QUANTITATIVE VULNERABILITY FUNCTIONS FOR USE IN MOUNTAIN HAZARD RISK MANAGEMENT

THE CHALLENGE OF TRANSFER

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ABSTRACT

In natural hazards research, risk is defined as a function of (1) the probability of occurrence of a hazardous process, and (2) the assessment of the related extent of damage, defined by the value of elements at risk exposed and their physical vulnerability. Until now, various works have been undertaken to determine vulnerability values for objects exposed to torrent processes. Yet, many studies only provide rough estimates for vulnerability values based on proxies for process intensities. However, the deduced vulnerability functions proposed in the literature show a high range, in particular with respect to medium and high process intensities. In our study, we compare vulnerability functions for torrent processes derived from studies in test sites located in the Austrian Alps and in Taiwan. Based on this comparison we address challenges for future research in order to enhance mountain hazard risk management with a particular focus on vulnerability on a catchment scale.

Keywords: Vulnerability, torrents, risk management, loss, Taiwan, Austria

INTRODUCTION

Major losses (world-wide, Keiler in press, as well as on the European level, Hübl et al. 2011) in mountain areas are associated with torrent events. The term torrent refers to steep rivers within a mountainous environment. Torrents are defined as constantly or temporarily flowing watercourses with strongly changing perennial or intermittent discharge and flow conditions (Aulitzky 1980; ONR 2009), originating within small catchment areas (Slaymaker 1988). At the outlet of these watersheds, torrent fans are developed which are used for settlement purpose since the beginning of the historical colonisation and commodification of the landscape. Therefore, torrent events are a main challenge for society in many countries, in particular due to the spatial overlap of these settlements with the potential deposition area in periods of extraordinary discharge.

The concept of risk has been introduced in natural hazard management since experiences from past years suggested that elements at risk and vulnerability should be increasingly considered within the framework of hazard management in order to reduce losses (e.g., Commission of the European Communities 2007; International Standards Organisation 2009). Following the axiom that natural hazard risk is a function of hazard and consequences, the ability to determine vulnerability quantitatively is an essential prerequisite for reducing these consequences and therefore natural hazard risk.

However, the review of the concept of risk for mountain areas resulted in gaps concerning appropriate tools for the assessment of vulnerability of elements at risk and of communities exposed (Papathoma-Köhle et al. 2011). To overcome these shortcomings, studies on vulnerability have been undertaken aiming at (1) the methodological development of loss functions with respect to buildings located in the run-out areas of torrent processes (Fuchs et al. 2007; Akbas et al. 2009; Tsao et al. 2010; Quan Luna et al. 2011; Totschnig et al. 2011); and (2) the conceptualisation of an overarching vulnerability

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model including structural, economic, social and institutional vulnerability (Fuchs 2009). Apart from Tsao et al. (2010), whose work was related on the mountain areas of Taiwan (Republic of China), these studies were all focused on the quantification of vulnerability in the context of the European Alps. With the exception of Quana Luna et al. (2011), who used a numerical debris flow model to obtain vulnerability curves, these studies were rooted in an ex-post assessment of the event magnitude or intensity, the height of loss and the reinstatement value of the buildings at risk in order to obtain a damage ratio. By combining these three factors, vulnerability curves were deduced for both, debris flows (Fuchs et al. 2007; Akbas et al. 2009; Tsao et al. 2010) and fluvial sediment transport (Totschnig et al. 2011).
When comparing the results of those studies undertaken in the European Alps with the data assessed in Taiwan, considerable differences and methodological issues arise even if the authors claimed a universal applicability of their studies on mountain areas with a comparable environment. These aspects will be discussed in the following sections in order to provide an outlook of the challenges that come up when a method developed within the specific setting in one mountain region is transferred to another region of the world with a slightly different setting. The aim is to highlight possible pitfalls and shortcomings in order to contribute to the ongoing discussion on vulnerability to torrent events in mountain areas; therefore, (1) possible aspects of physical vulnerability will be discussed but also (2) the wider implications with respect to social vulnerability.

METHOD: QUANTIFICATION OF VULNERABILITY

The assessment of vulnerability requires an ability to both identify and understand the susceptibility of elements at risk and – in a broader sense – of the society to these hazards (Birkmann 2006). Studies related to vulnerability of human and natural systems to mountain hazards, and of the ability of these systems to adapt to changes in the functional chain of hazards, are a relatively recent field of research that brings together experts from a wide range of disciplines, including natural science, social science, disaster management, policy development and economics, to name only a few. Researchers from these fields bring their own conceptual models to study vulnerability and adaptation, models which often address similar problems and processes using different languages (Brooks 2003). However, apart from the overall discussion on linguistic placements and semantic dimensions of the term (Cutter 1996, 2003; Alexander 2005), vulnerability in the context of mountain natural hazards is, from a practitioner's side, such as the *Austrian Torrent and Avalanche Control Service* or the *Soil and Water Conservation Bureau* in Taiwan, usually defined as the physical impact of hazardous events on elements at risk. Accordingly, if quantitatively assessed, vulnerability is defined as the expected degree of loss for an element at risk due to the impact of a defined hazardous event within a defined period of time and a defined location. These events are themselves conditioned by a certain intensity, frequency and duration, all of which affect vulnerability. From this technical point of view, as a general rule, vulnerability assessment is based on the evaluation of parameters and factors such as building categories or types, construction materials and techniques, state of maintenance, presence of protection structures, and presence of warning systems (Fell et al. 2008). Nevertheless, many of these factors are usually not assessed, above all due to limitations in the assessment method and due to practical limitations of feasibility (Kappes et al. 2012). For this reason, vulnerability values are used to describe the susceptibility of elements at risk to damage, which is conceptualised by a damage ratio between loss and the value of affected elements at risk, facing different process types with different spatial and temporal distributions of process intensities (e.g., flow depths, accumulation heights, flow velocities and pressures).
The overall framework of the method applied is outlined in Fig. 1. The damage ratio is quantified using an economic approach by establishing a ratio between the loss and the reconstruction value of every individual element at risk exposed, if data on incurring losses is available (Austrian case study, compare Fuchs et al. 2007). Alternatively, a synthetic approach of loss assessment may be used by using e.g. averaged damage values empirically derived (Taiwanese case study, compare Lo et al. in press). In a second set of calculations, this ratio obtained for every individual element at risk is linked to the respective process intensities which are regularly documented ex-post by the respective authorities or their subcontractors. Otherwise, if such data is not available, process intensities may

result from modelling approaches. For such assessment information on the elements at risk exposed on the individual torrent fans is necessary, as well as data on the process intensities for the particular hazardous events. As a result, scatterplots can be developed linking process intensities to object vulnerability values (Fuchs et al. 2007). These data can be analysed using regression approaches in order to develop vulnerability functions which serve as a proxy for the structural resistance of buildings with respect to fluvial sediment transport processes or debris flows on the studied torrent fans.

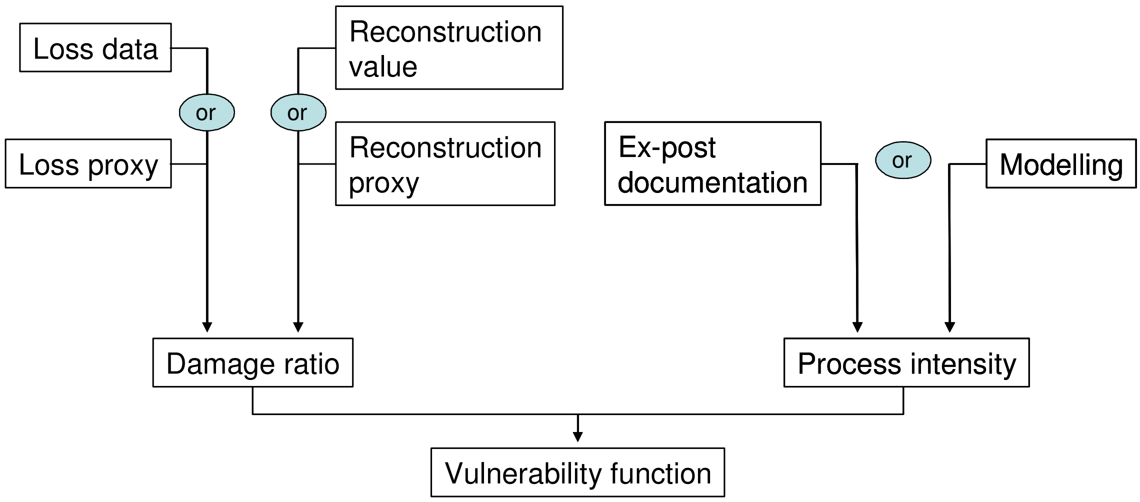

Fig. 1 Framework for the deduction of vulnerability functions for torrent events.

RESULTS FROM AUSTRIAN TEST SITES

Taking fluvial sediment transport as an example, Totschnig et al. (2011) presented a vulnerability function which was deduced from three well-documented events in the Austrian Alps. These events were triggered by extraordinary rainfall events and characterised by the mobilisation of high amounts of bedload leading to considerable damage to the settlements located on the torrent fans (Fuchs et al. in press). In total, 116 buildings were damaged in the three test sites, 67 of which were residential buildings and included in their study. The total damage of the considered houses amounted to approximately € 5.5 million while the individual loss was between € 438 and € 828,240. Because of different building sizes, the reconstruction values showed a wide range from about € 221,000 to € 1.34 million. These variations lead to individual vulnerabilities ranging from 0.001 to 1.0, whereas the mean vulnerability per exposed building was equal to 0.168. In Tab. 1, damage and property values, the range of vulnerability, and the mean vulnerability per exposed residential building for the individual test sites is shown.

Tab. 1 Number of buildings included in the study, reported loss, property value, range of vulnerability, and mean vulnerability for each test site in the Austrian Alps.

Test site (event)	Number of buildings [N]	Reported loss [€]	Property value [€]	Range in vulnerability	Mean vulnerability
Stubenbach (2005)	28	4,851,800	13,483,267	0.013-1.000	0.369
Schnannerbach (2005)	10	403,700	6,444,471	0.005-0.131	0.045
Vorderbergerbach (2003)	29	260,509	17,629,091	0.001-0.045	0.015

In Fig. 2 the resulting vulnerability curve is shown, based on absolute deposition heights as a proxy for process intensities in the affected area. The process intensity is plotted on the abscissa and the damage ratio is plotted on the ordinate. In general, vulnerability increases with increasing intensity. For low process intensities ($I < 1$ m) all distributions show a slow increase in vulnerability. For medium process intensities ($1 \text{ m} \leq I \leq 2.5$ m) the highest rate of increase in vulnerability is observed, following an almost linear shape. For high process intensities ($I > 2.5$ m) the observed rate of increase in vulnerability again decreases and the curves converge towards 1. Due to these specific shapes, the effect of an increase in process intensity is different in all three sections of these curves; an increase in process intensity of 0.5 m causes as such more additional damage at medium process intensities if compared to low and high intensities. For the process intensity of 1.0 m to 1.5 m, the statistical spread of the vulnerability values is considerable, which can be attributed to a possible intrusion of material through building openings (Fuchs et al. 2007). The best-fitting function to describe the range in the analysed data (highest value of utility) is a modified Weibull distribution (Totschnig et al. 2011), which is highlighted in Fig. 2 by a bold graph.

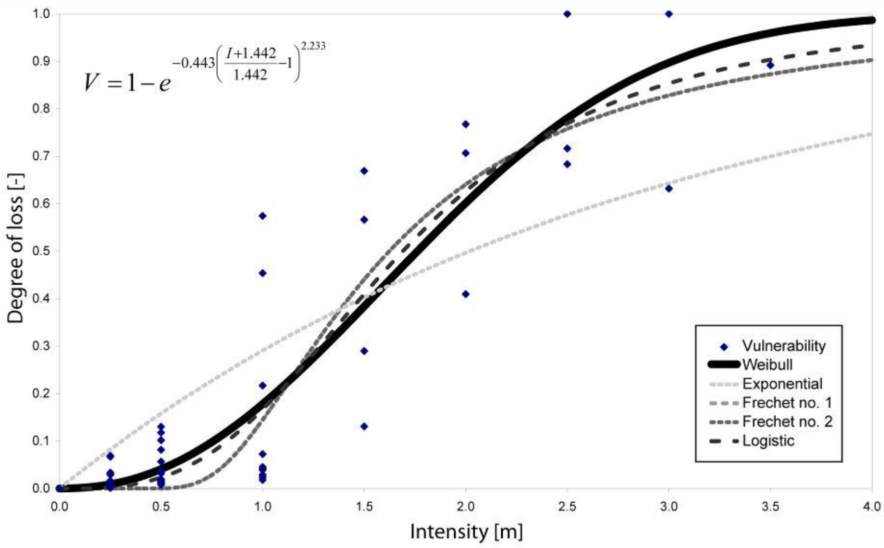

Fig. 2 Different vulnerability functions for residential buildings based on deposition height as a proxy for the process intensity. Vulnerability values originating from the study sites are indicated by dots. The best-fitting function to describe the range in the analysed data (highest value of utility; Weibull) is highlighted in bold, and is provided in terms of the mathematical notation (V = degree of loss, I = intensity, modified from Totschnig et al., 2011).

Physical susceptibility of elements at risk and thus vulnerability is strongly dependent on the construction material used. The developed vulnerability function is applicable to buildings which are constructed by using brick masonry and concrete, a typical design in post-1950s building craft in Alpine countries. Consequently, the adjusted function is applicable to this mixed construction type.

RESULTS FROM TEST SITES IN TAIWAN

Data from six counties were used in order to apply the method in mountain areas of Taiwan, almost all of them from torrent events that occurred as a result from one typhoon event. On 7 August 2009, typhoon Morakot hit Taiwan, resulting in more than 600 dead and approximately 70 missing persons, a temporary evacuation of almost 25,000 residents, and around € 3.6 billion economic loss (Central Emergency Operation Center 2009). For 39 buildings, the process intensity and the loss was recorded after the event with sufficient accuracy, these buildings with a damage ratio between 0.05 and 1.0 were included in our analysis (Tab. 2).

Tab. 2 Construction material, number of buildings considered, range in process intensity, range of vulnerability, and mean vulnerability for each construction type in the test sites in Taiwan.

Construction material	Number of buildings [N]	Range in process intensity [m]	Range in vulnerability	Mean vulnerability
Wood	3	1.0-3.0	-	1.00
Sheet metal	4	1.0-2.0	0.05-1.00	0.76
Brick	16	1.0-3.5	0.05-1.00	0.71
Reinforced brick	10	1.5-4.0	0.10-1.00	0.63
Reinforced concrete	6	1.6-5.0	0.20-1.00	0.73

The best fitting function was again a Weibull function, however, with a very low coefficient of determination ($R^2 = 0.172$). This is due to the wide range in process intensities observed (1.0-5.0 m),

which are clearly above intensities usually observed in European mountain regions. As a result, the mean vulnerability is also considerably higher than the mean values reported in Tab. 1 for the Austrian test sites. To give an example, four out of six buildings composed from reinforced concrete were affected a process intensities between 3.0 m and 5.0 m which obviously results in a high degree of loss and therefore also in a comparatively high mean vulnerability. Moreover, the study involved buildings with different construction material used, and therefore the resistance towards the impact of torrent processes is considerably different.
During the field work, 13 buildings were assessed with a process intensity between 1.0 and 2.0 m and a damage ratio of 100 %, which seems to be high compared to data presented for the European Alps (due to overlap only six data points are visible in Fig. 3). These buildings were composed from brick (7 buildings), wood (2 buildings), sheet-metal (3 buildings) and reinforced concrete (1 building). Only if these 13 buildings were excluded from the analysis, the Weibull function followed a similar shape as for the Austrian case study (Fig. 3), and the coefficient of determination was reasonable ($R^2 = 0.739$). Apparently, this is not the aim of a statistical treatment of data, since the exclusion of nearly one third of data from the population leads to considerable biases, and restricts the overall explanatory power.

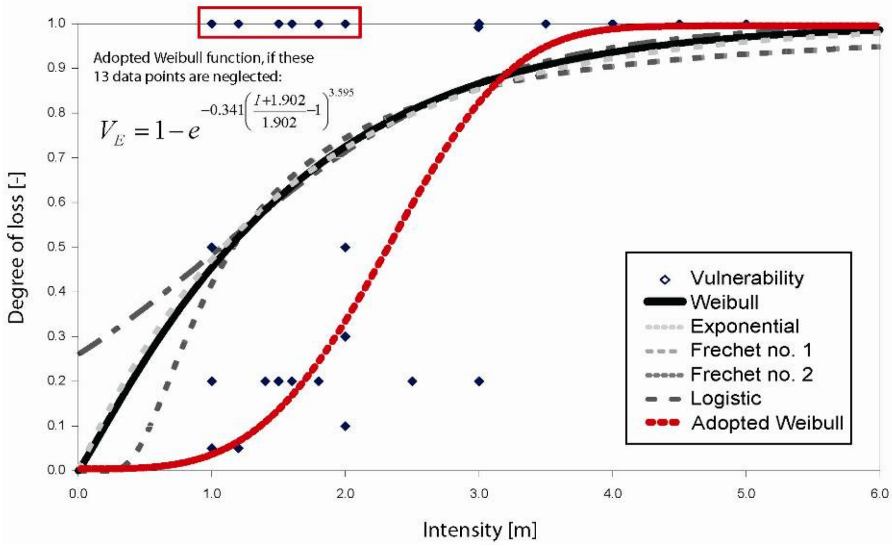

Fig. 3 Different vulnerability functions for buildings based on deposition height as a proxy for the process intensity. Vulnerability values originating from the study sites are indicated by dots. The best-fitting function to describe the range in the analysed data (highest value of utility; Weibull) is highlighted in bold. Since between 1.0 and 2.0 m process intensity, 13 buildings were assessed with a damage ratio of 1.0, the best fitting approach did not result in reasonable outcomes. If these data points were neglected in the statistical treatment, an adopted Weibull function results and is provided in terms of the mathematical notation (V = degree of loss, I = intensity).

DISCUSSION: LIMITATIONS OF TRANSFER

The application of a method developed in the context of the European Alps to another mountain environment clearly has some limitations.

(1) The first shortcoming is that in environments affected by tropical cyclones much higher rainfall intensities are observed than in regions characterised by a warm-temperate maritime and continental climate sensu Lauer and Frankenberg (1988). As a result, the triggered torrent magnitudes and intensities are much higher.

(2) Secondly, unlimited sediment supply – amplified by a multi-hazard situation such as translational landsliding of the slopes in the upper part of the torrent catchments (Kappes et al. 2010), which leads to a temporal channel blocking and a subsequent erosion with a high flood hydrograph (Chen et al. 2004) – may result in process patterns other than those observed in the European Alps so far.

Fig. 4 Typical damage patterns for buildings affected by torrent processes in Taiwan (top) and Austria (bottom). Upper left: Songhe community, Taiwan, event of August 2004, upper right: Min-Zu community, Taiwan, event of August 2009, lower left: Pfunds community, Austria, event of August 2005, lower right: Wartschensiedlung village, event of August 1997. Credits: upper left: S. Fuchs (27 August 2011), upper right: S. Fuchs (28 August 2011), lower left: Gebietsbauleitung 6.2 (23 August 2005), lower right: anonymous (event of 16 August 1997).

Putting these two aspects in a broader context, the application of the concept of frequency and magnitude to different mountain environments may be the explanation for these different system behaviours in Austria and Taiwan: Each process has internal threshold values or external trigger values at which the process becomes effective and is initiated, and sediment transport and landform change is mobilised (Brunsden 2002). Since the work of Melton (1958) there have been many attempts to predict the frequency or magnitude of torrent processes based on basin variables (Johnson et al. 1991) in combination with geomorphic indicators (Jakob and Jordan 2001). Traditional approaches to determining frequency and magnitude have centred on fluvial processes (Wolman and Miller 1960) and have dealt with frequency in terms of discrete hydrological events and magnitude by measures of volume or mass of water and sediment associated with those events. They assume a direct relationship between the hydrological processes and the geomorphic response, such as the capacity of the water body to entrain and transport a certain amount of sediment in dependence of the exerted shear stress (combination of flow velocity and flow depth) and the grain size (Hjulstöm 1935). Therefore, these approaches have been empirically applied to a wide spectrum of geomorphic processes in recent decades (see e.g., Crozier and Glade 1999). With respect to torrent processes, such a frequency-magnitude approach (1) provides the rationale for extrapolating short-term measurements of episodic processes over longer periods, and (2) allows at a first glance the statistical identification of the most relevant work force operating within a system, thereby providing a key variable for

predicting other system qualities (Crozier 1999) such as vulnerability. Nevertheless, multi-hazard patterns – understood in terms of a hazard chain such as landsliding and subsequent channel blocking within a catchment – are not a priori identifiable with such an approach.
Focusing on the elements at risk exposed damage patterns observed vary considerably. Even if building materials used and construction techniques differ between the two case studies, buildings in Taiwan and in Austria are regularly filled with debris material which penetrated through building openings and damaged outer walls (Fig. 4). While in Taiwan these buildings are either reinforced brick based on a concrete frame or reinforced concrete (16 out of 39 studied buildings), often due to the earthquake-resistance building codes, the typical alpine building style is dominated by brick masonry and concrete baseplates. As a result, given the same impact pressure the buildings in Austria would collapse while the buildings in Taiwan still resist even if an economic total loss is evident, as shown in Fig. 4, upper right. In Taiwan buildings are regularly heavily damaged (damage ratio > 50 %, 25 out of 39 buildings), while in Austria only few buildings are a total loss (Totschnig et al. 2011). These differences are again a result of different impact towards elements at risk exposed, resulting from different process characteristics.
With respect to the losses recorded, some issues arise for a transfer of the method. In the Austrian case studies, loss data was collected using information derived from the individual administrative bodies on the Federal State level. Professional damage appraisers of these administrative bodies estimated the loss of any individual element at risk in monetary terms on an object level. Losses which can be attributed to the building envelope only were identified and prepared for the subsequent analysis. These monetary loss assessments were applied within this study for the calculation of the damage ratio of every individual element at risk, defined by the ratio between loss and reconstruction value. Principally the case studies in Taiwan were assessed similarly, however, if the claimant received compensation in terms of an alternative building supplied by the governmental administration, by public social aid or relief organisations, the loss ratio of the damaged building mandatory had to be assessed with 1.0 since a further economic use of the (partly) damaged structure is not allowed. This regulation necessarily leads to some biases during the economic assessment of the loss ratio, such as for the building shown in Fig 4, upper left: Even if the accumulated debris could be removed from the interior, and even if serious structural damage was not reported, the building had to be abundant and therefore the loss ratio equals the construction costs of the building. In contrast, if the claimant is not supplied with a new building in an alternative location, the governmental compensation in Taiwan is a lump sum independent from the damage height, while losses in Austria (if they are compensated, compare the discussion in Holub and Fuchs 2009) are in relation to the actual amount of damage.

CONCLUSION: FUTURE CHALLENGES

Two particular challenges were identified during the comparison of case studies carried out in Austria and in Taiwan. Firstly, event documentation is a requirement to precisely identify process patterns and to provide an accurate input into hazard modelling. Secondly, a legally prescribed land-use planning and associated building regulation are inevitably necessary if future losses due to torrent events should be reduced.

(1) The fact that vulnerability is hazard-dependant should not be ignored (Papathoma-Köhle et al. 2011). Information regarding the properties of the hazardous phenomenon should be collected as well as information regarding the impact of past events on the built environment. Standardised event documentation is crucial which has been comprehensively discussed in the framework of the DIS-ALP project (Berger et al. 2007). Moreover, the vulnerability assessment method differs with the type of disaster and therefore, characteristics regarding its frequency and magnitude should be taken into consideration. For hazard analysis, the frequency of a torrent event may be described by several probability concepts and in different ways, such as 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. The determination of frequency must be accompanied by an estimation of magnitude for the potential event, which is a matter of scale. Therefore, it is necessary to

explicitly define which probability value is used in the set of calculations. Several methods have been proposed to estimate the likelihood of debris flow occurrence in a particular torrent catchment (e.g., Nakamura 1980; Rickenmann and Zimmermann 1993; VanDine 1985). However, there are no rigorous methods that allow a strict determination of an exact probability or magnitude for any torrential process so far, neither based on physically measured characteristics of a catchment nor based on statistical analyses. The information available on past torrential events is often the most reliable indication (Rickenmann 1999). Therefore, a sound multi-scale event documentation on the catchment level, but also on the level of individual elements at risk exposed, is desirable, and is a particular challenge with respect to climate change (Keiler et al. 2010) and multi-hazard analyses (Kappes et al. 2012).

(2) Legislation related to natural hazards is diverse in both countries studied. Due to the federal structure of the Republic of Austria, several articles at federal level are supplemented by various regulations on the level of the Federal States and even below at community level, in particular with respect to land use planning (Holub and Fuchs 2009). In Taiwan, the Disaster Prevention and Protection Act was issued in the year 2000. However, this act is less focused on regional development and land use planning than the Austrian regulations, it is rather centred on disaster response and recovery responsibilities of governmental agencies. A regulation or ordinance related to land development and land use zoning on a national scale is under development for almost two decades. On a regional scale, the Geology Act recently put into force regulates some development restrictions with respect to natural hazards, however, the enforcement with respect to hazard mapping and zoning will still take some years for a comprehensive implementation. Land use planning activities such as hazard maps are based on the concept of recurrence intervals of hazard processes. Since the hazard potential and thus the delimitation of hazard zones is subject to temporal changes, the resulting coping strategies in order to minimise risk have to be variable. From the point of view of spatial planning dealing with such changes is of particular difficulty since the required stability of the law restricts short-term modifications in land use planning regulations to a minimum. In particular building bans and re-zoning of already permitted land development activities remain an unsolved task since once enacted and approved by the regulatory authority additional prescriptions or prohibitions could hardly be accomplished. Hence, the overlap between hazard areas and areas used for settlement purpose and economic activities increasingly provokes conflicts of interest that need to be addressed in natural hazard risk management. Nevertheless, due diligence as legal obligation resulting in usage limitations and prohibitions executed during the individual construction process is inevitable, in particular with respect to the prescription of local structural protection.

WIDER IMPLICATIONS

Given the sharp rise in studies related to the quantification of vulnerability for buildings exposed to torrent processes (Fuchs et al. 2007; Akbas et al. 2009; Tsao et al. 2010; Quan Luna et al. 2011; Totschnig et al. 2011), a comparative analysis of data still remains vaguely proposed and fragmentary (see also Papathoma-Köhle et al., this volume). This is even more surprising if the limited amount of data, which is repeatedly stated in the conclusion sections of the above-cited papers, is taken into consideration. Within our study we combined data from Austrian test sites and data from Taiwan torrent fans in order to analyse similarities and differences with respect to the damage ratio and the process intensity. Moreover, methodological shortcomings and avoidable pitfalls were identified and discussed, aiming at a better applicability of the method and an in-depth understanding of vulnerability beyond economic quotients.

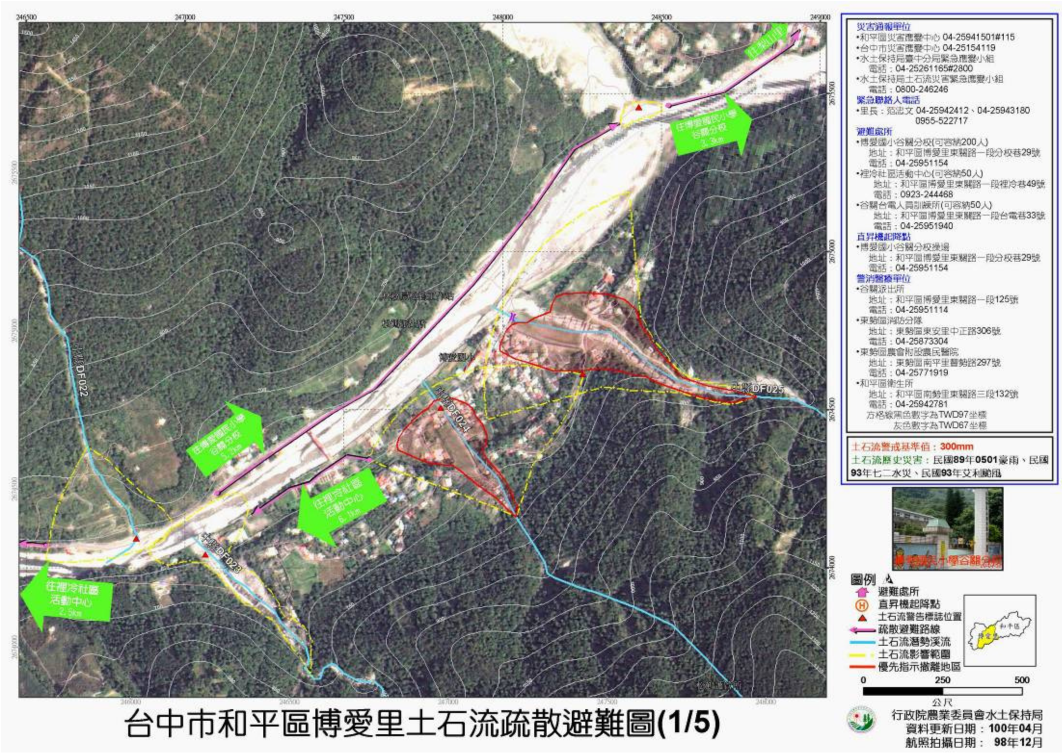

Fig. 5 Debris flow evacuation map for the Songhe community, Taiwan. Source: http://246eng.swcb.gov.tw/debrispage/refugeimg.asp, accessed 01 October 2011.

Fig. 6 Monitoring station of Qiang-Huang-Keng, catchment no. Tainan DF 048, Taiwan. Source: http://246eng.swcb.gov.tw/information/monitoringstations.aspx, accessed 01 October 2011.

Future needs concerning vulnerability research might include the temporal changes in vulnerability to natural hazards. During the past decades, European mountain regions as well as Taiwan experienced major transformations in population size, economic conditions, social characteristics and development patterns. As a result of this evolution in socio-economic activity, and an associated relative increase of individual assets, vulnerability might have changed considerably (Fuchs et al. 2005; Keiler et al. 2006). To improve natural hazard risk management, these changes should be quantified according to arising institutional, economic, and social implications.

Apart from such academic concerns, methods to reduce vulnerability to natural hazards may include innovative approaches of risk sharing, as discussed in Holub and Fuchs (2009). These approaches are pillared by a mandatory insurance system against natural hazards, based on premiums which are commensurate with the risk. Thereby, legislation, loss compensation, and risk transfer are accompanied by the overall aim to increase risk awareness and to implement a sustainable and long-term land use planning. In order to achieve this goal, information on hazard and risk at a specific location should be communicated in a target-oriented way to the stakeholders involved in order to create risk awareness and to provide incentives for vulnerability-reducing behaviour. So far, in European mountain regions the focus is more on loss compensation, while in Taiwan the emphasis is put on evacuation. Therefore, in Taiwan evacuation maps and procedures are publicly available (Fig. 5), and real-time information disaster prevention information is available online for major catchments (Fig. 6), while in Austria such information is not yet available. It has been shown by Fuchs et al. (2009) how standardised guidelines for the visual representation of risk could be used to improve the dissemination of information accordingly. As a result, overall vulnerability to mountain hazards may decrease in the future.

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