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ORIGINAL PAPER

Landslide risk analysis and its application in regional planning: an example from the highlands of the Outer Western Carpathians, Czech Republic

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Abstract Using detailed field mapping, an analysis of landslide risk has been undertaken in the flysch highlands of the Outer Western Carpathians. The standardized Czech methodology of expert derived susceptibility zonation widely used for land development planning purposes and deterministic modeling of shallow landslides was used to separately assess the susceptibility of different landslide types. The two susceptibility zonation maps were used to define landslide hazard using information about landslide reactivation and the return periods of precipitation that triggered the respective landslide types. A risk matrix was then used to qualitatively analyze the landslide risk to selected assets. The monetary value of these assets, according to actual market prices, was calculated and analyzed with respect to the risk classification. Since the study area is an important residential and recreational area, the practical application of the derived results was checked through a series of interviews conducted with personnel of the local government planning and construction office. This demonstrated a willingness to apply the landslide hazard maps as well as restraints of its successful application. The main one is the absence of legally binding regulations to enforce the spatial planers to use this information.

Keywords Landslides · Risk analysis · Susceptibility analysis · Flysch rocks · Regional planning

1 Introduction

The Outer Western Carpathians (OWC) covers a large part of Moravia, Czech Republic. This region is known to be highly susceptible to landslides due to the lithological and structural characteristics of the flysch rocks (Kováčik 1992). Indeed, even the first scientific descriptions of landslide events here mention their potentially devastating effects on private

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properties and transport infrastructure (Záruba 1922–1923). This scenario was borne out during a major landslide event in the village of Handlová, Slovakia (Záruba and Mencl 1982). The event destroyed the majority of the village along with an important local road. As a result, a national landslide inventory was compiled in 1962 and 1963 (Rybář and Nemčok 1968). From this inventory, it is clear that the OWC constitutes one of the most landslide prone areas in the Czech Republic and Slovakia. Repeated landslide events of different magnitudes have occurred in the study area during the past 20 years. Landslide event in July 1997 caused the destruction of thirty houses and severe damage to the railroad that serves as international train connection with Slovakia (Rybář and Stemberk 2000; Krejčí et al. 2002). Two further regionally significant events occurred in 2006 and 2010 (Bíl and Müller 2008; Pánek et al. 2011). These events show that any sustainable land planning within this region is dependent on reliable information regarding the future hazard and risk caused by landslides.

Landslide risk analysis is usually performed using two basic approaches, that is quantitative and qualitative. Quantitative risk analysis and consequent risk assessment use information about hazard probability, the value of the elements at risk and their vulnerability. Qualitative risk analysis and risk assessment use expert-based classifications of hazard as well as the elements at risk in order to obtain risk classes. Many studies in last years analyze and assess landslide risk. From the extensive list of papers, some examples are listed considering the similar medium scale (1:25,000–1:50,000) applied also in this contribution. Cardinali et al. (2002) performed landslide hazard and risk analysis in Umbria region, Italy. They used geomorphological approach to prepare multi-temporal landslide inventories and to map the hazard. Afterward, they assessed the vulnerability of the elements at risk to different landslide types and calculated the specific risk indices. Michael-Leiba et al. (2003) carried out a GIS-based regional landslide and debris flow risk analysis in Cairns Community, Australia based on hazard polygons delimited by magnitude recurrence relations and shadow angles. These were overlaid by vulnerabilities of resident people, buildings and roads in order to obtain quantitative estimation of total risk. Bell and Glade (2004) developed a new raster-based method for quantitative risk analysis for landslides in NW Iceland. They calculated individual and object risk to people in buildings and final risk considering different vulnerabilities and probabilities of spatial, temporal and seasonal impact of debris flows and rock falls. Remondo et al. (2005, 2008) applied a statistical approach to model quantitative landslide risk. The study, conducted in northern Spain, started from landslide susceptibility analysis. The total risk was estimated as potential loss in €/cell considering both direct and indirect economic losses. Probabilistic landslide risk analysis considering direct costs was applied also by Zêzere et al. (2008) in the area north of Lisbon (Portugal). Different hazard scenarios were used, and risk was estimated in €/cell.

In the Czech Republic, only few attempts to assess landslide risk exist so far. Most of the studies are focused on susceptibility mapping (Havlín 2010). Officially required risk mapping does not exist, so all the research is related to case studies or theoretical research (Blahůt and Klimeš 2011; Rozsypal 2009). However, the majority of the studies present scientific results without considering the actual needs of the stakeholders or local inhabitants threatened by the landslide hazards. To address this problem, the present paper has conducted a medium-scale landslide qualitative and semi-quantitative risk analysis based on susceptibility maps available to the local authorities in the studied region. Results have been subsequently reviewed by local stakeholders to find out how they fit into their practical needs. The geomorphological approach to the landslide spatial prediction was enriched by using physical-based model to assess shallow landslide (e.g., soil slips, earth flows) susceptibility, since these landslides are among the most common mass movement

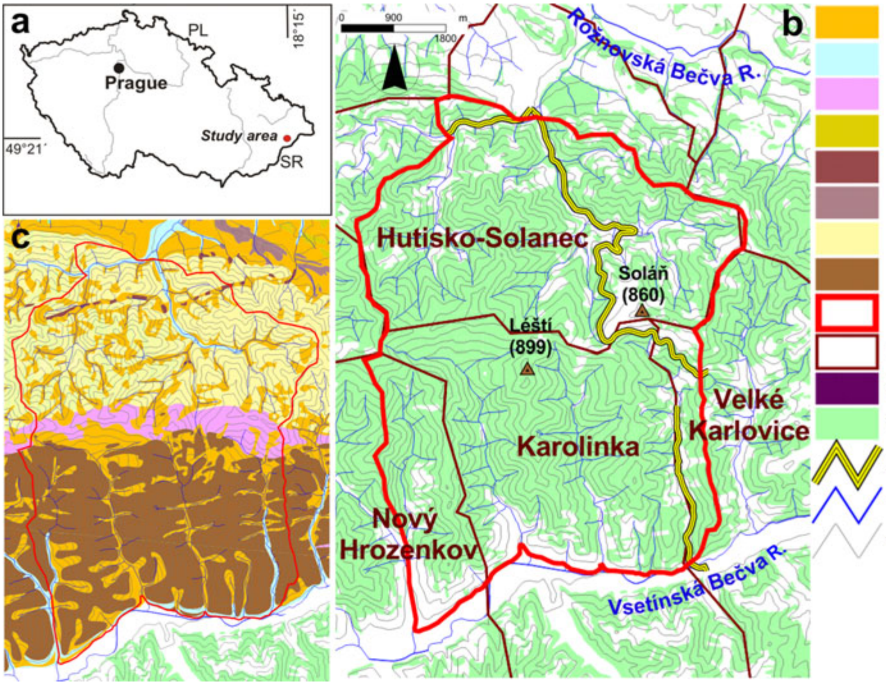

Fig. 1 A general location map of the study area (**a**), detailed topographical map (**b**) and geological map (**c**). *1* deluvial sediments; *2* fluvial sediments; *3* Beloveža Formation; *4* Istebná Formation; *5* Kaumberg Formation; *6* Podmenilit Formation; *7* Soláň Formation; *8* Zlín Formation; *9* study area; *10* administrative municipal limits; *11* urbanized areas; *12* forest; *13* regional roads; *14* streams; *15* contours with 40 m interval

types in the study region. Results of the semi-quantitative risk analysis were compared to assess theoretical losses caused by shallow landslides versus other landslide types.

2 Study area

The study area extends over 43 km^2 and is located in the highlands of the OWC close to the border with Slovakia (Fig. 1a). It is built up on of flysch rocks that alternate between competent permeable sandstone layers and plastic largely impermeable claystones and siltstones (Fig. 1c). The highest parts of the study area are composed of the thick bedded sandstone layers. Colluvial deposits cover 26 % of the study area and predominantly comprise loamy boulder rubble of sandstone or claystones. From sixty-six recorded boreholes, it is known that average thickness of these deposits is 4.2 m, but locally it may exceed 10 m.

The study area is roughly divided into two sections by a prominent east to west ridge reaching 911 m a.s.l. To north and south, altitudes gradually drop to the main river valleys (445 m a.s.l.). The southern part is divided by three ridges that separate narrow deeply incised valleys that form a rectangular river network. The northern part is less heavily dissected by a dendritic river network. The relative relief (i.e., the difference between the highest and lowest points) of the study area is 452 m. Generally, the difference in elevation between the valleys and interfluves is about 200 m. The long-term annual mean precipitation is 888.6 mm, the rainiest period being between May and August (Rožnov p. Radhoštěm Station, 1961–1990). At its most extreme, 46 % of the mean annual precipitation fell during just 10 days in July 1997 (Hladký 1998). Short-duration, high-intensity rainfall is the main trigger for landslide activity in the region (Krejčí et al. 2002). In general, precipitations are the major landslide trigger in the whole Czech Republic (Špůrek 1967), which determines limitation of the performed study.

In the study area, settlement patterns reflect the "Walachian" colonization that took place during the 1700 and 1800s. At that time, new settlements were founded near the pasture and agricultural land that was located close to the ridge tops. These houses are now used primarily for recreational purposes. The majority of the study area (76 %) is covered by spruce forest. It is also an important local tourist destination due to the forests, and the relatively high relief, and the picturesque scenery of surrounding mountains. The tourist facilities are concentrated around Soláň Hill. The hill incorporates three ski lifts, several restaurants, a parking lot, and accommodation facilities including a three-star hotel and a number of wooden chalets. Up to 54 % of the local labor force is employed in the tourism industry while 21 % of the buildings are used for recreational purposes including accommodation facilities (Cáb 2008). Between 4 and 10 % of the local inhabitants rely on forestry and agriculture for their source of income. The unemployment rate is about one-third higher than the average in the Czech Republic; this reached 10 % in October 2010 (Czech Statistical Office 2011). The main transport route in the study area is a north to south road that provides an important connection between urban centers in the valleys of Rožnovská and Vsetínská Bečva. All other routes are local or unpaved forestry roads. The two main villages within the study area are Hutisko-Solanec and Velké Karlovice, with populations of 2,011 and 2,596 respectively (Czech Statistical Office 2011).

2.1 Landslides in recent regional planning praxis

Two landslide inventories have been prepared for the study area. The first maps at 1:25,000 scales portrayed the outline of the landslides accompanied with a standardized description. As a single specialist was responsible for mapping an area of at least 1,400 km^2, these maps were far from comprehensive. Their reliability depended upon the experience and rigor of the specialist, and, therefore, this varied across the mapped region. The study area was mapped by a specialist in civil engineering (Jan Rybář, pers. comm.). These problems make the application of the maps rather difficult for the purpose of regional planning or regional susceptibility assessment. However, no other detailed landslide inventory was available before 1997.

In July 1997, heavy rains caused considerable flooding in the eastern part of the Czech Republic and the neighboring regions of Slovakia and Poland. This flooding affected the study area. Thousands of landslides were triggered during this rainfall event (Krejčí et al. 2002). In response, the Czech Geological Survey aimed to identify all morphologically recognizable landslide features through local field mapping at a scale of 1:10,000. The maps were prepared by several teams (including authors) according to the unified methodology and were used for the preparation of expert-based landslide susceptibility maps (Rybář 2001). The terrain in the susceptibility maps is classified into three slope stability classes for which limitations for regional development are defined. Within the Czech part of the OWC, these maps cover an area of more than 1,600 km^2. The maps are used for the purposes of regional planning and building permit procedures. Unfortunately, there have been no legally binding regulations defining how the maps should be used and, therefore, their use ranges from strict building prohibition inside highly susceptible areas to complete ignorance of the landslide susceptibility information. The lack of a consistent approach regarding the use of the susceptibility maps is also due, in part, to the large number of local authorities responsible for specific municipality cadastral areas. This problem is considered in the selection of a study area that contains elements regulated by four different municipalities (Fig. 1b).

During 2010 and 2011, new regional plans have to adhere to new regulations (Law 191/2008). These laws require that all information about the territory is incorporated into an information base (IB), used to prepare the plans. Any additional information required for the preparation of the plans is not considered. The law then requires the IB to be updated every 2 years when also new type of information may be introduced.

3 Data and methods

In the study area, landslides are represented by a variety of types, mainly by translational slides or earth flows. However, shallow soil slips and slumps also occur (Cruden and Varnes 1996). To assess landslide risk from these different phenomena, the types have been grouped into two categories, which also follow recommendation by van Westen et al. (2006) to execute risk mapping for single types of landslides. Firstly, susceptibility to translational slides was assessed using an available landslide inventory (Klimeš 2002) that was updated in the field during 2007 (Cáb 2008) and used for expert-based susceptibility assessment. Secondly, susceptibility to earth flows and shallow soil slips extracted from the available landslide inventory maps was analyzed using the SINMAP software (Pack et al. 1998). It couples infinite slope stability model with topographic wetness index to calculate factor of safety for each pixel. To assess the landslide hazard posed by these two landslide groups, the temporal probability was estimated for each of the susceptibility classes. Thereafter, a risk matrix has been used to compare the hazard classes with the vulnerability classes of the assets. From this, the landslide risk was obtained. In each of the presented risk maps, an estimation of the maximum potential losses was made for each risk class using the known market values of the elements at risk.

3.1 Translational landslides and complex slope deformations: expert-based susceptibility and hazard analysis

Landslides were classified into the inventory according to their level of activity. Active landslides are characterized by their clearly visible and fresh morphology changes. Temporarily inactive landslides are clearly visible but do not show signs of movement and their original terrain has been somewhat modified. It is, however, considered that these landslides could be reactivated under favorable conditions. Permanently inactive or stabilized landslides are severely denuded, and it is considered that their reactivation is improbable. While these definitions are somewhat subjective, they are based on field evidence. During field mapping, other distinct type of landslides was recognized. It is usually developed over several episodes of activity and comprises different types of movement (e.g., sliding, flowing and rock falls). This landslide type has been termed a complex slope deformation. They are usually associated with deep-seated failure planes, which generally extend to depths of more than 30 m but may locally extend to depths of more than 100 m (Baroň 2004).

The expert-based landslide susceptibility zonation is based on the observation that the majority of new landslides occur within or very close to pre-existing ones. It combines the environmental similarity approach (Carrara et al. 1995) with findings about the high spatial persistency of landslides in the study area (Rybář 1999; Krejčí et al. 2002). Thus, the unstable susceptibility class is defined by geomorphological evidence of the previous landslide occurrence including complex slope deformations (Rybář 2001). Earth flows and soil slips typically occur on the erosional slopes of gullies and dellens, and, therefore, these slopes have been categorized as unstable as well. Where no evidence for previous landslide occurrence can be found, slopes with an angle of more than 5° have been categorized as conditionally stable while slopes with an angle of less than 5° have been categorized as stable (Rybář 2001).

In order to obtain an estimation of landslide hazard from the susceptibility map, a temporal component was added for each susceptibility class based on expert judgment and the rainfall return period for the event known to trigger majority of the landslides mapped in the study area. These landslides were triggered after 3 days of rain during July 1997. The average return period for the total amount of precipitation that fell during these 3 days was calculated using rainfall data recorded from the end of the 19th century until 1996 (Hladký 1998). From this, the return period for the event was found to be 250–500 years. This temporal probability was assigned to the conditionally stable susceptibility. As a result, this becomes the medium hazard class; this class also incorporated permanently inactive landslides so as to reflect the uncertainty associated with the term "permanently". Return periods of less than 250 years were assigned to the unstable susceptibility class, and this therefore became the high hazard class. Return periods of more than 500 years were assigned to the stable susceptibility class, and this therefore became the low hazard class.

The expert-based landslide susceptibility zonation applied here can only be validated when the next landslide event occurs within the study area, as only known landslides are used to define the unstable susceptibility/high hazard classes.

3.2 Soil slips and slumps: SINMAP-based susceptibility and hazard analysis

Susceptibility to shallow landslides (up to 3 m) caused by an increase of the water table in the slope sediment was analyzed using a deterministic approach that calculated the factor of safety (FS). The FS was determined by an infinite slope stability model coupled with a static hydrological model using a topographic wetness index as a proxy for pore water pressure distribution (Pack et al. 1998). Points located in the scarp areas of shallow landslides and earth flows were used for model calibration and results validation. The digital elevation model was based on contour map with elevation interval of 5 m. The applied ranges of geotechnical parameters used in the program were based on mainly unpublished reports about laboratory tests describing mechanical properties of colluvium samples from the study area (Klimeš 2008a) and were further adjusted during the modeling process. The parameters include soil density (2,732 kg m^{-3}), effective cohesion (5–25 kPa), angle of internal friction (20°–28°) and infiltration coefficients (10^{-7}–10^{-9} m s^{-1}). The transmissivity/recharge ratio was calculated according to the Pack et al. (1998) using infiltration coefficients and known precipitations. Results showed quick saturation of the colluvium during the 1997 landslide, and thus, this static parameter was set to full saturation of the superficial layer. The FS calculated for each pixel (100 m^2) was reclassified based on experience of the study area into unstable ($FS < 1$), conditionally stable ($1.25 > FS > 1$) and stable ($FS > 1.25$) susceptibility classes.

Table 1 Susceptibility class definitions for the expert and deterministic models

	Class: unstable	Class: conditionally stable	Class: stable
Expert zonation	Landslides are very likely to occur due to specific site conditions and were clearly identified in the field	Landslide development cannot be excluded based on experience, but no field evidence of previous landsliding has been identified	Landslide occurrence is almost excluded due to very small slope dips. The accumulations of long run-out landslides and scarp areas of retrogressing landslides may reach this zone
SINMAP model	Zone with the most suitable conditions for landslide occurrence within the study area. Landslide development is a matter of time	Landslide development cannot be excluded	Landslide development is almost excluded. The accumulations of long run-out landslides may reach this zone

To validate the SINMAP model, the total number of shallow landslides was randomly divided into a training dataset (143 landslides) and a validation dataset (68 landslides). The latter was used to test reliability of the prediction of the model. The susceptibility classes of this deterministic model and the expert-based susceptibility assessment describe susceptibility for two distinct groups of landslide types. Thus, their meaning is also different as defined in Table 1.

As in the previous case, the hazard was estimated by assigning a temporal occurrence probability value to each susceptibility class. From the literature and field experience, it is known that torrential high-intensity short-duration rainfall events (e.g., 55 mm/24 h, Obdržálková 1992) with short return periods trigger shallow landslides nearly every year within the study area. A return period of less than 50 years was therefore assigned to the unstable susceptibility class, and from this, the high hazard class was determined. A return period of less than 50 years was chosen because the 1-day rainfall total that triggered majority of the shallow landslides during the event 1997 was associated with a return period of 50–100 years (Hladký ed. 1998). A return period of 50–100 years was assigned to the conditionally unstable class, and from this, the medium hazard class determined while a return period of more than 100 years was assigned to the stable class, and from this, the low hazard class determined.

3.3 Elements at risk and their vulnerability

The elements at risk were extracted from the official digital topographical database, ZABAGED (www.cuzk.cz), developed, populated and managed by the Czech Office for Surveying, Mapping and Cadastre (COSMC). The elements at risk were divided into linear features, and building, and land-use polygons. The linear features comprise transport infrastructure (regional, paved and unpaved roads) and others (high-voltage lines and ski lifts). Unfortunately, no information about other linear features such as gas or water pipelines is provided by the ZABAGED topographical database. Thus, these were not taken into account, though they are highly vulnerable to landslides. The high-voltage lines and ski lifts were represented as linear features due to incomplete information about locations of the poles. The buildings are divided according to their purpose into residential,

Table 2 Vulnerability class definitions for the different elements at risk

Vulnerability class	Elements at risk			
	Buildings	Roads	Other	Land use
Low vulnerability	Residential buildings with area larger than 350 m^2	Regional roads	None	Forests
Medium vulnerability	Residential buildings with area between 100 and 350 m^2	Paved roads	High-voltage lines and T-bar type ski lifts	Agricultural land
High vulnerability	Residential buildings with smaller area than 100 m^2	Unpaved roads	J-bar type ski lifts	Buildable areas

recreational and others. Planimetric information about buildings was updated and checked using orthophotographic images from 2004 (www.mapy.cz). No descriptive information is available for the recreational or other building classes. The study area was divided into three land-use classes (buildable areas, agricultural land and forests) for which vulnerability was evaluated separately.

Vulnerability in this study is defined as the propensity of the element at risk to cope with the landslide hazard or, in the case of the land-use areas, as potential loss due to the landslide hazard. A summary of the vulnerability classes is presented in Table 2. The definitions are based on available descriptive characteristics and field observations.

The vulnerability of residential buildings has been defined from field observations regarding the building footprint area. More specifically, it is known that large buildings are able to easily withstand the rather shallow and slow moving landslides that are typical for the study area. Large buildings ($\geq$350 m^2) have been assigned to the low vulnerability class as they are able to accommodate, to a certain extent, the deformation caused by landslides. Medium-size buildings (100–350 m^2) have been assigned to the medium vulnerability class. Small buildings ($\leq$100 m^2) have been assigned to the high vulnerability class. As no comprehensive information about construction materials was available for the whole study area, these were not taken into account.

Based on experience from the study area, the vulnerability of roads has been defined according to their type. As different road types show different susceptibility to damage from landslides. Regional roads, representing major transport routes, have been assigned to the low vulnerability class as they are well built and regularly maintained. All other paved roads have been assigned to the medium vulnerability class. All unpaved roads have been assigned to the high vulnerability class.

Field observations and information from ski lift owners have been used to define the vulnerability of high-voltage power lines and ski lifts. High-voltage power lines and T-bar ski lifts have been assigned to the medium vulnerability class due to the deep foundations used to secure these features. J-bar ski lifts have been assigned to the high vulnerability class due to the shallower foundations used to secure these features.

Buildable areas, agricultural land and forests have been assigned to a vulnerability class that reflects the potential economic loss ranging from high to low. Buildable areas have been assigned to the high vulnerability class. This comprises both pre-existing buildings and those areas that the various municipalities have designated for future development. Agricultural land has been assigned to the medium vulnerability class. This reflects the fact that agricultural practices often require the operation of heavy machinery, which can be severely impeded due to landslide occurrence. Forests have been assigned to the low

Fig. 2 Risk matrix (adapted after Australian Geomechanics Society 2000)

		H		
		1	2	3
V	1	1	1	2
	2	1	2	3
	3	2	3	3

vulnerability class since it is, in most cases, possible to harvest the timber after a landslide event and only limited restrictions for the future land use are caused by the landslides.

3.4 Risk analysis and estimation of prospective losses

A qualitative estimation of landslide risk was undertaken by applying a risk matrix (Fig. 2). The resulting landslide risk was estimated separately for buildings, land-use areas, roads and other linear elements. To compare the potential financial consequences, the value of the elements at risk had to be quantified; the applied monetary values are summarized in Table 3. For the roads, the construction costs have been used (Polešáková et al. 2010). All other costs reflect the market values as of December 2010. For buildings and land-use areas, the average market values have been calculated from surveys of real-estate agents within each of the four municipalities; each municipality was considered separately due to underlying differences in their market prices. The costs associated with skiing infrastructure were determined through interviews with lift owners and operators. These unit values were then used to calculate the maximum theoretical losses associated with each of the risk classes (Sect. 4.3). The maximum theoretical loss was calculated by multiplying the sum of areas (building area or land-use area) or lengths (linear features) within each risk class by their unit value.

3.5 Uncertainties in risk analysis

In risk analysis on medium scale, several limitations exist and consequently many uncertainties are present within the results. As summed by Bell and Glade (2004), the resulting risk values indicate a considerable uncertainty due to the uncertainties inherent in each input factor of risk analysis. Main limitation of susceptibility and hazard analysis is usually connected with the spatial resolution and reliability of the inputs. In this paper, the used expert approach based on geomorphological mapping is subjective by its nature (Cardinali et al. 2002). Nevertheless, its ability to predict spatial distribution of the future landslides and thus the hazard zones proved similar reliability as results of statistical methods (Klimeš 2008b). Uncertainties connected with shallow landslide susceptibility and hazard analysis arise mainly from extrapolation of geotechnical data for the whole study area and assumptions connected with the model itself. Other uncertainty is connected with the estimation of temporal probability component of the hazard assessment, which is linked to single rainfall event, which triggered landslides in 1997. So far, there is no other

Table 3 Value of elements at risk

Buildings	€/m^2 (€)
Hutisko-Solanec	1269.3
Karolinka	462.4
Nový Hrozenkov	637.9
Velké Karlovice	933.2
Linear features	**€/m (€)**
Regional roads	882.3
Paved roads	54.7
Unpaved roads	40.0
T-bar ski lifts	666.7
J-bar ski lifts	400.0
High-voltage lines	N.A.
Land-use areas	**€/m^2 (€)**
Buildable areas	
Hutisko-Solanec	20.6
Karolinka	21.8
Nový Hrozenkov	23.5
Velké Karlovice	19.3
Forests	1.8
Agricultural lands	3.8

N.A. not available

possibility how to estimate the temporal probability for the study area due to limited data availability. Elements at risk value estimates are mostly based on web survey among real-estate companies and thus represent minor part of the total uncertainty connected within the analysis.

It is important to mention another limitation, connected with the "static" expression of hazard and risk, showing only the situation according to the date of acquisition of the inputs of the analysis. IUGS Working Group on Landslides—Committee on Risk Assessment (1997) and Heinimann (1999) recommended that final results should be treated as relative results and not as absolute ones. This is probably the only way of using the very many valuable tools of hazard and risk analysis in natural disaster mitigation on the one hand, but not to lose the trust in the results on the other (Bell and Glade 2004).

3.6 Feedback from local authorities

The practical applicability of the landslide hazard and risk analysis undertaken in this study has been discussed with local authorities, specifically with respect to the process of regional planning and building control in light of the recent changes to the regulatory laws. A number of interviews were conducted with professionals involved in regional planning and relevant local government employees in the town of Vsetín. The town oversees regional planning and building control within the study area. The talks were focussed mainly to find whether the involved authorities are interested in landslide hazard and risk information and whether they would be willing to use them in practice.

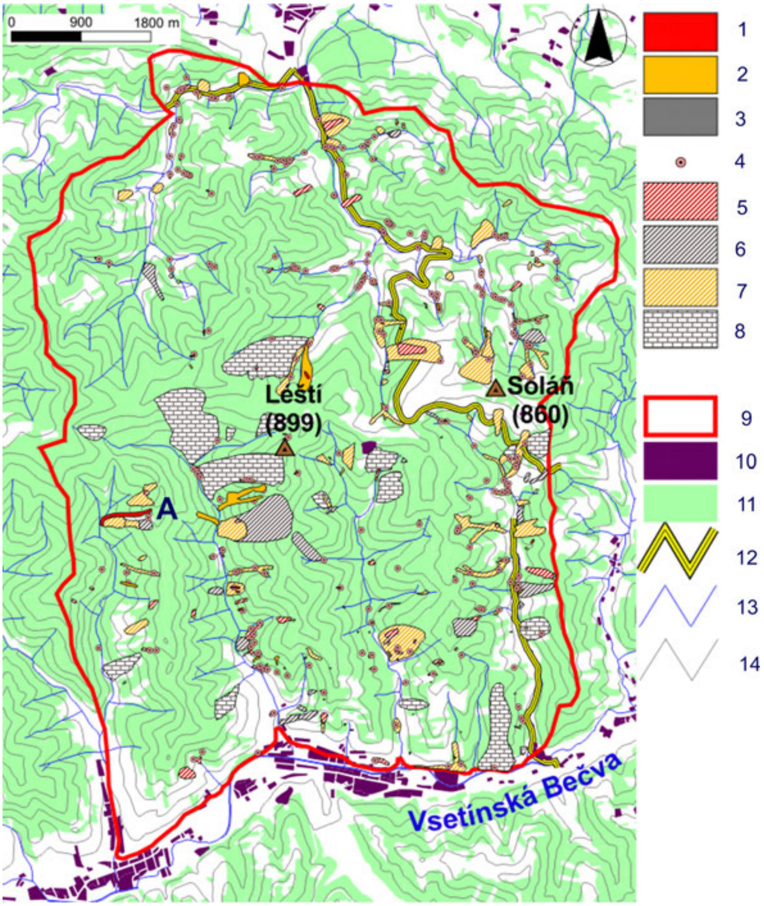

Fig. 3 A landslide inventory map of the area under consideration. *1* active flows; *2* temporarily inactive flows; *3* permanently inactive flows; *4* active slides <50 m; *5* active slides >50 m; *6* temporarily inactive slides; *7* permanently inactive slides; *8* complex slope deformations; *9* study area; *10* urbanized areas; *11* forest; *12* regional roads; *13* streams; *14* contours with 40 m interval; *A* largest active flow in the study area

4 Results

4.1 The landslide inventory

The landslide inventory mapping identified 285 landslides, covering a total area of 4.1 km^2 or 9.6 % of the study area (Fig. 3). Active landslides with dimensions of less than 50 m occur frequently along streams or in road cuts, and they are distributed quite evenly through the study area. To the south of the main ridge, landslides cover a total of 13 % of the area with complex slope deformations dominant. To the north of the main ridge, landslides cover a total of 6.2 % of the area with temporarily inactive landslides dominant.

The landslides of July 1997 caused considerable damage to the regional road that crosses the study area from south to north. Due to active landsliding, cracks opened and vertical steps formed in the road. In other places, the surface of the road was covered by

Table 4 The basic types and characteristics of landslides in the study area

	Number	Percentage of the total number of landslides	Total landslide area (km^2)	Percentage of the total landslide area
Slides	243	85	2.1	51.3
Flows	23	8	0.1	2.4
Complex slope deformations	19	7	1.9	46.3

landslide accumulations. Furthermore, one house was also subject to structural damage that led to claims for extensive mitigation work.

The basic characteristics of each type of landslide are presented in Table 4. Translational landslides and complex slope deformations occupy a similar area despite the fact that, within the study area, there are 243 instances of the former but only 19 instances of the latter. Earth flows have only a negligible areal extent, being strongly dominated by an exceptionally large case that permanently blocked a local stream (Point A on Fig. 3).

4.2 Elements at risk

In total, 883 buildings and 292 km of roads are located within the study area (Table 5). The majority of buildings (96.9 %) are of small or medium size (up to 350 m^2) with a significant concentration of permanently inhabited and recreational structures around the saddle near Soláň Hill. The majority of roads are solely used for logging purposes or to connect hamlets with the paved road network. Only a very small percentage forms part of the regional road network (12.4 %). The elements at risk are not uniformly distributed although the unpaved roads form a dense network. The majority of the elements at risk are clustered (e.g., houses) or linear (e.g., paved roads or high-voltage power lines). The houses usually occur close to rivers either within the valleys or on the lower parts of slopes (Fig. 4a).

Table 5 Characteristics of the elements at risk

Buildings	Number	(%)
Small-size buildings (<100 m^2)	405	45.8
Medium-size buildings (100–350 m^2)	451	51.1
Large-size buildings (>350 m^2)	27	3.1
Total	883	100
	Length (km)	(%)
Transport facilities		
Regional roads	12.4	4.3
Paved roads	77.4	26.5
Unpaved roads	202.2	69.2
Total	292	100
Other elements at risk		
High-voltage lines	19.7	86
Ski lifts	3.2	14

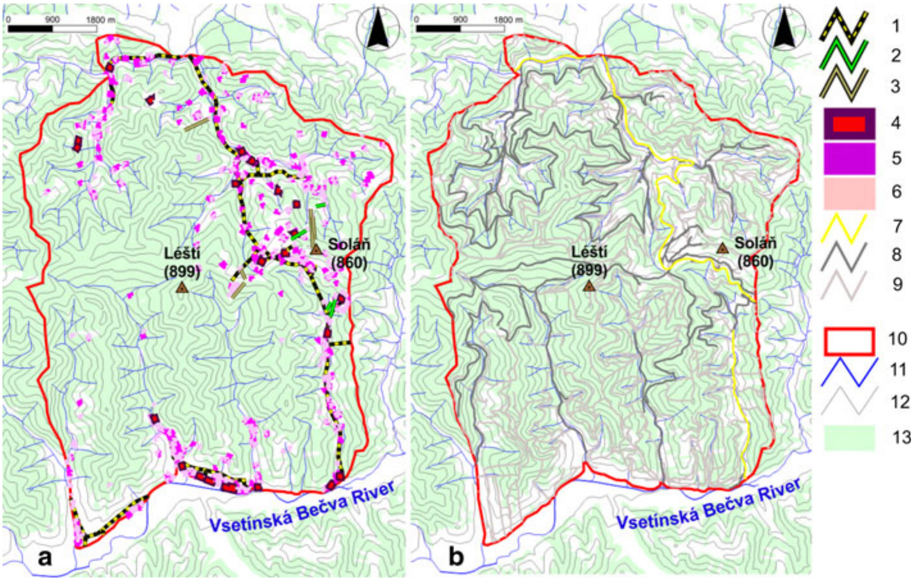

Fig. 4 The distribution of elements at risk. Map **a** shows—*1* high-voltage lines; *2* J-bar ski lifts; *3* T-bar ski lifts; *4* large-size buildings (>350 m^2); *5* medium-size buildings (100–350 m^2); *6* small-size buildings (<100 m^2). Map **b** shows—*7* regional roads; *8* paved roads. *9* unpaved roads; *10* study area; *11* streams; *12* contours with 40 m interval; *13* forest

4.3 Landslide susceptibility and hazard analysis

The results of the expert-based and deterministic susceptibility analysis are shown in Fig. 5. The expert-based map shows that large parts of the study area fall into the conditionally stable susceptibility class (78 %) while only very small parts fall into the stable susceptibility class (2 %). This result is caused by a combination of the morphology of the study area, with prevailing steep slopes and very narrow valley floors, and the very general rule that defines the conditionally stable class. The unstable susceptibility class of the expert-based map covers 20 % of the study area.

While transforming the expert-based susceptibility map to a hazard map, some modifications have to be made. In the expert map, some parts of the unstable susceptibility class have been classified as being of medium hazard. This is due to the fact that the landslides used to define high susceptibility are considered to be permanently inactive having shown no signs of mobilization during or following the events of 1997. Thus, it was assumed that the hazard associated with these landslides is lower than the hazard associated with other cases in the unstable susceptibility class. The high hazard class covers 13 % of the study area compared to the 20 % area of the unstable susceptibility class.

The SINMAP model clearly identified the majority of ridges as stable, with the unstable class primarily concentrated on steep slopes (>20°). The fit of the model, evaluated by the landslide training dataset used for its preparation, shows that 52 % of landslides were correctly classified into the unstable class while 17 % were classified into the stable class and thereby represent the model error (Table 6). The evaluation of the model, using the landslide validation dataset, shows that 46 % of landslides were correctly classified into the unstable class while 25 % were classified into the stable class. Geotechnical parameters

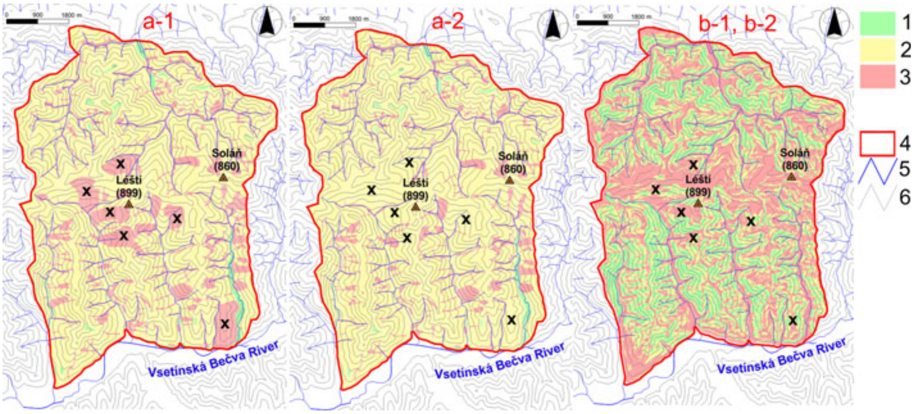

Fig. 5 Landslide susceptibility (**a-1**, **b-1**) and hazard (**a-2**, **b-2**) maps for the expert- (**a**) and SINMAP- (**b**) based approaches. For the SINMAP approach, the susceptibility and hazard zones are identical. *X* locations of permanently inactive landslides with medium hazard; *1* stable susceptibility and low hazard class; *2* conditionally unstable susceptibility and medium hazard class; *3* unstable susceptibility and high hazard class; *4* study area; *5* streams; *6* contours with 40-m interval

Table 6 Results of the landslide susceptibility analysis for SINMAP model with calibration parameters used for the model definition

Susceptibility class	Study area (%)	Percentage of number of landslides in each susceptibility class for training/validation datasets
Stable	44	17/25
Conditionally stable	29	32/29
Unstable	27	52/46

SINMAP calibration parameters: $\rho s = 2{,}732$ kg m^{-3}; T/R = 0; $c = 0.17$–0.7 kPa; $\varphi = 25°$–$27°$

used to achieve the presented results are slightly different form those suggested in the Chapter 3.2. Major difference is in the value of cohesion, which approaches 0 kPa and may reflect actual value under the full saturation conditions of the soils during the occurrence of shallow landslides.

Distribution of landslide hazard classes in the SINMAP-based hazard map is identical with the SINMAP susceptibility map. Only updating using rainfall return periods causing shallow landslides were made in order to fulfill the definition of hazard comprising both spatial and temporal probabilities.

The results of both susceptibility mapping techniques show a different spatial distribution of susceptibility classes. Areas covered by complex slope deformations are usually defined as stable by the SINMAP model (Fig. 5) although some exceptions have to be noted. In some cases, SINMAP model recognized as unstable areas lying within complex slope deformations in places of locally increased slope which locally creates suitable conditions for occurrence of shallow landslides.

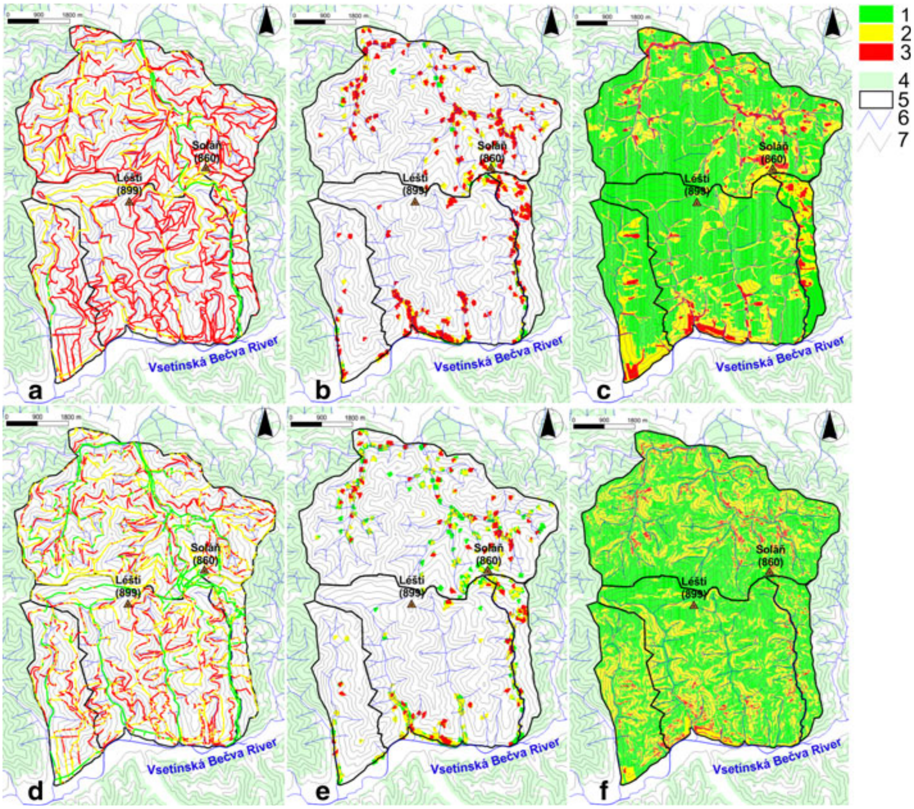

Fig. 6 Landslide risk maps for linear features, buildings and land use based on the expert (**a**, **b**, **c**) and SINMAP approaches (**d**, **e**, **f**). *1* low-risk class; *2* medium-risk class; *3* high-risk class; *4* forest; *5* division of the study area by cadastral borders; *6* streams; *7* contours with 40-m interval

4.4 Landslide risk analysis

The results of the landslide risk analysis based on the expert and SINMAP approaches are shown in Fig. 6. The risk classification of each class of elements of risk is summarized in Table 7.

4.4.1 Linear features

Majority of regional roads lie within low-risk class on both expert-based and SINMAP-based maps. Paved roads are mainly situated in areas of medium landslide risk on expert-based map. On the contrary, SINMAP-based risk map shows that half of the paved roads lay in areas of low landslide risk. This difference is a primarily a function of the larger area assigned to a medium landslide hazard on the expert-based map. On the expert-based map, it can be seen that unpaved roads are mainly placed in areas of high landslide risk. On the SINMAP-based map, unpaved roads are almost equally distributed in areas of medium or high landslide risk. In both cases, unpaved roads are not spatially associated with low landslide risk. On the expert-based map, it can be seen that ski lifts predominately occur in areas of medium or high landslide risk. The J-bar ski lifts only occur in areas of high

Table 7 Summary of the risk classification of the elements at risk for both hazard models

	Low risk		Medium risk		High risk	
	Expert zonation (%)	SINMAP (%)	Expert zonation (%)	SINMAP (%)	Expert zonation (%)	SINMAP (%)
Linear elements						
Regional roads	71.8	91.1	28.2	8.9	0.0	0.0
Paved roads	3.0	49.7	80.0	25.3	17.0	25.0
Unpaved roads	0.0	0.0	2.8	59.1	97.2	40.9
T-bar ski lifts	0.0	67.6	54.5	20.3	43.2	12.2
J-bar ski lifts	0.0	0.0	0.0	66.3	100.0	33.7
High-voltage lines	18.8	74.1	63.5	17.3	17.8	8.6
Buildings						
Hutisko-Solanec	14.2	67.6	50.9	22.2	35.0	10.2
Karolinka	35.6	71.7	39.7	23.6	24.7	4.7
Nový Hrozenkov	20.1	60.6	52.3	37.1	27.6	2.3
Velké Karlovice	18.8	55.1	40.9	39.8	40.3	5.1
Total	23.9	67.6	45.2	25.5	30.9	6.9
Expert zonation						
Buildable areas						
Hutisko-Solanec	0.0	0.0	2.0	73.8	98.0	26.2
Karolinka	0.0	0.0	18.8	80.8	81.2	19.2
Nový Hrozenkov	0.0	0.0	19.7	93.8	80.3	6.2
Velké Karlovice	0.0	0.0	11.3	83.5	88.7	16.5
Total Buildable Area	0.0	0.0	11.4	79.9	88.6	20.1
Agricultural Area	5.5	65.1	80.4	23.5	14.1	11.4
Forests	86.9	68.2	13.1	31.8	0.0	0.0

landslide risk. On the SINMAP-based map, ski lifts mainly occur in areas of low or medium landslide risk. On the expert-based map, it can be seen that high-voltage lines predominately occur in areas of medium landslide risk. On the SINMAP-based map, high-voltage lines mainly occur in areas of low landslide risk.

4.4.2 Buildings

Significant differences exist between the expert-based and SINMAP-based maps with regard to the areal extent of buildings within each risk class. Moreover, there are also significant differences with regard to the spatial distribution of these buildings across neighboring municipalities (Table 8).

On the expert-based map, majority of buildings lay in the medium-risk class with differences among the municipalities caused by different distribution of the buildings within each municipality. Highest proportion of buildings in high-risk class of the expert-based map belongs to the Velké Karlovice municipality.

On the SINMAP-based map, much larger proportion of the buildings belong to the low-risk class. This is caused by the limited extent of the low hazard class of the expert-based map. Highest share of buildings in high-risk class belongs to the Hutisko-Solanec municipality, which is partly caused by the presence of tourism facilities (buildings) in steep slopes of the study area.

4.4.3 Land use

In land-use areas risk classification, significant differences exist between the expert-based and SINMAP-based maps, particularly with regard to those areas defined as buildable within the different municipalities (Table 9). In case of the Hutisko-Solanec municipality, almost whole area is classified as high risk on the expert-based map, while only 26.2 % is classified as high-risk area in the SINMAP-based map. This is similar also for the other buildable areas in the remaining municipalities. Inverse situation occurs in the medium-risk class, where falls majority of the buildable area in the SINMAP-based risk map. Agricultural areas are equally distributed in the high-risk class on both risk maps. However in the expert-based risk map, majority of agricultural area lies within medium-risk class and least part in the low-risk class. For the SINMAP-based risk map, it is the reverse. Forests are equally distributed in the risk classes of both risk maps, when majority lies in low-risk class and no forest lie in the high-risk class area.

4.5 The quantification of potential losses

The values of all the elements at risk within each risk class are summarized in Table 8. These values represent the maximum theoretical losses within each of the risk classes. The value of the assets in the high-risk class as defined by the expert-based risk map comprises 13.9 % of the total value, whereas in the high-risk class of the SINMAP-based map comprises 4.3 % of the total value.

With regard to the linear elements, in areas of low landslide risk, the greatest total values have been determined using the SINMAP-based approach, in areas of medium landslide risk, the total values are roughly the same, and in areas of high landslide risk, the greatest total values have been determined using the expert-based approach. However, large variations are found between each of the constituent elements at risk. For example, in

Table 8 The values of the elements at risk within each risk class for the expert and SINMAP-based risk maps (values in thousands of euro)

	Low risk		Medium risk		High risk	
	Expert map (€)	SINMAP (€)	Expert map (€)	SINMAP (€)	Expert map (€)	SINMAP (€)
Regional roads	7,852	9,970	3,088	971	0	0
Paved roads	126	2,107	3,393	1,073	722	1,062
Unpaved roads	0	0	228	4,776	7,860	3,312
T-bar ski lifts	0	1,000	800	300	633	180
J-bar ski lifts	0	0	0	260	392	132
High-voltage lines	0	0	0	0	0	0
SUM	7,978	13,077	7,509	7,379	9,608	4,686
Hutisko-Solanec	8,611	40,872	30,939	13,402	21,277	6,189
Karolinka	7,751	15,589	8,626	5,140	5,367	1,016
Nový Hrozenkov	824	2,468	2,141	1,509	1,131	95
Velké Karlovice	2,126	6,229	4,620	4,497	4,561	581
SUM	19,311	65,158	46,326	24,547	32,336	7,881
Buildable areas						
Hutisko-Solanec	0	0	179	6,597	8,843	2,346
Karolinka	0	0	1,662	7,153	7,190	1,695
Nový Hrozenkov	0	0	656	3,148	2,677	210
Velké Karlovice	0	0	151	1,111	1,180	219
Agricultural areas	1,765	20,913	25,900	7,568	4,530	3,657
Forests	53,371	41,865	8,044	19,555	0	0
SUM	55,136	62,778	36,591	45,132	24,420	8,127

Table 9 Definitions of landslide susceptibility and hazard classes based on the expert approach

Susceptibility class	Hazard classes	Territorial development classes	Definitions of the territorial development classes
Stable	Low	Usable	No limitations with respect to landslide occurrence; limitations may be caused by possible flooding in the case of valley bottoms
Conditionally stable	Medium	Conditionally usable	Limitations due to the possibility of landslide triggering by unsuitable terrain modification (excavations, slope under cutting, increasing water infiltration). In the case of steep slopes (>18°), the increased expense of construction security needs to be considered
Unstable	High	Unusable	It is completely undesirable to develop these areas. The extremely high expenses regarding site reclamation, landslide mitigation and continuous slope stability monitoring need to be considered

The definitions were adapted from Rybář (2001) after interviews with officials responsible for territorial development

the medium class of the SINMAP-based risk map, a maximum theoretical loss of 4.8 million euro for unpaved roads is calculated, while the medium class of the expert-based risk map has a maximum theoretical loss of 0.228 million euro for the same features. The expert-based approach suggests that areas of high landslide risk have a maximum theoretical loss of linear features around 9.6 million euro while the SINMAP-based approach suggests that areas of high landslide risk have a maximum theoretical loss of linear features around 4.7 million euro.

With regard to the buildings, the highest maximum theoretical losses are expected in the municipality of Hutisko-Solanec irrespective of whether the expert-based or SINMAP-based approach is considered. However, the expert-based risk map expects about 21.2 million euro of losses, while the SINMAP-based risk map expects only 6.2 million of euro of losses. The expert-based approach suggests that areas of high landslide risk have a maximum theoretical loss of around 32.3 million euro while the SINMAP-based approach suggests that areas of high landslide risk have a maximum theoretical loss of around 7.9 million euro.

With regard to the land-use zones, the highest maximum theoretical losses are expected in the forests irrespective of whether the expert-based or SINMAP-based approach is considered. This is unsurprising given that forests cover the large majority of the study area. The expert-based approach suggests that areas of high landslide risk have a maximum theoretical loss of around 24.4 million euro while the SINMAP-based approach suggests that areas of high landslide risk have a maximum theoretical loss of around 8.1 million euro.

A comparison of the maximum theoretical losses for expert and SINMAP-based approaches is shown in Fig. 7. The SINMAP-based approach assigns much lower maximum theoretical losses to the high and medium hazard classes when compared to the expert-based approach. The high maximum theoretical losses assigned to the medium hazard class, as defined by the expert-based approach, reflect the large areal extent of the medium hazard class.

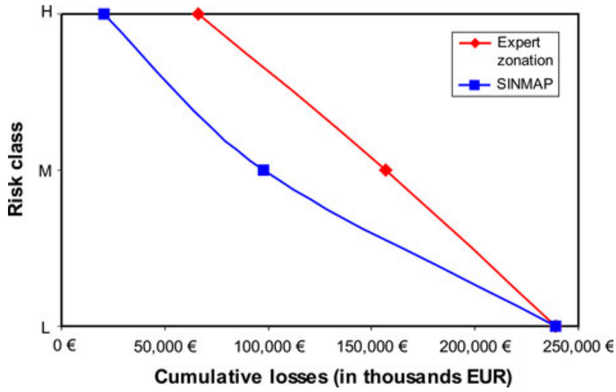

Fig. 7 Cumulative losses curves derived from the expert- and SINMAP-based hazard maps. *1* low hazard class; *2* medium hazard class; *3* high hazard class. Values are in thousands of €

4.6 Perspective of local authorities

From the perspective of the interviewed planners, the landslide hazard information is desirable for regional planning as it provides predictive information with regard to the possible location of future landslide events. The qualitative risk analysis only provides information regarding the location of existing landslides and elements at risk, and such information is not immediately useful to planners or local government officials. The relevant local government officials were willing to include the prepared landslide hazard zonation into the IB required for new regional planning schemes. Practical application of the available landslide hazard information was prevented by the lack of official guidelines regarding the role of such information in regional planning as well as building permit process. The extent to which the landslide hazard information would be useful will depend entirely on the agency responsible for maintaining the IB and preparing the regional plans as well as on the ability of the local authorities to ensure that this information can be used alongside other information in the IB. The local authorities required the landslide hazard information to be presented in an easy-to-understand form that clearly shows the extent to which different areas are suitable for development. For example, information regarding the limitations of the map and related uncertainties are not of high importance during its practical application. Table 9 suggests landslide hazard definitions for the purpose of regional planning.

It is important to note that new laws pertaining to regional planning require information regarding the *geological limitations* of the planned development. This includes information relating to landslides. However, the new laws do not provide guidelines that specify the type of information required (i.e., susceptibility, hazard, or quantitative risk analysis) or how this information should be applied during the planning process. Therefore, for any given planning proposal, landslide hazard and risk analyses are usually undertaken by those responsible for preparing scheme (usually an architect). The same people are also responsible for evaluating the relevance of the landslide information contained within the IB. However, a recent praxis states that development may only be allowed following a geological assessment of the construction site when the site is located in an area of high landslide susceptibility. This assessment only needs to include field reconnaissance and the use of available archive data sources. Based on the results of the assessment, it is then decided whether the development can proceed or whether more detailed geological surveying is required. This praxis further weakens the need for landslide hazard information during the regional planning process because regulation of the construction depends largely on action taken after the regional plan has been prepared and is already being applied in praxis.

The interviews showed that cost-benefit analysis does not form part of the decision-making process in either current or future risk assessment or in relation to the planning of remedial or mitigation works conducted by the local authorities.

5 Discussion

Detailed and quantitative risk assessment could not be performed due to unavailable input information, which is required by this type of analysis. Namely landslide occurrence frequency, magnitude and related damage to each type of elements at risk are very difficult to ascertain for each landslide type on middle scales (van Westen et al. 2006; van Westen et al. 2008). Information like type of construction material, type and depth of foundations of buildings or number of inhabitants in each building is unavailable for the scale of the performed analysis. Also landslide historical data for longer period are missing to be able to estimate more precisely future landslide frequencies (Remondo et al. 2008).

Validation of the SIMAP model showed that 25 % of new landslides, not used during the model preparation, were wrongly classified into the stable susceptibility class while only 46 % of new landslides were correctly classified into the unstable class. Validation of the expert-based map is less easily quantified. Nevertheless, results from a similar study area (Klimeš 2007) suggest that susceptibility maps based on landslide inventory mapping may produce more robust results than susceptibility maps based on deterministic models. The landslide inventory map, showing all known landslides each of them with a 75-m buffer zone assigned, was validated using the landslides that occurred during landslide event in 1997. In this case, 70 % of the new landslides were correctly classified into the unstable class.

It is important to bear in mind, that the SINMAP model provides end users with information about risk caused by shallow landslides controlled by water saturation of the colluvial material. These landslides occur more frequently, and spatial distribution of the most hazardous areas differs from the distribution of the other landslide types included in the expert-based approach. Thus, the maps based on SINMAP model provide additional and relevant information about landslide hazard and risk in the study area. The two hazard and risk maps should be consulted together for practical use to provide complex information about areas with multiple landslide hazard and risk caused by different landslide types. This information could be used during building permit procedures to better defined conditions of construction of different structures based on landslide hazard type at the respective construction site. Practical use of such information entirely depends on personal understanding and interest of each involved decision maker.

The difference in total monetary value for all the elements at risk within the high-risk class highlights striking differences between the expert-based and SINMAP-based approaches. The greatest differences in landslide risk distribution between the two approaches relate to the buildings, as they comprise the assets with highest value. The expert-based map puts more than 30 % of all buildings into the high-risk class, while the SINMAP-based map puts less than 7 % into the same risk class. The expert-based map puts around 25 % of all buildings into the low-risk class, while the SINMAP-based map puts around 67 % into the same risk class. It may be that houses are not, intentionally or unintentionally, built in places susceptible to the shallow landslides (described by the SINMAP model). In contrast, the houses are more likely to be built in places susceptible to other types of landslide. This may be due to practical considerations such as the close proximity to a river or the presence of gentle platforms formed often by previous landslide events.

Interesting results regarding the landslide risk to buildings can be found by comparing the municipalities of Hutisko-Solanec and Karolinka. A greater number of buildings are located in the high-risk class in Hutisko-Solanec than in Karolinka even though the landslide density is higher in the Karolinka. In Hutisko-Solanec, buildings are frequently located on slopes and near ridges where high landslide hazard areas are more likely to occur. In Karolinka, the vast majority of buildings are located on floodplains where the landslide hazard is very low (Fig. 4). With respect to the risk assessment, it is interesting to note that the unit value or market cost of buildings in Hutisko-Solanec is more than three times higher than it is for buildings in Karolinka. Therefore, the value of the buildings assigned to the high-risk class in Hutisko-Solanec is greater than the value of the buildings assigned to the high-risk class in Karolinka. It is theoretically possible that information about higher landslide risk to buildings in Hutisko-Solanec could affect their market cost. However, prices are defined by demand. This probably includes only very little, if any, consideration about the landslide hazard in the study area.

Previous work undertaken in the region suggests that well-designed mitigation measures are likely to greatly reduce the landslide hazard (Záruba and Mencl 1982). Experience testifies that landslides that have been subject to structural mitigation work have not subsequently been reactivated during later landslide events. Based on these observations, it is possible to reduce the landslide hazard associated with structurally mitigated landslides from high to medium. Then it is possible to calculate the value of the assets that had previously been ascribed to the high hazard class. Within the study area, the value is calculated to be 940,000 euro. This directly reflects a positive effect of the applied mitigation measures and may be used for the assessment of cost-effectiveness of the planned structural measures. However, this needs to be codified in legal norms; otherwise, the application of cost-benefit analysis for mitigation measures is probably not feasible.

A comparison of the areas suggested for future housing development with the hazard maps derived by the expert-based approach has shown that only 10 % of the proposed areas fall into the high hazard class while the rest belong to the medium hazard class. The same comparison for the SINMAP-based hazard map showed that only 7 % of the suggested development areas are included into the high hazard class while 82 % lie within the low hazard class. This well corresponds to differences in building distribution in the risk classes as described above. It also probably results from the general trend in housing development, which tries to avoid slopes due to more difficult and thus costly construction conditions.

The interviews conducted with local authorities revealed their willingness to use information about landslide hazard. However, this willingness is not supported by binding legal guidelines. It may be, therefore, problematic for the local authorities to choose the appropriate map. The authorities do not take into consideration the limitations or uncertainties associated with the different types of map. This can result in serious consequences if, for example, a landslide occurs in a zone classified as low hazard or if housing development is prohibited in area classified as highly hazardous by the model but known to be generally stable.

6 Conclusions

The expert-based landslide risk map is somewhat conservative, due to the fact that the landslide hazard caused by a number of different types of landslides is represented on a single map. As a result, it places large portions of the elements at risk into areas with medium or high landslide risk. The SINMAP-based landslide risk map is more sensitive to the conditions that lead to the occurrence of shallow landslides and assigns fewer elements at risk into medium or high landslide risk. This is also reflected in the cumulative loss curves calculated for respective landslide risk maps. Simultaneous use of these two risk maps provides complex information about landslide hazard and risk caused by different landslide types, which may improve the process of building permits procedures and land-use planning.

Regional roads represent the most important transportation corridors in the study area, and their majority falls into the low-risk class defined by the SINMAP as well as the expert-based models. Forested areas belong either to the low or medium-risk class defined by both approaches and thus are the land-use type with lowest landslide risk within the study area. J-bar ski lifts are tourist-related facilities with the highest landslide risk, since all of them are classified into high-risk class. Degree of landslide risk to other tourist infrastructure (e.g., hotels, restaurants and T-bar ski lifts) differs depending on applied risk assessment approach.

The comparison of two neighboring municipalities has demonstrated that landslide risk may differ significantly even over very short distances in areas with very similar natural conditions. This results from differences in both the spatial distribution of the elements at risk and their market prices. Based on a careful review of the current local government regional planning praxis, serious threats undermine the effective implementation of the presented landslide hazard information. These threats include the formalized manner with which information is collected for use in the regional planning process, a lack of legal regulations that specify how the landslide hazard information should be applied, and partly also lack of expert control with regard to the technical elaboration of the regional plans.

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