti et al. 2005). Thereby, the alpine regions of Italy have suffered twice as much missing people than the residual part of the country (Guzzetti 2000). Considerable efforts to establish a database on mountain hazards have been undertaken by Zischg et al. (2007) in order to assess floods and torrent events since the mediaeval times for the Autonomous Province of Bolzano-South Tyrol in the alpine part of Italy. The major focus thereby was on a characterisation of events according to magnitude and frequency and on the establishment of chronologies for individual watersheds.
- Recently, a Swiss database was established by Hilker et al. (2009) based on comprehensive information in Röthlisberger (1991) and Fraefel et al. (2004). In the period 1972–2007, 102 persons lost their lives due to floods, debris flows and landslides in Switzerland. Naturally triggered floods, debris flows, landslides and rockfall events have caused financial damage amounting to nearly € 8,000 million in total within the last 36 years (taking inflation into account, Hilker et al. 2009), which results in an average of approximately € 222 million per year. However, the data are not equally distributed, and distinct years with above-average loss (due to the category flood/inundation) were traceable (1978, 1987, 1993, 1999, 2000, 2005 and most recently 2007 and 2012). Approximately 90 % of the costs originated from floods and inundations (including torrent processes such as hyperconcentrated flow and flooding with moderate bedload transport), while debris flows and landslides were only responsible for 4 and 6 % of the losses, respectively. Since 1972, nearly 50 % of the losses had been registered in the months of July and August, which clearly indicates the importance of stratiform (dynamic) precipitation and convective precipitation as triggering events (Hilker et al. 2009). However, between 1972 and 2007, a statistically significant trend with regard to an increase in the annual cost of damage could not be proven.

  A similar conclusion had been drawn by Schneebeli et al. (1997) with respect to snow avalanches in Switzerland for the period 1947–1993. While the large avalanche events in 1951, 1954, 1968, 1975 and 1984 can clearly be traced, the entire data set shows no obvious trend. As subsequent studies have shown, the long-term natural avalanche activity in the Swiss Alps seems to be constant (Laternser and Pfister 1997; Laternser and Schneebeli 2002), although it is pointed out that the variability of events makes an exact statement difficult. Due to the construction of mitigation measures, the number of devastating avalanches (Schneebeli et al. 1998) as well as the corresponding losses has declined over the last 50 years in Switzerland (Fuchs and Bründl 2005). Within the period 1946–1992, 295 individuals were buried inside buildings, 135 of which (46 %) died and 56 (19 %) were injured (Wilhelm 1997). A detailed study within the canton of Grisons in the western part of Switzerland concluded in a reduction of annual damage costs between 1950 and 2000 (Fuchs and Bründl 2005), in particular with respect to the years with above-average avalanche activity. The total sum of avalanche losses due to direct building damage in Grisons amounted to € 63.3 million. This is 40 % of the sum paid by the mandatory building insurer for natural hazards losses in the canton, but avalanches make up only 15 % of the number of all incidents. This means an average of € 1.25 million per year, compared with € 1.77 million per year for losses due to other natural hazards, such as debris flows, rock fall events and floods. Damage resulting from avalanches amounted to an average of € 17,500 per event, while losses caused by other types of natural hazard processes cost an average of € 6,000 per event (Fuchs and Bründl 2005; Holub et al. 2012).

- In Austria, a database of destructive torrent events was established and analysed concerning monetary losses by Oberndorfer et al. (2007). A total number of 4,894 damaging torrent events were reported between 1972 and 2004. For almost 4,300 events, the process type could be determined ex-post, resulting in a classification between floods (0.3 %), flooding with bedload transport (21.8 %), hyperconcentrated flows (49.2 %) and debris flows (28.7 %). The average direct loss per event due to these 4,300 records amounted to approximately € 175,000 (in 2012 values), and annually losses due to torrent events amounted to around € 25 million. Approximately two-third of the losses could be ascribed to buildings and one-third to infrastructure facilities (Fuchs 2009). Within the period under investigation, 21 people were physically harmed and 49 people died. The annual distribution of the losses showed that considerable cumulative damage exceeding € 1 million per event occurred in 1975, 1978 and 1991. In contrast, in 1976 and 1984, the average damage per event summed up to € 11,000 and € 16,000, respectively. A considerable number of events were reported from 1974, 1990 and 2002, leading to the conclusion that a high number of events do not necessarily result in high losses, and vice versa, which is a clear indication for nonlinear relationships. An additional analysis of destructive torrent events between 1950 and 2008 derived from a reanalysis of written reports which were compiled during the implementation of hazard maps by the Austrian Torrent and Avalanche Control Service had shown a decreasing trend related to the overall number [$N = 9{,}852$, annual mean = 167]. However, considerable events were observed in individual years, in particular in the western part of Austria (see Fig. 1a).

  With respect to snow avalanches, information related to destructive events is rather sparse in Austria. Between 1967 and 1992, a total of 5,135 avalanches had been reported by Luzian (2002), 4,032 of which caused damage to settlements and infrastructure. The data did not show any trend; however, large events were reported from 1969, 1974, 1980, 1981 and 1983 during the period under investigation. For a separately studied period between 1998 and 2003, 172 avalanches causing damage to settlements and infrastructure were reported by Luzian and Eller (2007); 94 of which resulted from the winter 1998/1999 and 47 from the winter 1999/2000. The amount of losses was not reported in these sources, apart from the figure of 718 destroyed and 570 damaged structures between 1967 and 2002 (Luzian 2002), and 29 lives lost in buried buildings between 1998 and 2003 (Luzian and Eller 2007). An ex-post analysis of destructive avalanches between 1950 and 2008 shows a decreasing trend related to the overall number [$N = 4{,}334$, annual mean = 74.7]. However, considerable events were observed in the western part of Austria (see Fig. 1b).
- For the Russian Federation, the threats due to mountain hazards are substantially predetermined by the geographical settings of the country, including natural and climatic conditions (Porfiriev 1999, Shnyparkov et al. 2012) as well as land-use policies. Semenov (2011) reported a general increase in flood events in the twenty-first century compared with the last decade of the twentieth century, which may be in line


Torrent events 1950-2008
Rivers
Lakes
Federal States
Standard deviations from mean
- 1
+ 1
+ 2
+ 3
no events
no data
10°0'0"E
12°0'0"E
14°0'0"E
16°0'0"E
48°0'0"N
46°0'0"N
Km
0
50
100
150
N
Number
Year
(a)
Avalanches 1950-2008
(b)
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005

◀**Fig. 1** Data related to torrent events (**a**) and avalanches (**b**) collected from the reports which were compiled during the implementation of hazard maps by the Austrian Torrent and Avalanche Control Service for the period 1950–2008. Even if a spatial concentration of events can be proven for the western part of Austria, the overall trend for both process categories is decreasing. With respect to avalanches, an equivalent decrease was reported by Fuchs and Bründl (2005) for the western part of Switzerland. *Data source*: Institute of Mountain Risk Engineering, University of Natural Resources and Applied Life Sciences, Vienna, Austria, see also Totschnig et al. (2011)

with an earlier observation on the frequency of atmospheric phenomena causing natural hazards (Vasil'ev et al. 1994). In particular, it is stated that 'over the last 20–30 years in most [catchments] the trend of changes in the maximum run-off became positive under conditions of the present-day climate changes as a result of the most intense warming in the spring months accompanied by an increased precipitation amount in the southern, mainly mountain, regions of Russia, increased precipitation amount in the winter-spring period and maximum snow water equivalent by the beginning of snow melting in the river basins of the northern part of European Russia, Ural, and Siberia' (Semenov 2011, p. 124). As a result, there may be a negative impact on the Russian national economy, as also stated earlier by Alshanskii et al. (1999); they additionally related this negative impact of hydrometeorological phenomena on the Russian economy to the global human–environment interaction.

Major incidents of national importance (defined by more than 50 victims per event, Government of Russian Federation 2007) with respect to mountain hazards are reported between the 1930s and the 1950s:

- 5 December 1935: A total of 89 persons were killed and 42 injured due to a snow avalanche release at the Yukspor Mountain in Kirovsk, Kola Peninsula.
- 9 February 1945: According to Shmigel'skii (2008), a snow avalanche buried 236 persons, the rescue station, the kindergarten, one three-floor building and several private houses in Srednyaya Medvezhka settlement (Sakhalin), resulting in 149 fatalities (76 of which were children).
- 25 February 1948: A snow avalanche completely destroyed a settlement at the beach of the Zhirovaya bay (Kamchatka), 54 out of 154 inhabitants died and eleven were injured (Gavrilov 2006).
- 28 March 1951: In the Seymchan river basin (Magadan region), an avalanche caused many deaths and totally destroyed the Gulag penal camp (Seliverstov et al. 2008).

Incidents with a regional impact resulting from mountain hazards are reported from Sakhalin (1950, 1958, 1970), the Kuril Islands (1952, 1959), the Kamchatka region (1969), Kabardino-Balkaria (1976), the Magadan region (1982) and the Komi Republic (1988); these events resulted in between 10 and 50 victims each (Government of Russian Federation 2007). Minor events are regularly reported; however, details other than qualitative are not available on the national scale (Government of Russian Federation 2007). Out of 144 cases of torrent events that caused damage to the population in 1991–2008, 130 occurred in the Northern Caucasus, five in East Siberia and four in the Far East. In 2001–2008, compared with 1991–2000, the number of torrent events with known damage almost doubled in the Russian mountain regions (Semenov 2011), which may be a result of urbanisation and changes in the land cover. With respect to snow avalanches, Seliverstov et al. (2008) reported that avalanche-prone areas affect considerable parts of the Russian territory. Avalanche-prone areas

> include mountain systems such as the Khibiny mountains located at the Kola peninsula, the Ural and the Northern Caucasus in the European part of the country. The highest avalanche fatality rates are recorded from the Caucasus (and from Sakhalin in the Far East), whereas a general inventory on losses and fatalities from mountain hazards is hardly available so far. According to Seliverstov et al. (2008), approximately 60 % of the avalanche fatalities can be ascribed to outdoor activities, 10 % occurred in settlements and 20 % on the road network.

Despite this list of reports, which is neither comprehensive nor consistent if compared with each other, and besides many national and international efforts to reduce natural hazard impact on society, considerable damage has still occurred in recent years in mountain regions of the selected countries, as shown for snow avalanche fatalities in Table 1.

Why has there been so little progress in our ability to mitigate and adapt to natural hazards? This recurrent question appears after each disaster or event with high human and/or economic loss and is comprehensible to all persons concerned as well as to scientists in the field of natural hazard and risk research. White, Kates and Burton (2001) summarised this emergent question in their article ‘Knowing better and losing even more—the use of knowledge in hazard management’. Thereby, greater availability of information of natural hazard occurrence both on a scientific basis but also due to broader media coverage resulted in an increase in hazard awareness on a societal level, in particular due to a perceived increase in property damage and fatalities. The increased public awareness has often been misconstrued as an indication for increased frequency and magnitude of events which will trigger the potential increase in losses. It is still under debate, however, to which extent recent increases in damage ratios can be related to changing process behaviour and thus increased magnitude and frequency (Mazzorana and Fuchs 2010, Mazzorana et al. 2012), and to which extent these developments are a result from increased utilisation of

Table 1 Annual fatalities due to snow avalanches in the Russian Federation (RUS), the Republic of Austria (A), the Swiss Confederation (CH) and the Republic of Italy (I) for the period 1996/1997–2010/2011

Years	RUS	A	CH	I
1996/1997	12	n.s.	n.s.	n.s.
1997/1998	13	n.s.	n.s.	n.s.
1998/1999	20	50	37	12
1999/1900	30	39	20	16
2000/2001	13	22	32	29
2001/2002	27	17	24	7
2002/2003	18	34	20	25
2003/2004	34	8	11	21
2004/2005	24	48	26	10
2005/2006	35	21	24	23
2006/2007	13	18	21	5
2007/2008	28	29	11	16
2008/2009	14	31	28	21
2009/2010	30	38	29	43
2010/2011	13	n.s.	n.s.	n.s.
Sum	324	355	283	228
Mean	21.6	29.6	23.6	19.0

On average, more people died from an avalanche in Austria and Switzerland than in the Russian Federation, while in Italy less people died. *Data source*: RUS: Research Laboratory of Snow Avalanches and Debris Flows, Faculty of Geography, Moscow State University, Russian Federation. A, CH, I: European Environment Agency (2010) areas prone to hazardous events for human settlement, economic activities and infrastructure corridors (Keiler et al. 2005, 2006). Therefore, both of these possibilities need further research efforts in order to allow for an economically efficient (Fuchs and McAlpin 2005; Fuchs et al. 2007a) and socially acceptable way of dealing with mountain hazards.

Closely related to these challenges are the continuous changes in space and over time of landscape processes and of society. Landscape processes and society are subjects to dynamical but also interactive changes (Hufschmidt et al. 2005) both in the spatial and in the temporal dimension. Moreover, research questions due to these changes on the interlinkage between individual landscape processes (e.g. coupled and multi-hazards, Kappes et al. 2012) as well as between landscape systems and human systems have not sufficiently been studied so far (Gregory 2006; Slaymaker and Embleton-Hamann 2009; Slaymaker 2010). Considering these dynamic and interactive evolution, rising losses related to natural hazard processes can neither be solely connected to the changes of the natural processes nor to the development of the society (e.g. increase in population, values at risk and vulnerability). Thus, an increasing knowledge about one part, such as the understanding of the hazard processes, elements at risk or vulnerability without analysing the interaction between these components and their spatial and temporal dynamics does not help to find improved and suitable management strategies to reduce risk. Accordingly, only a coupled research framework based on such analyses enables us to improve the understanding of interactive dynamics and thus changing risk.

3 Towards a dynamic risk approach

The quantitative definition of risk (Eq. 2) provides the framework for probabilistic risk assessment in natural sciences. Nevertheless, as recently stated by Eckert et al. (2012), the definitions used and modelling assumptions made remain slightly different from one proposal to another, mainly because of different foci on either hazardous processes (Cappabianca et al. 2008), vulnerability (Fuchs 2010) or elements at risk exposed (Fuchs et al. 2004; Keiler et al. 2006; Zischg et al. 2005b). The numerical combination of magnitude, frequency and consequences assumes equal weight for the hazard component, the vulnerability and the elements at risk. Consequently, mathematically no difference is made between high-consequence/low-probability and low-consequence/high-probability events, whereas people show distinct preferences for one or the other (Slovic 1987; Myagkov et al. 2003).

So far, mainly static risk concepts were developed and applied with respect to mountain hazards (e.g. Jónasson et al. 1999; Keylock et al. 1999; Bell and Glade 2004), neglecting any past risk levels and the history of evolution to the current situation under consideration as well as possible future risk levels. As a result, considerable gaps with respect to a possible adaptation of the risk concept applied in natural sciences and integrated risk management approaches remain open: Risk related to natural hazards is subject to spatiotemporal changes since the risk-influencing factors are variable over time and they interact within space. Therefore, reviews and studies focused on identifying, analysing and modelling the spatiotemporal development of hazard processes, elements at risk and vulnerability are needed in order to provide information of short- as well as long-term changes of risk, and to better understand the underlying risk pattern. The implication of these needs regarding risk dynamics on multiple spatial and temporal scales to integrated risk management is discussed in the following sections.

4 The temporal dimension

According to the concept of risk, the temporal dimension to be considered includes process dynamics of mountain hazards, that is, related to the most important triggering factors and dynamics of the elements at risk exposed.

4.1 Temporal dynamics of mountain hazards

The main objective of hazard analysis is to identify and characterise potential processes together with an evaluation of their corresponding frequency of occurrence and magnitude (Fuchs et al. 2008). The qualitative identification of hazard processes requires an understanding of triggering mechanisms in relationship to the process characteristics, that is, the relationship between geomorphology, hydrogeology, geology, failure mechanics, climate conditions and vegetation cover (e.g. Fell et al. 2008). However, with respect to mountain hazards, the probability of the event itself is often not quantifiable due to a lack of measurement data resulting from the complexity between cause and effect (e.g. Föhn and Meister (1981), Fuchs and McAlpin (2005) for snow avalanches and Innes (1985), Zimmermann et al. (1997), Helsen et al. (2002) for torrent processes; an overall framework is provided by the early seminal article of Wolman and Miller (1960)). Consequently, the probability of the main triggering mechanism (e.g. recurrence interval of meteorological phenomena) or the probability to reach a defined point during run-out in the deposition area is used as a proxy instead, which results in considerable uncertainties of the hazard assessment (Mazzorana et al. 2009). Historical data appear to be particularly important for establishing frequency–magnitude relationships (Innes 1985; van Steijn 1996; Zimmermann et al. 1997; Crozier and Glade 1999; Brunsden 2002); especially with respect to torrent processes (but principally also with respect to other mountain hazards such as snow avalanches), the major problem related to the establishment of frequency–magnitude relationships is the inherent complexity of the system. At the watershed scale, the magnitude of channel-based hazard processes is often expressed by the measured geomorphic features, such as potential debris volume, mean flow velocity, peak discharge and run-out distance (Fuchs et al. 2008), while the frequency is assessed by either event documentations or taking external system triggers such as precipitation measurements as a proxy. In doing so, connectivity is assumed and therefore empirical and semi-empirical equations, supplemented by dynamic (often numerical) simulation models, are considered to assess the process properties and the depositional behaviour. However, the conversion of, for example, precipitation intensities into frequencies used as a proxy for the probability of occurrence of process magnitudes is highly dependent on temporal changes in the precipitation regime (e.g. Auer et al. 2007; Keiler et al. 2010).

Climate and environmental changes are being increasingly identified in the European mountain regions (e.g. Field et al. 2012), which affects the activity of natural hazards. Taking the European Alps as an example, temperature changes have increased twice as much as the global average since the late nineteenth century (Auer et al. 2007). Furthermore, precipitation has also changed nonlinearly, with significant regional and seasonal dynamics as well as differences by elevation and aspect (Haeberli et al. 2007, Brunetti et al. 2009). Resulting changes in snow and rainfall have implications for snow cover thickness and duration (which also affect subsurface temperatures) and catchment runoff (Beniston 2003). Furthermore, temperature and precipitation changes can also be linked to changes in glacier mass balance and terminus position, in particular at high elevations (Zemp et al. 2006, Lambrecht and Kuhn 2007, Steiner et al. 2008). Permafrost monitoring sites throughout the Alps also show changes in alpine permafrost distribution, temperature profiles and active layer thickness (Harris et al. 2003; Luetschg et al. 2008). While the direct effects of the changing hydroclimate on these systems have now been monitored for several decades (Huggel et al. 2012), the indirect effects on geomorphological processes and on sedimentary systems are less well known.

Furthermore, in particular, the effects of temporally changing channel morphology and associated erosion phenomena were found to amplify process intensities considerably, which is not taken into account sufficiently by the respective models (Keiler 2011; Keiler et al. 2012). Hence, the established relationship between process magnitude and frequency is only a rough approximation and has to be evaluated carefully with respect to temporal dynamics (Keiler 2011; Mazzorana et al. 2012). Such dynamics are usually addressed through sensitivity analysis or conservative parameter estimation, which in turn results in increased ranges of the results of risk analyses. Geomorphological processes in high-relief areas are strongly influenced by various interacting factors, for example, slope angle and aspect, weathering, sediment availability, slope moisture supply and land cover. These processes evolve in a downslope direction, leading to high temporal variability in the process domain and thus in hazard probabilities. Moreover, changes in cryospheric systems can give rise to downstream interconnected geomorphological impacts such as hazard events that represent periods of decreased land surface stability (Stoffel and Beniston 2006).

Hazard analyses include future possible scenarios and provide a basis for sustainable land-use and risk management; therefore, also factors of global change have to be considered. Future climate change can be predicted by global climate models, but downscaled results from different scenarios highlight regional uncertainty in these predictions (e.g. Wanner et al. 2006, Reichler and Kim 2008), especially of the effects in high-relief regions (Calanca et al. 2006). Nevertheless, the modelled predictions of future climate change in the European Alps, including spatial and temporal patterns of temperature and precipitation anomalies relative to present conditions, suggest rising mean values in temperature with a higher expected increase in summer and autumn and a corresponding increase in precipitation intensities (Auer et al. 2007); the latter may result in a seasonal shift of mean and extreme precipitation values, with more spring and autumn heavy precipitation events than at present, and fewer in summer (Beniston 2006). As a result, magnitude and frequency will most probably slightly increase in the case of those hazard processes where water is a main trigger.

However, there is considerable temporal variation in response within catchments, including changes in sediment erosion rates, deposition and flood extension, both across mountain regions as a whole and within individual catchments, including the transition from headwaters to immediately adjacent alpine valleys (Keiler et al. 2010) and foreland rivers (Semenov 2011). Antecedent conditions may be less important in flashy, upland catchments, but response is strongly modified by catchment relief and sediment availability which have potential to inhibit downstream water and sediment transport (Keiler et al. 2010).

Consequently, subsequent risk reduction measures will not necessarily provide the most efficient management strategy, and therefore, the implemented solutions will only be suboptimal (Fuchs et al. 2007a). In order to improve risk analyses and to support decision making, underlying scenarios have to be re-defined based on these issues, in particular with respect to temporal aspects affecting the predictability of hazardous phenomena. So far, the (heuristically gained) information available on process magnitudes which occurred in the past is often the most reliable indication (Rickenmann 1999).

4.2 Temporal dynamics of elements at risk exposed

Socio-economic developments in the human-made environment have led to an asset concentration over time and a shift in urban and suburban population in the many mountain regions. Thus, the temporal variability of elements at risk is an important key variable in the assessment of risk.

Recently, conceptual studies related to the temporal variability of elements exposed to mountain hazards have been carried out, with respect to both the long-term and the short-term evolution of indicators (Fuchs et al. 2005; Keiler et al. 2005, 2006). Long-term changes are rooted in the significant increase in numbers and values of buildings endangered by natural hazard processes and can be observed in both rural and urban areas in mountain regions of Europe (Fuchs et al. 2005; Keiler et al. 2006) and the Russian Federation (Shnyparkov et al. 2012). Short-term fluctuations in values at risk supplemented the underlying long-term trend, in particular with respect to temporary variations of persons and of vehicles on the road network (Fuchs and Bründl 2005; Keiler et al. 2005; Zischg et al. 2005a, b). By implementing a quantifying fluctuation model, it was shown that strong variations could be observed during the winter season for mountain resorts as well as over daytime (Keiler et al. 2005).

If the elements at risk on traffic corridors are considered, temporal short-term variability becomes obvious: The number of persons or the freight traffic potentially affected by mountain hazards is subject to high fluctuations on different temporary scales. As a consequence, risk (resulting from the respective average daily traffic during the period of investigation, the mean number of passengers per car and the mean value of good being transported, the speed of the vehicles crossing the endangered sections of the traffic corridor, their mean widths, and the probability of death in vehicles, Kristensen et al. 2003; Zischg et al. 2005a; Vikulina and Shnyparkov 2006; Hendrikx and Owens 2008) is variable with a high temporal resolution.

To provide an example, in Fig. 2a, an analysis of daily traffic in 2010 is shown for the main access road to the community of Davos, Switzerland (Wolfgang pass). The annual curve shows for both the daily and the weekly data, two minima in April and May as well as in October and November, and the maxima occurred during the summer months (July and August) as well as during the winter months (November and December). In particular for the months of January and February, a considerable weekly peak is detectable during the weekend, when a large amount of tourists is using this connection to access the ski resorts. In contrast, in Fig. 2b, the mean daily traffic is shown for a road connecting the city centre of Kirovsk, Russian Federation, with the mining facilities in the region. Since the mining industry is operating on a 24/7 basis, particular differences in traffic quantities are observable in accordance with the shift schedule of the mining company: While the overall traffic during night is considerably below the daytime traffic, in the early morning, shortly after noon and in the early evening, traffic peaks are apparent.

If elements at risk such as buildings are considered, the long-term variability becomes evident: Based on a model to quantify the long-term evolution of the built environment, Fuchs and Keiler (2008) reported a significant increase in the number and value of elements at risk exposed. In both urban and rural test sites of the European Alps, the total number of buildings exposed to snow avalanches had almost tripled since the 1950s, and the total value rose by a factor of almost four. The proportional increase in the value of buildings was significantly higher than the proportional increase in the number of buildings. Buildings inside hazard-prone areas showed a lower average value as buildings outside those areas. A major part of this increase was found within the category of

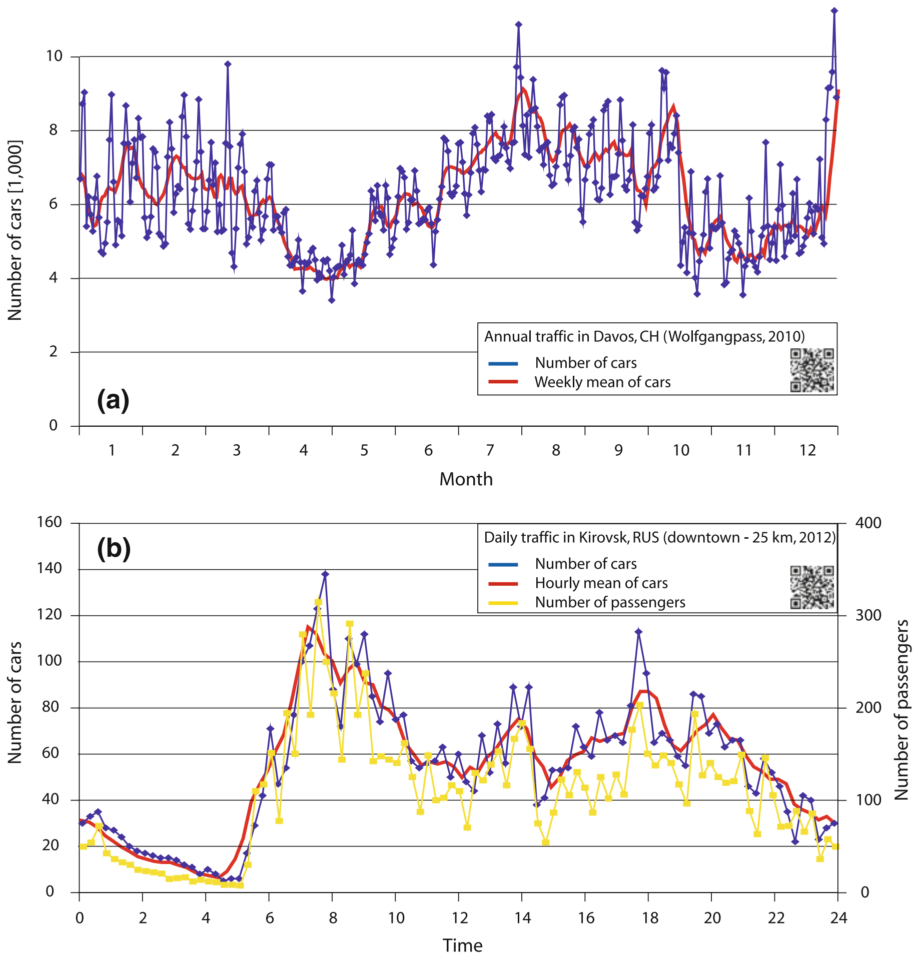


Fig. 2 Variability of elements at risk exposed on traffic corridors. Variability of daily traffic in 2010 for an alpine main access road (**a** *data source*: Tiefbauamt Graubünden 2011) and variability of the hourly traffic on a diurnal basis in 2012 for a major road connection in the Khibiny mountains, Russian Federation (**b**)

residential buildings: In 1950, the proportion of residential buildings was less than 15 %, compared with the total amount of endangered buildings. By 2000, this ratio had changed to almost 50 %. Regarding the category of hotels and guest houses as well as the category of special risks, nearly no increase in value could be observed. However, those categories showed a higher average value per building than residential buildings. The number of endangered persons increased substantially between 1950 and 2000. The increase in residential population was about 60 %, while the increase in temporal population and tourists was a factor of ten (Fuchs et al. 2005; Keiler et al. 2006).

Both long-term and short-term temporal changes of elements at risk exposed contribute considerably to the risk level and should, therefore, be included in operational risk analyses.

5 The spatial dimension

Here, the concept of space refers to places where hazards are located, their distribution and regional patterns. Due to human–environment interaction (Turner II 2002), the concept of space is inseparably bound to human actions within a region or an area and is linked to any spatial development activity. Hence, a sustainable use of mountain areas is obliged to include spatial aspects in the assessment and management of natural hazard risk due to the relative scarceness of areas suitable for development activities.

Taking countries in the European Alps and the Russian Federation as an example, only 38.7 % of the territory is suitable for such purposes in the Republic of Austria (Statistik Austria 2008). In Switzerland, 26 % of the territory is classified as non-productive, and approximately 68 % is suitable for agriculture and forestry purposes; only around 7 % is suitable for settlement and infrastructure purposes (Hotz and Weibel 2005). According to EMERCOM (2004), approximately 10 % of the Russian territory with an average population density of 8.3 persons/km^2 is prone to mountain hazards, which indicates the need for a spatially based approach in risk analysis.

The historical shift of a traditionally agricultural society to a post-modern service-based society is reflected by an increasing usage of mountain areas for human settlement, industry and recreation. Due to population dynamics and economic transformation processes, an increase in people at risk and assets exposed is traceable. Accordingly, a conflict between human requirements on the one hand and naturally determined conditions on the other hand is observable. This conflict is particularly noticeable with respect to agglomerations along the larger valleys of the European Alps and in the Alpine foreland (Bätzing 2002; Fuchs and Bründl 2005), but also in the growing region of Sochi in the Caucasus (i.e. Krasnaya Polyana due to the construction boom caused by the Winter Olympics 2014). As a consequence, an increasing number of persons are exposed to natural processes, which are considered as natural hazards when they are likely to cause harm to human life or property.

However, the challenge of spatiality in dealing with natural hazard risk in mountain regions is not a new one as can be shown for the Republic of Austria as an example of a densely populated mountain region in Europe.

In the Republic of Austria, strategies to prevent or to reduce adverse effects of natural hazards in areas used for settlement and economic purpose can be traced back to the Middle Ages. Official authorities were only founded in 1884, based on the first legal regulations (Österreichisch-Ungarische Monarchie 1884). In the second half of the nineteenth century and in the early twentieth century, protection against natural hazards mainly consisted of implementing permanent measures in the upper parts of the torrent catchments to retain solids from erosion, as well as in the release areas of avalanches. These measures were supplemented by afforestation efforts at high altitudes. Since the 1950s, such conventional mitigation concepts, which were aimed at decreasing both the magnitude and the frequency of events, were increasingly complemented by more sophisticated technical mitigation measures. Before the 1970s, mitigation concepts were mainly aimed at the deflection of hazard processes into uninhabited areas, and watershed management measures as well as technical measures were implemented (Holub and Fuchs 2009). However, due to the increasing spatial needs associated with land-use activities (Holub and Fuchs 2008), passive mitigation was introduced in the 1970s, that is, hazard zoning in the context of spatial planning (for technical details, see "Appendix"). The overall aim of such passive prevention measures is to reduce losses without directly influencing the process by a spatial separation of process trajectories and values at risk.

Such a separation, which has been laid down in the respective legal framework in many Alpine countries (Schweizerische Eidgenossenschaft 1991; Republik Österreich 1975, 1976; Repubblica Italiana 1998), is based on the approach of separating areas that are by definition safe from those areas that are endangered. This separation is undertaken by using the spatial approach of a so-called design event with a defined frequency and magnitude. This approach refers to institutional and therefore collective efforts to translate public expenditures into priorities for area investment and according to principles of land-use regulation. As a result, there is a need for dividing space (defined as any location in first approximation) by distinct boundaries which have to be identified in terms of hazard characteristics, and to analyse how development sites are positioned in relation to the identified hazard threats. Position is here not defined as a geographical point, but in terms of the spatial characteristics of the built environment, such as the distance of elements at risk from the impact pressure threshold of the design event. By the normatively formalised act of delineating hazard zones, a spatial distinction is made between those areas that are—per legal definition—at risk and areas that are safe and therefore suitable for development activities (Keiler and Fuchs 2010). As a result, a difference is recognised between the acts of accumulating geographical facts and representing the spatial form embedded in these facts, and understanding the processes involved in analysing these facts (Golledge 2002): By intersecting the defined hazardous areas with values at risk, new information (on risk) is produced that is not directly a result of data mining.

6 Discussion

The evolution of risk due to socio-economic transformation, but also due to changes in the frequency and magnitude of processes varies remarkably on different temporal and spatial scales. Long-term changes are superimposed by short-term fluctuations, and both have to be considered when evaluating risk resulting from mountain hazards.

Long-term changes in risk could be regarded as the basic disposition (Fig. 3). To reduce the risk resulting from this basic disposition, permanent constructive mitigation measures and land-use regulations could be implemented. As a consequence, the basic risk may be reduced due to a spatial reduction in the run-out area. An example for such a development is reported by Fuchs et al. (2004) for an urban study area, where the risk has decreased fundamentally since the 1950s, even if the values at risk in the municipality have increased. This development was mainly attributed to the construction of permanent mitigation measures and was strongly related to immobile values. Similar results were obtained for rural study areas (Keiler et al. 2006). However, extraordinary losses can be estimated if rare events with severe effects occur, because the delimitation of the respective run-out areas is based on defined design events. Short-term fluctuations in risk supplement this continuing development within a specific range. Thus, they can be considered as the variable disposition. To mitigate these fluctuations, temporal measures can be applied, such as evacuations or temporary road closures.

Long-term as well as short-term dynamics should be integrated into risk management approaches. In Fig. 3a, the significance of this for a consideration of dynamics in basic (long-term) as well as variable (short-term) risk is presented. As shown in example (a) for the period of time t_n, the event will not affect any values at risk, and thus, the level of risk reduction is sufficient. In example (b) for the period of time t_{n+1}, due to high number of variable values at risk, damage will occur even if the event magnitude is lower compared with event (a). As a result, passive and temporal mitigation strategies such as evacuation or

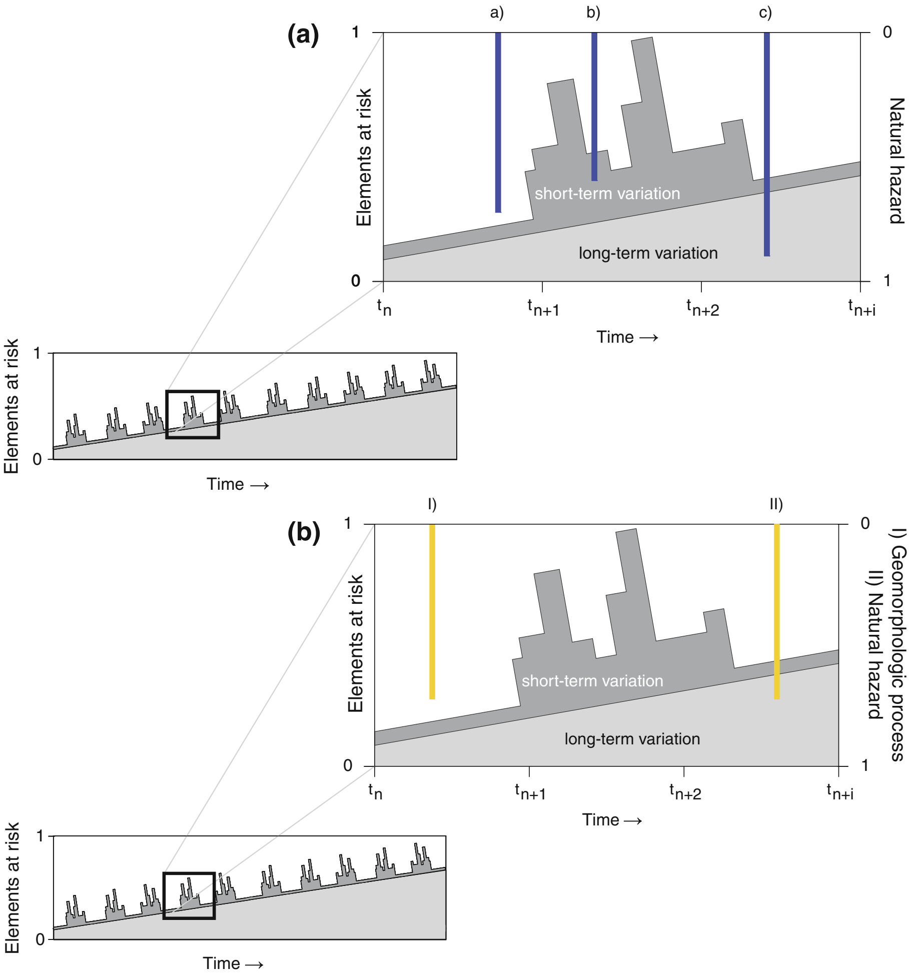


Fig. 3 The concept of basic (long-term) and variable (short-term) evolution of risk resulting from natural hazards given a dynamic process magnitude (**a**). The concept of basic (long-term) and variable (short-term) evolution of risk resulting from natural hazards given dynamics in elements at risk exposed and assuming a steady-state process magnitude (**b**)

road closures could reduce the variable risk to a critical level. In example (c) for the period of time $t_{n+2\ldots i}$, basic and variable risk are affected by a process due to the larger event magnitude. Thus, temporal measures are no longer sufficient for effective risk reduction. Consequently, active and permanent measures have to be undertaken. These examples clearly indicate the strong need for incorporation of dynamic assessments of risk in community risk management strategies.

Apart from these issues directly applicable in operational risk management, the multi-temporal evolution of risk results in significant institutional demands (Fig. 3b). In a certain period of time t_n, a natural event will not cause any losses since the run-out area of the respective design event does not overlap with elements at risk (example (I)); therefore, it is considered as geomorphological process. Due to the evolution of elements at risk, the geomorphological process with similar magnitude will be transformed into a hazard, since elements losses occur due to the increase in values at risk associated with a spatial expansion of elements at risk (example (II) for the period of time $t_{n+2\ldots i}$). The importance of considering such developments has recently been stated by Fuchs et al. (2004, 2005) and Keiler et al. (2005, 2006) for alpine settlements and is of particular importance with respect to the different temporal dimensions in land-use planning practices, as well as with respect to the discussion on climate change and possible variations in the frequency–magnitude relationship of events. These issues pose a challenge not only from a scientific point of view, but also in particular for those institutions and practitioners responsible for planning, since variable risk management strategies taking into account this temporal and associated spatial evolution will become necessary. Until now, a substantial diversity of interpretation is detectable with respect to the consideration of risk management strategies in the spatial planning processes in different European countries. Since regulations related to regional planning and development include—besides the prevention against the adverse effects of natural hazards—several other aims, multiple interests in utilisation and possibilities of development are confronted with the need to protect settlements and infrastructure against possible losses resulting from hazard processes. Hence, a conflict of objectives is inevitable, and the consideration of dynamics in all spatial planning activities would be a purposeful tool to convert prevention into action.

7 Conclusion

Despite the efforts from both the scientific and the practitioner's side, losses due to mountain hazards still pose a threat to communities exposed, as it was exemplified by data from the European Alps and the Russian Federation. In both regions, major losses are associated with an increase in land-use, population density and economic activities, which shows the need for a consideration of these aspects in natural hazard management. During the last decades, the management of natural hazards was shifted from a process-based approach focusing on conventional technical measures—which were targeted at decreasing either the frequency or the magnitude of an event—towards the concept of risk which allows for an assessment of the effects of hazards on the anthroposphere and their impact on the built environment. The concept of risk has proven as being a valuable instrument to reduce the susceptibility of buildings and infrastructure to natural hazards (e.g. Fuchs et al. 2004; Keiler 2004; Kienholz et al. 2004; Zischg et al. 2004) and thus to reduce losses. The concept of risk is used to measure the probability and severity of an adverse effect on the society and is quantified by a function of probability of a phenomenon of a given magnitude times the consequences. Based on this concept, tailored strategies for a sustainable use of mountain areas for settlement, economic purpose and recreation can be developed.

However, in practice, the concept of risk is regularly applied taking a static viewpoint, while losses are the predictable result of interactions between three major dynamic systems: The physical environment, which includes hazardous events; the social and demographic characteristics of the communities that experience them; and the elements at risk such as buildings, roads and other components of the built environment.

Even if research on mountain hazards has a long tradition, above all in engineering sciences (e.g. Schuster 1996; Glade et al. 2005; Bründl et al. 2010), there is a lack of studies related to the spatiotemporal development of risk (Fuchs and Keiler 2008), and the underlying vulnerability of values at risk and of communities (Fuchs 2008; Fuchs et al. 2011; Papathoma-Köhle et al. 2011). Recently, these shortcomings have been addressed focusing either on process dynamics (e.g. Keiler (2011) with respect to climate change or

Fuchs et al. (2007b) with respect to the implementation of technical mitigation measures) or on dynamics of elements at risk exposed (Fuchs et al. 2005, 2012; Zischg et al. 2005a; Keiler et al. 2006).

It has been argued in the previous sections that an extension of the risk approach towards such dynamics is necessary due to the inherent temporal and spatial dynamics. It has been shown how these dynamics influence the risk level, and a model of the multi-temporal and spatial assessment has been discussed.

The identification of dynamics in natural hazard risk, as well as the underlying processes, contributes to an improved understanding of present-day risk levels and allows to consider the different aspects of risk evolution for a future sustainable risk management. To meet these challenges, a research focus should be put on the complexity resulting from interactions and moreover, on the development of innovative approaches that allow to integrate multi-temporal and multi-scale interactions within risk analyses. Though, multi-temporal and multi-scale interactions cannot be treated separately since they are interwoven and correspond to each other. Furthermore, changes may propagate through different scales resulting in a multi-temporal co-evolution which pose several challenges for a dynamical risk analysis.

The spatiotemporal quantification of risk, as well as a subsequently tailored risk management strategy, promotes from a conceptual point of view questions linked to sustainable development in mountain environments. Potentials and limitations which may occur due to mountain hazards under global change conditions, driven by both climate change and socio-economic development, may not be foreseen definitely and contain many aspects of uncertainty. As these uncertainties refer to aspects of magnitude–frequency, probability of occurrence and vulnerability versus resilience, the concept of risk is becoming increasingly important. The concept of risk provides information on such uncertainties, and by means of risk management plans, a decision basis for multiple stakeholders involved could be established. Such management plans are foreseen by the Commission of the European Communities (2007) until 2015. They should provide tailored solutions according to the needs and mitigation priorities of the areas covered, and focus on prevention, protection and preparedness. In order to have available an effective and target-oriented tool for information and communication (Fuchs et al. 2009; Meyer et al. 2012), as well as a valuable basis for priority setting and further technical, financial and political decisions regarding the management of negative effects resulting from the impact of hazardous events, a dynamic concept of risk is indispensable.

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Appendix

In the Republic of Austria, the legal prescriptions for delimiting hazard zones are regulated by a national 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) and by the Federal Water Engineering Administration.

In § 8b of the Forest Act of 1975, the delimitation of hazard zones in catchment areas prone to natural hazards such as torrential floods or avalanches is prescribed. In § 11, the compilation of hazard maps and the involvement of communes and population are regularised. The contents and designs of these maps are specified by the decree associated to the Forest Act (Republik Österreich 1976). According to § 5 (2) of this Decree on Hazard Zoning, all available data and information on natural hazards as well as interactions between individual hazard processes have to be considered during the compilation of hazard maps. Furthermore, interferences with the human environment, such as infrastructure facilities and settlements, have to be taken into account.

Hazard maps are typically based on the area of an individual community and should be compiled in a reproducible manner to allow for validation during the approval process by the Federal Ministry of Agriculture, Forestry, Environment and Water Management.

Hazard maps are based on a design event with a return period of 1 in 150 years, and an event occurring more frequently with a return period of approximately 1 in 10 years (Republik Österreich 1976). In § 6 of the Decree on Hazard Zoning, the criteria for delimitation of hazard zones are prescribed. According to these prescriptions, red hazard zones indicate those areas where the permanent utilisation for settlement and traffic purposes is not possible or only possible with extraordinary efforts for mitigation measures, whereas detailed economical figures of such efforts are not given. Yellow hazard zones indicate those areas where a permanent utilisation for settlement and traffic purposes is impaired by hazard processes. Furthermore, specific other areas have to be displayed in the hazard maps: (1) Blue colours mark areas to be provided for future mitigation measures, (2) brown colours indicate areas affected by land slides and rock fall and (3) purple colours indicate areas that can be used as protection due to their natural properties, such as protection forests or natural retention basins.

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