universität
wien

DISSERTATION

Titel der Dissertation

„Spatial and temporal development of landslide risk - a contribution to risk management in the context of global change “

Verfasserin

Mag. Catrin Promper

angestrebter akademischer Grad

Doktorin der Naturwissenschaften (Dr. rer. nat.)

Wien, 2014

Studienkennzahl lt. Studienblatt:	A 796 605 452
Dissertationsgebiet lt. Studienblatt:	Geographie
Betreuerin / Betreuer:	Univ.-Prof. Dipl.-Geogr. Dr. Thomas Glade

It is always wise to look ahead,
but difficult to look further than you can see.
(Winston Churchill 1874 – 1965)

Acknowledgements

Many people encouraged and supported me in my research activities and the writing of this PhD thesis. I would like to take the opportunity to express my gratitude for all the support.

I would like to first thank Thomas Glade, who gave me the opportunity to be part of the ENGAGE group working in the projects ChangingRISKS and SEERISK. Thank you, Thomas for encouraging me to work on the topic of landslide risk and all your support for my PhD. thesis.

I thank Jean-Philippe Malet, Alexandre Remaître and Anne Puissant for welcoming me at CNRS and the Laboratoire Image, Ville et Environnement of the University of Strasbourg. I am grateful for the warm welcome, the productive research stay and fruitful discussions. Further I want to thank Santiago Bégueria for the good collaboration and discussions.

This thesis would not have been possible without the generous provision of data by the Provincial Government of Lower Austria. I would like to express my gratitude to the department "Raumordnung und Regionalpolitik" and especially Gilbert Pomaroli and Friedrich Pühringer for the interest in this thesis and the continuous support.

All current and former ENGAGEis who shared a part of the journey with me, thank you for good advice, ongoing discussions, relaxing coffee breaks and open ears. For a great time we spent together in our office and for fruitful discussions I would like to thank Maria Papathoma-Köhle. Christine Gassner, I am grateful for a great collaboration and your support which you provided unconditionally in many different ways. Thank you, Martin, Karin and Marius for your assistance and good company in the field and during the time consuming mapping tasks of my thesis. For proof-reading I would like to express my gratitude to Melanie, Karin, Helene, Maria and Rainer.

Helene, Melanie, Karin and Sven thank you for all your support, especially in the final phase. Thank you for the good times we had and your friendship.

The last phase of this thesis was supported by continuous motivation of my colleagues from the Austrian Service of Torrent and Avalanche Control. Thank you for your back-up.

I would also like to express my gratitude to all my friends and all the people I might have forgot, thank you for open ears and your support.

Ein riesen Dankeschön möchte ich hier auch meiner Familie aussprechen. Ohne eure Unterstützung und den kontinuierlichen Rückhalt wäre es mir nicht möglich gewesen diese Arbeit zu schreiben. Es ist schön zu wissen, dass ich bei euch immer ein zu Hause haben werde.

Lieber Rainer, du hast in den richtigen Momenten motivierende Worte gefunden, mir den Rücken freigehalten und immer an mich geglaubt. Vielen Dank für alles!

TABLE OF CONTENTS

LIST OF FIGURES

I tried my best, to identify and cite all sources of the pictures and figures. In case any copyright infringement occurred I would politely like to ask the copyright holder to contact me.

LIST OF TABLES

1. BACKGROUND

Natural hazards have caused vast damages over the last decades. Among the ten costliest events are for example the earthquake and the subsequent tsunami in Japan 2011, Hurricane Katrina in the USA 2005, the Kobe earthquake 2005 or the floods in 2004 in Thailand (MUNICHRE 2014). Referring to landslides, precipitation is the most common trigger (PETLEY 2010), however also earthquakes may induce or predispose respective events. Subsequently the disasters mentioned above are also related to land sliding and therefore are listed among the largest catastrophes in combination with hurricanes, floods or earthquakes each year causing not only damages but also a significant number of fatalities (e.g. MUNICHRE 2009, 2010, 2011).

In mountainous and hilly regions of the world, landslides are a major threat and cause direct impacts e.g. collision or deformation but also indirect impacts (GLADE and CROZIER 2005) e.g. road or river blockages. These damages affect various elements, for example infrastructure, constructed facilities, the natural environment but also human lives (LACASSE and NADIM 2009). The annual costs related to landslides for Italy, Austria, Switzerland and France are estimated around 1 – 5 billion USD (KJEKSTAD and HIGHLAND 2009).

The challenge of reducing landslide damages is dependent on various aspects not only related to predisposing and preparatory factors but also, to triggering factors and the subsequent combination to indicate the potential locations of future landslides. The controlling factors of landslides are manifold and range from the geological setting and climate to the resulting soil conditions and topography to land use and hydrology (e.g. PEREIRA ET AL. 2012, JEMEC AND KOMAC 2011, GLADE AND CROZIER 2005). Additionally to these factors it is important to assess the location of the potential elements at risk, which are also manifold and variable over time. Examples for such elements would be population, residential buildings, linear infrastructure, critical infrastructure and services, but also natural resources and reserves (e.g. COROMINAS 2013, FELL ET. AL.2008). These elements at risk are exposed due to their location (UN-ISDR 2009) and have individual characteristics determining the respective vulnerability to a hazard with given magnitude and frequency. The combination of these potential consequences of an event, expressed by an exposed element at risk, its vulnerability, and the associated probability of occurrence of a landslide event defines landslide risk (IEC/ISO 2009).

Therefore, landslide risk analysis is an integral part of risk management that implies reducing the likelihood of occurrence of an event and the adverse consequences or both (FELL ET AL. 2005; CROZIER AND GLADE 2005). Risk analysis in general contributes to risk management by revealing potentially hazardous events and the respective consequences (VON ELVERFELDT et al. 2008). This is especially important to decision makers in order to consider areas that are potentially affected by hazards such as landslides into development plans or appropriate risk mitigation measures (COROMINAS et al. 2013).

The interaction of the listed sets of elements at risk and triggering or predisposing factors is affected by changes induced by components of global change; therefore various so called “dynamic factors” related to landslide risk analysis can be identified. Examples that increase the activity of landslides herein are changing precipitation patterns or continued land cover change, e.g. deforestation and an increased trend in urbanization (ALCÁNTARA-AYALA ET AL. 2006, SCHUSTER AND HIGHLAND 2001, SCHUSTER 1996). At the same time people tend to move into more mountainous areas for settlement, tourism and recreation, leading to an increase of tangible elements in areas exposed to hazardous phenomena (FUCHS AND KEILER 2013, ADAPTALP 2011) including landslides. Therefore diverse effects of global change alter the spatiotemporal pattern of landslide risk and from the viewpoint of adaptation to climate change it is necessary to analyse potential future risk scenarios and therewith support the planning of alternative development actions.

THESIS OUTLINE

This thesis focusses on landslide exposure as a central part of landslide risk assessment aiding spatial development planning. However a comprehensive risk analysis including vulnerability and frequency magnitude analysis is not embraced. As a cumulative thesis it is containing two parts namely a monographic part and the related publications. Therefore the first part is uniting the content of the publications as a framework. The structure of this part is aligned with the developed hypothesis and objectives on implementing methodological approaches and the performed studies. The main parts are accordingly:

- The elaboration of the background of landslide risk assessment in a changing environment and the subsequent research gap.
- The presentation of the methodological approach incorporating the regional landslide exposure analysis and the spatiotemporal development therein.
- The presentation and illustration of the results.
- The discussion of the results and concluding remarks leading to perspectives for future research.

The second part of the thesis incorporates the individual publications in international journals, book chapters and conference proceedings. In these publications the related content of the monographic part is described in full detail. The status of publication and the contribution of the author of this thesis and the co-authors is indicated clearly ahead of the relevant publication. This implies that not all details are presented in the monographic part but referenced accordingly to the publications in the annex. Furthermore, verbatim repeated sentences or paragraphs from the publications are clearly indicated and cited. Terms that are frequently used throughout this thesis are defined in annex C.

2. NATURAL HAZARD RISK ASSESSMENT IN A CHANGING ENVIRONMENT

2.1 CONCEPT OF NATURAL HAZARD RISK ASSESSMENT

In this chapter the concept of risk will be elaborated, whereas risk is defined as *a combination of the consequences of an event (hazard) and the associated likelihood/probability of its occurrence* (IEC/ISO 2009). This definition relates to a methodological approach for determining the nature and extent of risk by analysing the potential hazards and evaluating existing conditions of vulnerability that could potentially harm exposed people, property, services, livelihoods and the environment on which they depend (UN-ISDR 2009). Related to natural hazards it can be described as a measure of the probability and severity of loss to the elements at risk, usually expressed for a unit area, object, or activity, over a specified period of time (GLADE et al. 2005). The introduction of this concept to management of natural hazards in the 1980s and 1990s aimed at quantifying the degree of hazard (BRÜNDL et al. 2009). The origin of the concept can be found in technical hazards, especially core melt downs in the nuclear industry (HOLLENSTEIN 2005, HOLLENSTEIN ET AL. 2004). Related to natural hazards, this concept, from the beginning, was closely linked to the idea of insuring possible damages thus make future events appraisable (FELGENTREFF and GLADE 2008).

According to the ISO31010 risk assessment covers the following three phases (EC 2010):

- risk identification,
- risk analysis and
- risk evaluation.

The result of the first step, risk identification is the process of finding, recognizing and describing the risks which are examined in the next step, risk analysis (EC 2010). In the risk analysis phase the probability of its occurrence and the severity of the potential impacts of all identified risks in the first phase are investigated (HOLLENSTEIN ET AL. 2004; EC 2010). The last phase covers the risk evaluation which is a comparative process where the acceptable/tolerable risk is defined according to certain terms of reference against which the significance of a risk is evaluated (EC 2010). The question to be answered is: *How save is save enough? (*HOLLENSTEIN et al. 2004*)*.

As mentioned above, the consequences of a disaster can be expressed in terms of human impacts, economic and environmental impacts and political/social impacts (EC 2010.) Therefore risk assessment necessitates a detailed investigation of the natural process and the possible consequences. When the potential risks are identified, risk analysis is conducted and can be based on qualitative, semi-quantitative, or quantitative methods (VON ELVERFELDT et al. 2008). The qualitative assessment is a non-mathematical description (VON ELVERFELDT et al. 2008) whereas quantitative risk assessment requires the calculation of certain components: magnitude of potential loss and the probability that the loss will occur (ANDREYCHOUK and TYC 2013). The rating of these impacts requires different scales of analysis wherein economic and environmental, as well as human-related effects are measured quantitatively (fatalities/euro), while political/social impacts are measured on a semi-quantitative or qualitative scale (EC 2010). These ratings enable to assess, compare and possibly also insure potential damages, set priorities referring to mitigation measures or balance financial and political support.

Focussing on a quantitative assessment, the basic approach is illustrated by the following equation:

$$R = f(H, C)$$

where R = *risk*, H = hazard (probability or likelihood) and C = Consequences as combination of damage potential, vulnerability. The following Table 2.1, indicates variations of this formula, all incorporating the combination of hazard and potential impacts.

Table 2.1 List of disaster risk assessment approaches that are similar to the conventional approach (modified after Nirupama 2013)

Proposed risk evaluation equation	**Variable other than probability and impact**	**Expert(s)**
$\mathbf{R = (E) \times (R_s) = (E) \times ((H \times V)}$	R_s = specific risk	Varnes 1984
$\mathbf{R = p \times L^x}$	x(>1)= people's perception	Whyte and Burton 1982
$\mathbf{R = p \times V^n}$	n= social consequences	Ferrier and Haque 2003
$\mathbf{R = p \times L}$		Smith 2009
$\mathbf{R = p \times L \times F(x)}$	f(x)= risk aversion factor as a function of consequences	Schneider et al. 2006
$\mathbf{R = H \times V \times M}$	M= manageability or ability of humans	Noson 2009
$\mathbf{R = H \times (V \times cp)}$	cp= community perception	Nirupama 2013
$\mathbf{R = (E) \times (H \times V)}$		Varnes 1984
$\mathbf{R = H \times C \times E}$	C= consequences;	Bell and Glade 2004
$\mathbf{R = \sum (H \sum (VA))}$	A= amount or cost of particular element at risk	van Westen et al. 2006
$\mathbf{R = H \times V \times E}$		Zêzere et al. 2008, Smith 2013
R= risk, L = loss, p= probability, V= vulnerability, H = hazard, E= elements at risk		

All these expressions are also illustrated in the following Figure 2.1 where it is clearly indicated that only through the combination of hazard and consequences, both influencing environment and society, risk emerges.

Figure 2.1. Natural hazard risk assessment (modified after ALEXANDER 2002)

In this thesis the concept of risk is therein extended by splitting the consequences in exposure, which is defined by the location of elements at risk within a hazardous area, and vulnerability of elements at risk, which is defined as the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard (UN-ISDR 2009).

2.2 RISK ASSESSMENT AS CRUCIAL PART OF RISK MANAGEMENT

Risk management is defined as steering of all measures for the protection of natural hazards with the aim of reaching an intended level of security and to adapt this security planning to changing circumstances (RUDOLF-MIKLAU 2009). Risk management therein describes a systematic application of management principles and strategies to reduce 1) likelihood of the occurrence of an event or 2) the adverse consequences, or 3) both, the consequences and the likelihood of occurrence (e.g. FELL ET AL. 2005, CROZIER AND GLADE 2005; UNISDR 2009). This means that risk management is a set of adequate actions being applied to reduce and prevent damages and fatalities related to natural hazards potentially occurring in future. Conceptually this has been described in the risk management circle (HOLLENSTEIN ET AL. 2004, SUKARNA ET AL. 2012) wherein risk assessment, as part of risk management is applied in all phases (Figure 2.2): response, recovery, prevention, mitigation and preparedness. The recovery phase describes the restoration and improvement of facilities, livelihoods and living conditions of the affected communities where appropriate (UN-SPIDER 2014). Ideally the risk management thought is already implemented in this first phase after the initial event. Related to the phases before an event, prevention and mitigation, the necessity to assess the potential hazardous event and the potential impact is inevitable. Further also SUKARNA ET AL. (2012) indicate that risk assessment is closely linked to pre-disaster, pre-event phases being especially important in the prevention and mitigation phase.

In this risk management cycle an additional phase referring to the reconstruction and development of the area at risk (SUKARNA et al. 2012) was integrated which should indicate the dynamics of the related areas. A critical key-phrase herein is "risk-sensitive development planning", which indicates that, additionally highlighted by the DEPARTMENT FOR INTERNATIONAL DEVELOPMENT (2004), learning from disasters can stimulate adaptation and modification in development planning which would be more positive than a simple reconstruction. "Building back better" is a keyword appearing frequently in this context and often refers to reducing risks and building resilience (e.g. CLINTON 2006, WHO 2013).

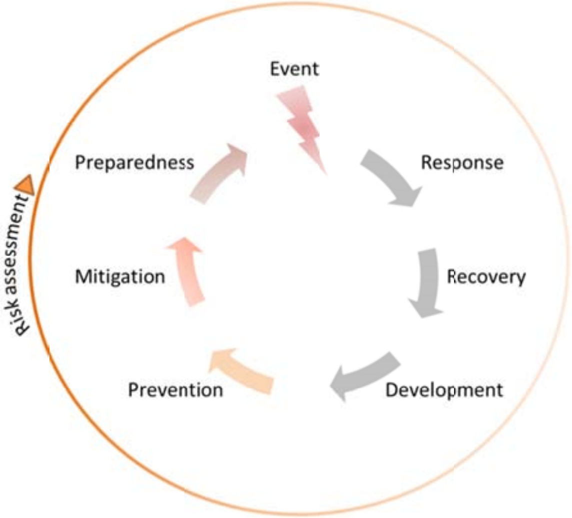


Figure 2.2. Risk management cycle (modified after FOCP 2012, SUKARNA ET AL. 2012, UN-SPIDER 2014 and HOLLENSTEIN ET AL. 2004)

Concluding, a comprehensive risk assessment provides the required information for decision makers and planners SUKARNA ET AL. (2012) to reduce and prevent natural hazard impacts by reducing exposure and vulnerability of the potentially affected elements at risk.

2.3 NATURAL HAZARD RISK IN A CHANGING ENVIRONMENT

The earth surface is a dynamic system which is influenced by natural and anthropogenic factors (USGS 2010). This relates to global change which comprises more than climate change, but also covers changes in population; the economy, including magnitude and distribution; resource use, especially for production of energy; transport and communication; land use and land cover; urbanization; globalization; coastal ecosystems; atmospheric composition; riverine flow; the nitrogen cycle; the carbon cycle; the physical climate; marine food chains; and biological diversity (LE COZANNET ET AL. 2013, KLEIN GOLDEWIJK AND RAMANKUTTY 2004, STEFFEN ET AL. 2004a, SLAYMAKER AND SPENCER 2009). It refers to a remarkable change in the human-environment relationship that has occurred during the last centuries (STEFFEN et al. 2004a). These interactions between environmental change and human societies have a long complex history and vary greatly from place to place and through time (STEFFEN et al. 2004b). It is widely understood that the major driving factors for changes are the change in atmospheric composition, climate change arising from the first and land use change driven by both socio-economic factors and by climate change (BAZZAZ and SOMBROEK 1996). In this context also the earth orbital parameters have an influence on climatic changes, however over a longer time span and related to the current changes the human-made climate forcing make these changes marginal (HANSEN and SATO 2012).

Especially alpine areas are very sensitive to natural but also anthropogenic changes as frequently stated in the last decades (BÄTZING 2003). In the 1960s and even stronger in the 1980s the modern world extensively spread peripheral in alpine areas (BÄTZING 2003). Higher mobility, better access but also the impressive relief and the special climate increased touristic activity on the expense of cultivated pasture. However, these special natural conditions in alpine regions consequently imply factors like high relief energy or heavy rainfalls which in turn lead to natural hazards like floods, snow avalanches or landslides including debris flows, slides and rock falls. In addition an increasing number of publications indicates a correlation between climate change and the frequency and intensity of natural hazards (IPCC 2007a, 2012, HÖPPE 2007).

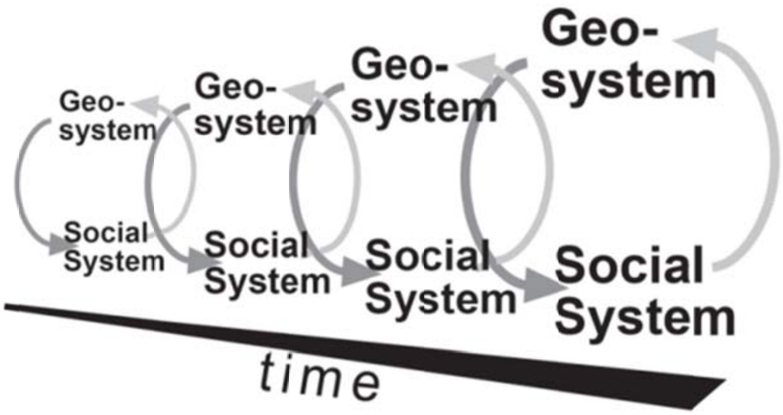


Figure 2.3. Interaction of a system through time (HUFSCHMIDT ET AL. 2005). (in reference to “spacetime” according to MASSEY (1999) this concept was extrapolated also to space)

The assumption that hazards are complex phenomena involving the interaction between natural, social and technological systems (CUTTER 2006), enhanced by the factor time (HUFSCHMIDT et al. 2005) is illustrated in Figure 2.3. It is shown that changes in the social-system levy demands on the geosystem to the extent of changing the landscape and even provoking a physical response, e.g. a landslide. This enhanced process in turn encourages a reaction of the social system. The same holds true vice versa for the geo-system.

Subsequently this interaction over “spacetime” leads to a change in risk, which is a function of hazard (geo-system) and consequences (social-system) including all components: hazard, exposure, vulnerability and the communities´ capacity to respond (LE COZANNET ET AL. 2013, PELLING 2003), as delineated in chapter 2.1. In this context FUCHS AND KEILER (2013) state that *space and time are key factors when information on risk has to be assessed*.

2.4 REGIONAL LANDSLIDE RISK ASSESSMENT

At different spatial levels, different types of risk assessments are carried out addressing different objectives. On a national level, risk assessment as basis for risk management, is an important input for planning and policy making in numerous areas of public and private activity (EC 2010). This is also true for regional risk management, which is a valuable approach in various sectors, ranging from the scale of elements at risk, e.g. a highway, to financial assistance in case of damage. Therein regional risk assessment, which this thesis is focused on, serves as a basis for e.g. identification of priority areas for financial support or mitigation planning.

DAI ET AL. (2002) state that landslide risk assessment requires addressing the probability of a landslide, the landslide runout behaviour, vulnerability, landslide risk, management strategies and decision-making. Referring to mitigation measures as a crucial part of risk management to avoid or limit adverse effects of hazards either by structural but also non-structural measures (UNISDR 2004), the different factors related to risk assessment stated above are listed in the following Table 2.2. Specifically regarding landslides, mitigation measures can be classified into stabilization and control, referring to structural measures and avoidance / tolerance related to non-structural measures (SAFELAND 2011). There are several measures that can be summarised under spatial planning, e.g. land use planning, locational decisions regarding public services and infrastructures or building codes related to both, structural and non-structural mitigation measures. Spatial planning is an integrated part of risk management in the context of avoiding further development in potentially hazardous areas. It can create, increase or reduce risk like no other policy (ESTEBAN et al. 2011) and therefore captures a key role in disaster prevention. KEILER ET AL. (2004) herein also underline that strengthening the tools of spatial planning can facilitate reducing the damage potential. Underlining the time scale of the effect of spatial planning measures, the related measures are all listed under long-term measures, influencing the pattern of exposure and vulnerability (ESTEBAN et al. 2011) which is clearly indicated in Table 2.2. Avoiding development in undesirable conditions is one example of these long-term mitigation measures which can be regarded as very efficient and economic (CASCINI 2008, POMAROLI 2011) and needs to be addressed at a regional scale.

Table 2.2. Short and long-term mitigation measures addressing different risk components (modified after ESTEBAN ET AL. 2011)

	STRUCTURAL		**NON-STRUCTURAL**			
	decreasing hazards	**reducing exposure**	**reducing vulnerability**			
			physical	**social and economic**	**built environment**	**natural environment**
long-term mitigation measures	building consolidation *(comment: referring to reduction of vulnerability)*	land use planning to avoid the most hazardous zone	building codes	preparedness programs	land use planning	preserving diversity of agricultural activities
	levees, outlets, etc.	relocation from the most critical areas	building retrofit codes	education, training of various public sectors	locational decisions regarding public services and infrastructure	tailoring agricultural practices to the type of soil/terrain
	avalanche defence landslide consolidation	insurance integrated to land use planning	norms to secure public facilities, factories etc.	development of programs with the media		protection of marsh areas, humid zones , shoreline dunes
	reduction of gas emissions			adaptation to reduce the impact of climate change		
short-term mitigation measures	lava flow diversion	evacuation	building usability checks	improvement of civil protection, organisational capabilities	accessibility to services and to potentially damaged areas	sustainable practices in lave water flow diversion
	sandbags and barriers		temporary repairs particularly for lifelines	business continuity plans also for the public sector		
	fire control			use of media to dispatch emergency messages		

Additional to dealing with reduction of risk in terms of mitigation planning and risk avoidance, a major issue when dealing with landslides are the related costs referring to recovery and rebuilding, as well as, sustainable planning of reduction strategies. Landslide damages are one of the major consequences of hazards in mountainous areas and account for enormous ramifications in terms of both direct, e.g. physical damage to assets, and indirect, e.g. traffic disruption, costs (BUBECK and KREIBICH 2011), underlining the economic importance. These costs are further related to different stakeholders from e.g. community leaders to related departments/ministries operating within different facilities and sectors ranging from planning, infrastructure, transport to emergency facilities (WEF, 2011). As mentioned above herein also several functions of regional representatives are included underlining additionally the need for regional assessments. Additionally CARPIGNANO AND GOLIA (2009) underline the essentiality of regional assessment also in connecting it to a multi-risk and multi-hazard analysis.

Regional risk assessment, aiming to support issues, such as mitigation planning and reduction of consequences to the affected communities requires detailed investigation including mapping and identification of relevant risks in a certain area. In summary SUKARNA ET AL. (2012) identify three purposes of risk mapping on a provincial, hence regional level:

- *identifying priority areas, where special attention is needed to mitigate the risk caused by natural hazards. A response to such a need could be to establish a regional disaster management agency;*
- *ensuring comparability of the assessment of risk exposure throughout the province, in order to ensure fair and balanced political and financial support to regions in need. This is particularly important for the allocation of budgets for disaster management and mitigation counter measures;*
- *identifying regions at threat, where inter-local cooperation in disaster management is logistically and economically more viable.*

As a first step regional landslide hazard and risk zoning could therefore identify areas with different landslide risk levels which can further provide an ideal framework for non-structural measures (DAI et al. 2002) that can be implemented through policies and law, public awareness raising, training and education (UN-ISDR 2009). An example provided would be avoidance of development in potentially hazardous areas (CASCINI et al. 2005).

For a better understanding of the general framework and theoretical background of risk analysis, and the importance of regional risk assessment, as stated above. The following chapters outline the various components of risk assessment in general as well as for the regional level in more detail.

2.4.1 ELEMENTS AT RISK

One major component of landslide risk assessment is the evaluation of potential consequences. These consequences can be expressed by elements at risk that are damaged or destroyed by the landslide event. Elements at risk can be defined as population, property, buildings and engineering works, infrastructure, environmental features and economic activities also including public services in the area affected by a hazard (FELL ET AL. 2005, COROMINAS ET AL. 2013, PAPATHOMA-KÖHLE ET AL. 2007). Related to population these elements can be further divided into for example residents, commuters and tourists (FUCHS and KEILER 2013). Elements at risk have both, spatial and non-spatial characteristics (COROMINAS et al. 2013) which in the framework of risk assessment express exposure (location based) and vulnerability (object-based), as defined in chapter 2.1. Therein physical vulnerability represents the degree of loss of a given set of elements at risk resulting from the probability of occurrence of a natural phenomenon which is expressed from no loss (0) to total loss (1) (VARNES 1984, FUCHS 2008). As elaborated above the characteristics of the object itself determine the respective vulnerability, e.g. a reinforced concrete building is potentially less vulnerable to a landslide impact than a non-reinforced building. Therefore the detailed analysis of elements at risk is at utmost importance for vulnerability assessment.

Elements at risk can be exposed to a natural hazard due to their spatial location (FRA PALEO 2009), independent of their internal vulnerability which is determined by the specific characteristics of the object (PROMPER and GLADE subm.) This also relates to the dual structure of vulnerability proposed by CHAMBERS (2006) or BOHLE (2001),wherein the external part of vulnerability defined as risks, shocks and stress to which an individual or household is subject. Fuchs (2009) herein also refers to this external part of vulnerability as exposure to natural hazards. However, the degree of damage of an exposed element is dependent on the respective (internal) vulnerability which underlines that exposure analysis as part of vulnerability assessment, is a central part of risk assessment.

Datasets to capture information on elements at risk can be categorized into those providing information on physical assets and those including social aspects, wherein physical elements cover e.g. buildings and life lines and the social elements cover demographic data (HANCILAR 2012). The physical elements that are affected by landslides are for example buildings, infrastructure and life lines of various types (PITILAKIS et al. 2011 . However, PAPATHOMA-KÖHLE ET AL. (2007) include building types also in the assessment of human vulnerability which indicates that various elements at risk can be an indicator for both, social and physical impacts. Physical elements can further be classified into quantitative, qualitative and descriptive datasets (PAPATHOMA-KÖHLE et al. 2007). The following table gives an overview of examples related to buildings and population for the respective analysis level.

Table 2.3. Examples of characteristics of elements at risk within the different categories (modified after PAPATHOMA-KÖHLE ET AL. 2007 and PITILAKIS ET AL. 2011)

Category	Example	Analysis level
Quantitative	• Number of households • Population density	• Regional / local • Regional / local
Qualitative	• Condition • Building surrounding	• Element specific • Element specific
Descriptive	• Building use	• Element specific

LAND COVER AS A COMPONENT OF REGIONAL RISK MANAGEMENT

Elements at risk are an integral part of landslide risk assessment. These elements at risk can be represented by various features depending on the target. When assessing landslide risk on the regional scale or potential future changes, land cover serves as indicator on the spatial distribution of elements at risk e.g. building area, street area or agricultural areas.

Herein land cover is defined as the observed (bio)physical cover on the earth's surface (DIGREGORIO and JANSEN 2000). Therein it includes vegetated areas and built-up areas that are defined as land cover but, in practice also water surfaces, bare rock and artificial structures are included when referring to land cover besides the physical and biological cover (ELLIS 2013). This implies that land cover also implies anthropogenic features, thus elements of land use. Related to land use there are various sources of human impacts besides urbanisation, e.g. shifting cultivation, land abandonment or deforestation (POYATOS et al. 2003) leading to a link between anthropogenic action and natural land cover. Additionally, as elaborated in chapter 2.3, spatial planning has a major influence on the resulting land cover. Therefore land cover implies the distribution of elements at risk and represents an adequate proxy for assessing these assets on a regional scale. Further it also contains natural and anthropogenic impacts that relate to landslide processes.

2.4.2 LANDSLIDE HAZARD ASSESSMENT

Landslides may be classified according to the type of movement: slide, topple, flow or fall and can further be classified according to the type of material (e.g. CRUDEN AND VARNES 1996, DIKAU ET AL. 1996, HIGHLAND AND BOBROWSKY 2008, VARNES 1984) as shown in Table 2.4

Table 2.4. All types of landslides are comprised of three different units namely source or detachment (scarp) area, the track (transition or transit) and the toe (accumulation) (CORSINI et al. 2009).

Table 2.4. A simplified classification scheme for main types of landslide movements (Petley 2010 after Varnes and Krizek 1978)

	Type of material		
	Rock	Engineering soils	
Type of movement		Coarse grained	Fine grained
Falls	Rock fall	Debris fall	Earth fall
Topples	Rock topple	Debris topple	Earth topple
Slides Rotational	Rock slump	Debris slump	Earth slump
Translational	Rockslide	Debris slide	Earth slide
Lateral spreads	Rock Spread	Debris spread	Earth spread
Flows	Rock flow	Debris flow	Earth flow
Complex slope movements (i.e. combinations of two or more types)			

In this thesis the focus is on slides, which are a downslope movements of a soil or rock mass occurring on rupture surfaces on thin zones of intense shear strain (Highland and Bobrowsky 2008). There are several types of slides ranging from curved or rotational to planar or translational (Crozier and Glade 2005, Lee et al. 2004, Nadim et al. 2005), wherein material moves often as coherent or semi-coherent mass with little internal deformation (Highland and Bobrowsky 2008). Comparing the two main types of slides, rotational slides are characterised by a concavely upward curved surface of rupture (spoon shaped) and the slide movement is more or less rotational, a translational slide is characterised by a mass moving along a relatively planar surface which does not show backward tilting and only little rotation (see Figure 2.4) (Clague 2013, Highland and Bobrowsky 2008, Fema 1989). The occurrence of rotational landslides is most frequent in homogenous materials and so called “fill materials”, whereas translational slides are found worldwide in all types of environments and conditions (Highland and Bobrowsky 2008). Translational slides are generally shallower than rotational slides and their size can be in a range of local to regional being several kilometres wide (Highland and Bobrowsky 2008).

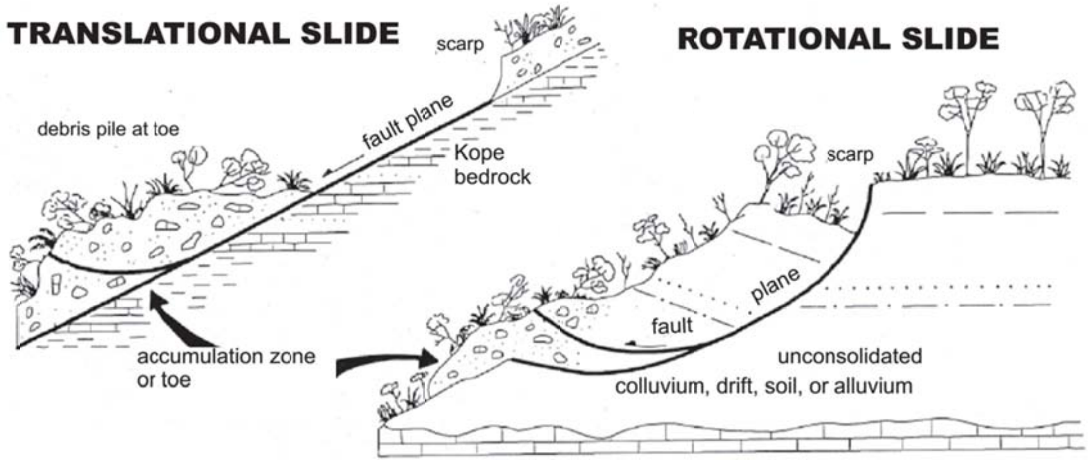


Figure 2.4.Translational and rotational slide in cross section (modified after POTTER 2007)

Landslides may be activated and reactivated by certain triggering factors e.g. precipitation and earthquakes (GLADE et al. 2014). Nonetheless certain predisposing factors for the occurrence of these natural processes (CROZIER AND GLADE 2005, CROZIER 2005) need to be existent. GLADE AND CROZIER (2005) refer to preconditions or predisposing, preparatory and triggering factors related to the initiation of landslides. Preconditions or predisposing factors are inherent and static factors that influence the stability, however also act as catalysts allowing dynamic factors to destabilize the slope more effectively (SRI HADMOKO AND ENGEL-DI MAURO 2012, GLADE AND CROZIER 2005). Preparatory factors are factors that decrease the slope stability over a period of time, however do not initiate movement (GLADE and CROZIER 2005). Consequently, there are two different types of preparatory factors: one type acts over a long time period e.g. tectonic uplift (e.g. LARSEN AND MONTGOMERY 2012, SHRODER AND BISHOP 1998) or climate change (e.g. DEHN AND BUMA 1999). The other, acting on a shorter period of time, for example deforestation (e.g. ALCÁNTARA-AYALA ET AL. 2006, BEGUERÍA 2006a), have proven to have a potentially greater impact on landslides in the upcoming decades (COLLISON et al. 2000). Factors that initiate slope movement are called triggering factors and include for example intense precipitation, longer wet periods and/or snow melt, earthquakes, or also anthropogenic factors such as slope undercutting (ALCANTARA-AYALA ET AL. 2004, LEROI ET AL. 2005; GLADE AND CROZIER 2005). These external stimuli cause a near-immediate response in form of a landslide due to rapidly increasing the stresses or reducing the strength of the material (WIECZOREK 1996). Summarizing various factors ranging from precipitation patterns to slope, aspect, drainage density, lithology, soils/material, land use/cover etc. can be identified as examples of the influencing factors mentioned above related to land sliding (SOETERS AND VAN WESTEN 1996; JEMEC AND KOMAC 2011). In landslide hazard assessment all those factors have to be taken into consideration which makes this a complex undertaking. To overcome these challenges, various approaches for landslide hazard zonation have been introduced: inventory, heuristic, statistic and deterministic assessments (SOETERS and VAN WESTEN 1996), which will be elaborated in the following paragraphs.

The first approach are landslide inventories which are also often the basis for susceptibility maps (JEMEC and KOMAC 2011). According to MALAMUD ET AL. (2004) there are two types of inventories: a) inventories related to triggers and b) historical, geomorphological inventories being the sum of one or many slide events in a region. These inventories allow for a detailed analysis related to distribution and in case of multi-temporal inventories, activity patterns of landslides (THIEBES 2012, MALAMUD et al. 2004). Another approach is the heuristic analysis which is basically the combination of a landslide inventory and preparatory factors which are weighted by experts (JEMEC and KOMAC 2011), which has also been used in several studies (e.g. RUFF AND CZURDA 2008, SCHLEIER ET AL. 2014 or JAEDICKE 2014). Another approach is the aforementioned statistical approach, which can be a bi- or multivariate analysis of parameter maps (PARDESHI et al. 2013) and is always based on a landslide inventory. This approach determines the relationship of landslides and landslide-controlling factors (WANG et al. 2013) and is widely used by e.g. BELL ET AL. (2013), WANG ET AL. (2013), MANCINI ET AL. (2010), THIERY ET AL. (2007), VAN DEN EECKHAUT ET AL. (2006), CHUNG ET AL. (1995) and many more. One statistical approach is for example artificial neural networks, commonly based on a self-organizing structure that resembles the biological neural system of mammalian brains (ERMINI et al. 2005). The models are composed by simple and highly interrelated units that are in connection with each other permanently and these connections between processing units are physically represented by weights and rules for summing the input and calculating the output (ERMINI et al. 2005).

The deterministic approach is mostly site specific and does not account for the spatial distribution of input parameters (VAN WESTEN and TERLIEN 1996). Typically these analysis are based on simple models of groundwater flow combined with infinite slope-stability in order to estimate the potential or relative instability of slopes in a wider region (GODT et al. 2008). When taking into account rainfall induced failures, it is mostly a coupling of shallow subsurface flow caused by rainfall of various return periods, predicted soil thickness and soil mantle landslides (JEMEC and KOMAC 2011). The main disadvantage is that this approach requires a large amount of data on e.g. soil and hydrological conditions to calculate the safety factors over larger areas (VAN WESTEN and TERLIEN 1996). However, VAN WESTEN AND TERLIEN (1996) argue, that after the hazard definition by VARNES (1984) this is the only method resulting in a real hazard map. Further details on the afore mentioned approaches can be found for example in VAN WESTEN AND TERLIEN (1996), ERMINI ET AL. (2005), JEMEC AND KOMAC (2011), RUFF AND CZURDA (2008), YILMAZ (2009) or GUZZETTI ET AL.(1999).

Referring to the different types of landslide susceptibility assessments the relationship to the target scale has to be considered (Table 2.5). This underlines that for the scope of the analyses presented here, a statistical approach is regarded as highly feasible taking into account the targeted regional analysis of landslide hazard. Therefore susceptibility mapping applying a statistical approach is elaborated in more detail in the following chapter.

Table 2.5. Recommended quantitative Methodologies for landslide susceptibility applied at different scales (COROMINAS ET AL. 2013)

Scale	**Quantitative methods**	
	Data-driven statistical models	**Deterministic physically based methods**
National scale (<1:250,000)	No	No
Regional scale (1:25,000–1:250,000)	Yes	No
Local scale (1:5,000–1:25.000)	Yes	Yes
Site-specific (>1:5,000)	No	Yes

LANDSLIDES SUSCEPTIBILITY MAPS FOR REGIONAL RISK ASSESSMENT

On a regional scale " landslide prone areas" or "areas with a certain probability to land sliding" are terms that are frequently used (e.g. TASSER ET AL. 2003, ERCANOGLU AND GOKCEOGLU 2002, PRADHAN ET AL. 2006 or MCINNES ET AL. 2002) which reveals that areas affected by landslides can be identified given a set of environmental conditions (FELL et al. 2008, GUZZETTI et al. 2005), however does not account for information on time or magnitude of landslide occurrence (GUZZETTI et al. 2005).

Landslide susceptibility models are particularly useful for modelling large areas on medium scale (PETSCHKO et al. 2014) and can further be used for a more detailed analysis in relevant areas. DAI ET AL. (2002) argue that on a scale of 1:10,000 – 1:50,000 statistical analysis techniques are considered as most appropriate for landslide susceptibility mapping, as is also stated similar by COROMINAS ET AL. (2013), Table 2.5, because at this scale the occurrence of landslide can be mapped and it is also possible to collect information on the relevant variables e.g. soil, lithology or land cover.

The basic objective of landslide modelling is the spatial and temporal prediction of landslide prone areas (BRENNING 2005). Within this spatial prediction of landslide hazards statistical classification rules are applied for identifying areas that are susceptible to future land sliding (BRENNING 2005) based on the concept that past and present are key to the future (VARNES 1984). This relates to the importance of landslide inventories and therefore to the knowledge on past landslide events. Additionally the relevant parameters with their spatial extent are taken into account. This method is widely used to identify areas that are potentially prone to land sliding in numerous studies especially in mountain areas (e.g. AYALEW AND YAMAGISHI 2005, GROZAVU AND PLEŞCAN 2013 or NANDI ET AL.2010).

Hence modelling landslides susceptibility with logistic regression is a method to acquire information derived from various factors (REGMI et al. 2014) which are aggregated to a certain disposition (JEMEC and KOMAC 2011). In this analysis logistic regression is applied to model the susceptibility which establishes a relationship between landslide location and region-specific landslide-related factors (LEE 2007). Therein the absence or presence of landslides serves as dependent variable (dichotomous), whereas independent variables can be represented by various factors e.g. lithology, slope, aspect, precipitation, land cover etc. predicting the dependent variable (VAN DEN EECKHAUT ET AL. 2012, AYALEW AND YAMAGISHI 2005, YESILNACAR

AND TOPAL 2005, VAN DEN EECKHAUT ET AL. 2006, DAI ET AL. 2001). Logistic regression therefore incorporates independent variables to create a mathematical formula that predicts the probability that a landslide might occur at any given location (YESILNACAR and TOPAL 2005).

2.4.3 LANDSLIDE EXPOSURE ASSESSMENT

In the previous chapters it has already been indicated that landslide risk assessment combines data input from many different sources thus including numerous disciplines (VAN WESTEN et al. 2008) and the scale of analysis is dependent on the aim of the analysis and determined by the size of the study area, the data availability and the temporal and financial limitations (VON ELVERFELDT et al. 2008). Natural hazard exposure is majorly defined by the elements at risk (people, property, systems or other elements) that are subject to potential losses due to the location in a hazardous zone (UN-ISDR 2009, KEILER et al. 2005). Therefore exposure assessments are a reasonable alternative if detailed data on vulnerability or magnitude and frequency of the respective hazard are not available for the regional analysis level. These can provide richness of information at the targeted regional level (SMITH et al. 2014) and in a further step these maps can serve as a basis for in-depth analysis of highly exposed areas. This is also referred to as a top-down approach which represents an approximation on a small scale and in a next step a more detailed an sophisticated methods are applied on a larger scale (KAPPES et al. 2012).

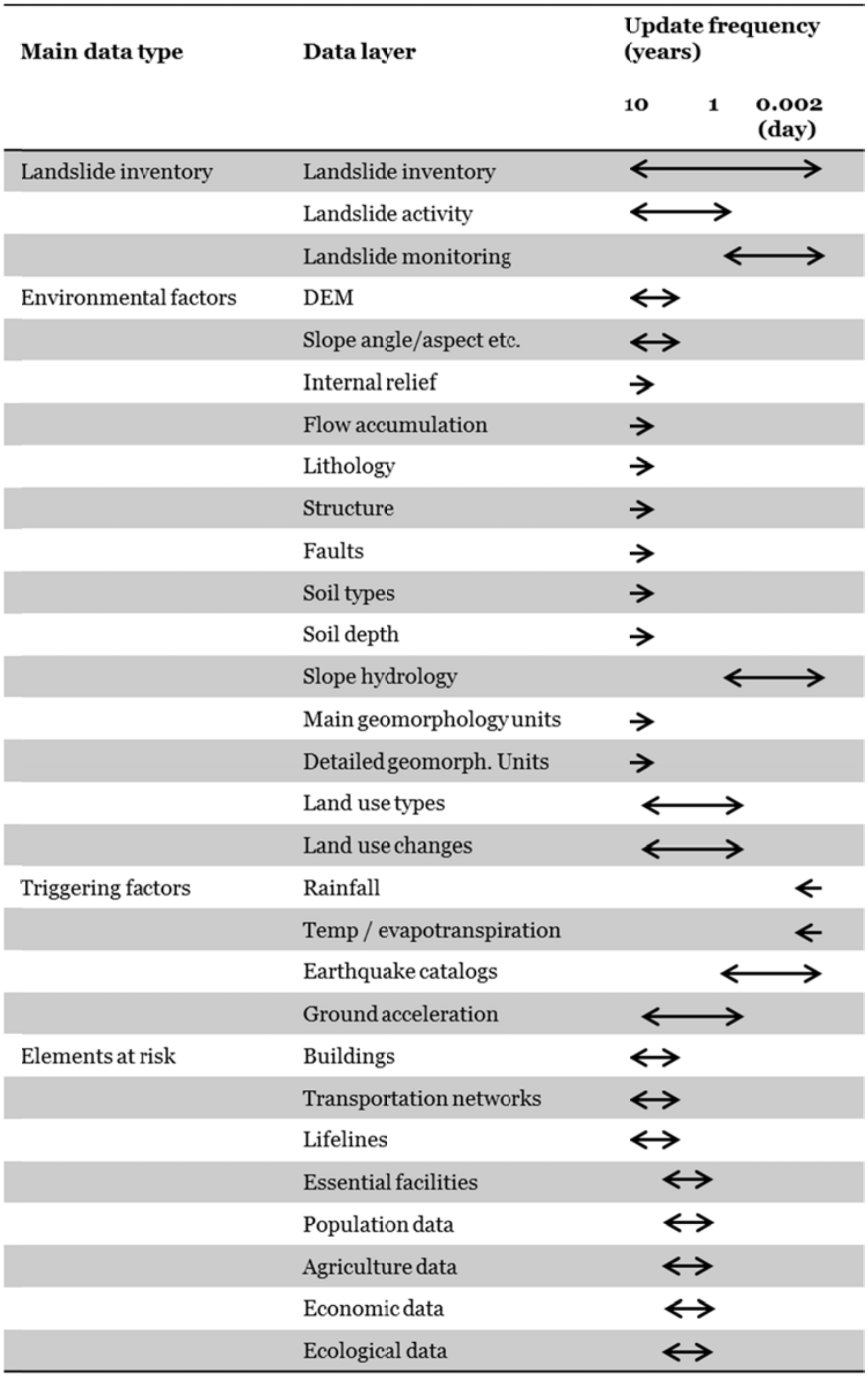
Exposure is the result of a basic locational decision on an individual but also collective basis which is influenced by the demand to satisfy basic needs e.g. income, job or mode of production (FRA PALEO 2009). Additionally exposure can be relatively static, for example referring to buildings, but can also be dynamic when taking into account for example commuting patterns, moving traffic or level of occupancy of a hotel (BRÜNDL et al. 2009). There are several examples of exposure analyses in literature on single-hazard exposure, but also on multi-hazard exposure (e.g. GLADE ET AL. 2012). Examples for single-hazard exposure assessments are: flood exposure analysed for example by DE MOEL AND AERTS (2011), CAMMERER ET AL. (2013) or SMITH ET AL. (2014), LØVHOLT ET AL. (2012) investigated tsunami exposure and PELLICANI ET AL. (2013) conducted a landslide exposure assessment. SMITH ET AL. (2014) and CAMMERER ET AL. (2013) expanded this analysis also by a temporal dimension.

2.4.4 DYNAMIC FACTORS OF LANDSLIDE RISK ASSESSMENT

As mentioned before there are different driving factors of global change, wherefrom two can be associated with landslide risk assessment: 1) climate change resulting from atmospheric changes (first driving factor) and 2) land-use / cover change resulting from socio-economic changes. FELL ET AL. (2005) state that among elements at risk there are two types: fixed or static assets, that change over time and the so called mobile assets, which mark short-term fluctuations, however this superimposition of short-term fluctuations (FUCHS and KEILER 2013) cannot be accounted for in this thesis. Further also the basic data for landslide susceptibility modelling can be subdivided into static and dynamic types (VAN WESTEN et al. 2008). VAN WESTEN ET AL. (2008) subsequently underline that data related to land use and elements at risk (static) need an update of frequency ranging from 1 to 10 years, in dependence on the study area, which is indicated in the following Table 2.6.

.

Table 2.6. Frequency of updating datasets for landslide susceptibility, hazard and risk assessment (modified after VAN WESTEN ET AL.2008)



Main data type	**Data layer**	**Update frequency (years)** **10**	 **1**	 **0.002 (day)**
Landslide inventory	Landslide inventory	←	—	→
	Landslide activity	←	→	
	Landslide monitoring		←	→
Environmental factors	DEM	↔		
	Slope angle/aspect etc.	↔		
	Internal relief	→		
	Flow accumulation	→		
	Lithology	→		
	Structure	→		
	Faults	→		
	Soil types	→		
	Soil depth	→		
	Slope hydrology		←	→
	Main geomorphology units	→		
	Detailed geomorph. Units	→		
	Land use types	←	→	
	Land use changes	←	→	
Triggering factors	Rainfall			←
	Temp / evapotranspiration			←
	Earthquake catalogs		←	→
	Ground acceleration	←	→	
Elements at risk	Buildings	↔		
	Transportation networks	↔		
	Lifelines	↔		
	Essential facilities		↔	
	Population data		↔	
	Agriculture data		↔	
	Economic data		↔	
	Ecological data		↔	

This clearly underlines that there are various factors that need to be updated more or less frequently for a thorough landslide risk analysis. Most of the environmental aspects seem rather static, whereas the data on landslide inventories and triggering events need to be updated regularly. Additionally it is the elements at risk that need to be updated every 1 to 10 years. In the following chapters two main factors, land cover as proxy for elements at risk, and precipitation, are analysed in more detail on their dynamics and relationship to landslide risk assessment.

LAND COVER

Land cover is a predisposing factor for landslides (JEMEC and KOMAC 2011) and therein land cover change does have an influence on the spatial pattern of landslide occurrence and subsequently landslide hazard. Further ALCÁNTARA-AYALA ET AL. (2006) state that especially the loss of vegetation, induced by for example deforestation, can have a major impact on landslide occurrence. BATHURST ET AL. (2010) or BEGUERÍA (2006a) delineate a decrease in land sliding processes with increased forest and pasture cover. Additionally PAPATHOMA-KÖHLE AND GLADE (2012), GLADE (2003) or GERRARD AND GARDNER (2002) investigated the influence of land use and land cover respectively and the coherent landslide activities, and clearly define a link herein.

Land cover is defined by the physical and biological cover over the surface of land and includes water surfaces, vegetation, bare soils and also artificial structures (ELLIS 2013) and is often considered as a static factor in landslide hazard studies (FEIZIZADEH et al. 2013). Subsequently only some research studies involve changes in land use as a factor in the landslide hazard analysis (FEIZIZADEH ET AL.2013, VAN BEEK AND VAN ASCH 2004). However, land cover is changing due to various causes of global change and these changes show an impact on the hazard processes and the distribution of elements at risk. Therefore, VAN WESTEN ET AL. (2008) argue for example that depending on the dynamics of land cover, the hazard analysis needs to be updated accordingly (VAN WESTEN et al. 2008).

Changes in land cover are driven by the interactions between biophysical and human dimensions over space and time (VELDKAMP and VERBURG 2004). These changes in land use can be defined by the anthropogenic replacement of one land use type by another (FISCHLIN et al. 2007). However, DI GREGORIO AND JANSEN (2000) also refer to activities and inputs people undertake in a certain land cover type to produce, change or maintain it. This leads to land use (change) as a link between land cover and the actions of people in their environment (DIGREGORIO and JANSEN 2000).

As delineated above land cover and land use also influences the socio-economic aspect of landslide risk assessment, especially as it refers to the spatial distribution of elements at risk. For instance the development of settlements represents the most profound alteration of the environment, where people impose structures, buildings, paved surfaces and compact bare soils on ground surface (MEYER and TURNER 1994). However, these settlements have secondary effects in multiple scales which encompass material for production and consumption, biodiversity and hydrosystems etc. and thereby alter the land cover in a wider sphere of influence (GRIMM et al. 2008) e.g. by excavation or erosion of acreage.

Related to future changes the EUROPEAN ENVIRONMENT AGENCY (2010) states that recent land use trends also most likely determine the future trends, for example:

- demand for more living space per inhabitant,
- improved transport infrastructure,
- socio-economic forces in agriculture that result in simplification of farming systems and
- concentration on the more productive areas e.g. increase in forest area at the expense of semi-natural grassland and scrub cover.

These future trends imply further development and enlargement of elements at risk e.g. building area and infrastructure and an increase in forested areas.

PRECIPITATION

Changes in temperature and precipitation are likely to have a range of effects e.g. on natural hazards in mountainous environments (GOBIET et al. 2014). As elaborated in chapter 2.4.2 the main triggering factors of landslides are earthquakes and precipitation. There are two reasons precipitation changes should be analysed in more detail 1) Precipitation-triggered landslides are more frequent than landslides triggered by earthquakes (COE et al. 2004) and 2) climate change will influence precipitation in its seasonality and intense precipitation extremes e.g. in the Alps (GOBIET ET AL. 2014, IPCC 2007b, IPCC 2012).

Herein IPCC (2012) states that, on the one hand, models on a global scale project substantial warming in temperature extremes, e.g. leading to an increase in liquid precipitation in Alpine areas (BOGATAJ 2007). On the other hand projected changes indicate more extreme precipitation events, even in regions with an overall precipitation decrease, and a tendency towards an increase in heavy daily precipitation events over most areas of the globe (IPCC 2012; IPCC 2007b). Related to extreme events there are three criteria these can be classified in (BENISTON et al. 2007):

- *Rare – Events that occur with relatively low frequency/rate. Definitions of "rare" vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile.'*
- *Intense – Events characterized by relatively small or large values (i.e. events that have large magnitude deviations from the norm). Not all intense events are rare: for example, low precipitation totals are often far from the mean precipitation but can still occur quite frequently.*
- *Severe – Events that result in large socio-economic losses. Severity is a complex criterion because damaging impacts can occur in the absence of a rare or intense climatic event: for example, thawing of mountain permafrost leading to rock falls and mud-slides.*

BENISTON ET AL. (2007) further state that related to impacts on other systems e.g. agriculture, depending on the system´s state, the spatial and temporal patterns of an event are important. From this an influence of the spatial pattern of precipitation on the occurrence pattern of landslides can be deducted.

Related to this relationship of precipitation and landslides various authors have published research results e.g. KORUP AND GÖRÜM (2011), JAKOB ET AL. (2009), MONTRASIO ET AL. (2009), DIXON AND BROOK (2007), GLADE (2000) or DEHN AND BUMA (1999) dealing also with reactivation of landslides due to climate change. The results of the different studies underline that precipitation does influence the occurrence of landslides, depending on the related preparatory and predisposing factors. Related to rainfall-induced landslides basically a threshold defines the amount of rainfall, soil moisture or hydrological conditions that, when exceeded or reached, are likely to trigger a landslide (GUZZETTI et al. 2007). Therefore it is not only the change in the amount of precipitation, but also the characteristics and duration of precipitation events that are important referring to landslide-triggers.

Another important factor when addressing precipitation and landslides, as mentioned in chapter 1, is the coincident occurrence and interactions of landslides and flooding. This relates to the fact that both are connected to precipitation, runoff, and the saturation of ground by water but also floods that undercut banks of streams and rivers can be a cause for landslides (HIGHLAND and BOBROWSKY 2008). However, this interaction can also be vice versa e.g. a landslide blocking a river and subsequently causing a flood.

2.4.5 CONCEPT OF GLOBAL CHANGE SCENARIOS IN RISK ASSESSMENT

In the sections above it was clearly stated how natural hazard risk assessment is influenced by various factors of global change. Figure 2.5 aims at integrating the role of a changing environment in natural hazard risk assessment and thereby enhance Figure 2.1. It is illustrated that a change in the natural processes or a change in the exposed elements leads to a change in risk. Therein the environmental and climate change influences the hazardous process whereas the socio-economic change impacts the vulnerability. Depending on the future scenarios, including e.g. climate and socio-economic scenarios, changes in risk can be anticipated. Scenarios, in this context, can thus be defined as a simplified but plausible description of future development , based on a coherent and internally consistent set of assumptions referring to driving forces and key relationships (IPCC 2007a). Therefore scenarios are alternative futures wherein the uncertainties represent the scenarios as such (ROUNSEVELL et al. 2006), therein being the reason for scenario analysis.

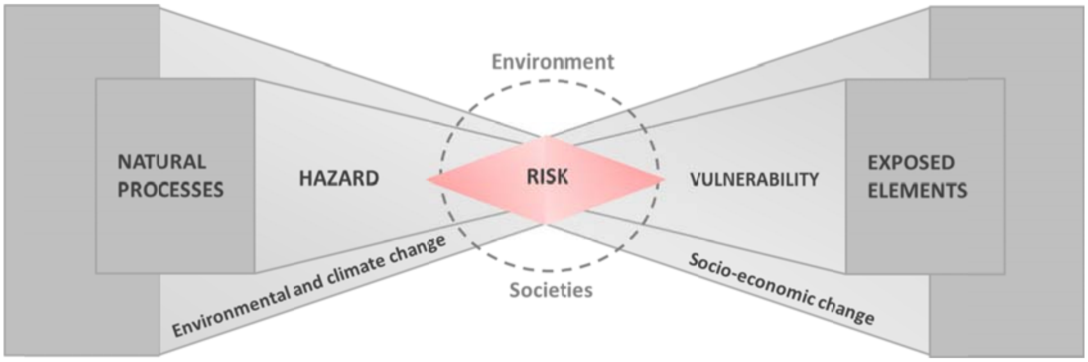


Figure 2.5.Natural hazard risk assessment in a changing environment (modified after ALEXANDER 2002 and MALET ET AL. 2012)

This concept of developing and changing input for vulnerability and consequences respectively has been applied for example by KEILER ET AL. (2004), who analysed the past change of damage potential in different hazard zones, referring to avalanches. CAMMERER ET AL. (2013) assessed the dynamic in flood exposure by a combination of future land cover modelling and flood datasets based on past events. These datasets are based on hydraulic modelling of different return periods by MERZ (2008). Therefore they combined the dynamic factor of land cover with different scenarios of inundation based on the current situation. The same is true for SMITH ET AL. (2014) wo implied modelled population data and spatial footprints of the flood hazard 2012 in Southampton. Therein both studies approximated future risk to a given flood hazard event. Referring to future landslide risk assessment the SAFELAND PROJECT (2012) investigated landslide risk to roads and different land cover types incorporating future land cover maps in the process assessment and the assessment of potential consequences.

Summarizing, landslide risk depends on several dynamic factors like precipitation as triggering factor and land cover as predisposing factor but also reflecting the distribution of elements at risk. Global change augments some aspects of these factors, e.g. frequency and intensity of landslides, which is often connected to either heavy precipitation or precipitation over a longer period of time. Further the elements at risk like productive area or building area are changing over time due to e.g. socio-economic changes. These elements at risk either change their location, spatially or the specific characteristics, hence vulnerability. These spatial changes of the landslide processes, as well as of the elements at risk can coincide thus lead to an increase or spatial shift in landslide risk.

2.5 RESEARCH GAP AND HYPOTHESES

It has been clearly stated in the chapters above that numerous publications and analyses regarding landslide susceptibility have been already carried out, e.g. PETSCHKO ET AL. (2014), PARDESHI ET AL. (2013), GUZZETTI ET AL. (2005), ZÊZERE ET AL. (2004), MALAMUD ET AL. (2004), DAI ET AL. (2001). There are also various publications elaborating the connection of landslide hazards and climate change, e.g. HUGGEL ET AL. (2012), KORUP ET AL. (2011), CROZIER (2010), DIXON ET AL. (2007), BMLFUW (2001) or DEHN AND BUMA (1999). Additionally, several studies show the influence of land cover change on landslide processes, such as BEGUERÍA (2006a), ALCÁNTARA-AYALA ET AL. (2006), GARCÍA-RUIZ ET AL. (2010), VAN BEEK AND VAN ASH (2004), GERRARD AND GARDNER (2002), ZIEMER (1991). Moreover, there is a considerable amount of research on risk and vulnerability connected to landslides from a theoretical point of view, e.g. WINTER AND BROMHEAD (2012), LACASSE AND NADIM (2009), FELL ET AL. (2008), VAN WESTEN AND VAN ASH (2006), LEE (2004), DAI (2002), FELL (1994) and from an operational point of view presenting case study approaches, like JAISWAL ET AL. (2011), CASTELLANOS ABELLA (2008), STERLACCHINI (2007), GUZZETTI (2000).

However, based on the chapters above, it can be stated that risk due to natural hazards changes over time and these spatiotemporal changes are an essential part within integrated natural hazard risk management (see also AUBRECHT ET AL. 2013 or FUCHS AND KEILER 2013). Further, KEILER (2004) postulated improvements in natural hazard risk management by considering damage potential. One of these improvements refers to scenarios showing that process or damage potential influence states of risk. This information on potential future natural hazard risk would be especially useful for insurance business, spatial planning and thus for future adaption and management (e.g. HUFSCHMIDT ET AL. 2005 or HÖPPE 2007). Therefore, there is a specific need to investigate the spatiotemporal development of landslide risk, which has not been extensively analysed so far.

Due to increasing land consumption as a result of increasing need of living space, infrastructural or economic development and a subsequent expansion of elements at risk, a strategic risk management approach on a regional level is essential for planning e.g. aversion of potential risks. Therein it is important to efficiently assess the current situation of landslide risk. If this is not possible due to various constraints, e.g. data availability, an exposure map may serve as basis for detailed analysis in subsequent potential risk hotspots. This is the basis for the first hypothesis:

- ☐ **Hypothesis 1 [H1]:** A regional exposure assessment facilitates identification and ranking of current landslide exposure hotspots in order to support detailed risk analysis.

The main objectives the analysis of this hypothesis aims to explore can thus be stated as follows:

Objective I: Achieving a comprehensive understanding of current potential elements at risk, as well as their exposure to landslides on a regional scale.

Objective II: Identifying different classes of landslide exposure for certain areas within the study area.

Objective III: Identifying exposure hotspots that require subsequent detailed risk analysis.

As delineated in the chapters above, landslide risk depends on various dynamic factors which alter the preparatory and / or triggering factors of an event and the anticipated consequences. Global change herein possibly augments these factors and therefore the second hypothesis can be stated as:

- ☐ **Hypothesis 2 [H2]**: Aspects of global change lead to a change in landslide risk.

Related to the influences of global change implied in the second hypothesis, the respective research objectives consist of:

Objective I: Investigating specific aspects of global change which potentially influence landslide risk.

Objective II: Establishing a methodology for integrating global change into landslide risk assessment by implementing the identified dynamic factors of landslide risk.

The main parameters referring to consequences of landslide impacts are the spatial location of the elements at risk and their specific characteristics. With factors of global change, e.g. higher mobility or higher land consumption, elements at risk can change their location, expand over the study area or change their specific characteristics, hence vulnerability and risk. Based on the spatial development the following hypothesis was developed:

- ☐ **Hypothesis 3 [H3]:** Land cover change influences the spatiotemporal development of landslide risk.

To investigate the impact of land cover change on the spatiotemporal development of landslide risk, the following objectives need to be addressed:

Objective I: Incorporating land cover in the landslide hazard and consequence analysis.

Objective II: Implementing land cover scenarios in a spatially explicit future landslide risk assessment.

The elaborated spatial changes of the landslide processes, as well as changes of the elements at risk often coincide, thus, they lead to an increase in landslide risk. However, also a spatial shift of exposed areas is possible by e.g. changed pattern of susceptibility on existing elements at risk. Additionally, there are so called hotspots of landslide risk which require special attention. This leads to the final hypothesis:

- ☐ **Hypotheses 4 [H4]:** Changes of landslide risk are expected in the future: new elements at risk will develop in susceptible areas and existing elements at risk are superimposed by areas of increasing susceptibility. However, the locations of exposure hotspots will remain unchanged over time.

The specific investigation of exposure hotspots and potential changes in landslide risk thus refers to assessment of the following research objectives:

Objective I: Analysing the spatial and temporal changes of past and future landslide risk.

Objective II: Identifying the location of landslide risk hotspots and compare their locations for different time periods.

3. WAIDHOFEN/YBBS – INTRODUCTION AND DATASETS

To provide an overview of the study area, as it relates to the scope of analysis, the following chapter will delineate the study area of this thesis. Further it contains a presentation of the available input data as well as the generated datasets and land cover scenarios. This should not only serve as an outline of basic input information for further analyses but also comprise all details to gain an overview of the investigated area and the respective datasets used.

3.1 WAIDHOFEN/YBBS - A REGIONAL CENTRE IN THE ALPINE FORELAND

The study area of Waidhofen/Ybbs is located in the alpine foreland in the south east of Lower Austria (see Figure 3.1). It stretches from about 300 m a.s.l. to about 1,115 m a.s.l. at the “Wetterkogel” in Opponitz. The selection of the study area was based on the following considerations:

- the district Waidhofen/Ybbs is located in the Alpine foreland and the main lithological units are calcareous rocks and Flysch, which is prone to landslides (SCHWENK 1992) and according to Petschko et al. (2010) the study area shows one of the highest landslide activities in the region of Lower Austria;
- the city of Waidhofen/Ybbs is a regional centre comprising basic infrastructure and business locations.

First records of natural hazards date back to 1312 with floods caused by the Ybbs river, which occurred repeatedly over the past centuries (STADTARCHIV Waidhofen/Ybbs). The first rock fall was reported as early as 1589 (STADTARCHIV Waidhofen/Ybbs). Additionally debris flows blocking roads or rail tracks were also reported regularly. Slides were only indicated more recently in the archives and from the 1950s onwards the building ground register (BGR) was started, where all events related to earth science such as floods and landslide events were collected and catalogued (GOTTSCHLING 2006). However, this register only includes events that have been reported by affected citizens; therefore mostly events that have caused damages are included therein. Since the introduction of the BGR landslides are thus reported on a regular basis, however, still mostly related to landslide damages (LEITNER et al. 2014).

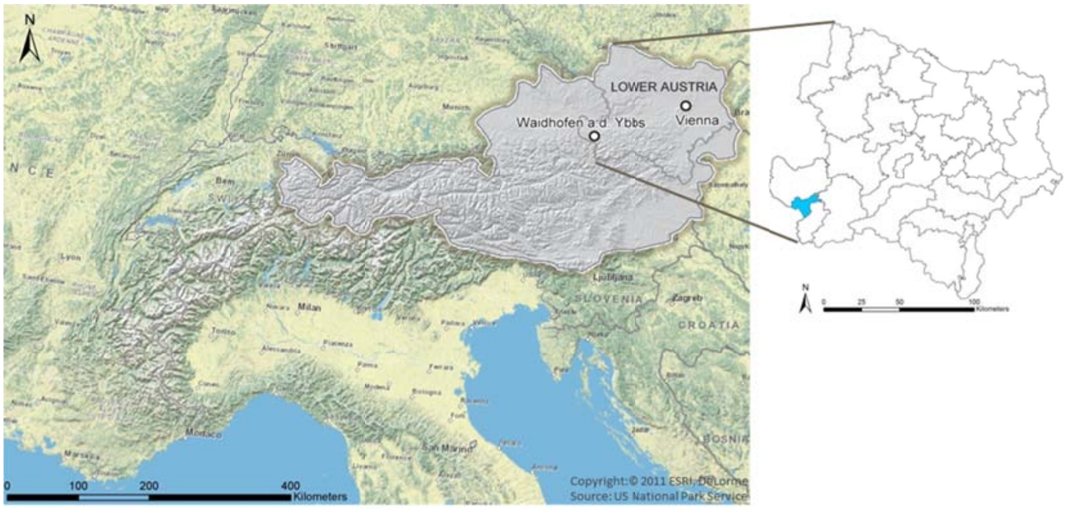


Figure 3.1. Location of Waidhofen/Ybbs (Source administrative boundaries Lower Austria: Provincial Government of Lower Austria)

POPULATION AND ECONOMY

The region of Waidhofen/Ybbs holds the administrative status of a district as well as municipality and comprises an area of around 130 km^2 with about 11,300 inhabitants leading to a population density of around 90 inhabitants per km^2. Around one quarter of the inhabitants live in the city of Waidhofen/Ybbs located in the centre of the district along the Ybbs river which traverses the study area from south to north, see Figure 3.2.

Figure 3.2.Topographic map of the district Waidhofen/Ybbs (Source: Provincial Government of Lower Austria)

The rest of the population is distributed in nine villages and scattered farmhouses mostly located on the hilltops. Overall a slight population decrease has been recorded from 1961 to 2014 (STATISTIKAUSTRIA 2014). In former times the economy of this region was well known for its iron processing, whereas today tourism and educational establishments are the main drivers of the local economy (WAGNER 2005). These business locations are mostly located along the Ybbs to the North and the South of the city of Waidhofen/Ybbs, as well as in the city itself. The municipality income per capita was more than € 4,000 in 2002 (WAGNER 2005) with an increase from 1992 to 2002 (STATISTIKAUSTRIA 2012). Further an increase of overnight stays in the study area was indicated over the last ten years (WAGNER 2005). Due to these generally expanding socio-economic factors and the expected increase in population in the region, an increase of damage potential is indicated for the study area.

GEOLOGY AND GEOMORPHOLOGY

The investigated area is located in the Alpine foreland, which is characterised by tertiary and quaternary sediment deposits incised by the river Ybbs and other small rivers, cutting their way to the Danube. The Ybbs river enters the study area in the south east and turning to the North crossing the city of Waidhofen/Ybbs, where it is deeply incised. The lithology is composed of Limestone, Flysch, the "Klippenzone" and Dolomite (WESSELY 2006). The northern part of the study area, the Ybbsitzer unit (DECKER 1990), is characterised by the Flysch zone with an abundance of sandstone, marlstone and mudstone (WESSELY 2006) and therefore prone to sliding and flowing (KRENMAYR and HOFMANN 2002).

Figure 3.3. Gentle hill slopes in the Northern area of the district (a) and scattered settlements (b) in the region Waidhofen/Ybbs, Lower Austria (pictures taken by (a) Canli, 2012 (b) Gokesch, 2012).

This part of the study area is characterised by smooth hills Figure 3.3., whereas the southern part, the northern limestone Alps, comprise calcareous rocks, dolomite and marles (DECKER 1990). Therefore the southern part is dominated by steep slopes and deeply incised valleys. The two lithological units are separated by the Klippenzone which is comprised by cretaceous shales and marls (WESSELY 2006).

CLIMATE AND CLIMATE CHANGE

According to the climate classification of Bobek et al. (1971) Waidhofen/Ybbs generally can be ascribed to the Alpine foreland, which is characterised by a mean annual precipitation of 1,000–1,500 mm. This fits perfectly with the current climate data for the district of Waidhofen/Ybbs according to the ZAMG (Austrian Central Institution for Meteorology and Geodynamics). The daily mean temperature is 8.2 °C and ranges from the maximum temperature of 37.3 °C to the minimum temperature -25.8 °C ZAMG 2014). The yearly precipitation sum is 1,133.6 mm and the days with more than 1 mm of precipitation are 140.4 wherefrom 36 days indicate precipitation of more than 36.8 mm (ZAMG 2014). The highest precipitation sums (monthly), as well as the maximum precipitation sums in 24 hours are recorded in the summer months. Extreme precipitation events in this area can reach a daily maximum of over 100 mm.

According to LOIBL ET AL. (2007) an increase in temperature and an overall decrease in precipitation is expected. The warming in autumn is expected to be stronger than the expected warming in winter. The overall amount of precipitation will decrease around 10 % (LOIBL et al. 2007). The mean intensity of precipitation will be increasing whereas the frequency of events will decrease (LOIBL et al. 2007).

SOIL TYPES AND LAND COVER

The main soil type in Waidhofen/Ybbs is brown earth, however, patches of Rendsina, Gley and Pseudogley are also present in the study area. The soil depths range from profound to medium depth with shallow patches (BFW 2013). However, especially the South of Waidhofen/Ybbs can be classified as one of the regions in lower Austria with high uncertainties concerning soil data.

The land cover in Waidhofen/Ybbs is dissected. The steep slopes in the southern part of the study area are dominated by forest cover. The forested areas are characterized by either large coherent areas or thin rows of trees for wind shelter PROMPER and GLADE 2012). The latter are often aligned between the grassland and arable land creating a rather dissected picture of the land cover in the study area, Figure 3.4 (PROMPER ET AL. 2012, PROMPER ET AL. 2014) The rolling hills in the northern part are dominated by grassland and arable land. The villages are mostly located in the valleys while farms and hamlets are scattered over the hilltops.

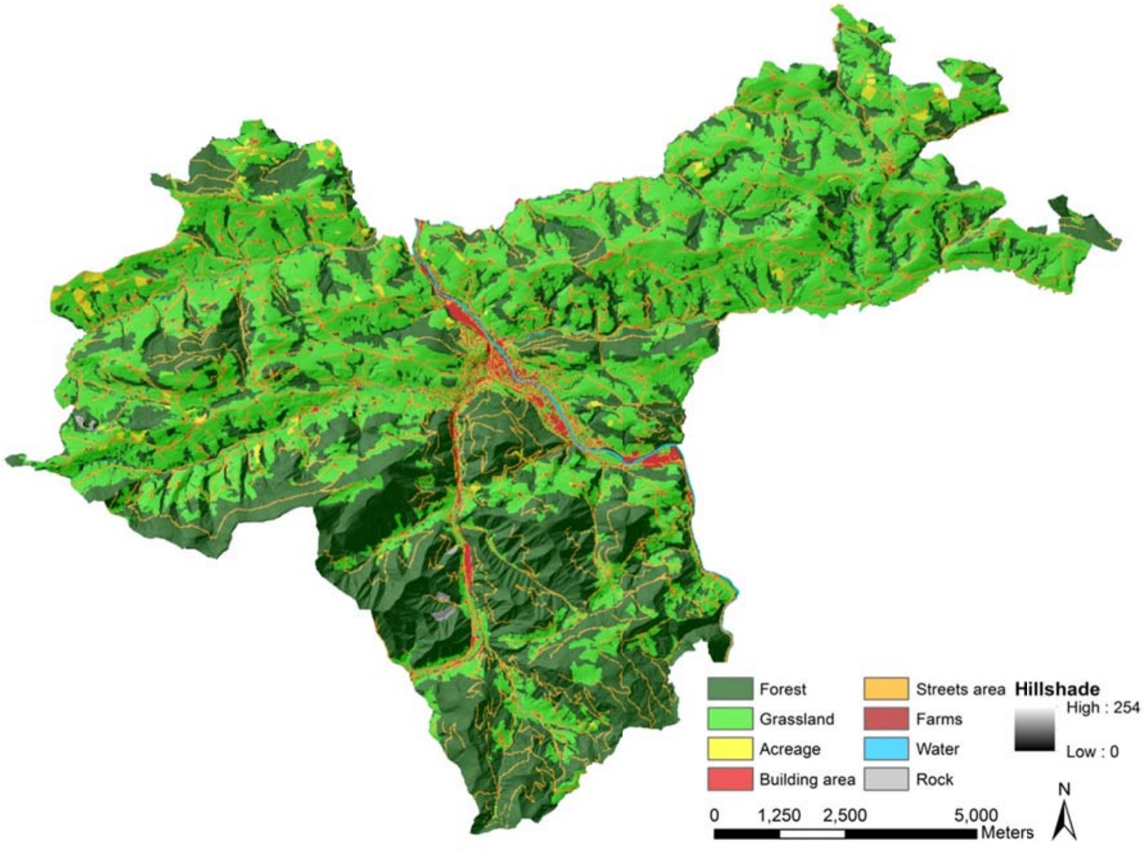


Figure 3.4. Land cover in Waidhofen/Ybbs 2005

LANDSLIDES AND LANDSLIDE DAMAGES

As described above, the Flysch area and the Klippenzone is characterising the northern part, whereas calcareous rocks comprise the southern part of the study area. SCHWENK (1992) indicated that especially the Flysch zone and the Klippenzone are highly prone to landslides compared to all the other lithological units in Lower Austria. PETSCHKO ET AL. (2010) analysed the different types of landslides for the district of Waidhofen/Ybbs (Figure 3.5) resulting in a total number of 691 landslides mapped on the ALS (airborne laser scanning). From these a majority was classified as slides whereas also flows and complex landslides could be identified (PETSCHKO et al. 2010). In the southern and central part of the study area (limestone and dolomite) the number of landslides is significantly lower (PETSCHKO et al. 2010) which was also indicated in the study of SCHWENK (1992). In the BGR, which as previously stated covers all reported events from the 1950s onwards, a total number of 150 damaging events is reported, which affected mainly infrastructure and buildings.

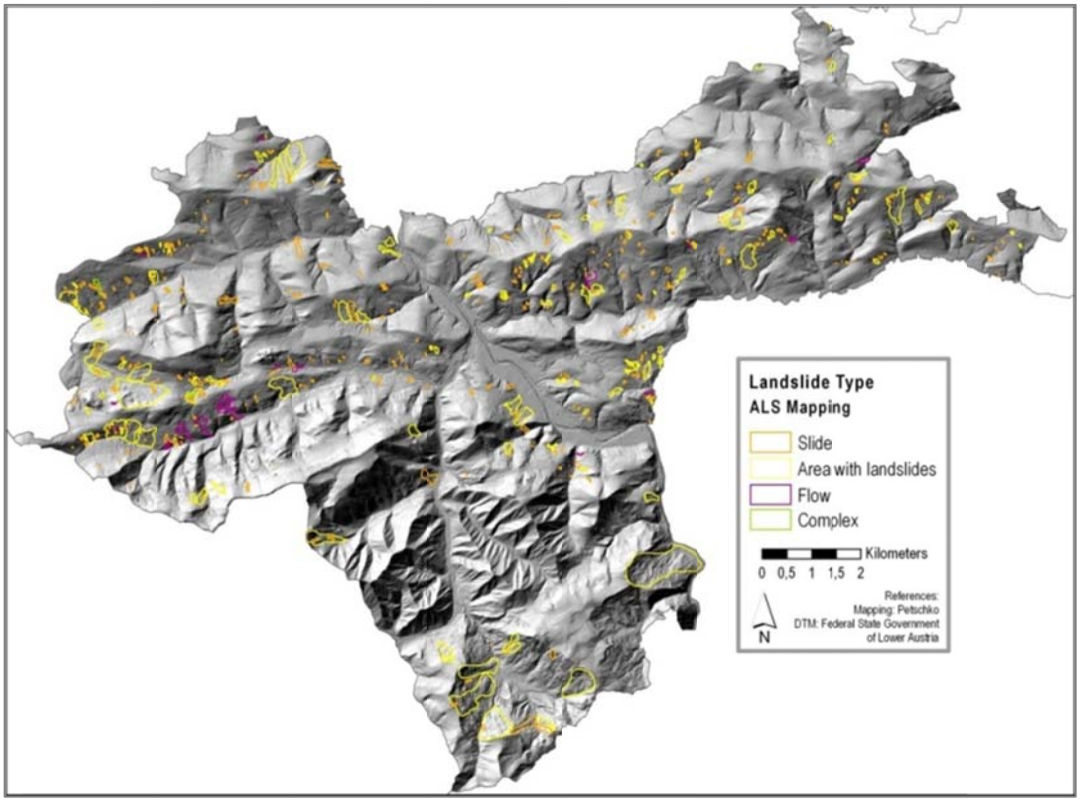


Figure 3.5. Landslide types as mapped on the basis of ALS DTMs (PETSCHKO ET AL. 2010)

3.2 DATASETS

For this thesis several input datasets were used for the analysis. Additionally further datasets were generated throughout the analysis. For better understanding of the methodological approach all datasets used in this analysis are listed in Table 3.1.

Table 3.1. Input datasets and generated datasets

Dataset	Time period/year	Resolution / Scale	Source
Aerial Photographs	1962	1:29,000	BEV
Aerial Photographs	1979	1:38,000	BEV
Aerial Photographs	1988	1:36,000	BEV
Orthophoto	2005	25cm	Provincial Government of Lower Austria
DEM	2006-2009	1m	Provincial Government of Lower Austria
Topographic Map	2007	1:50,000	Provincial Government of Lower Austria
Digital Cadaster Map	2011	1:1,000	Provincial Government of Lower Austria
Landslide susceptibility map	1962	20m	GASSNER et al. 2013
Landslide susceptibility map	1979	20m	GASSNER et al. 2013
Landslide susceptibility map	1988	20m	GASSNER et al. 2013
Landslide susceptibility map	2005	20m	GASSNER et al. 2013
Susceptibility maps scenario 1	2030, 2050, 2100	20m	GASSNER et al. 2013
Susceptibility maps scenario 2	2030, 2050, 2100	20m	GASSNER et al. 2013
Susceptibility maps scenario 3	2030, 2050, 2100	20m	GASSNER et al. 2013
Susceptibility maps scenario 4	2030, 2050, 2100	20m	GASSNER et al. 2013
	Generated datasets		
Land cover map	1962	20m	
Land cover map	1979	20m	
Land cover map	1988	20m	
Land cover map	2005	20m	
Land cover map scenario 1	2030, 2050, 2100	20m	
Land cover map scenario 2	2030, 2050, 2100	20m	
Land cover map scenario 3	2030, 2050, 2100	20m	
Land cover map scenario 4	2030, 2050, 2100	20m	
Cumulated map of elements at risk	2013	20m	
Multilayer exposure map	2013	20m	
Exposure map scenario 1	2030, 2050, 2100	20m	
Exposure map scenario 2	2030, 2050, 2100	20m	
Exposure map scenario 3	2030, 2050, 2100	20m	
Exposure map scenario 4	2030, 2050, 2100	20m	

SUSCEPTIBILITY MODELLING AND SCENARIOS

The creation of the landslide susceptibility maps required for this study are presented here in detail, as they are an integral part of the further analysis but were not created within this thesis. However, the land cover scenarios developed in this thesis serve as input for the susceptibility maps, therein it is necessary to give some details on the susceptibility modelling approach. The way the scenarios are integrated into the analysis is also illustrated in Figure 4.1 in the following chapter.

Landslide susceptibility analysis can be helpful in identifying areas that are potentially prone to landslides (PETSCHKO et al. 2014). As delineated in chapter 2.4.2 landslide susceptibility maps can serve as a good basis for a regional assessment since different parts of an area are more prone to sliding than others. The susceptibility for the assessment of the current situation was investigated based on statistical regression analysis (ATKINSON AND MASSARI 1998, BELL 2007, VAN DEN EECKHAUT 2006).

The susceptibility modelling was carried out using multivariate statistical regression analysis which was also applied by e.g. (REICHENBACH ET AL. 2014 or SHAHABI ET AL. 2013). It is based on dependent and independent variables. Therein a landslide inventory serves as dependent variable, whereas various environmental factors were inserted as independent or explanatory variables (see Table 3.2). For the modelling a random sample of n = 606 slides as well as non-slides are equally distributed (GASSNER et al. 2014). The regression coefficients are elaborated based on Akaike´s Information Criterion (AKAIKE 1974) by a stepwise backward variable selection. The validation is based on the AUROC value (BEGUERÍA 2006b) and therefore the area under the ROC curve was used as a validation criterion (GASSNER et al. 2013). The input parameters are summarized in the Table 3.2.

Table 3.2. Input parameters for the current susceptibility modelling

Dataset	Resolution / Scale	Source
Lidar DTM (derivates: plan/ profile curvature, slope, aspect, elvation	1 m	Provincial Government of Lower Austria
Precipitation daily sum 1961-2100	downscaled 1 km	ZAMG LOIBL et al. 2007
Land cover year: 2005	20 m	PROMPER et al. 2014
Landslide inventory	n = 103, polygons	shallow landslides occurred in the periods 1962-2007, mapped on orthophotos verified with damage reports at the Geological Survey
Lithological map	1:200,000	Geological Survey of Austria, simplified (reclassified) by Austrian Institute of Technology

The decision for considering the daily sum for precipitation data is based on the following Figure 3.6 which clearly indicates that the daily sum of precipitation is decisive for the occurrence of landslides in the Flysch zone which inhabits most of the occurred landslide events in the study area. Further SCHWENK (1992) also refers to heavy precipitation events as main triggering factor for landslide in the study area (see also chapter 3.1).

Landslide susceptibility is the probability that a region will be affected by landslides considering a set of environmental conditions (GUZZETTI et al. 2005). Herein it is important to distinguish between static, e.g. lithology as a predisposing factor (see chapter 2.4.2) and dynamic factors. Since, as already described above, the environmental conditions change over time, it is necessary to implement certain dynamic factors of landslide processes into the susceptibility analysis. This relates to preparatory and triggering factors elaborated in chapter 2.4.2. The implementation of these variables related to changing conditions was conducted by applying regression coefficients that were calculated for the current situation. These calculated coefficients, as well as the datasets on static parameters remained the same over the whole modelling process. However, the datasets for the dynamic parameters, land cover and precipitation were exchanged for analysing the past and future steps, see also Reichenbach (2014).

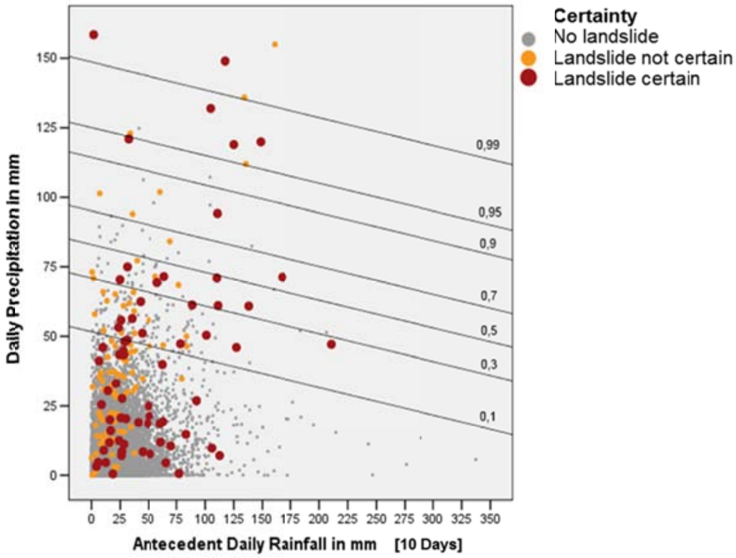


Figure 3.6. The application of the Antecedent Daily Rainfall model for the Rheno Danubian Flysch zone in Lower Austria for the period 01.1971 - 08.2009 (WALLNER 2012)

The method for the creation of the susceptibility scenarios is based on the statistical approach presented above supplemented by the inclusion of the dynamic factors land cover and precipitation. This was conducted by applying the regression coefficients for precipitation (time period 1988 – 2005) to the future scenarios where precipitation data was replaced for each time step (GASSNER et al. 2014). The same was applied for the land cover coefficients (land cover map 2005), whereas the static parameters (i.e. lithology, slope etc.) remained unchanged within the different calculation steps (GASSNER et al. 2014). For further analysis the susceptibility maps were classified in quartiles resulting in 4 classes from “very low” to “high”. This classification was chosen to achieve a better comparison of the different maps and it was established that four classes are reasonable considering that more classes would not necessarily present more accuracy and therein enhance clarity(COROMINAS et al. 2013).

4. ASSESSMENT OF SPATIOTEMPORAL DEVELOPMENT OF REGIONAL LANDSLIDE RISK – A METHODOLOGICAL APPROACH

As elaborated above, there are various aspects influencing preparatory and triggering factors of landslide processes but also dynamic factors influencing the spatial development of elements at risk. In this analysis several steps are combined in order to develop scenarios of spatiotemporal development of regional landslide exposure as integral part of landslide risk assessment. The following Figure 4.1 indicates the procedure of regional landslide exposure assessment displaying the current situation and the approach for spatiotemporal landslide exposure analysis.

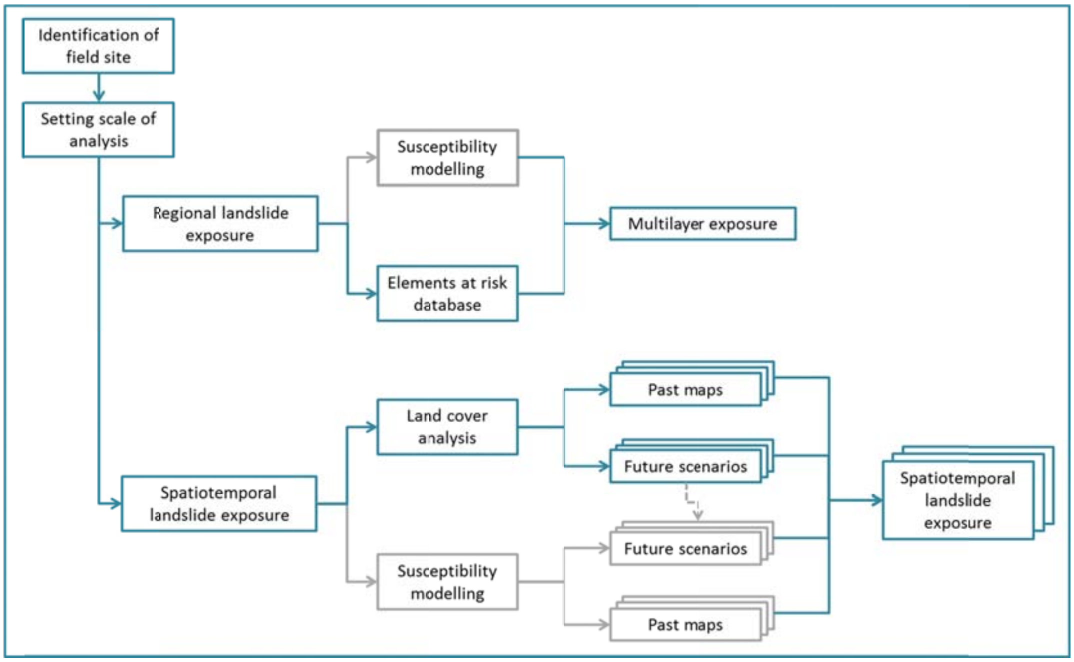


Figure 4.1. Overview of the applied exposure assessment (contribution within this thesis in blue)

As delineated above in Figure 4.1 this thesis is divided in two main parts:

- the regional landslide exposure,
- and the spatiotemporal development of landslide exposure.

The regional landslide exposure is assessing which types of elements at risk are exposed to landslides on a regional level and the results display the current situation of exposure. Herein, the assessment of exposure is based on the concept of elements at risk being subject to losses due to the location in a hazardous zone (UNISDR, 2009). In the second part spatiotemporal scenarios of landslide exposure are developed wherein the assessment of past and the modelling of future land cover is an integral part.

In Figure 4.1 the elements related to susceptibility mapping are illustrated in grey, indicating that the susceptibility modelling was not carried out within this study but implemented in the final exposure scenarios by integrating the results of the susceptibility study into the modelling process. For details on the susceptibility analysis please refer to chapter 3.2.

4.1 REGIONAL LANDSLIDE EXPOSURE ASSESSMENT

Within the regional exposure assessment physical elements at risk that are affected by landslides in a range of impact mechanisms, like for example: burial, collision impact, earth pressures, or plastic deformation by object displacement (GLADE and CROZIER 2005), are investigated. Indirect impacts may comprise the interaction of landslides with other systems or processes (GLADE and CROZIER 2005) e.g. fluvial systems by damming a lake or also infrastructural systems, e.g. road blockage. The impact of landslides on elements at risk does not only depend on the magnitude of the process but also on the structural properties of the exposed elements at risk (PITILAKIS et al. 2011 , thus the respective physical vulnerability, see also PAPATHOMA-KÖHLE ET AL. (2011). Additionally the damage costs are related to the characteristics of elements at risk, e.g. the living area of a residential building. Therefore it is important to assess the location and the respective characteristics of all potentially affected elements at risk. In this section a spatially explicit approach to assess landslide exposure on regional scale is elaborated. The aim is to display the exposure of elements at risk and explicitly refer to the different types of elements at risk that can be exposed in a certain location. Therefore the base for exposure assessment is information on elements at risk as well as information on landslide susceptibility (see also chapter 2.4.1 and 2.4.3).

4.1.1 ELEMENTS AT RISK DATABASE

A basic part of risk assessment is to obtain detailed information on the elements at risk. Therefore field mapping was conducted within this analysis to generate a detailed database of the elements at risk in the study area. The focus herein is laid on buildings and the respective characteristics and usage as it relates to vulnerability and damage potential towards landslides. Therefore a detailed catalogue of all assets with different categories was set up for a structured way of data collection and efficient field work (see Table 4.1). In total 27 building types, which were identified in the field, the number of storeys and a visual interpretation of the condition were recorded (PROMPER and GLADE subm.) This number of storeys and the condition have a direct influence on damage potential, however the condition can also impact the structural property of a building.

The building types are differentiated according to their usage based on visual interpretation. In more detail the building types did not only include the general building-types, e.g. offices, shops, farmhouses or residential buildings, but in the latter two examples a further differentiation on the approximation of the number of parties living in these buildings, therefore single-family houses (SP) and multiple-family houses (MP) were differentiated. Further several combinations of building-types were assessed to provide a more detailed view on the elements at risk in the area. The same visual approach was applied to assess the storeys of each building; however, the cellars of the buildings were not included. The assessment of the condition is based on various criteria which can be identified visually from the outside:

- **bad:** cracks in walls, open roof, old windows, semi- intact render
- **moderate:** old windows, discoloured but intact render
- **good:** intact windows, intact render, intact roof

Further optional information regarding any other important features or characteristics of a building, such as “in renovation” or a special use e.g. fire brigade were added to the database. This detailed catalogue ensures an efficient and comprehensive recording of the buildings in the study area which can further be included in the exposure assessment.

Table 4.1. Building Categories and characteristics

type	storeys (1-5)	condition (bad, moderate, good)	description (optional e.g. "in renovation")
office building			
shop			
industry			
hotel			
restaurant			
wayside cross			
transformer			
fuel station			
church			
other			
garden shed			
garage + stable			
shed + garage			
shed + stable			
stable			
shed			
garage			
farmhouse + garage			
farmhouse + shed			
farmhouse + stable			
farmhouse MP			
farmhouse SP			
residential building MP + shop			
residential building SP + shop			
residential building MP			
residential building SP			
school			

4.1.2 MULTILAYER EXPOSURE ASSESSMENT

The multilayer exposure analysis is based on the fact that landslides do not only have a source area but do have a run out zone which needs to be accounted for. Therefore it is possible that within the area of one landslide different elements at risk are affected, which should be accounted for by superimposition of the different elements at risk.

In this section the landslide exposure was assessed by the intersection of various sets of elements at risk with a landslide susceptibility map. This method is based on e.g. PELLICANI ET AL. (2013) or GLADE ET AL. (2012), however, it implies multiple layers of different types of elements at risk that may be superimposed in one location in order to enable to distinguish between different degrees of exposure. As a first step the different elements at risk were enlarged by a buffer representing the average length of landslides in the study area. To account for the whole area of a landslide a minimum distance from the landslide scarps to the potential impact on an element at risk is selected as buffer distance. This serves as approximation of the range of a landslide potentially impacting various elements at risk (PROMPER et al. in press). In a second step these layers of the different types of elements at risk including the buffer area were converted to binary raster files with 0 (element at risk not present) and 1 (element at risk including buffer present) for each type of element at risk over the whole study area (PROMPER et al. in press). They were prepared binary in order to enable a potential superimposition by overlaying them and at the same time identify afterwards which layers exactly are affected. Further, the susceptibility map described in chapter 3.2 was adducted. The calculation itself was conducted by multiplying the susceptibility map as first layer by 1000, the second layer (EaR_1) by 100 the third (EaR_2) by 10 and the fourth (EaR_3) representing the different layers of elements at risk by 1 with a raster calculator in a GIS environment (PROMPER and GLADE subm). The layers of different types of elements at risk e.g. streets or residential buildings can be extended by additional layers by adjusting the calculation. This procedure is illustrated in the Figure 4.2.

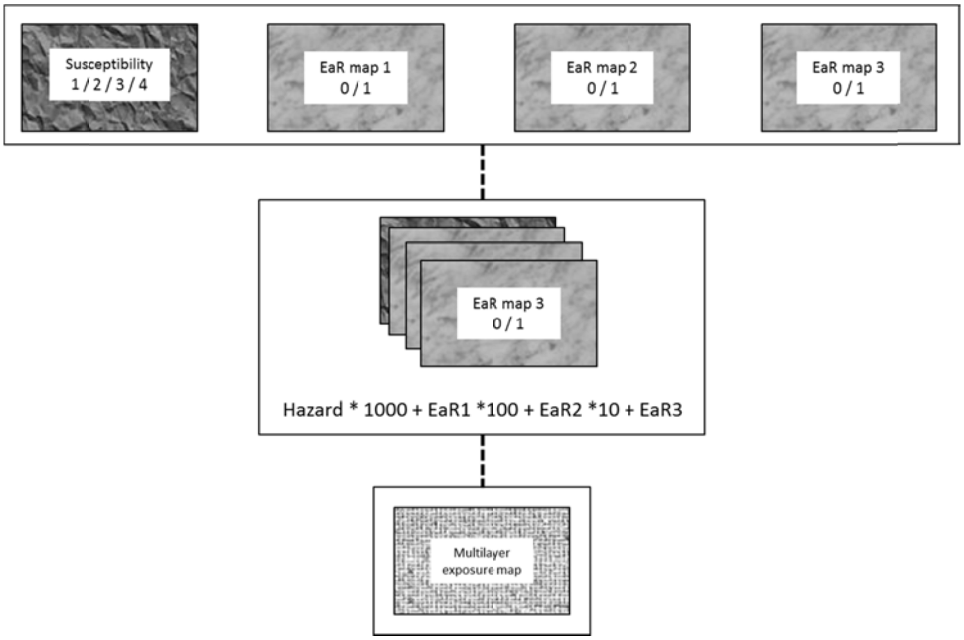


Figure 4.2. Procedure of intersecting the process and elements at risk datasets (PROMPER AND GLADE SUBM)

The resulting four digit code represents a susceptibility value for each pixel and the number of respective layers of elements at risk present in the specific location. Table 4.2 indicates the different codes resulting from the elaborated analysis. Further details can be read in PROMPER ET AL. (subm).

Table 4.2. Possible codes of intersection results (PROMPER AND GLADE SUBM)

EaR layer affected / **Susceptibility**	**No EaR**	**EaR_3**	**EaR_2**	**EaR_1**	**EaR_3 and EaR_2**	**EaR_1 and EaR_2**	**EaR_1 and EaR_3**	**EaR_1 and EaR_2 and EaR_3**
1	1000	1001	1010	1100	1011	1110	1101	1111
2	2000	2001	2010	2100	2011	2110	2101	2111
3	3000	3001	3010	3100	3011	3110	1301	3111
4	4000	4001	4010	4100	4011	4110	4101	4111

4.2 LAND COVER ANALYSIS

As delineated in 2.4.1 land cover in this analysis is a linkage between land cover and anthropogenic influence (DIGREGORIO and JANSEN 2000), thus land use therein represents natural land cover elements and anthropogenic structures. This is important for the consequence analysis, which is further important for the risk assessment. In this chapter the detailed method for past and future land cover analysis is described.

4.2.1 SETTING THE SCALE OF ANALYSIS

The first step for the analysis is to set the appropriate scale. This is the scale which, according to GIBSON (2000), is defined by the spatial, temporal, quantitative, or analytical dimensions to measure and study a phenomenon. It is important to take the extent and the resolution of the analysis into account, which covers the size of the dimensions mentioned above (GIBSON et al. 2000). In the following setting the spatial and temporal scale and their subsequent extent and resolution are elaborated.

SPATIAL SCALE

The spatial extent of the analysis is set according to the scope of analysis and thus can be referred to as local, regional, national or global. As an example “regional” could be interpreted at many different geographical levels depending on the story lines and therefore becomes a judgement by the scenario developer and herein is likely to vary as a function of geographical extent and objectives of a particular study (ROUNSEVELL et al. 2006). Further the respective resolution related to the target phenomena is selected based on the available data for the study area and the minimum size of the target elements at risk and landslide area. In this study a regional assessment is the scope of the analysis. The resolution of the datasets was selected in accordance to the minimum size of elements at risk and according to a reasonable size related to the study area.

TEMPORAL SCALE

Related to the past analysis datasets with the same time interval should be selected. If possible the selection should also be in accordance with the datasets of the landslide inventories. Ideal datasets are aerial photographs in similar resolution covering the same extent and comprise the study area respectively (PROMPER and GLADE 2012). For recent land cover, available orthophotos serve as a mapping basis. Related to the duration in the future frequently used periods e.g. analysis periods of IPCC can be applied in order to ensure comparability. The whole analysis duration therefore is determined by the first year in the past and the last year defined in the future. The temporal resolution is preassigned by the analysis intervals that are represented by intermediate years of analysis which are analysed for different scenarios to ensure a comparability of results.

4.2.2 DEFINING APPROPRIATE LAND COVER CLASSES

For the land cover analysis the classification, defining which land cover types are mapped and modelled respectively, has to be set. This classification is bound to 1) the study area and the predominant land cover classes and 2) to the importance of the respective land cover classes for the scope of analysis (Figure 4.3). Therefore it is important when reclassifying land cover types to e.g. not include streets into built up areas but leave them as separate type of element at risk for landslide risk analysis as infrastructural element but also as potential anthropogenic trigger. The classes within this analysis were thus chosen based on the visual interpretation of the aerial photographs.

4.2.3 ANALYSIS OF PAST LAND COVER

The analysis of past land cover comprises the spatial delineation of the different land cover classes for each analysis period. This delineation needs to be based on certain criteria in order to ensure comparability when analysing changes. Therefore the first step for this analysis should be to set criteria for distinguishing and mapping the respective land cover classes. This can be done by delineating surface structures e.g. smooth surfaces in contrast to lined areas that for example evolved due to mowing. Therein the border of the land cover types can be defined according to the visual difference of one to another. In the second step the land cover maps have to be prepared either on the basis of aerial photographs or orthophotos or by reclassifying existing land cover data e.g. CORINE land cover. However, if other maps related to past or current land cover exist it is important to streamline these in order to delineate changes over time. Therein it is important to indicate the same land cover types for each time step and also the resolution of the different datasets needs to be accounted for in order to compare and analyse the past land cover changes.

4.2.4 ANALYSIS OF FUTURE LAND COVER

For the analysis of future land cover a special framework was developed in order to account for the specific needs of landslide risk analysis. In this chapter of the thesis the land cover modelling process is described alongside the framework in Figure 4.3.

The first steps given in the framework concern spatial and temporal scale [1] and availability of data which has already been elaborated above. Further also the selection of the land cover classes [2] is described above. The next step to be covered is the selection of the model [3] and the development of scenarios [4]. This will be elaborated in the next paragraphs, whereas the detailed application of the model for the specific study area and the subsequent parameter definition for this study is described in chapter 5.2.4.

SELECTION OF THE LAND COVER MODEL

The selection of the land cover model is done according to certain criteria. Therein (AGRAWAL ET AL. 2002) propose a framework which was also integrated in the methodological framework for land cover modelling for landslide susceptibility and consequence analysis, Figure 4.3. In this analysis it needs to feed into the hazard as well as the consequence component of landslide risk. The main factors herein are 1) space, 2) time and 3) human decision making (AGRAWAL et al. 2002). This is based on the interaction in space and time of biophysical but also anthropogenic factors after (VELDKAMP AND FRESCO 1996). The factors space and time were already elaborated above delineating duration, spatial extent and resolution. The model needs to serve the necessities presented for these two factors, therefore serve a regional analysis and allow yearly steps appropriate for land cover changes to be detected. Additionally the factor of human decision making is a major aspect to be considered as spatial planning has a crucial influence on the spatial development of elements at risk. Therefore the model is also selected according to the possibility of implementing spatial planning tools and human decisions e.g. deforestation.

ADAPTATION OF LAND COVER DEVELOPMENT SCENARIOS

A scenario of land cover change is a story told in words, numbers and maps creating alternative images on how the future might unfold (PONTIUS AND NEETI 2010, NAKIĆENOVIĆ ET AL. 2000). In a more technical way land cover scenarios can comprise various components e.g. spatial planning restrictions, location specific characteristics like aspect or slope, conversion settings and land cover type specific demand, representing the increase or decrease of the different land cover types per year. The quantitative demand represents the increase or decrease of each land cover type in hectare per year. Often these quantitative scenarios are only available at a national scale. In this case they need to be adapted for the regional scale related to the specific characteristics of the study area. For this study the focus was on the land cover types that increase and it needs to be verified if and to what extent this is also true for the study area. In a further step, depending on the story line, it is decided on the expense of which land cover class a certain other land cover class is increasing. This leads to a balanced increase and decrease in hectare per year for each scenario which is necessary as input to the land cover model because the overall area (including both increasing types and decreasing types) does not change. Further there might be other scenario-specific components, depending on the selected land cover model, which need to be implemented according to the respective model-requirements.

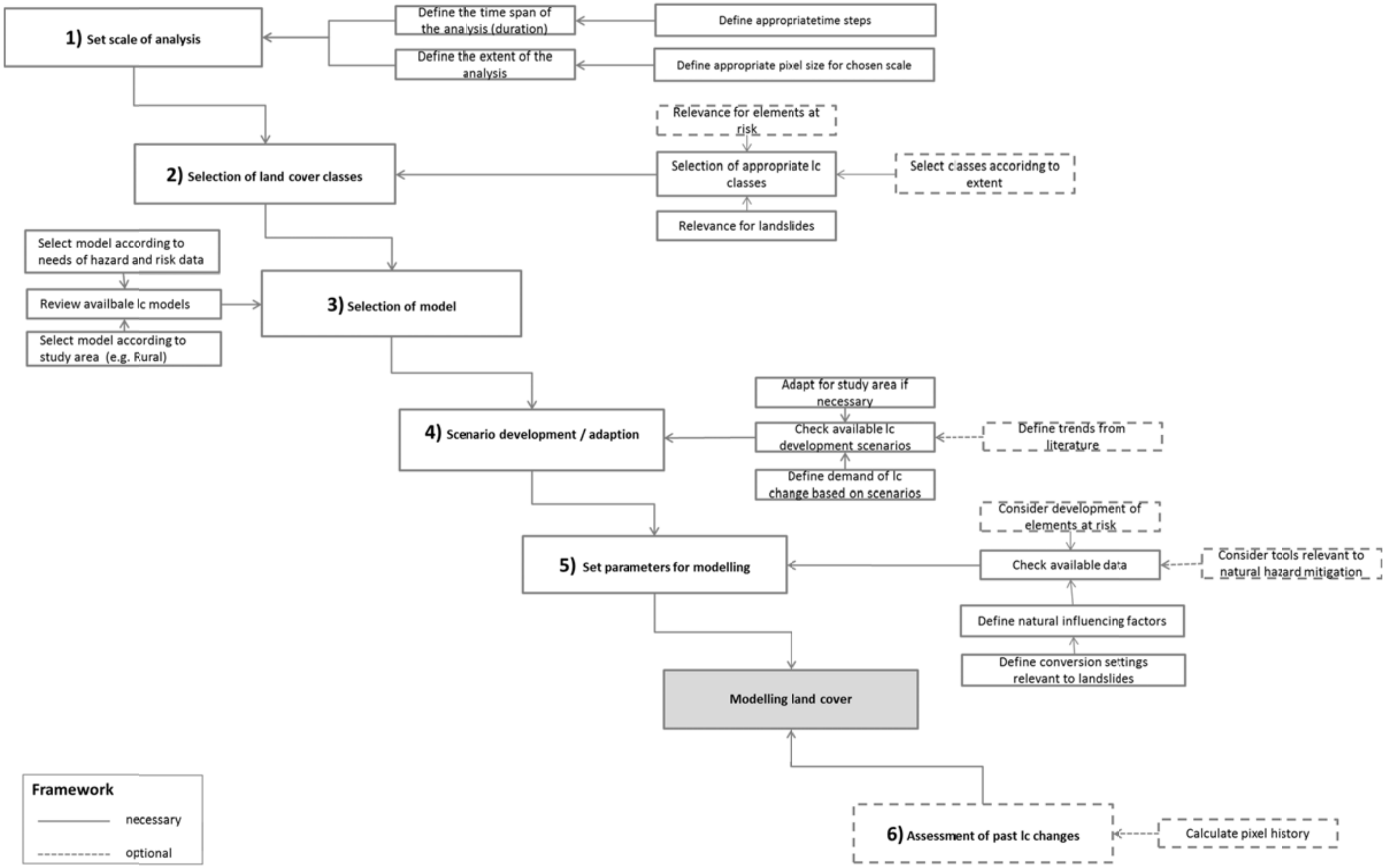


Figure 4.3. Framework for land cover modelling as basis for landslide hazard analysis

4.3 SPATIOTEMPORAL ASSESSMENT OF LANDSLIDE EXPOSURE

The exposure assessment is based on the concepts elaborated in chapters 2.4.3 and 4.1.2 . To implement the changes over time it is the dynamic factors for landslide susceptibility and the spatial development of elements at risk that need to be integrated in the analysis.

4.3.1 LAND COVER SCENARIOS

The preparation of the land cover scenarios has already been explained in detail in chapter 4.2. Land cover scenarios thus imply different potential changes due to selected variable conditions which can be incorporated in spatiotemporal analyses of landslide exposure. These prepared land cover scenarios were therefore selected 1) as input for the subsequent susceptibility modelling and 2) as input representing the elements at risk for the subsequent exposure analysis.

4.3.2 EXPOSURE ASSESSMENT

In chapter 4.1.2 the method for the multilayer exposure assessment is delineated. The spatiotemporal assessment of the development of exposure is based on this concept, intersecting information on landslide processes and consequences; however it is not a superimposition of different elements at risk but one dataset comprising the potential future land cover development.

The exposure assessment herein follows a simple raster calculation and therefore enables a location specific depiction of the results in a GIS environment. For the calculation the susceptibility map was prepared with classes 1 (very low susceptibility) to 4 (high susceptibility) and the land cover dataset was classified from 0 – 8 for the different classes. The multiplication in the raster calculation implies the multiplication of the susceptibility map by 10 before it is added to the land cover classes to ensure replicability in the final exposure dataset.

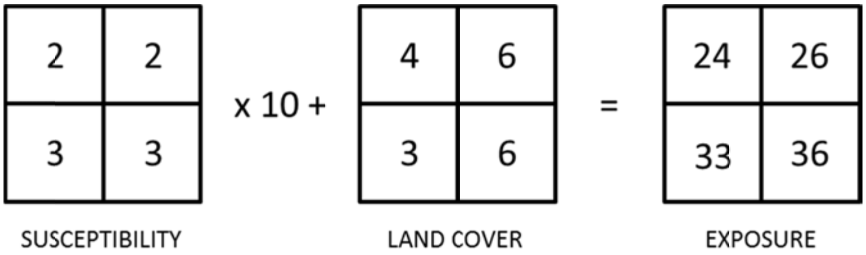


Figure 4.4. Raster calculation for exposure assessment(PROMPER ET AL. IN PRESS)

Therein the resulting possible codes for the final exposure datasets are displayed in Table 4.3. This combination of susceptibility class and the different land cover classes enable a detailed quantitative analysis of the changes of exposure, however also a qualitative and spatially explicit analysis is possible. Further the adequate illustration of this code in a map allows a visual identification of hotspots, representing areas that indicate e.g. highly exposed building or street area.

Table 4.3. Possible codes for the exposure results (PROMPER ET AL. IN PRESS)

Land cover type	**Forest**	**Grassland**	**Acreage**	**Building area**	**Streets**	**Farms**	**Water**	**Rock**
Susceptibility class	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Very low (1)	10	11	12	13	14	15	16	17
Low (2)	20	21	22	23	24	25	26	27
Medium (3)	30	31	32	33	34	35	36	37
High (4)	40	41	42	43	44	45	46	47

5. SPATIOTEMPORAL DEVELOPMENT OF REGIONAL LANDSLIDE EXPOSURE

To present the main results according to the aforementioned applied methodology, the following chapters will provide an overview of the outcome for each analysis step respectively. The structure is set in accordance to the previously described methodology following also the analysis steps presented in Figure 4.1.

5.1 REGIONAL LANDSLIDE EXPOSURE

The regional exposure assessment was carried out for the current situation combining various layers of elements at risk and the susceptibility map. The creation of the different components including the results is illustrated in the following paragraphs.

5.1.1 ELEMENTS AT RISK DATABASE

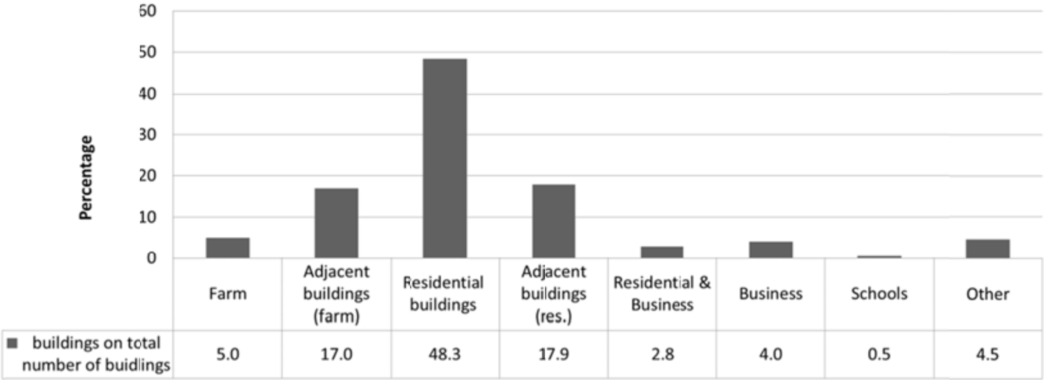
The element at risk database is based on the building polygons of the digital cadastral map. These were extracted and displayed on the orthophoto for validation and completion in the field. The catalogue with 27 different types of buildings and other descriptive characteristics was used for data collection in the field. These were then grouped to eight categories (Table 5.1) for further analysis, because 27 categories would not give a clear overview on the building types in the study area, however the original coding was kept in the database (PROMPER and GLADE subm). To keep this code enables for example that buildings of critical infrastructure e.g. fire departments can be distilled easily from the database at a later stage of analysis, but also to extract further information if needed in a later stage.

Table 5.1. Grouped building categories of the elements at risk database

Grouped category	Original category
Residential buildings	residential building MP
	residential building SP
Adjacent buildings (res.)	garden shed
	garage
Farm	farmhouse + garage
	farmhouse + shed
	farmhouse + stable
	farmhouse MP
	farmhouse SP
Adjacent buildings (farm)	garage + stable
	shed + garage
	shed + stable
	stable
	shed
Residential & Business	residential building MP + shop
	residential building SP + shop
Business	office building
	shop
	industry
	hotel
	restaurant
Schools	school
Other	wayside cross
	transformer
	church
	fuel station
	other

The following Figure 5.1 indicates the percentages of the buildings in the different categories in relation to all buildings in the database. The results show a high percentage of residential buildings and the respective adjacent buildings comprising for example garden houses and garages. In combination with farms, which also represent a residential function, the total residential buildings make up for more than 50% of the total number of buildings in the study area. In the category "Other" specific buildings related to critical infrastructure and other specific uses are integrated. As these have either a respective code or description these can be filtered separately for further analysis. A very small percentage of 0.5 % in the study area is categorised as school.

The distribution of the elements at risk over the study area illustrates that residential buildings concentrate in the valley bottoms whereas farms are mostly distributed on the hilltops, scattered over the study area. The buildings related to critical infrastructure are also distributed over the study are, however a concentration in the main valleys can be observed.



	Farm	Adjacent buildings (farm)	Residential buildings	Adjacent buildings (res.)	Residential & Business	Business	Schools	Other
■ buildings on total number of buidlings	5.0	17.0	48.3	17.9	2.8	4.0	0.5	4.5

Figure 5.1. Percentage of buildings in the different categories on all buildings (PROMPER and GLADE subm)

5.1.2 MULTILAYER EXPOSURE MAPS

For the multilayer exposure maps three layers of elements at risk: "street area", "residential buildings & schools" and buildings of "critical infrastructure" were extracted for the analysis and for each of the three groups group a binary file (0,1) was created (PROMPER and GLADE subm). To approximate the range of landslide events in the study area which potentially affect various elements at risk a buffer around the elements at risk was calculated. The buffer distance was calculated from an analysis of reported events wherein the length of landslide events was documented and 50 m average length was approximated (PROMPER and GLADE subm). The assumption herein is that the landslide has an impact over the whole length of the process. Each element at risk was enlarged by this buffer to ensure that although a landslide might occur in a distance of 50 m from the building the impact is still recorded in this analysis. Further the assumption is also that although a landslide might occur downslope of an element at risk it still has an impact on the respective building or street.

In a second step the layers of elements at risk were cumulated to illustrate how many and which layers of different elements at risk are present in a specific location. The intersection with the susceptibility map results in a total of 32 classes (see also Table 4.3) which are difficult to distinguish and especially interpret visually in a regional map. Therefore the following procedure (see also Figure 5.2) was applied:

- the layers of elements at risk were cumulated again, according to the number of types of elements at risk present [A]
- and this layer [A] was then intersected with the susceptibility map [B] resulting in a multilayer exposure map [C].

In map [A] it is possible to delineate how many layers of elements at risk, from one (light blue), two (medium blue) to three layers (dark blue), are affected. This combined layer of cumulative elements at risk is then intersected with the susceptibility map [B]. In the resulting multilayer exposure map [C], four classes of susceptibility with the respective quantity of elements at risk (cumulative) can be identified, see Figure 5.3.

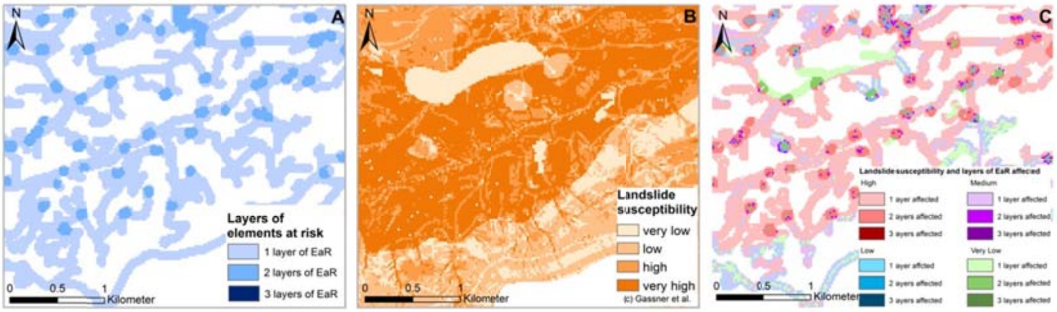


Figure 5.2. Schematic presentation of the method displayed in maps including the number of layers of elements at risk (A), the landslide susceptibility map (B), and the final combined map (C) (PROMPER AND GLADE SUBM)

The multilayer exposure map indicates clearly where different susceptibility classes coincide with multiple layers of elements at risk. The assumption herein is that the more layers of elements at risk, hence different types of elements at risk, are affected by e.g. high susceptibility, the higher is the subsequent exposure. Therein the darker the colour tone the higher is the exposure to the relevant level of susceptibility. The following Figure 5.3 indicates high landslide susceptibility with various spots of more than one layer of elements at risk being affected in the western part of the study area. It is clearly identifiable that the city of Waidhofen is located along the Ybbs valley because there is a dense superimposition of at least two layers of elements at risk, however, the landslide susceptibility is very low. When zooming in in the South, it is indicated that there are various areas with medium to high susceptibility and in many locations at least two or even three layers are affected. These areas are mostly located in the valley bottoms.

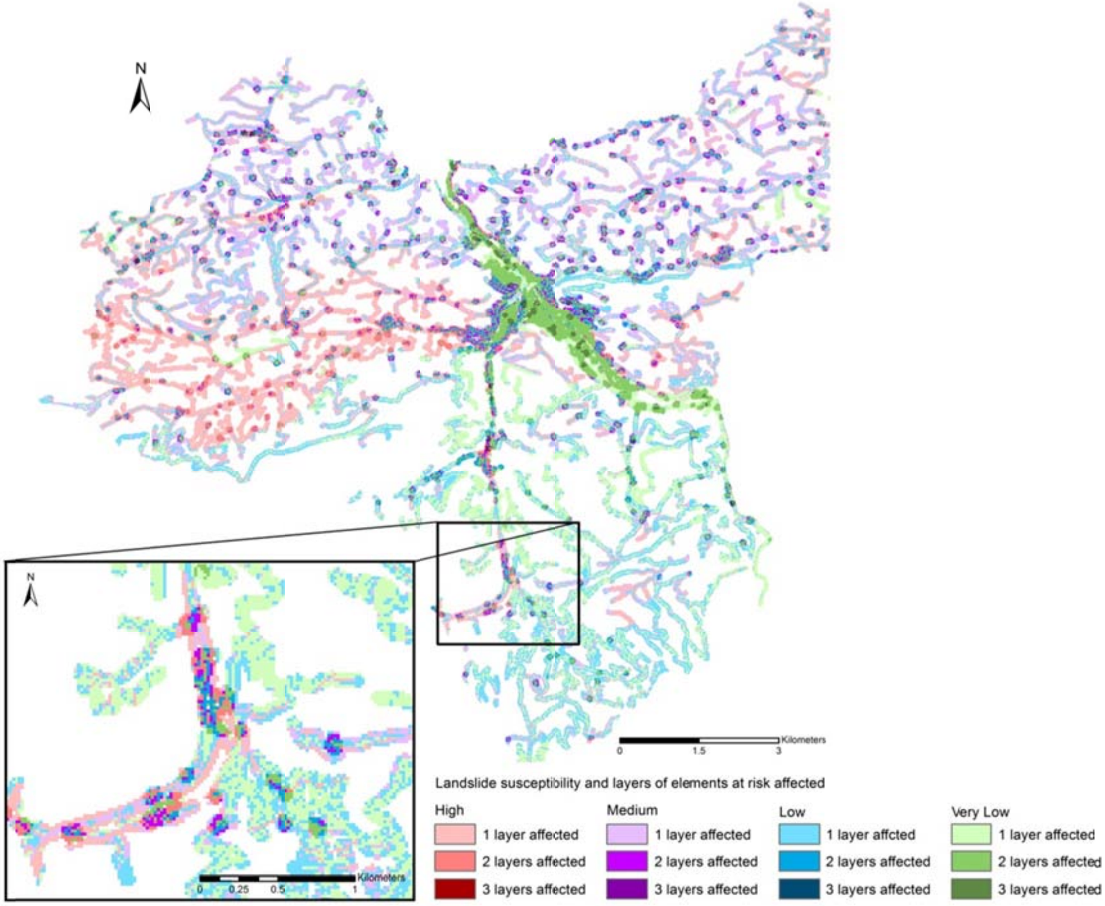


Figure 5.3. Multilayer exposure map for Waidhofen/Ybbs (Promper and Glade subm)

5.2 LAND COVER ANALYSIS

The land cover analysis is a central part of this thesis including the analysis of past land cover changes and modelling of probable future shifts. These are all described along the framework displayed in Figure 4.3.

5.2.1 SETTING THE SCALE OF ANALYSIS

SPATIAL SCALE

For the past analysis the available aerial photographs of the years 1962, 1997, 1988 were orthorectified for subsequent land cover mapping. However it was not possible to cover the whole study area. Therefore, the analysis of past land cover is limited to around 112 km^2 whereas for the modelling of future shifts the whole district with about 130 km^2 is covered. The comparison of past and future land cover is therefore limited to the extent of the past land cover maps, which have a resolution of 20 m.

DURATION

The first step was to gain an overview on the available datasets for the district of Waidhofen/Ybbs. Aerial photographs of 1962, 1979, 1988, 1992 were available, however the aerial photographs of 1992 were excluded because of the short time span between 1988 and 1992 (PROMPER et al. 2014). In addition to that, the land cover maps for the future analysis were defined reflecting the IPCC analysis periods. The basic map for future modelling was a combination of the digital cadastre which was aligned with the orthophoto. This orthophoto is mainly of 2005, however for full coverage, the orthophoto from 2007 covers the north-eastern part. Further this base land cover map and the orthophoto are only referred to as 2005 or current. This data availability and the selected future periods results into the analysis periods shown in Figure 5.4.

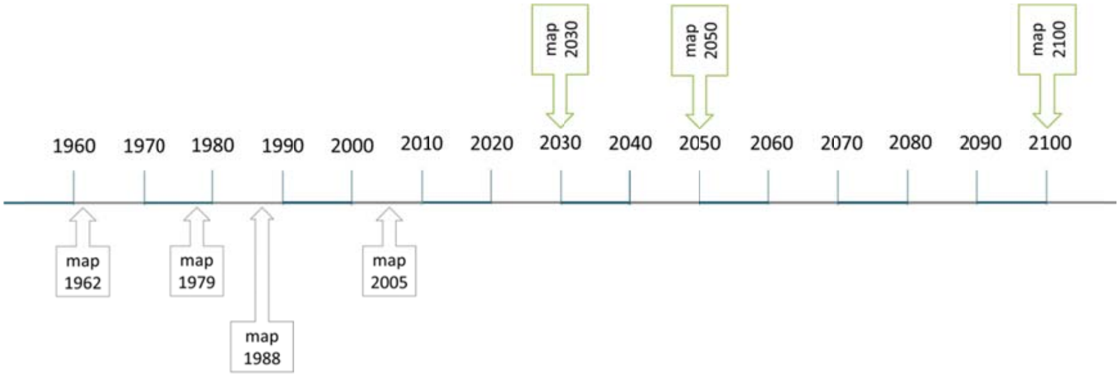


Figure 5.4. Time scale of analysis (PROMPER et al. 2014)

5.2.2 DEFINITION OF APPROPRIATE LAND COVER CLASSES

For the past land cover maps a unified classification scheme was developed (see Table 5.2) which was also applied for the analysis of future land cover changes with the exclusion of alluvium because the spatial extent compared to the other classes would be too small to obtain reasonable results. In order to provide the land cover class “alluvium” was combined with “rock” for the land cover modelling process.

5.2.3 ANALYSIS OF PAST LAND COVER

The analysis of the past land cover is the first step to approach the situation in study area and the predominant land cover types. The main challenge regarding the mapping process of the panchromatic aerial photographs of the years 1962, 1977 and 1988 was the distinction between the different land cover types (PROMPER and GLADE 2012). To encounter this challenge six predominant land cover classes were identified and criteria for delineating these types from one another specified (PROMPER and GLADE 2012). The criteria were assigned according to the visual interpretation by using the surface patterns and the different colours that were identified. An example herein is grassland which is characterised by a light uniform grey colour or also linear structures ascribed to mowing. Another example is acreage which indicates narrower linear structures and is delineated by ridges. The detailed criteria are listed in Table 5.2. The mapping of the land cover classes was then conducted in a GIS environment. For the creation of the map for 2005 a combination of the digital cadastral map and the orthophoto was applied. Further details on the mapping process can be found in PROMPER AND GLADE (2012).

Table 5.2. Criteria for mapping the different land cover types (PROMPER AND GLADE 2012)

Land cover type	**Surface**	**Mapping criteria**
Grassland	Vegetation cover	Smooth and uniformly coloured but sometimes also linear structures due to mowing
Acreage	Partly covered by vegetation	Surface structure narrower than linear structures on grassland; often delineated through ridges; partly not vegetated
Forest	Vegetation cover	Single trees and single lines of trees are not considered
Building Area	Sealed surface	Sealed surfaces also surrounding farming houses; settlements mapped as a whole
Farms	Sealed surface	Special shape as usual for farms in this area
Streets	Sealed surface	Linear feature; differences in width
Water	Smooth surface	Is delineated clearly if not covered by forest
Alluvium	Gravel surface	Not vegetated areas next to water surfaces; where topography allows alluvial deposition
Rock	Uniform / rough	Not vegetated; sharp edges

The results for the analysis of the land cover development from 1962 – 2005 indicate a clear trend towards an increase in building as well as street areas (PROMPER et al. 2014). The area used for acreage is fluctuating constantly, reaching the largest extent in 1979 and the lowest in 1962.

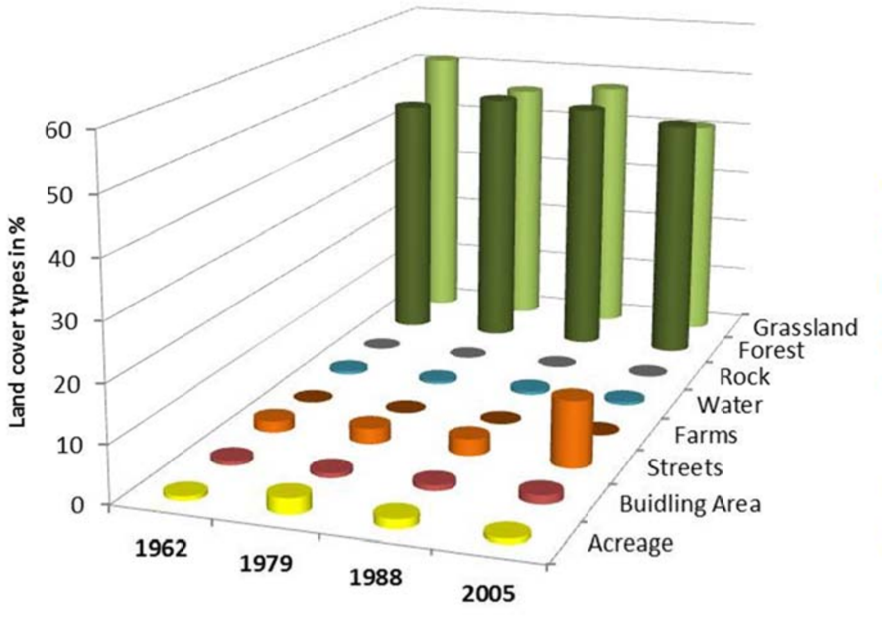


Figure 5.5. Development of past land cover for the study area of Waidhofen/Ybbs (PROMPER ET AL. 2014)

From Figure 5.5 it is clearly visible that forest and grassland are the dominant land cover classes (PROMPER et al. 2014). While the area covered by forest decreased from 1979 onwards, grassland is fluctuating throughout the analysis duration reaching its minimum of 40 % in 2005 (PROMPER et al. 2014). The increase of street and building area is mainly attributed to a decrease in grassland, which also explains the related decrease thereof.

5.2.4 ANALYSIS OF FUTURE LAND COVER

In this chapter the application of the framework for land cover mapping as input to landslide susceptibility and risk analysis, which is illustrated in Figure 4.3 is further presented. For a better understanding of the following subchapters the main data inputs for the land cover model are explained shortly. After this brief introduction the chapter is structured according to the framework presented in chapter 4.2.4.

The following four main types of input data for the modelling process are split in spatial and non-spatial inputs (VEBURG 2010):

- Spatial policies and restrictions (spatial),
- Location characteristics (spatial),

- Land use type specific conversion settings (non-spatial) and
- Land use requirements (non-spatial).

The first set of input data is spatially explicit and covers spatial restrictions e.g. natural reserves or areas that are favourable for building area. The location specific characteristics are attributed to the distribution of land cover types according to driving factors like aspect or slope. The third dataset on land use type specific conversion settings is prepared by setting the potential changes form one land cover type to another, such as grassland is allowed to turn to e.g. building area, forest, acreage etc. This is a non-spatial setting that is applied to a land cover type for the whole area or only within a specific area that is defined before. The last set of input data are land use requirements, e.g. an increase of building area or decrease of forest, which are non-spatial and define the change in unit area for each land cover type for each year, representing a main part of land cover scenarios.

SELECTION OF THE MODELLING FRAMEWORK DYNA-CLUE

The modelling framework was selected on the basis of the criteria set in chapter 4.2.4, namely space, time and human decision making. The Dyna-CLUE modelling framework allows scenario based spatially explicit analysis of land cover and the time steps of one year are appropriate to capture land cover changes. Further it does serve the purpose of a regional analysis (VERBURG and OVERMARS 2009). Therefore the Dyna-CLUE modelling framework (VERBURG and OVERMARS 2009) shows a good performance on all three criteria, which is also stated by AGRAWAL ET AL. (2002) for the precursor models CLUE Model (Conversion of Land Use and Its Effects) (VELDKAMP and FRESCO 1996) and CLUE-CR (Conversion of Land Use and Its Effects – Costa Rica) (VELDKAMP and FRESCO 1996).

LAND COVER DEVELOPMENT SCENARIOS

Land cover development scenarios applied in this thesis are available from the Agency ”Austrian Conference on Spatial Planning”. The scenarios were developed during a two-day conference as well as four workshops held in 2007 attended by experts, as well as selected public, in the context of the project “Scenarios for the spatial and regional development of Austria in the European context” (HIESS et al. 2009). The megatrends identified have different facets, e.g. ageing of society, wild cards like extreme events with strong effects on total system and scenarios which are aimed to be consistent and representing the most diverse potential of the future (HIESS et al. 2009). These quantitative approximations for Austria are then detailed with story lined for different regions e.g. peripheral regions or urban regions (HIESS et al. 2009). The following description of the scenarios by HIESS ET AL. (2009) is verbatim to the description in the paper PROMPER ET AL. (2014, p. 13,) where they were summarised shortly:

Scenario 1: Overall Growth

*The Overall growth scenario considers a general increase of the main forces driving spatial development, such as economy, population, tourism, mobility and transport. Moreover, this scenario type is characterized by improved energy efficiency, resulting in reduced emissions. Although the interactions between state, market and civil society prevent widening of disparities, the pressure on space grows rapidly according to the Overall Growth scenario. These developments lead to a conflict of the usage of space between the different sectors, such as tourism, nature conservancy, agriculture, as well as settlement areas. (*HIESS et al. 2009)

Scenario 2: Overall Competition

*In the scenario Overall competition, the main driving factors of spatial development are also growing strongly. However, the social and, consequently, the spatial disparities widen. This implies that pressures on the growth zones and other regions are confronted with out-migration. The basic assumption in this scenario is that markets respond in time to scarcities, thus far reaching energy and environmental crisis are avoided. (*HIESS et al. 2009)

Scenario 3: Overall Security

*In contrast to the previous scenario types, the Overall security scenario considers a moderate growth of the main driving factors (economy, population and tourism). This moderate growth results in an increase in pressure in areas being used for farming and agriculture, due to high demand for biomass energy. Increasing disparities can only be avoided by strict government regulation, social security systems and restrictive in-migration. (*HIESS et al. 2009)

Scenario 4: Overall Risk

*This is similar to the Overall competition scenario; however, the market does not develop any mechanisms against sudden energy scarcity. For this reason, energy prices rise suddenly in the absence of adequate countermeasures. High energy and mobility costs are the main driving forces in this scenario. The consequences for rural areas imply migration of enterprises population. (*HIESS et al. 2009)

ADAPTATION OF LAND COVER DEVELOPMENT SCENARIOS FOR WAIDHOFEN/YBBS

The land cover development scenarios were designed for Austria alongside four land cover classes which increase or decrease respectively in hectare per year. For adapting these scenarios according to the study area the numbers given were downscaled from the area of Austria to the area of Waidhofen/Ybbs in (PROMPER et al. 2014). For the model input, the land use requirements in hectare land cover, are adapted focussing on the increasing land cover types to which the decreasing types were adjusted proportionally (PROMPER et al. 2014). The resulting demand input for the land cover model represents for each year the same total area, meaning that increase of specific land cover types is based on decrease of other land cover types. Additionally to the quantitative changes, HIESS ET AL. (2009) also provided a story line for each scenario for different development regions in Austria. For the study area Waidhofen/Ybbs the story line “Alpine peripheral regions” was integrated and the quantitative demand, as well as other model parameters aligned accordingly.

The main changes within the proposed scenarios refer to a general increase in forest areas (HIESS et al. 2009). Further the migration to lower lying areas continues and in central areas the population number is stable or increases (HIESS et al. 2009). Therein the story lines support the adaptation process and the focus on the increasing land cover types. To complete the scenario development process, exchange with experts on several parameters underlined the selected approach. In Figure 5.6 the combination of the scenarios with the proposed trends of the story lines consolidated to the aggregated land cover demand is shown. For this thesis these available scenarios, that were developed for 2030 were extrapolated up to 2050 and 2100, based on the assumption that the development from 2005 to 2100 is steady.

APPLICATION OF THE LAND COVER MODELLING FRAMEWORK

Based on the possibilities of the Dyna-CLUE model, mentioned above, various advantages for the purpose of land cover modelling as input for landslide risk assessment unfold. Firstly it allows implementing a statistical relationship between current land cover and different driving factors e.g. aspect or slope. Secondly, the allocation of pixels is modified by possible autonomous development and the competition between the different land cover types. This means that each pixel is dependent on its elasticity to change, its statistical determined relationship to the driving factors and on competition regarding other pixels (VERBURG et al. 2002). All these factors are elaborated in detail below.

The preparation of the modelling parameters is split into the non-spatial inputs and spatial inputs as the model contains the non-spatial demand model and a model for the spatially explicit allocation procedure (VERBURG et al. 2002). The integrated parameters will be described along the following Figure 5.6. numbers 1-4.

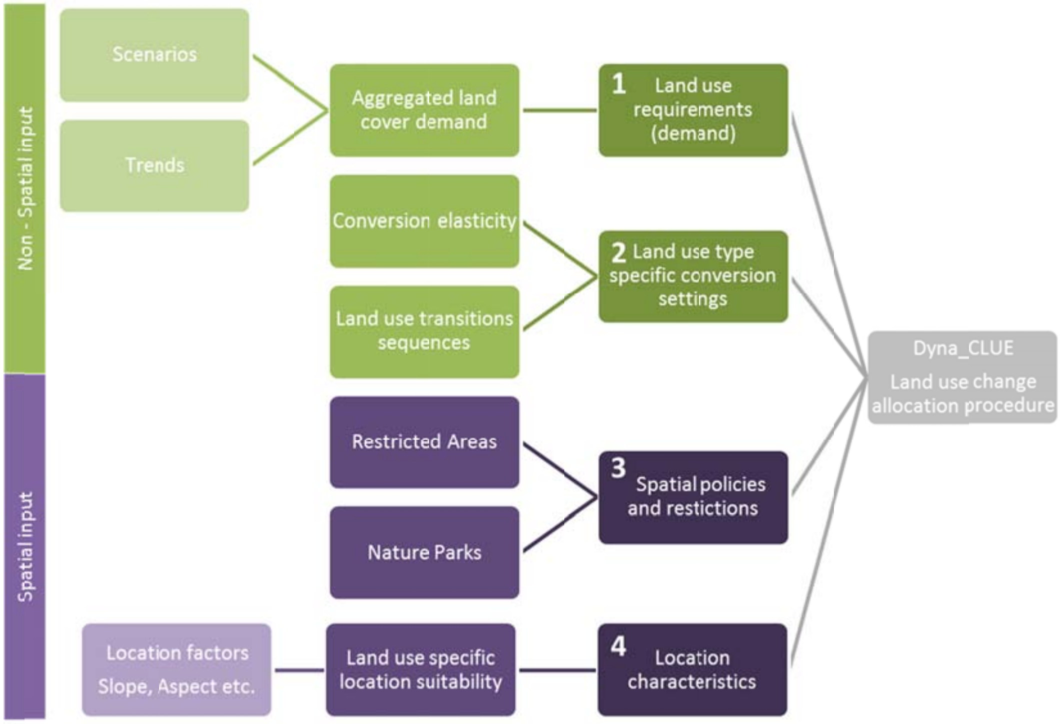


Figure 5.6.Spatial and non-spatial input data to the Dyna-CLUE modelling framework (altered from Verburg et al. 2009)

The allocation procedure of the changes defined in the demand module allocates at time (t) for each location (i) the land use/cover type (lu) with the highest total probability ($Ptot_{i,t,lu}$) (VERBURG and OVERMARS 2009). The total probability therein is defined as the sum of location suitability ($Ploci_{t,lu}$), neighbourhood suitability ($Pnbh_{i,t,lu}$), conversion elasticity ($Elas_{lu}$) and competitive advantage ($Compt_{lu}$) following VERBURG AND OVERMARS (2009):

$$Ptot_{i,t,lu} = Ploc_{i,t,lu} + Pnbh_{i,t,lu} + Elas_{lu} + Compt_{lu}.$$

Further details on the allocation procedure can be found in VERBURG ET AL. (2009).

The demand module [1] was applied appropriately to the land cover classes: forest, acreage, grassland, and building area. Several assumptions and observations influenced the demand model:

- The assumption that no new roads will be constructed until 2100 since the new building area will mainly focus on areas close to existing roads. This assumption is also used in other studies, e.g. SAFELAND (2012).
- The assumption that the only allowed development for farm area is from farm to building area. This is based on the analysis of the past and also relates to the abandonment of agricultural areas (see also PROMPER et al. 2014).
- For rock and water the rate of change, derived from the past analysis, cannot really be represented in a yearly mode of change and thus was not accounted for in the modelling process.

Therefore the demand parameters for the land cover classes water, alluvium and rock were set to zero regarding their spatial development. Additionally the demand for the streets was set to zero. This had the technical reason, that this class is a line feature and would within the model be “forced” to develop spatially. For better understanding the procedure on how the demand was adapted for the study area is described in the following chapter. The results of the adaptation process for the four different scenarios applied, is presented in the Table 5.3.

Table 5.3. Land cover demand in ha/year for Waidhofen/Ybbs (adapted after PROMPER ET AL. 2014)

land cover **scenario**	**forest**	**grassland**	**acreage**	**building area**
Overall Growth	5	-5.80	-0.40	1.20
Overall Competition	18.50	-19.70	-0.30	1.50
Overall Security	12.30	-13.02	-0.17	0.89
Overall Risk	12.30	-12.90	-0.10	0.70

The land use type specific conversion [2] settings can be split into two parts, the conversion elasticity and the possible transition sequences. The conversion matrix defines the possible sequence of land cover types. It is a matrix representing the present land cover and the potential future land cover and therein, possible sequences and also time shifted sequences can be defined (Table 5.4). The elasticity expresses how easy a land cover type can change in respect to e.g. costs. Therein for some land cover types it involves high costs to change (1) and for some a change is not really expensive (0) and subsequent changes easier in comparison to another land cover type. This reason can also be expressed by the simplicity of cultivation of e.g. grassland in comparison to forest where the effort is disproportionally higher.

Table 5.4 Conversion matrix

		Potential future land cover type			
		forest	**grassland**	**acreage**	**building area**
Current land cover type	forest	1	130	8	9
	grassland	1	1	8	9
	acreage	0	1	1	0
	building area	0	0	0	1
	street area	0	0	0	0
	farms	0	0	0	1
	water	0	0	0	0
	Rock	0	0	0	0

[Conversion allowed (1); conversion not allowed (0); conversion allowed after 30 years (130) conversion only allowed taking restriction maps into consideration (8,9)]

For the conversion matrix a set of rules on the changes of the different land cover types has to be elaborated. An example is that grassland is likely to develop to several other types of land cover whereas building area is not changing. Herein Table 5.4 indicates the possible changes (1) and the changes that are not allowed (0). Further it is possible to indicate after how many years a land cover type is allowed to change which in this case is true for forest (30 years). In special cases e.g. when new building area should be averted/prevented from dispersion it is also possible to allow conversions to building area preferably in selected areas (VERBURG and OVERMARS 2009). These areas can be defined in binary raster files which are represented by the numbers 8 and 9 in the matrix. The elasticity of the different land cover types, from (0) very likely to change to (1) very difficult for a land cover type to change to another, was also set according to the scenarios applied (see Table 5.5.).

Table 5.5. Elasticities defined for the different scenarios (PROMPER ET AL. 2014)

	Forest	**Grassland**	**Acreage**	**Building area**
Overall Growth	0.7	0.3	0.3	0.7
Overall Competition	0.9	0.3	0.3	0.6
Overall Security	0.8	0.3	0.5	0.9
Overall Risk	0.7	0.3	0.3	0.8

In the next step the spatial restrictions were set [3] according to local conditions e.g. natural reserves and according to the story lines of the applied scenarios. Therein location specific restrictions (area specific restrictions) and non-location specific (conversion specific) restrictions are set (VERBURG and OVERMARS 2009). The area specific restrictions cover distance files which result from general spatial planning principles, as well as zones that are explicitly excluded from development e.g. natural reserves, see Table 5.6. These distance files are binary raster files indicating spatially where e.g. new building is only allowed to develop 100 m from existing roads or building area. The distance files for the study area for example prevents urban sprawl as defined in the Austrian strategy for sustainable development (BMLFUW 2011). The distance files are mainly focused on existing built up areas and are prepared using Euclidean distance.

Table 5.6.: Location specific restrictions (modified after Promper et al. 2014)

Land cover type	**Restriction applied**
Building area	Distance to existing building area max. 100m Distance to existing roads max. 100m Distance to existing farms max. 100m Restricted within natural reserves
Acreage	Aspect: 180 – 270

Implementing location characteristics [4] into the modelling process is another main factor of the analysis. These maps, representing probabilities of the different land cover types, were created by using logistic regression which is frequently used in land cover analysis (e.g. LIU ET AL. 2009, RUTHERFORD ET AL. 2008, GELLRICH ET AL. 2007, HU AND LO 2007). Thereby, independent variables which include all relevant driving factors of land cover change are related to the land cover as dependent variable. In alpine areas especially aspect and slope are important driving factors for land cover development (HIETEL et al. 2004) but also parameters such as distance to roads or building areas may play a role. In this study a set of independent variables was created based on the digital elevation model, slope, aspect and several distance files (Table 5.7). A major assumption herein is, that for the potential change in land cover the anthropogenic influence is considerably larger than climate change and therefore climate change was not included into the land cover modelling process.

Table 5.7. Regression coefficients integrated in the land cover modelling framework

Regression coefficients	**Forest**	**Grassland**	**Culture**	**Building area**
Constant	-4.331	1.951	-3.413	7.216
DEM	-	-	-	-0.012
Slope	0.143	-0.085	-	0.066
Aspect	-	-	-	-
Distance to road	-	-	-	-
Distance to building area	-	-	-	-
Distance to farms	-	-0.001	-0.003	-
Distance to constructions	0.005	-	-	-0.789
-) dropped out in the final model				

The logistic regression within this analysis step provides knowledge of the relationships of land cover types and the different driving factors. Inputs for the logistic regression are the regression coefficients which showed the highest explanatory values in a first stepwise logistic regression. Then the results are tested once more with the area under the ROC (receiver operating curve) curve and only the cumulative probabilities with

ROC values of higher than 0.7 (fair) according to the traditional diagnostic point system TAPE 1990 are then integrated in the land cover modelling framework, Table 5.7.

5.3 SPATIOTEMPORAL ASSESSMENT OF LANDSLIDE EXPOSURE

This chapter describes the results of the land cover analysis referring to the development of potential consequences. Further the application of the landslide exposure assessment is described in detail and the chapter is finalised by the landslide exposure scenarios which are analysed quantitatively and qualitatively.

5.3.1 LAND COVER SCENARIOS

The results for the land cover scenarios illustrate similar areas of growth for the specific land cover types, however the extent of e.g. new building areas and forest vary. When analysing the land cover maps for one scenario the largest changes are indicated for the last time step. An example is indicated in Figure 5.7, where a section in the southwestern part of the study area is shown. The presented scenario is the “overall competition” (2) scenario which implies a high increase of building area from (A) to (C) and in this case mostly on the expense of grassland. Additionally the scenario based increase of forest is indicated in the following Figure 5.7 which is esepcially increasing from (A) to (B). For the same scenario some patches of new grassland can be observed. These increase mostly on the expense of forest (see also PROMPER ET AL. (2014)). For the change from 2005 to 2050 scenario 2 indicates a vast increase of forest in the central and southern parts of the study area, whereas for 2050 – 2100 the increase in forest shifts to north-eastern part of the study area (PROMPER et al. 2014).

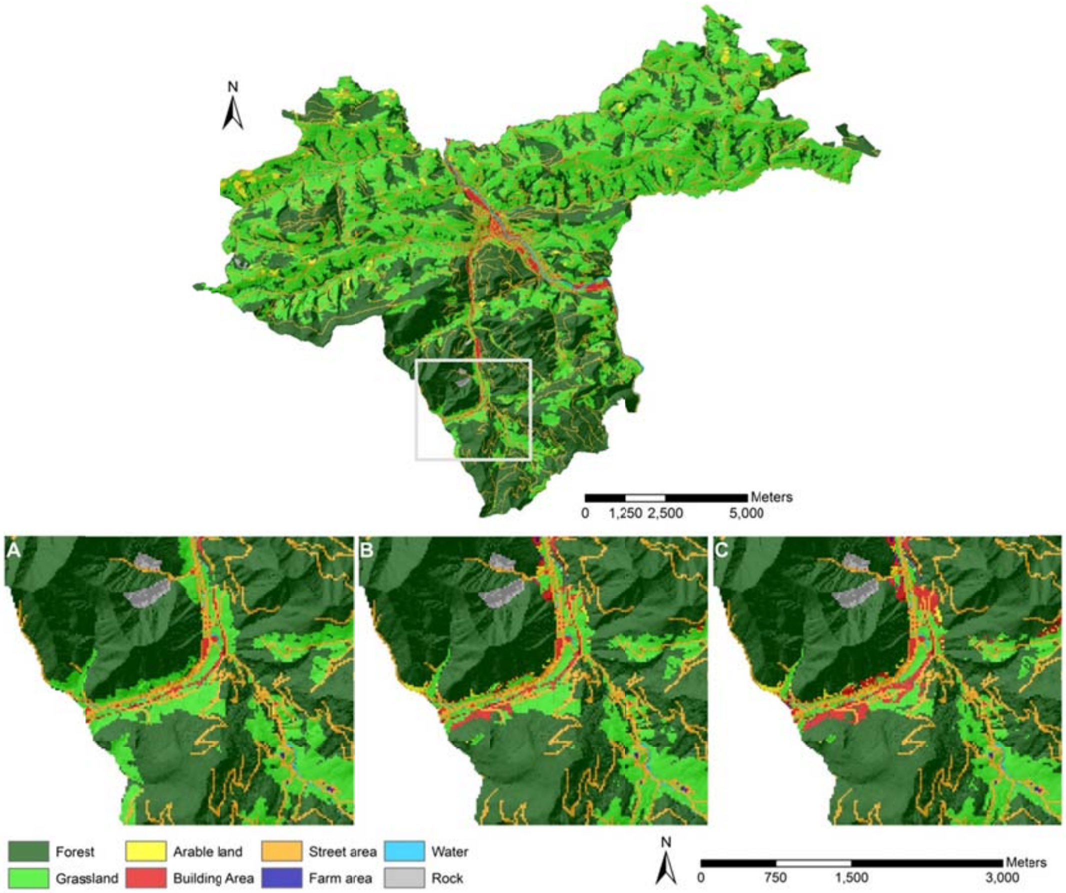


Figure 5.7. Land cover scenario “Overall Competition” for 2005 (A), 2050 (B) and 2100(C), the overview is from 2005

As mentioned above the difference between the scenarios is rather the extent of e.g. new areas than different locations. In the following Figure 5.8 this is illustrated by presenting the same part of the maps of 2100 for all four scenarios. The different extent of the patches of new building area are clearly indicated in all scenarios , however for scenario 1 and 2 the extent is larger than for scenarios 3 and 4. The same can be observed for forest areas which in this example are largest for scenario 2 and 3. Especially related to forests the results indicate that new forest area develops next to existing forest areas enlarging the forest areas but not creating “new” forests.

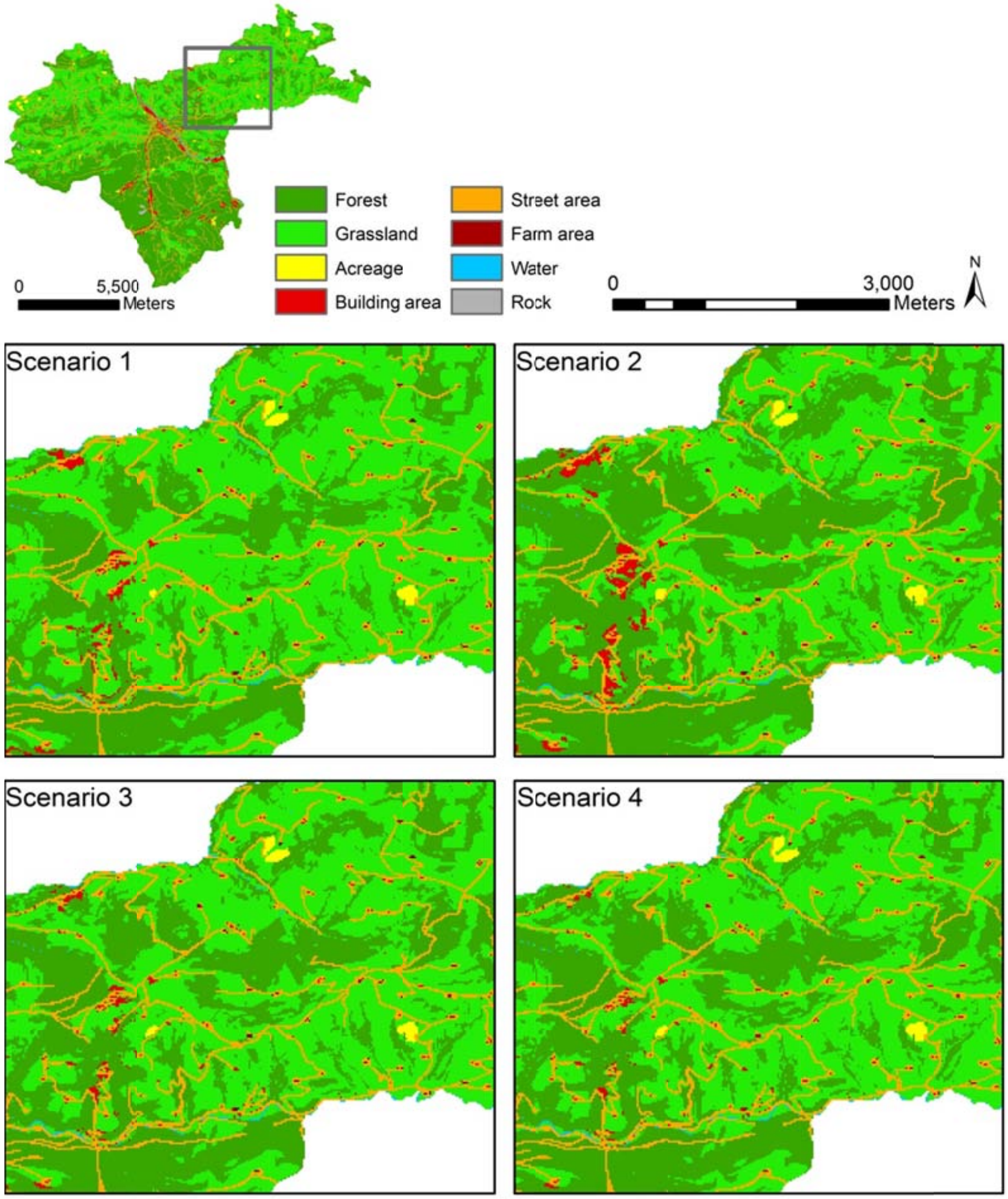


Figure 5.8. Comparison of scenario results for 2100 ("Overall Growth" (1), "Overall Competition" (2), "Overall Security" (3), "Overall Risk" (4))

In summary the results of the modelled future land cover indicate a range of outcomes for the different scenarios. The different scenarios approximate similar areas of development. However, the extent of these areas differs dependent on the applied scenario. The most extreme scenario is "Overall Competition" which indicates the highest demand for building and forest area. The development, therefore, implies that the pressure on space increases enormously which is also indicated in the story line of the scenario (see chapter 5.2.4). These increasing areas mostly developed on the expense of grassland which is also favoured through the high elasticity applied for this land cover type. In general there are three potential development areas that can be approximated for all scenarios, wherefrom two evolve in the southern part and one in the north-western part of the study area. The development areas in the southern part evolve early whereas on the long run especially the development area in the south-eastern part develops. This probably relates to the fact that according to the defined parameters the southern hotspots are more suitable for development of building area than the northern part. This location specific, explicit analysis approximates potential development areas for the given constraints.

5.3.2 EXPOSURE ASSESSMENT

The application of the method for the exposure analysis elaborated in chapter 4.3.2 is based on two basic datasets: the susceptibility map and the land cover map. The intersection of these two layers is then conducted for each analysis period individually. The results generally represent an increase of exposure related to street and building areas. The following figure 5.9. illustrates the landslide exposure for building and farm areas. The lighter the colour of the bars the lower is the susceptibility. The different scenarios are separated by different colours. The results clearly indicate that the exposure in the high and very high classes increases towards 2100. The highest increase is detectable in scenario 2 for the two medium exposure classes (high and low exposure). The time steps from 2005 to 2030 and 2030 to 2050 only indicate a slight increase in exposure. Especially the highest exposure class covers only a very small percentage of the study area below 1 %. The land cover class with around 10 % of the study area in the highest exposure class is grassland followed by forest (see also Table B.1 and B.2).

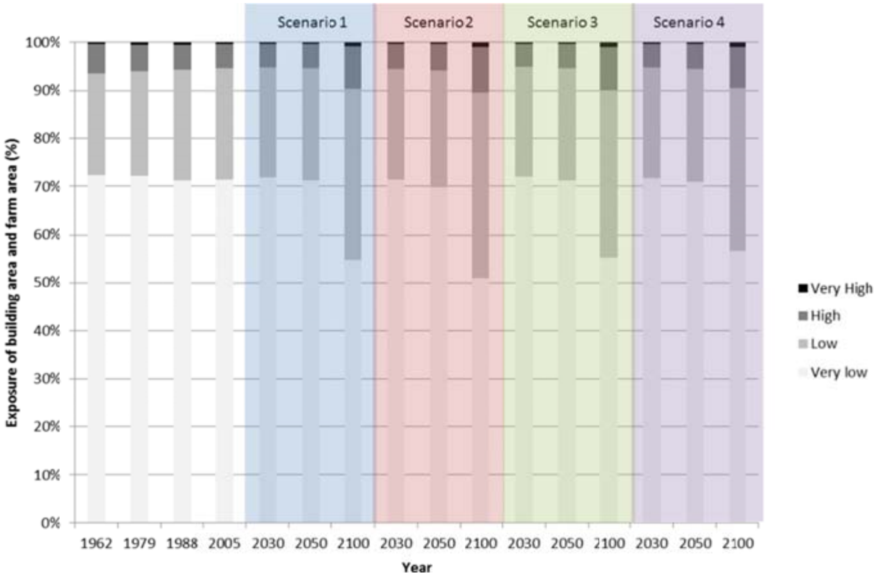


Figure 5.9. Percentage of area of landslide exposure for building and farm area from 1962 to 2100 for all scenarios (PROMPER et al. in press)

In the following Figure 5.10 the exposure for street area is displayed for all the scenarios and the past analysis. It is clearly indicated that the exposure for the past is fluctuating whereas for the scenarios the distribution of exposure is similar, increasing vastly from 2050 to 2100. Especially the percentage of the highest exposure class is twice as high for all the scenarios as it is for building and farm area.

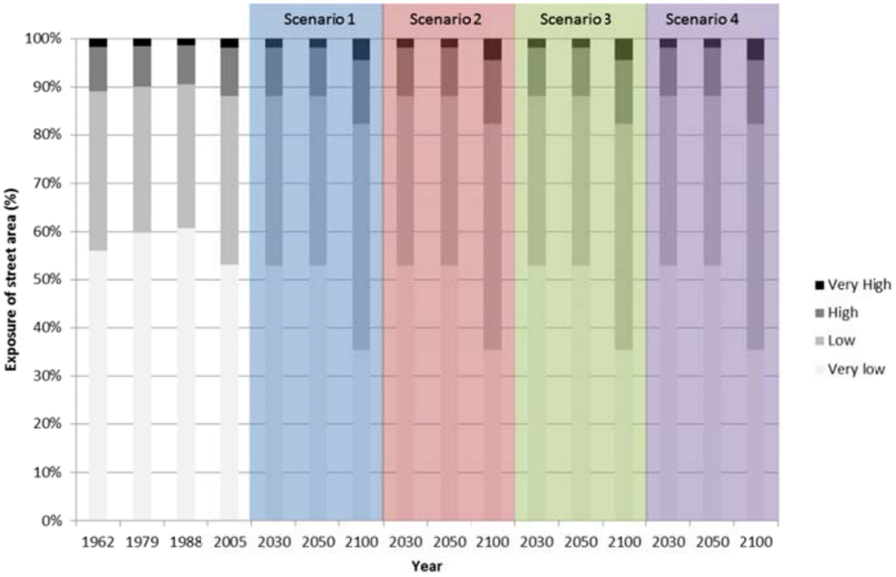


Figure 5.10. Percentage of area of landslide exposure for street area from 1962 to 2100 for all scenarios (PROMPER et al. in press)

The very low exposure class for all time intervals analysed ranges from 35 % to approximately 60 % on the total percentage of street area. In general the exposure in the medium and high classes for street area is higher than for building and farm area. Referring to Table B. 1 and Figure 5.10 an increase of exposure can be observed in the medium classes and affects mostly buildings and infrastructure. This indicates that not only elements at risk develop in susceptible areas but also an increase in landslide susceptibility changes the pattern of exposure. This is evident because the street area, as a linear feature, did not develop while land cover modelling, and therefore the increased exposure, refers to existing street area only.

Related to a qualitative exposure assessment the following Figure 5.11 illustrates the exposure for the scenario Overall Competition for 2030 and 2100. It is shown that for 2030 there are areas of medium exposure of streets in the western part of the study area. In contrast to that, the map for 2100 approximates new exposure hotspots (darkest colours) referring to highly exposed building area in the southern part and the north eastern part of the study area. The exposure of streets in the western part increases and enlarges compared to building area in this part of Waidhofen/Ybbs. Concluding, the new hotspots are mainly derived from new areas of development of building area, whereas the hotspots related to street area remained the same but intensified. These hotspots can serve as an indication where the landslide exposure is increasing in the future, and detailed risk analysis should be conducted.

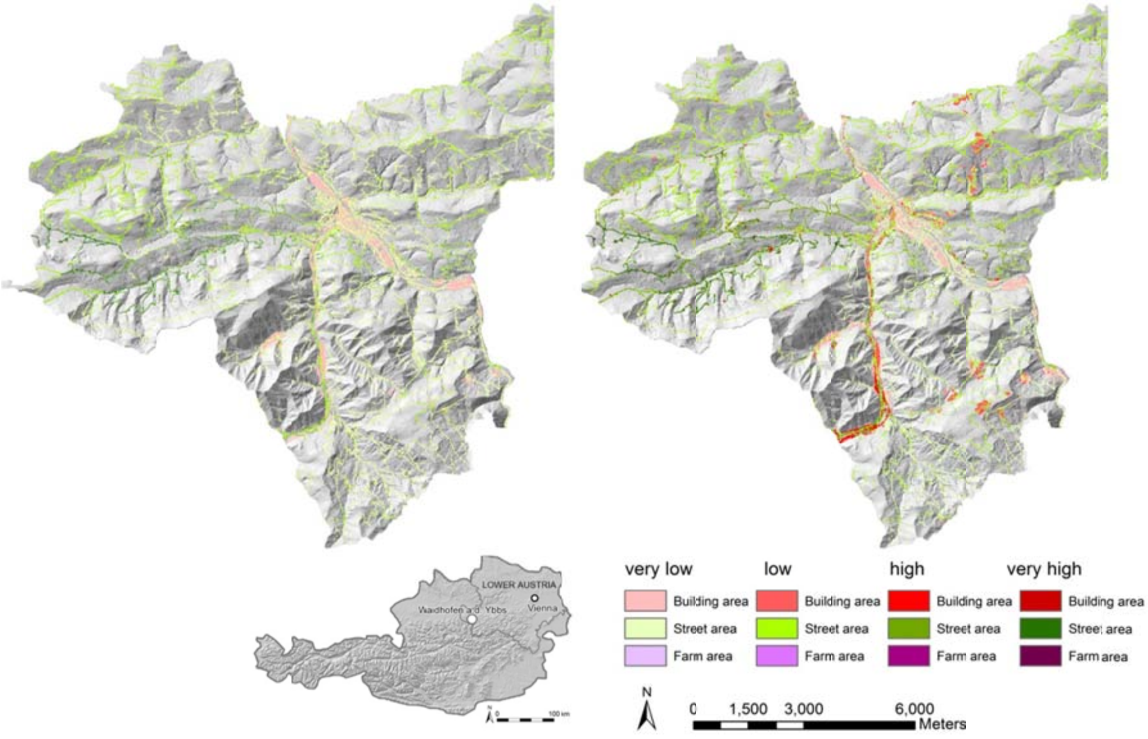


Figure 5.11. Comparison of exposure in 2030 and 2100 for scenario Overall Competition

6. DISCUSSION OF RESULTS AND HYPOTHESES

At the beginning of this thesis four hypotheses were formulated referring to the topic of landslide risk, exposure assessment and the related spatiotemporal development of landslide risk. The methodological approach presented allows an indication on the potential spatial changes of landslide risk by approximating future landslide exposure as a central part of landslide risk assessment. In chapter 1, the methodological approach of testing these hypotheses is detailed followed by chapter 5, presenting the application and the results of the approach. A thorough discussion of the results is given in the respective publications as included in the Annex A.1 to A.4. In this following discussion section the previously raised challenges and arguments are synthesized and put in the light of testing the four analysed hypotheses. Naturally, references to previously published discussion material of the author are included in this section. This section is concluded by the summary of potential applications and limitations of the results.

The results of this thesis represent spatially explicit landslide exposure scenarios which can only be evaluated considering the parameters that were integrated in the different models and the accumulated uncertainties. Therefore, the results represent a methodological approach testing potential future landslide exposure as a central part of landslide risk analysis. This thesis further focusses on land cover as a major input to landslide exposure assessment as land cover change links natural and human systems (KOOMEN 2007) which is a key issue in the context of natural hazard and risk assessment (PROMPER et al. 2014). RINDFUSS ET AL. (2004) further state that the change in land use and land cover respectively, is related to the aforementioned interactions of the human and natural subsystems.

Dealing with future scenarios naturally implies uncertainties. Further, the validation of potential future scenarios is difficult because of the fact that relationships derived from the past not necessarily describe potential future land use change ROUNSEVELL et al. 2006. Moreover, the past only represents one realisation of a potential land use change development (ROUNSEVELL et al. 2005). However, ROUNSEVELL ET AL. (2005) also state that scenarios themselves are models of how the real world functions. Therefore, scenarios themselves approximate different alternative futures by changing parameters, and the inherent uncertainty of these parameter values is acceptable and according to ROUNSEVELL ET AL. (2006) the inherent nature of scenario analysis.

6.1 ON THE CHALLENGES OF MULTILAYER EXPOSURE MAPS

This part of the discussion refers to the identification and ranking of landslide exposure hotspots. Before analysing landslide exposure scenarios, the current landslide exposure was assessed. Accordingly, the first hypothesis aimed at analysing the feasibility of identifying and ranking landslide exposure hot spots in the study area. This analysis included expert decisions that can have a strong effect on the assessment of landslide exposure. The multilayer exposure map in this analysis is based on a detailed database of elements at risk and the susceptibility map. The selection of the different layers of elements at risk relates to population (where residential buildings and schools are grouped into one category), critical infrastructure (all buildings identified as critical infrastructure are summarised) and the streets representing one type of linear infrastructure. The grouping of elements at risk varies among various studies. HANCILAR (2012) for example takes garages, fuel stations etc. into the group of infrastructure or schools into the group of public buildings. PAPATHOMA-KÖHLE (2007) analyse human vulnerability by multiplying the population of each house by the respective vulnerability of the house. PELLICANI ET AL. (2013) explore the exposure by indicators wherein buildings and population are considered for physical and social indicators respectively. Although the categorisation in this thesis is indeed very general, it gives an overview on the composition of elements at risk in the study area and a notion of which types of vulnerability assessments need to be applied in a further step. Therefore schools and residential buildings were grouped as an indication on potentially affected population. As the buildings and hamlets in the district are dispersed, streets are an important element of infrastructure as they link these different assets and were therefore considered for this analysis.

The categorisation of the elements at risk layers to be included in the multilayer exposure map bears some assumptions that might be acclaimed critically. The buildings that are related to critical infrastructure e.g. emergency services or transformers were included in the category “others” however can be extracted of this category due to the keeping of the original codes. The category of buildings on critical infrastructure is diverse and includes buildings like emergency services, that are mostly clustered in areas with a higher density of buildings, whereas for example transformers are scattered all over the study area. The assumption herein is that, all buildings related to critical infrastructure are equally important. The database of elements at risk, collated in extensive field work, indicates a high number of residential buildings that corresponds to the exceeding number of adjacent buildings. This is also true for farms where each farm is accompanied by several adjacent buildings e.g. a stable and a garage or shed. This leads to a very high number of buildings with a highly varying damage potential. On the one hand a garage of a farm can hold very high values and on the other hand the building itself can be of eminent value. In contrast, a shed may also not cover this high damage potential due to the content and the building itself. Additionally the specific vulnerability from a building on a concrete foundation to a wooden shed without foundation differs largely. The dataset on critical infrastructure is regarded as inherent to the analysis of exposure and therefore was included in the multilayer exposure map whereas, due to this high variability in specific vulnerability characteristics, the adjacent buildings where neglected in this investigation.

The second input dataset for the multilayer exposure map is the susceptibility dataset. This is based on several environmental factors as explanatory variables, indicating areas that are more prone to sliding than others. The quality of the resulting landslide susceptibility map is highly dependent on the input data quality and the model performance (PETSCHKO et al. 2014). Furthermore, the amount of classes has an effect on the resulting landslide exposure map. The decision on classifying the susceptibility map into 4 classes using quartiles is based on the need of comparability of the different maps. A larger amount of classes would imply a detailing of the results that does not represent the allowed interpretation of the map given the used input data (COROMINAS et al. 2013).

Ensuring the possibility to evaluate landslide impacts on elements at risk located in the reach of the landslides a buffer representing this reach was approximated with 50 m. The inherent assumption is that the impact of a potential landslide is the same over the entire reach of a landslide. In reality, the landslide impact may be considered of different intensity depending on the section of a landslide the element is located in and on the distance to the scarp of the landslide. This is also elaborated by FELL ET AL. (2008) stating that related to large landslides the impact on elements at risk is higher at e.g. the boundaries of the landslide. However, the buffer serves to ensure that the impacts of landslides on elements at risk potentially lying within the reach of the landslide are not underestimated.

The junction of all layers to a multilayer exposure map helps to indicate where several layers of elements at risk are potentially affected in one location and therein supports the identification of potential exposure hotspots. The visualisation of the results enables to identify areas where and how many layers of elements at risk are located in e.g. highly susceptible areas at the first sight. It is possible to delineate tendencies for different areas. However due to the very detailed picture of how many layers are affected in one spot it is difficult to reveal hotspots of landslide exposure at first sight. For this analysis, it is therefore necessary to zoom in on areas that e.g. indicate darker colours in the higher susceptibility classes and thus show potential exposure hotspots.

A limitation to the interpretation is related to the assumption that all buildings of one group analysed are treated the same which implies for example that a multiparty residential building is treated the same way as a single family residential building. This distinction would have a major influence on human vulnerability as presented in PAPATHOMA-KÖHLE ET AL. (2007). Therefore, it is also difficult to rank the exposure hotspots based on the regional map. This could be overcome by an interactive tool encompassing the multilayer exposure map, but also providing the elements at risk database for a quick analysis of the detailed exposure.

Related to this analysis, there are various sources of uncertainty. Within the data basis of elements at risk, it is a visual interpretation of the type of building that implies epistemic uncertainty (ELITH ET AL. 2002, ROUGIER ET AL. 2013). Another source of uncertainty is the potential impact of the landslide wherein it is assumed that when one location, superimposed by several layers, is affected all layers of elements at risk are affected. However, when, for example, a building is diverging the impact of the landslide (similar to the divergence of avalanches SAUERMOSER et al. 2011) the street or building located downslope may be less or not affected at all. Aleatory sources of uncertainty are incorporated in the statistical analysis of the landslide susceptibility (Hill et al. 2013, Hora 1996). However, this is also partly related to epistemic sources of uncertainty associated to the input datasets e.g. the landslide inventory (ARDIZZONE ET AL. 2002, PETSCHKO 2014).

Being aware of all these uncertainties the results of the exposure analysis allow to support the first hypothesis within the conducted investigation considering one limitation:

Hypothesis 1 [H1]: *A regional exposure assessment facilitates identification and ranking of landslide exposure hotspots in order to support detailed risk analysis.*

It is possible to identify areas that indicate a tendency for high susceptibility and are thus characterized by various superimposed layers of elements at risk. However, with the presented methodology the ranking of the potential exposure hotspots is only allowed by delineating the highest exposed areas.

6.2 ON THE EFFECT OF GLOBAL CHANGE ON LANDSLIDE RISK

Landslide risk depends on various factors and some of these factors are changing and can be referred to as dynamic. These factors concern preparatory or triggering factors of an event, or both, depending on the landslide process (GLADE and CROZIER 2005). Referring to the anticipated consequences, the spatial distribution and the vulnerability of elements at risk is decisive.

HUGGEL (2012) argues that historical unprecedented landslide activity is not necessarily related to a change in climate but also to natural variability. CROZIER (2010) herein underlines the importance of improvement of the resolution of GCMs and their ability to translate global changes to accurate local outcomes in order to get a clearer picture of landslide response to changes in precipitation. However, REMAÎTRE ET AL. (2007) established some interesting trends related to climate change and slope stability. Further IPCC (2012) state that more frequent and intense precipitation events introduce factors of risk into new areas and also reveal potentially underlying vulnerability.

For the study area the overall amount of precipitation is predicted to decrease, however the mean intensity of precipitation is increasing and at the same time, the frequency of events is also decreasing (LOIBL et al. 2007). Therefore, precipitation events are expected to be less frequent but more intense in the future. For the study area, it is precisely these events that are the main triggers of landslides (WALLNER 2012, SCHWENK 1992). This supports the assumption that also the spatial pattern of landslides in the study area will change. However, as mentioned above, there are uncertainties related to future precipitation data. LOIBL ET AL. (2007) refer to the fact that climate change signals for precipitation carry much larger uncertainties than temperature signals and therefore cannot be regarded as strongly significant regarding uncertainties. Further APCC (2014) state that especially the overall trend of precipitation shows no definite trend because Austria is located in a larger transition region of two climatic zones with opposing trends.

The second dynamic factor that is influencing the occurrence of landslide processes is land cover (JEMEC AND KOMAC 2011, GLADE 2003), which subsequently also alters the pattern of landslide susceptibility. Additionally land cover was identified as a basic influential factor for the spatial and temporal distribution of elements at risk. On the one hand, the assumption that land cover is a proxy for the allocation of elements at risk is limiting the distinction of e.g. different buildings and building types, which is further excluding the assessment of physical vulnerability. On the other hand, land cover maps illustrate the distribution of different elements at risk e.g. street and building area on a regional scale and enhance the possibility for analysing potential future development. Referring to the consequence analysis it is the spatiotemporal distribution of elements at risk that is decisive (PROMPER et al. 2014). The spatial distribution of these elements changes due to the shift from a traditionally agricultural society to a post-modern service-based society (FUCHS and KEILER 2013). According to FUCHS AND KEILER (2013), this implies increasing usage of mountain areas for human settlements, industry and recreation which leads to an increase in intangible assets in regions exposed to natural hazard processes.

Based on this discussion and considering the elaborated uncertainties the following hypothesis [2] can also be supported.

***Hypothesis 2 [H2]**: Aspects of global change lead to a change in landslide risk.*

Global change does show an influence on the potential development of landslide risk through different parameters. Considering all uncertainties changes are expected within the spatiotemporal patterns of landslide risk related to changes in both, the geo- and the socio-economic system. This is also supported by the different scenarios modelled for Waidhofen/Ybbs which are discussed in the following chapter. Therein follows that for this hypotheses, independent of the land cover scenarios, the spatial pattern of landslide risk is potentially highly impacted by land cover change and precipitation.

6.3 ON THE EFFECT OF CHANGES IN LAND COVER TO LANDSLIDE EXPOSURE

The land cover over the analysis duration from 1962 to 2100 indicates past and potential future changes throughout the study area. The analysis of the past land cover indicates a steady increase in building and street area which is in contrast with a slight population decrease in the study area in the years 1961 to 2014 from 11.894 to 11.341 inhabitants (STATISTIKAUSTRIA 2014). This probably relates to higher land consumption per capita for residential use (STATISTIKAUSTRIA 2013) and infrastructure. Further the land cover analysis indicates a striking development, which is indicated by an abrupt rise of street area from 1988 to 2005. This can partially be related to the long analysis period of 17 years; however, it may also be related to the incorporation of the digital cadastre which offers additional information, which might not be visually recognizable when mapping the aerial photographs (PROMPER et al. 2014). The development of forested areas from 1962 to 2005 is striking as the trend in this area is towards increasing forest that is also indicated in the future scenarios.

The results of the analysis of past land cover change are associated with several uncertainties related to (see also PROMPER AND GLADE 2012 or PROMPER ET AL. 2014):

- the mapping basis is comprised of orthorectified aerial photographs which implies an increase of uncertainty in the boundary areas due to higher distortion,
- the varying quality of the different aerial photographs and orthophotos related to e.g. overexposure or shading etc.,
- the quality of visual interpretation which might has changed with enhanced mapping practice in spite of applying certain criteria (CARRARA ET AL. 1995 or ARDIZZONE ET AL. 2002 indicate this uncertainty with landslide mapping).

These uncertainties need to be accounted for when interpreting the land cover maps and also the subsequent exposure analysis for the past. For the analysis of future landslide risk the implication of dynamic factors is accumulating uncertainty, which is detailed in the following paragraphs.

The modelled precipitation dataset that is integrated into the future susceptibility analysis is afflicted with aleatory uncertainty related to the modelling process on the one hand and uncertainties evolving from downscaling to a regional scale on the other hand (LOIBL et al. 2007). Related to land cover modelling PONTIUS AND NEETI (2010) identify three grouped sources of uncertainties: 1) the data that contain uncertainties, 2) models containing various types of uncertainty associated with how accurately their algorithms express important processes which are then used to simulate land transitions and 3) future land use change processes can be uncertain because decision making involves human decision-making (free will). As a result, the land cover dataset which is implemented in this study is also afflicted with aleatory uncertainty related to the modelling process itself and epistemic uncertainty, as creating scenarios after ROUNSEVELL (2005) is affected by:

- the subjective nature of qualitative interpretations,
- assumptions underpinning the land use change models used in scenario development,
- the problem of validating future change scenarios,
- the quality of the observed baseline, and
- errors within statistical downscaling techniques.

Related to modelling of land cover scenarios various sources of uncertainties thus have to be discussed. When models are used to create scenarios the input parameters are adjusted in order to develop alternative futures leading to inherent uncertainties of these parameters which, according to is acceptable for scenario analysis (ROUNSEVELL et al. 2006). However, these have to be discussed and communicated accordingly. Further the results of the parametrisation according to the story-lines and the results of the spatially explicit illustration are bound to “what-if” scenarios which have exploratory and projective capacities (PROMPER et al. 2014). This parametrisation of the model according to the story lines is bound to the subjective nature of qualitative interpretation and the assumptions and related sensitivity of land use and land cover change models (IPCC 2007a) that are used in scenario development, underpinning the land use change models and the quality of the baseline scenario (ROUNSEVELL et al. 2006). However, these can be used as a communication and learning environment (VERBURG et al. 2006).

Therefore performing quality management is necessary on as many intermediate steps as possible. It was for example performed when testing the relationship of land cover types to certain environmental factors. Only the regression coefficients which showed ROC values higher than 0.7 in the second test are integrated as beta values representing the location specific suitability. The value higher than 0.7 indicates a “fair” value on the diagnostic point system (TAPE 1990). This is also true for the applied neighbourhood coefficients. Additionally the implemented distance files and restrictions were discussed with several experts to ensure a valid parametrisation according to the story lines on the one hand and the implementation of spatial planning trends e.g. no housing sprawl in the modelling framework on the other hand. The key component in this analysis is the coupling of potential hazardous areas with the location and redistribution of elements at risk (PROMPER et al. in press). The results of this analysis indicate increasing risk due to both, rising exposure from development in susceptible areas and an increase in landslide susceptibility which also affects existing elements at risk.

The changes in the high and very high landslide exposure class for building and farm area are marginal over the duration of the analysis, except for the change from 2050 – 2100 where a significant increase can be expected. This increase of 5% can be related to the larger time span of 50 years. Analysing the results qualitatively, location based, an apparent increase of exposure hotspots can be expected. The potential spatial change in risk is related to increasingly exposed street and building area. These developments can be ascribed to new building area in the highly susceptible areas, increasing landslide susceptibility in locations of existing elements at risk and areas where development, as well as landslide susceptibility increases.

In this analysis, no spatial restrictions related to non-structural mitigation measures like avoidance are applied. Further, no spatial development plans except general trends were implemented. The implementation of such policies could lead to a different picture and even higher pressure on space related to further increase in building area.

The results of the spatiotemporal exposure assessment therefore delineate certain trends and illustrate potential future scenarios according to the restrictions and parameters applied. Considering the uncertainties and underlining the importance of how to communicate scenario results the methodological framework supports hypothesis [3], whereas hypothesis [4] only partly:

Hypothesis 3 [H3]: *Land cover change influences the spatiotemporal development of landslide risk.*

Although no full landslide risk assessment was carried out in this study, this hypothesis can be supported. Exposure is a central part of risk and as it is location bound (FRA PALEO 2009) it also influences the spatiotemporal development of landslide risk.

__Hypotheses 4 [H4]:__ *There will be changes of landslide risk in the future: new elements at risk will develop in susceptible areas, and existing elements are superimposed by areas of increasing susceptibility. However, the locations of exposure hotspots will remain unchanged over time.*

The analysis of the results indicates that new elements at risk are expected to develop in areas susceptible to landslides however also existing elements at risk that are superimposed on an increase of susceptible areas. Additionally there are some development areas that coincide with increased susceptibility over the duration of the analysis. The second part of the hypothesis referring to the remaining locations of exposure hotspots has to be rejected, since new hotspots evolve additionally.

6.4 POTENTIAL APPLICATION AND LIMITATIONS

The methodological approach suggested in this study was developed for the identification of potential exposure hotspots and their spatiotemporal development. Two levels of exposure maps for the regional scale were produced:

- detailed multilayer exposure map for the current situation, and
- spatiotemporal exposure maps approximating potential future developments.

The current multilayer exposure map gives a sound overview of the composition of the overall exposure and illustrates where landslide susceptible areas coincide with multiple layers of elements at risk. Therefore, the map enables to detect high exposed areas related to landslides that could be necessary when deciding on the application of detailed vulnerability and risk analysis. With a comprehensive database as available from this study, it is further possible to delineate quickly which elements exactly are affected and in which conditions the respective buildings are located. This means that a ranking of the exposure hotspots on the first sight of the map is not possible. Considering a top-down approach, areas where three different types of elements at risk are highly exposed provide a good basis for detailed analysis, which subsequently enables a ranking of the hotspots.

The limitation of this analysis is clearly the elaborate illustration of the multilayer exposure map on a regional scale which only allows detecting highly exposed areas, but makes no differentiation in the medium classes due to the highly detailed level presented on regional scale. Further, the small number of buildings of critical infrastructure in relation to the high number of residential buildings and streets make the medium classes with two affected layers too large in comparison to the high class with three layers affected. Additionally all elements at risk in one layer are treated equally, therefore, the presence of critical infrastructure in one location can refer to the fire station being very imperative in comparison to a small transformer. A further development of this method therefore could focus on taking into account these differences.

Referring to the analysis of future exposure, increasing land consumption in areas exposed to natural hazards and increasing susceptibility to natural hazards raise the damage potential and increase pressure on the limited alpine space (ADAPTALP 2011, FUCHS AND KEILER 2013). This indicates a need for adaptation to potential future circumstances and spatial planning is an opportunity to navigate changes and negotiate between competing demands (ADAPTALP 2011). Although the methodological approach for approximating the future exposure development is connected to various sources of uncertainty, it gives a range of possible developments that could be interesting for future land use planning and land management. MECHLER AND THE RISK TO RESILIENCE TEAM (2008) herein state that *accounting for changes in exposure is important, as reductions in future damages and losses often may be compensated by sheer increase in people and assets in harm´s way*. The results in this thesis indicate potential development for various scenarios and illustrate on where potential changes in landslide exposure can be expected. The applied analysis at regional scale therefore, gives an indication to stakeholders undertaking decisions on a broader scale. SUKARNA ET AL. (2012) refer to the importance of risk mapping on a regional scale for balanced financial or political support or identification of priority areas. For these priority areas a detailed risk analysis could indicate the potential loss. This potential loss may be traded off against protection costs, a classical procedure within cost/benefit analysis (Fuchs 2013, FEMA 1997). Additionally, detailed vulnerability and risk analysis is always connected to high data or financial needs, and therefore, a hierarchical approach, in which regional analysis can guide the selection of local investigation areas, serves to strategically use the available resources.

The limitations of this application are the missing inputs of actual development plans and also hazard zone mapping as both already exclude certain areas from development. The implications of hazard zone maps vary among different countries. As an example the Austrian hazard zone map includes a red zone (high process intensity), wherein constant use of the respective area for settlement and traffic purposes is not possible or only possible with disproportionally high costs and in the yellow zones (medium process intensity) permanent use is impaired (RUDOLF-MIKLAU and SAUERMOSER 2014). Therefore, taking into consideration land development plans and hazard zone mapping would have increased the plausibility of the scenarios and therefore increased the impact of the scenarios on decision makers. However, the indication of changes on this long time frame can also initiate discussions on a general approach for tackling the potential changes related to the natural and the socio-economic environment in the region. This also refers to the discussion on potential adaptation strategies.

7. CONCLUSION AND PERSPECTIVES

In this thesis an approach for an assessment of current landslide exposure and a spatiotemporal analysis of future landslide exposure were performed. On regional scale the results indicate exposure hotspots and the change of these hotspots over time.

The multilayer exposure maps allow delineating exposure hotspots for the current situation while they allow a delineation of the highest exposed areas rather than the ranking of hotspots as initially aspired. The presented approach allows an indication on which types of vulnerability assessments need to be applied in a detailed vulnerability and risk analysis. This refers to the possibility of selecting specific elements at risk (e.g. schools) as a layer for an indication where also social vulnerability e.g. considering coping capacity, has to be considered.

The scenarios of spatiotemporal development of landslide exposure indicate potential changes in spatial development thereof, hence landslide risk in future. The results indicate that besides a shift of exposure also new hotspots of landslide risk may evolve. The landslide exposure assessment on a regional scale provides an overview of the area and thereby a good indication of where in-depth analysis of landslide risk analysis is needed.

Further the results of the future exposure analysis show that not only new development of elements at risk implies an increase in exposure but also increasing landslide susceptibility is imposing a spatial shift in exposure due to the evolution in areas of existing elements at risk.

The incorporation of dynamic factors of global change in hazard and consequence analysis shows a multitude of further research potential. This thesis aims at contributing to the following specific aspects:

- ☐ The development of a framework for modelling land cover as input to landslide risk assessment,
- ☐ a spatially explicit approximation of the development of elements at risk with land cover scenarios over time on a regional scale in Waidhofen/Ybbs, and

☐ the implementation of land cover and precipitation change into scenario based landslide exposure assessment tested in Waidhofen/Ybbs .

The basic procedure of the methodological approach was clearly demonstrated and can easily be repeated for other regions. Constraints, uncertainties and limitations were pointed out and should be considered in future applications of the method.

Concluding, the results confirmed the hypothesis of spatial shifts in landslide exposure that may be kept in mind as a word of caution for prospective spatial planning and development in this area. Further the transferability of the framework for analysing scenarios of landslide risk development is a major advantage considering the potential climate change and its implication on landslide processes.

Perspectives on future research based on methods and results of this thesis range from the benefits drawn from the collection of additional attributes to the elements at risk to the potential of extending the modelling of land cover scenarios. The perspectives include a more detailed investigation and assembly of additional data. This could clearly improve the applicability of the outcomes of the study in regional spatial and civil protection planning practices. Referring to the land cover modelling, research perspectives are the incorporation of development plans from the municipality, hazard zone maps or other available data that provide parameters for improving the translation of scenarios of land cover development.

Tackling the cartographical challenges an index-based approach could facilitate visualizing and ranking the landslide exposure hot spots. With such an index-based approach areas of high exposure where more detailed risk analysis is necessary could be indicated. The implementation of the database and the results in an interactive Web-GIS platform with advanced query functions may facilitate an easy integration of all the relevant aspects of landslide risk (and exposure) in development plans.

Moreover, the data collected on elements at risk can serve for additional analysis on the specific vulnerability of buildings in the study area. This may guide a targeted investing of public resources in prevention measures as areas of high vulnerability can be identified quickly. The characteristics of the buildings, including condition, as well as the distinction between single-party and multi-party residential buildings and the number of floors, can additionally give an indication on affected population. The knowledge of the exact location of the respective buildings or elements of critical infrastructure in combination with the estimation of number of present people is crucial for targeting civil protection interventions.

The modelling of land cover scenarios and the possibility to design story lines of development therein is a store of research perspectives. An example is the possibility to define areas restricted to development. Modelling of land cover scenarios allows integrating restriction areas e.g. for wind farms or recreation which are excluded for future development to any other land cover type. This allows simulating upcoming additional pressure on space and integrating potential future elements at risk that could emerge due to e.g. energy scarcities.

In a multi-hazard or multi-exposure perspective, the land cover scenarios may be facilitated to analyse the effects of future land cover change also on other natural hazards such as floods or debris flows. This analysis can help to identify areas and elements at risk which are not only exposed to one type of natural hazard but to multiple hazards maybe even at the same time. The result of an integration of future land cover scenarios can be scenarios of future multi-hazard risk can support natural hazard risk management

The methodological approach applied in this thesis can stimulate the initiation of a discussion process among stakeholders on potential future hazard exposure scenarios. Further improvements and integration of supplementary expert input can help to further adjust the scenarios to the characteristics of the respective study area. However, it is important to keep in mind that scenarios are alternative future developments, and therefore the interpretation is limited. Detailed risk analysis and detailed hazard analysis in potential development areas are necessary to effectively apply long-term risk mitigation measures like avoidance and thus facilitate reducing future risk for the affected areas.

8. REFERENCES

ADAPTALP 2011. ADVANCE Common Strategic Paper.

AGRAWAL C., GREEN M. G., GROVE J. M., EVANS T. P. andSCHWEIK C. M. 2002. *A review and assessment of land-use change models [electronic resource] : dynamics of space, time, and human choice /* U.S. Dept. of Agriculture, Forest Service, Northeastern Research Station.

AKAIKE H. 1974. A new look at the statistical model identification. *Automatic Control, IEEE Transactions on,* **19.** 6**.** 716-723.

ALCANTARA-AYALA I. 2004. Hazard assessment of rainfall-induced landsliding in mexico. *Geomorphology,* **61.** 1–2**.** 19-40.

ALCÁNTARA-AYALA I., ESTEBAN-CHÁVEZ O. andPARROT J. F. 2006. Landsliding related to land-cover change: A diachronic analysis of hillslope instability distribution in the Sierra Norte, Puebla, Mexico. *Catena,* **65.** 2**.** 152-165.

ALEXANDER D. 2002. Principles of Emergency Planning and Management.

ANDREYCHOUK V. andTYC A. 2013. Karst hazards. In: BOBROWSKY P. (ed.) *Encyclopedia of Natural Hazards.* Dordrecht, Heidelberg, New York, London: Springer.

APCC 2014. *Österreichischer Sachstandsbericht Klimawandel 2014 Austrian Assessment Report 2014 (AAR14),* Wien.

ARDIZZONE F., CARDINALI M., CARRARA A., GUZZETTI F. andREICHENBACH P. 2002. Impact of mapping errors on the reliability of landslide hazard maps. *Nat. Hazards Earth Syst. Sci.,* **2.** 1/2**.** 3-14.

ATKINSON P. M. andMASSARI R. 1998. Generalized Linear Modelling of suceptibility to landsliding in the Central Apennines, Italy. *Computers & Geosciences,* **24.** 4**.** 373-385.

AUBRECHT C., FUCHS S. andNEUHOLD C. 2013. Spatio-temporal aspects and dimensions in integrated disaster risk management. *Natural Hazards,* **68.** 3**.** 1205-1216.

AYALEW L. andYAMAGISHI H. 2005. The application of GIS-based logistic regression for landslide susceptibility mapping in the Kakuda-Yahiko Mountains, Central Japan. *Geomorphology,* **65.** 1–2**.** 15-31.

BATHURST J. C., BOVOLO C. I. andCISNEROS F. 2010. Modelling the effect of forest cover on shallow landslides at the river basin scale. *Ecological Engineering,* **36.** 3**.** 317-327.

BÄTZING W. 2003. *Die Alpen Geschichte und Zukunft einer europäischen Kulturlandschaft,* München, C. H. Beck. ^431.

BAZZAZ F. andSOMBROEK W. (eds.) 1996. *Global climate change and agricultural production. Direct and indirect effects of changing hydrological, pedological and plant physiological processes,* Chichester: FAO & John Wiley & Sons Ltd.

BEGUERÍA S. 2006a. Changes in land cover and shallow landslide activity: A case study in the Spanish Pyrenees. *Geomorphology,* **74.** 1-4**.** 196-206.

BEGUERÍA S. 2006b. Validation and Evaluation of Predictive Models in Hazard Assessment and Risk Management. *Natural Hazards,* **37.** 3**.** 315-329.

BELL R. 2007. Lokale und regionale Gefahren- und Risikoanalyse gravitativer Massenbewegungen an der Schwäbischen Alb (Dissertation). Universität Bonn.

BELL R. andGLADE T. 2004. Quantitative risk analysis for landslides ‒ Examples from Bíldudalur, NW-Iceland. *Nat. Hazards Earth Syst. Sci.,* **4.** 1**.** 117-131.

BELL R., GLADE T., GRANICA K., HEISS G., LEOPOLD P., PETSCHKO H., POMAROLI G., PROSKE H. andSCHWEIGL J. Landslide susceptibility maps for spatial planning in lower Austria. Landslide Science and Practice: Landslide Inventory and Susceptibility and Hazard Zoning, 2013. 467-472.

BENISTON M., STEPHENSON D., CHRISTENSEN O., FERRO C. T., FREI C., GOYETTE S., HALSNAES K., HOLT T., JYLHÄ K., KOFFI B., PALUTIKOF J., SCHÖLL R., SEMMLER T. andWOTH K. 2007. Future extreme events in European climate: an exploration of regional climate model projections. *Climatic Change,* **81.** 1**.** 71-95.

BFW. 2013. ebod [Online]. Bundesforschungs- und Ausbildungszentrum für Wald, Naturgefahren und Landschaft (BFW)

Available: http://gis.lebensministerium.at/eBOD [Accessed 27.05.2013.

BMLFUW 2011. ÖSTRAT- Österreichische Strategie Nachhaltige Entwicklung Arbeitsprogramm 2011ff des Bundes und der Länder.

BOBEK H., KURZ W. andZWITTKOVITS F. 1971. *Hölzl-Universalatlas zu Geographie und Geschichte,* Wien, Freytag-Berndt und Artaria.

BOGATAJ L. K. 2007. How will the Alps Respond to Climate Change? Scenarios for the Future of Alpine Water. iup • innsbruck university press. 10

BOHLE H.-G. 2001. Vulnerability and Criticality: Perspectoves from Social Geography. *IHDP Update 2/2001, Newsletter of the International Human Dimensions Programme on Global Environmental Change,* 1-7.

BRABB E. E. 1984. Innovative approaches to landslide hazard mapping. Toronto, Canada.

BRENNING A. 2005. Spatial prediction models for landslide hazards: Review, comparison and evaluation. *Natural Hazards and Earth System Science,* **5.** 6**.** 853-862.

BRÜNDL M., ROMANG H. E., BISCHOF N. andRHEINBERGER C. M. 2009. The risk concept and its application in natural hazard risk management in Switzerland. *Nat. Hazards Earth Syst. Sci.,* **9.** 3**.** 801-813.

BUBECK P. andKREIBICH H. 2011. CONHAZ Costs of Natural Hazards WP 1 Final Report: Natural Hazards: direct costs and losses due to the disruption of production processes WP 1 Final Report.

CAMMERER H., THIEKEN A. andVERBURG P. 2013. Spatio-temporal dynamics in the flood exposure due to land use changes in the Alpine Lech Valley in Tyrol (Austria). *Natural Hazards,* **68.** 3**.** 1243-1270.

CARPIGNANO A., GOLIA E., DI MAURO C., BOUCHON S. andNORDVIK J.-P. 2009. A methodological approach for the definition of multi-risk maps at regional level: first application. *Journal of Risk Research,* **12.** 3-4**.** 513-534.

CARRARA A., CARDINALI M., GUZZETTI F. andREICHENBACH P. 1995. Gis Technology in Mapping Landslide Hazard. In: CARRARA A. andGUZZETTI F. (eds.) *Geographical Information Systems in Assessing Natural Hazards.* Springer Netherlands.

CASCINI L. 2008. Applicability of landslide susceptibility and hazard zoning at different scales. *Engineering Geology,* **102.** 3–4**.** 164-177.

CASCINI L., BONNARD C., COROMINAS J., JIBSON R. andMONTERO-OLARTE J. 2005. Landslide hazard and risk zoning for urban planning and development In: HUNGR O., FELL R., COUTURE R. andEBERHARD E. (eds.) *Landslide Risk Management.* CRC.

CASTELLANOS ABELLA E. A. 2008. Multi-scale landslide risk assessment in Cuba. ITC Dissertation 154, University of Utrecht.

CHAMBERS R. 2006. Vulnerability, Coping and Policy (Editorial Introduction). *IDS Bulletin,* **37.** 4**.** 33-40.

CHUNG C.-J., FABBRI A. andVAN WESTEN C. 1995. Multivariate Regression Analysis for Landslide Hazard Zonation. In: CARRARA A. andGUZZETTI F. (eds.) *Geographical Information Systems in Assessing Natural Hazards.* Springer Netherlands.

CLAGUE J. J. 2013. Landslide. In: BOBROWSKY P. (ed.) *Encyclopedia of Natural Hazards.* Dordrecht, Heidelberg, New York, London: Springer.

CLINTON W. J. 2006. Key Propositions for Building Back Better A Report by the United Nations Secretary-General's Special Envoy for Tsunami Recovery, William J. Clinton.

COE J. A., MICHAEL J. A., CROVELLI R. A., SAVAGE W. Z., LAPRADE W. T. andNASHEM W. D. 2004. Probabilistic Assessment of Precipitation-Triggered Landslides Using Historical Records of Landslide Occurrence, Seattle, Washington. *Environmental & Engineering Geoscience,* **10.** 2**.** 103-122.

COLLISON A., WADE S., GRIFFITHS J. andDEHN M. 2000. Modelling the impact of predicted climate change on landslide frequency and magnitude in SE England. *Engineering Geology,* **55.** 3**.** 205-218.

COROMINAS J., WESTEN C., FRATTINI P., CASCINI L., MALET J. P., FOTOPOULOU S., CATANI F., EECKHAUT M., MAVROULI O., AGLIARDI F., PITILAKIS K., WINTER M. G., PASTOR M., FERLISI S., TOFANI V., HERVÁS J. andSMITH J. T. 2013. Recommendations for the quantitative analysis of landslide risk. *Bulletin of Engineering Geology and the Environment,* **73.** 2**.** 209-263.

CORSINI A., BORGATTI L., CERVI F., DAHNE A., RONCHETTI F. andSTERZAI P. 2009. Estimating mass-wasting processes in active earth slides – earth flows with time-series of High-Resolution DEMs from photogrammetry and airborne LiDAR. *Nat. Hazards Earth Syst. Sci.,* **9.** 2**.** 433-439.

CROZIER M. J. 2010. Deciphering the effect of climate change on landslide activity: A review. *Geomorphology,* **124.** 3-4**.** 3-15.

CROZIER M. J. andGLADE T. 2005. Landslide hazard and risk: issues, concepts, and approach. In: GLADE T., ANDERSON M. G. andCROZIER M. J. (eds.) *Landslide hazard and risk.* Chichester: Wiley.

CRUDEN D. M. andVARNES D. J. 1996. Landslide types and processes. In: TURNER A. K. andSCHUSTER R. L. (eds.) *Landslides: investigation and mitigation.* Washington, D.C.: National Academey Press.

CUTTER S. L. 2006. Societal Response to Environmental Hazards. *Hazards, Vulnerability and Environmental Justice.* London: Earthscan.

DAI F. C., LEE C. F., LI J. andXU Z. W. 2001. Assessment of landslide susceptibility on the natural terrain of Lantau Island, Hong Kong. *Environmental Geology,* **40.** 3**.** 381-391.

DAI F. C., LEE C. F. andNGAI Y. Y. 2002. Landslide risk assessment and management: an overview. *Engineering Geology,* **64.** 1**.** 65-87.

DE MOEL H., AERTS J. C. J. H. andKOOMEN E. 2011. Development of flood exposure in the Netherlands during the 20th and 21st century. *Global Environmental Change,* **21.** 2**.** 620-627.

DECKER K. 1990. Bericht 1990 über geologische Aufnahmen an der Kalkalpen-Flysch-Grenze auf Blatt 70 Waidhofen an der Ybbs. 477-478

DEHN M. andBUMA J. 1999. Modelling future landslide activity based on general circulation models. *Geomorphology,* **30.** 1–2**.** 175-187.

DFID 2004. Disaster risk reduction: a development concern. Department for International Development

DIGREGORIO A. andJANSEN L. J. M. 2000. Land Cover Classification System (LCCS): Classification Concepts and User Manual FAO.

DIKAU R., BRUNSDEN D., SCHROTT L. andIBSEN M. (eds.) 1996. *Landslide Recognition. Identification, movement and causes,* Chichester: John Wiley & Sons Ltd.

DIXON N. andBROOK E. 2007. Impact of predicted climate change on landslide reactivation: case study of Mam Tor, UK. *Landslides,* **4.** 2**.** 137-147.

EC 2010. COMMISSION STAFF WORKING PAPER Risk Assessment and Mapping Guidelines for Disaster Management SEC(2010) 1626 final

EEA 2010. The european environment state and outlook 2010 - land use. European Environment Agency.

ELITH J., BURGMAN M. A. andREGAN H. M. 2002. Mapping epistemic uncertainties and vague concepts in predictions of species distribution. *Ecological Modelling*, **157.** 2–3**.** 313-329.

ELLIS E. 2013. Land - use and land cove change [Online]. Available: http://www.eoearth.org/view/article/154143/ [Accessed 01.05.2014.

ERCANOGLU M. andGOKCEOGLU C. 2002. Assessment of landslide susceptibility for a landslide-prone area (north of Yenice, NW Turkey) by fuzzy approach. *Environmental Geology*, **41.** 6**.** 720-730.

ERMINI L., CATANI F. andCASAGLI N. 2005. Artificial Neural Networks applied to landslide susceptibility assessment. *Geomorphology*, **66.** 1–4**.** 327-343.

ESTEBAN J. F., IZQUIERDO B., LOPEZ J., MOLINARI D., MENONI S., DE ROON A., DEEMING H., WALKER G. andEFTICHIDIS G. 2011. Current Mitigation Practices in the EU. In: MENONI S. andMARGOTTINI C. (eds.) *Inside risk: A Strategy for Sustainable Risk Mitigation*. Milan Dordrecht Heidelberg London New York: Springer-Verlag Italia.

FEIZIZADEH B., BLASCHKE T., NAZMFAR H. andREZAEI MOGHADDAM M. H. 2013. Landslide Susceptibility Mapping for the Urmia Lake basin, Iran: A multi-Criteria Evaluation Approach using GIS. *International Journal of Environmental Research*, **7.** 2**.** 319-336.

FELGENTREFF C. andGLADE T. 2008. Naturrisiken - Sozialkatastrophen: zum Geleit. In: FELGENTREFF C. andGLADE T. (eds.) *Naturrisiken und Sozialkatastrophen*. Berlin: Springer-Verlag.

FELL R. 1994. Landslide risk assessment and acceptable risk. *Canadian Geotechnical Journal*, **31.** 2**.** 261-272.

FELL R., COROMINAS J., BONNARD C., CASCINI L., LEROI E. andSAVAGE W. Z. 2008. Guidelines for landslide susceptibility, hazard and risk zoning for land use planning. *Engineering Geology*, **102.** 3-4**.** 85-98.

FELL R., HO K. K. S., LACASSE S. andLEROI E. 2005. A framework for landslide risk assessment and management. In: HUNGR O., FELL R., COUTURE R. andEBERHARDT E. (eds.) *Landslide risk management*. London: Taylor and Francis Group.

FEMA 1989. Landslide Loss Reduction: A Guide for Stae and Local Government Planning. Federal Emergency Management Agency.

FEMA 1997. Report on Costs and Benefits of Natural Hazard Mitigation.

FERRIER N. andHAQUE C. E. 2003. Hazards Risk Assessment Methodology for Emergency Managers: A Standardized Framework for Application. *Natural Hazards,* **28.** 2-3**.** 271-290.

FISCHLIN A., MIDGLEY G. F., PRICE J. T., LEEMANS R., GOPAL B., TURLEY C., ROUNSEVELL M. D. A., DUBE O. P., TARAZONA J. andVELICHKO A. A. 2007. Ecosystems, their properties, goods and services. In: PARRY M. L., CANZIANI O. F., PALUTIKOF J. P., P.J. V. D. L. andHANSON C. E. (eds.) *Climate change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel of Climate Change (IPCC).* Cambridge, UK: Cambridge University Press.

FOCP 2012. Integral Risk Management Cycle. Federal Office for Civil Protection, Switzerland.

FRA PALEO U. 2009. *Building Safer Communities: Risk Governance, Spatial Planning and Responses to Natural Hazards, NATO science for peace and security series: Human and societal dynamics,Vol 58,*, IOS Press.

FUCHS S. 2008. Vulnerability to torrent processes. *WIT Transactions on Information and Communication Technologies,* **39.** p. 289-298.

FUCHS S. 2009. Mountain hazards, vulnerability, and risk – a contribution to applied research on human-environment interaction. Habilitationsschrift, Universität Innsbruck

FUCHS S. 2013. Cost-benefit analysis of natural hazard mitigation. In: BOBROWSKY P. (ed.) *Encyclopedia of Natural Hazards.* Dordrecht, Heidelberg, New York, London: Springer.

FUCHS S. andKEILER M. 2013. Space and time: coupling dimensions in natural hazard risk management? In: MÜLLER-MAHN D. (ed.) *The spatial dimension of risk – how geography shapes the emergence of riskscapes.* London: Earthscan.

GARCÍA-RUIZ J. M., BEGUERÍA S., ALATORRE L. C. andPUIGDEFÁBREGAS J. 2010. Land cover changes and shallow landsliding in the flysch sector of the Spanish Pyrenees. *Geomorphology,* **124.** 3–4**.** 250-259.

GASSNER C., PROMPER C., BEGUERÍA S. andGLADE T. Climate change impact for spatial landslide susceptibility IAEG XII Congress Engeneering Geology for Soiety and Territory 2014 Torino. Springer.

GASSNER C., PROMPER C., PETSCHKO H. andGLADE T. 2013. Scenarios of future landslide susceptibility - incorporating changes in land cover and climate. *European Geoscience Union General Assembly 2013.* Vienna: Copernicus Publications.

GELLRICH M., BAUR P., KOCH B. andZIMMERMANN N. E. 2007. Agricultural land abandonment and natural forest re-growth in the Swiss mountains: A spatially explicit economic analysis. *Agriculture, Ecosystems & Environment,* **118.** 1–4**.** 93-108.

GERRARD J. andGARDNER R. 2002. Relationships Between Landsliding and Land Use in the Likhu Khola Drainage Basin, Middle Hills, Nepal. *Mountain Research and Development,* **22.** 1**.** 48-55.

GIBSON C. C., OSTROM E. andAHN T. K. 2000. The concept of scale and the human dimensions of global change: A survey. *Ecological Economics,* **32.** 2**.** 217-239.

GLADE T. 2000. Applying Probability Determination to Refine Landslide-triggering Rainfall Thresholds Using an "Empirical Antecedent Daily Rainfall Model" . *Pure and Applied Geophysics,* **157.** 6 - 8**.** 1059-1079.

GLADE T. 2003. Landslide occurrence as a response to land use change: A review of evidence from New Zealand. *Catena,* **51.** 3-4**.** 297-314.

GLADE T., ANDERSON M. G. andCROZIER M. J. (eds.) 2005. *Landslide hazard and risk,* Chichester: Wiley.

GLADE T., BELL R., DOBESBERGER P., EMBLETONHAMANN C., FROMM R., FUCHS S., HAGEN K., HÜBL J., LIEB G., OTTO J. C., PERZL F., PETICZKA R., PRAGER C., SAMIMI C., SASS O., SCHÖNER W., SCHRÖTER D., SCHROTT L., ZANGERL C. andZEIDLER A. 2014. Der Einfluss des Klimawandels auf die Reliefsphäre. In: Österreichischer Sachstandsbericht Klimawandel 2014 (AAR14). Austrian Panel on Climate Change (APCC). 557-600

GLADE T. andCROZIER M. J. 2005. The Nature of Landslide Hazard Impact. *Landslide Hazard and Risk.* John Wiley & Sons, Ltd.

GLADE T., KAPPES M. S., FRIGERIO S. andMALET J. P. Multi-Hazard Exposure Analyses with MULTIRISK - a platform for user-friendly analysis. 12th Congress INTERPRAEVENT, 2012 Grenoble, France.

GOBIET A., KOTLARSKI S., BENISTON M., HEINRICH G., RAJCZAK J. andSTOFFEL M. 2014. 21st century climate change in the European Alps—A review. *Science of The Total Environment,* **493.** 1138-1151.

GODT J. W., BAUM R. L., SAVAGE W. Z., SALCIARINI D., SCHULZ W. H. andHARP E. L. 2008. Transient deterministic shallow landslide modeling: Requirements for susceptibility and hazard assessments in a GIS framework. *Engineering Geology,* **102.** 3–4**.** 214-226.

GOTTSCHLING P. 2006. Dr. Harald SCHWENK 18. März 1927 – 11. Jänner 2006. *Jahrbuch der Geologischen Bundesanstalt.* Wien: Geologische Bundesanstalt.

GRIMM N. B., FAETH S. H., GOLUBIEWSKI N. E., REDMAN C. L., WU J., BAI X. andBRIGGS J. M. 2008. Global Change and the Ecology of Cities. *Science,* **319.** 5864**.** 756-760.

GROZAVU A., PLEŞCAN S., PATRICHE C., MĂRGĂRINT M. andROŞCA B. 2013. Landslide Susceptibility Assessment: GIS Application to a Complex Mountainous Environment. In: KOZAK J., OSTAPOWICZ K., BYTNEROWICZ A. andWYŻGA B. (eds.) *The Carpathians: Integrating Nature and Society Towards Sustainability.* Springer Berlin Heidelberg.

GUZZETTI F. 2000. Landslide fatalities and the evaluation of landslide risk in Italy. *Engineering Geology,* **58.** 2**.** 89-107.

GUZZETTI F., CARRARA A., CARDINALI M. andREICHENBACH P. 1999. Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy. *Geomorphology,* **31.** 1–4**.** 181-216.

GUZZETTI F., PERUCCACCI S., ROSSI M. andSTARK C. P. 2007. Rainfall thresholds for the initiation of landslides in central and southern Europe. *Meteorology and Atmospheric Physics,* **98.** 3-4**.** 239-267.

GUZZETTI F., REICHENBACH P., CARDINALI M., GALLI M. andARDIZZONE F. 2005. Probabilistic landslide hazard assessment at the basin scale. *Geomorphology,* **72.** 1-4**.** 272-299.

HANCILAR U. 2012. Identification of elements at risk for a credible tsunami event for Istanbul. *Natural Hazards and Earth System Sciences,* **12.** 107-119.

HANSEN J. andSATO M. 2012. Paleoclimate Implications for Human-Made Climate Change. In: BERGER A., MESINGER F. andSIJACKI D. (eds.) *Climate Change.* Springer Vienna.

HIESS H., GRUBER M., PAYER H., PENKER M., SCHRENK M., WANKIEWICZ H. andZUMBUSCH K. 2009. Szenarien der Raumentwicklung Österreichs 2030 Regionale Herausforderungen & Handlungsstrategien. Geschäftsstelle d. Österr. Raumordungskonferenz (ÖROK).

HIETEL E., WALDHARDT R. andOTTE A. 2004. Analysing land-cover changes in relation to environmental variables in Hesse, Germany. *Landscape Ecology,* **19.** 5**.** 473-489.

HIGHLAND L. M. andBOBROWSKY P. 2008. *The Landslide Handbook - A Guide to Understanding Landslides,* Reston, Virginia, U.S. Geological Survey Circular. ^129.

HILL L. J., SPARKS R. S. J. andROUGIER J. C. 2013. *Risk assessment and uncertainty in natural hazards,* Cambridge University Press. ^1-18.

HOLLENSTEIN K. 2005. Reconsidering the risk assessment concept: Standardizing the impact description as a building block for vulnerability assessment. *Natural Hazard and Earth System Science,* **5.** 3**.** 301-307.

HOLLENSTEIN K., MERZ H. andBÄHLER F. 2004. Methoden des risikobasierten Planens und Handelns bei der Naturgefahrenabwehr Schlussbericht. Eidgenössische Technische Hochschule Zürich.

HÖPPE P. 2007. Naturkatastrophentrends - Änderungsrisiko Klimawandel. In: BRUNS A. andGROBENSKI Z. (eds.) *Die Versicherung von Umweltrisiken.* Karlsruhe: Verlag Versicherungswirtschaft GmbH Karlsruhe.

HORA S. C. 1996. Aleatory and epistemic uncertainty in probability elicitation with an example from hazardous waste management. *Reliability Engineering & System Safety,* **54.** 2–3**.** 217-223.

HU Z. andLO C. P. 2007. Modeling urban growth in Atlanta using logistic regression. *Computers, Environment and Urban Systems,* **31.** 6**.** 667-688.

HUFSCHMIDT G., CROZIER M. J. andGLADE T. 2005. Evolution of natural risk: research framework and perspectives. *Natural Hazards and Earth System Sciences,* **5.** 3**.** 375-387.

HUGGEL C., CLAGUE J. J. andKORUP O. 2012. Is climate change responsible for changing landslide activity in high mountains? *Earth Surface Processes and Landforms,* **37.** 1**.** 77-91.

IEC/ISO 2009. IEC 31010:2009 Risk management -- Risk assessment techniques.

IPCC. 2007a. Climate Change 2007: Impacts, Adaptation and Vulnerability - Summary of Policymakers. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Online]. Available: http://www.ipcc.ch/WG1_SPM_17Apr07.pdf [Accessed 15.03.2008.

IPCC 2007b. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri, and A. Reisinger (eds.)]. 104

IPCC 2012. Summary for Policymakers: Managing the risk of extreme events and disasters to advance climate change adaptation. 1-19

JAEDICKE C., VAN DEN EECKHAUT M., NADIM F., HERVÁS J., KALSNES B., VANGELSTEN B., SMITH J., TOFANI V., CIUREAN R., WINTER M., SVERDRUP-THYGESON K., SYRE E. andSMEBYE H. 2014. Identification of landslide hazard and risk 'hotspots' in Europe. *Bulletin of Engineering Geology and the Environment*, **73.** 2**.** 325-339.

JAISWAL P., VAN WESTEN C. J. andJETTEN V. 2011. Quantitative estimation of landslide risk from rapid debris slides on natural slopes in the Nilgiri hills, India. *Nat. Hazards Earth Syst. Sci.,* **11.** 6**.** 1723-1743.

JAKOB M. andLAMBERT S. 2009. Climate change effects on landslides along the southwest coast of British Columbia. *Geomorphology,* **107.** 3–4**.** 275-284.

JEMEC M. andKOMAC M. 2011. An Overview of Approaches for Hazard Assessment of Slope Mass Movements. *Alpine Mass Movements: Implications for hazard assessment and mapping, Special Edition of Journal Torrent, Avalanche, Landslide and Rock Fall Engeneering* **166.**

KAPPES M. S., GRUBER K., FRIGERIO S., BELL R., KEILER M. andGLADE T. 2012. The MultiRISK platform: The technical concept and application of a regional-scale multihazard exposure analysis tool. *Geomorphology,* **151–152.** 139-155.

KEILER M. 2004. Development of the damage potential resulting from avalanche risk in the period 1950-2000, case study Galtür. *Natural Hazards and Earth System Sciences,* **4.** 249-256.

KEILER M., ZISCHG A., FUCHS S., HAMA M. andSTÖTTER J. 2005. Avalanche related damage potential - changes of persons and mobile values since the mid-twentieth century, case study Galtür. *Natural Hazard and Earth System Science,* **5.** 1**.** 49-58.

KJEKSTAD O. andHIGHLAND L. 2009. Economic and Social Impacts of Landslides. In: SASSA K. andCANUTI P. (eds.) *Landslides – Disaster Risk Reduction.* Springer Berlin Heidelberg.

KLEIN GOLDEWIJK K. andRAMANKUTTY N. 2004. Land cover change over the last three centuries due to human activities: The availability of new global data sets. *GeoJournal,* **61.** 4**.** 335-344.

KOOMEN E. 2007. *Modelling Land-Use Change: Progress and Applications,* Springer.

KORUP O., GÖRÜM T. andHAYAKAWA Y. 2011. Without power? Landslide inventories in the face of climate change. *Earth Surface Processes and Landforms,* **37.** 1**.** 92-99.

KRENMAYR H. G. andHOFMANN T. 2002. *Rocky Austria: eine bunte Erdgeschichte von Österreich,* Geolog. Bundesanst.

LACASSE S. andNADIM F. 2009. Landslide Risk Assessment and Mitigation Strategy. In: SASSA K. andCANUTI P. (eds.) *Landslides – Disaster Risk Reduction.* Springer Berlin Heidelberg.

LARSEN I. J. andMONTGOMERY D. R. 2012. Landslide erosion coupled to tectonics and river incision. *Nature Geosci,* **5.** 7**.** 468-473.

LE COZANNET G., MODARESSI H. andDESRAMAUT N. 2013. Global change and its implications for natural disasters. In: BOBROWSKY P. (ed.) *Encyclopedia of Natural Hazards.* Dordrecht, Heidelberg, New York, London: Springer.

LEE E. M. andJONES D. K. C. 2004. *Landslide risk assessment,* London, Thomas Telford. ^454.

LEE S. 2007. Comparison of landslide susceptibility maps generated through multiple logistic regression for three test areas in Korea. *Earth Surface Processes and Landforms,* **32.** 14**.** 2133-2148.

LEITNER M., AUER I. andMOJAISKY M. 2014. Climate Change impacts and response options in Mountain areas. An overview of the CIRCLE-MOUNTain Research Projects (2009-2013). Foundation of the Faculty of Sciences.

LEROI E., BONNARD C., FELL R. andMCINNES R. 2005. Risk assessment and management. In: HUNGR O., FELL R., COUTURE R. andEBERHARDT E. (eds.) *Landslide risk management.* London: Taylor and Francis Group.

LIU M., HU Y., CHANG Y., HE X. andZHANG W. 2009. Land Use and Land Cover Change Analysis and Prediction in the Upper Reaches of the Minjiang River, China. *Environmental Management,* **43.** 5**.** 899-907.

LOIBL W., BECK A., DORNINGER H., FORMAYER H., GOBIET A. andSCHÖNER W. 2007. Kwiss-Programm reclip:more research for climate protection: model run evaluation. Final report.

LØVHOLT F., GLIMSDAL S., HARBITZ C. B., ZAMORA N., NADIM F., PEDUZZI P., DAO H. andSMEBYE H. 2012. Tsunami hazard and exposure on the global scale. *Earth-Science Reviews,* **110.** 1–4**.** 58-73.

MALAMUD B. D., TURCOTTE D. L., GUZZETTI F. andREICHENBACH P. 2004. Landslide inventories and their statistical properties. *Earth Surface Processes and Landforms,* **29.** 6**.** 687-711.

MALET J. P., REMAÎTRE A., PUISSANT A., SPICKERMANN A., GLADE T., PROMPER C., PETSCHKO H., BÉGUERIA S. andSANCHEZ G. ChangingRISKS: Changing pattern of landslide risks as a response to global changes in mountain areas. Circle2 midterm Meeting, 2012 Innsbruck.

MANCINI F., CEPPI C. andRITROVATO G. 2010. GIS and statistical analysis for landslide susceptibility mapping in the Daunia area, Italy. *Nat. Hazards Earth Syst. Sci.,* **10.** 9**.** 1851-1864.

MASSEY D. 1999. Space-time, `science´, and relationship between physical geography and human geograpy. *Transactions of the Institute of British Geographers,* **24.** 261-276.

MCINNES R. G., JAKEWAYS J. andENVIRONMENT I. O. W. C. F. T. C. 2002. *Instability: Planning and Management : Seeking Sustainable Solutions to Ground Movement Problems : Proceedings of the International Conference Organised by the Centre for the Coastal Environment, Isle of Wight Council, and Held in Ventnor. Isle of Wight, UK on 20-23rd May 2002*, Thomas Telford.

MECHLER R. andRTRT 2008. The Cost-Benefit Analysis Methodology, From Risk to Resilience Working Paper No. 1. ISET-Nepal and ProVention, Kathmandu, Nepal. 34

MERZ R., BLÖSCHL G. andHUMER G. 2008. Hochwasserabflüsse in Österreich – das HORA-Projekt. *Österreichische Wasser- und Abfallwirtschaft,* **60.** 9-10**.** 129-138.

MEYER W. B. andTURNER B. L. 1994. *Changes in Land Use and Land Cover: A Global Perspective,* Cambridge University Press.

MONTRASIO L., VALENTINO R. andLOSI G. 2009. Rainfall-induced shallow landslides: a model for the triggering mechanism of some case studies in Northern Italy. *Landslides,* **6.** 3**.** 241-251.

MUNICHRE. 2009, 2010, 2011. NatCatSERVICE [Online]. [Accessed 16.11.2014.

MUNICHRE 2014. NatCatSERVICE.

NADIM F., EINSTEIN H. andROBERDS W. 2005. Probabilistic stability analysis for individual slopes in soil and rock. In: HUNGR O., FELL R., COUTURE R. andEBERHARDT E. (eds.) *Landslide risk management.* London, UK: Taylor & Francis Group plc.

NAKIĆENOVIĆ N., ALCAMO J., DAVIS G., DE VRIES B., FENHANN J., GAFFIN S., GREGORY K., GRÜBLER A., JUNG T. Y., KRAM T., LEBRE LA ROVERE E., MICHAELIS L., MORI S., MORITA T., PEPPER W., PITCHER H., PRICE L., RIAHI K., ROEHRL A., ROGNER H. H., SANKOVSKI A., SCHLESINGER M., SHUKLA P., SMITH S., SWART R., VAN ROOIJEN S., VICTOR N. andDADI Z. 2000. *IPCC Special Report on Emissions Scenarios (SRES)*, Cambridge University Press.

NANDI A. andSHAKOOR A. 2010. A GIS-based landslide susceptibility evaluation using bivariate and multivariate statistical analyses. *Engineering Geology*, **110.** 1–2**.** 11-20.

NIRUPAMA N. 2013. Disaster risk mangement. In: BOBROWSKY P. (ed.) *Encyclopedia of Natural Hazards*. Dordrecht, Heidelberg, New York, London: Springer.

NOSON L. 2009. Hazard Mapping and Risk Assessment. Asian Hazard Preparedness Center.

PAPATHOMA-KÖHLE M. andGLADE T. 2012. The role of vegetation cover change for landslide hazard and risk. In: RENAUD G., SUDMEIER-RIEUX K. andESTRELLA. M. (eds.) *The Role of Ecosystems in Disaster Risk Reduction*. Tokyo: UNU Press.

PAPATHOMA-KÖHLE M., KAPPES M., KEILER M. andGLADE T. 2011. Physical vulnerability assessment for alpine hazards: state of the art and future needs. *Natural Hazards*, **58.** 2**.** 645-680.

PAPATHOMA-KÖHLE M., NEUHÄUSER B., RATZINGER K., WENZEL H. andDOMINEY-HOWES D. 2007. Elements at risk as a framework for assessing the vulnerability of communities to landslides. *Natural Hazards and Earth System Science*, **7.** 6**.** 765-779.

PARDESHI S., AUTADE S. andPARDESHI S. 2013. Landslide hazard assessment: recent trends and techniques. *SpringerPlus*, **2.** 1**.** 523.

PELLICANI R., VAN WESTEN C. andSPILOTRO G. 2013. Assessing landslide exposure in areas with limited landslide information. *Landslides*, **11.** 3**.** 1-18.

PELLING M. 2003. *Natural Disaster and Development in a Globalizing World*, Taylor & Francis. ^250.

PEREIRA S., ZÊZERE J. L. andBATEIRA C. 2012. Technical Note: Assessing predictive capacity and conditional independence of landslide predisposing factors for shallow landslide susceptibility models. *Nat. Hazards Earth Syst. Sci.*, **12.** 4**.** 979-988.

PETLEY D. 2010. Landslide Hazards. In: ALCÁNTARA-AYALA I. andGOUDIE A. (eds.) *Geomorphological Hazards and Disaster Prevention*. Cambridge: Cambridge University Press.

PETSCHKO H., BRENNING A., BELL R., GOETZ J. andGLADE T. 2014. Assessing the quality of landslide susceptibility maps – case study Lower Austria. *Nat. Hazards Earth System Science*, **14.** 95-118.

PETSCHKO H., GLADE T., BELL R., SCHWEIGL J. andPOMAROLI G. Landslide inventories for regional early warning systems. In: MALET J.-P., GLADE T. andCASAGLI N., eds. Mountain Risks: Bringing science to society, 2010 Firenze, Italy. CERG, 277-282.

PITILAKIS K., FOTOPOULOU S., ARGYROUDIS S., PITILAKIS D., SENETAKIS K., TREULOPOULOS K., KAKDERI K. andRIGA E. 2011 Physical vulnerability of elements at risk to landslides: methodology for evaluation, fragility curves and damage states for buildings and lifelines SafeLand Deliverable 2.5.

POMAROLI G., BELL R., GLADE T., HEISS G., LEOPOLD P., PETSCHKO H., PROSKE H. andSCHWEIGL J. 2011. Darstellung der Gefährdung durch gravitative Massenbewegungen im Bundesland Niederösterreich als Grundlage der Raumplanung. *Gefahrendarstellungen für Massenbewegungen. Wildbach- und Lawinenverbau, Zeitschrift für Wildbach-, Lawinen-, Erosions- und Steinschlagschutz*, **74.** 166**.** 198-206.

PONTIUS R., JR. andNEETI N. 2010. Uncertainty in the difference between maps of future land change scenarios. *Sustainability Science*, **5.** 1**.** 39-50.

POTTER P. E. 2007. Exploring the Geology of the Cincinnati/ Northern Kentucky Region. Kentucky Geological Survey.

POYATOS R., LATRON J. andLLORENS P. 2003. Land Use and Land Cover Change After Agricultural Abandonment. *Mountain Research and Development*, **23.** 4**.** 362-368.

PRADHAN B., SINGH R. P. andBUCHROITHNER M. F. 2006. Estimation of stress and its use in evaluation of landslide prone regions using remote sensing data. *Advances in Space Research*, **37.** 4**.** 698-709.

PROMPER C., GASSNER C. andGLADE T. in press. Spatiotemporal patterns of landslide exposure – a step within future landslide risk analysis on a regional scale applied in Waidhofen/Ybbs Austria. *International Journal of Disaster Risk Reduction*.

PROMPER C. andGLADE T. Land cover changes for landslide risk evolution – first results from Lower Austria. In: EBERHARDT E., FROESE C., TURNER A. K. andLEROUEIL S., eds. 11th International Symposium on Landslides and 2nd North American Symposium on Landslides and Engineered Slopes Protecting Society through Improved Understanding, 2012 Banff, Canada. 409-413.

PROMPER C. andGLADE T. subm. Multilayer exposure maps as a basis for a regional vulnerability assessment - applied in Waidhofen/Ybbs, Austria. In: FUCHS. S. andGLADE T. (eds.) *Vulnerability Assessment in Natural Hazard Risk: A Dynamic Perspective.* London: The Geological Society.

PROMPER C., PUISSANT A., MALET J. P. andGLADE T. 2014. Analysis of land cover changes in the past and the future as contribution to landslide risk scenarios. *Applied Geography,* **53.** 11-19.

REGMI N., GIARDINO J., MCDONALD E. andVITEK J. 2014. A comparison of logistic regression-based models of susceptibility to landslides in western Colorado, USA. *Landslides,* **11.** 2**.** 247-262.

REICHENBACH P., BUSCA C., MONDINI A. C. andROSSI M. 2014. The Influence of Land Use Change on Landslide Susceptibility Zonation: The Briga Catchment Test Site (Messina, Italy). *Environmental Management,* **54.** 6**.** 1372-1384.

REMAÎTRE A., ETCHEVERS P., BEEK L. P. H. V., MALET J. P., DURAND O. M. Y., DÉQUÉ M. andGUYOMARC?H G. 2007. Assessing the influence of climate change on the activity of landslides in the Ubaye Valley. *Landslides and Climate Change: Challenges and Solutions.* Taylor & Francis.

RINDFUSS R. R., WALSH S. J., TURNER B. L., FOX J. andMISHRA V. 2004. Developing a science of land change: Challenges and methodological issues. *Proceedings of the National Academy of Sciences of the United States of America,* **101.** 39**.** 13976-13981.

ROUGIER J. C., BEVEN K. J., ROUGIER J. C. andBEVEN. K. J. 2013. *Model and data limitations: the sources and implications of epistemic uncertainty*

Risk and Uncertainty Assessment for Natural Hazards, Cambridge University Press.

ROUNSEVELL M. D. A., EWERT F., REGINSTER I., LEEMANS R. andCARTER T. R. 2005. Future scenarios of European agricultural land use: II. Projecting changes in cropland and grassland. *Agriculture, Ecosystems & Environment,* **107.** 2–3**.** 117-135.

ROUNSEVELL M. D. A., REGINSTER I., ARAÚJO M. B., CARTER T. R., DENDONCKER N., EWERT F., HOUSE J. I., KANKAANPÄÄ S., LEEMANS R., METZGER M. J., SCHMIT C., SMITH P. andTUCK G. 2006. A coherent set of future land use change scenarios for Europe. *Agriculture, Ecosystems & Environment,* **114.** 1**.** 57-68.

RUDOLF-MIKLAU F. 2009. *NaturgefahrenManagement in Österreich Vorsorge – Bewältigung – Information*, Wien, LexisNexis ^241.

RUDOLF-MIKLAU F., BÄK R., SKOLAUT C. andSCHMID F. (eds.) 2001. *Alpine Mass Movements: Implications for hazard assessment and mapping*

RUDOLF-MIKLAU F. andSAUERMOSER S. 2014. Avalanche hazard assessment and planning. In: RUDOLF-MIKLAU F., SAUERMOSER S. andMEARS A. (eds.) *The Technical Avalanche Protection Handbook*. Wiley.

RUFF M. andCZURDA K. 2008. Landslide susceptibility analysis with a heuristic approach in the Eastern Alps (Vorarlberg, Austria). *Geomorphology*, **94.** 3–4**.** 314-324.

RUTHERFORD G. N., BEBI P., EDWARDS P. J. andZIMMERMANN N. E. 2008. Assessing land-use statistics to model land cover change in a mountainous landscape in the European Alps. *Ecological Modelling*, **212.** 3–4**.** 460-471.

SAFELAND 2011. Deliverable 5.2 Toolbox of landslide mitigation measures.

SAFELAND 2012. Deliverable 3.9: Methodology for predicting the changes in the landslide risk during the next 50 years at selected sites in Europe. Changing pattern of landslide risk in hotspot and evolution trends in Europe according to global change scenarios

SAUERMOSER S., GRANIG M., KLEEMAYR K. andMARGRETH S. 2011. Grundlagen und Modelle der Lawinendynamik und Lawinenwirkung. *Handbuch Technischer Lawinenschutz*. Wiley-VCH Verlag GmbH & Co. KGaA.

SCHLEIER M., BI R., ROHN J., EHRET D. andXIANG W. 2014. Robust landslide susceptibility analysis by combination of frequency ratio, heuristic GIS-methods and ground truth evaluation for a mountainous study area with poor data availability in the Three Gorges Reservoir area, PR China. *Environmental Earth Sciences*, **71.** 7**.** 3007-3023.

SCHNEIDER T. 2006. Risk aversion - a delicate issue in risk assessment. In: AMMANN W. J., DANNENMANN S. andVULLIET L. (eds.) *RISK21 - Coping with Risks due to Natural Hazards in the 21st Century: Proceedings of the RISK21 Workshop, Monte Verità, Ascona, Switzerland, 28 November - 3 December 2004*. Taylor & Francis.

SCHUSTER R. L. 1996. Socioeconomic significance of landslides. In: TURNER A. K. andSCHUSTER R. L. (eds.) *Landslides - investigation and mitigation*. Washington, D.C.

SCHUSTER R. L. andHIGHLAND L. M. 2001. Socioeconomic and environmental impacts of landslides in the western hemisphere.

SCHWENK H. 1992. Massenbewegungen in Niederösterreich 1953 - 1990. *Jahrbuch der Geologischen Bundesanstalt,* **135.** 2**.** 597-660.

SHAHABI H., AHMAD B. B. andKHEZRI S. 2013. Evaluation and comparison of bivariate and multivariate statistical methods for landslide susceptibility mapping (case study: Zab basin). *Arabian Journal of Geosciences,* **6.** 10**.** 3885-3907.

SHRODER JR J. F. andBISHOP M. P. 1998. Mass movement in the Himalaya: new insights and research directions. *Geomorphology,* **26.** 1–3**.** 13-35.

SLAYMAKER O., SPENCER T. andEMBLETON-HAMANN C. (eds.) 2009. *Geomorphology and Global Environmental Change,* New York: Cambridge University Press.

SMITH A., MARTIN D. andCOCKINGS S. 2014. Spatio-Temporal Population Modelling for Enhanced Assessment of Urban Exposure to Flood Risk. *Applied Spatial Analysis and Policy*.

SMITH K. 2009. *Environmental Hazards: Assessing Risk and Reducing Disaster*, Routledge. ^383.

SMITH K. 2013. *Environmental Hazards: Assessing Risk and Reducing Disaster*, Routledge. ^478.

SOETERS R. andVAN WESTEN C. 1996. Slope instability recognition, analysis, and zonation. In: TURNER A. K. andSCHUSTER R. L. (eds.) *Landslides: Investigation and mitigation.* National Academy Press.

SRI HADMOKO D. andENGEL-DI MAURO S. 2012. Landslides and other Mass Movements. In: WISNER B., GAILLARD J. C. andKELMAN I. (eds.) *Handbook of Hazards and Disaster Risk Reduction and Management.* Taylor & Francis.

STADTARCHIV. Waidhofen/Ybbs. [Accessed 2012.

STATISTIKAUSTRIA. 2012. Statistische Daten Waidhofen/Ybbs [Online]. Available: http://www.statistik.at.

STATISTIKAUSTRIA 2013. Gebäude- und Wohnungszählungen 1971 - 2001.

STATISTIKAUSTRIA 2014. Volkszählungsergebnisse, Statistik der Standesfälle, Datenbank POPREG.

STEFFEN W., ANDREAE M., O., BOLIN B., COX P. M., CRUTZEN P. J., CUBASCH U., HELD H., NAKICENOVIC N., SCHOLES R. J., TALAUE-MCMANUS L. andTURNER II B. L. 2004a. Abrupt Changes The achilles´ heel of the earth system. *Environment,* **46.** 3**.** 8-20.

STEFFEN W., SANDERSON A., TYSON P., JÄGER J., MATSON P., MOORE III B., OLDFIELD F., RICHARDSON K., SCHELLNHUBER J., TURNER II B. L. andWASSON R. 2004b. *Executive Summary - Global Change and the Earth System: A Planet Under Pressure,* Stockholm, IGBP Secretariat Royal Swedish Academy of Sciences. ^41.

STERLACCHINI S., FRIGERIO S., GIACOMELLI P. andBRAMBILLA M. 2007. Landslide risk analysis: a multi-disciplinary methodological approach. *Natural Hazard and Earth System Science,* **7.** 6**.** 657-675.

SUKARNA D., WIRAKUSUMAH A. D., SUHAEMI I. A., EKA S., SURONO, SOEDRADJAT G. M., SOLIHIN A., HENDRASTO M., ABDURACHMAN K. E., ANDREASTUTI M. C. S. D., DANARYANTO H., MURDOHARDONO D., SUGALANG, WAFID M., HERUDIYANTO, MULYASARI F., KASTUARI A., ADAR S., TISSAHADI I. K., JAEGER S., HOFFMANN-ROTHE A., PISCHKE B., RANKE U. andWEILAND L. 2012. Guidebook for Assessing the Risks to Natural Hazards Case Study: Province of Central Java.

TAPE T. G. 1990. Interpreting Diagnostic Tests [Online]. University of Nebraska Medical Center. Available: http://gim.unmc.edu/dxtests/Default.htm [Accessed 07.09.2014.

TASSER E., MADER M. andTAPPEINER U. 2003. Effects of land use in alpine grasslands on the probability of landslides. *Basic and Applied Ecology,* **4.** 3**.** 271-280.

THIEBES B. 2012. *Landslide Analysis and Early Warning Systems Local and Regional Case Study in the Swabian Alb, Germany*, Berlin Heidelberg, Springer Verlag.

THIERY Y., MALET J. P., STERLACCHINI S., PUISSANT A. andMAQUAIRE O. 2007. Landslide susceptibility assessment by bivariate methods at large scales: Application to a complex mountainous environment. *Geomorphology,* **92.** 1-2**.** 38-59.

UN-ISDR. 2009. 2009 UNISDR Terminology on Disaster Risk Reduction [Online]. [Accessed 10.11.2013.

UN-SPIDER. 2014. Glossary [Online]. Available: http://www.un-spider.org/glossary/ [Accessed 05.10.2014.

UNISDR 2004. Living With Risk. United Nations International Strategy for Disaster Reduction.

USGS. 2010. Climate Change Science [Online]. U.S. Department of the Interior | U.S. Geological Survey. Available: http://geochange.er.usgs.gov/ [Accessed 07.02.2012.

VAN BEEK L. P. H. andVAN ASCH T. W. J. 2004. Regional Assessment of the Effects of Land-Use Change on Landslide Hazard By Means of Physically Based Modelling. *Natural Hazards*, **31.** 1**.** 289-304.

VAN DEN EECKHAUT M., HERVÁS J., JAEDICKE C., MALET J. P., MONTANARELLA L. andNADIM F. 2012. Statistical modelling of Europe-wide landslide susceptibility using limited landslide inventory data. *Landslides*, **9.** 3**.** 357-369.

VAN DEN EECKHAUT M., VANWALLEGHEM T., POESEN J., GOVERS G., VERSTRAETEN G. andVANDEKERCKHOVE L. 2006. Prediction of landslide susceptibility using rare events logistic regression: A case-study in the Flemish Ardennes (Belgium). *Geomorphology*, **76.** 3â€“4**.** 392-410.

VAN WESTEN C. J., CASTELLANOS E. andKURIAKOSE S. L. 2008. Spatial data for landslide susceptibility, hazard, and vulnerability assessment: An overview. *Engineering Geology*, **102.** 3â€“4**.** 112-131.

VAN WESTEN C. J., VAN ASCH T. W. J. andSOETERS R. 2006. Landslide hazard and risk zonation - why is it still so difficult? *Bulletin of Engineering Geology and the Environment*, 1-18.

VAN WESTEN C. J. V. andTERLIEN M. J. T. 1996. AN APPROACH TOWARDS DETERMINISTIC LANDSLIDE HAZARD ANALYSIS IN GIS. A CASE STUDY FROM MANIZALES (COLOMBIA). *Earth Surface Processes and Landforms*, **21.** 9**.** 853-868.

VARNES D. J. 1978. Slope movement types and processes. Transportation Research Board. 11-33

VARNES D. J. 1984. *Landslides hazard zonation: a review of principles and practice*, Paris, France, UNESCO.

VEBURG P. 2010. The CLUE Modelling framework - The Conversion of Land Use and its Effects. University of Amsterdam Intitute for Environmental Studies.

VELDKAMP A. andFRESCO L. O. 1996. CLUE: a conceptual model to study the Conversion of Land Use and its Effects. *Ecological Modelling*, **85.** 2–3**.** 253-270.

VELDKAMP A. andVERBURG P. H. 2004. Modelling land use change and environmental impact. *Journal of Environmental Management*, **72.** 1–2**.** 1-3.

VERBURG P. andOVERMARS K. 2009. Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model. *Landscape Ecology,* **24.** 9**.** 1167-1181.

VERBURG P. H., KOK K., PONTIUS JR. R. andVELDKAMP A. 2006. Modeling Land-Use and Land-Cover Change. In: LAMBIN E. andGEIST H. (eds.) *Land-Use and Land-Cover Change.* Heidelberg.

VERBURG P. H., SOEPBOER W., VELDKAMP A., LIMPIADA R., ESPALDON V. andMASTURA S. S. A. 2002. Modeling the Spatial Dynamics of Regional Land Use: The CLUE-S Model. *Environmental Management,* **30.** 3**.** 391-405.

VON ELVERFELDT K., GLADE T. andDIKAU R. 2008. Naturwissenschaftliche Gefahren- und Risikoanalyse. In: FELGENTREFF C. andGLADE T. (eds.) *Naturrisiken und Sozialkatastrophen.* Berlin.

WAGNER K. 2005. Die Regionalwirtschaftliche Situation im Einzugsgebiet der Ybbs - Teilergebnisse aus dem Interreg IIIB Projekt ILUP (Integrated Land Use Planning and River Basin Management) *Ländlicher Raum: Online-Fachzeitschrift des Bundesministeriums für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft,* 1-7.

WALLNER S. 2012. Niederschlagsschwellenwerte für die Auslösung von gravitativen Massenbewegungen – Eine Analyse in der rhenodanubischen Flyschzone Niederösterreichs. Diplomarbeit, University of Vienna.

WANG L.-J., SAWADA K. andMORIGUCHI S. 2013. Landslide susceptibility analysis with logistic regression model based on FCM sampling strategy. *Computers & Geosciences,* **57.** 81-92.

WESSELY G. 2006. *Geologie der österreichischen Bundesländer - Niederösterreich,* Wien, Geologische Bundesanstalt. ^416.

WESTEN C. J., ASCH T. W. J. andSOETERS R. 2006. Landslide hazard and risk zonation—why is it still so difficult? *Bulletin of Engineering Geology and the Environment,* **65.** 2**.** 167-184.

WHO 2013. Building back better: sustainable mental health care after emergencies. World Health Organization.

WHYTE A. V. andBURTON I. 1982. Perception of Risk in Canada. In: BURTON I., FOWLE C. D. andMCCULLOUGH R. S. (eds.) *Living with Risk.* Toronto: University of Toronto.

WIECZOREK G. 1996. Landslide triggering mechanisms. In: TURNER A. K. andSCHUSTER R. L. (eds.) *Landslides: investigation and mitigation.* Washington, D.C.: National Academey Press.

WINTER M. andBROMHEAD E. 2012. Landslide risk: some issues that determine societal acceptance. *Natural Hazards,* **62.** 2**.** 169-187.

YESILNACAR E. andTOPAL T. 2005. Landslide susceptibility mapping: A comparison of logistic regression and neural networks methods in a medium scale study, Hendek region (Turkey). *Engineering Geology,* **79.** 3–4**.** 251-266.

YILMAZ I. 2009. Landslide susceptibility mapping using frequency ratio, logistic regression, artificial neural networks and their comparison: A case study from Kat landslides (Tokat—Turkey). *Computers & Geosciences,* **35.** 6**.** 1125-1138.

ZAMG Zentralanstalt für Meteorologie und Geodynamik.

ZAMG. 2014. Klimadaten von Österreich 1971 - 2000: Waidhofen/Ybbs [Online]. Vienna. Available: http://www.zamg.ac.at [Accessed 06.09.2014.

ZÊZERE J. L., GARCIA R. A. C., OLIVEIRA S. C. andREIS E. 2008. Probabilistic landslide risk analysis considering direct costs in the area north of Lisbon (Portugal). *Geomorphology,* **94.** 3–4**.** 467-495.

ZÊZERE J. L., REIS E., GARCIA R., OLIVEIRA S., RODRIGUES M. L., VIEIRA G. andFERREIRA A. B. 2004. Integration of spatial and temporal data for the definition of different landslide hazard scenarios in the area north of Lisbon (Portugal). *Nat. Hazards Earth Syst. Sci.,* **4.** 1**.** 133-146.

ZIEMER R. R. An approach to evaluating the long-term effects of land use on landslides, erosion, and stream channels. In: ORGANIZING COMMITTEE OF THE JAPAN-U.S. WORKSHOP ON SNOW AVALANCHE L., DEBRIS FLOW PREDICTION AND CONTROL, ed. Workshop on Snow Avalanche, Landslide, Debris Flow Prediction and Control. 30 Sept-5 Oct 1991, 1991 Tsukuba, Japan. 533-542.

A. PUBLICATIONS AND MANUSCRIPTS

The following section contains the publications and manuscript that are subject of this thesis. These are briefly introduced by giving the title, full citation and also the status of the respective publication /manuscript. In addition the contributions of the author of this thesis and all co-authors are described before the full publications and manuscripts are provided.

A.1 LAND COVER CHANGES FOR LANDSLIDE RISK EVOLUTION – FIRST RESULTS FROM LOWER AUSTRIA

PROMPER C. AND GLADE T., 2012. **Land cover changes for landslide risk evolution – first results from Lower Austria.** In: Eberhardt E., Froese C., Turner A.K., and S. Leroueil (eds.) Proceedings of the 11th International Symposium on Landslides and 2nd North American Symposium on Landslides and Engineered Slopes, Protecting Society through Improved Understanding, Banff, Canada, 409-413.

The publication was initiated by Thomas Glade. Substantial parts of the manuscript preparation and the entire land cover mapping and analysis was done by Catrin Promper. The results were assessed by Catrin Promper and Thomas Glade contributed substantial feedback on the manuscript.

Status: released publication

Landslides and Engineered Slopes: Protecting Society through Improved Understanding – Eberhardt et al. (eds)

Land cover changes for landslide risk evolution—first results from lower Austria

C. Promper & T. Glade
Department for Geography and Regional Research, University of Vienna, Austria

ABSTRACT: Landslide occurrence is part of landform development in mountainous regions. The changes in landslide initiations relate to numerous environmental conditions and, more increasingly, also to the human activity in our landscapes. For example, not only landslide triggering factors like precipitation but also the exposed elements at risk change significantly in time and determine therefore the evolution of landslide risk. These human induced changes are strongly related to development of settlements including land cover changes, building of new infrastructure, and expansion or intensification of urban regions. When interested in potential future consequences of spatial landslide occurrence—besides understanding the changes in future spatiotemporal probabilities of landslide occurrence—it is of major importance to take into account future significant changes of the elements at risk. In order to develop scenarios for the evolution of landslide risk, it is required to investigate also the past development of the elements at risk. This study aims to understand the development of elements at risk in the frame of a landslide risk assessment. Therefore, land cover as one element at risk is classified from aerial photography referring to landslide relevant aspects. The respective change of monetary value for assessing potential damage will be investigated in a further step. The results show significant changes during the period 1962 to 2005, especially with respect to arable land.

1 INTRODUCTION

The increase of damage potential and loss through landslides in alpine regions is not only caused by an increased accumulation of landslide hazard but also because of people moving into hazard zones and intervention into ecosystem coherences (Fischer 1999). This interlinks with the idea of global environmental change where climate change is only one factor. The change in land cover, increasing mobility of people moving into remote areas and improvements in buildings also constitute to the evolution of landslide risk. Hufschmidt et al. (2005) associate the term "evolution" with gradual development and with inevitable irreversible processes. In terms of elements at risk this may stand for removing the vegetation cover, deforestation or increased values of buildings due to protective measures. These are all processes that change the ecosystem and may not be reversed easily. Consequently the attention to these elements at risk and their evolution is inevitable for future risk management and adaption strategies.

Due to the fact that the interest in direct and indirect damages due to natural hazards is increasing (Brambilla & Giacomelli 2007) the necessity to analyze all different kinds of elements at risk and the linked development is unavoidable. Not only in the public but also decision makers are asking for scenarios of socioeconomic development (Brambilla & Giacomelli 2007) to face the changing risk in the future. Amongst natural hazards, landslides account for enormous property damage in terms of both direct and indirect costs (Dai et al., 2002) worldwide. In order to conquer the changes of elements at risk towards landslides a detailed analysis of the past evolution is a first step to understand and to predict subsequent future changes.

The quantitative analysis of these elements at risk can be conducted either by using the evaluation of areas of land cover types plus the value of these different types. However it may also be done by estimating the value of buildings or also the rebuilding costs per m^2. For an first approximation of the change of elements at risk it is suitable to quantify the different land cover types and the spatial change over time.

In this study we investigate the evaluation of past land cover changes by an analysis of aerial photographs and a spatial evaluation within an ArcGIS environment. The mapping results are analysed statistically.

2 METHOD

To delineate the land cover change, relevant past time periods for mapping have to be identified.

Considering a regular interval as well as the fact that changes have to be visible, a 10 year interval seems appropriate. However these time slices are always limited to data availability. Ideal data are aerial photographs in similar resolution covering the same extent and comprise the study area respectively. These have to be orthorectified to map respective polygons. For this study the five time periods as provided in Figure 1 were selected.

The different land cover types vary according to the study area. Linking to landslide risk, categories are divided into surfaces with vegetation cover, without vegetation cover as well as sealed surfaces. Further the different values of certain areas are taken into consideration. The categories for this study comprise the following 6 land cover types: arable land, grassland, forest, building area, alluvium and water.

First mapping results showed that the interpretation of the panchromatic aerial photographs for the first four time slices are challenging, especially the distinction from arable land and grassland. Due to that the following mapping criteria were set:

- *Arable land*: surface structure narrower than linear structures on grassland; often delineated through ridges; partly not vegetated
- *Grassland*: smooth and uniformly colored but sometimes also linear structures due to mowing
- *Forest*: single trees and single lines of trees are not considered;
- *Building area*: sealed surfaces also surrounding farming houses; settlements mapped as a whole; streets included
- *Water*: is delineated clearly if not covered by forest
- *Alluvium*: not vegetated areas next to water surfaces; where topography allows alluvial deposition

After setting the criteria the different land cover types are mapped in an ArcGIS environment. In addition available topographic maps were used to complement the mapping. To obtain a comprehensive land cover map it is important to avoid overlaps and gaps. An example of an orthophoto section from 1988 is shown in Figure 2. It displays arable land and grassland as well as building area.

For the last time slice the mapping method was adjusted to the better data availability including a high resolution orthophoto and a digital cadastral map. The digital cadastral map was used, reclassified and adapted to fit the land cover types for this study. In a further step the classification was validated using the orthophoto of 2005. Another exception in the method was applied for the land cover type "water". As it is difficult to delineate it due to the lining of the channels through bush vegetation etc., this type is moved from the digital cadastral map to the other maps. In a further step these surfaces are refined wherever possible.

Statistical analysis is used to evaluate the results. For each time slice the percentage of land cover units was calculated and additionally the change of the different land cover types was compared via the calculation of indexes.

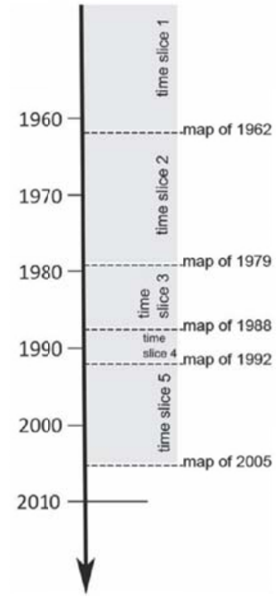


Figure 1. Time slices for the five investigation periods.

Figure 2. Section of the orthophoto 1988 showing building area, arable land and grassland.

3 STUDY AREA

The selected study area is a region in Austria located in the smooth hilly Flysch zone abundant in sandstone. This geological unit is prone to sliding and flowing (Krenmayr & Hofmann 2002). The section selected for the analysis is located in the district of Waidhofen/Ybbs situated in the south west of the Province of Lower Austria comprising 13 km^2, Figure 3.

The area is characterized by increased slope angles see Figure 4. The steep slopes may also be a reason for the high spatial proportion of grassland and rather less arable land. Moreover the building areas are characterized by concentrations of buildings in the valleys and farm houses sparsely distributed on the slopes. The forest areas are characterized by either large coherent areas or thin rows of trees for wind shelter. The letter tree lines are often aligned between the grassland and arable land which makes a dissected picture of the different land cover types.

Concerning the occurrence of landslides the different predisposing factors like lithology and land cover give rise to frequent landslide hazards. Schwenk (1992) examined landslides in Lower Austria between 1953 and 1990 and conclude that most of the landslides occur within grassland. They offer two reasons: 1) grassland is found in steeper areas whereas arable land without permanent vegetation cover is mostly found in flatter areas; 2) the forest areas are determined by deeply weathered soils which are more stable than grassland (Schwenk 1992).

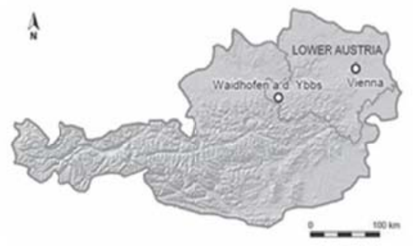


Figure 3. Location of the study area Waidhofen/Ybbs.

Figure 4. Section of Waidhofen/Ybbs (© Catrin Promper).

Regarding the climate in the study area the data from 1971 to 2000 underline the predisposition for landslides. The precipitation accumulates to 1133.6 mm/year and the daily totals can be up to 84 mm (ZAMG 2011). Further 63.4 days/year have a snow cover with more than 1 cm and a snow height of more than 20 cm is reached at 11.7 days/year including fresh snow from December to April (ZAMG 2011). Regarding the snow data one has to consider that the climate station is at a sea level height of only 421 m whereas the study area partly reaches up to 665 m above sea level. Comparing the precipitation data to other parts of Austria e.g., Vienna the values are quite high. For example even at the highest station in Vienna, the yearly precipitation total reaches only 741 mm/year (ZAMG 2011).

4 DATA

The data for the selected study area are aerial photographs, an orthophoto, a digital cadastral map and topographical maps. The scale of the aerial photographs in Table 1 indicates clearly that these have been taken during high flights in comparison to normal flight heights displaying a scale of about 1:5.000. On the contrary the orthophoto is of a reasonable quality with a resolution of 25 cm.

5 FIRST RESULTS

The first results include maps for all time slices except the map for 1992. This has not been finalized yet. The analysis of the different land cover maps shows that there are significant changes in

Table 1. Data quality for different time slices.

Year	Type	Scale/resolution
1962	Aerial photograph	1:29.000
1979	Aerial photograph	1:38.000
1988	Aerial photograph	1:36.000
1992	Aerial photograph	1:38.000
2005	Orthophoto	25 cm

all determined land cover types. The following Table 2 gives the area of the different land cover in per cent for the total study area for four time slices.

The general distribution of land cover classes comprises most of the study area with grassland and forest which make up to nearly 90 per cent. The rest of the area is covered by either arable land or building area. The contribution of water ranges between 0.3 and 0.4 per cent for all presented time slices. Further the land cover class alluvium is striking. It covers only 0.01 for the first time slices and totally disappears for the other time slices.

The following Figure 5 shows the changes of the classes: grassland, building area, forest and water based on the first time slice analysed. The large change of arable land is not allowing to present this type in the same graph as the other types, which are characterized by small differences.

It is clearly shown that only the building area and the water has increased since 1962. The changing land cover types include grassland and forest. Considering also Figure 6 it can be delineated that also the land cover type arable land has increased for all the time slices based on the basis of 1962. The largest increase is shown in the time slice from 1963 to 1979, whereas the increase of arable land in general decreased over the course of the investigation period.

Overall the results show a trend towards more grassland and building areas. This is at the expenses of the decrease in forest areas as well as arable land.

Table 2. Areas of different land cover types in % based on the total study area.

Land cover type	1962	1979	1988	2005
Grassland	59.29	54.69	54.43	59.46
Arable land	1.61	4.25	2.74	1.67
Building area	3.93	4.08	4.98	4.80
Forest	34.83	36.63	37.51	33.67
Water	0.35	0.35	0.35	0.39
Alluvium	0.01	0.00	0.00	0.00

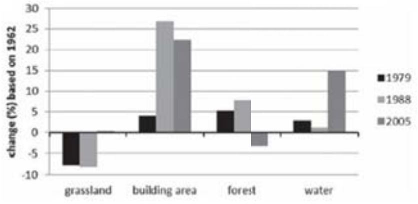


Figure 5. Change of land cover based on the year 1962 for the classes: grassland, building area, forest and water.

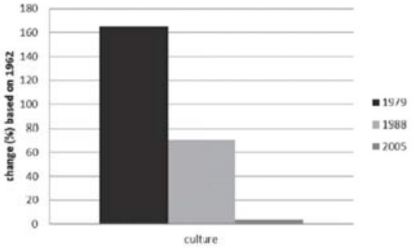


Figure 6. Changes of land cover based on the year 1962 for arable land.

6 DISCUSSION & CONCLUSION

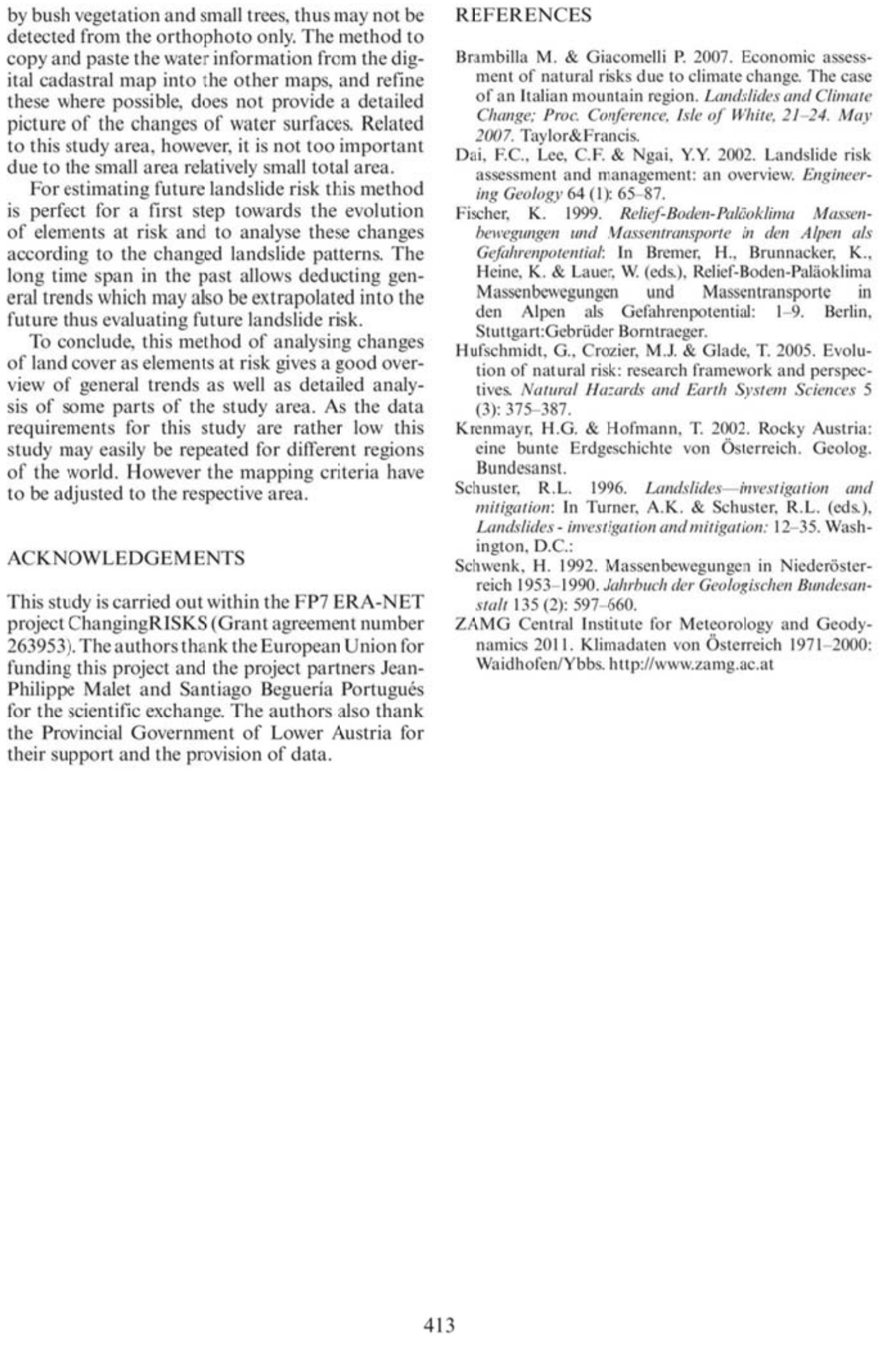
The evolution of land cover in the past is definitely an interaction of both: steady development and irreversible processes. An example would be deforested areas which then suffered landslide hazard, which changes the topography irreversibly. This leads to the assumption that anthropogenic influence is a major factor on land cover changes.

Regarding different land cover types as elements at risk e.g., building areas or arable land one can delineate the evolution of these elements at risk by analysing the land cover change in detail. Schuster (1996) stated that landslide activity increase is a continuing trend in the 21st century due to:

- Increased urbanization and development in landslide-prone areas
- Continued deforestation of landslide-prone areas; and
- Increased regional precipitation caused by changing climatic patterns.

The first two statements relate to the preliminary results of this study. Clear trends towards an increase in building area as well as grassland on the expense of forested areas as well as arable land are shown. The study gives a detailed picture of the changes of land cover over 43 years. This will improve by analysing the map of 1992.

Data quality is another issue to be discussed here. It definitely influences the mapping results. Comparing the quality of the aerial photographs only, it is not only the scale but also the different exposure to light and different flight routes. Further it is study area specific how well features may be delineated. An example would be the vast increase in water: Channels in this area are often accompanied



by bush vegetation and small trees, thus may not be detected from the orthophoto only. The method to copy and paste the water information from the digital cadastral map into the other maps, and refine these where possible, does not provide a detailed picture of the changes of water surfaces. Related to this study area, however, it is not too important due to the small area relatively small total area.

For estimating future landslide risk this method is perfect for a first step towards the evolution of elements at risk and to analyse these changes according to the changed landslide patterns. The long time span in the past allows deducting general trends which may also be extrapolated into the future thus evaluating future landslide risk.

To conclude, this method of analysing changes of land cover as elements at risk gives a good overview of general trends as well as detailed analysis of some parts of the study area. As the data requirements for this study are rather low this study may easily be repeated for different regions of the world. However the mapping criteria have to be adjusted to the respective area.

ACKNOWLEDGEMENTS

This study is carried out within the FP7 ERA-NET project ChangingRISKS (Grant agreement number 263953). The authors thank the European Union for funding this project and the project partners Jean-Philippe Malet and Santiago Beguería Portugués for the scientific exchange. The authors also thank the Provincial Government of Lower Austria for their support and the provision of data.

REFERENCES

Brambilla M. & Giacomelli P. 2007. Economic assessment of natural risks due to climate change. The case of an Italian mountain region. *Landslides and Climate Change; Proc. Conference, Isle of White, 21–24. May 2007.* Taylor&Francis.

Dai, F.C., Lee, C.F. & Ngai, Y.Y. 2002. Landslide risk assessment and management: an overview. *Engineering Geology* 64 (1): 65–87.

Fischer, K. 1999. *Relief-Boden-Paläoklima Massenbewegungen und Massentransporte in den Alpen als Gefahrenpotential*: In Bremer, H., Brunnacker, K., Heine, K. & Lauer, W. (eds.), Relief-Boden-Paläoklima Massenbewegungen und Massentransporte in den Alpen als Gefahrenpotential: 1–9. Berlin, Stuttgart:Gebrüder Borntraeger.

Hufschmidt, G., Crozier, M.J. & Glade, T. 2005. Evolution of natural risk: research framework and perspectives. *Natural Hazards and Earth System Sciences* 5 (3): 375–387.

Krenmayr, H.G. & Hofmann, T. 2002. Rocky Austria: eine bunte Erdgeschichte von Österreich. Geolog. Bundesanst.

Schuster, R.L. 1996. *Landslides—investigation and mitigation*: In Turner, A.K. & Schuster, R.L. (eds.), *Landslides - investigation and mitigation:* 12–35. Washington, D.C.:

Schwenk, H. 1992. Massenbewegungen in Niederösterreich 1953–1990. *Jahrbuch der Geologischen Bundesanstalt* 135 (2): 597–660.

ZAMG Central Institute for Meteorology and Geodynamics 2011. Klimadaten von Österreich 1971–2000: Waidhofen/Ybbs. http://www.zamg.ac.at

A.2 ANALYSIS OF LAND COVER CHANGES IN THE PAST AND THE FUTURE AS CONTRIBUTION TO LANDSLIDE RISK SCENARIOS

PROMPER C., PUISSANT A., MALET J. P. AND GLADE T., 2014. **Analysis of land cover changes in the past and the future as contribution to landslide risk scenarios**. *Applied Geography,* 53**,** 11-19.

While the publication was initiated by Thomas Glade, the manuscript preparation and the land cover analysis was done by Catrin Promper. Anne Puissant and Jean-Philippe Malet advised the modelling process and, in addition to Thomas Glade, contributed to the publication with constructive feedback.

Status: released publication

Applied Geography 51 (2014) 11–19

Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

Analysis of land cover changes in the past and the future as contribution to landslide risk scenarios

C. Promper [a,*], A. Puissant [b], J.-P. Malet [c], T. Glade [a]

[a] University of Vienna, Department of Geography and Regional Research, Austria
[b] Laboratoire Image, Ville, Environnement, CNRS UMR 7362, University of Strasbourg, France
[c] Institut de Physique du Globe de Strasbourg, CNRS UMR 7516, University of Strasbourg, France

Keywords:
Land cover change
Natural hazards
Scenario analysis
Landslide hazard risk
Waidhofen/Ybbs

ABSTRACT

Various factors influence the spatial and temporal pattern of landslide risk. Land cover change is one of the crucial factors influencing not only the natural process "landslide" and thus the hazard, but also the spatial distribution of elements at risk. Therefore the assessment of past and future landslide risk at regional scales implies the analysis of past and future land cover development. In this study, the first step in the analysis of landslide risk development over time is approached by analysing past land cover, as well as modelling potential future scenarios. The applied methods include analysis of orthophotographs and landcover scenario modelling with the Dyna-CLUE model. The timespan of the analysis covers 138 years from 1962 to 2100. The study area is located in Waidhofen/Ybbs (Austria) in the alpine foreland. A high number of landslides are recorded in the district. The predominant land cover types are grassland and forest. Buildings and residential areas are located in the valley bottoms and scattered on the hilltops. The results show clear changes in the land cover development of the past and in the future including spatial changes in the distribution of elements at risk. The trends show an increase in forest on the expense of grassland. The spatial evolution of the surfaces of arable land is rather high whereas the surfaces of residential zones increase steadily. The spatial analysis indicates also the development of new building areas and consequently potentially new landslide risk hotspots.

Introduction

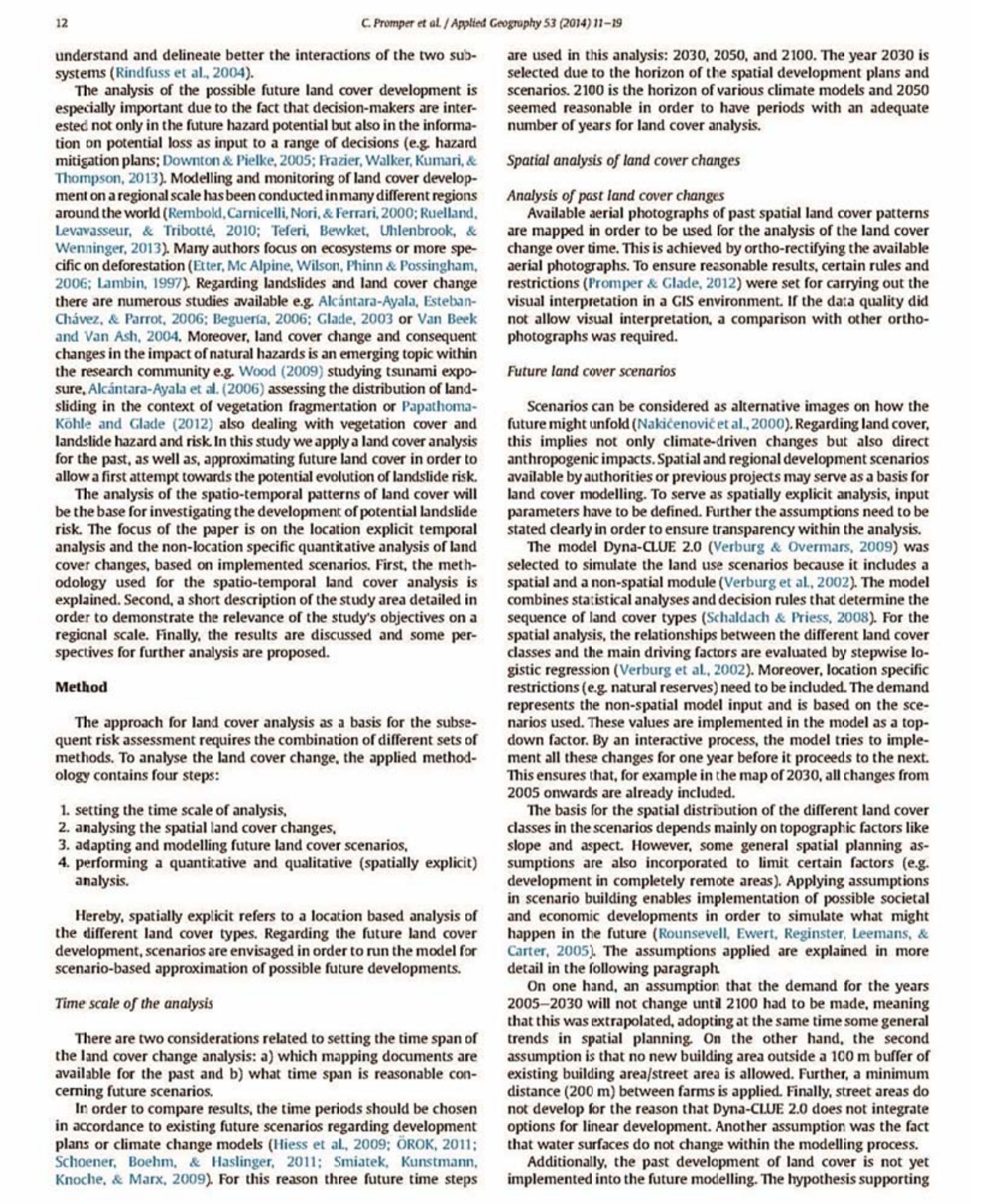
The change in temporal and spatial patterns of landslide risk is attributed to several factors of global change. The changing climate is not only influencing intensity and frequency of extreme weather events, but also their extent, duration and occurrence time (IPCC, 2012). Alternating land use and land cover respectively may act as predisposing factors of landslide occurrence (Glade, 2003; Beguería, 2006), but may also control the spatial distribution of landslide consequences. The fact that not only the natural processes but also the elements at risk change continuously, leads to the assumption that risk assessment cannot be a static process (van Westen, 2010). To address the spatio-temporal variability of landslide risk, one aspect is to analyse past land cover changes, as well as future development of the land use and land cover using scenario-based approaches.

According to Slaymaker, Spencer, and Embleton-Hamann (2009), human activity, especially as far as land use and land cover patterns are concerned, is the most rapid driver of global change. Rindfuss, Walsh, Turner, Fox, and Mishra (2004) refer to the interaction of human and natural subsystems that lead to alterations in land use and land cover. New land cover patterns may occur not only due to natural factors but also as a result of a number of anthropogenic activities such as economic developments, population growth or land abandonment. The scenario based analysis serves as a tool to determine *what could happen* assuming different pre-conditions (Verburg, Eickhout, & Meijl, 2008). These pre-conditions mostly imply the interaction of factors of the subsystems as mentioned above (e.g. demographic or climate change). Modelling these scenarios and their uncertainties is an explorative analysis that helps to delineate the margins of the possible and conceivable (Verburg et al., 2008). Moreover, the analysis of the past and future land cover is significant to thoroughly investigate two of the major research questions dealing with land cover processes: 1) understanding in which locations land cover change occurs, and 2) assessing the rates of change (Lambin, 1997). The spatially explicit analysis enables to

---

* Corresponding author. University of Vienna, Department of Geography and Regional Research, Universitaetsstrasse 7, 1010 Wien, Austria.
E-mail address: catrin.promper@univie.ac.at (C. Promper).

http://dx.doi.org/10.1016/j.apgeog.2014.05.020



understand and delineate better the interactions of the two subsystems (Rindfuss et al., 2004).

The analysis of the possible future land cover development is especially important due to the fact that decision-makers are interested not only in the future hazard potential but also in the information on potential loss as input to a range of decisions (e.g. hazard mitigation plans; Downton & Pielke, 2005; Frazier, Walker, Kumari, & Thompson, 2013). Modelling and monitoring of land cover development on a regional scale has been conducted in many different regions around the world (Rembold, Carnicelli, Nori, & Ferrari, 2000; Ruelland, Levavasseur, & Tribotté, 2010; Teferi, Bewket, Uhlenbrook, & Wenninger, 2013). Many authors focus on ecosystems or more specific on deforestation (Etter, Mc Alpine, Wilson, Phinn & Possingham, 2006; Lambin, 1997). Regarding landslides and land cover change there are numerous studies available e.g. Alcántara-Ayala, Esteban-Chávez, & Parrot, 2006; Beguería, 2006; Glade, 2003 or Van Beek and Van Ash, 2004. Moreover, land cover change and consequent changes in the impact of natural hazards is an emerging topic within the research community e.g. Wood (2009) studying tsunami exposure, Alcántara-Ayala et al. (2006) assessing the distribution of landsliding in the context of vegetation fragmentation or Papathoma-Köhle and Glade (2012) also dealing with vegetation cover and landslide hazard and risk. In this study we apply a land cover analysis for the past, as well as, approximating future land cover in order to allow a first attempt towards the potential evolution of landslide risk.

The analysis of the spatio-temporal patterns of land cover will be the base for investigating the development of potential landslide risk. The focus of the paper is on the location explicit temporal analysis and the non-location specific quantitative analysis of land cover changes, based on implemented scenarios. First, the methodology used for the spatio-temporal land cover analysis is explained. Second, a short description of the study area detailed in order to demonstrate the relevance of the study's objectives on a regional scale. Finally, the results are discussed and some perspectives for further analysis are proposed.

Method

The approach for land cover analysis as a basis for the subsequent risk assessment requires the combination of different sets of methods. To analyse the land cover change, the applied methodology contains four steps:

1. setting the time scale of analysis,
2. analysing the spatial land cover changes,
3. adapting and modelling future land cover scenarios,
4. performing a quantitative and qualitative (spatially explicit) analysis.

Hereby, spatially explicit refers to a location based analysis of the different land cover types. Regarding the future land cover development, scenarios are envisaged in order to run the model for scenario-based approximation of possible future developments.

Time scale of the analysis

There are two considerations related to setting the time span of the land cover change analysis: a) which mapping documents are available for the past and b) what time span is reasonable concerning future scenarios.

In order to compare results, the time periods should be chosen in accordance to existing future scenarios regarding development plans or climate change models (Hiess et al., 2009; ÖROK, 2011; Schoener, Boehm, & Haslinger, 2011; Smiatek, Kunstmann, Knoche, & Marx, 2009). For this reason three future time steps are used in this analysis: 2030, 2050, and 2100. The year 2030 is selected due to the horizon of the spatial development plans and scenarios. 2100 is the horizon of various climate models and 2050 seemed reasonable in order to have periods with an adequate number of years for land cover analysis.

Spatial analysis of land cover changes

Analysis of past land cover changes

Available aerial photographs of past spatial land cover patterns are mapped in order to be used for the analysis of the land cover change over time. This is achieved by ortho-rectifying the available aerial photographs. To ensure reasonable results, certain rules and restrictions (Promper & Glade, 2012) were set for carrying out the visual interpretation in a GIS environment. If the data quality did not allow visual interpretation, a comparison with other orthophotographs was required.

Future land cover scenarios

Scenarios can be considered as alternative images on how the future might unfold (Nakićenović et al., 2000). Regarding land cover, this implies not only climate-driven changes but also direct anthropogenic impacts. Spatial and regional development scenarios available by authorities or previous projects may serve as a basis for land cover modelling. To serve as spatially explicit analysis, input parameters have to be defined. Further the assumptions need to be stated clearly in order to ensure transparency within the analysis.

The model Dyna-CLUE 2.0 (Verburg & Overmars, 2009) was selected to simulate the land use scenarios because it includes a spatial and a non-spatial module (Verburg et al., 2002). The model combines statistical analyses and decision rules that determine the sequence of land cover types (Schaldach & Priess, 2008). For the spatial analysis, the relationships between the different land cover classes and the main driving factors are evaluated by stepwise logistic regression (Verburg et al., 2002). Moreover, location specific restrictions (e.g. natural reserves) need to be included. The demand represents the non-spatial model input and is based on the scenarios used. These values are implemented in the model as a top-down factor. By an interactive process, the model tries to implement all these changes for one year before it proceeds to the next. This ensures that, for example in the map of 2030, all changes from 2005 onwards are already included.

The basis for the spatial distribution of the different land cover classes in the scenarios depends mainly on topographic factors like slope and aspect. However, some general spatial planning assumptions are also incorporated to limit certain factors (e.g. development in completely remote areas). Applying assumptions in scenario building enables implementation of possible societal and economic developments in order to simulate what might happen in the future (Rounsevell, Ewert, Reginster, Leemans, & Carter, 2005). The assumptions applied are explained in more detail in the following paragraph.

On one hand, an assumption that the demand for the years 2005–2030 will not change until 2100 had to be made, meaning that this was extrapolated, adopting at the same time some general trends in spatial planning. On the other hand, the second assumption is that no new building area outside a 100 m buffer of existing building area/street area is allowed. Further, a minimum distance (200 m) between farms is applied. Finally, street areas do not develop for the reason that Dyna-CLUE 2.0 does not integrate options for linear development. Another assumption was the fact that water surfaces do not change within the modelling process.

Additionally, the past development of land cover is not yet implemented into the future modelling. The hypothesis supporting this decision is that changes in the planning system and changes in the needs of the population overrule the importance of past developments. This is strongly supported by the fact that human activity is regarded as the most rapid and a very important factor regarding land cover change (Briassoulis, 2003; Meyer & Turner, 1994; Slaymaker et al., 2009).

Study area and datasets

Regional setting

Waidhofen/Ybbs is located in the Province of Lower Austria in the alpine foreland (Fig. 1). The administrative unit is a district as well as municipality and covers approximately 130 km^2. Due to data availability, the study area focuses to 112 km^2 of the district. The topography is characterized partly by steep slopes and partly by gentle hilltops.

Land cover and land use types are strongly linked to relief characteristics such as slope height, slope angle and slope exposition. It is composed mainly by cultivated grassland as well as by forest (Fig. 3). The acreage areas are scarce and depend on the exposition, as well as the location on the hill slope.

Waidhofen/Ybbs has approximately 11.500 inhabitants leading to a population density of about 90 inhabitants per km^2. Due to the relief, population is mainly concentrated in the valley bottoms and scattered settlements and farmhouses at the hilltops (Fig. 2). Furthermore, public buildings, as well as industrial areas, are concentrated in the valley along the Ybbs river.

The main soil type in Waidhofen/Ybbs is brown earth; however, patches of relict soils such as Rendsina, Gley and Pseudogley can also be found. The lithology is composed of Limestone, Flysch, the "Klippenzone" and Dolomite (Wessely, 2006). The Northern part is characterized by gentle hillslopes underlayed by Flysch.

The majority of landslides occur in the Flysch and the Klippenzone (Schwenk, 1992). Moreover, the district Waidhofen/Ybbs has one of the highest amounts of landslides in the province of Lower Austria (Petschko, Glade, Bell, Schwaigl & Pomaroli, 2010). In more detail, the landslide inventory of Waidhofen/Ybbs (Petschko et al., 2010) indicates a total of 691 landslides, mapped from the ALS (Airborne Laser Scanning). The landslide types have been classified by visual interpretation and include 522 distinct slides, 141 areas with slides, 25 with flows and 3 with complex landslides (Petschko et al., 2010). Therefore, the predominant landslide process for the study area of Waidhofen/Ybbs is sliding. The analysis of the reported damage in the landslide inventory (extracted from the building ground register provided by the Provincial Government of Lower Austria), includes estimations with respect to the depth and the size of the landslides. The depth of most of the landslides has been estimated in the range one to three meters. The reported damages are mostly related to infrastructures and agricultural areas whereas the smallest portion of the records is related to buildings.

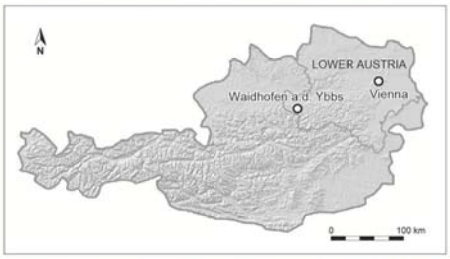


Fig. 1. Location of the study area Waidhofen/Ybbs in Austria (Promper & Glade, 2012).

The analysis of the land cover in the study area is based on the orthophotograph of 2005. The digital cadastre shows that two predominant land cover types are *forest* and *grassland*. Further, the land cover types *rock* and *water* only represent a very small portion of the whole investigation area. Some land cover types (e.g. *acreage*) fluctuate more than others (e.g. *farms*).

Datasets

The aerial photographs available for the study area cover the years 1962, 1979 and 1988. The orthophotographs for 1992, as well as a combination of 2005 and 2007 (later referred to as 2005 only) are available. Further the digital cadastre including a high number of land use classes serves as basis for the analysis. Additionally a layer comprising protectorates and the digital elevation model (DEM), are available as basis for restricted areas according to slope or aspect. The scenarios used for the land cover development is explained separately in the following paragraphs.

Land cover development scenarios are available from the Agency "Austrian Conference on Spatial Planning". The scenarios are part of the outcome of discussions of four workshops by experts, as well as expert public, in the context of the project *Scenarios for the spatial and regional development of Austria in the European context* (Hiess et al., 2009). The future driving forces are presented in the form of megatrends with different facets e.g. ageing of society, wild cards like extreme events with strong effects on total system and scenarios which are aimed to be consistent and representing the most diverse potential of the future (Hiess et al., 2009). These quantitative approximations for Austria are then described for the different sub regions e.g. peripheral regions, urban regions (Hiess et al., 2009). In the following the different available scenarios are described in more detail.

Scenario 1: overall growth

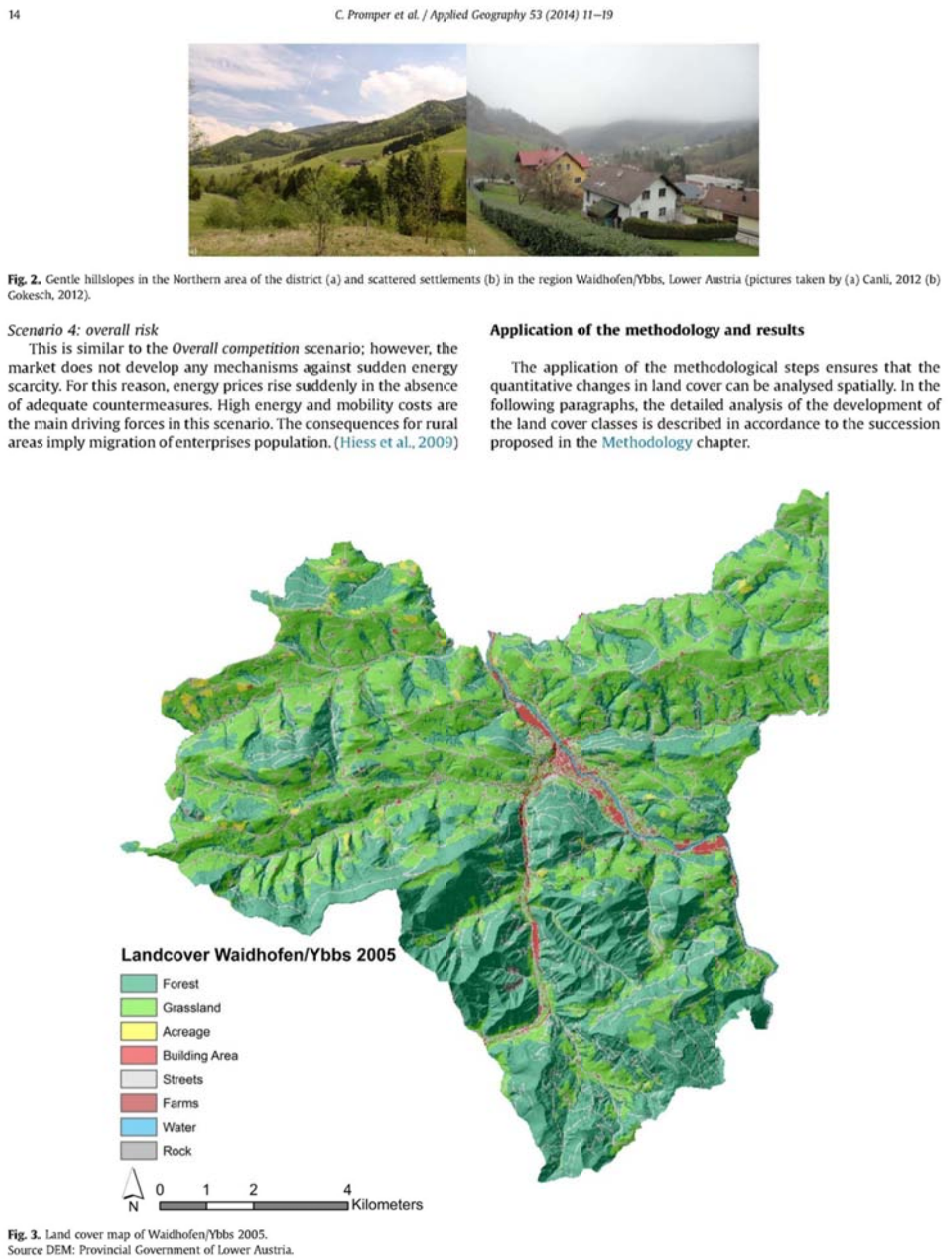
The *Overall growth* scenario considers a general increase of the main forces driving spatial development, such as economy, population, tourism, mobility and transport. Moreover, this scenario type is characterized by improved energy efficiency, resulting in reduced emissions. Although the interactions between state, market and civil society prevent widening of disparities, the pressure on space grows rapidly according to the *Overall Growth* scenario. These developments lead to a conflict of the usage of space between the different sectors, such as tourism, nature conservancy, agriculture, as well as settlement areas. (Hiess et al., 2009)

Scenario 2: overall competition

In the scenario *Overall competition*, the main driving factors of spatial development are also growing strongly. However, the social and, consequently, the spatial disparities widen. This implies that pressures on the growth zones and other regions are confronted with out-migration. The basic assumption in this scenario is that markets respond in time to scarcities, thus far reaching energy and environmental crisis are avoided. (Hiess et al., 2009)

Scenario 3: overall security

In contrast to the previous scenario types, the *Overall security* scenario considers a moderate growth of the main driving factors (economy, population and tourism). This moderate growth results in an increase in pressure in areas being used for farming and agriculture, due to high demand for biomass energy. Increasing disparities can only be avoided by strict government regulation, social security systems and restrictive in-migration. (Hiess et al., 2009)



14 C. Promper et al. / Applied Geography 53 (2014) 11–19

Fig. 2. Gentle hillslopes in the Northern area of the district (a) and scattered settlements (b) in the region Waidhofen/Ybbs, Lower Austria (pictures taken by (a) Canli, 2012 (b) Gokesch, 2012).

Scenario 4: overall risk

This is similar to the *Overall competition* scenario; however, the market does not develop any mechanisms against sudden energy scarcity. For this reason, energy prices rise suddenly in the absence of adequate countermeasures. High energy and mobility costs are the main driving forces in this scenario. The consequences for rural areas imply migration of enterprises population. (Hiess et al., 2009)

Application of the methodology and results

The application of the methodological steps ensures that the quantitative changes in land cover can be analysed spatially. In the following paragraphs, the detailed analysis of the development of the land cover classes is described in accordance to the succession proposed in the Methodology chapter.

Fig. 3. Land cover map of Waidhofen/Ybbs 2005.
Source DEM: Provincial Government of Lower Austria.

Time scale

The four orthophotographs of 1962, 1979, 1988 and 2005 are used as mapping basis. The orthophotograph of 1992 is excluded due to the short time period between 1988 and 1992. This leads to the final analysis periods that are displayed in Fig. 4. Due to the availability of aerial photographs, the time slices for the past differ from 9 up to 17 years.

Spatial and quantitative analysis of land cover changes

The results of the land cover mapping from 1962 to 2005 indicate a clear trend towards an increase in *building* as well as *street* areas. The land cover type *farms* remains more or less the same over the analysis period. However, the acreage is fluctuating constantly, reaching the largest extension in 1979. The lowest extent of acreage is in the first time slice. Regarding the dominant land cover class *forest* and *grassland* the development is controversial. The *forest* area is decreasing from 1979 onwards, whereas the extension of grassland is fluctuating over time reaching its minimum in 2005. The coverage of grassland decreased from approximately 50% of the study area to its minimum of approximately 40% over the investigation period. The *forest* area always fluctuates around 40%. The land cover classes *water* and *rock* range below 1% of the whole study area summarizes to a total area of approximately two hectare. In Fig. 5, these changes are presented as percentage of the whole study area from 1962–2005.

Scenarios development

The development of the scenarios implies data preparation and the tuning of the scenarios to the respective study area. This is necessary due to the specific characteristics of the region of interest.

Data preparation

The applied land cover scenarios were developed for whole Austria (see chapter Datasets), and thus need to be adapted for the regional analysis. Within the scenarios, the changes for the different land cover classes are described in hectares of increase/decrease per year. Adaption to the study area was performed by accustoming the numbers for the whole area of Austria to the area of Waidhofen/Ybbs. As model input the estimation of a balanced increase and decrease of hectare land cover is demanded. In a first step, the focus was on the increasing land cover types; in a second step, the decreasing areas were calculated proportionally.

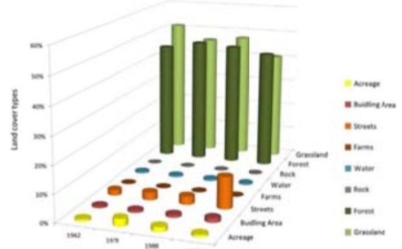


Fig. 5. Changes in land cover delineated from aerial photographs between 1962 and 2005.

The Table 1 details the demand specifically calculated for Waidhofen/Ybbs in hectare per year. These numbers indicate the increase or decrease in hectare area, considering all top down factors that are incorporated additionally.

Quantification of the scenarios

Regarding the future development of the different land cover types, the scenario-based approach is presented in Fig. 6. Note that the building area includes the farms, due to the very low number of farms in the study area. The past development of the land cover classes shows an overall trend within the investigation period. However, it is important to consider that this figure represents the demand that was set for the different scenarios. Thus, it only allows to visually comparing the different trends, also in correspondence to the past development.

Fig. 6 shows a clear trend for future increase in *forest* areas, for all scenarios. Moreover, a clear trend towards an increase of the building area is indicated. On the opposite, the future trend for grassland is decreasing. In more detail, the *scenario 2* shows the highest number of changes compared to the other scenarios.

Table 1
Land cover demand adapted for Waidhofen/Ybbs for each scenario.

Change in ha/year for Waidhofen/Ybbs	Forest	Grassland	Acreage	Building area
overall growth	5.0	−5.8	−0.4	1.2
overall competition	18.5	−19.7	−0.3	1.5
overall security	12.3	−13.0	−0.2	0.9
overall risk	12.3	−12.9	−0.1	0.7

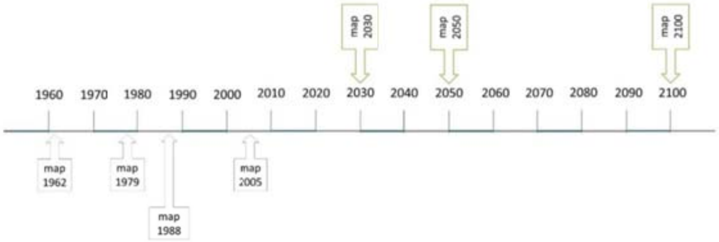


Fig. 4. Time periods of the past and future land cover analysis.

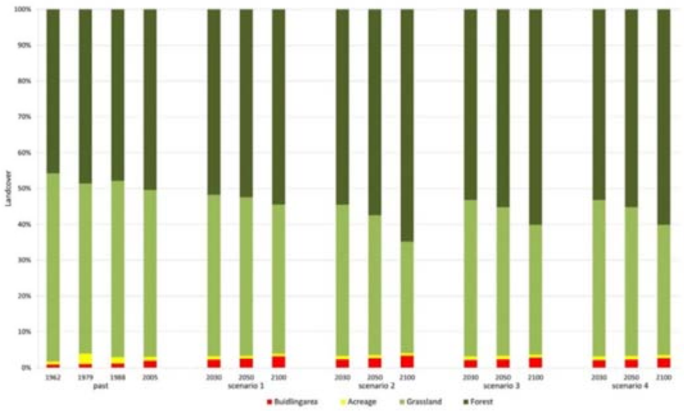


Fig. 6. Changes in land cover types in percentage of total changes for the past periods, the current land cover map and the four scenario developments.

Especially the forest areas increase by more than 10% of the total changes from 2030 up to 2100. Comparing this area of forest to the forest area in 1962, the increase is more than 20%. In each scenario, the building area shows an increase, however, *scenario 2* shows the highest overall increase of building area.

Location specific restrictions

These top-down factors were included to create location specific criteria where certain land cover conversions are not possible. Further, these are used to keep distances between specific developments within the modelling process. The restrictions were set by expert judgement and computed by analysing the distribution of the different land cover types in the current land cover map. The Table 2 represents the location specific restrictions used for this study.

Modelling process

The modelling was carried out with the Dyna-CLUE (Dynamic Conversion of Land Use and its Effects, v 2.0) modelling framework (Verburg & Overmars, 2009). The model combines bottom-up and top-down effects and allows modelling several land cover types in one modelling set-up. This model combines a non-location specific demand module and a spatially-explicit allocation procedure (Verburg et al., 2002). The demand described in the chapter Scenarios development was used as top-down input on how the land cover should develop quantitatively. For the location specific restrictions (Table 2), different binary maps, including these restricted areas only, were created. Further the analysis of the land cover classes and their driving factors were evaluated by using logistic regression.

Table 2
Location specific and non-location specific restrictions.

Restriction	Land cover type	Applied restrictions
Location specific	Building area	Distance to existing building area max. 100 m Distance to existing roads max. 100 m Distance to existing farms max. 100 m Restricted within natural reserves
	Acreage	Aspect: 180°–270°
Non location specific	Forest	Change only allowed after 30 years

The allocation of the pixels within the model are then, based on these probability maps, the decision rules and the actual land use map, conducted by an iterative procedure (Verburg et al., 2002). This iteration is conducted for each year, thus each output map already incorporates all changes that have occurred up to this specific moment in time. The spatial analysis of the results follows in the following paragraphs.

Location specific analysis of land cover changes

More insight into changing patterns is provided by the location specific analysis, as well as the examination of which land cover types change to which other land cover type. Scenario 2 is selected as an example for the spatial analysis because it indicates the largest areas of changed land cover. This probably relates to the story line that energy scarcities are prevented timely. The changes for the other scenarios are similar, due to the same location specific parameters applied. Fig. 7 shows the changes from 2005 to 2030 and 2005 to 2100 for the respective scenario.

The intense colours "New areas" in Fig. 7 indicate clearly the new land cover type. The changes from 2005 to 2030 mainly show an increase in *forest* in the central and southern parts of the study area. Additionally, an increase in *building* area along the valley in the South is observed. Referring to Tables 3 and 4 this change is on the expense of *grassland* only and covers around 0.3% of the total study area. On the hill slopes, in the South Eastern part of Waidhofen/Ybbs, a new area of *acreage* is also visible. The *forest* area increased mostly at the expense of grassland and covers approximately 4% of the study area however, new grassland has also developed on forest areas. The change from *forest* to *acreage* is extremely low, but it can occur.

The changes from 2005 to 2100 cover a larger area, indeed. The increase of forested areas expands towards the north-eastern part as well. Regarding the building area, the expansion is vast and covers almost completely the valleys in the southwest. Further, it increases on the hillslopes in the South Western part and, in the last

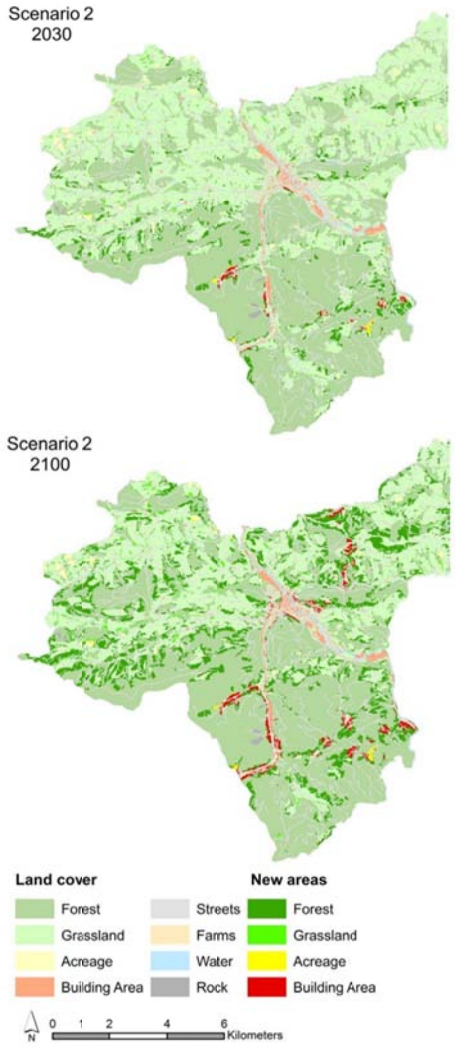


Fig. 7. Spatial changes in land cover *scenario 2* between 2005–2030 and 2030–2100.

developments steps, also in the North Western part of the study area. Moreover, it is striking that new acreage areas seem closely linked to locations of new *building* area. Approximately 13% of the study area turned from *grassland* to *forest* areas and less than 1% from forest to grassland. The building area increases solely at the expense of *grassland* (Tables 3 and 4). In contrast to the changes up to 2030, there are changes from acreage to forest and a larger shift from *acreage* to *grassland*. However, the new grassland in 2100 mostly developed at the expense of forest (Tables 3 and 4).

Discussion

The results of this analysis show two different types of data: the mapped results and the scenario based analysis on possible future developments. In both analysis, uncertainties have to be accounted for, however, the nature of uncertainty is different. In the following paragraphs, the sources of uncertainty are explained in more detail.

On the one hand, the mapping procedure is affected by different problems e.g. visual interpretation may change with enhanced practice, quality of the aerial photographs due to overexposure or shading, etc. Regarding the modelled data, this analysis is bound to "what-if" scenarios which have exploratory and projective capacities. However, these can be used as a communication and learning environment (Verburg, Kok, Pontius, & Veldkamp, 2006).

The results of the analysis from 1962 to the scenarios up to 2100 show a vast range of changes over the study area. Especially the increase in *forest* over *grassland*, as well as the increase of *building* area on the hillslopes in the Southern part of Waidhofen/Ybbs is evident. In the following sections, these results are discussed in more detail alongside the chronology of the analysis.

Past land cover analysis potential

Additionally to the aforementioned limitations the outer rim of the coverage of Waidhofen/Ybbs is less accurate than the central parts, where more aerial photographs were available.

The fact that between 1988 and 2005, some land cover types register an abrupt rise can partially be related to the long time span of 17 years; however, it may also be related to the incorporation of the digital cadastre which offers additional information, which might not be visually recognizable. Anyway, the results definitely show an increase in building area, as well as a lot of fluctuation concerning *acreage* and *grassland*.

Future land cover scenarios potential

The scenarios for the future analysis represent general trends like increase in *building* and *forest* area. The location explicit analysis demonstrates clearly possible areas of development for the given constraints. All scenarios suggest potential for building area in the southern part of the study area and on the long run also in the north-eastern part. Moreover, all scenarios suggest an expansion of existing *forest* areas all over the study area. The expansion of these areas on the expense of *grassland* and *acreage* follows a trend that can be observed throughout the Alps (e.g. Gellrich, Baur, Koch, & Zimmermann, 2007; Gehrig-Fasel, Guisan, & Zimmermann, 2007; Tasser, Walde, Tappeiner, Teutsch, & Noggler, 2007). This phenomenon is observed at moderate to high altitudes, steep slopes, areas with low temperature averages, but also to former alpine pastures (Gellrich et al., 2007). Further, Gellrich et al. (2007) refer to this phenomenon as a regional development which is largely restricted to municipalities with increasing population, higher proportions of part-time farms and higher farm abandonment (Gellrich et al., 2007). Apart from farm abandonment these characteristics apply for the study area, which support the suggested increase of forest area represented in the demand of the scenarios.

Table 3
Matrix of land cover changes for *scenario 2* from 2005 to 2030.

Scenario 2 in ha/year 2030	Forest	Grassland	Acreage	Building area	Streets	Farms	Water	Rock
Forest	43.84	**0.36**	**0.00**	–	–	–	–	–
Grassland	**3.91**	36.48	**0.12**	**0.29**	–	–	–	–
Acreage	–	**0.19**	0.73	–	–	–	–	–
Building area	–	–	–	1.54	–	–	–	–
Streets	–	–	–	–	11.65	–	–	–
Farms	–	–	–	–	–	0.14	–	–
Water	–	–	–	–	–	–	0.59	–
Rock	–	–	–	–	–	–	–	0.16

Bold values represent change to other land cover type.

Change in possible landslide consequences

The location specific analysis, offers the possibility to analyse not only potential future consequences but also the development of the spatial pattern of elements at risk. This evolution of landslide risk is strongly connected to the spatial development of elements at risk, thus analysis corresponding to this paper is inevitable for future risk management (Promper & Glade, 2012).

Regarding location specific changes of potential consequences, all new building area needs to be examined in detail. Especially the building area that increases in the north-eastern part of the study area approaching the year 2100 requires in depth analysis. These areas are within the Flysch zone, where most of the landslides occurred in the past within the study area (Petschko et al., 2010). Moreover, the southern part of the study area where building area is increasing on the hillslopes, the steep hillslopes below need in depth analysis. This increase is location wise the same for all scenarios. The difference is the expansion of the new built up area.

Modelling framework

The modelling framework Dyna-CLUE allowed incorporating a lot of different datasets, also at different spatial and temporal scales, covering different parameters. However, the necessity of quantified scenarios can be regarded as disadvantageous on this scale of analysis in a dichotomous study area, due to the fact that the same demand must apply for the whole study area. Further it is difficult to quantify the demand in ha/year at such scale because the portions of the different classes are partially very small. Generally there are several limitations to land cover modelling. On the one hand, it can be a constraint or a consequence of land use (Verburg, van de Steeg, Veldkamp, & Willemen, 2009), which leads actually to a desired modelling of the interactions. On the other hand, these drivers of change, thus interactions are very data intensive resulting in a lack of data, limiting the modelling results.

Incorporation of results in landslide risk assessment

The results enable the implementation of the modelled land cover maps in future landslide hazard assessment. Further the potential future distribution of elements at risk on a regional scale is shown within the different scenarios. With further analysis it is therefore possible to develop landslide susceptibility and hazard analysis using the results as one model input. Combining these landslide hazard maps with the existing modelling results, landslide exposure hotspot can be delineated. These hotspots then serve as a basis for detailed analysis in order to meet the local characteristics and needs regarding hazard and vulnerability to obtain a solid risk assessment for each hotspot.

Transferability

The basic inputs for this regional assessment further imply the transferability of the method in other regions where textual or quantitative scenarios regarding land cover are available. Further the transferability is not only given on a spatial extent but also towards risk assessment regarding other kind of hazards e.g. floods or torrential processes. Moreover the method allows additional input and therefore the results could be refined.

Conclusion and perspectives

The complex and dynamic process of land-use change links natural and human systems (Koomen, 2007). In the context of natural hazard and risk assessment, this linkage is a key issue. However, the importance of the consequence analysis is underlined by the fact that these have a greater influence on the risk than the hazard (Alexander, 2004). Concluding the social system has a large influence on land cover development, thus on the distribution of elements at risk, the linkage between the system is evident but not balanced. Consequently, depending on the elements at risk of interest, land cover analysis can serve as a solid tool for the consequence analysis. Regarding the predictive character, the scenario based analysis of possible future distribution of e.g. buildings or agricultural areas may be a first indication of future implications. For further analysis the land cover maps can be directly implemented in hazard models, considering land cover in order to evaluate different scenarios of hazard susceptibility e.g. landslides. The comprehension of past risk development, as well as the incorporation of these results into the scenario-based analysis of

Table 4
Matrix of land cover changes for *scenario 2* from 2005 to 2100.

Scenario 2 in ha/year 2100	Forest	Grassland	Acreage	Building area	Streets	Farms	Water	Rock
Forest	43.48	**0.72**	**0.00**	–	–	–	–	–
Grassland	**13.31**	26.16	**0.16**	**1.16**	–	–	–	–
Acreage	**0.05**	**0.37**	0.51	–	–	–	–	–
Building area	–	–	–	1.54	–	–	–	–
Streets	–	–	–	–	11.65	–	–	–
Farms	–	–	–	–	–	0.14	–	–
Water	–	–	–	–	–	–	0.59	–
Rock	–	–	–	–	–	–	–	0.16

Bold values represent change to other land cover type.

C. Promper et al. / Applied Geography 53 (2014) 11–19 19

future risk development, may support emerging issues connected to sustainable development. Rounsevell et al. (2005) state that scenarios themselves are models of how the real world functions and like in other models, exploration of understanding is allowed. Further, the development of the scenarios aimed at representing the most diverse potential scenarios and being as consistent as possible (Hiess et al., 2009). This leads to the fact that the results support an enhanced awareness regarding land cover developments and, through the follow up risk analysis, the understanding and consideration of the related change in potential consequences of natural hazards.

Acknowledgements

This work has been supported by the European Union within the FP7 ERA-NET Project ChangingRISKS (Grant agreement N° 263953; 2011-2013). The authors thank the Provincial Government of Lower Austria for their support and the provision of data.

References

Alcántara-Ayala, I., Esteban-Chávez, O., & Parrot, J. F. (2006). Landsliding related to land-cover change: a diachronic analysis of hillslope instability distribution in the Sierra Norte, Puebla, Mexico. *Catena, 65*(2), 152–165.

Alexander, D. (2004). Vulnerability to landslides. In T. Glade, M. Anderson, & M. J. Crozier (Eds.), *Landslide hazard and risk* (pp. 175–198). Chichester: John Wiley and Sons.

Beguería, S. (2006). Changes in land cover and shallow landslide activity: a case study in the Spanish Pyrenees. *Geomorphology, 74*(1–4), 196–206.

Briassoulis, H. (2003). Factors influencing land-use and land-cover change. In *UNESCO encyclopedia of life support systems*. Oxford: Eolss Publishers.

Downton, M., & Pielke, R. (2005). How accurate are Disaster loss data? The case of U.S. Flood damage. *Natural Hazards, 35*(2), 211–228.

Etter, A., McAlpine, C., Wilson, K., Phinn, S., & Possingham, H. (2006). Regional patterns of agricultural land use and deforestation in Colombia. Agriculture. *Ecosystems & Environment, 114*(2–4), 369–386.

Frazier, T. G., Walker, M. H., Kumari, A., & Thompson, C. M. (2013). Opportunities and constraints to hazard mitigation planning. *Applied Geography, 40*, 52–60.

Gehrig-Fasel, J., Guisan, A., & Zimmermann, N. E. (2007). Tree line shifts in the Swiss Alps: climate change or land abandonment? *Journal of Vegetation Science, 18*(4), 571–582.

Gellrich, M., Baur, P., Koch, B., & Zimmermann, N. E. (2007). Agricultural land abandonment and natural forest re-growth in the Swiss mountains: a spatially explicit economic analysis. Agriculture. *Ecosystems & Environment, 118*(1–4), 93–108.

Glade, T. (2003). Landslide occurrence as a response to land use change: a review of evidence from New Zealand. *Catena, 51*(3–4), 297–314.

Hiess, H., Gruber, M., Payer, H., Penker, M., Schrenk, M., Wankiewicz, H., et al. (2009). *Szenarien der Raumentwicklung Österreichs 2030 Regionale Herausforderungen & Handlungsstrategien. ÖROK Schriftenreihe 176/II, Geschäftsstelle d. Österr.* Wien: Raumordungskonferenz (ÖROK).

IPCC. (2012). Summary for policymakers. In C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, et al. (Eds.), *Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of working groups I and II of the Intergovernmental Panel on Climate Change* (pp. 1–19). Cambridge, UK, and New York, NY, USA: Cambridge University Press.

Koomen, E. (2007). *Modelling land-use Change: Progress and applications*. Springer.

Lambin, E. F. (1997). Modelling and monitoring land-cover change processes in tropical regions. *Progress in Physical Geography, 21*, 375–393.

Meyer, W. B., & Turner, B. L. (1994). *Changes in land use and land cover: A global perspective*. Cambridge University Press.

Nakićenović, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., et al. (2000). *IPCC special report on emissions scenarios (SRES)*. Cambridge University Press.

ÖROK. (2011). *Austrian Spatial Development Concept ÖREK 2011 ÖROK Schriftenreihe 185en, Geschäftsstelle d. Österr.* Wien: Raumordungskonferenz (ÖROK).

Papathoma-Köhle, M., & Glade, T. (2012). The role of vegetation cover change for landslide hazard and risk. In G. Renaud, K. Sudmeier-Rieux, & M. Estrella (Eds.), *The role of ecosystems in disaster risk reduction*. Tokyo: UNU Press.

Petschko, H., Glade, T., Bell, R., Schweigl, J., & Pomaroli, G. (2010). Landslide inventories for regional early warning systems. In J.-P. Malet, T. Glade, & N. Casagli (Eds.), *Mountain Risks: Bringing science to society* (pp. 277–282). Firenze, Italy: CERG.

Promper, C., & Glade, T. (2012). Land cover changes for landslide risk evolution – first results from Lower Austria. In E. Eberhardt, C. Froese, A. K. Turner, & S. Leroueil (Eds.), *2012, Proceedings of the 11th International Symposium on landslides and 2nd North American Symposium on landslides and Engineered slopes protecting society through improved understanding* (pp. 409–413). Banff, Canada.

Rembold, F., Carnicelli, S., Nori, M., & Ferrari, G. A. (2000). Use of aerial photographs, Landsat TM imagery and multidisciplinary field survey for land-cover change analysis in the lakes region (Ethiopia). *International Journal of Applied Earth Observation and Geoinformation, 2*(3–4), 181–189.

Rindfuss, R. R., Walsh, S. J., Turner, B. L., Fox, J., & Mishra, V. (2004). Developing a science of land change: challenges and methodological issues. *Proceedings of the National Academy of Sciences of the United States of America, 101*(39), 13976–13981.

Rounsevell, M. D. A., Ewert, F., Reginster, I., Leemans, R., & Carter, T. R. (2005). Future scenarios of European agricultural land use: II. Projecting changes in cropland and grassland. Agriculture. *Ecosystems & Environment, 107*(2–3), 117–135.

Ruelland, D., Levavasseur, F., & Tribotté, A. (2010). Patterns and dynamics of land-cover changes since the 1960s over three experimental areas in Mali. *International Journal of Applied Earth Observation and Geoinformation, 12*, 11–17.

Schaldach, R., & Priess, J. A. (2008). Integrated models of the land system: a review of modelling approaches on the regional to global scale. *Living Reviews in Landscape Research, 2*(1), 1863–7329.

Schoener, W., Boehm, R., & Haslinger, K. (2011). Klimaaenderung in Oesterreich – hydrologisch relevante Klimaelemente. *Oesterreichische Wasser- und Abfallwirtschaft, 63*(1–2), 11–20.

Schwenk, H. (1992). Massenbewegungen in Niederösterreich 1953–1990. *Jahrbuch der Geologischen Bundesanstalt, 135*(2), 597–660.

Slaymaker, O., Spencer, T., & Embleton-Hamann, C. (2009). *Geomorphology and global environmental change*. New York: Cambridge University Press.

Smiatek, G., Kunstmann, H., Knoche, R., & Marx, A. (2009). Precipitation and temperature statistics in high-resolution regional climate models: evaluation for the European Alps. *Journal of Geophysical Research: Atmospheres, 114*(D19), D19107.

Tasser, E., Walde, J., Tappeiner, U., Teutsch, A., & Noggler, W. (2007). Land-use changes and natural reforestation in the Eastern Central Alps. Agriculture. *Ecosystems & Environment, 118*(1–4), 115–129.

Teferi, E., Bewket, W., Uhlenbrook, S., & Wenninger, J. (2013). Understanding recent land use and land cover dynamics in the source region of the Upper Blue Nile, Ethiopia: spatially explicit statistical modeling of systematic transitions. Agriculture. *Ecosystems & Environment, 165*, 98–117.

Van Beek, L. P. H., & Van Asch, T. W. J. (2004). Regional assessment of the effects of land-use change on landslide Hazard by means of physically based modelling. *Natural Hazards, 31*(1), 289–304.

Verburg, P., Eickhout, B., & Meijl, H. (2008). A multi-scale, multi-model approach for analyzing the future dynamics of European land use. *The Annals of Regional Science, 42*(1), 57–77.

Verburg, P. H., Kok, K., Pontius, R., Jr., & Veldkamp, A. (2006). Modeling land-use and land-cover change. In E. Lambin, & H. Geist (Eds.), *Land-use and land-cover change* (pp. 117–135). Heidelberg.

Verburg, P., & Overmars, K. (2009). Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model. *Landscape Ecology, 24*(9), 1167–1181.

Verburg, P. H., Soepboer, W., Veldkamp, A., Limpiada, R., Espaldon, V., & Mastura, S. S. (2002). Modeling the spatial dynamics of regional land use: the CLUE-S model. *Environmental Management, 30*(3), 391–405.

Verburg, P. H., van de Steeg, J., Veldkamp, A., & Willemen, L. (2009). From land cover change to land function dynamics: a major challenge to improve land characterization. *Journal of Environmental Management, 90*(3), 1327–1335.

Wessely, G. (2006). *Geologie der österreichischen Bundesländer – Niederösterreich*. Wien: Geologische Bundesanstalt.

van Westen, C. (2010). GIS for the assessment of risk from geomorphological hazards. In I. Alcantara-Ayala, & A. Goudie (Eds.), *Geomorphological hazards and disaster prevention* (pp. 205–219). Cambridge University Press.

Wood, N. (2009). Tsunami exposure estimation with land-cover data: Oregon and the Cascadia subduction zone. *Applied Geography, 29*(2), 158–170.

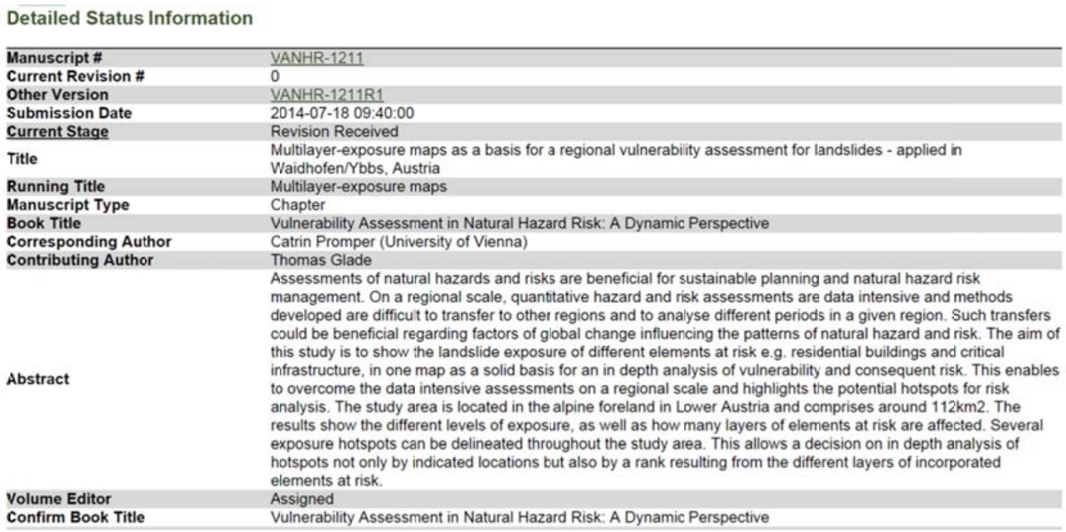
A.3 MULTILAYER EXPOSURE MAPS AS A BASIS FOR A REGIONAL VULNERABILITY ASSESSMENT - APPLIED IN WAIDHOFEN/YBBS, AUSTRIA

PROMPER C. AND GLADE T. acc. **Multilayer exposure maps as a basis for a regional vulnerability assessment - applied in Waidhofen/Ybbs, Austria**. In: Fuchs S. & Glade T. (eds), Vulnerability Assessment in Natural Hazard Risk: A Dynamic Perspective, Geological Society, London.

The manuscript preparation and the analysis was performed by Catrin Promper. The assessment was supported by discussion inputs during the analysis by Thomas Glade who also gave substantial feedback on the manuscript.

Status: revised submission

Confirmation of the revised submission



Detailed Status Information

Manuscript #	VANHR-1211
Current Revision #	0
Other Version	VANHR-1211R1
Submission Date	2014-07-18 09:40:00
Current Stage	Revision Received
Title	Multilayer-exposure maps as a basis for a regional vulnerability assessment for landslides - applied in Waidhofen/Ybbs, Austria
Running Title	Multilayer-exposure maps
Manuscript Type	Chapter
Book Title	Vulnerability Assessment in Natural Hazard Risk: A Dynamic Perspective
Corresponding Author	Catrin Promper (University of Vienna)
Contributing Author	Thomas Glade
Abstract	Assessments of natural hazards and risks are beneficial for sustainable planning and natural hazard risk management. On a regional scale, quantitative hazard and risk assessments are data intensive and methods developed are difficult to transfer to other regions and to analyse different periods in a given region. Such transfers could be beneficial regarding factors of global change influencing the patterns of natural hazard and risk. The aim of this study is to show the landslide exposure of different elements at risk e.g. residential buildings and critical infrastructure, in one map as a solid basis for an in depth analysis of vulnerability and consequent risk. This enables to overcome the data intensive assessments on a regional scale and highlights the potential hotspots for risk analysis. The study area is located in the alpine foreland in Lower Austria and comprises around 112km2. The results show the different levels of exposure, as well as how many layers of elements at risk are affected. Several exposure hotspots can be delineated throughout the study area. This allows a decision on in depth analysis of hotspots not only by indicated locations but also by a rank resulting from the different layers of incorporated elements at risk.
Volume Editor	Assigned
Confirm Book Title	Vulnerability Assessment in Natural Hazard Risk: A Dynamic Perspective

Multilayer exposure maps as a basis for a regional vulnerability assessment - applied in Waidhofen/Ybbs, Austria

Multilayer-exposure maps as a basis for a regional vulnerability assessment for landslides - applied in Waidhofen/Ybbs, Austria

C. Promper* & T. Glade

Department for Geography and Regional Research

University of Vienna

Universitätsstrasse 1

1010 Wien

*Corresponding author (catrin.promper@univie.ac.at)

7489 words, 7 figures, 3 tables

Abbreviated title: Multilayer-exposure for vulnerability analysis

Abstract

Assessments of natural hazards and risks are beneficial for sustainable planning and natural hazard risk management. On a regional scale, quantitative hazard and risk assessments are data intensive and methods developed are difficult to transfer to other regions and to analyse different periods in a given region. Such transfers could be beneficial regarding factors of global change influencing the patterns of natural hazard and risk. The aim of this study is to show the landslide exposure of different elements at risk in one map, e.g. residential buildings and critical infrastructure, as a solid basis for an in depth analysis of vulnerability and consequent risk. This enables to overcome the data intensive assessments on a regional scale and highlights the potential hotspots for risk analysis. The study area is located in the alpine foreland in Lower Austria and comprises around 112km2. The results show the different levels of exposure, as well as how many layers of elements at risk are affected. Several exposure hotspots can be delineated throughout the study area. This allows a decision on in depth analysis of hotspots not only by indicated locations but also by a rank resulting from the different layers of incorporated elements at risk.

The impact of landslides on both assets and human lives is clearly evident in different regions of the world (e.g. Guzzetti et al. (2000); Listo & Carvalho Vieira (2012); Lee & Chi (2011); Zêzere et al. (2008)). Every year damages caused by landslides are related to high direct and indirect costs for the various parties concerned (Dai et al. (2002); Schuster & Highland (2001); Zêzere et al. (2008)). Therefore the complex issue of landslide risk is an emerging challenge in different parts of the world (Anderson & Holcombe (2013); Corominas et al. (2013); Dai (2002);Glade et al. (2005); Glade (2003b) Guzzetti (2000); Martha et al. (2013); Winter & Bromhead (2012)). However, besides the analysis of landslide processes, it is important to focus on potential consequences and the respective spatial and temporal changes therein. Therefore, elements at risk and the respective vulnerability need to be taken into account. According to Chambers (2006) vulnerability consists of an external part determining the risks, shocks and stress to which an individual or household is subject to. The internal part relates to the defencelessness which signifies a lack of means to cope without damaging loss (Chambers 2006). This dual structure of vulnerability implies an internal side which can be referred to as the characteristics of an element at risk which also implies coping capacity and an external side which can be translated to natural hazard exposure (see also (Fuchs 2009)). Therefore an element at risk, such as a linear structure (e.g. road, electricity line), a local structure (e.g. a bridge, a house, a person) or a spatial structure (e.g. an agricultural field, a forest) can be exposed to a natural hazard due to their spatial location (Fra Paleo 2008) independent of the respective internal vulnerability which is determined by the specific characteristics of the considered object.

Taking a step forward, aspects of global change such as a changed population distribution and land cover conversion influence the spatial and temporal pattern of landslide risk (Gassner et al. 2014). Therefore the occurrence of natural processes such as landslides is not only dependent on the precipitation changes related to climate change, but also to changes of the preparatory factors e.g. land cover (Glade (2003a); Jemec & Komac (2011); Papathoma-Köhle & Glade (2012)). Further changes in land cover influence the spatial distribution of elements at risk. However, not only the location of elements at risk is affected by changes, but also the internal vulnerability due to changing characteristics of the element at risk.

In this chapter, the term “landslide exposure” refers to the exposure of elements at risk towards landslides. Changes of this external spatial component of vulnerability is largely influencing the spatiotemporal pattern of landslide risk. Regarding the anticipated changes mentioned above the aim of this study focuses on this external side of vulnerability. This represents a first step towards a comprehensive vulnerability analysis as a central part of risk assessment. The results of this study subsequently serve as a solid basis for a detailed vulnerability and hazard analysis in the delineated exposure hotspots and can further be integrated in a comprehensive risk assessment strategy. Further, it should serve as a decision tool on how to rank the different exposure hotspots and apply certain levels of action.

Challenges in regional vulnerability assessments

The costs related to the occurrence of natural hazards can be generally divided into direct and indirect costs e.g. physical damage to assets (direct) or traffic disruption (indirect) (Bubeck and Kreibich 2011). These different costs affect various stakeholders e.g. local community leaders, emergency service personnel, related departments/ministries, professional associations, academic institutions (WEF 2011). Referring to risk mitigation and prevention of the aforementioned costs of natural hazards one important category is spatial planning / land use management (Frazier et al. (2013); Pfurtscheller et al. (2011); WEF (2011)). Spatial planning is an effective tool for future mitigation (Pomaroli et al. 2011) and is commonly conducted on a regional scale, that also serves balancing political and financial support (Sukarna et al. 2012). Subsequently, stakeholders and decision makers need detailed data on potential risks and herein damage potential for respective cost/benefit judgements and the related mitigation planning on a regional scale. Therefore the overall aim of a quantitative risk assessment is to provide the degree of loss or costs per unit area, both direct and indirect respectively (Hufschmidt et al. (2005); Sterlacchini et al. (2007); Varnes (1984)). A quantitative risk assessment on this detailed level incorporates many different datasets on elements at risk e.g. data on building type, number of inhabitants or details on critical infrastructure (Corominas et al. (2013); van Westen et al. (2008)). The results of these assessments need to be provided on a highly precise level also related to vulnerability (Hufschmidt and Glade 2010). Therefore, it is important to serve the need for a regional assessment as a first step towards the identification of locations where in-depth analysis is required, Kappes et al. (2012) refer to such a procedure as top-down approach. The subsequent results of the detailed analysis then indicate the potential loss and these may be traded off against protection costs, a classical procedure within cost/benefit analysis (FEMA (1997);Fuchs (2013)). This is also referred to in various studies dealing with exposure to different hazards e.g. Løvholt et al. (2012) on tsunami exposure, Kappes et al. (2012) on multi-hazards or Pellicani et al. (2013) on landslides.

In this chapter landslide risk is understood as a function of physical vulnerability of different sets of elements at risk, their potential damage and a frequency and magnitude relation of landslide processes, thus the landslide hazard (Varnes 1984). Therefore it is an interaction of vulnerability including the exposure and hazard (Birkmann et al. (2013); Fuchs et al. (2013a); Keiler et al. (2006); Bell & Glade (2004); Lee & Jones (2004), to name a few studies only).

Related to the aforementioned need for quantitative assessments, the applied definition for physical vulnerability is associated with "the degree of loss to a given element, or set of elements, within the area affected by a hazard and it is expressed on a scale of 0 (no loss) to 1 (total loss)" (Fuchs et al. (2013b); Glade (2013b); Papathoma-Köhle et al. (2012); Pitilakis et al. (2011); Totschnig et al. (2011); Varnes (1984); UNDRO (1984)). Focusing on physical vulnerability assessments, several examples show how intense these data requirements are (e.g. Birkmann (2013); Papathoma-Köhle et al. (2011); van Westen et al. (2008)). As an example of physical vulnerability assessment, engineers focus in particular on the individual behaviours of structures such as buildings, bridges, roads, etc. towards the impact of a natural process (Papathoma-Köhle et al. (2011); Pitilakis et al. (2011)). This leads to the demand of specific process related data such as pressure, velocity, depth, etc. and of detailed data on the construction type of the building and its characteristics.

Related to spatiotemporal changes exposure is changing on a different time scale than internal vulnerability. The change in exposure is mostly related to new development areas or increased susceptibility to a natural hazard in a location of existing elements at risk. In contrast, internal vulnerability varies with changes of e.g. standards of living (Fra Paleo 2008) which is based on individual, local basis and therefore can change more quickly. The assessment of the landslide exposure can therefore serve as a first indicator where detailed analysis on internal vulnerability and hazard aspects is needed. These can also be referred to as landslide exposure hotspots.

The method applied in this study is trying to account for the spatial changes since the spatial and temporal dimensions are very important within any integrated disaster risk management (Aubrecht et al. 2013). Therefore the suggested and applied method is not trying to reflect the perfect local site conditions; it rather serves as a flexible concept in which a minimum number of two datasets can be extended to an infinite number of available datasets. In this study, multiple layers of elements at risk are assessed and analysed in order to define the aforementioned exposure hotspots. The focus is clearly on the built environment and their physical vulnerability (Papathoma-Köhle et al. 2011). However, the method also allows a connection to the affected population via the building use.

The main objective of this study is to apply a method for a regional multilayer-exposure assessment of elements at risk that can be transferred in space (to other regions) and with exchange of input data also a transfer in time is conceivable. The results will show how many types of building assets and streets are potentially affected by landslides in a specific location on the regional scale and indicate where additional in-depth analysis is necessary. In the following paragraphs, the applied method is explained in detail, and the study area is introduced. Then the analysis of the obtained results is presented, and a discussion concludes this chapter.

Data preparation and methods

The analysis is based on the exposure concept presented above and is technically implemented by the overlay of a set of elements at risk and a landslide susceptibility map (Glade et al. (2012); Kappes et al. (2012); Pellicani et al. (2013)). As delineated above, a susceptibility map for this analysis is adequate because it is conducted on a regional scale and provides general information on the spatial probability of landslide occurrence. In this chapter, we decided to delineate the different datasets before explaining the method applied because the knowledge on the various datasets facilitates the comprehensibility of the method section.

Data

Three sets of elements at risk are integrated in the exposure analysis: 1) critical infrastructure (buildings), 2) roads and streets and 3) residential buildings and schools. These sets refer to buildings of critical infrastructure e.g. fire brigades, transformers, etc. (1), to infrastructure related to e.g. road blockages (2) and to buildings where presence of people is highly likely (3). This approach is similar to the concept of Papathoma et al. (2007),wherein the building type determines respective types of vulnerability assessed. For example, `human´ vulnerability is calculated by multiplying residents with the vulnerability of the building.

For the generation of the vector datasets, the basic data (e.g. street network; digital cadastral map) were provided by the Provincial Government of Lower Austria. The road and street network and the buildings were extracted from the provided datasets and complemented by orthophoto mapping and field work. In Table 1, all established datasets used for this analysis are listed and briefly characterized.

Table 1: Established datasets used in this analysis (including examples, refer to text)

Dataset ID	**Description**	**Type**
build_code	Buildings	vector (polygon)
stre_code	Roads and streets	vector (line)
EaR_1	Residential and school buildings extracted from buil_code	raster (20m)
EaR_2	Buildings representing critical infrastructure extracted from build_code	raster (20m)
EaR_3	Street rasterized from stre_code	raster (20m)
Sc_Ls	Landslide susceptibility map (Source: Gassner (2013))	raster (20m)

These process related data can be related to either a landslide hazard or a susceptibility map. Herein, the susceptibility map presents the potential location of landslides based on various terrain factors. The hazard map includes information about temporal probability and intensity based on a frequency/magnitude relationship (e.g. Glade et al. (2005); Guzzetti et al. (1999); Lee et al. (2004)). The intensity represents the localized impact of the landslide event and the characteristic of the landslide mass that can be locally variable (SafeLand 2011). This additional information leads to the possibility of the application of e.g. vulnerability functions where detailed information on the process intensity is needed. However, for regional assessments landslide susceptibility maps are an adequate tool to approximate potentially endangered areas.

Methodological approach

In the following, the preparation of layers of elements at risk and the subsequent analysis is explained in detail. Details on the the calculation of the applied landslide susceptibility map are provided in Gassner et al. (2014) and Promper et al. (2015). As the presented analysis requires detailed information on the elements at risk, it was necessary to design and implement a building database.

The building database is based on a vector data layer where all buildings in the study area are defined as polygons. Given the ID of each polygon, this database was complemented during field work by the type of building (27 categories), the number of storeys (max. 5 stories) and a visual inspection of the condition of the buildings (classified in three conditions). If necessary an additional description on any particular features was recorded. In the data analysis, all 27 codes assigned to buildings were regrouped to 8 categories (see Table 2). This simplification was required because the analysis of 27 categories would not give a clear overview on the composition of the different building types. However, the additional codes serve to extract, the dataset on critical infrastructure from the building database for the exposure analysis.

Table 2: Building categories

Categories	**type**	**storeys**	**condition**	**description**
1	Residential building	1	Bad	Optional
2	Adjacent buildings (residential)	2	moderate	Optional
3	Farm	3	Good	in renovation
4	Adjacent buildings (farm)	4		Optional
5	Residential and Business	5		Optional
6	Business			Optional
7	Schools			Optional
8	Other			Optional

Eight regrouped categories a building can be assigned (please refer to text below for the example in grey

The example in grey indicates a building which is a residential building with two storeys in an overall good condition. For assigning the condition of the building criteria such as intact roof, façade and windows were adduced. The description of the example (highlighted as grey in Table 2) indicates that the building is renovated at the moment; therefore the condition “good” was already assigned. Regarding the type of buildings “Residential and Businesses” all buildings with business and one or two floors of residence are included. The category “Adjacent Buildings” comprises more or less garages or sheds related to residential buildings. Additionally also stables and sheds as adjacent buildings to farms are included in the group “Adjacent Buildings” (farms). The category “other” refers to buildings that did not match any other category. The total number of these specific buildings, e.g. buildings related to critical infrastructure like the fire department, is very low. These building functions are then indicated in the description field of the respective building (Table 2).

For the preparation of the multiple layers of elements at risk the first step was to extract the different types of elements at risk e.g. buildings of critical infrastructure and to enlarge them by a buffer of 50m. This buffer represents the average length of landslides in the study area and is applied to account for the whole area of a landslide. Therefore it represents a minimum distance from the landslide scarps to the potential impact on an element at risk. This buffer distance is calculated by the square root of the average area of all landslides occurred in Waidhofen/Ybbs and recorded within the building ground register (BGR - provided by the Provincial Government of Lower Austria). It serves as approximation of the range of a landslide potentially impacting various elements at risk. In a second step these layers of the different types of elements at risk including the buffer area were prepared as binary raster files with 0 (element at risk not present) and 1 (element at risk including buffer present) for each type of element at risk.

This leads to the raster set EaR_1 (see Table 1) which indicates all schools and residential buildings. For the second dataset EaR_2, all buildings related to critical infrastructure were extracted of the category “others” and rasterized. The third layer EaR_3 represents the roads and streets. The results are three binary files containing pixels with 1 for either the respective building or street including the 50m buffer and 0 for the rest of the data layer (see also figure 1).

The susceptibility map was calculated by statistical logistic regression modelling (Atkinson & Massari (1998); Bell (2007); Van Den Eeckhaut et al. (2006)) with a random sample (n=606) having slides and non-slides equally distributed (Gassner et al. 2014). The statistical modelling of input parameters was conducted in R using stepwise backward variable selection, based on Akaike´s information criterion (1974). For the validation, the Area Under the ROC is used as a criterion (refer to Gassner et al. (2014) and Promper et al. (2015) for details). For visualisation and comparability classification is conducted by equal interval to obtain four classes.

The principle aim is to overlay the layers of elements at risk with the landslide susceptibility in order to define where and how many layers of elements at risk are affected by e.g. high landslide susceptibility. For traceability of the four overlayed datasets, it is important to define a code consisting of four digits. This is achieved by multiplying the first layer (susceptibility) by 1000, the second (EaR_1) by 100, the third (EaR_2) by 10 and the fourth (EaR_3) by 1 with a raster calculator in a GIS environment (see figure 1). The four values are summed for a final code consisting of four digits.

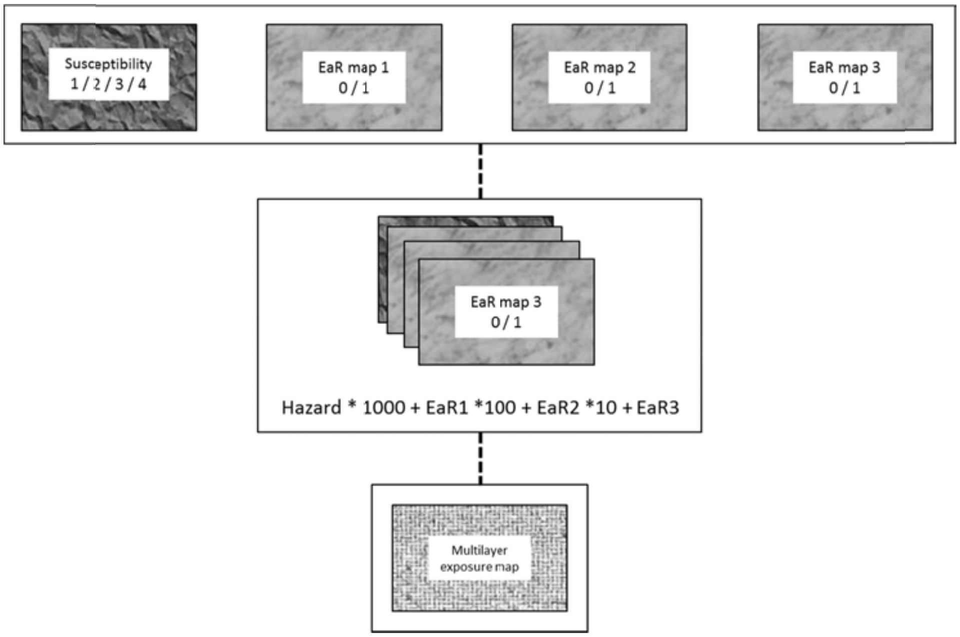


Figure 1: Procedure of intersecting the process and elements at risk datasets

The final four-digit code represents the result of the multilayer-exposure map. Consequently, each pixel is assigned this code expressing the value for landslide susceptibility and the respective elements at risk (figure 1). The possible combinations of the generated codes are listed in table 3.

Table 3: Possible codes of intersection results

EaR layer affected / **Susceptibility**	No EaR	EaR_3	EaR_2	EaR_1	EaR_3 and EaR_2	EaR_1 andEaR_1	EaR_1 and EaR_3	EaR_1 and EaR_2 and EaR_3
1	1000	1001	1010	1100	1011	1110	1101	1111
2	2000	2001	2010	2100	2011	2110	2101	2111
3	3000	3001	3010	3100	3011	3110	1301	3111
4	4000	4001	4010	4100	4011	4110	4101	4111

It needs to be stressed that the codes do not represent numbers but an order of digits describing the exposure of the relevant elements at risk e.g. 4011 means that the layers EaR_2 and EaR_3 are overlayed in this specific location and are highly exposed because of the landslide susceptibility class 4. Further, it can be delineated that a building related to critical infrastructure, as well as a street is located in this specific spot which is highly susceptible to landslides.

The illustration of these 32 possible combinations (Table 3) in one map would not give a distinct overview on the regional scale and it would not be possible to delineate clearly the landslide exposure hotspots. Therefore, only the three layers of the elements at risk are overlayed in a first step using the same procedure as described above. This allows the calculation of a single map on how many layers of elements at risk are present in one location (Figure 2A). Thereafter this aggregated layer is multiplied with the susceptibility map (Figure 2B). This leads to a reduction from 32 to 12 classes (see legend Figure 2C) which is acceptable as a first approximation. However, in the database the codes are still available, and it is easy to detect which layers of elements at risk are affected in the area of interest. Furthermore, it is also possible to search specific codes e.g. show all pixels in high susceptibility level where EaR_1 and EaR_2 are affected (code = 4110). Therefore, the resulting map enables a fast approximation to identify exposure hotspots including the possibility of accessing quickly details on locations of interest.

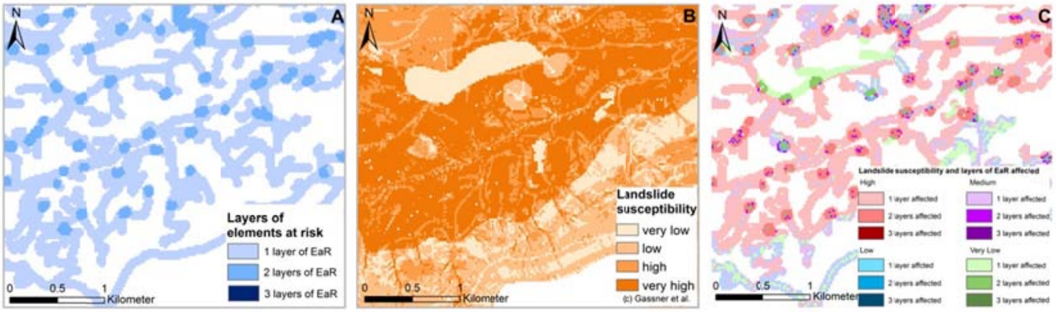


Figure 2: Schematic presentation of the method displayed in maps including A)the number of layers of elements at risk , B) the landslide susceptibility map and C) the final combined map.

Study area

The district Waidhofen/Ybbs is located in the alpine foreland in Lower Austria (figure 3). The region comprises approximately 112 km2 and covers the lithological units of Flysch in the Northern part and Calcareous rocks in the Southern part (Wessely 2006). The dominating land cover classes are grassland in the northern part of the study area and forest in the southern part. There is a high activity of landslides throughout the study area with many different types including slides, flows and complex landslides (Petschko et al. 2010). These occur on natural slopes and artificial slope cuts. The impact of landslides in this area often cause damages on roads and on buildings (figure 4A and 4B) (Pomaroli et al. 2011).

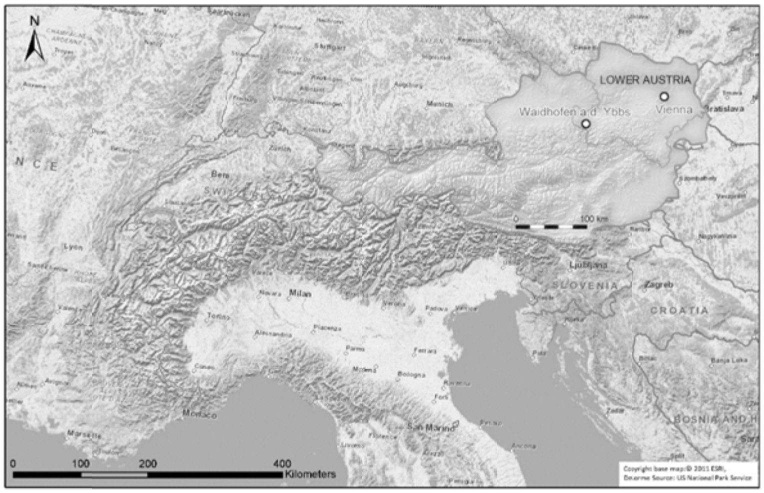


Figure 3: Location of study area “Waidhofen an der Ybbs” in Austria

Around 11.500 people are living in the study area giving a population density of about 90 inhabitants per km2. The distribution of the building area is twofold. Firstly, buildings are concentrated along the flat valleys and secondly, scattered hamlets and farm houses can be found throughout the hilly region. Typical buildings are shown in figure 4c and 4d. Partially these scattered farm houses are difficult to reach by unpaved streets. The city Waidhofen/Ybbs serves as a regional centre where basic infrastructure such as schools and emergency services are provided.

Figure 4: Landslides affecting a street and a building in Waidhofen/Ybbs (A,B), typical farm house and a typical single family house (C,D) (Pictures taken by: (A) Canli 2013, (B,D) Gokesch 2014), (C) Langmann& Zwirner 2011).

Results

Building database

The building database comprises in total more than 4,400 buildings. More than 80% of the buildings in the study area have 1-2 storeys, and approximately 90% are in good condition. In Figure 5, all building types are grouped in eight categories showing the percentage on the total number of buildings. It clearly indicates the high number of 2,150 residential buildings followed by the “adjacent buildings”. About 754 adjacent buildings such as sheds and stables can be found at the 225 farms. Thus, each farm has one or more adjacent building. Overall, the total number of residential buildings including farms and the combination of residential and business cover more than 50% of all buildings.

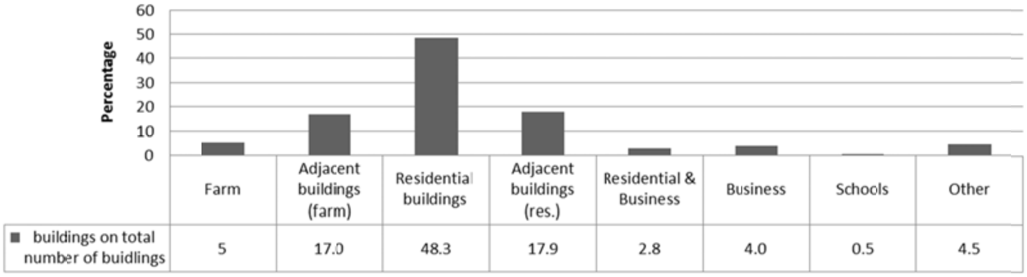


Figure 5: Percentage of different buildings types on total number of buildings in study area

The general distribution of the buildings in the study area is displayed in Figure 6. The spatial analysis shows that especially buildings related to critical infrastructure are concentrated in the center of the study area, in particular near Waidhofen/Ybbs. This relates to the high number of inhabitants and the respective requirements on the critical infrastructures e.g. water, energy or emergency units. Furthermore, the concentration of the residential buildings in the valley bottoms, the scattered settlements and the farmhouses on the hilltops are obvious. Topographical factors in combination with centralized access to infrastructure and services can be factors influencing this distribution.

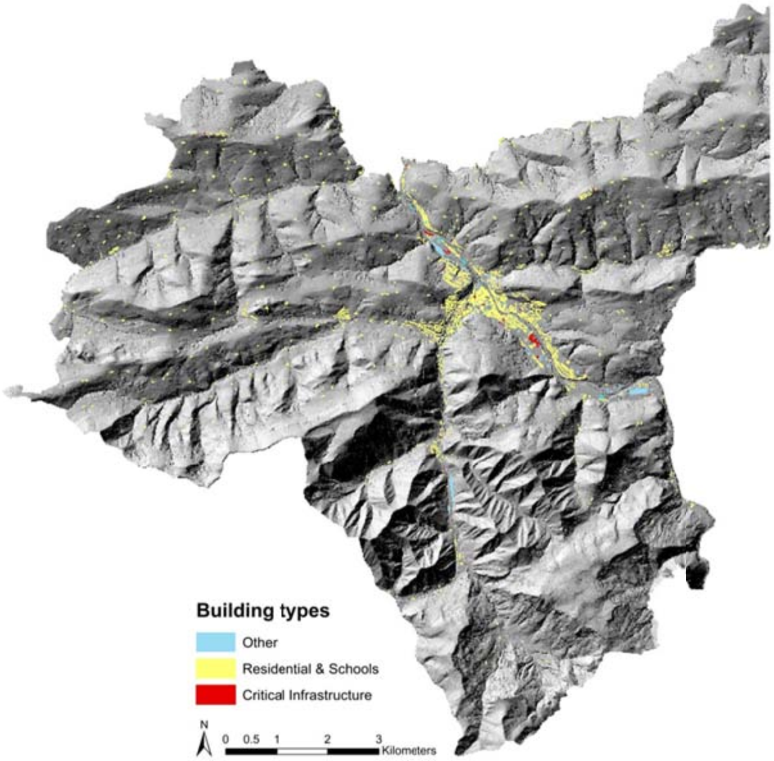


Figure 6: Distribution of the different elements at risk layers in Waidhofen/Ybbs (DEM provided by the Provincial Government of Lower Austria; Note: There is no aerial photography of the top right corner, therefore, this had to be excluded in the further analysis.)

Multilayer-exposure map

The colours of the spatial analysis of the multilayer-exposure map (Figure 7) indicate that areas with high and medium landslide susceptibility are located in the Northern part, whereas areas with lower susceptibility can be found in the South of the study area. However, in the Southwestern region are also spots of high susceptible areas. The mapping of the landslides in the study of Petschko et al. (2010), based on ALS (airborne laser scanning), indicates fewer but larger landslides in the Southern part of the study area, probably following the lithology.

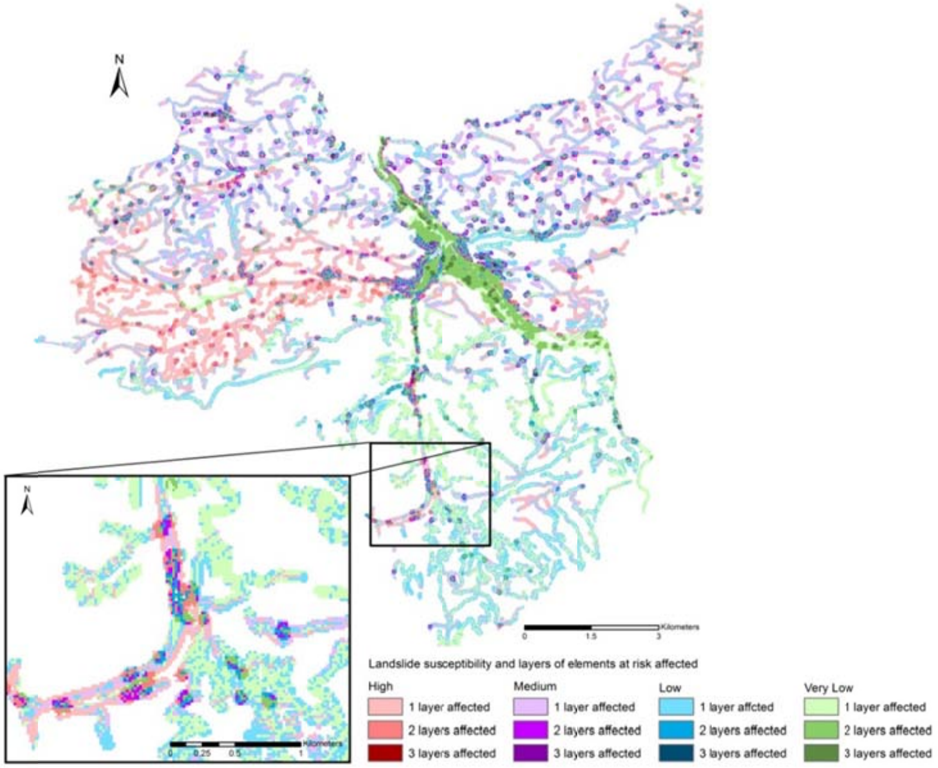


Figure 7: Multilayer-exposure map of Waidhofen/Ybbs (including the layers, critical infrastructure (buildings), roads and streets and residential buildings and schools) and a detailed section.

Combining this landslide susceptibility map with the different layers of elements at risk the hotspots of exposure of respective elements at risk towards a given landslide susceptibility can be directly delineated. In particular alongside the valleys in the West of the city, the respective exposure hotspots are located, whereas in the East of the city of Waidhofen/Ybbs , locations with multiple layers of elements at risk are only affected by low or medium landslide susceptibility. Additionally certain locations in the Southern area show susceptible regions coinciding with various layers of elements at risk, therefore, further hotspots of exposure can be allocated.

Regarding the Northern part of the study area, several locations of multiple layers of elements at risk can be found, especially in medium and high susceptible landslide areas. The city of Waidhofen/Ybbs itself provides a lot of different elements at risk, however all are located in flat areas and, therefore, only in the lowest landslide susceptibility class. The results clearly indicate that also in sparsely populated areas multiple layers may be exposed to different landslide susceptibilities, thus need attention by the respective stakeholder

In the Figure 7, a section of the study area is presented. This section has been selected because it demonstrates the various classes of the multilayer-exposure map eloquently. The Figure identifies that although located in a region where landslide susceptibility is generally rather low, there are hotspots where many layers of elements at risk can be found in areas of high landslide susceptibility. A detailed view on the section indicates large areas where only one layer is located in the high landslide susceptibility class. However, upslope next to the road there are locations where e.g. besides street area also building area or a layer of critical infrastructure is superimposed by high susceptibility.

Discussion and Conclusion

Building database

The results from the analysis of the building database enable a good overview on the general compound of the different building types and the overall condition of the buildings in the study area. This enables to detecting immediately where people e.g. residents in houses or children at schools can be potentially affected by a landslide impact. This is also possible for buildings related to critical infrastructure (e.g. power transformer), which is important not only regarding responses after an impact but also with respect to disaster risk management planning. In the meantime, one has to bear in mind the associated uncertainty based on the visual allocation of the building type. Not necessarily, all buildings are the visually allocated building type. Nevertheless, specific buildings of a certain type appear similar or have clear indication on the respective usage and therefore it is assumed that the respective epistemic uncertainty is very low. Additionally all buildings in one class are treated equally in this study e.g. a building related to an emergency service is classified equally to a transformer.

Multilayer-exposure map

The results enable to distinguish landslide exposure hotspots of buildings and streets respectively. Especially the highly exposed areas can be delineated by visual interpretation on a regional scale. Thus, the applied method meets the basic requirements for assessing landslide exposure hotspots and shows distinctively where further investigation on vulnerability and risk is needed. However, looking at the map depicting the whole study area, the overview appears cluttered and in some locations multiple exposure hotspots may be overseen. Further, it is difficult to distinguish between the medium levels of exposure. This relates to the fine pixel size that was selected for this study. This can be encountered by e.g. upscaling the map. This would give a better overview and enable an even faster assessment of where more detailed analysis is necessary. On the other hand upscaling could imply missing smaller hotspots.

Using the multilayer exposure map as an interactive map provides an additional feature which makes it possible delineating which types of elements at risk are affected in a certain location in a short time by analysing the underlying code of the multilayer exposure. Another feature could also be e.g. selecting all areas where critical infrastructure and residential buildings as well as schools are affected. Using these additional information, it is also possible to make a ranking of measures by assessing efficiently which elements at risk are affected in the aforementioned hotspots. These results can serve as a basis to delineate where which vulnerability assessments need to be carried out for the respective types of elements at risk. An example would be to define hotspots and immediately derive that a vulnerability assessment is not only needed for buildings but also for population.

As for the spatial transferability, this method does not require a large amount of data; however a spatial distribution of landslide susceptibility is required. Regarding the elements at risk a primary dataset of buildings or streets can be mapped by aerial photo interpretation or field work. Moreover, the temporal transferability can be conducted by incorporating updated datasets referring to elements at risk or also the landslide process.

Uncertainties

When applying the results of this study, one has to be aware of the associated uncertainties. This results from input data, as well as from the modelling procedures. Firstly the susceptibility map, based on logistic regression, contains uncertainties. Further, the applied buffer of 50m surrounding the elements at risk is based on an average assumption related to occurred and reported landslides. However, the real and future landslide areas may vary significantly. Further this is afflicted with the assumption that the damage to an element at risk is the same throughout the landslide. This is in contrast to other findings, e.g. by Fell et al. (2008) who reported higher damage on the boundaries or scarps when analysing large landslides. However, this assumption had to be taken due to missing alternatives, but significant improvements are indeed possible. The underestimation of this buffer distance or also an overestimation due to the modelled susceptibility data can influence the results of this study in either way. Referring to the elements at risk, the conversion of polygonal data into raster data adds additional uncertainty. This increases the inaccuracy of the location of the elements at risk, however for the regional assessment this uncertainty is acceptable because the datasets are not analysed on precise divisions, e.g. on the plot level. Despite the knowledge of these uncertainties, it was not possible to address these in the current analysis but nevertheless, these need to be stated clearly.

Advantages and disadvantages

The overall aim of the study of applying a simple method enabling an easy transferability in space and time of the exposure assessment can be regarded as accomplished. The results show the landslide exposure hotspots of the different sets of elements at risk. This overlay of several elements at risk, in a further step, enables the potential user to assess which elements are specifically affected in a particular location. Especially regarding spatial planning, the transferability into the future of this method is important because social and economic losses due to landslide processes can be reduced by effective planning (Greiving & Angingnard (2014); Pomaroli et al. (2011)) and management (Dai et al. (2002); Fra Paelo (2008)). Another option for further analysis is to add other data such as population distribution that improves the usability of the method in landslide risk management, but also disaster risk management.

The advantages of this method, therefore, include the possibility of adding changed datasets quickly, thus a new output with updated datasets can be generated with an adequate amount of resources. For example, if new land cover scenarios are available this method can be used to analyse future scenarios such as analysing the exposure of future building areas. Another asset is the possibility of rating the different exposure hotspots according to either the relevant layer or the number of layers of elements at risk affected. For example, a hotspot where all three layers of elements at risk are affected by high landslide susceptibility can be analysed in depth before the analysis of two layers located in an area of medium susceptibility. Providing this map on an interactive basis enables further to distinguish quickly how many types of elements at risk are affected in a certain location or vice versa where e.g. a particular number of elements at risk is affected. This is advantageous when taking different types of vulnerability into account. Although the target of this study is physical vulnerability it is possible to connect it to social vulnerability (similar to Papathoma-Köhle et al. (2007)) by extracting a layer of buildings of e.g. hospitals, primary schools etc. from the database as a first indication where high vulnerable population groups are exposed. Referring herein to economic vulnerability it is also possible to extract buildings related to business and therein analyse where potential business interruption can be expected in case of a landslide event. In a second step, the related internal vulnerability of these assets needs to be analysed.

The disadvantages of this method are clearly that, despite of the detailed results that are provided on a regional scale, these cannot be illustrated efficiently on the respective level. Therefore, a ranking of hotspots is not possible on visual interpretation but only by consulting an interactive map. Further, the assumption that all buildings in one group are of the same importance when e.g. talking about critical infrastructure, is problematic.

Concluding this method provides a sound and efficient method to illustrate how many layers of elements at risk are affected by a potential landslide impact in a certain location. Depending on the selected elements at risk (in this study case the building type), this can be the basis for the assessment of different vulnerability types and in a further step landslide risk assessment. The method enables to consider spatial changes over time of the landslide exposure, however does not consider internal vulnerability factors like coping capacity.

This study is carried out within the FP7 ERA-NET project ChangingRISKS (Grant agreement number 263953). The authors thank the European Union for funding this project. The authors also thank the Provincial Government of Lower Austria for their support and the provision of data.

Literature

Akaike, H. 1974. A new look at the statistical model identification. Automatic Control, IEEE Transactions on, 19, 716-723.

Anderson, M.G. & Holcombe, E. 2013. Community-Based Landslide Risk Reduction Managing Disasters in Small Steps. World Bank, Washington D.C.

Atkinson, P.M. & Massari, R. 1998. Generalized Linear Modelling of suceptibility to landsliding in the Central Apennines, Italy. Computers & Geosciences, 24, 373-385.

Aubrecht, C., Fuchs, S. & Neuhold, C. 2013. Spatio-temporal aspects and dimensions in integrated disaster risk management. Natural Hazards, 68, 1205-1216, doi: 10.1007/s11069-013-0619-9.

Bell, R. 2007. Lokale und regionale Gefahren- und Risikoanalyse gravitativer Massenbewegungen an der Schwäbischen Alb (Dissertation), Universität Bonn.

Bell, R. & Glade, T. 2004. Quantitative risk analysis for landslides ‒ Examples from Bíldudalur, NW-Iceland. Nat. Hazards Earth Syst. Sci., 4, 117-131, doi: 10.5194/nhess-4-117-2004.

Birkmann, J., Cardona, O.D., Carreño, M.L., Barbat, A.H., Pelling, M., Schneiderbauer, S., Kienberger, S., Keiler, M., Alexander, D., Zeil, P. & Welle, T. 2013. Framing vulnerability, risk and societal responses: the MOVE framework. Natural Hazards, 67, 193-211, doi: 10.1007/s11069-013-0558-5.

Bubeck, P. & Kreibich, H. 2011. CONHAZ Costs of Natural Hazards WP 1 Final Report: Natural Hazards: direct costs and losses due to the disruption of production processes WP 1 Final Report.

Chambers, R. 2006. Vulnerability, Coping and Policy (Editorial Introduction). IDS Bulletin, 37, 33-40, doi: 10.1111/j.1759-5436.2006.tb00284.x.

Corominas, J., Westen, C., Frattini, P., Cascini, L., Malet, J.P., Fotopoulou, S., Catani, F., Eeckhaut, M., Mavrouli, O., Agliardi, F., Pitilakis, K., Winter, M.G., Pastor, M., Ferlisi, S., Tofani, V., Hervás, J. & Smith, J.T. 2013. Recommendations for the quantitative analysis of landslide risk. Bulletin of Engineering Geology and the Environment, 73, 209-263, doi: 10.1007/s10064-013-0538-8.

Dai, F.C., Lee, C.F. & Ngai, Y.Y. 2002. Landslide risk assessment and management: an overview. Engineering Geology, 64, 65-87.

Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E. & Savage, W.Z. 2008. Guidelines for landslide susceptibility, hazard and risk zoning for land use planning. Engineering Geology, 102, 85-98.

FEMA. 1997. Report on Costs and Benefits of Natural Hazard Mitigation.

Fra Paleo, U. 2008. On Exposure to Natural Hazards: Revisiting a Neglected Primal Action. In: Fra Paelo, U. (ed.) NATO Advanced Research Workshop on Spatial Planning as a Strategy for Migration and Adaptation to Natural Hazards. IOS Press, Santiago de Compostela, 1-34.

Frazier, T.G., Walker, M.H., Kumari, A. & Thompson, C.M. 2013. Opportunities and constraints to hazard mitigation planning. Applied Geography, 40, 52-60, doi: http://dx.doi.org/10.1016/j.apgeog.2013.01.008.

Fuchs, S. 2009. Mountain hazards, vulnerability, and risk – a contribution to applied research on human-environment interactionHabilitationsschrift, Universität Innsbruck

Fuchs, S. 2013. Cost-benefit analysis of natural hazard mitigation. In: Bobrowsky, P. (ed.) Encyclopedia of Natural Hazards. Springer, Dordrecht, Heidelberg, New York, London, Encyclopedia of Earth Sciences Series.

Fuchs, S., Keiler, M., Sokratov, S. & Shnyparkov, A. 2013a. Spatiotemporal dynamics: the need for an innovative approach in mountain hazard risk management. Natural Hazards, 68, 1217-1241, doi: 10.1007/s11069-012-0508-7.

Fuchs, S., Keiler, M. & Tsao, T.-C. 2013b. Magnitude and frequency: challenges for the assessment of vulnerability to geomorphic hazards In: Brebbia, C.A. (ed.) Risk Analysis VIII. WIT Press, Southampton, UK.

Gassner, C., Promper, C., Beguería, S. & Glade, T. 2014. Climate change impact for spatial landslide susceptibility IAEG XII Congress Engeneering Geology for Soiety and Territory Springer, Torino.

Gassner, C., Promper, C., Petschko, H. & Glade, T. 2013. Scenarios of future landslide susceptibility - incorporating changes in land cover and climate. European Geoscience Union General Assembly 2013. Copernicus Publications, Vienna.

Glade, T. 2003a. Landslide occurrence as a response to land use change: A review of evidence from New Zealand. Catena, 51, 297-314.

Glade, T. 2003b. Vulnerability assessment in landslide risk analysis. Die Erde, 134, 128-139.

Glade, T., Anderson, M.G. & Crozier, M.J. 2005. Landslide hazard and risk. Wiley, Chichester, 807.

Glade, T., Kappes, M.S., Frigerio, S. & Malet, J.P. 2012. Multi-Hazard Exposure Analyses with MULTIRISK - a platform for user-friendly analysis. 12th Congress INTERPRAEVENT, Grenoble, France.

Greiving, S. & Angignard, M. 2014. Disaster Mitigation by Spatial Planning. In: Van Asch, T., Corominas, J., Greiving, S., Malet, J.-P. & Sterlacchini, S. (eds.) Mountain Risks: From Prediction to Management and Governance. Springer Netherlands, Advances in Natural and Technological Hazards Research, 287-302.

Guzzetti, F. 2000. Landslide fatalities and the evaluation of landslide risk in Italy. Engineering Geology, 58, 89-107.

Guzzetti, F., Carrara, A., Cardinali, M. & Reichenbach, P. 1999. Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy. Geomorphology, 31, 181-216, doi: http://dx.doi.org/10.1016/S0169-555X(99)00078-1.

Hufschmidt, G., Crozier, M.J. & Glade, T. 2005. Evolution of natural risk: research framework and perspectives. Natural Hazards and Earth System Sciences, 5, 375-387.

Hufschmidt, G. & Glade, T. 2010. Vulnerability analysis in geomorphic risk assessment. In:Alcántara-Ayala, I. & Goudie, A. (eds.) Geomorphological Hazards and Disaster Prevention. Cambridge University Press, 233-243.

Jemec, M. & Komac, M. 2011. An Overview of Approaches for Hazard Assessment of Slope Mass Movements. Alpine Mass Movements: Implications for hazard assessment and mapping, Special Edition of Journal Torrent, Avalanche, Landslide and Rock Fall Engeneering, 166.

Kappes, M.S., Gruber, K., Frigerio, S., Bell, R., Keiler, M. & Glade, T. 2012. The MultiRISK platform: The technical concept and application of a regional-scale multihazard exposure analysis tool. Geomorphology, 151–152, 139-155, doi: http://dx.doi.org/10.1016/j.geomorph.2012.01.024.

Keiler, M., Sailer, R., Jörg, P., Weber, C., Fuchs, S., Zischg, A. & Sauermoser, S. 2006. Avalanche risk assessment - a multi-temporal approach, results from Galtür, Austria. Nat. Hazards Earth Syst. Sci., 6, 637-651, doi: 10.5194/nhess-6-637-2006.

Lee, E.M. & Jones, D.K.C. 2004. Landslide risk assessment. Thomas Telford, London.

Lee, Y.-F. & Chi, Y.-Y. 2011. Rainfall-induced landslide risk at Lushan, Taiwan. Engineering Geology, 123, 113-121, doi: http://dx.doi.org/10.1016/j.enggeo.2011.03.006.

Listo, F.d.L.R. & Carvalho Vieira, B. 2012. Mapping of risk and susceptibility of shallow-landslide in the city of São Paulo, Brazil. Geomorphology, 169–170, 30-44, doi: http://dx.doi.org/10.1016/j.geomorph.2012.01.010.

Løvholt, F., Glimsdal, S., Harbitz, C.B., Zamora, N., Nadim, F., Peduzzi, P., Dao, H. & Smebye, H. 2012. Tsunami hazard and exposure on the global scale. Earth-Science Reviews, 110, 58-73, doi: http://dx.doi.org/10.1016/j.earscirev.2011.10.002.

Martha, T.R., van Westen, C.J., Kerle, N., Jetten, V. & Vinod Kumar, K. 2013. Landslide hazard and risk assessment using semi-automatically created landslide inventories. Geomorphology, 184, 139-150, doi: http://dx.doi.org/10.1016/j.geomorph.2012.12.001.

Papathoma-Köhle, M. & Glade, T. 2012. The role of vegetation cover change for landslide hazard and risk. In: Renaud, G., Sudmeier-Rieux, K. & Estrella., M. (eds.) The Role of Ecosystems in Disaster Risk Reduction. UNU Press, Tokyo.

Papathoma-Köhle, M., Kappes, M., Keiler, M. & Glade, T. 2011. Physical vulnerability assessment for alpine hazards: state of the art and future needs. Natural Hazards, 58, 645-680, doi: 10.1007/s11069-010-9632-4.

Papathoma-Köhle, M., Keiler, M., Totschnig, R. & Glade, T. 2012. Improvement of vulnerability curves using data from extreme events: debris flow event in South Tyrol. Natural Hazards, 64, 2083-2105, doi: 10.1007/s11069-012-0105-9.

Papathoma-Köhle, M., Neuhäuser, B., Ratzinger, K., Wenzel, H. & Dominey-Howes, D. 2007. Elements at risk as a framework for assessing the vulnerability of communities to landslides. Natural Hazards and Earth System Science, 7, 765-779.

Pellicani, R., Van Westen, C. & Spilotro, G. 2013. Assessing landslide exposure in areas with limited landslide information. Landslides, 1-18, doi: 10.1007/s10346-013-0386-4.

Petschko, H., Glade, T., Bell, R., Schweigl, J. & Pomaroli, G. 2010. Landslide inventories for regional early warning systems. In: Malet, J.-P., Glade, T. & Casagli, N. (eds.) Mountain Risks: Bringing science to society. CERG, Firenze, Italy, 277-282.

Pfurtscheller, C., Locher, B. & Thieken, A.H. 2011. CONHAZ Costs of Natural Hazards WP 8 Final Report: Costs of Alpine Hazards.

Pitilakis, K., Fotopoulou, S., Argyroudis, S., Pitilakis, D., Senetakis, K., Treulopoulos, K., Kakderi, K. & Riga, E. 2011 Physical vulnerability of elements at risk to landslides: methodology for evaluation, fragility curves and damage states for buildings and lifelines SafeLand Deliverable 2.5.

Pomaroli, G., Bell, R., Glade, T., Heiss, G., Leopold, P., Petschko, H., Proske, H. & Schweigl, J. 2011. Darstellung der Gefährdung durch gravitative Massenbewegungen im Bundesland Niederösterreich als Grundlage der Raumplanung. Gefahrendarstellungen für Massenbewegungen. Wildbach- und Lawinenverbau, Zeitschrift für Wildbach-, Lawinen-, Erosions- und Steinschlagschutz, 74, 198-206.

Promper, C., Gassner, C. & Glade, T. 2015. Spatiotemporal patterns of landslide exposure – a step within future landslide risk analysis on a regional scale applied in Waidhofen/Ybbs Austria. International Journal of Disaster Risk Reduction.

SafeLand. 2011. Deliverable 2.4: Guidelines for landslide susceptibility, hazard and risk assessment and zoning

Schuster, R.L. & Highland, L.M. 2001. Socioeconomic and environmental impacts of landslides in the western hemisphere.

Sterlacchini, S., Frigerio, S., Giacomelli, P. & Brambilla, M. 2007. Landslide risk analysis: a multi-disciplinary methodological approach. Natural Hazard and Earth System Science, 7, 657-675.

Sukarna, D., Wirakusumah, A.D., Suhaemi, I.A., Eka, S., Surono, Soedradjat, G.M., Solihin, A., Hendrasto, M., Abdurachman, K.E., Andreastuti, M.C.S.D., Danaryanto, H., Murdohardono, D., Sugalang, Wafid, M., Herudiyanto, Mulyasari, F., Kastuari, A., Adar, S., Tissahadi, I.K., Jaeger, S., Hoffmann-Rothe, A., Pischke, B., Ranke, U. & Weiland, L. 2012. Guidebook for Assessing the Risks to Natural Hazards Case Study: Province of Central Java.

Totschnig, R., Sedlacek, W. & Fuchs, S. 2011. A quantitative vulnerability function for fluvial sediment transport. Natural Hazards, 58, 681-703, doi: 10.1007/s11069-010-9623-5.

UNDRO. 1984. Disaster prevention and mitigation—a compendium of current knowledge, Vol 11. Preparedness Aspects, New York.

Van Den Eeckhaut, M., Vanwalleghem, T., Poesen, J., Govers, G., Verstraeten, G. & Vandekerckhove, L. 2006. Prediction of landslide susceptibility using rare events logistic regression: A case-study in the Flemish Ardennes (Belgium). Geomorphology, 76, 392-410.

van Westen, C.J., Castellanos, E. & Kuriakose, S.L. 2008. Spatial data for landslide susceptibility, hazard, and vulnerability assessment: An overview. Engineering Geology, 102, 112-131.

Varnes, D.J. 1984. Landslides hazard zonation: a review of principles and practice. UNESCO, Paris, France.

WEF. 2011. A vision for managing natural disaster risk - Proposals for public/private stakeholder solutions.

Wessely, G. 2006. Geologie der österreichischen Bundesländer - Niederösterreich. Geologische Bundesanstalt, Wien.

Winter, M. & Bromhead, E. 2012. Landslide risk: some issues that determine societal acceptance. Natural Hazards, 62, 169-187, doi: 10.1007/s11069-011-9987-1.

Zêzere, J.L., Garcia, R.A.C., Oliveira, S.C. & Reis, E. 2008. Probabilistic landslide risk analysis considering direct costs in the area north of Lisbon (Portugal). Geomorphology, 94, 467-495, doi: http://dx.doi.org/10.1016/j.geomorph.2006.10.040.

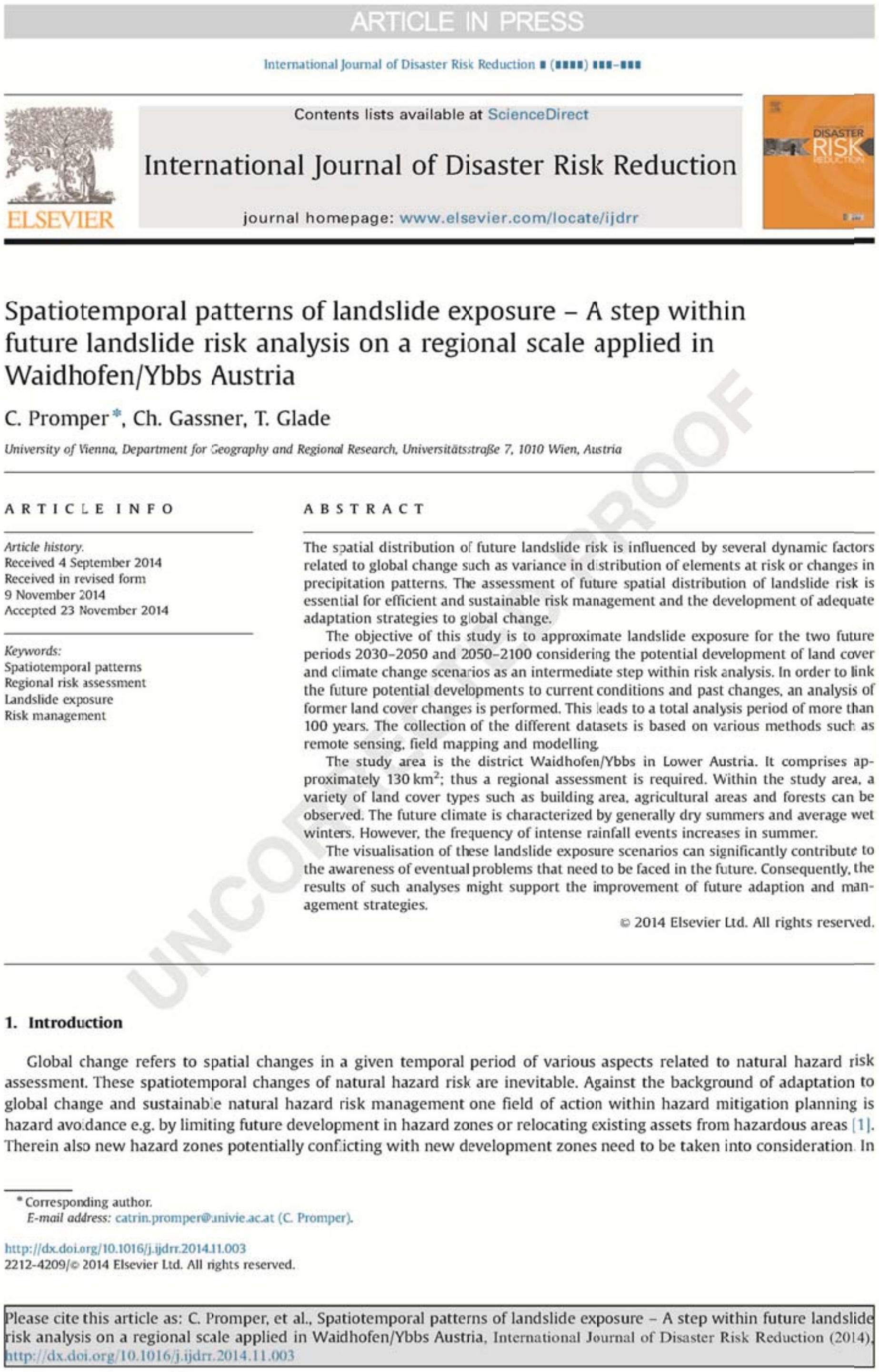
A.4 SPATIAL AND TEMPORAL PATTERNS OF LANDSLIDE RISK – A CASE STUDY IN LOWER AUSTRIA.

PROMPER C., GASSNER C. AND GLADE T., in press. **Spatial and temporal patterns of landslide risk – a case study in Lower Austria.** International Journal of Disaster Risk Reduction

The manuscript preparation and the analysis was carried out by Catrin Promper. The susceptibility modelling was carried out by Christine Gassner. The results of the analysis were obtained by Catrin Promper and Thomas Glade contributed substantial feedback on the manuscript and valuable input on the analysis.

Status: in press

NOTE: In the proofreading phase section 2.2 and table 2 were corrected exceedingly, these parts are marked yellow in the uncorrected proof. This has been communicated to the journal, for clarification the corrected version of paragraph 2.2 and table 2 are attached after the uncorrected proof.



ARTICLE IN PRESS

International Journal of Disaster Risk Reduction ■ (■■■■) ■■■–■■■

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr

Spatiotemporal patterns of landslide exposure – A step within future landslide risk analysis on a regional scale applied in Waidhofen/Ybbs Austria

C. Promper*, Ch. Gassner, T. Glade

University of Vienna, Department for Geography and Regional Research, Universitätsstraße 7, 1010 Wien, Austria

ARTICLE INFO

Article history:
Received 4 September 2014
Received in revised form
9 November 2014
Accepted 23 November 2014

Keywords:
Spatiotemporal patterns
Regional risk assessment
Landslide exposure
Risk management

ABSTRACT

The spatial distribution of future landslide risk is influenced by several dynamic factors related to global change such as variance in distribution of elements at risk or changes in precipitation patterns. The assessment of future spatial distribution of landslide risk is essential for efficient and sustainable risk management and the development of adequate adaptation strategies to global change.

The objective of this study is to approximate landslide exposure for the two future periods 2030–2050 and 2050–2100 considering the potential development of land cover and climate change scenarios as an intermediate step within risk analysis. In order to link the future potential developments to current conditions and past changes, an analysis of former land cover changes is performed. This leads to a total analysis period of more than 100 years. The collection of the different datasets is based on various methods such as remote sensing, field mapping and modelling.

The study area is the district Waidhofen/Ybbs in Lower Austria. It comprises approximately 130 km^2; thus a regional assessment is required. Within the study area, a variety of land cover types such as building area, agricultural areas and forests can be observed. The future climate is characterized by generally dry summers and average wet winters. However, the frequency of intense rainfall events increases in summer.

The visualisation of these landslide exposure scenarios can significantly contribute to the awareness of eventual problems that need to be faced in the future. Consequently, the results of such analyses might support the improvement of future adaption and management strategies.

1. Introduction

Global change refers to spatial changes in a given temporal period of various aspects related to natural hazard risk assessment. These spatiotemporal changes of natural hazard risk are inevitable. Against the background of adaptation to global change and sustainable natural hazard risk management one field of action within hazard mitigation planning is hazard avoidance e.g. by limiting future development in hazard zones or relocating existing assets from hazardous areas [1]. Therein also new hazard zones potentially conflicting with new development zones need to be taken into consideration. In

---

* Corresponding author.
E-mail address: catrin.promper@univie.ac.at (C. Promper).

http://dx.doi.org/10.1016/j.ijdrr.2014.11.003
2212-4209/

Please cite this article as: C. Promper, et al., Spatiotemporal patterns of landslide exposure – A step within future landslide risk analysis on a regional scale applied in Waidhofen/Ybbs Austria, International Journal of Disaster Risk Reduction (2014), http://dx.doi.org/10.1016/j.ijdrr.2014.11.003

general risk analysis approaches are static procedures [2]. However, natural hazard risk is influenced by various dynamic factors related to the geo- and the social-system: process, value and susceptibility can change over short time periods [3–5]. Therefore it is important to include changes in the natural system, as well as the social system when analysing natural hazard risk. Both systems are characterized by many factors, which are also interrelating, e.g. by cascading effects. Indeed, this has not yet been addressed comprehensively. While being fully aware of the limitations, this study selects two of the most important factors determining landslide risk. In the chosen approach precipitation scenarios and land cover scenarios are included to analyse different future scenarios of spatiotemporal development of landslide risk.

Cutter [6] made the point that hazards are complex phenomena involving interaction between natural, technological but also social systems. This was enhanced by Hufschmidt et al. [2] where another dimension in this complex issue was introduced: time. Changes in the social system levy demands on the geosystem up to the extent of changing the landscape and even provoking a physical response, e.g. a landslide. This interrelated process in turn, forces a reaction of the social system. The same holds true vice versa for the geosystem. Herein, the concept of probabilistic risk assessment, based on the function of hazard and consequences [7,8] incorporating the specific vulnerability of elements at risk [9,10] within the consequences, implies the interconnection of the two systems [11–13]. The elements at risk herein are defined as population, buildings, economic activities but also public service utilities, infrastructure and environmental features which are potentially affected by landslides hazards [14].

The inclusion of time in the basic concept of risk assessment further leads to the assumption that based on several factors in the geo- and the social-system, patterns of landslide hazard risk change over a certain time span. Variations in precipitation patterns, plus characteristics of torrential events herein, and changes in land use expressed in vegetation cover, as well as surface alterations, can be identified as two of the main factors influencing landslide occurrence [15–17]. However, land cover change is not only connected to modifications in the geo-system but is traceable related to human impact and the interaction of both systems therein [18]. Modifications in land cover thus often imply both, changes in the geo- and in the social-system. Related to natural hazards this refers in particular to changes in vegetation cover, slope incision due to artificial cuts, surface sealing or changes of drainages [17,19–22], all of which potentially influence the respective processes.

Further the change in land cover alters the spatial distribution of elements at risk [11,5] through e.g. new settlements, abandoned and demolished building area, expanding industrial sites, etc. This is especially relevant referring to the partial increase of losses due to the location and structure of emerging communities [1,23]. In this study land cover serves as a proxy for elements at risk, as it is not the specific future location of a building or farm, but the building area or farm area that this regional analysis is based on. Therefore also different future scenarios can be illustrated by land cover development.

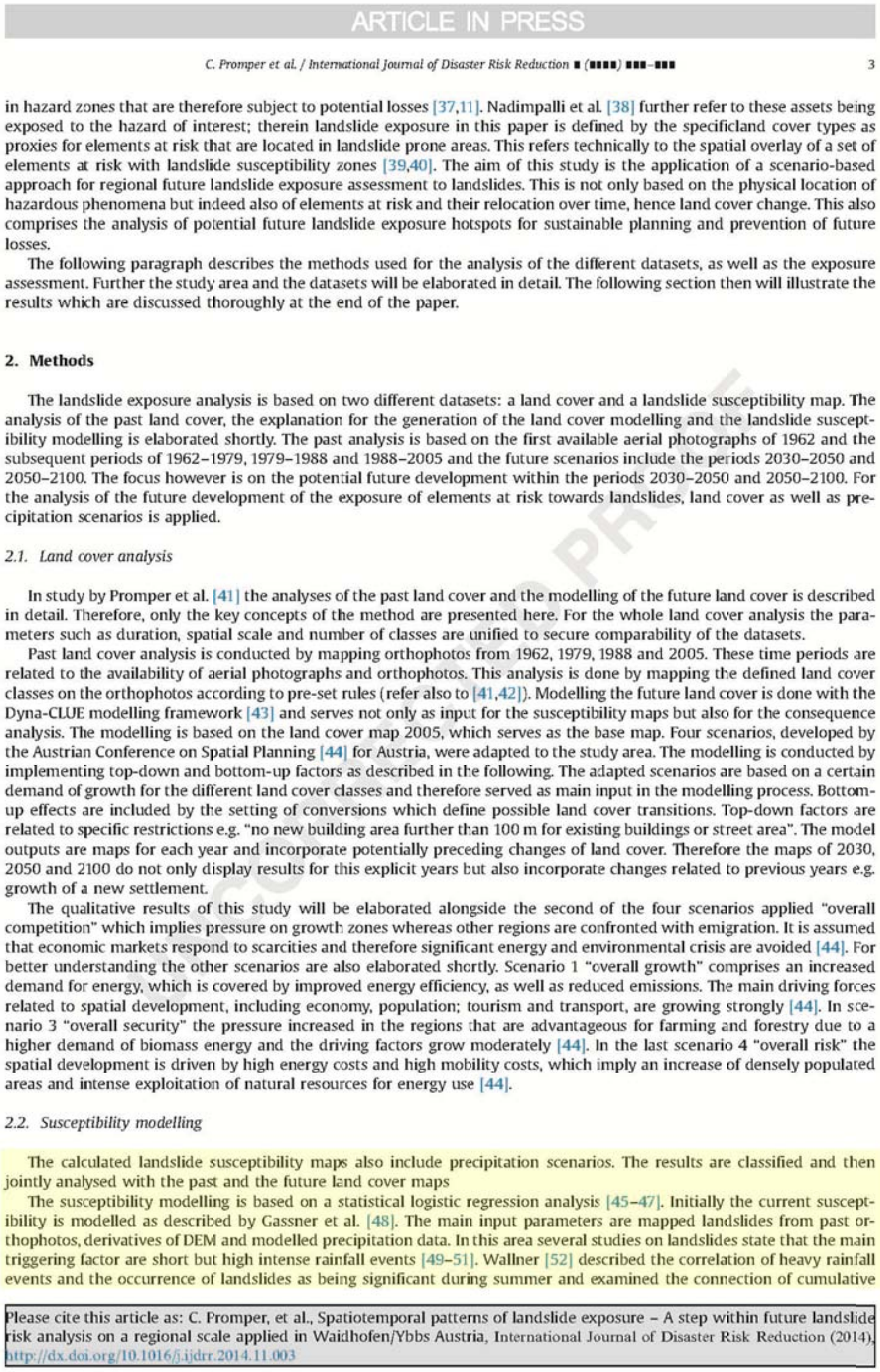
As mentioned above, the changes in the geo- and the social-system may happen independently, but also interlinked with each other [24]. Changes in the social system only could change the pattern of risk [25]. In this study an example could be a new settlement that is built in a landslide prone area. This also holds true for a change in the geo-system only e.g. increased precipitation in a region where existing elements at risk are suddenly endangered. However, also the conjunction of the two systems can cause a change in landslide risk. This can be illustrated by a new settlement that leads to an increase of sealed surfaces, causing a change in drainage and runoff system. Consequently landslide initiation is influenced by soil saturation depending on land cover and land use [26]. This all refers to the interaction of the two systems which can be regarded as constant and reciprocal [2,24]. Additionally there are short term fluctuations superimposing the long term changes in the socio-economic system leading to risk peaks [3]; however these peaks cannot be accounted for in a long-term regional assessment.

There are demands to incorporate spatiotemporal determinants e.g. land cover scenarios into landslide risk assessment (e.g. [27,28]) and some attempts have been presented (e.g. [29,30]). Herein most researchers focus on implementing climate scenarios in landslide hazard analysis (e.g. [31–34]). The constantly changing environment, as well as the worldwide socio-economic developments underlines the need for scenario-based approaches on both geo- and socio-economic system. The socio-economic system can be represented by the distribution of elements at risk, herein represented by the respective land cover types. Herein the changes observed in the past and the incorporation of socio-economic factors underlines the need to develop the scenarios further [35] and not extrapolating the past. Based on the assumptions above it is not only necessary to integrate long-term climate scenarios into risk analysis but also socio-economic scenarios (e.g. increased agricultural areas and increase in building area) which are closely related to the consequences of potential future landslide impacts.

However, the lack of knowledge on how future landslide risk might develop, the scenario-based approach is only a first step towards adaptation to potential future developments. Analysing long-term changes of environmental and socio-economic trends needs to be conducted on a regional scale due to the fact that local changes can be superimposed by other factors not relevant on regional scale e.g. geotechnical intervention. This is also true for the national and global scale; however within this analysis it is important to integrate regional factors e.g. spatial planning constraints. Consequently the challenge of assessing potential future landslide risk incorporates the inclusion of scenarios being aware of limitations and uncertainties. For the analysis of future landslide risk information on the spatial pattern of elements at risk and on landslide hazard is necessary. Dai et al. [36] state that for the assessment of the probability of landslides on a regional scale, it might be feasible to consider landslide susceptibility based on the long term landslide history and therewith smoothen the spatiotemporal effects of landslide occurrence. According to Fell et al. [14] landslide susceptibility assessment involves the spatial distribution and rating of the terrain units according to their propensity to landslides.

As the available data at regional scale determine the use of a susceptibility map [36] it is not possible to quantify risk but assess the respective exposure. Exposure hereby refers to the elements at risk (people, property, systems or other elements)

Please cite this article as: C. Promper, et al., Spatiotemporal patterns of landslide exposure – A step within future landslide risk analysis on a regional scale applied in Waidhofen/Ybbs Austria, International Journal of Disaster Risk Reduction (2014), http://dx.doi.org/10.1016/j.ijdrr.2014.11.003



in hazard zones that are therefore subject to potential losses [37,11]. Nadimpalli et al. [38] further refer to these assets being exposed to the hazard of interest; therein landslide exposure in this paper is defined by the specificland cover types as proxies for elements at risk that are located in landslide prone areas. This refers technically to the spatial overlay of a set of elements at risk with landslide susceptibility zones [39,40]. The aim of this study is the application of a scenario-based approach for regional future landslide exposure assessment to landslides. This is not only based on the physical location of hazardous phenomena but indeed also of elements at risk and their relocation over time, hence land cover change. This also comprises the analysis of potential future landslide exposure hotspots for sustainable planning and prevention of future losses.

The following paragraph describes the methods used for the analysis of the different datasets, as well as the exposure assessment. Further the study area and the datasets will be elaborated in detail. The following section then will illustrate the results which are discussed thoroughly at the end of the paper.

2. Methods

The landslide exposure analysis is based on two different datasets: a land cover and a landslide susceptibility map. The analysis of the past land cover, the explanation for the generation of the land cover modelling and the landslide susceptibility modelling is elaborated shortly. The past analysis is based on the first available aerial photographs of 1962 and the subsequent periods of 1962–1979, 1979–1988 and 1988–2005 and the future scenarios include the periods 2030–2050 and 2050–2100. The focus however is on the potential future development within the periods 2030–2050 and 2050–2100. For the analysis of the future development of the exposure of elements at risk towards landslides, land cover as well as precipitation scenarios is applied.

2.1. Land cover analysis

In study by Promper et al. [41] the analyses of the past land cover and the modelling of the future land cover is described in detail. Therefore, only the key concepts of the method are presented here. For the whole land cover analysis the parameters such as duration, spatial scale and number of classes are unified to secure comparability of the datasets.

Past land cover analysis is conducted by mapping orthophotos from 1962, 1979, 1988 and 2005. These time periods are related to the availability of aerial photographs and orthophotos. This analysis is done by mapping the defined land cover classes on the orthophotos according to pre-set rules (refer also to [41,42]). Modelling the future land cover is done with the Dyna-CLUE modelling framework [43] and serves not only as input for the susceptibility maps but also for the consequence analysis. The modelling is based on the land cover map 2005, which serves as the base map. Four scenarios, developed by the Austrian Conference on Spatial Planning [44] for Austria, were adapted to the study area. The modelling is conducted by implementing top-down and bottom-up factors as described in the following. The adapted scenarios are based on a certain demand of growth for the different land cover classes and therefore served as main input in the modelling process. Bottom-up effects are included by the setting of conversions which define possible land cover transitions. Top-down factors are related to specific restrictions e.g. "no new building area further than 100 m for existing buildings or street area". The model outputs are maps for each year and incorporate potentially preceding changes of land cover. Therefore the maps of 2030, 2050 and 2100 do not only display results for this explicit years but also incorporate changes related to previous years e.g. growth of a new settlement.

The qualitative results of this study will be elaborated alongside the second of the four scenarios applied "overall competition" which implies pressure on growth zones whereas other regions are confronted with emigration. It is assumed that economic markets respond to scarcities and therefore significant energy and environmental crisis are avoided [44]. For better understanding the other scenarios are also elaborated shortly. Scenario 1 "overall growth" comprises an increased demand for energy, which is covered by improved energy efficiency, as well as reduced emissions. The main driving forces related to spatial development, including economy, population; tourism and transport, are growing strongly [44]. In scenario 3 "overall security" the pressure increased in the regions that are advantageous for farming and forestry due to a higher demand of biomass energy and the driving factors grow moderately [44]. In the last scenario 4 "overall risk" the spatial development is driven by high energy costs and high mobility costs, which imply an increase of densely populated areas and intense exploitation of natural resources for energy use [44].

2.2. Susceptibility modelling

The calculated landslide susceptibility maps also include precipitation scenarios. The results are classified and then jointly analysed with the past and the future land cover maps

The susceptibility modelling is based on a statistical logistic regression analysis [45–47]. Initially the current susceptibility is modelled as described by Gassner et al. [48]. The main input parameters are mapped landslides from past orthophotos, derivatives of DEM and modelled precipitation data. In this area several studies on landslides state that the main triggering factor are short but high intense rainfall events [49–51]. Wallner [52] described the correlation of heavy rainfall events and the occurrence of landslides as being significant during summer and examined the connection of cumulative

Please cite this article as: C. Promper, et al., Spatiotemporal patterns of landslide exposure – A step within future landslide risk analysis on a regional scale applied in Waidhofen/Ybbs Austria, International Journal of Disaster Risk Reduction (2014), http://dx.doi.org/10.1016/j.ijdrr.2014.11.003

rainfall scenarios. Therefore the main focus here is on the 90% interval of cumulative summer precipitation. A range of 1–10 day scenarios were tested. This includes the main weather conditions triggering landslides in this area [51]. Afterwards the computed regression parameters were transferred to the parameters of future and past time periods of the precipitation as well as the modelled and historic land cover. The susceptibility values are classified in four classes with equal intervals. For each scenario the 1–10 day precipitation outputs are modelled for present, the period 2021–2050 and the period 2071–2100. In total 90 data sets are exhibited. As an example the datasets of scenario 2 are listed in Table 2.

2.3. Landslide exposure analysis

Exposure is defined by elements at risk being subject to losses due to the location in a hazardous zone [37]. In this paper this refers to specific land cover types that coincide with specific susceptibility classes. An example for this analysis would be the location of various pixel of building area located in different susceptibility classes and consequently different exposure is attributed. Therefore exposure is location bound [53]. Consequently it is necessary to analyse for each class/type of elements at risk the respective location within a specific susceptibility class of the respective hazard in this study, landslides. To serve this aim on a regional basis the land cover map is intersected with the susceptibility map. This analysis is done by adding two raster layers, overlaying each land cover cell (class 1–7) with the correspondent susceptibility cell (class 1–4), similar to the approach by Pellicani et al. [39] with the following basic formula:

$$EX = SC \times 10 + LC.$$

Similar approaches related to floods are used by e.g. Cammerer et al. [54] or De moel et al. [25]. The exposure (EX) for one pixel is a code calculated by multiplying the value of susceptibility (SC) by 10 and adding the number of the type of land cover (LC), see Fig. 1. Therefore the first number indicates the susceptibility class and the second number indicates the land cover type. This formula ensures that the results can be ascribed to the original data in order to delineate not only between the different exposure classes but also between the different land cover classes affected. In this case 10 is used as a multiplier to keep the code simple and thus allow a quick attribution to the respective exposure. (Table 1)

The application of this formula to the different raster datasets leads to the following possible combinations of codes Q2 (Table 2) that are assigned to the respective pixels of the exposure (results) raster dataset. These values of the exposure dataset do not refer to quantitative numbers but only to the codes of the respective raster cell.

This allocation of a code to each pixel allows a quantitative and a qualitative analysis of the exposure over a regional extent, which enables further to delineate exposure hotspots. These hotspots refer to areas where zones of elements at risk of interest e.g. build area are located within zones of high susceptibility. This method is applied for all time steps that were determined for this analysis (see Section 1).

2.4. Quantitative and qualitative analysis of results

The quantitative analysis is based on the number of pixel for each code e.g. for all pixel of building area in susceptibility Q3 class high [33]. Thereby a quantitative analysis on a percentage basis can be conducted. This further allows indicating the potential changes in landslide exposure regarding different types of elements at risk. The qualitative analysis only allows a visual interpretation of the exposure map. Therein it is optional which type(s) of land cover hence elements at risk are analysed. For landslide exposure hotspots detailed visual interpretation can be conducted.

3. Study area

The study area Waidhofen/Ybbs covers an area of approx. 112 km² and corresponds mainly to the respective administrative district in Lower Austria. A total of around 11,500 inhabitants are living in this area. In former times the economy of this region was well known for its iron processing, whereas today tourism and educational establishments contribute to the economic performance [55]. The study area is mostly covered by grassland in the northern part and forest in the southern part. The building area is concentrated in the valley bottoms as well as dispersed farm houses and small settlements on the hilltops. Furthermore different types of landslides (e.g. slides, flows, and complex movements) occurred in the smooth hills mainly comprised of Flysch in the north and in the steeper slopes underlayed by calcareous rocks in the south as described in [49]. In this area landslides are mainly triggered by extreme rainfall events [50,51]. The main soil type in Waidhofen/Ybbs

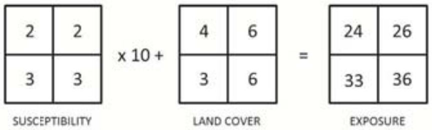


Fig. 1. Raster calculation for exposure assessment.

Please cite this article as: C. Promper, et al., Spatiotemporal patterns of landslide exposure – A step within future landslide risk analysis on a regional scale applied in Waidhofen/Ybbs Austria, International Journal of Disaster Risk Reduction (2014), http://dx.doi.org/10.1016/j.ijdrr.2014.11.003

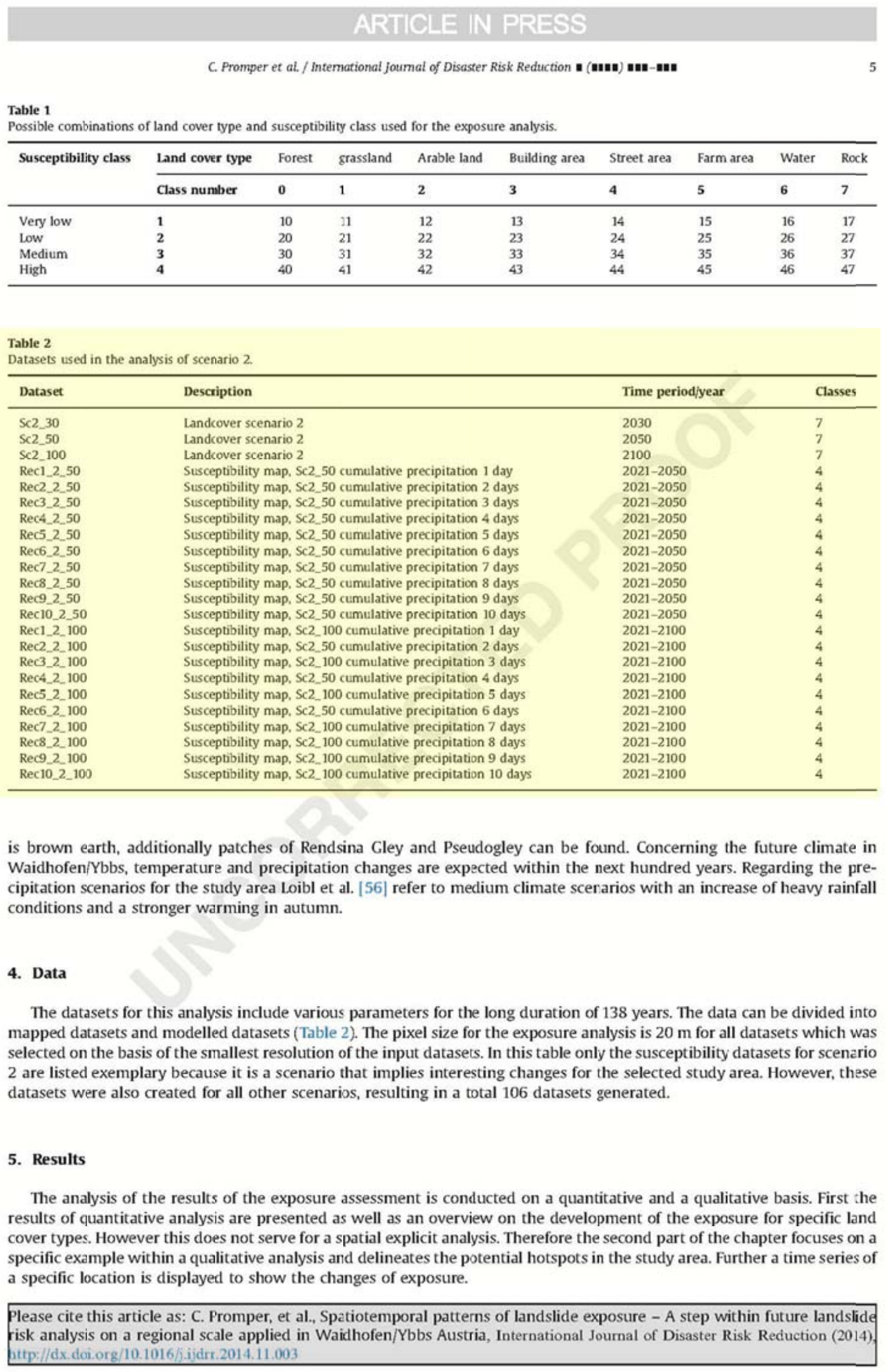


Table 1
Possible combinations of land cover type and susceptibility class used for the exposure analysis.

Susceptibility class	**Land cover type**	Forest	grassland	Arable land	Building area	Street area	Farm area	Water	Rock
	Class number	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Very low	**1**	10	11	12	13	14	15	16	17
Low	**2**	20	21	22	23	24	25	26	27
Medium	**3**	30	31	32	33	34	35	36	37
High	**4**	40	41	42	43	44	45	46	47

Table 2
Datasets used in the analysis of scenario 2.

Dataset	**Description**	**Time period/year**	**Classes**
Sc2_30	Landcover scenario 2	2030	7
Sc2_50	Landcover scenario 2	2050	7
Sc2_100	Landcover scenario 2	2100	7
Rec1_2_50	Susceptibility map, Sc2_50 cumulative precipitation 1 day	2021–2050	4
Rec2_2_50	Susceptibility map, Sc2_50 cumulative precipitation 2 days	2021–2050	4
Rec3_2_50	Susceptibility map, Sc2_50 cumulative precipitation 3 days	2021–2050	4
Rec4_2_50	Susceptibility map, Sc2_50 cumulative precipitation 4 days	2021–2050	4
Rec5_2_50	Susceptibility map, Sc2_50 cumulative precipitation 5 days	2021–2050	4
Rec6_2_50	Susceptibility map, Sc2_50 cumulative precipitation 6 days	2021–2050	4
Rec7_2_50	Susceptibility map, Sc2_50 cumulative precipitation 7 days	2021–2050	4
Rec8_2_50	Susceptibility map, Sc2_50 cumulative precipitation 8 days	2021–2050	4
Rec9_2_50	Susceptibility map, Sc2_50 cumulative precipitation 9 days	2021–2050	4
Rec10_2_50	Susceptibility map, Sc2_50 cumulative precipitation 10 days	2021–2050	4
Rec1_2_100	Susceptibility map, Sc2_100 cumulative precipitation 1 day	2021–2100	4
Rec2_2_100	Susceptibility map, Sc2_50 cumulative precipitation 2 days	2021–2100	4
Rec3_2_100	Susceptibility map, Sc2_100 cumulative precipitation 3 days	2021–2100	4
Rec4_2_100	Susceptibility map, Sc2_50 cumulative precipitation 4 days	2021–2100	4
Rec5_2_100	Susceptibility map, Sc2_100 cumulative precipitation 5 days	2021–2100	4
Rec6_2_100	Susceptibility map, Sc2_50 cumulative precipitation 6 days	2021–2100	4
Rec7_2_100	Susceptibility map, Sc2_100 cumulative precipitation 7 days	2021–2100	4
Rec8_2_100	Susceptibility map, Sc2_100 cumulative precipitation 8 days	2021–2100	4
Rec9_2_100	Susceptibility map, Sc2_100 cumulative precipitation 9 days	2021–2100	4
Rec10_2_100	Susceptibility map, Sc2_100 cumulative precipitation 10 days	2021–2100	4

is brown earth, additionally patches of Rendsina Gley and Pseudogley can be found. Concerning the future climate in Waidhofen/Ybbs, temperature and precipitation changes are expected within the next hundred years. Regarding the precipitation scenarios for the study area Loibl et al. [56] refer to medium climate scenarios with an increase of heavy rainfall conditions and a stronger warming in autumn.

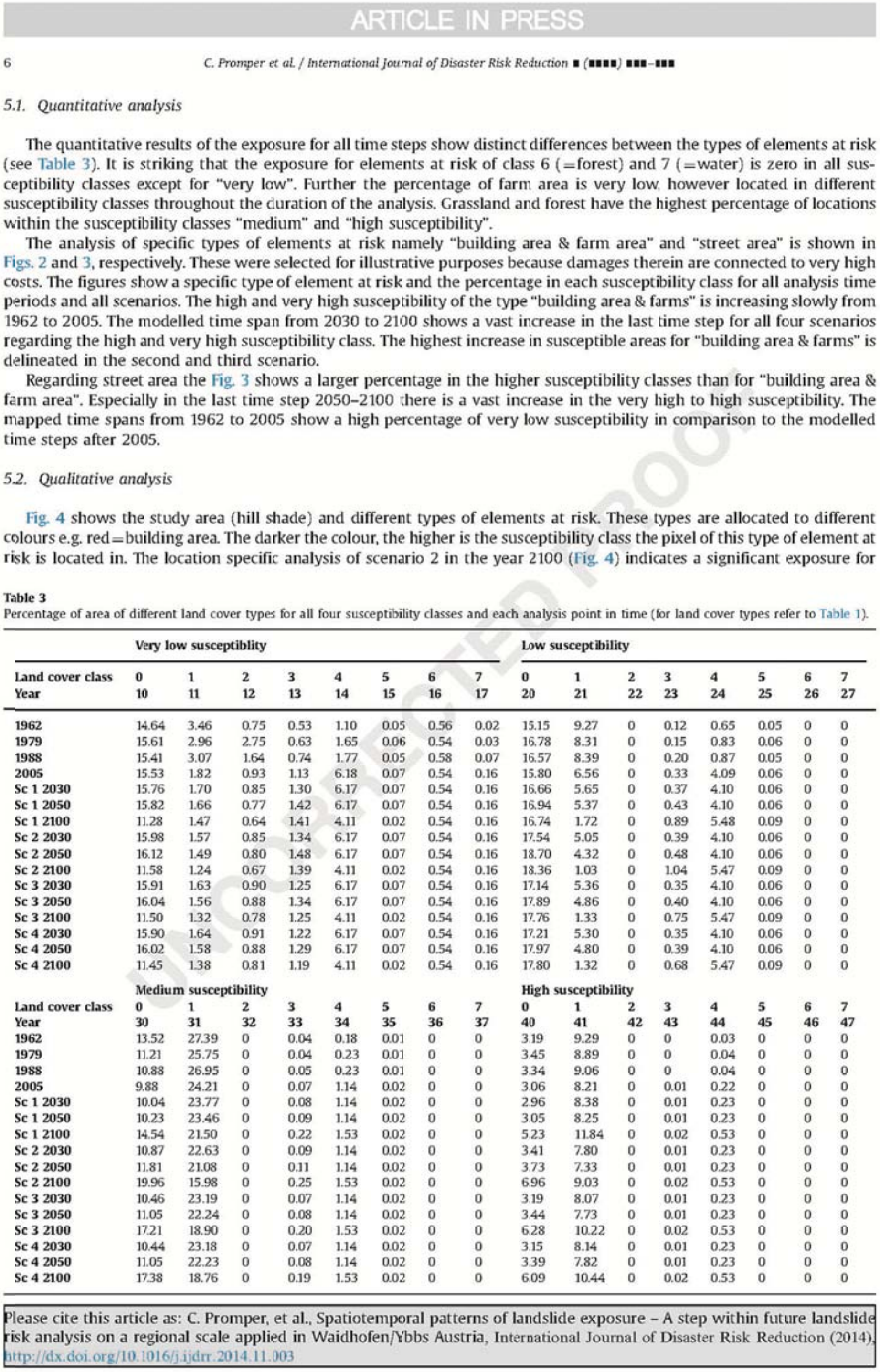
4. Data

The datasets for this analysis include various parameters for the long duration of 138 years. The data can be divided into mapped datasets and modelled datasets (Table 2). The pixel size for the exposure analysis is 20 m for all datasets which was selected on the basis of the smallest resolution of the input datasets. In this table only the susceptibility datasets for scenario 2 are listed exemplary because it is a scenario that implies interesting changes for the selected study area. However, these datasets were also created for all other scenarios, resulting in a total 106 datasets generated.

5. Results

The analysis of the results of the exposure assessment is conducted on a quantitative and a qualitative basis. First the results of quantitative analysis are presented as well as an overview on the development of the exposure for specific land cover types. However this does not serve for a spatial explicit analysis. Therefore the second part of the chapter focuses on a specific example within a qualitative analysis and delineates the potential hotspots in the study area. Further a time series of a specific location is displayed to show the changes of exposure.

Please cite this article as: C. Promper, et al., Spatiotemporal patterns of landslide exposure – A step within future landslide risk analysis on a regional scale applied in Waidhofen/Ybbs Austria, International Journal of Disaster Risk Reduction (2014), http://dx.doi.org/10.1016/j.ijdrr.2014.11.003



5.1. Quantitative analysis

The quantitative results of the exposure for all time steps show distinct differences between the types of elements at risk (see Table 3). It is striking that the exposure for elements at risk of class 6 (=forest) and 7 (=water) is zero in all susceptibility classes except for "very low". Further the percentage of farm area is very low however located in different susceptibility classes throughout the duration of the analysis. Grassland and forest have the highest percentage of locations within the susceptibility classes "medium" and "high susceptibility".

The analysis of specific types of elements at risk namely "building area & farm area" and "street area" is shown in Figs. 2 and 3, respectively. These were selected for illustrative purposes because damages therein are connected to very high costs. The figures show a specific type of element at risk and the percentage in each susceptibility class for all analysis time periods and all scenarios. The high and very high susceptibility of the type "building area & farms" is increasing slowly from 1962 to 2005. The modelled time span from 2030 to 2100 shows a vast increase in the last time step for all four scenarios regarding the high and very high susceptibility class. The highest increase in susceptible areas for "building area & farms" is delineated in the second and third scenario.

Regarding street area the Fig. 3 shows a larger percentage in the higher susceptibility classes than for "building area & farm area". Especially in the last time step 2050–2100 there is a vast increase in the very high to high susceptibility. The mapped time spans from 1962 to 2005 show a high percentage of very low susceptibility in comparison to the modelled time steps after 2005.

5.2. Qualitative analysis

Fig. 4 shows the study area (hill shade) and different types of elements at risk. These types are allocated to different colours e.g. red=building area. The darker the colour, the higher is the susceptibility class the pixel of this type of element at risk is located in. The location specific analysis of scenario 2 in the year 2100 (Fig. 4) indicates a significant exposure for

Table 3
Percentage of area of different land cover types for all four susceptibility classes and each analysis point in time (for land cover types refer to Table 1).

	Very low susceptiblity								**Low susceptibility**							
Land cover class	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Year	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
1962	14.64	3.46	0.75	0.53	1.10	0.05	0.56	0.02	15.15	9.27	0	0.12	0.65	0.05	0	0
1979	15.61	2.96	2.75	0.63	1.65	0.06	0.54	0.03	16.78	8.31	0	0.15	0.83	0.06	0	0
1988	15.41	3.07	1.64	0.74	1.77	0.05	0.58	0.07	16.57	8.39	0	0.20	0.87	0.05	0	0
2005	15.53	1.82	0.93	1.13	6.18	0.07	0.54	0.16	15.80	6.56	0	0.33	4.09	0.06	0	0
Sc 1 2030	15.76	1.70	0.85	1.30	6.17	0.07	0.54	0.16	16.66	5.65	0	0.37	4.10	0.06	0	0
Sc 1 2050	15.82	1.66	0.77	1.42	6.17	0.07	0.54	0.16	16.94	5.37	0	0.43	4.10	0.06	0	0
Sc 1 2100	11.28	1.47	0.64	1.41	4.11	0.02	0.54	0.16	16.74	1.72	0	0.89	5.48	0.09	0	0
Sc 2 2030	15.98	1.57	0.85	1.34	6.17	0.07	0.54	0.16	17.54	5.05	0	0.39	4.10	0.06	0	0
Sc 2 2050	16.12	1.49	0.80	1.48	6.17	0.07	0.54	0.16	18.70	4.32	0	0.48	4.10	0.06	0	0
Sc 2 2100	11.58	1.24	0.67	1.39	4.11	0.02	0.54	0.16	18.36	1.03	0	1.04	5.47	0.09	0	0
Sc 3 2030	15.91	1.63	0.90	1.25	6.17	0.07	0.54	0.16	17.14	5.36	0	0.35	4.10	0.06	0	0
Sc 3 2050	16.04	1.56	0.88	1.34	6.17	0.07	0.54	0.16	17.89	4.86	0	0.40	4.10	0.06	0	0
Sc 3 2100	11.50	1.32	0.78	1.25	4.11	0.02	0.54	0.16	17.76	1.33	0	0.75	5.47	0.09	0	0
Sc 4 2030	15.90	1.64	0.91	1.22	6.17	0.07	0.54	0.16	17.21	5.30	0	0.35	4.10	0.06	0	0
Sc 4 2050	16.02	1.58	0.88	1.29	6.17	0.07	0.54	0.16	17.97	4.80	0	0.39	4.10	0.06	0	0
Sc 4 2100	11.45	1.38	0.81	1.19	4.11	0.02	0.54	0.16	17.80	1.32	0	0.68	5.47	0.09	0	0
	Medium susceptibility								**High susceptibility**							
Land cover class	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Year	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**
1962	13.52	27.39	0	0.04	0.18	0.01	0	0	3.19	9.29	0	0	0.03	0	0	0
1979	11.21	25.75	0	0.04	0.23	0.01	0	0	3.45	8.89	0	0	0.04	0	0	0
1988	10.88	26.95	0	0.05	0.23	0.01	0	0	3.34	9.06	0	0	0.04	0	0	0
2005	9.88	24.21	0	0.07	1.14	0.02	0	0	3.06	8.21	0	0.01	0.22	0	0	0
Sc 1 2030	10.04	23.77	0	0.08	1.14	0.02	0	0	2.96	8.38	0	0.01	0.23	0	0	0
Sc 1 2050	10.23	23.46	0	0.09	1.14	0.02	0	0	3.05	8.25	0	0.01	0.23	0	0	0
Sc 1 2100	14.54	21.50	0	0.22	1.53	0.02	0	0	5.23	11.84	0	0.02	0.53	0	0	0
Sc 2 2030	10.87	22.63	0	0.09	1.14	0.02	0	0	3.41	7.80	0	0.01	0.23	0	0	0
Sc 2 2050	11.81	21.08	0	0.11	1.14	0.02	0	0	3.73	7.33	0	0.01	0.23	0	0	0
Sc 2 2100	19.96	15.98	0	0.25	1.53	0.02	0	0	6.96	9.03	0	0.02	0.53	0	0	0
Sc 3 2030	10.46	23.19	0	0.07	1.14	0.02	0	0	3.19	8.07	0	0.01	0.23	0	0	0
Sc 3 2050	11.05	22.24	0	0.08	1.14	0.02	0	0	3.44	7.73	0	0.01	0.23	0	0	0
Sc 3 2100	17.21	18.90	0	0.20	1.53	0.02	0	0	6.28	10.22	0	0.02	0.53	0	0	0
Sc 4 2030	10.44	23.18	0	0.07	1.14	0.02	0	0	3.15	8.14	0	0.01	0.23	0	0	0
Sc 4 2050	11.05	22.23	0	0.08	1.14	0.02	0	0	3.39	7.82	0	0.01	0.23	0	0	0
Sc 4 2100	17.38	18.76	0	0.19	1.53	0.02	0	0	6.09	10.44	0	0.02	0.53	0	0	0

Please cite this article as: C. Promper, et al., Spatiotemporal patterns of landslide exposure – A step within future landslide risk analysis on a regional scale applied in Waidhofen/Ybbs Austria, International Journal of Disaster Risk Reduction (2014), http://dx.doi.org/10.1016/j.ijdrr.2014.11.003

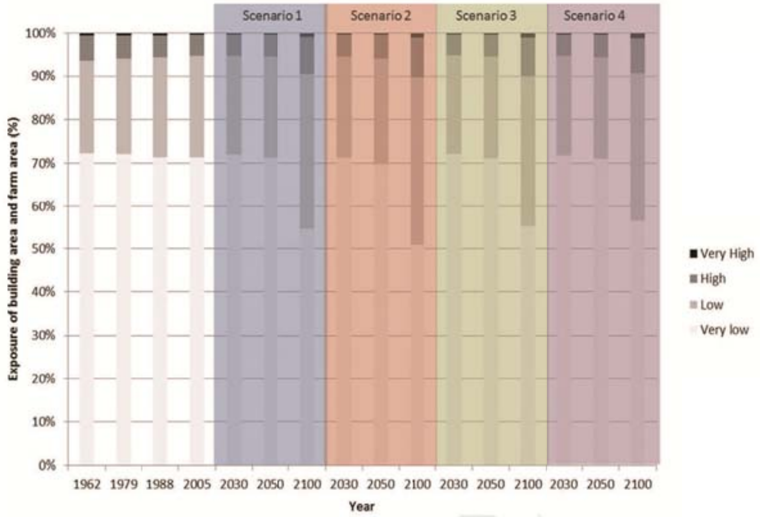


Fig. 2. Percentage of "building area & farms" in different susceptibility classes.

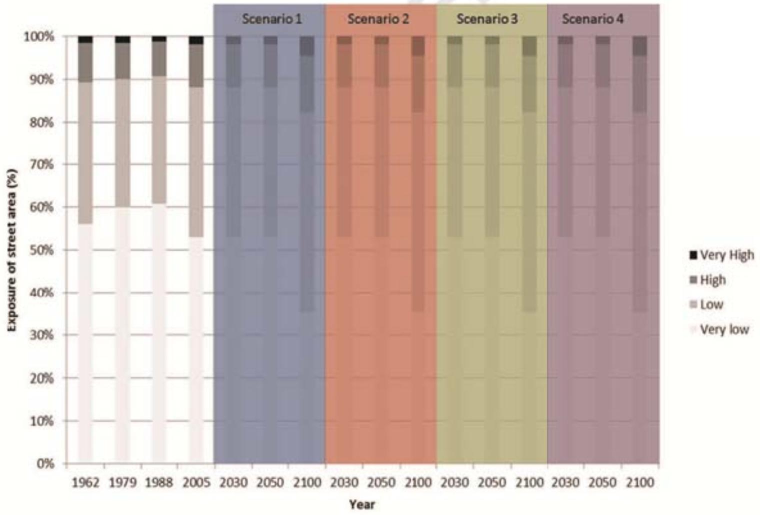


Fig. 3. Percentage of "street area" in different susceptibility classes.

building area and streets in the south western part of the study area, which could be regarded as future hotspot. Another future hotspot is located in the north eastern part of the study area, where building area is also located within high susceptible areas. The third hotspot in the south east of the analysed region (black square in Fig. 4) is presented in detail in Fig. 5.

The development of exposed building area in these specific hotspots can be clearly seen comparing the three selected years (Fig. 5). On the one hand an increase of building area is shown on the other hand this new building area is also located

Please cite this article as: C. Promper, et al., Spatiotemporal patterns of landslide exposure – A step within future landslide risk analysis on a regional scale applied in Waidhofen/Ybbs Austria, International Journal of Disaster Risk Reduction (2014), http://dx.doi.org/10.1016/j.ijdrr.2014.11.003

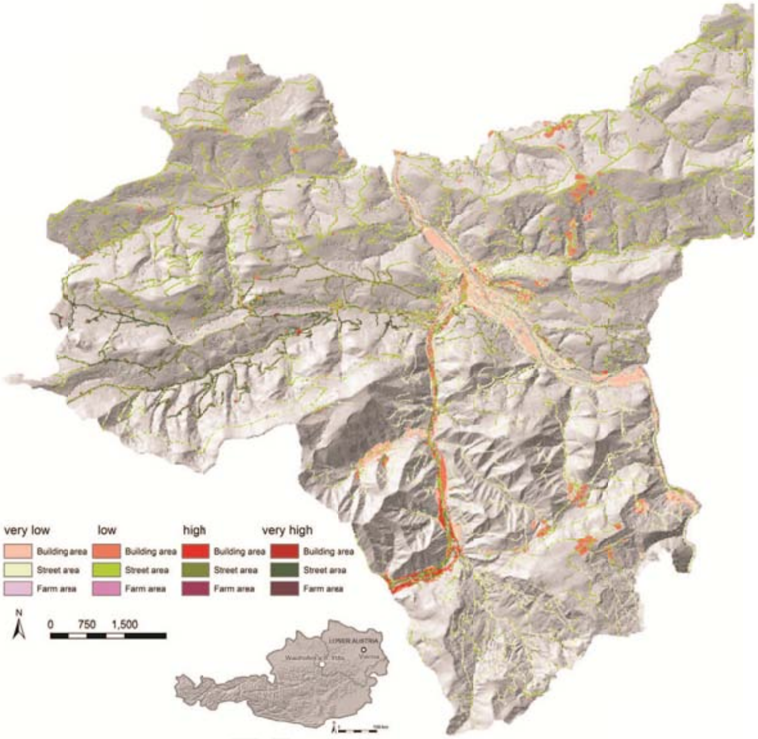


Fig. 4. Overview on regional exposure of "building area", "farm area" and "street area" for the year 2100 in scenario 2. Source DEM: Provincial Government of Lower Austria

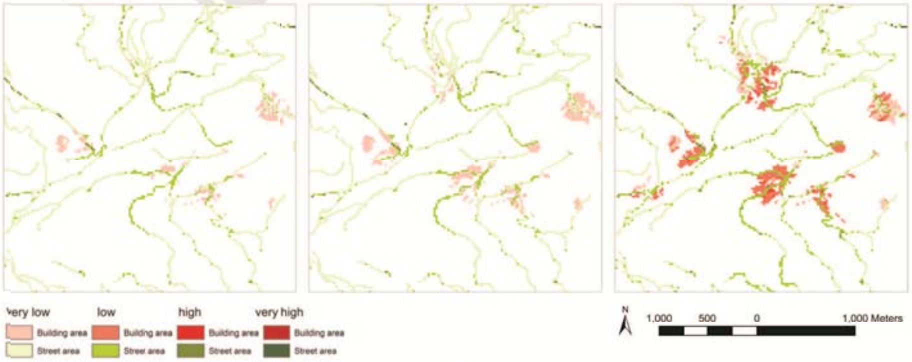


Fig. 5. Exposure development (section indicated in Fig. 4) for scenario 2 of the years 2025, 2050 and 2100.

Please cite this article as: C. Promper, et al., Spatiotemporal patterns of landslide exposure – A step within future landslide risk analysis on a regional scale applied in Waidhofen/Ybbs Austria, International Journal of Disaster Risk Reduction (2014), http://dx.doi.org/10.1016/j.ijdrr.2014.11.003

in potential susceptible zones. Especially for the year 2100 the increasing number of building area pixel in a high or very high susceptibility class is very apparent. At this scale it is also possible to see that the exposure of street area increases, however not related to new street area but increased susceptibility in existing locations of street area.

6. Discussion

The key element of this analysis is the coupling of potential hazardous areas with the location and redistribution of elements at risk on a regional scale. The location based exposure is decisive for delineating potential landslide exposure hotspots, thus serving as basis for in depth analysis herein. Subsequently the combination of the regional assessment and the local analysis can serve as strategic tool in land use planning. This relates to the fact that losses are partially related to the design and location of a community hence building area, etc. (see also Berke and Smith [1]). Overall the results do not indicate a very high increase in landslide exposure for all scenarios in the given region. However there is an indication that spatially, new landslide exposure hotspots can be expected.

The landslide exposure analysis on a regional basis is conducted using the land cover map and consequently allows to analyse the results for all different land cover types, hence elements at risk. In this evaluation the focus is based on building area and street area covering the highest values in terms of damages by landslides in the study area. The method applied for this analysis serves the need of a regional assessment by combining the different raster layers of the different parameters which can be provided on this scale with adequate input of resources. Additionally the calculated code enables to delineate the type of element at risk, as well as the related exposure. By conveying this code to a colour scheme on a map it is possible to delineate exposure hotspots of the different land cover types. However, by applying raster datasets it is not possible to analyse single features on a local scale. Therefore a detailed risk analysis comprising vulnerability and values of objects is only possible by an in-depth analysis of potential landslide exposure hotspots that were identified.

The overall increase of elements at risk in high and very high susceptible areas is marginal (Table 3). However, especially in the last period 2050–2100 the increase in susceptibility is indicated for various types of elements at risk. The quantitative analysis also shows that the high exposed areas, independent of the applied scenario, do not exceed 20% of the study area. This can be related to the long analysis period of 50 years including various changes, but can also be related to an increase in incisive changes in precipitation and land cover.

The classes that cover the largest areas are in the medium and high susceptibility, and thus show a high exposure of forest and grassland summing up to approximately 30% of the total study area. It is also striking that that land cover class three (=arable land) is only located in the very low susceptibility class (Table 3). These phenomena can probably be related to the steepness of the slope leading to unsuitability for e.g. building area.

The exposure increases especially in the medium classes and affects mostly buildings and infrastructure. The next step of the analysis focuses on the quantitative risk assessment incorporating social aspects e.g. population distribution.

The results of the qualitative, location based, analysis shows a clear increase in landslide exposure hotspots. These are mainly related to the new building areas in the north- and south-east of the study area. This increase is indicated in all scenarios, however with different peculiarities. Further it is indicated that not only existing building area is affected by an increase in the location of landslide susceptibility but there is a clear extent of building area into susceptible areas, therefore new areas of landslide exposure might develop. Within this analysis no spatial restrictions for development are applied, which definitely could alter the results of the spatiotemporal pattern of exposure. This alteration would on the one hand exclude certain areas from development of e.g. building area. On the other hand an increase in building area leads to the need to allocate on other locations within the study area which subsequently could lead to a shift of exposure.

This qualitative analysis additionally allows delineating that street area is affected by increased exposure (see Figs. 4 and 5). The changes in the exposure of street area from 2030 to 2100 are only bound to changes in areas of landslide susceptibility because within the modelling the location of the street area did not change due to being a linear element [41]. Plans of planned streets for future development of transport infrastructure were not available for this analysis.

Although the results show some apparent future changes, there are still some limitations that need to be accounted for. Firstly the results are afflicted with multi-dimensional uncertainties ranging from spatial fluctuation, varying time spans regarding the changes, as well as the interlinkage of the respective systems. Secondly scenario-based analysis provides several possibilities on potential developments, thus no distinct projection of the future. Therefore an analysis on a local scale, e.g. on pixel or object basis, is not possible without additional analysis. Further the modelled input data already incorporate uncertainties which must be kept in mind additionally when interpreting and further developing the model results. Consequently this exposure hotspot analysis can only serve as a basis for further investigations and as foundation for profound risk assessment. However, the scenario-based analysis and variations therein need to be accounted for.

7. Conclusion

In conclusion it can be stated that it is possible to calculate the exposure of elements at risk towards landslides which is a very important step within a comprehensive landslide risk assessment. However, the applied method does not offer the possibility to calculate the expected future landslide risk. The scenario-based approach on a regional scale can serve as basis

Please cite this article as: C. Promper, et al., Spatiotemporal patterns of landslide exposure – A step within future landslide risk analysis on a regional scale applied in Waidhofen/Ybbs Austria, International Journal of Disaster Risk Reduction (2014), http://dx.doi.org/10.1016/j.ijdrr.2014.11.003

for the aforementioned hotspot analysis and therefore, in combination with in depth risk analysis, can serve as a basis for sustainable planning approach despite its limitations. Future work should thus also focus on the detailed assessment of spatially distributed information on landslide magnitude and frequency in order to perform a sound landslide hazard calculation which can then be used within a landslide risk analysis. Nevertheless exposure analysis related to other hazards would certainly enrich this attempt towards a sustainable planning approach.

Acknowledgements

This study is carried out within the FP7 ERA-NET project ChangingRISKS (Grant agreement number 263953). The authors thank the European Union for funding this project and the project partners Jean-Philippe Malet, Anne Puissant and Santiago Beguería Portugués for the scientific exchange. The authors also thank the Provincial Government of Lower Austria for their support and the provision of data.

References

[1] P. Berke, G. Smith, Hazard mitigation, planning, and disaster resiliency: challenges and strategic choices for the 21st Century, in: U. Fra Paleo (Ed.), Building Safer Communities: Risk Governance, Spatial Planning and Responses to Natural Hazards, IOS Press, 2009.
[2] G. Hufschmidt, M.J. Crozier, T. Glade, Evolution of natural risk: research framework and perspectives, Nat. Hazards Earth Syst. Sci. 5 (2005) 375–387.
[3] S. Fuchs, M. Keiler, Space and time: coupling dimensions in natural hazard risk management?, in: D. Müller-mahn (Ed.), The Spatial Dimension of Risk – How Geography Shapes the Emergence of Riskscapes, Earthscan, London, 2013.
[4] B. Mazzorana, L. Levaggi, M. Keiler, S. Fuchs, Towards dynamics in flood risk assessment, Nat. Hazards Earth Syst. Sci. 12 (2012) 3571–3587.
[5] S. Fuchs, M. Keiler, S. Sokratov, A. Shnyparkov, Spatiotemporal dynamics: the need for an innovative approach in mountain hazard risk management, Nat. Hazards 68 (2013) 1217–1241.
[6] S.L. Cutter, Societal response to environmental hazard, in: Hazards, Vulnerability and Environmental Justice. 2006, Earthscan, London, 2006.
[7] D.J. Varnes, Landslides Hazard Zonation: A Review of Principles and Practice, UNESCO, Paris, France, 1984.
[8] K. Hollenstein, Reconsidering the risk assessment concept: standardizing the impact description as a building block for vulnerability assessment, Nat. Hazards Earth Syst. Sci. 5 (2005) 301–307.
[9] S. Fuchs, K. Heiss, J. Hübl, Towards an empirical vulnerability function for use in debris flow risk assessment, Nat. Hazards Earth Syst. Sci. 7 (2007) 495–506.
[10] M. Papathoma-Köhle, B. Neuhäuser, K. Ratzinger, H. Wenzel, D. Dominey-Howes, Elements at risk as a framework for assessing the vulnerability of communities to landslides, Nat. Hazards Earth Syst. Sci. 7 (2007) 765–779.
[11] M. Keiler, A. Zischg, S. Fuchs, M. Hama, J. Stötter, Avalanche related damage potential-changes of persons and mobile values since the mid-twentieth century, case study Galtür, Nat. Hazards Earth Syst. Sci. 5 (2005) 49–58.
[12] M.J. Crozier, T. Glade, Landslide hazard and risk: issues, concepts, and approach, in: T. Glade, M.G. Anderson, M.J. Crozier (Eds.), Landslide Hazard and Risk, Wiley, Chichester, 2005.
[13] E.M. Lee, D.K.C. Jones, Landslide Risk Assessment, Thomas Telford, London, 2004.
[14] R. Fell, J. Corominas, C. Bonnard, L. Cascini, E. Leroi, W.Z. Savage, Guidelines for landslide susceptibility, hazard and risk zoning for land use planning, Eng. Geol. 102 (2008) 85–98.
[15] T. Glade, Landslide occurrence as a response to land use change: a review of evidence from New Zealand, Catena 51 (2003) 297–314.
[16] M. Jemec, M. Komac, An overview of approaches for hazard assessment of slope mass movements, Alpine Mass Movements: Implications for hazard assessment and mapping, Special Edition of Journal Torrent, Avalanche, Landslide and Rock Fall Engeneering, 2011, pp. 166.
[17] M. Papathoma-Köhle, T. Glade, The role of vegetation cover change for landslide hazard and risk, in: G. Renaud, K. Sudmeier-Rieux, M. Estrella. (Eds.), The Role of Ecosystems in Disaster Risk Reduction, UNU Press, Tokyo, 2012.
[18] A. Veldkamp, P.H. Verburg, Modelling land use change and environmental impact, J. Environ. Manag. 72 (2004) 1–3.
[19] T. Glade, A. Dix, Humanity as an agent of natural disasters, in: P. Bobrowsky (Ed.), Encyclopedia of Natural Hazards, Springer, Dordrecht, Heidelberg, New York, London, 2013.
[20] A.S. Goudie, The Human Impact on the Natural Environment: Past, Present, and Future, Wiley, 2013.
[21] R. Scalenghe, F.A. Marsan, The anthropogenic sealing of soils in urban areas, Landsc. Urban Plan. 90 (2009) 1–10.
[22] B. Matheussen, R.L. Kirschbaum, I.A. Goodman, G.M. O'donnell, D.P. Lettenmaier, Effects of land cover change on streamflow in the interior Columbia River Basin (USA and Canada), Hydrol. Process. 14 (2000) 867–885.
[23] D. Mileti, Disasters by Design: A Reassessment of Natural Hazards in the United States, The National Academies Press, 1999.
[24] I. Lorenzoni, A. Jordan, M. Hulme, R. Kerry Turner, T. O'riordan, A co-evolutionary approach to climate change impact assessment: Part I. Integrating socio-economic and climate change scenarios, Glob. Environ. Change 10 (2000) 57–68.
[25] H. De moel, J.C.J.H. Aerts, E. Koomen, Development of flood exposure in the Netherlands during the 20th and 21st century, Glob. Environ. Change 21 (2011) 620–627.
[26] SAFELAND. Deliverable 3.9: Methodology for predicting the changes in the landslide riskduring the next 50 years at selected sites in Europe. Changing pattern of landslide risk in hotspot and evolution trends in Europe according to global change scenarios. SafeLand: Living with landslide risk in Europe: Assessment, effects of global change, and risk management strategies, 2012.
[27] C.J. Van Westen, E. Castellanos, S.L. Kuriakose, Spatial data for landslide susceptibility, hazard, and vulnerability assessment: an overview, Eng. Geol. 102 (2008) 112–131.
[28] T. Glade, M.G. Anderson, M.J. Crozier, Landslide Hazard and Risk, Wiley, Chichester.
[29] C. Huggel, J.J. Clague, O. Korup, Is climate change responsible for changing landslide activity in high mountains? Earth Surf. Process. Landf. 37 (2012) 77–91.
[30] J.-P. Malet, Y. Durand, A. Remaître, O. Maquaire, P. Etchevers, G. Guyomarc'h, M. Déqué, L. Van Beek, Assessing the influence of climate change on the activity of landslides in the Ubaye Valley, in: R. Mcinnes, J. Jakeways, H. Fairbank, E. Mathie (Eds.), International Conference on Landslides and Climate Change – Challenges and Solutions, 2007, Taylor & Francis, London, 2007, pp. 195–205.
[31] M. Schmidt, T. Glade, Linking global circulation model outputs to regional geomorphic models: a case study of landslide activity in New Zealand, Clim. Res. 25 (2003) 135–150.
[32] J.L. Zêzere, E. Reis, R. Garcia, S. Oliveira, M.L. Rodrigues, G. Vieira, A.B. Ferreira, Integration of spatial and temporal data for the definition of different landslide hazard scenarios in the area north of Lisbon (Portugal), Nat. Hazards Earth Syst. Sci. 4 (2004) 133–146.
[33] A. Collison, S. Wade, J. Griffiths, M. Dehn, Modelling the impact of predicted climate change on landslide frequency and magnitude in SE England, Eng. Geol. 55 (2000) 205–218.

Please cite this article as: C. Promper, et al., Spatiotemporal patterns of landslide exposure – A step within future landslide risk analysis on a regional scale applied in Waidhofen/Ybbs Austria, International Journal of Disaster Risk Reduction (2014), http://dx.doi.org/10.1016/j.ijdrr.2014.11.003

[34] M. Jakob, S. Lambert, Climate change effects on landslides along the southwest coast of British Columbia, Geomorphology 107 (2009) 275–284.

[35] E. Erle, Land-use and land cove change [Online]. Available: ⟨http://www.eoearth.org/view/article/154143/⟩ , 2013 (accessed 01.05.2014).

[36] F.C. Dai, C.F. Lee, Y.Y. Ngai, Landslide risk assessment and management: an overview, Eng. Geol. 64 (2002) 65–87.

[37] UNISDR, 2009 UNISDR terminology on disaster risk reduction [Online], 2009 (accessed 10.11.2013).

[38] K. Nadimpalli, M. Edwards, D. Mullaly, National Exposure Information System (Nexis) for Australia: risk assessment opportunities. in: L. Oxley, D. Kulasiri, (Eds.), Proceedings of the International Congress on Modelling and Simulation (MODSIM 2007), 2007, pp. 1675–1680.

[39] R. Pellicani, C. Van Westen, G. Spilotro, Assessing landslide exposure in areas with limited landslide information, Landslides (2013) 1–18.

[40] T. Glade, M.S. Kappes, S. Frigerio, J.P. Malet, Multi-hazard exposure analyses with MULTIRISK – a platform for user-friendly analysis,in: Proceedings of the 12th Congress INTERPRAEVENT, Grenoble, France, 2012.

[41] C. Promper, A. Puissant, J.P. Malet, T. Glade, Analysis of land cover changes in the past and the future as contribution to landslide risk scenarios, Appl. Geogr. 53 (2014) 11–19.

[42] C. Promper, T. Glade, Land cover changes for landslide risk evolution – first results from Lower Austria. In: Proceedings of the 11th International Symposium on Landslides and 2nd North American Symposium on Landslides and Engineered Slopes Protecting Society through Improved Understanding. Banff, Canada, 2012 pp. 409–413.

[43] P. Verburg, K. Overmars, Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model, Landsc. Ecol. 24 (2009) 1167–1181.

[44] H. Hiess, M. Gruber, H. Payer, M. Penker, M. Schrenk, H. Wankiewicz, K. Zumbusch, Szenarien der Raumentwicklung Österreichs 2030 Regionale Herausforderungen & Handlungsstrategien, ÖROK Schriftenreihe, Geschäftsstelle d. Österr, Raumordungskonferenz (ÖROK), 2009.

[45] P.M. Atkinson, R. Massari, Generalized Linear Modelling of suceptibility to landsliding in the Central Apennines, Italy, Comput. Geosci. 24 (1998) 373–385.

[46] R. Bell, Lokale und regionale Gefahren- und Risikoanalyse gravitativer Massenbewegungen an der Schwäbischen Alb (Dissertation), Universität Bonn, 2007.

[47] M. Van Den Eeckhaut, T. Vanwalleghem, J. Poesen, G. Govers, G. Verstraeten, L. Vandekerckhove, Prediction of landslide susceptibility using rare events logistic regression: a case-study in the Flemish Ardennes (Belgium), Geomorphology 76 (2006) 392–410.

[48] C. Gassner, C. Promper, S. Beguería, T. Glade. Climate change impact for spatial landslide susceptibility, in: Proceedings of the XII International Conference on Engineering Geology in New Millennium (IAEG XII Congress), Torino, Springer, 2014.

[49] H. Petschko, T. Glade, R. Bell, J. Schweigl, G. Pomaroli, Landslide inventories for regional early warning systems, in: J.-P. Malet, T. Glade, N. Casagli (Eds.), Mountain Risks: Bringing Science to Society, Proceedings of the Mountain Risks International Conference, CERG, Firenze, Italy, 2010, pp. 277–282.

[50] H. Schwenk, Massenbewegungen in Niederösterreich 1953–1990, Jahrb. Geol. Bundesanst. 135 (1992) 597–660.

[51] A. Remaitre, S. Wallner, C. Promper, T. Glade, J.P. Malet, Rainfall characteristics associated to the triggering of fast- and slow-moving landslides – a comparison between the South French Alps and Lower Austria, Geophys. Res. Abstr. (2013) 15.

[52] S. Wallner, Niederschlagsschwellenwerte für die Auslösung von gravitativen Massenbewegungen – Eine Analyse in der rhenodanubischen Flyschzone Niederösterreichs, University of Vienna, Diplomarbeit, 2012.

[53] U. Fra Paleo, On exposure to natural hazards: revisiting a neglected primal action, in: U. Fra Paleo (Ed.), Building Safer Communities: Risk Governance, Spatial Planning and Responses to Natural Hazards, IOS Press, 2009.

[54] H. Cammerer, A. Thieken, P. Verburg, Spatio-temporal dynamics in the flood exposure due to land use changes in the Alpine Lech Valley in Tyrol (Austria), Nat. Hazards 68 (2013) 1243–1270.

[55] K. Wagner, Die Regionalwirtschaftliche Situation im Einzugsgebiet der Ybbs-Teilergebnisse aus dem Interreg IIIB Projekt ILUP (Integrated Land Use Planning and River Basin Management). Ländlicher Raum: Online-Fachzeitschrift des Bundesministeriums für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, 2005, pp. 1–7.

[56] W. Loibl, A. Beck, H. Dorninger, H. Formayer, A. Gobiet, W. Schöner, Kwiss-Programm Reclip: More Research for Climate Protection: Model Run Evaluation. Final Report, 2007.

Please cite this article as: C. Promper, et al., Spatiotemporal patterns of landslide exposure – A step within future landslide risk analysis on a regional scale applied in Waidhofen/Ybbs Austria, International Journal of Disaster Risk Reduction (2014), http://dx.doi.org/10.1016/j.ijdrr.2014.11.003

Corrected version of chapter 2.2. and table 2

2.2 Susceptibility modelling

The calculated landslide susceptibility maps also include previously modelled precipitation scenarios. The susceptibility modelling is based on a statistical logistic regression analysis [45–47]. Initially the current susceptibility is modelled as described by Gassner et al. [48]. The main input parameters are mapped landslides from past orthophotos, derivatives of DEM and modelled precipitation data. In this area several studies on landslides state that the main triggering factor are short but high intense rainfall events [49–51]. Wallner [52] described the correlation of heavy rainfall events and the occurrence of landslides as being significant during summer. Therefore the main focus here is on the daily maximum precipitation. This includes the main weather conditions triggering landslides in this area [51]. Afterwards the computed regression parameters were transferred to the parameters of future and past time periods of the precipitation as well as the modelled and historic land cover. For each land cover scenario the precipitation outputs are modelled for present, the period 2021–2050 and the period 2071–2100. The susceptibility values are classified in four classes with equal intervals. As an example the datasets of scenario 2 are listed in Table 2.

Table 2 Datasets used in the analysis of scenario 2.

Dataset	Description	Year	Classes
Sc2_30	Landcover scenario 2	2030	7
Sc2_50	Landcover scenario 2	2050	7
Sc2_100	Landcover scenario 2	2100	7
Rec1_2_30	Susceptibility map (Sc2_30; max precipitation period 2005-2030)	2030	4
Rec2_2_50	Susceptibility map (Sc2_50; max precipitation period 2021-2050)	2050	4
Rec3_2_100	Susceptibility map (Sc2_100; max precipitation period 2071-2100)	2100	4

B. TABLES

Table B. 1 Exposure for all land cover classes for the duration of the analysis (Very low and Low susceptibility)

	Very low susceptibility								Low susceptibility							
Land cover class	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Year	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
1962	14.64	3.46	0.75	0.53	1.10	0.05	0.56	0.02	15.15	9.27	0.00	0.12	0.65	0.05	0	0
1979	15.61	2.96	2.75	0.63	1.65	0.06	0.54	0.03	16.78	8.31	0.00	0.15	0.83	0.06	0	0
1988	15.41	3.07	1.64	0.74	1.77	0.05	0.58	0.07	16.57	8.39	0.00	0.20	0.87	0.05	0	0
2005	15.53	1.82	0.93	1.13	6.18	0.07	0.54	0.16	15.80	6.56	0.00	0.33	4.09	0.06	0	0
Sc 1 2030	15.76	1.70	0.85	1.30	6.17	0.07	0.54	0.16	16.66	5.65	0.00	0.37	4.10	0.06	0	0
Sc 1 2050	15.82	1.66	0.77	1.42	6.17	0.07	0.54	0.16	16.94	5.37	0.00	0.43	4.10	0.06	0	0
Sc 1 2100	11.28	1.47	0.64	1.41	4.11	0.02	0.54	0.16	16.74	1.72	0.00	0.89	5.48	0.09	0	0
Sc 2 2030	15.98	1.57	0.85	1.34	6.17	0.07	0.54	0.16	17.54	5.05	0.00	0.39	4.10	0.06	0	0
Sc 2 2050	16.12	1.49	0.80	1.48	6.17	0.07	0.54	0.16	18.70	4.32	0.00	0.48	4.10	0.06	0	0
Sc 2 2100	11.58	1.24	0.67	1.39	4.11	0.02	0.54	0.16	18.36	1.03	0.00	1.04	5.47	0.09	0	0
Sc 3 2030	15.91	1.63	0.90	1.25	6.17	0.07	0.54	0.16	17.14	5.36	0.00	0.35	4.10	0.06	0	0
Sc 3 2050	16.04	1.56	0.88	1.34	6.17	0.07	0.54	0.16	17.89	4.86	0.00	0.40	4.10	0.06	0	0
Sc 3 2100	11.50	1.32	0.78	1.25	4.11	0.02	0.54	0.16	17.76	1.33	0.00	0.75	5.47	0.09	0	0
Sc 4 2030	15.90	1.64	0.91	1.22	6.17	0.07	0.54	0.16	17.21	5.30	0.00	0.35	4.10	0.06	0	0
Sc 4 2050	16.02	1.58	0.88	1.29	6.17	0.07	0.54	0.16	17.97	4.80	0.00	0.39	4.10	0.06	0	0
Sc 4 2100	11.45	1.38	0.81	1.19	4.11	0.02	0.54	0.16	17.80	1.32	0.00	0.68	5.47	0.09	0	0

Table B. 2 Exposure for all land cover classes for the duration of the analysis (Medium and High susceptibility)

	Medium Susceptibility								High susceptibility							
Land cover class	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Year	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**
1962	13.52	27.39	0.00	0.04	0.18	0.01	0	0	3.19	9.29	0.00	0.00	0.03	0.00	0	0
1979	11.21	25.75	0.00	0.04	0.23	0.01	0	0	3.45	8.89	0.00	0.00	0.04	0.00	0	0
1988	10.88	26.95	0.00	0.05	0.23	0.01	0	0	3.34	9.06	0.00	0.00	0.04	0.00	0	0
2005	9.88	24.21	0.00	0.07	1.14	0.02	0	0	3.06	8.21	0.00	0.01	0.22	0.00	0	0
Sc 1 2030	10.04	23.77	0.00	0.08	1.14	0.02	0	0	2.96	8.38	0.00	0.01	0.23	0.00	0	0
Sc 1 2050	10.23	23.46	0.00	0.09	1.14	0.02	0	0	3.05	8.25	0.00	0.01	0.23	0.00	0	0
Sc 1 2100	14.54	21.50	0.00	0.22	1.53	0.02	0	0	5.23	11.84	0.00	0.02	0.53	0.00	0	0
Sc 2 2030	10.87	22.63	0.00	0.09	1.14	0.02	0	0	3.41	7.80	0.00	0.01	0.23	0.00	0	0
Sc 2 2050	11.81	21.08	0.00	0.11	1.14	0.02	0	0	3.73	7.33	0.00	0.01	0.23	0.00	0	0
Sc 2 2100	19.96	15.98	0.00	0.25	1.53	0.02	0	0	6.96	9.03	0.00	0.02	0.53	0.00	0	0
Sc 3 2030	10.46	23.19	0.00	0.07	1.14	0.02	0	0	3.19	8.07	0.00	0.01	0.23	0.00	0	0
Sc 3 2050	11.05	22.24	0.00	0.08	1.14	0.02	0	0	3.44	7.73	0.00	0.01	0.23	0.00	0	0
Sc 3 2100	17.21	18.90	0.00	0.20	1.53	0.02	0	0	6.28	10.22	0.00	0.02	0.53	0.00	0	0
Sc 4 2030	10.44	23.18	0.00	0.07	1.14	0.02	0	0	3.15	8.14	0.00	0.01	0.23	0.00	0	0
Sc 4 2050	11.05	22.23	0.00	0.08	1.14	0.02	0	0	3.39	7.82	0.00	0.01	0.23	0.00	0	0
Sc 4 2100	17.38	18.76	0.00	0.19	1.53	0.02	0	0	6.09	10.44	0.00	0.02	0.53	0.00	0	0

C. DEFINITIONS

In this section frequently used terms are defined to the accordant use in the subsequent chapters.

Natural hazard: *means the probability of occurrence within a specific period of time and within a given area of a potentially damaging phenomenon* VARNES 1984.

Landslide hazard*: aims to determine the spatial and temporal probability of occurrence of landslides in the target area, along with their mode of propagation, size and intensity* COROMINAS et al. 2013.

Vulnerability: *is defined by characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard* (UNISDR, 2009).

Exposure: *is defined by people, property, systems, or other elements present in hazardous zones that are thereby subject to potential losses* (UNISDR, 2009).

Landslide exposure: is defined by the link of elements at risk and landslide susceptibility (similar to Pellicani et al. 2013.

Risk: *is the combination of the consequences of an event (hazard) and the associated likelihood/probability of its occurrence* (IEC/ISO 2009).

Consequences: *are the negative effects of a disaster expressed in terms of human impacts, economic and environmental impacts, and political/social impacts* (IEC/ISO 2009)

Landslide susceptibility: describes the likelihood or spatial probability of a landslide event occurring in an area on the basis of the local terrain conditions. (GUZZETTI et al. 2005, BRABB 1984)

Land cover: *refers to the physical and biological cover over the surface of land, including water, vegetation, bare soil, and/or artificial structures (*ELLIS 2013).

Land use: *is characterized by the arrangements, activities and inputs people undertake in a certain land cover type to produce, change or maintain it. Definition of land use in this way establishes a direct link between land cover and the actions of people in their environment. (*DIGREGORIO and JANSEN 2000)

D. ABBREVIATIONS

APCC	Austrian Panel on Climate Change
BEV	Bundesamt für Eich- und Vermessungswesen
BGR	Building ground register
CORINE	Coordination of Information on the Environment
DEM	Digital Elevation Model
GCM	General Circulation Model
IPCC	Intergovernmental Panel on Climate Change
MP	Multi-party
SP	Single-party
UN-ISDR	United Nations Office for Disaster Risk Reduction

E. GERMAN AND ENGLISH SUMMARY

Spatial and temporal development of landslide risk - a contribution to risk management in the context of global change

Zusammenfassung

Die räumliche Verteilung von zukünftigem Risiko gegenüber gravitativen Massenbewegungen ist ein wesentlicher Faktor im integralen Risikomanagement. Durch aufzeigen potentiell gefährdeter Gebiete, können jene Regionen, in welchen besondere Vorsicht bei zukünftiger oder geplanter örtlicher Entwicklung geboten ist, ausgewiesen werden. Raumplanung ist also ein wesentliches Element um ungünstige Formen der Entwicklung in potenziell gefährdeten Gebieten zu vermeiden und somit auch ein wichtiger Teil des Risikomanagements. Szenarien zukünftiger Entwicklung des Risikos gegenüber gravitativen Massenbewgungen auf regionaler Ebene dienen daher der Identifikation von potenziellen Hotspots und von Bereichen die eine Änderung des Risikos in einem gewissen Zeitraum erfahren könnten. Die resultierenden Risikokarten können als eine Entscheidungshilfe für die Raumordnung dienen und aufzeigen wo eine detaillierte Risikoanalyse von höchstem Interesse für zukünftige Planung wäre. Sie erlauben somit eine Anpassung oder Planung von zukünftigen Risikomanagementstrategien.

Die räumliche Verteilung von Risiko durch Rutschungen wird von verschiedenen dynamischen Faktoren des globalen Wandels beeinflusst. Beispielsweise sind hier Änderungen in der räumlichen Verteilung von Risikoelementen oder Veränderungen von Niederschlagsmustern zu nennen. Das Ziel dieser Dissertation ist, Überschneidungsbereiche dieser Änderungen und deren Auswirkungen auf das Risiko gegenüber gravitativen Massenbewegungen zu analysieren und aufzuzeigen.

Um die Abschätzung dieser möglichen Änderungen durchzuführen wurden im Rahmen dieser Studie zahlreiche Analysen der aktuellen und vergangenen Verteilung von Risikoelementen bzw. im Speziellen der Landnutzung durchgeführt. Dazu wurde die

Lage der aktuellen Risikoelemente auf Basis von Orthofotos kartiert und in eine Datenbank der Risikoelemente überführt. Des Weiteren wurde Information zur Landnutzung und deren Änderungen in der Vergangenheit durch Kartierung mittels Orthofotos der letzten 52 Jahre abgeleitet. Das Wissen aus der Landnutzungsentwicklung der Vergangenheit wurde in eine Modellierung von zukünftigen Landnutzungsszenarien implementiert. Diese Informationen zur aktuellen, vergangenen und zukünftigen Landbedeckungsentwicklung und zur Entwicklung der Niederschlagsverteilung und Summe dienten als Input zur Erstellung einer Gefahrenhinweiskarte für Rutschungen. Aus der Kombination der Gefahrenhinweiskarten mit der Landbedeckung wurden abschließend Szenarios der Exposition gegenüber gravitativer Massenbewegungen erstellt.

Das Untersuchungsgebiet umfasst 130 km² und liegt im Alpenvorland des österreichischen Bundeslandes Niederösterreich. Waidhofen/Ybbs hat ca. 11.500 Einwohner was einer Einwohnerdichte von etwa 90 Personen pro km² entspricht. Die Stadt Waidhofen/Ybbs ist ein regionales Zentrum welches den Einwohnder der Region grundlegende Infrastruktur und Basisdienste bietet. Die dominierenden Landnutzungsklassen sind Grünland und Wald und die wesentlichen lithologischen Einheiten umfassen Flysch und Kalkstein.

Die Analyse der Entwicklung der Landbedeckung in der Vergangenheit zeigte eine Zunahme von Siedlungsgebiet und Abnahme von Ackerflächen. Dieser Trend kann auch in der zukünftigen Entwicklung der Landbedeckung angenommen werden. Die Kombination der Szenarien der vergangenen und zukünftigen Entwicklung der Landbedeckung mit der Gefahrenhinweiskarte für Rutschungen zu einer Karte der Exposition gegenüber Rutschungen zeigt einen zu erwartenden Anstieg von exponierten Bereichen bis zum Jahre 2100 auf.

Die Ergebnisse der Analyse untermauern die Hypothese, dass sich die räumliche Verteilung der rutschungsexponierten Bereiche ändern wird. Des Weiteren deuten die Ergebnisse auf eine Änderung der Exposition von bestehenden aber auch neuen Siedlungsgebieten hin. Mit dieser Studie konnte ein Rahmenwerk für zukünftige Analysen des Wandels der Exposition gegenüber Rutschungsgefährdung geschaffen und erfolgreich getestet werden. Dieses Rahmenwerk soll für zukünftige ähnliche Analysen als Anhaltspunkt dienen.

Summary

Spatial distribution of future landslide risk is an important factor in integrated risk management. Showing where additionally to existing risk areas new areas might be exposed to landslide hazard is a key objective when analysing future landslide risk. Therein prospective spatial planning serves as an effective mitigation measure to avoid undesirable development in hazardous areas. The approximation of future landslide risk scenarios on a regional scale supports the identification of potential hotspots and areas of spatial shifts of landslide risk. This first indication of possibly exposed areas can foster in depth analysis of landslide risk for the implementation into risk management strategies.

The spatial distribution of future landslide risk is influenced by several dynamic factors related to global change. Examples analysed in this study are variances in the distribution of elements at risk or changes in precipitation patterns. These altered precipitation patterns might be leading to a spatial change of the occurrence of related natural processes. The aim of this thesis is to approximate future landslide risk scenarios by including effects of coincident changes of dynamic factors. The study comprises a regional exposure assessment of different types of elements at risk for the current situation, as well as a spatiotemporal assessment of exposure development. Analysing the past and future land cover included creating a database of elements at risk, mapping land cover and its changes from the last 52 years and modelling future land cover scenarios. The future land cover scenarios portray potential development of elements at risk. Additionally to the distribution of elements at risk the land cover maps serve as input into the landslide susceptibility assessment. Scenarios of exposure to landslides were built using a landslide susceptibility map which incorporated the resulting past and future land cover maps and precipitation changes.

The study area of this analysis, the district of Waidhofen/Ybbs, is located in the Alpine foreland of the Austrian federal state of Lower Austria, and has a size of 130 km^2. Around 11,500 people are living in the study area resulting in a population density of about 90 inhabitants per km^2. The city of Waidhofen/Ybbs is a regional centre taking over functions for the provision of infrastructure and services. The dominating land cover classes are grassland and forest, and the main lithological units are Flysch and Limestone.

The analysis of past land cover changes indicates an increase in building area and a slight decrease in acreage. This trend can be assumed to be followed in the future land cover development. Combining the past and future scenarios of land cover with the available susceptibility map, the resulting landslide exposure map shows several new potentially exposed areas until 2100.

The results confirmed the hypothesis of spatial shifts in landslide exposure which may be kept in mind as a word of caution for prospective spatial planning and development in this area. This study gives a framework for analysing scenarios of landslide risk development which may aid similar analyses in other areas.

F. EIDESSTATTLICHE ERKLÄRUNG

Hiermit erkläre ich, Catrin Promper, geboren am 08.08.1986 in Wels die vorliegende Dissertation selbstständig angefertigt zu haben. Aus fremden Quellen direkt oder indirekt übernommene Informationen und Gedanken sind als solche kenntlich gemacht.

Die Arbeit wurde bisher weder in gleicher noch in ähnlicher Form einer anderen Prüfungsbehörde vorgelegt oder veröffentlicht.

Wien, Dezember 2014 ....

G. CURRICULUM VITAE

Personal Data

Name	**Promper Catrin**
Address	Albrechtsbergergasse 19/10, 1120 Wien
E-Mail	catrin.promper(at)univie.ac.at

Professional experience

	Since October 2013
Function	Associate (October 2013 – October 2014 Administrative Trainee)
Main activities and responsibilities	International affairs Vulnerability analysis Editing of publications (e.g. conference proceedings or collected volumes) Organsational tasks /administration
Name and address of employer	Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management Unit III/5 Torrent and Avalanche Control, Marxergasse 2, 1030 Vienna
	May 2011 – October 2013
Function	Research Associate
Projects	**ChangingRISKS**: Changing pattern of landslide risk as response to global changes in mountain areas (EU-FP7) **SEERisk:** Joint Disaster Management Risk Assessment and Preparedness in the Danube macro-region (South East Europe Transnational collaboration program)
Main activities and responsibilities	Research Administrative and organisational tasks in the projects Participation in conferences and workshops Publishing research results Support in supervising bachelor- and master theses
Name and address of employer	University of Vienna Department of Geography and Regional Research, Universitätsstraße 7, 1010 Wien
	2012 - 2014

Function	External Lecturer
Main activities and responsibilities	UE Exercises in Geomorphology PR Field Class in Physical Geography in Obergurgl PRS Project Seminar Physical Geography Supervision of bachelor theses
Name and address of employer	University of Vienna Department of Geography and Regional Research, Universitätsstraße 7, 1010 Wien

	November 2008 – April 2011
Function	Teaching assistant, Physical Geography
Main activities and responsibilities	Assistance in course preparation and administration Research Maintenance of the literature data base Organization of workshops and small meetings Layout and graphics of course documents
Name and address of employer	University of Vienna Department of Geography and Regional Research, Universitätsstraße 7, 1010 Wien

Education and training

	October 2011 – January 2015 (expected)
Educational institution	University of Vienna Department of Geography and Regional Research, Universitätsstraße 7, 1010 Wien Advisor: Univ-Prof. Dr. Thomas Glade
Main subject	PhD Student, Natural Sciences
Topic	Quantitative risk assessment; temporal and spatial patterns of landslide risk, land cover development

	October 2005 - March 2011
Educational institution	University of Vienna Department of Geography and Regional Research, Universitätsstraße 7, 1010 Wien Advisor: Univ-Prof. Dr. Thomas Glade
Main subject	Geography
Qualification acquired	First Diploma Certificate 2008 (February); Final exam March 2011 Thesis (translated title): Anthropogenic influenced landscape – a multi-temporal analysis of high alpine catchments Main subjects: Physical Geography (Geomorphology, Natural Hazards & Risk research), Geoinformation & Visualization
	November 2012

Educational institution	University of Strasbourg, France Advisors: Dr. Jean-Philippe Malet, Dr. Anne Puissant
Main subject	Visiting PhD student
Topic	Land cover modelling

1997 - 2005

Educational institution	Linz International School Auhof, Aubrunnerweg 4, 4040 Linz Bilingual secondary school with focal point languages: English, French, Italian
Qualification acquired	School Certificate International Baccalaureate (IB)

Grants

- Marietta Blau scholarship for a research stay abroad (12 month) (not taken)
- Grant for conducting research work (thesis) University of Vienna
- Excellence Grant University of Vienna 2012
- Excellence Grant University of Vienna 2011
- Excellence Grant University of Vienna 2010

Personal Skills

Languages

- German (mother tongue)
- English (excellent)
- French (good knowledge)
- Italian (good knowledge)

Job-related memberships and other activities

- European Geoscience Union
- Austrian Association on Geomorphology and Environmental Change (geomorph.at)
- ÖGG Austrian Geographical Society
- nowaGEA Network of Women in Academia at the Faculty of Earth Sciences, Geography and Astronomy
- Department council: elected representative for project funded employees at the Department of Geography and Regional Research, University Vienna 2012 - 2013
- EGEA European Geography Association for students and young geographers (member of Scientific Committee 2011/2012, member of the Editorial Board: European Geographer 2012/2013)

Publications & Presentations

Journal papers (peer reviewed)

PROMPER C., GASSNER C. AND GLADE T., 2015. Spatiotemporal patterns of landslide exposure – a step within future landslide risk analysis on a regional scale applied in Waidhofen/Ybbs Austria. *International Journal of Disaster Risk Reduction.*

PROMPER C., PUISSANT A., MALET J. P. AND GLADE T. 2014. Analysis of land cover changes in the past and the future as contribution to landslide risk scenarios. *Applied Geography*, 53, 11-19.

Book chapters

PROMPER C. AND GLADE T., 2015. Multilayer-exposure maps as a basis for a regional vulnerability assessment for landslides - applied in Waidhofen/Ybbs, Austria. In: Fuchs, S. and Glade, T. (eds.) *Vulnerability Assessment in Natural Hazard Risk: A Dynamic Perspective.* The Geological Society of London.

PAPATHOMA-KÖHLE M., **PROMPER C.,** AND GLADE T., 2014. General description of the common risk assessment methodology. In: *SEERISK 2014. Guideline on climate change adaptation and risk assessment in theDanube macro-region*

Conference proceedings (peer-reviewed)

GASSNER C., **PROMPER C.**, BEGUERÍA S. AND GLADE T., 2014. Climate change impact for spatial landslide susceptibility. In: IAEG XII Congress Engeneering Geology for Soiety and Territory . Springer. Torino.

PROMPER C., AND GLADE T. 2012. Landcover changes for landslide risk evolution – first results from Lower Austria. In: EBERHARDT, E., FROESE, C., TURNER, A. K. AND LEROUEIL, S. (eds.) *Proceedings of the 11th International Symposium on Landslides and 2nd North American Symposium on Landslides and Engineered Slopes, Protecting Society through Improved Understanding.* Banff, Canada. Taylor & Francis, 409-413.

LEMENKOVA P., **PROMPER C.** AND GLADE T. 2012. Economic assessment of landslide risk for the Waidhofen a. d. Ybbs region, Alpine Foreland, Lower Austria. In: EBERHARDT, E., FROESE, C., TURNER, A. K. AND LEROUEIL, S. (eds.) *Proceedings of the 11th International Symposium on Landslides and 2nd North American Symposium on Landslides and Engineered Slopes, Protecting Society through Improved Understanding.* Banff, Canada. Taylor & Francis, 279-285.

Oral presentations

PROMPER C., PUISSANT A., MALET J.-P. AND GLADE T. 2012. Landslides as irreversible processes in the geomorphic system - future developments regarding land cover. Oral Presentation: International Geographical Congress, 26.08. – 30.08. 2012. Köln, Germany.

PROMPER C. AND GLADE T. 2012. Land cover changes for landslide risk evolution – first results from Lower Austria. 11th International Symposium on Landslides and 2nd North American Symposium on Landslides and Engineered Slopes, Protecting Society through Improved Understanding. Banff, Canada

PROMPER C. 2011. Multi-temporal analysis of surface processes of an anthropogenic influenced high alpine catchment (Idalpe, Ischgl). Scientific Symposium of the EGEA Annual Congress 2011. Ebermannstadt, Germany

Other publications

Promper C., Poeppl R.E. (2014): Friedrich Simony – visionärer Geomorphologe und Alpenforscher. G*EOGRAPHIEaktuell* 19 I/2014: p. 3

PROMPER C. 2012. Multi-temporal analysis of surface processes of an anthropogenic influenced high alpine catchment (Idalpe, Ischgl). European Geographer: Special Edition on Scientific Symposium & oral presentation at Scientific Symposium of the EGEA Annual Congress 2011. Ebermannstadt, Germany

Poster presentations

PAPATHOMA-KOEHLE M., **PROMPER C.** AND GLADE T. 2014. SEERISK concept: Dealing with climate change related hazards in southeast Europe: A common methodology for risk assessment and mapping focusing on floods, drought, winds, heat wave and wildfire. *Geophysical Research AbstractsVol. 16, EGU2014-3432*

PAPATHOMA-KOEHLE M., **PROMPER C.**, BOJARIU R., CICA R., SIK A., PERGE K., LÁSZLÓ P., BALÁZS CZIKORA E., AND GLADE T. 2014. SEERISK: A risk assessment methodology for climate change related hazards-mapping heat wave risk in Romania. *Geophysical Research Abstracts Vol. 16, EGU2014-3459*

GOKESCH K., **PROMPER C.**, PAPATHOMA-KOEHLE M., AND GLADE T. 2014. Assessing human vulnerability: Daytime residential distribution as a vulnerability indicator. *Geophysical Research Abstracts Vol. 16, EGU2014-10815*

GOKESCH K., **PROMPER C.**, VAN WESTEN C.J. AND GLADE T. 2014. Spatiotemporal patterns of population distribution as crucial element for risk management. *Geophysical Research AbstractsVol. 16, EGU2014-11015-1*

PROMPER C., GASSNER C. AND GLADE T. 2013. Spatial and temporal patterns of landslide risk – a case study in Lower Austria, Austria. *In:* 8th IAG International Conference on Geomorphology – Paris (France) August 27th to 31st, 2013.

PROMPER C. AND GLADE T. 2013. Multilayer exposure maps as a basis for a regional vulnerability assessment - applied in Waidhofen/Ybbs, Austria. *Geophysical Research AbstractsVol. 15, EGU2013-3027-1*

GASSNER C., **PROMPER C.**, PETSCHKO H. AND GLADE T. 2013. Scenarios of future landslide susceptibility - incorporating changes in land cover and climate. Geophysical Research Abstracts Vol. 15, EGU2013-6786.

MALET J.-P., BÉGUERIA-PORTUGUÈS S., GLADE T., REMAÎTRE A., PUISSANT A., **PROMPER C.** AND MORAJVEK A. 2012. ChangingRISKS: Research challenges for the assessment and communication on possible effects of global changes on landslide risks. *Geophysical Research AbstractsVol. 14, EGU2012-12623*

REMAÎTRE A., WALLNER S., **PROMPER C.**, GLADE T. AND MALET J.-P. 2013. Mechanisms and processes of landslides induced by water and earthquakes. *Geophysical Research AbstractsVol. 15, EGU2013-4711*

PAPATHOMA-KÖHLE M., **PROMPER C.** AND GLADE T. 2013. The development of a common risk assessment methodology for local authorities in southeast Europe focusing on climate change related hazards – first results from the SEERISK project. *Geophysical Research Abstracts Vol. 15, EGU2013-2949*

PROMPER C., PAPATHOMA-KÖHLE M. AND GLADE T. 2012. Vulnerability and natural hazards - Key elements in risk analysis and management. *In:* International Geographical Congress, 26.08. – 30.08. 2012, Köln, Germany.

PROMPER C., GLADE T., PUISSANT A. AND MALET J.-P. 2012. Land cover as an important factor for landslide risk assessment. *Geophysical Research Abstracts*
Vol. 14, EGU2012-4422

PROMPER C., KEILER M. AND GLADE T. 2011. Analysis of changing channels in an anthropogenic influenced high alpine catchment. Managing Alpine Future II International Conference 2011, Innsbruck, Austria.