DIE ERDE **134** 2003 (2) | Beitrag zur Erdsystemforschung | S. 123-146

• *Landslide hazard – Vulnerability assessment – Risk analysis*

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Vulnerability Assessment in Landslide Risk Analysis

Vulnerabilitätsbewertung in der Naturrisikoanalyse gravitativer Massenbewegungen

With 2 Figures, 10 Tables and 3 Photos

A literature review demonstrates a lack of vulnerability studies in landslide risk research with regard to both social and natural science approaches. Existing approaches to vulnerability assessment have been adopted from technological risk research. These approaches determine risk associated with landslide processes of a given magnitude as a function of landslide hazard, elements at risk with attributed damage potentials and vulnerabilities of each of these elements at risk. This approach is applied in regional landslide risk analyses in Rheinhessen, Germany and Bíldudalur, Iceland. While in the Rheinhessen study, the vulnerability of each element at risk is assumed to equal total damage, a more elaborate concept of landslide vulnerability is applied in the Iceland case study. Although differing in complexity, both approaches demonstrate the advances in, and the necessity for, application of vulnerability assessments to landslide risk analysis.

1. Introduction

Landslides are natural geomorphic processes occurring at locations characterized by specific environmental conditions. They are a component of the natural geosystem and in numerous regions contribute significantly to landscape evolution (*Beck* 1994). Various magnitude and frequency studies have highlighted their continuous (*Crozier* and *Glade* 1999) and widespread (*Hovius* et al. 1997) occurrence. It is obvious, however, that field observations of landslide size and temporal frequency of occurrence are biased, considering the fact that only the remnants of large events remain visible in the landscape over longer periods and that of small failures can be lost as a result of subsequent erosion.

The landscape is not only in a continuous natural evolution, it is also the basis for any life. In various regions, large populations live or are forced to live in areas which are highly prone to geomorphic processes. Examples are settlements in flood prone deltas (e.g. Brahmaputra, Bangladesh), in close vicinity of volcanoes (e.g. Vesuvio, Italy), on faults (e.g. Wellington, New Zealand), or on steep slopes (e.g. Buenos Aires, Argentina). However, the extent of potential damage varies enormously. One major source for estimating costs of damage associated with specific natural processes is claims data held by insurance companies. Unfortunately, such statistics do not provide data for losses attributed specifically to landslides (*Kron* 2000). Damages caused by landslide are mostly subsumed in official reports within "floods" or "storm" categories. Considering worldwide examples (e.g. *Brabb* 1991), however, it can be assumed that landslides cause significant impacts. Nevertheless, assuming an identical failure in France, South Africa or in Nepal, the consequences are not comparable.

This observation is the basis for this study, which advances the hypothesis that different consequences of a similar event are caused by different vulnerabilities of society. In order to investigate this hypothesis in more detail, landslides are defined and characterised, and different types of vulnerability are investigated with respect to landslide occurrence. Various approaches to landslide risk assessment are reviewed. Examples of vulnerability assessment in landslide research in Rheinhessen, southwest Germany and Bíldudalur, northwest Iceland demonstrate the potential for applying this type of analysis to different environments.

2. Landslides

According to *Crozier* (1999), a landslide is a mass of soil, debris or/and rock which moves downslope driven by gravitational forces. In nature, landslides can rarely be attributed to a single landslide type; it is rather a complex failure. Various landslide types differ in their specific vulnerability aspects. In order to avoid confusion resulting from terminology, this study follows the internationally accepted classification by *Cruden* and *Varnes* (1996) and *Dikau* et al. (1996), who categorise landslides in terms of material (rock, debris, earth) and the moving process (fall, topple, slide, flow, spread), including complex movements.

With respect to vulnerability, it is important to consider the spatial extent of individual landslides as well as of widespread landslide occurrence, the speed of onset, and the travel distance of landslides. Landslide area might involve a few m^2 (small slide) or up to some km^2 (e.g. Clyde dam landslide, *Brown* et al. 1993). Widespread landsliding occurs in areas on the order of 500 km^2 with 240 failures (*Jäger* 1997) or in regions of 50 km^2 with more than 19,500 landslides (*Glade* 2001), to name two examples only. Landslide velocity depends on the type of failure and ranges from creeps with velocities of mm/yr to falls with rates measured in m/s (e.g. *Cruden* and *Varnes* 1996). Examples of landslide velocities are given for mm/yr to cm/yr by *Glade* et al. (2001), for a few hundred metres per minutes by *Zimmermann* et al. (1997), or for exceptional cases with estimated kilometres per minutes by *Plafker* and *Ericksen* (1975). In addition to the speed of onset, duration of movement might vary significantly. Landslides might move continuously with seasonal variations (*Gasparetto* et al. 1996), or only within specific periods within a given year (*Demoulin* and *Glade* forthcoming), decade or century (*Panizza* et al. 1997), or they may occur only once and are then stable (*von Poschinger* and *Thom* 1995). The latter type can be used for estimating the magnitude and the date of the triggering event (e.g. *Crozier* and *Pillans* 1991).

Landslides are complex processes and difficult to predict in terms of location, time of failure, speed of onset, and travel distance. While re-activated failures can be observed and monitored, and have been forecast in some cases on the basis of continuous measurements, first time failures are difficult to determine in advance. This has considerable influence on the assessment of vulnerability with respect to the landslide process.

3. Vulnerability

Vulnerability relates to the consequences or the results of an impact of a natural force, and not to the natural process or force itself (*Lewis* 1999). Consequences are generally measured in terms of damage and losses, either on a metric scale in terms of a given currency, or on a non-numerical scale based on social values or perceptions and evaluations. Thus it is important to define different types of consequences with respective vulnerabilities, before attributing single types, or a set of types to the natural forces. Two fundamentally different perspectives on examining vulnerability exist: investigations based on natural science and on social science methods and assumptions.

3.1 Social science perspective

Social scientists tend to criticise the technological usage of the term "natural risk" because it assumes that "nature" is endangering "humans". But nature is not doing anything wrong – or good. There is no "intention" or "consciousness" behind process occurrence. Any process operating in nature is based on physical laws only, even when chaotic behaviour is identified. Therefore, any natural hazard, natural risk, and consequently any form of "natural" disaster is caused by humans (*Geipel* 1992). As *Weichselgartner* (2001: 85) argues, "... natural disasters are socially constructed ..." and consequently, the ".... so-called natural disasters are primarily the products of political economies and not the natural hazards themselves ..." (*Mileti* 1999: 120). Any "natural" disaster is thus the result of bad or false adaptation to nature (*Dombrowsky* 2001). *Pohl* (1998; 2002) states that if a natural event is endangering people or property, the event will be perceived as a hazard. If the person – or society – that is threatened or endangered can make decisions and react to potential process occurrence, the hazard becomes a risk. Consequently, if an individual or a society has no opportunity to make decisions, the natural event is "just" a hazard, not a risk. *Smith* (2001: 6) notes that "... risk means different things to different people because each person holds a unique view of the environment ..." and gives therefore a vague definition only. As early as 1956, *Simon* ".... argued that perception is a filter through which the decision maker views the 'objective' environment and its hazards ..." (in *Smith* 2001: 67). It can be concluded that there is no unique - or agreed - definition and understanding of risk in social science. However, the vulnerability of a given structure or person is directly or indirectly included in all attempts.

Numerous definitions are reviewed and listed by *Weichselgartner* (2001). *Wilches-Chaux* (1992) has summarised different views of vulnerability and differentiates between natural, physical, ecological, technical, economical, social, political, institutional, ideological, cultural, and educative vulnerability. Also, *Cutter* (1996) states that there are no unique definitions of vulnerability in social sciences. *Chambers* (1989) refers to both internal and external dimensions affecting vulnerability. While the internal dimension includes defencelessness and insecurity of threatened people, the external dimension refers to exposure to risk, shock and stress (*Bohle* 2001). As *Winchester* (1992: 45) points out, *Chambers* (1989: 1) also states that "... vulnerability ... is not the same as poverty. It means not lack of want, but defenceless and an inability to cope with risk, shocks and stress". *Blaikie* et al. (1994: 9) define vulnerability as ".... the characteristics of a person or a group in terms of their capacity to anticipate, cope with, resist, and recover from the impact of a natural hazard." As a consequence, vulnerability is closely correlated with socio-economic position and depends on class, caste, ethnicity, gender, disability, age, education and seniority (*Blaikie* et al. 1994; *Hewitt* 1997). Hence, vulnerability is determined by factors closely related to conditions, whether or not people and their environment are able to withstand or cope with a natural disaster (*Hewitt* 1997; *Smith* 2001).

As one consequence, the effect of a landslide is totally different for rich or poor people. The rich may have adapted to the potential hazard by structural building reinforcement, or appropriate insurance cover, or have available resources and access to credit in order to re-establish their livelihood. The concept of "voluntary" and "involuntary" activities within risk assessments (*Adams*

1998; *Starr* 1969) has been further developed and applied to natural hazards. *Smith* (2001) differentiates between involuntary risk and voluntary risks, both closely related to vulnerability. For example, living in a hazardous area is more voluntary for the rich (*Smith* 2001). In contrast, the poor often do not have the choice (*Blaikie* et al. 1994). They have to live in highly susceptible areas. As *Blaikie* et al. (1994: 10) quote, *Hardoy* and *Satterthwaite* (1989) state that "... if the structure of urban landownership and rent means that the closest they can get to economic opportunities is a hillside slum, people will locate there regardless of the landslide risk ...", the choice of exposing themselves is involuntary (*Smith* 2001) – "... poverty and vulnerability is inextricably linked ..." (*Winchester* 1992: 45).

A major difficulty in assessing risk, and in particular vulnerability, is that "... not only are people different, but they are changing continuously, both as individuals and as groups. This constant change within the human system ... interacts with the physical system to make hazard, exposure, and vulnerability all quite dynamic" (*Mileti* 1999: 119). Nevertheless, it is important to address these issues in detail, because "... local planning will require multi-hazard, community-scale risk assessment maps that incorporate information ranging from global physical processes to local resources and buildings. This information is not now available ..." (*Mileti* 1999: 11). And "... vulnerability reduction itself would be socially and environmentally sustainable development ..." (*Lewis* 1999: 42).

3.2 *Engineering* and *natural science perspective*

Within engineering and natural science, vulnerability is generally related to the susceptibility of elements at risk, in particular to built structures (e.g. *Meskouris* et al. 2001) with respect to a hazard (*van Essche* 1986). The detailed determination of vulnerability is a component of risk assessment. A comprehensive natural risk assessment includes risk analysis, risk perception and evaluation, and risk management (e.g. *Hollenstein* 1997). This concept is suggested for application in Switzerland (*Heinimann* 1999a; 1999b; *Heinimann* et al. 1998). Although vulnerability issues influence all three parts of risk assessments, they are of particular importance within risk analysis. Herein, the statistical analysis is based on theories of probability. This has been used extensively in technological risk estimation (e.g. *Cutter* 1993; *Kates* and *Kasperson* 1983; *Kirby* 1990; *Zeigler* et al. 1983). Risk issues have been applied to natural processes by various authors (e.g. *Cutter* 1994; *Petak* and *Atkisson* 1982) and discussed by *Cannon* (1994) and *Cutter* (1996) in the specific context of vulnerability analysis. Generally, risk is based on the definition of UNDRO (1979), which is expressed in the general function

$$R = H \times E \times V$$

with R = *Risk*, referring to the expected number of lives lost, persons injured, damage to property, or disruption of economic activity due to a particular event;

H = *Natural Hazard* defined as the probability of occurrence of a potentially damaging event within a specified time and a given area;

E = *Elements at Risk*, including population, buildings and engineering structures, infrastructure areas and lines, public service utilities and economic activities;

V = *Vulnerability*, relating to the (potential) results from event occurrence expressed with qualitative, semi-quantitative or quantitative methods in terms of loss, disadvantage or gain, damage, injury or loss of life.

Guzzetti (2000) extended this definition by inclusion of "types of landslide" and "magnitude". Although this is an important extension of the given definition, determining the probability of occurrence for specific landslide types and their respective magnitudes requires detailed data which are commonly very difficult to obtain in practical applications. Thus, *Guzzetti*'s suggestion is not followed within this study. The product of *Elements at Risk* and *Vulnerability* is also often expressed as *consequences* (e.g. *Wu* et al. 1996), but should not to be confused with *exposure* (*Alexander* 2000).

Vulnerability is important in the determination of the *consequence* and refers to the degree of loss of a given element at risk, or set of elements at risk resulting from event occurrence of a given magnitude (*Newman* and *Strojan* 1998). Vulnerability is commonly expressed on a scale of 0 (no loss) to 1 (total loss) and relates either to monetary values such as the loss of a given property or to loss of life through the probability of loss of life.

4. Vulnerability Assessment in Landslide Risk Analysis

4.1 General considerations

As explained earlier, vulnerability is commonly integrated in risk analysis. This concept has been transferred to landslide issues by various authors (*Brabb* 1984; *Einstein* 1988; *Fell* 1994; *Gill* 1974; *Hearn* and *Griffiths* 2001; *Hicks* and *Smith* 1981; *Leone* et al. 1996; *Leroi* 1996; *Stevenson* 1977; *Stevenson* and *Sloane* 1980; *Wu* and *Swanston* 1980). One comprehensive publication summarising various attempts addressing landslide risk is the proceedings of a workshop on landslide risk assessment edited by *Cruden* and *Fell* (1997). Since then, various case studies have been published on landslide risk (e.g. *Dai* et al. 2002; *Finlay* et al. 1999; *Guzzetti* 2000; *Hardingham* et al. 1998; *Hearn* and *Griffiths* 2001; *Michael-Leiba* et al. 2000). A comprehensive and generalised definition of landslide risk was proposed to the Australian Geomechanics Society by *Fell* (Australian Geomechanics Society 2000) and to the international community by the IUGS Working Group on Landslides – Committee on Risk Assessment (1997). This report refers not only to the above definitions, but also to "specific" and "total", "acceptable" and "tolerable", "single" and "collective" risk, and thus to social aspects included in landslide risk. It can be concluded, however, that the majority of landslide hazard and risk literature is based on the technical aspects of landslide risk (*Aleotti* and *Chowdhury* 1999).

Commonly, vulnerability assessments in landslide risk research are based on natural science approaches such as *Liu* et al. (2002). In contrast to other natural processes such as flooding and earthquakes, it is very difficult to assess vulnerability to landslides due to the complexity and the wide range of variety of landslide processes (*Leroi* 1996). Diverse effects have to be considered:

- Vulnerability of different elements at risk varies for similar processes.

  Fell (1994: 263) states that "... a house may have similar vulnerability to a slow- and a fast-moving landslide, but persons living in the house may have a low vulnerability to the slow-moving landslide (they can move out of the way) but a higher vulnerability to the fast-moving landslide ...." because they cannot escape. If the scale of investigation is increased, there are also differences within a single house. For examples, rooms facing towards the slope are more vulnerable to destruction by e.g. debris flows than valley-facing rooms. Furthermore, the larger the windows are, the more vulnerable is the room and its contents. Even people sleeping in this room will have a higher vulnerability than other occupants of the house (*Fell* 1994; *Fell* and *Hartford* 1997).

- Temporal probability of a person being present during the landslide event is variable.

While a house is fixed to the ground, a car or inhabitants are mobile and might not be present during the event. For example at night, a family is sleeping in the house while during the day, children are at school and the parents are working, and thus the house would be empty. In contrast, less people are in commercial buildings at night, thus the potential consequences would be less severe, although property damage may be extensive.

- Different groups of humans have different coping potentials.

  In contrast to most adults, children might not be able to react adequately to endangering processes. Similarly, elderly or handicapped people might not have the possibility to escape, although they may be equally able to judge the extent of risk. This is one example of different coping potentials, which has been addressed in landslide risk analysis by *Liu* et al. (2002).

- Early warning systems affect the vulnerability of people.

  If a warning system is installed, people might be able to escape (*Smith* 2001), or at least to reach safe places (*Fell* and *Hartford* 1997) and thus change vulnerability to given event magnitudes.

- Spatial probability of landslide occurrence varies.

  The spatial probability of the occurrence of a potentially damaging event at a given location has to be examined. For example, although a landslide occurs in the predicted zone, the probability that a small building or an individual person being affected is significantly different for a single rock fall or for a debris flow affecting larger areas. Hence it is absolutely essential to differentiate landslides by type, such as rock fall, debris flow, or translational earth slides, to name a few only (*Fell* 1994).

Although this list could be continued, it gives a first impression of aspects which have to be considered in vulnerability assessment within landslide risk analysis. Despite all these limitations and complex, sometimes even unsolved problems, it is an economic and political necessity to assess vulnerability to landslides. Various attempts have been carried out. For preliminary studies, the vulnerability has been set to 1, referring to a total damage as soon as the element at risk is hit by landslide (e.g. *Carrara* 1993, *Glade* and *von Davertzhofen* submitted). More detailed investigations apply damage matrices (*Leone* et al. 1996) based on either qualitative (e.g. *Cardinali* et al. 2002) or quantitative approaches (e.g. *Fell* 1994, *Finlay* and *Fell* 1997, *Heinimann* 1999b, *Leone* et al. 1996, *Michael-Leiba* et al. 2000, *Ragozin* 1996).

4.2 Review of vulnerability applications in landslide risk analysis

Within recent years, vulnerability assessments have been introduced to natural hazard and risk analysis, and some of them have even been specifically designed for landslide analysis. Some applications will be presented in the following to provide an overview of existing and currently available approaches.

Various studies investigate the vulnerability of people, houses and infrastructure to landslides in more detail and suggest classifications. These include approaches describing elements at risks and their potential vulnerability to specific landslide events (e.g. *Dikau* et al. 2001, *Moser* and *Weidner* 1998). *Cardinali* et al. (2002) propose a qualitative approach in landslide risk analysis and distinguish three different types of damage:

- superficial (aesthetic, minor) damage,
- functional (medium) damage,
- structural (total) damage.

Tab. 1 Vulnerability of various elements at risk according to the type of damage through landslides (modified after *Leone* et al. 1996) / *Die Vulnerabilität verschiedener Risikoelemente in Bezug zum Schadenstyp verursacht durch gravitative Massenbewegungen (nach Leone et al. 1996)*

Element at risk	Damage intensity	Type of damage	Vulnerability (0-1)
Building	I	Slight non-structural damage, stability not affected, furnishing or fitting damaged	0.01 - 0.1
	II	Cracks in the wall, stability not affected, reparation not urgent	0.2 - 0.3
	III	Strong deformations, huge holes in wall, cracks in supporting structures, stability affected, doors and windows unusable, evacuation necessary	0.4 - 0.6
	IV	Structural breaks, partly destructed, evacuation necessary, reconstruction of destructed parts	0.7 - 0.8
	V	Partly or totally destructed, evacuation necessary, complete reconstruction	0.9 - 1
Road	I	Slight damage of road	0.05 - 0.3
	II	Damage of roadway, reparation using 10th m^3 material	0.3 - 0.6
	II	Damage of roadway, reparation using 100th m^3 material	0.5 - 0.8
	IV	Destruction of roadway	0.8 - 1
Person	I	Moral disadvantage	0.001
	II	Psychological problems	0.002
	II	Slight physical injury	0.003 - 0.005
	IV	Severe physical injury. Invalidity	0.04 - 0.1
	V	Death	1

These types of damage are also used by *Leone* et al. (1996) to define damage intensity and the degree of loss. Considering human, technological, economic, institutional, functional, and structural factors influencing vulnerability, *Liu* et al. (2002) differentiate the four categories of physical, economic, environmental and social vulnerability. They define an equation for each vulnerability type and combine the results with the derived hazard values. The final product is ranked according to traditional equidistant value classification and a regional debris flow risk is calculated for each prefecture in the Yunnan province in southwestern China (*Liu* et al. 2002).

Leone et al. (1996) suggest damage matrices based on the damaging factors and the resistance of the elements at risk towards these processes. The vulnerability for various elements at risk is given in *Table 1*.

Wong et al. (1997) examine the people exposed to landslides and determine the vulnerability of a person hit in open space, in a vehicle, or in a building by a landslide. Although this investigation is based on research in Hong Kong, it gives a first introduction to the different kinds of vulnerability that can apply to people (*Tab. 2*).

Michael-Leiba et al. (2000) performed an analysis of the vulnerability of residents, buildings, and roads to landslides (including debris flows) for the Cairns City Council in Australia. For people and buildings on hill slopes, data were derived from the Australian Landslide Database and for roads

Tab. 2 Vulnerability of a person being affected by a landslide in open space, in a vehicle and in a building (modified from *Wong* et al. 1997) / *Die Vulnerabilität einer von einer gravitativen Massenbewegung beeinträchtigten Person im Freien, in einem Fahrzeug und in einem Gebäude (nach Wong et al. 1997)*

Location	**Description**	**Vulnerability of a person**		
		Data range	**Recommended value**	**Comment**
Open space	Struck by rock fall	0.1 - 0.7	0.5	May be injured but unlikely to cause death
	Buried by debris	0.8 - 1	1	Death by asphyxia
	Not buried, but hit by debris	0.1 - 0.5	0.1	High chance of survival
Vehicle	Vehicle is buried/crushed	0.9 - 1	1	Death almost cetrain
	Vehicle is damaged only	0 - 0.3	0.3	High chance of survival
Building	Building collapse	0.9 - 1	1	Death almost certain
	Inundated building with debris and person is buried	0.8 – 1	1	Death is highly likely
	Inundated building with debris, but person is not buried	0 - 0.5	0.2	High chance of survival
	Debris strikes the building only	0 - 0.1	0.05	Virtually no danger

on hill slopes, the assessment is based on information provided by the Cairns City Council. Although numerous assumptions were made in order to provide vulnerability values for landslide risk analysis at a regional scale, their approach has a practical application and is indeed of high interest for planning agencies (*Tab. 3*).

Ragozin and *Tikhvinsky* (2000) compared the vulnerability of buildings and population to landslides. They also included other natural and technological hazards and differentiate between light, serious, and fatal injuries. Thus not only the vulnerability of loss of life has been considered, also different types of injuries were taken into account. The authors point out, however, that the maximum vulnerabilities correspond to earthquake events. Thus their rank of vulnerability assessment is not only designed for landslides. For example, the Nicaragua earthquake of 1972 resulted in a vulnerability

Tab. 3 Vulnerability of various elements at risk with respect to landslides including debris flows (modified from *Michael-Leiba* et al. 2000) / *Die Vulnerabilität verschiedener Risikoelemente in Bezug zu gravitativen Massenbewegungen inklusiv der Murgänge (nach Michael-Leiba et al. 2000)*

Process	**Vulnerability of**		
	Residents	**Buildings**	**Roads**
Landslides on hill slopes	0.05	0.25	0.3
Susceptible to proximal debris flows	0.9	1	1
Susceptible to distal debris flows	0.05	0.1	0.3

Tab. 4 Vulnerability of buildings and constructions and population to landslides and other natural and technological hazards (modified from *Ragozin* and *Tikhvinsky* 2000) / *Die Vulnerabilität von Gebäuden und Konstruktionen und der Bevölkerung in Bezug zu gravitativen Massenbewegungen und anderen natürlichen und technologischen Gefahren (nach Ragozin and Tikhvinsky 2000)*

Vulnerability of buildings and constructions	Population damages - injuries			
	Light	Serious	Fatal	Total
0.1	0.0012	0.00016	0.0004	0.0014
0.3	0.0138	0.00184	0.00046	0.0161
0.5	0.0686	0.00914	0.00229	0.08
0.7	0.2229	0.02971	0.00743	0.26
0.9	0.39	0.22	0.105	0.675
1.0	0.4	0.4	0.2	1

value for buildings of 0.7 and for the loss of life of 0.012. In Spitak (Armenia), the 1988 earthquake resulted in 0.51 and 0.025, and for an earthquake in Neftegorsk 1 and 0.58 respectively (*Tab. 4*).

Heinimann (1999b) presents a comprehensive method for risk analysis focussing specifically on gravitational mass movements. In this approach, different landslide types are classified with respect to the probability of occurrence at a given location (*Tab. 5*).

Although based on qualitative analysis, this table gives an overview of spatial probabilities of different landslide types. In order to include vulnerability information in risk analysis, elements at risk are classified as well. In *Table 6*, the resistance of the building structure as one type of an element at risk is estimated.

For each category, the vulnerability to different magnitudes of events is determined. *Table 7* gives respective values for the example of rock falls. In

Tab. 5 Classification of the probability of spatial occurrence for different landslide types (*Heinimann* 1999b) *Klassifikation der räumlichen Auftretenswahrscheinlichkeit unterschiedlicher gravitativer Massenbewegungen (Heinimann 1999b)*

Spatial Probability	Class	Landslide type
0.01	Minimum	Rock fall
0.1	Very low	
0.3	Low	
0.5	Medium	Rock fall, earth slide
0.7	High	
0.9	Very high	
1.0	Certain	Rock or earth slide

Tab. 6 Building categories and estimated resistance based on *Heinimann* (1999a)
Gebäudekategorien und angenommene Resistenz basierend auf Heinimann (1999a)

Building category	Building structure	Resistance
0	Lightest structure (simple timber constructions)	No
1	Light structure	Very weak
2	Mixed structure (concrete and timber)	Weak
3	Brick walls, Concrete	Medium
4	Reinforced concrete	Strong
5	Reinforced	Very strong

addition to structural vulnerabilities, the probability of fatalities within a given type of building is delimited for different event magnitudes. *Table 8* gives examples of chosen values.

Heinimann (1999a) states clearly that a major limitation of the approach is that most of the data have to be assumed. However, this approach provides an initial general means of assessing vulnerability in risk analysis for gravitational mass movements, including rock falls, debris flows, and rotational and translational slides.

4.3 Discussion

The approaches described above vary significantly in detail of analysis and resulting vulnerability values. With the exception of *Heinimann* (1999b), most approaches do not distinguish between types of processes (e.g. *Leone* et al. 1996, *Ragozin* and *Tikhvinsky* 2000, *Wong* et al. 1997) or magnitudes (e.g *Leone* et al. 1996, *Michael-Leiba* et al. 2000, *Ragozin* and *Tikhvinsky* 2000, *Wong* et al. 1997). Further, vulnerability estimates of elements at risk vary. Although the vul-

Tab. 7 Vulnerability of buildings according to the magnitude of the rock falls. Building category refers to *Table 6* (modified from *Heinimann* 1999a) / *Die Vulnerabilität von Gebäuden in Bezug zur Steinschlag Magnitude. Die Gebäudekategorien beziehen sich auf Tabelle 6 (nach Heinimann 1999a)*

Building category	Low magnitude	Medium magnitude	High magnitude
0	0.2	1	1
1	0.15	0.5	0.9
2	0.1	0.3	0.8
3	0.08	0.25	0.7
4	0.05	0.2	0.5
5	0	0.1	0.3

Tab. 8 Vulnerability of people in buildings to debris flows and rock falls considering the magnitude of process, the building type or location (modified from *Heinimann* 1999a)
Die Vulnerabilität von Menschen in Gebäuden in Bezug zu Murgängen und Steinschlag unter Berücksichtigung der Prozessmagnitude und des Gebäudetyps oder der Lokalität (nach Heinimann 1999a)

Building type	**Debris flow magnitude**			**Rock fall magnitude**		
	Low	**Medium**	**High**	**Low**	**Medium**	**High**
Settlement area	0.001	0.01	0.1	0.0001	0.01	0.1
Centre of settlement	0.001	0.01	0.1	0.0001	0.01	0.1
One-/two-family house	0.001	0.01	0.1	0.0001	0.01	0.1
Apartment building	0.001	0.01	0.1	0.0001	0.01	0.1
Commercial building	0.001	0.01	0.1	0.001	0.01	0.1
Industrial building	0.001	0.01	0.1	0.001	0.01	0.1
Bam	0.001	0.01	0.1	0.001	0.01	0.1

Photo 1 Landslide OCK3 in northwest Rheinhessen, view to east (Photo: *Thomas Glade, Oct. 1997*). The consequences are significant when direct and indirect costs through decreased production of this vineyard are considered / *Die gravitative Massenbewegung OCK3 im Nordwesten Rheinhessens, Blickrichtung nach Osten (Foto: Thomas Glade, Okt. 1997). Sichtbar sind die Auswirkungen, die mit den assoziierten direkten und indirekten Kosten durch reduzierten Ertrag aus dem gesamten Weinberg bedeutend sind*

Tab. 9 Elements at risk with attributed damage potential in €/m² (refer for details of sources and calculations to *Glade* and *von Davertzhofen* submitted). / *Risikoelemente mit zugewiesenen Schadenspotentialen in € / m² (Details zu Quellen und berechnungen finden sich bei Glade und von Davertzhofen submitted).*

Elements at risk	**Damage potential [€/m²]**
Residential area	255
Industrial area	205 – 255
Multiple use areas	255 - 410
Special areas (e.g. school, kindergarten)	205
Country road	13 - 15
Motorway	85 - 128
Pasture	0.5 - 0.7
Agricultural area	0.3
Vineyards	10
Forests	2

nerability of buildings is assessed in terms of degree of loss (e.g. *Leone* et al. 1996), absolute values of vulnerability differ significantly. Similarly, vulnerability of people is assessed in totally different ways. Some authors distinguish between different levels of injury including actual loss of life (e.g. *Ragozin* and *Tikhvinsky* 2000), while others just define the probability of loss of life (e.g. *Michael-Leiba* et al. 2000; *Wong* et al. 1997). In addition, absolute values are spread over a wide range and make consequent comparisons of approaches very difficult.

There are various reasons for these difficulties:

- Not all authors state explicitly, or in detail, how their values are derived. It is suspected that most of the values have been estimated due to missing information;
- Most studies are empirical, e.g. *Wong* et al. (1997) derive the values in and for Hong Kong.
- Local historical databases are reviewed, and derived results are thus heavily dependent on such databases actually containing socio-economic indicators of community vulnerability to natural hazards (e.g. *King* 2001). For example, *Michael-Leiba* et al. (1999) assess the vulnerability of buildings and people by using the Australian Landslide Database and of roads by information provided by the Cairns City Council;
- Back analysis of specific past events; e.g. *Ragozin* and *Tikhvinsky* (2000) examine past landslide and earthquake events and *Heinimann* (1999a, 1999b) investigate past events and derived estimates, but also assumed missing values;
- Indeed, uncertainty is inherent in all the studies. It can be concluded that – although *Heinimann* (1999a, 1999b) introduces a very detailed approach in determining risk to gravitational mass movements – a general strategy in determining vulnerability of elements at risk to specific landslide events is still missing. This is a major drawback for any landslide risk analysis.

5. Two Case Studies of Vulnerability Assessments in Landslide Risk Analysis

Despite these sobering conclusions, the following two examples give two potential applications of vulnerability assessments in different environments. The first study is a regional assessment at a scale of 1:25,000 which has been carried out in Rheinhessen, Germany, for a 50 km² area. The second application was undertaken for community Bíldudalur. located in northwest Iceland, at a scale 1:5,000 for a study area of approximately 5 km².

5.1 A preliminary vulnerability study in Rheinhessen, Germany

The Rheinhessen study (*Fig. 1a*) aimed to carry out a landslide risk analysis applying simplified vulnerability issues. Regional details and the general background of slope instability in Rheinhessen are given in *Glade* and *von Davertzhofen* (submitted). Dominant landslide types are shallow translational failures and rotational slides (*Photo 1*).

Landslide risk analysis is based on a landslide hazard map derived from *Jäger* (1997). Ele-

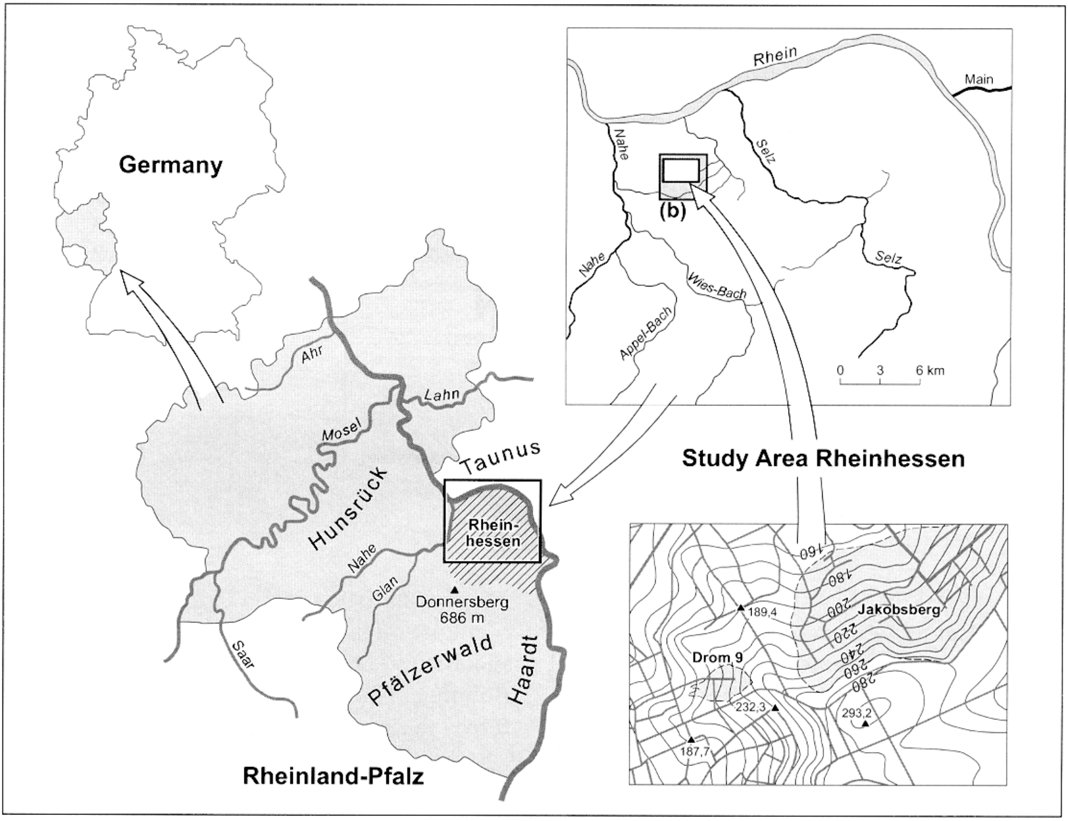

Fig. 1a Location of the study area in northwest Rheinhessen, Germany, including the two landslides DROM 9 and Jakobsberg (grey shaded area in map bottom right) / *Lage des Untersuchungsgebietes in Nordwest-Rheinhessen, Deutschland, mit den zwei Massenbewegungen DROM 9 und Jakobsberg (grau unterlegte Fläche in der Karte unten rechts)*

Fig. 1b Map of the results of the regional landslide risk analysis (*Glade* and *von Davertzhofen* submitted). Area covered is marked by the frame (b) in Fig. 1a. Vulnerability of elements at risk is assumed to be 1, referring to total loss if an element is affected by a landslide.
Karte der Ergebnisse der regionalen Risikoanalyse gravitativer Massenbewegungen (Glade und von Davertzhofen eingereicht). Der untersuchte Bereich ist als (b) in Fig. 1a markiert. Vulnerabilität der Risikoelemente ist mit 1 angenommen, d.h. ein Risikoelement wird von einer gravitativen Massenbewegung vollständig zerstört.

ments at risk are classified according to the land use units "Residential areas", "Industrial areas", "Multiple use areas', and "Special areas" (MURL 2000), "Agricultural area", "Pasture", "Motorway" and "Country road" (*Pflügner* 1997), "Vineyards" (KTBL 1996), and "Forests" (HMWVL 1996). These units are digitised from official land use plans. For each element at risk, a damage potential is defined, which is based on the review of the previously mentioned literature and on data from national statistics yearbooks. In Germany, the literature on the monetary damage potential of specific elements at risk is well developed for flooding. Thus, these values have been transferred to the elements at risk (*Tab. 9*).

For the Rheinhessen region, no information on vulnerability of elements at risk for landslide initiation is available. Therefore, vulnerability was addressed by the assumption that if an element at risk is affected by a landslide, it will be totally de-

Photo 2 View to south downslope towards Bíldudalur, northwest Iceland. Relief is approximately 400 m (Photo: *Thomas Glade*, Sept. 2000). Debris flow levees and large boulders from rock falls and snow avalanches reach the village and indicate the potentially high natural hazard. / *Blick nach Süden hangabwärts auf Bíldudalur, NW Island. Höhendifferenz ca. 400 m (Foto: Thomas Glade, Sept. 2000). Murgang-Levees und große Blöcke aus Steinschlag und Schneelawinen erreichen die Gemeinde und weisen auf eine potenziell hohe Naturgefahr hin.*

Photo 3 Rock fall deposit on a slope above a house in Bíldudalur. View to south downslope. Rock diameter approximately 1.7 m (Photo: *Thomas Glade,* Sept. 2000). While this particular boulder stopped right above the house, other rocks crashed into houses and caused considerable damage. / *Steinschlag-Block auf einem Hang über einem Haus in Bíldudalur, Blick hangabwärts nach Süden. Steindurchmesser ca. 1,7 m (Photo: Thomas Glade, Sept. 2000). Während dieser spezielle Block nicht das Haus erreichte, schlugen andere Steine in Häuser ein und führten zu schweren Schäden.*

stroyed. Consequently, vulnerability of 1 is assigned to all elements at risk. Due to the low probability that a person will be injured or even killed from a landslide event, risk to life is excluded from the analysis. All land use units are classed in the four damage groups "Low" ("Pasture", "Agricultural area", "Forests"), "Moderate" ("Vineyards"), "High" ("Country roads", "Motorway"), and "Very high" ("Residential area", "Industrial area", "Multiple use areas", "Special areas").

The combination of these damage potential classes with natural hazard information and the elements at risk lead to a qualitative matrix of different landslide risk classes. The landslide risk matrix include "low", "moderate", "high" and "very high" risk classes. These classes were established by a combination of the degree of natural hazard as defined by *Jäger* (1997) and the classes of potential damage of risk elements ("Low": <5 €/m^2; "Moderate": 5-13 €/m^2; "High": 13-150 €/m^2; "Very high": >150 €/m^2). The combination and ranking of both factors lead to risk classes "Low", "Moderate", "High", and "Very high" (refer to *Glade* and *von Davertzhofen* (submitted) for more details). The spatial distribution of these classes are shown in the landslide risk map (*Fig. 1b*).

Of the total area, 90% is classified as "low", 8% as "moderate", 2% as "high", and 0.2% as "very high" landslide risk. In general, "low" risk areas refer to flat or moderately steep slopes with pasture. In contrast, "high" and "very high" classes are the steep slope units with buildings. This result highlights the importance of the potential effects of landslides in the study area, which can be considered as representative for the whole Rheinhessen area.

5.2 Advanced vulnerability assessment in Bíldudalur, Iceland

In Iceland, a comprehensive study on assessing landslide hazard has been carried out by *Jensen* and *Sönser* (2002) for the east-coast region and by *Glade* and *Jensen* (2003) for the northwest Fjord region. Detailed descriptions of the environmental setting of Bíldudalur, the local landslide history and the method and results of calculating runout zones for debris flows and rock falls are given in *Glade* and *Jensen* (2003). *Photos 2* and *3* give an impression of the study area.

Based on this study, *Bell* and *Glade* (forthcoming a) developed a methodology for landslide risk analysis for Bíldudalur. Moreover, *Bell* and *Glade* (forthcoming b) applied *Heinimann*'s approach (1999b) and determined the vulnerability of building structures and their resistance, with respect to debris flows and rock falls of different magnitudes. Vulnerability of persons in buildings was assessed with regard to processes, magnitudes and building types. A review of historical data did not add to the reliability of vulnerability values because respective information is not available (*Bell* and *Glade* forthcoming b). Historical records give no fatalities caused by landslide events (*Glade* and *Jensen* 2003). Therefore, the probability of loss of life in and outside a building is assumed to be very low. Nevertheless, the differentiation of each vulnerability value for respective elements at risk is described in detail by *Bell* and *Glade* (forthcoming a). A summary of the vulnerabilities for specific processes and respective magnitudes is given in *Table 10*.

After defining vulnerability values, landslide run-out zones calculated by *Glade* and *Jensen* (2003) were transferred into hazard zones by attributing a return period for each event magnitude. Landslide risk was then calculated using these hazard zones in combination with potential damage values and respective vulnerabilities of the elements at risk. Six risk maps are drawn for individual risk to life, object risk to life, and economic risk with regard to both debris flows and rock falls (*Bell* and *Glade* forthcoming b). The map on object risk to life for rock falls is given as an example in *Figure 2*.

Tab. 10 Vulnerability values for different elements at risk for debris flows and rock falls of different magnitudes applied to Bíldudalur, northwest Iceland (modified from *Bell* and *Glade* forthcoming b)
Auf Bíldudalur, NW-Island, angewandte Vulnerabilitätswerte unterschiedlicher Risikoelemente für Murgänge und Steinschläge mit unterschiedlicher Magnitude (nach Bell and Glade forthcoming b)

Magnitude	Elements at risk	Debris flow	Rock fall
Low	Power line	1	1
	Roads & infrastructure	0.2	0.2
	Properties	0.1	0.1
	People	0.2	0.2
	People in buildings	0.02	0.02
Medium	Power line	1	1
	Roads & infrastructure	0.4	0.2
	Properties	0.2	0.3
	People	0.3	0.4
	People in buildings	0.06	0.12
High	Power line	1	1
	Roads & infrastructure	0.6	0.4
	Properties	0.5	0.5
	People	0.5	0.5
	People in buildings	0.25	0.25

6. Conclusion and Perspectives

The review of current vulnerability approaches demonstrates that those used in social science partly cover natural processes, but have not addressed landslide issues extensively in the past. Natural science approaches relate in particular to the classical risk analysis developed from technological risk research. Herein, landslide risk is a function of hazard, elements at risk, and vulnerability, whereby the latter is based in particular on consequences of an impact. This approach is applied to two assessments with different complexities: an analysis with simplified vulnerability assumptions in Rheinhessen, Germany, and with advanced information in Bíldudalur, Iceland. For both studies, the following conclusions can be derived:

- No unique and simple method is currently available for vulnerability assessments within landslide risk analysis.
- Vulnerability estimates are heavily dependent on availability of historical data for the region, and on the landslide type.
- Even when information on past events is available, details of vulnerabilities of given elements at risk towards a specific type and magnitude of process is frequently missing.
- If none of the information sources is available, vulnerability of elements at risk have to be estimated based on examples from other regions, or even other processes (e.g. earthquakes).

Despite these limitations in vulnerability assessments, numerous advantages result from detailed landslide risk analysis:

- Risk calculation is objective, and reproduction is possible and applicable for other studies and regions.

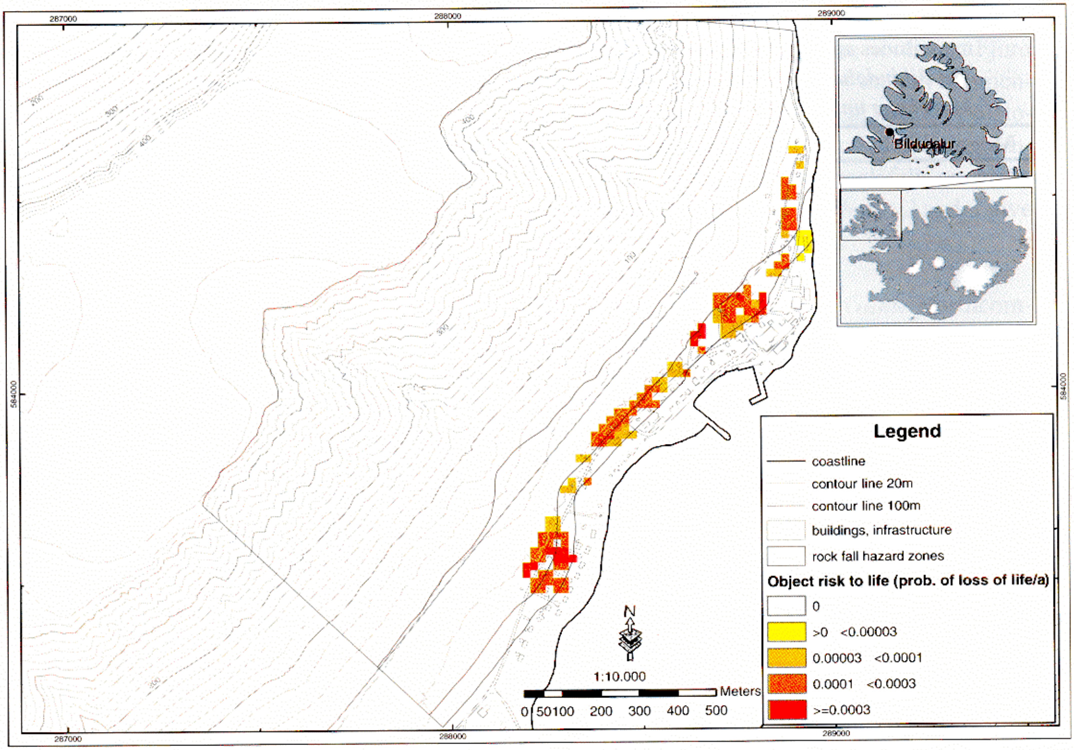

Fig. 2 Object risk to life for rock falls in Bíldudalur, northwest Iceland (*Bell* and *Glade* forthcoming b)
Objektives Todesrisiko in Bezug zu Steinschlag in Bíldudalur, NW Island (Bell und Glade forthcoming b)

- Risk can be calculated for specific magnitudes and types of processes.
- Different natural processes can be combined towards a multi-risk analysis.
- Single elements at risk of high interest (e.g. schools, hospitals) can be analysed in detail.
- The effects of changing the vulnerability of elements at risk can be analysed, thus scenarios of potential future developments can be calculated.

As a perspective, future research might focus in more detail on vulnerability assessments of elements at risk within landslide risk analysis. Future research might include:

- Details on elements at risk and their specific vulnerability to the respective magnitude of event might be collected in order to develop a comprehensive data base available for future investigations.
- Vulnerability curves of each element at risk might be developed for each landslide type using the type of database described above.
- Advanced vulnerability modelling approaches for various natural hazards (e.g. *Hollenstein* et al. 2002, *Melching* 1999) or the calculation of vulnerability maps – instead of "risk" maps (e.g. *Weichselgartner* 2001) – should be applied in practical landslide risk application.
- Generally, landslide hazard analysis should move towards landslide risk analysis.

- Landslide risk calculations should be used more frequently to advise local and regional planning agencies by providing scenarios for different development options.

- Besides natural science based analysis, landslide risk assessment should also include the investigation of the communication, the perception and evaluation of all affected stakeholders in order to implement sound, comprehensive and sustainable management of the respective processes.

- Landslide risk analysis should not only be available for local and regional scales. Also investigations at national scale have numerous potential for future applications (e.g. *Dikau* and *Glade* 2003).

Acknowledgements

Richard Dikau, *Jürgen Weichselgartner*, *Ria Hidajat* and *Holger Voss* enriched my understanding of vulnerability issues through continuous discussions over the past years. Without the support of *Ursula von Davertzhofen*, *Esther Jensen* and *Rainer Bell*, regional landslide risk analysis could not have been performed in the presented way. My special thanks belong to *Rainer Bell*, who supported this study throughout the last years in the field and through extensive discussions on practical vulnerability matters. *Jürgen Weichselgartner* gave helpful comments on the manuscript and *Nick Preston* improved the final text significantly. Finally, Deutsche Forschungsgemeinschaft (DFG) and the Icelandic Meteorological Office (IMO) provided financial support for the presented case studies in Rheinhessen and Bíldudalur respectively.

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Summary: Vulnerability Assessment in Landslide Risk Analysis

Landslide risk assessments are traditionally carried out by natural scientists. Landslide risk is commonly defined as a function of landslide hazard, elements at risk with attributed damage potentials and given vulnerabilities of each element at risk to a landslide with a defined magnitude. Although vulnerability estimation is an important part within this assessment, a literature review demonstrates a lack of vulnerability studies in landslide risk research with regard to both social and natural science approaches. It is concluded that most existing approaches to vulnerability assessments are adopted from technological risk research. The approach of vulnerability estimation is adopted for regional landslide risk analysis in Rheinhessen, Germany and Bíldudalur, Iceland. While in the Rheinhessen study, vulnerability of each element at risk is assumed to equate to total damage, a more elaborate concept of landslide vulnerability is applied in the Iceland case study. For Rheinhessen, the total damage potential is derived from official yearbook statistics and adopted from studies on flood risk. It is shown, that the risk map gives more information than the hazard map and is thus of great interest for parties such as government agencies and councils, and also for insurance companies and affected people. For Iceland, the risk is based on estimation of spatial and temporal probability of landslide occurrence. In addition, the probability of a person being hit and killed by a landslide is included in the analysis. This comprehensive approach results in a map, which gives a more detailed information on landslide risk. Within this study, the example of the yearly probability that a person being killed by a debris flow is analysed and displayed in a map. Although different in complexity, both approaches demonstrate the advances in, and the necessity for, of applying vulnerability assessments to landslide risk analysis.

Zusammenfassung: Vulnerabilitätsbewertung in der Naturrisikoanalyse gravitativer Massenbewegungen

Die Risikobetrachtung von gravitativen Massenbewegungen wird traditionell von Naturwissenschaftlern durchgeführt. Das Risiko von gravitativen Massenbewegungen ist definiert als eine Funktion der Gefahr durch gravitativen Massenbewegungen, den Risikoelementen mit den zugeschriebenen Schadenspotentialen und den Vulnerabilitäten für jedes Risikoelement unter Berücksichtigung der entsprechende Stärke einer gravitativen Massenbewegung. Obwohl die Vulnerabilitätsermittlung einen wichtigen Teil der gesamten Risikobetrachtung darstellt zeigt eine Auswertung der Literatur, dass ein großes Defizit von Vulnerabilitätsstudien in der wissenschaftlichen Risikobetrachtung von gravitativen Massenbewegungen auf sozial- und naturwissenschaftlicher Grundlage existiert. Es wird festgestellt, dass sich die meisten Ansätze von der Vulnerabilitätsbetrachtung von der technologischen Risikoforschung ableiten. Der Ansatz der Vulnerabilitätsabschätzung ist in regionale Risikoanalysen gravitativer Massenbewegungen für die Beispiele Rheinhessen, Deutschland und Bíldudalur, Island durchgeführt. Während in der Rheinhessenstudie die Vulnerabilität eines einzelnen Risikoelementes gleich dem Totalschaden gesetzt wird, ist für Island eine detailliertere Vulnerabilitätsbetrachtung zur Anwendung gelangt. Das maximale Schadenspotential ist in Rheinhessen aus den Statistischen Jahrbüchern abgeleitet und aus Untersuchungen von Überflutungsrisiken übertragen worden. Es kann gezeigt werden, dass die Risikokarte mehr Informationen bereitstellt als eine Gefahrenkarte und somit von großem Interesse ist für die involvierten Akteure wie z.B. Regierungen, Bürgermeister, aber auch für Versicherungsgesellschaften und der lokal betroffenen Bevölkerung. Für Island basiert die Kalkulation des Risikos auf der räumlichen und zeitlichen Wahrscheinlichkeit des Auftretens gravitativer Massenbewegungen. Zusätzlich ist die Wahrscheinlichkeit berücksichtigt, dass eine Person von einer gravitativen Massenbewegung getroffen und getötet wird. Die Durchführung dieses umfassende Ansatzes resultiert in einer Karte, die detailliertere Informationen zum Risiko der gravitativen Massenbewegungen darstellt. Aus dieser Studie ist als ein Beispiel die kartographische Darstellung der jährliche Wahrscheinlichkeit eines Todesfalls durch einen Murgang präsentiert. Obwohl sich die Studien aus Rheinhessen und Bíldudalur in der Komplexität stark unterscheiden, zeigen beide Ansätze die Vorteile und die Notwendigkeit, die Vulnerabilitätsbetrachtung in die Risikoanalyse gravitativer Massenbewegungen zu integrieren.

Résumé: Analyse de la vulnérabilité pour le risque lié aux glissements de terrain

L'analyse du risque de glissements de terrain est généralement effectuée en fonction des caractéristiques de l'aléa naturel et des dommages potentiels pour un glissement de terrain d'intensité donnée. Cette second partie, quoique très importante dans l'estimation du risque, reste insuffisamment traitée dans la littérature scientifique, notamment pour ce qui concerne les aspects socio-économiques liés aux phénomènes naturels. La plupart des approches de vulnérabilité existantes reprennent des méthodes développées pour le risque technologique. La présente étude de la vulnérabilité concerne une analyse régionale des glissements de terrain en Allemagne (Rheinhessen) et en Islande (Bíldudalur). Sur le premier secteur d'étude, le dommage potentiel est estimé d'après les statistiques officielles de dommages, par ailleurs exploitées pour l'étude du risque d'inondation. La cartographie du risque donne davantage d'information que la seule estimation de l'aléa naturel. Elle intéresse les différents acteurs concernés, comme les maires, mais aussi les compagnies d'assurance et les personnes exposées. Sur le second secteur d'étude, le risque est estimé d'après une analyse spatio-temporelle de la probabilité d'occurrence des glissements de terrain, en incluant la probabilité qu'une personne soit touchée et tuée. La cartographie finale fournit ainsi une information plus complète que dans le premier cas d'étude, avec par exemple la probabilité annuelle d'avoir un décès lié à des crues torrentielles. Quoique différentes dans leur degré de restitution, ces deux approches montrent l'intérêt et la nécessité d'inclure une analyse de vulnérabilité dans l'étude des risques de glissement de terrain.

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Manuskripteingang: 20.2.2003
Annahme zum Druck: 22.8.2003