Acta Geodyn. Geomater., Vol. 8, No. 4 (164), 443–452, 2011

LANDSLIDE SUSCEPTIBILITY ASSESSMENT IN URBANIZED AREAS: EXAMPLE FROM FLYSCH CARPATHIANS, CZECH REPUBLIC

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(*Received* March 2011, *accepted* June 2011)

ABSTRACT

The ongoing development of landslide prone regions increases future potential losses caused by landslide occurrence. The first step towards landslide mitigation on a regional scale is a susceptibility assessment. This study focuses on the area surrounding the regional capital of Zlín, in the Outer Western Carpathians. The city is located in the flysch highlands. Statistical analysis of the distribution of landslide scarps was undertaken in relation to various preparatory factors (geology, slope angle, slope aspect, slope curvature, distance from closest stream). This analysis provided insights into the main initiating factors and allowed our results to be compared with other studies in similar regions. Thereafter, a regional landslide susceptibility assessment was undertaken. The model performance was evaluated with respect to the landslide information used during its preparation and with a separate validation dataset. The results show that the main predisposing factors are the claystone rich bedrock unit, thick accumulations of slope sediments, and slope angles between 10° and 15°. The possible application of the presented results for urban planning purposes is also outlined.

KEYWORDS: landslide susceptibility assessment, multi-variety statistical analysis, flysh highlands, urban development, Czech Republic

1. INTRODUCTION

The dynamic development of urban areas creates increasing pressure to build in places that are susceptible to landslides (Schuster and Highland, 2007; Mihai et al., 2010). This pattern can be seen in many areas in the Outer Western Carpathians, where significant urban expansion has occurred during the past fifty years. The region is highly susceptible to landsliding (Záruba and Mencl, 1982; Rybář and Stemberk, 2000). It was, therefore, decided that an important economic and administrative regional centre should be selected in order to undertake landslide susceptibility mapping.

The regional capital of Zlín has been affected by a number of widespread landslide events caused by extreme precipitation. Of those recorded in detail, the first and most severe landslide event occurred in June 1997. This caused hundreds of landslides in the flysch highlands of the Czech Republic (Krejčí et al., 2002, Rybář and Stemberk 2000). A second landslide event occurred in spring 2006. This caused tens of predominately shallow landslides, with depths of up to four meters, in the study area due to a combination of intensive precipitation and rapid snow thaw (Baldík et al., 2006; Bíl and Müller, 2008). Recently, several landslides have occurred within the urban area itself. These were caused by extreme precipitation in May and June 2010 (Krejčí et al., 2010; Šikula et al., 2010). However, only minor damage to the infrastructure was recorded. Despite the frequent landslides that have occurred in the last thirteen years, the phenomenon has not yet been studied in detail using objective statistical methods for landslide susceptibility assessment.

Nevertheless, the area is covered by field landslide inventory mapping during which expert based landslide susceptibility maps of the entire area were prepared (Rybář, 2001; Krejčí at al., 2008). The maps are now used by local authorities for territorial planning procedures. The susceptibility assessment is based on the identification of landslides in the field and the observed relationship between landslides and slope angle. These form the basic criteria for defining the various susceptibility classes. The unstable susceptibility class defines areas where previous or recent landslides have occurred. The conditionally stable susceptibly class defines areas with slope angles in excess of 5°. The remaining areas are defined stable.

Within the literature, numerous studies have shown that the spatial distribution of landslides can be better understood through objective, GIS-based, susceptibility assessment. Süzen and Doyuran (2004) present examples of the successful use of bivariate statistics across a wide range of geological and morphological settings. However, it seems more

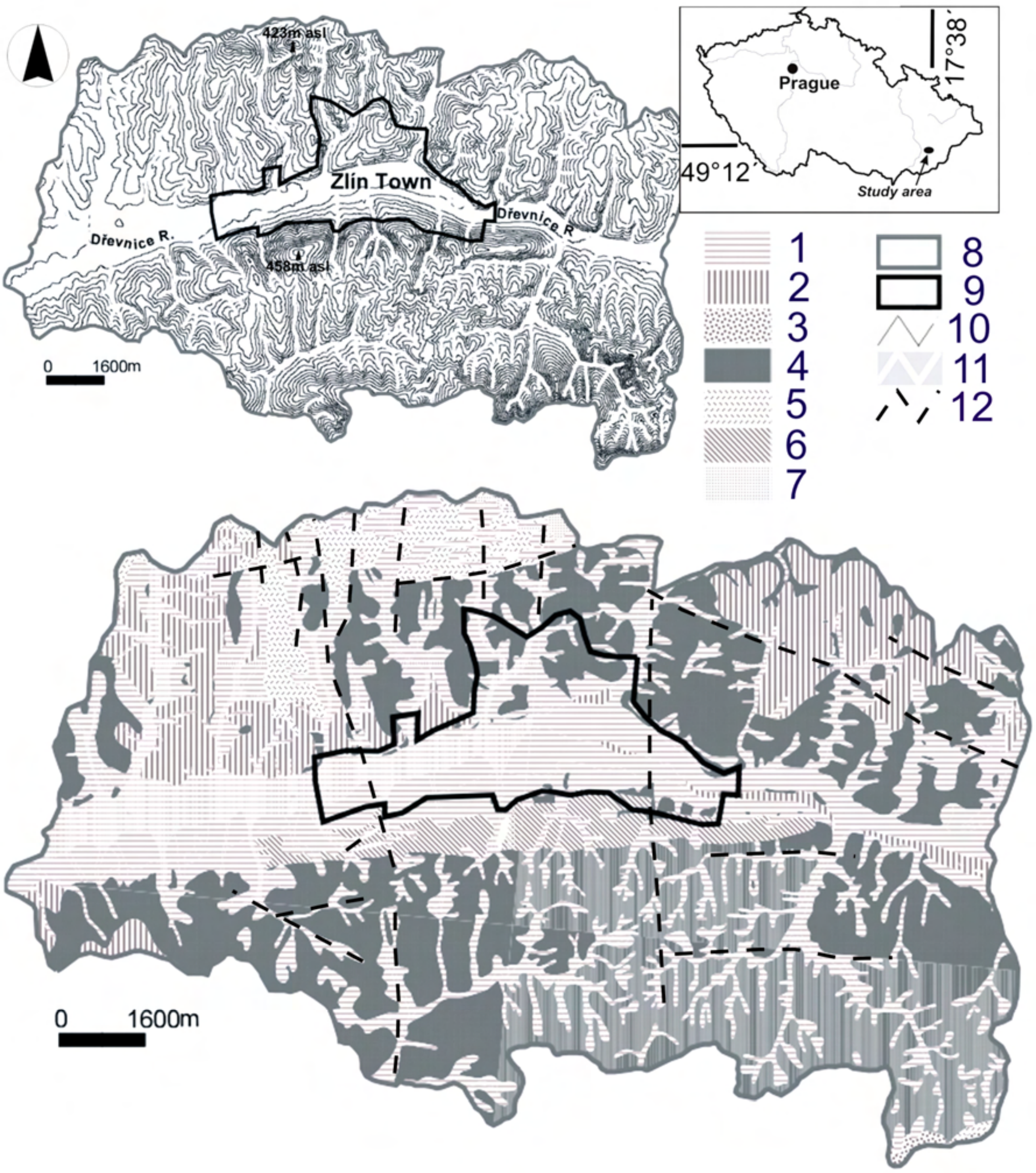

Fig. 1 Location of the study area (1 – Quaternary sediments, 2 – loess, 3 – Luhačovice Member of the Zlín Formation, 4 – Vsetín Member of the Zlín Formation, 5 - Lukov Member of the Soláň Formation, 6 – Újezd Member of the Zlín Formation, 7 - Ráztoka Member of the Soláň Formation, 8 – limits of the study area, 9 - Zlín city boundary, 10 - contour lines with an interval of 15 m, 11 – streams, 12 – faults, R. - river).

appropriate to use multivariate statistics for susceptibility assessment as these are able to simultaneously evaluate many landslide preparatory or triggering factors (Carrara et al., 1995). This more closely resembles the natural environment, in which all factors are operating concurrently. Different statistical methods may be implemented including Weight of Evidences technique (Blahut et al., 2010), Principal Component Analysis, logistic regression, discriminant analysis, artificial neural networks, or fuzzy logic (Chacón et al., 2006; Mihai et al., 2010). All of the statistical methods use information about landslide density on selected preparatory factor variables that are weighted during the modeling process (Eeckhaut et al., 2006). Therefore, the spatial and temporal accuracy and completeness of the applied landslide inventory directly affects the modeling results. This stresses the fact that all these methods are data driven.

This work aims to assess landslide susceptibility of the Zlín town and its close surrounding using detailed field landslide inventory and direct statistical method. Specific attention is focused on evaluating the performance of the susceptibility assessment using training and validation landslide datasets.

2. THE STUDY AREA

The study area (163 km^2) is elongated in a W-E direction following the main Dřevnice River valley (Fig. 1) where the Zlín town with more than 80,000 inhabitants (2000, Czech Statistical Office) is situated. Its limits respect river basin divides. The area is situated in the Outer Western Carpathians with base rocks built by tectonic Rača unit of the Magura Nappe which formed during Eocene – Paleocene. The base rocks originated during flysch sedimentation are formed with interbeded claystones and sandstones characterized by high tectonic and structural complexity and hydrological heterogeneity. The basic structural settings are shown in Figure 1. The rocks are usually densely fractured, which in case of claystones may lead to disintegration into fragments than 5cm in size. These conditions contribute to the rock weathering which produces landslide highly susceptible slope sediments.

The majority of the study area is part of the flysch highlands in which the overall altitude drops towards the west. North of the Dřevnice River, the highest peak reaches 423 m asl. The river network is formed by streams that generally trend N-S, and these are fed by short, often seasonal, tributaries that trend E-W. South of the Dřevnice River, the highest peak reaches 458 m asl. The river network is more complex with the main streams generally trending E-W, and these are fed by short, straight, tributaries that trend N-S. The northern slopes of the main valley are mostly straight, at least 500 m long, with an average slope angle of ~ 10°. The southern slopes have distinct lower sections that may attain heights of 65 m, with an average slope angle of ~ 17°. The upper parts of these southern slopes are less steep.

The highest hill tops north of the main valley are formed by Lukov Member of the Soláň Formation (Fig. 1) compound mostly by sandstones. Similarly, highest hills south of the valley are formed by belts (Újezd Member of the Zlín Formation, Fig. 1) compound of medium to thick bedded sandstones with only thin clay stones layers. However, most the study area in underlain by belts that are composed of alternating sandstones and claystones (Vsetín Member of the Zlín Formation, Fig. 1). This formation, in particular the claystones, is highly susceptible to weathering. The Quaternary mantle typically comprises loess to the north of the main valley whilst deluvial sediments, containing a large portion of clay particles, are abundant across the whole study area.

The Dřevnice River valley is filled with Holocene fluvial deposits compound of gravels, sandy-gravels and, locally, with clay sediments which prevail in oxbow lakes causing high heterogeneity in basic mechanical properties of the soils (Krejčí, 1943). Remnants of Pleistocene river terraces are often covered by thick accumulation of slope sediments near the valley floor.

Within the study area, landslides and soil slips are mostly shallow with depths of up to 5 m and planar or compound shear planes (Fig. 2). Less abundant are deep-seated landslides with depths of more than 10 m and compound shear planes. Field observations suggest that landslides occur mainly in the thick deluvial sediments that are typical for the lower slopes or the uppermost parts of the valley (Kirchner, 2002). Specific hydrological conditions occur on the northern slopes of the main valley, where the remnants of river terraces are buried by deluvial sediments. The sediments accumulate underground water and this may subsequently initiate sliding of the overlying slope material (Krejčí, 1943). Therefore, the main conditions that determine landslide occurrence in the study area are the tectonic fragmentation of the bedrock, its lithological properties, and its susceptibility to weathering. The main triggering factor is precipitation, and this may be combined with snow thaw such as those that occurred in March 2006. The total cumulative precipitation calculated for this event reached 155 mm (Bíl and Müller, 2008). Anthropogenic activity often contributes to slope instability as a result of unloading at the toe of the slope or loading in its upper part.

3. METHODS

3.1. INPUT INFORMATION FOR THE SUSCEPTIBILITY ASSESSMENT

The input data layers used for the statistical susceptibility assessment comprised the landslide inventory, geology, slope angle, slope aspect, slope curvature, and distance from streams (Table 1). All the digital maps were converted into a grid format with a pixel resolution of 100 m^2.

The landslide inventory was prepared during field mapping undertaken predominately by the Czech Geological Survey. The study area was mapped by several scientists (Krejčí at al., 2008). Whilst this may negatively affect the homogeneity of the database, a single mapping methodology was applied (Rybář, 2001) and the maps were later verified in the field by independent persons.

The 1:10,000 maps depict landslides classified according their activity as active, temporarily inactive, or permanently inactive (Rybář, 2001). Features with dimensions of less than 50 m are shown only as points and, therefore, could not be used in the statistical susceptibility assessment. These small landslides include flow-type events that are generally less than 50 m, although such landslides are rare within the study area. No rockfalls have been recorded. The

Fig. 2 Examples of shallow landslides with planar shear planes mobilizing clay loam slope sediments and weathered, clay rich bed rock (Vsetín Member of the Zlín Formation), A – shallow (aprox. 1m deep) scarp area of landslide (photo by R. Novotný), B – 2.5m thick accumulation part of different landslide which damaged dirt road (photo by J. Klimeš).

Table 1 Description of the used input data layers (CGS - Czech geological survey, COSMC - Czech Office for Surveying, Mapping, and Cadastre).

Input Layer	Data Source	Original Scale	Raster Maps Resolution
Geology	CGS	1:50,000	10 m
Slope Angle	COSMC	1:10,000	10 m
Slope Aspect	COSMC	1:10,000	10 m
Slope Curvature	COSMC	1:10,000	10 m
Distance from Streams	COSMC	1:10,000	10 m

active and temporarily inactive landslides are mainly represented by landslides with transitional shear planes and depths of less than 4 m. The permanently inactive landslides are usually complex deep-seated landslides with depths of more than 5 m. For the susceptibility assessment, only the active and temporarily inactive landslides where used as the preparatory factors for the permanently inactive landslides differ significantly (Krejčí at al., 2002; Klimeš, 2007).

In total, the scarps of 286 landslides were incorporated into the susceptibility analysis. These were identified by the authors during field mapping and verification.

The landslide inventory map shows several cases of landslides that have been mapped on the steep erosional slopes, described earlier, predominately along the main river valley. Field checking has shown that in most cases these slopes represent an entire zone prone to landslides rather simply hosting individual landslides with well defined scarp and accumulation areas (Fig. 3). Consequently, this zone was also not included in the susceptibility assessment in order to keep the landslide database as homogenous as possible.

The available geological maps (at scale 1:50,000) show bedrocks covered by Quaternary sediments (Fig. 1), thus the geological units combine base rock formations and lithologicaly defined Quaternary sediments.

The slope angle, aspect, and curvature were derived from a digital elevation model (DEM) constructed from a 1:10,000 topographic map with contour lines every 5 m. The slope angle was classified into 5° class intervals. The slope aspect was classified into nine classes including flat areas. The slope curvature was classified into three classes representing concave, linear, and convex slopes following Havlín (2010). The distance to streams was classified into two classes with a 100 m break value defined on the basis of field observations relating to the maximum reach of the side erosion and length of the erosion slopes along the streams.

The input maps differ in their spatial accuracy due to varying scales. The most reliable is topographic map from which the DEM was constructed. The landslide inventory map has been drawn onto this topographic map and, thus, its spatial accuracy is also good. Far less reliable in terms of both spatial accuracy and thematic content is the geological map.

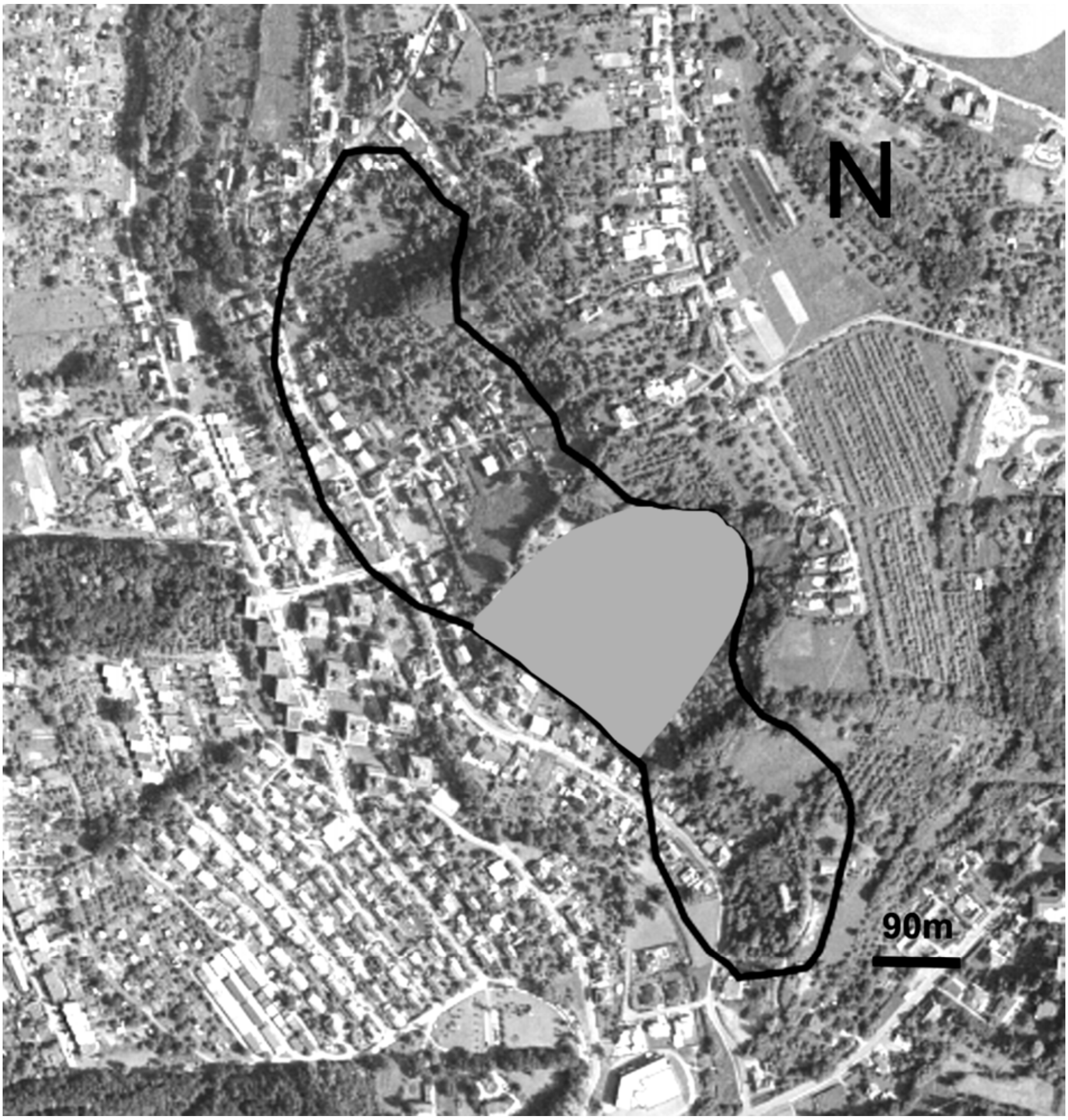

Fig. 3 An example showing landslide mapped in the original landslide inventory (solid black line) and landslide area identified during the field verification (grey shading). The aerial orthophoto map was provided by the Czech Office for Surveying, Mapping, and Cadastre (2006).

The main reason is its coarse map scale and also the fact that the geological units are defined on paleontological, rather than lithological, characteristics.

The percentage of the total scarp areas that occur within each preparatory factor class was calculated for each landslide type defined in the landslide inventory. Such information is useful to better understanding the relationship between landslides and their preparatory factors. From this, it was then possible to compare the results with previous studies undertaken in similar geological environments.

3.2. LANDSLIDE SUSCEPTIBILITY ASSESSMENT

The landslide susceptibility analysis was assessed by conditional analysis (Clerici et al., 2002), which calculates the probability of landslide occurrence (P) on each unique conditional unit (UCU). These units are prepared by combining all feature classes of each available preparatory factor maps at the same time, thus may be viewed as very basic multi-variety approach. The landslide dataset of the scarp areas was randomly divided into a training group containing 75 % (214 cases) of landslide scarps and a validation data set, containing the rest of the

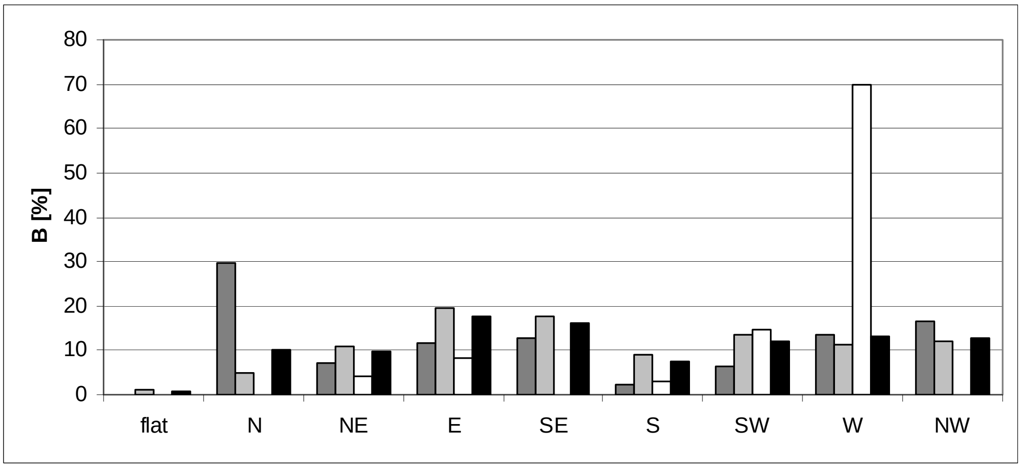

Fig. 4 Landslide distribution (% of total landslide area of each landslide type and all different types together) on geological units (A), slope aspect (B) and slope dip classes (C). (1 – undefined Quaternary sediments, 2 – antropogenic sediments, 3 – sand and gravel sediments, 4 - sandy-loamy to loamy-sandy sediments, 5 – boulderly sediments, 6 – alluvial sediments, 7 – loess, 8 – Luhačovice Member of the Zlín Formation, 9 – Vsetín Member of the Zlín Formation, 10 - Lukov Member of the Soláň Formation, 11 – Újezd Member of the Zlín Formation, 12 - Beloveža Formation, 13 – Menilit Member, 14 - Ráztocka Member of the Soláň Formation).

data (72 cases). Combining the available input factor maps resulted in 3,979 unique conditional units for which the landslide density was calculated:

$$P(L/UCU) = A_L/A_{UCU}$$

Where (P) is the probability of landslide (L) occurrence given a unique combination of factors (UCU) defined by the landslide density in that specific UCU. A_L stands for landslide area in the UCU, A_{UCU} is area of respective UCU.

The resulting density of landslide occurrence was reclassified into three susceptibility classes: stable, conditionally stable, and unstable. Intervals of each susceptibility class were determined subjectively so the unstable class is capable of capturing maximum landslide scarps on minimum study area and the stable class contains minimum landslide scarps, which represent mistake of the model. The success rate curve was also used during the classification procedure. The regions assigned as stable are expected to be free of landslides, only accumulations of long run-out events may reach these areas. Slopes defined as conditionally stable, require certain conditions to be preserved to stay stable. Within unstable areas, one needs to expect landslide occurrence in a future under recent conditions of the preparatory factors.

4. RESULTS

4.1. *LANDSLIDE DISTRIBUTION ON PREPARATORY FACTOR MAPS*

The mapped landslides cover 4.4 % of the study area. Of the total area covered by landslides, 9 % are active, 23.5 % are complex, and 67.5 % are temporarily inactive. The distribution of landslide scarp areas over preparatory factor maps is shown in Figure 4. The distribution of different landslide types over the various geological units is quite similar. The majority of landside scarps occur within the Vsetín Member of the Zlín Formation, which has the greatest amount of easily weathered claystones. A second important geological units are the boulder slope sediments that cover most of the shallow slope valleys. Here, water may accumulate easily and cause landsliding. The uniform landslide distribution on slopes with different aspects shows one anomaly in relation to both complex and active landslides. 70 % of complex landslides occur on westerly oriented slopes whilst 30 % of active landslides occur on northerly facing slopes. When evaluating the distribution of all the different landslide types, 33.8 % of scarp areas occur on easterly and northeasterly slopes with the fewest on southern slopes. The majority of active (43.6 %) and complex (50.0 %) landslide scarps are situated on slopes with angles of 10°-15°. The temporarily inactive landslide scarps are almost equally distributed on slopes with angles of 5°-10° (34.7 %) and 10°-15° (30.2 %).

The distribution of different landslide types on slope curvature classes is similar. Concave slopes contain 51.1 % and convex slopes contain 48.2 % of the total landslide area, with only 0.7 % on linear slopes. Concave slopes allow water and weathered material to accumulate and this leads to suitable conditions for landsliding. The majority of active (58.4 %) and temporarily inactive (68.3 %) landslides are situated more than 100 m from a stream whereas

Table 2 Results of the landslide susceptibility assessment.

	% of study area in susceptibility class	% of landslide **training** dataset area	% of landslide **validation** dataset area
Stable	50	1.1	8.6
Conditionally Stable	21.5	11.8	31.8
Unstable	28.5	87.1	59.6

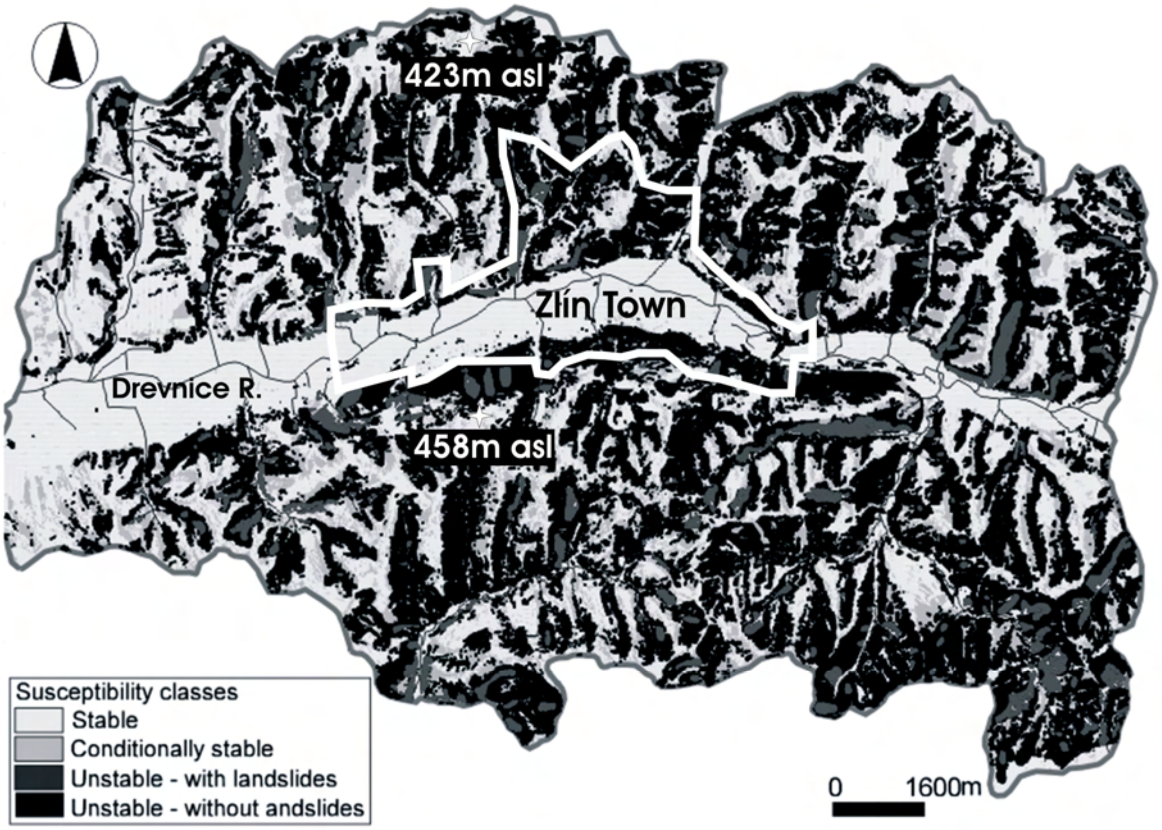

Fig. 5 The landslide susceptibility map based on unique condition analysis (streams are shown as thin solid black lines, white thick line limits the town of Zlín, R. – river).

72.9 % of complex landslides are situated less than 100 m from a stream.

The most susceptible UCU (with L > 0.1) defined for active and temporarily inactive landslides are characterized by a highly variable combination of environmental conditions. Geology is represented by the Vsetín or Menilit Members and sandy-loamy to loamy-sandy sediments on slopes. The lithological characteristics and geotechnical properties of these geological units vary significantly. The Vsetín Member covers 43 % of the whole study area. These geological conditions are combined with slope angles that vary from 15° to 40°, east and northwest slope aspects, and concave or linear slope curvature. In all cases, the UCU are characterized by more than a 100 m distance from the rivers.

4.2. LANDSLIDE SUSCEPTIBILITY ASSESSMENT

The unique conditional analysis susceptibility model performed very well in explaining the spatial distribution of landslides within the training dataset, but its capability to predict the spatial distribution of landslide scarp areas in the validation dataset dropped by more than 25 % (Table 2). The model was able to correctly depict 87.1 % of the landslides in the training dataset. The model error defined by pixels of landslide training dataset contained within the stable susceptibility class was only 1.1 %. Nevertheless, in the case of the validation datasets error increased up to 8.6 %.

The landslide susceptibility map for Zlín and its surrounding area is shown in Figure 5. It shows that a significant proportion of the northerly facing slopes within the main valley belong to the unstable susceptibility class as well as the southeastern part of the study area. Unstable slopes often follow streams that trend N-S, especially south of the main valley. This reflects the effect of slope aspect and distance to streams on landslide susceptibility. The map also shows unstable areas where no landslides have not been recorded so far. Those should be of particular interest to urban planners. It is evident that, in order to further develop the city, unstable areas are likely to be used for new construction.

The stable regions include the main valley floor where majority of the built up areas are presently located. Other stable parts of the study area include the flat ridges and other less steep slopes. These areas are particularly evident in the western part of the study area where more gentle relief prevails.

5. DISCUSSION

The quantitative description of landslide scarp area distribution on preparatory factor maps confirmed some of the observations on landslide occurrence recognised during field mapping of the study area. For example, Kirchner and Krejčí (2002) suggest that the majority of the landslides occur on easterly slopes. This is shown to be true when evaluating all landslide types at once although complex landslides are, in contrast, strongly associated with westerly slopes and active landslides are associated with the northerly slopes. The assumption that landslides occur mainly within deluvial sediments has also proved to be correct. The high landslide susceptibility of the Vsetín Member of the Zlín Formation has been demonstrated, presumably due to its susceptibility to rapid weathering that results from the high claystone content and tectonic fragmentation.

The distribution of landslides according to slope curvature classes contrasts with the findings of Havlín (2010). That study was also conducted in a highland area composed of flysch rocks of the Rača Unit of the Magura Nappe. However, in contrast to the finding presented here, the majority of the landslide area occurs on linear slopes (1 % in the present study/65 % in Havlín (2010)). This contrast may be explained by the fact that the whole landslide area, including its accumulation, was included in Havlín (2010). Such an approach does not correctly define the part of the landslide that best reflects the factors responsible for its initiation, which is so important when preparing a susceptibility map. To counter this problem, Poli and Sterlacchini (2007) suggest the use of points located within scarp areas to most appropriately describe relationship between predictor variables and landslides. Süzen and Doyuran (2004) use the “seed cells” concept in which a buffer zone around the source area defines the conditions that lead to landslide initiation. The landslide distribution according to slope angle is quite similar in both studies, with the majority of landslides (75.3 %) occurring on slopes of between 7° and 17° (Havlín, 2010).

The landslide susceptibility assessment has confirmed that the flysch region is highly prone to landsliding and that only a small proportion of the slopes may be considered to be stable. The presented results are similar to those obtained using a deterministic model on shallow landslides in the flysch region located ~ 50 km to the northeast of this study area (Klimeš, 2008) as well as to the region mapped by Havlín (2010). In those studies, the unstable or very high susceptibility classes represent between 22 % and 25.54 % of the study area. Whilst the unstable susceptibility class represents that part of the slope that is most prone to landslide initiation, the landslide is likely to move downslope or extend upslope due to retrogressive scarp movement. In the second case, areas originally identified as stable may be involved in the landslide movement which needs to be considered when applying results of the susceptibility mapping.

Evaluation of the most susceptible UCU shows that variable environmental conditions are important for the occurrence of landslides. This may explain why such a large proportion of the study area has been defined as unstable. It may be that the environmental conditions in which the landslides develop are not constrained sufficiently by the available spatial data. To counter this problem it may be possible to increase the number of the preparatory factors or to improve the spatial resolution of the data through more detailed field mapping. The latter of these is especially desirable with regard to the geology as important lithological details are missing.

The percentage of buildings, as shown on the 1:10,000 topographic maps, situated within the unstable susceptibility class is low (16.1 %) whilst the majority are situated within the stable class (73 %). However, the percentage of residential buildings situated within the unstable susceptibility class is greater as many of the buildings within the stable susceptibility class are industrial or administrative located along main river valley.

The spatial probability of building being struck by a landslide may be quantified using the spatial distribution of the active landslides in the inventory mapping. To do this, two assumptions have to be accepted and these may not hold true. First, a similar area will be mobilized by landslides during a future single landslide initiating event. Second, all these landslides will occur within the unstable susceptibility class. The actual landslide area that develops during a single landslide event is unknown and may be larger or smaller than the one captured in the landslide inventory. It is also clear that not all new landslides

Fig. 6 Relationship between landslide susceptibility zoning and future development area (D) found on the south slopes of the Dřevnice River valley.

will occur within the unstable susceptibility class. Therefore, the calculated spatial probability should be considered rather as a pessimistic scenario for future development. It can be calculated as a ratio of the area covered by the active landslides and the area covered by buildings on the unstable susceptibility class. The calculated spatial probability is 1.10^{-2}. Whilst this figure is low, urban planners should nevertheless carefully consider the stability conditions in order to avoid possible damage caused by landslides due to inappropriate development. Damage is likely to increase significantly by increasing the building density on unstable slopes.

The applied statistical approach for landslide susceptibility assessment allows an evaluation of the preparatory factors that contribute to landslide susceptibility at the pixel scale (Fig. 6). The evaluation of such information for each suggested construction site by an experienced geologist may serve as the basis for further steps in landslide mitigation. Those may include a detailed engineering geological evaluation and the design of specific landslide mitigation measures. A practical example of this approach is illustrated in Figure 6. This shows intention to develop an area that was identified by the model as unstable despite no previous landslides recorded (D in Figure 6). An experienced geologist may use the information about UCU variable classes to evaluate where to perform further field investigations and which sites to avoid completely.

6. CONCLUSIONS

Performed multi-variety landslide susceptibility assessment for the urbanized area within flysch highlands of the Outer Western Carpathians proved high susceptibility of the region to the landsliding. Objective evaluation of the landslide distribution over preparatory factor maps largely confirmed previous assumptions based on field investigation as well as previous studies. The most important factor for landslide occurrence based on analyzed information is the occurrence of the bedrock (Vsetín Member of the Zlín Formation) highly susceptible to weathering due to lithological and tectonic characteristics. Secondly, thick slope sediments contribute to the conditions suitable for landslide occurrence. The statistical analysis undertaken in this study has shown that such an approach is able to rank landslide susceptibility on slopes where no evidence of previous landslide activity can be recognized. This represents a significant advance on the recently prepared expert based susceptibility maps

ACKNOWLEDGEMENT

Authors would like to acknowledge the financial support provided by Czech Grant Agency (Grant No. 205/09/P383).

REFERENCES

Baldík, V., Havlín, A., Kašperáková, D., Kirchner, K., Klimeš, J., Krejčí, O., Repková, H., Slavík, M. and Vít, J.: 2006, Svahové nestability vzniklé jako důsledek extrémního jarního tání v březnu a dubnu 2006 (Slope instabilities triggered by extream spring thawing in April and March 2006), MS, ČGS, Praha, Brno, CD, (in Czech).

Bíl, M. and Müller, I.: 2008, The origin of shallow landslides in Moravia (Czech Republic) in the spring 2006. Geomorphology, 99, 246–253.

Blahut, J., van Westen, C.J. and Sterlacchini, S.: 2010, Analysis of landslide inventories for accurate prediction of debris flows source areas. Geomorphology, 119, 36–51.

Chacón, J., Irigaray, C., Fernández, T. and El Hamdouni, R.: 2006, Engineering geology maps: landslides and geographical information systems. Bull Eng Geol Environ 65, 341–411.

Clerici, A., Perego, S., Tellini, C., Vescovi, P.: 2002, A procedure for landslide susceptibility zonation by the conditional analysis method. Geomorphology, 48, 349–364.

Havlín, A.: 2010, Hodnocení náchylnosti k sesouvání ve střední části Chřibů (Landslide susceptibility assessment in the middle part of the Chřiby). Geotechnika 3-4, 3–9, (in Czech).

Kirchner, K.: 2002, To the distribution of slope deformations in the notheastern vicinity of Zlín town, Vizovická vrchovina Highland (Outer Western Carpathians). In: Rybář J., Stemberk J., Wagner P. (eds.): Landslides, A.A. Balkema, Lisse, 363–366.

Kirchner, K. and Krejčí, O.: 2002, Slope movements in the Flysch Carpathians of eastern Czech Republic triggered by extreme rainfalls in 1997: a case study. Physics and Chemistry of the Earth 27, 3, 1567–1576.

Klimeš, J.: 2007, Analýza podmínek vzniku svahových deformací ve Vsetínských vrších (Analysis of preparatory factors of landslides, Vsetínské vrchy Highland). MS Ph.D. thesis, Katedra fyzické geografie a geoekologie, PřF UK, Praha, (in Czech).

Klimeš, J.: 2008, Deterministický model náchylnosti území ke vzniku svahových deformací ve Vsetínských vrších (Use of the deterministic approach for the landslide susceptibility mapping, Vsetínské vrchy Highland, Czechia. Geografie, 113, 1, 48–60, (in Czech).

Krejčí, J.: 1943, Sesuvná území na Zlínsku (Landslides in the area of Zlín). Práce Moravské přírodovědecké společnosti. XV., 10, 1–21, (in Czech).

Krejčí, O., Baroň, I., Bíl, M., Hubatka, F., Jurová, Z. and Kirchner, K.: 2002, Slope movements in the Flysch Carpathians of Eastern Czech Republic triggered by extreme rainfalls in 1997: a case study. Physics and Chemistry of the Earth, 27, 1567–1576.

Krejčí, O., Kycl, P., Baroň, I., Šikula, J., Čoupek, P., Moravcová, O., Petrová, V., Krejčí, Z., Zemková, M., Kašperáková, D., Rybář, J., Kirchner, K., Klimeš, J., Hubatka, F., Nešvara, P., Sekyra, Z., Bíl, M. and Bílová, M.: 2008, Dokumentace a mapování svahových pohybů v ČR, podprogram ISPROFIN č. 215124-1, Přehled provedených prací (Description and mapping of landslides in the Czech Republic, project ISPOFIN no. 215124-1, overview of the works). MS, MS ČGS Brno, Praha, 114, (in Czech).

Krejčí, O., Bíl, M., Havlín, A., Kašpárek, M., Klimeš, J., Petrová, V. and Šikula, J.: 2010, Hodnocení svahových nestabilit ve Zlínském kraji po extrémních srážkách v květnu a červnu 2010 (Assessment of landslides in the Zlín Region after extreme rainfalls from May and July 2010). MS, ČGS Brno, Praha, 18, (in Czech).

Mihai, B., Sandric, I., Savulescu, I. and Chitu, Z.: 2010, Detailed mapping of landslide susceptibility for urban planning purposes in Carpathian and Subcarpathian towns of Romania. In: Gartner G., Ortag, F. (eds.): Cartography in Central and Eastern Europe, Lecture Notes on Geoinformatics and Cartography, Springer Verlag, 417–427.

Poli, S. and Sterlacchini, S.: 2007, Landslide representation strategies in susceptibility studies using weights-of-evidence modeling technique. Natural Resources Research, 16, 2, 121–134.

Rybář,J. and Stemberk, J.: 2000, Avalanche-like occurrences of slope deformations in the Czech Republic and coping with their consequences. Landslide News, 13, 28-33.

Rybář, J.: 2001, Mapy náchylnosti území k sesouvání v České republice (Landslide susceptibility maps in the Czech Republic). Zborník referátov z 2. konferencie: “Geológia a životné prostredie“, Bratislava, 24.–25. 1. 2001, Vydavatelstvo Dionýza Štůra, Bratislava, 22–24, (in Czech).

Schuster, R.L. and Hihland, L.M.: 2007, The third Hans Cloos Lecture. Urban landslides: socioeconomic impacts and overview of mitigative strategies. Bull Eng Geol Environ 66, 1–27.

Süzen, M.L. and Doyuran, V.: 2004, Data driven bivariate landslide susceptibility assessment using geographical information systems: a method and application to Asarsuyu catchment, Turkey. Eng Geol 71, 303–321.

Šikula, J., Krejčí, O., Nývlt, D., Novotný, R., Havlín, A., Hroch, T., Malík, J., Baldík, V., Poul, I. and Petrová, V.: 2010, Dokumentace svahových nestabilit v Moravskoslezském kraji po přívalových srážkách v květnu 2010 (Identification of landslides in the Moravskoslezský Region after torrential rainfalls in May 2010). MS ČGS Brno, 320, (in Czech).

Van Den Eeckhaut, M., Vanwallegem, T., Poesen, J., Govers, G., Verstraeten, G. and Vandekerckhove, L.: 2006, Prediction of landslide susceptibility using rare events logistic regression: A case-study in the Flemish Ardennes (Belgium). Geomorphology, 76, 411–429.

Záruba, Q. and Mencl, V.:1982, Landslides and their control. Praha, 2nd edition, Academia, 324.