Charles University in Prague

Faculty of Science

Department of Physical Geography and Geoecology

<u>Analysis of preparatory factors of landslides, Vsetínské vrchy Highland, Czech Republic</u>

Summary of the Ph.D. Thesis

Mgr. Jan Klimeš

Prague, 2007

The work is seeking the most accurate spatial prediction of landslide occurrence in regional scale through field mapping of present day as well as previous landslide activity and identifying the most susceptible parts of the study area by the means of GIS based landslide susceptibility models. Several types of models are used to evaluate susceptibility of the studied region. Their results are compared by different validation techniques and along with detailed knowledge of the local geomorphologic conditions are used to outline methodology for the best fitted susceptibility map of the area under study.

The importance of the landsliding for the recent landscape evolution was evaluated through describing the contribution of the landslides to the erosion rates of the study area under conditions of heavy rainfalls.

The study area lays in the Outer Western Carpathians and covers the geomorphic districts of the Vsetínské vrchy Highland and part of the Rožnovská brázda (Demek et al. 1987), which are spreading east and north east of the city of Vsetín situated close to the border with Slovak Republic. This area is formed by flysh rocks with highly variable composition of the competent, permeable sandstone layers and plastic, rather impermeable claystones and siltstones. This area was subject to the avalanche like occurrence of mostly shallow landslides during the floods provoked by heavy rains occurred between 4. – 8.7. and 17. – 21.7. 1997 (Rybář, Stemberk 2000).

Several data acquisition techniques were employed to acquire necessary data about landslides originated during the July 1997 rainfall event as well as evidences of previous landslide occurrences. The techniques included aerial photo interpretation and field mapping using mobile GIS technology (ArcPad 5.0.1 software by ESRI and palm top computer iPAQ Compaq) and conventional geomorphologic mapping. The aim of the field work was to gain detailed knowledge about existing landslides within the selected part of the study area and to map important preparatory factors influencing their occurrence. The original data were integrated with available landslide inventory maps to produce several new inventory maps used for the preparation of the landslide susceptibility models. The historical inventory map includes all available information about landslide occurrence prior the rainfall event in 1997. The map was compiled from the results of the field work, data from national landslide inventory database maintained by Geofond and results of detailed landslide inventory mapping managed by CGS (Czech Geologic Survey). Separately was stored information about landslides which occurred during the 1997 rainfall event, from which the specific inventory for the use of SINMAP project was prepared. This inventory had to satisfy requirements of the SINAMP model, therefore all landslides which occurrence was governed by other causes than the accumulation of water due to shallow sub-surface water flow, had to be eliminated. The selection was done for the most of the study area without detailed knowledge about individual landslides, but the model results prove that the selection was successful.

The susceptibility of the study area was evaluated using different models ranging from the basic to the more sophisticated deterministic and statistical ones. The historical inventory map and slope map were used as basic susceptibility models. Later, the bi-variant statistical model proposed by Carrara et al. (1995) and deterministic SINMAP model (Pack et al. 1998) were employed. All the models were pixel-based with the 10 m x 10 m pixel dimensions. The most important model input data are landslide inventory represented by points and DEM (digital elevation model) for the SINMAP model and historical inventory map with geologic, soil, slope, aspect and distance to the tectonic lines preparatory factors maps for the bi-variant statistical model.

The final susceptibility of the studied area was represented for each of the susceptibility maps by occurrence of the landslides in the historical inventory map, slope classes of the slope map, value of factor of safety (FS) for the SINMAP model and value of calculated resulted weight (RW) for the results of the statistical model. The RW was calculated by following formula:

$$RW = W_{pf1}*FR_{cl1} + W_{pf2}*FR_{cl1} + W_{pf3}*FR_{cl1} + W_{pf4}*FR_{cl1} + ...$$

W_{pf1} is the weight of the first preparatory factor map (e.g. geologic or slope map) and the FR_{cl1} is the failure rate (Wieczorek 1994) of the first class of the first preparatory factor map (e.g. 0°- 5° for the slope map).

Apart from the susceptibility mapping, separate evaluation of each preparatory factors was made calculating the failure rate. This evaluation was used to compare susceptibility of each preparatory factor for the landslides included in the historical and July 1997 inventory maps. For the later one, separate evaluation of the susceptibility conditions among landslide scar and accumulation areas was performed.

Results of each model represented by landslide susceptibility map were evaluated calculating landslide densities for each susceptibility class and also their predictive power (Chung, Fabbri 2003). The time partitioning of the known landslides and evaluation of the successful prediction by comparing the portion of the study area defined as "unstable" necessary to capture majority of the predicted landslides, were also used. The latest approach allows to defined "mistake" of the model represented by the portion of the total landslide area or number belonging to the stable class of the susceptibility map. The evaluation of each model is considered the crucial part of the model construction.

Definition of the susceptibility classes should not only classify the predictive values (e.g. FS or RW) calculated by the models, but also needs to explain meaning of each susceptibility class for the users. The classification of the FS values calculated by the SINMAP model, are shown in the table 1. The resulted values of RW index were classified individually for each model.

Tab. 1 Susceptibility class's definition for the SINMAP model is using calculated value of the factor of safety (FS).

value of factor of safety (FS)	**susceptibility class**
FS > 1,25	stable
1,25 > FS > 1	conditionally stable
1 > FS > 0	unstable

Explanation of the used susceptibility class, which were shown on the susceptibility maps with the traffic light colors are as follows:

• **Stable** – occurrence of landslides is almost excluded, in some cases, only the accumulation parts of the landslides may reach this zone.

• **Conditionally stable** – it is not possible excluded occurrence of the landslides in this zone.

• **Unstable** – parts of the study area with the most suitable conditions for occurrence of the landslides, the landslide occurrence is only the matter of time range of the prediction. The landslide susceptibility map based on the historical inventory map has only two susceptibility classes – stable for areas with now evidence of previous landsliding and unstable for the areas where landslides were identified.

Results

Extend (in terms of number as well as area) and claimed looses of the landslide event from the July 1997 can not be compared with another known event from the study area. Calculation of landslide event magnitude (Malamud et al. 2004a) was used to compare its extreme nature with other landslide events. The resulted magnitude based on area of identified landslides is 2.9 and the magnitude based on their number is 3.2. The magnitudes of landslide events presented in Malamud et al. (2004a) ranged between 3.6 and 4 for both ways of landslide event magnitude calculation.

Qualitative evaluation of the effects of the July 1997 landslide event on the sediment transport in the studied area was made indirectly, through the evaluation of portion of the studied area covered by the landslides from July 1997, their average run-out distance and observed stream's transport capability. The analogy with results from comparable areas was also used for the evaluation. The highest occurrence of July 1997 landslides was found in the Raťkov basin, where they covered 0.8 % of its area. Comparison of the average run-out distance of the mapped landslides (which is 129 m) and distance of their scarp areas from streams showed, that only 25% of the accumulations could reach the valley bottoms and may serve as direct input of the sediment to the river system. The field investigation also proved that the streams, in many cases, were not able to remove substantial part of the landslide accumulations from the river beds. This observation was made several years after the July 1997 rainfall event. Results from comparable areas (Catani et al. 2005) also strengthen the conclusions that the July 1997 landslides did not contributed substantially to the overall river sediment load which reached extreme values during the July 1997 rainfall event (Hrádek 2000, Hladký ed. 1998).

Comparison of the landslide susceptibility maps (tab. 2) shows that most successful map was constructed based on the historical inventory map. This map was able to capture 70% of the total landslide are within 14% of the studied region defined as unstable. This class was defined by the bodies of mapped landslides and 75 m wide buffers around them. The results of the SINMAP model were mostly affected by the morfometric characteristics of three calibration regions into which the entire study area was divided. The best results were gained in the calibration region with the lowest average slope and occurrence of the structural ridges with steep slopes that highly contrast with otherwise gently rolled relief of that region. Considerably worst results were gained in the regions with higher average slope, but without high contrast in the relief topography. Interesting is also finding that the SINMAP model was considerably better than the results of susceptibility map based on the slope map. This finding is contrary to the results gained in the Aquasparta region (Umbria, Italy), where the slope map and SINMAP model achieved similar results (Klimeš 2003).

Tab. 2 Landslide densities for the susceptibility classes of used landslide susceptibility models (l. – landslides, * evaluated for the „unknown“ landslides, which were not used for the model preparation).

Model/susceptibility class	Landslide densities calculated for the areas of landslides and susceptibility classes		
	stable	conditionally stable	unstable
slope map	0,3	0,8	1,3
historical l. inventory map	0,8	not available	4,7
historical l. inventory map with buffer of 75 m	0,4	not available	5
statistical model	0,6*	0,5*	1,7*
SINMAP model - region 1	0,5	1	1,8
SINMAP model - region 2	0,4	0,8	3
SINMAP model - region 3	0,5	1	2,2

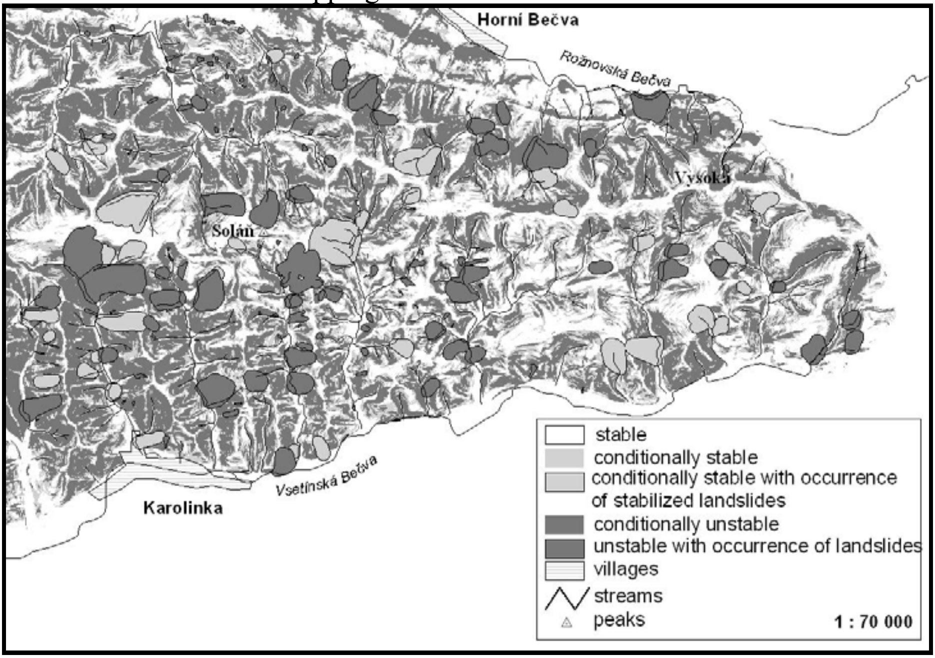
The worst results were gained by the bi-variant statistical model which tested the use of historical inventory map for prediction of the landslides originated in July 1997. The low performance could be partly explained by the presence of the distinct landslide type in the historical inventory, which did not occur during July 1997 event. Another source of errors was poorly defined weights of some of the preparatory factor input layers (defined through analytic hierarchy process, Saaty 1990) and insufficient spatial resolution of the majority of the preparatory factor maps. Results of the statistical model showed that the highly variable lithological and structural conditions of the studied region are very difficult to capture in the regional scale and available geologic maps are not sufficient. At the same time, even frequency distribution of the slope classes leads to formation of large zones with homogenous susceptibility conditions. Therefore to specify the most susceptible areas is very difficult.

The detailed analyses of the susceptibility of each preparatory factor map separately for the scarp and accumulation areas proved differences especially for the geologic conditions and slope dips. Ignoring these differences may also contributed to the low performance of the bi-variant statistical model.

New methodology for preparation of landslide susceptibility maps of the Vsetínské vrchy Highland was suggested. The example of the map constructed by the new methodology is shown on the figure 1. Each stability classes are defined as follows:

- **Stable** – occurrence of landslides is almost excluded, in some cases, only the accumulation parts of the landslides may reach this zone.
- **Conditionally stable** – areas where the stabilized landslides were identified and where it is not possible to excluded occurrence of the new landslides based on results of statistical or deterministic landslide susceptibility models.
- **Conditionally unstable** – areas with the highest susceptibility defined by statistical or deterministic landslide susceptibility models.
- **Unstable** – areas with identified active or potentially active landslides in the initial or developed states of their evolution.

Fig. 1 Landslide susceptibility map of the Vsetínské vrchy Highland prepared according the new definition of the susceptibility classes. The conditionally unstable class was defined using the SINMAP model and detailed field landslide mapping.



References

Carrara, A., Cardinali, M., Guzzetti, F., Reichenbach, P., (1995): GIS technology in mapping landside hazard. In: Carrara, A., Guzzetti, F. (eds.): Geographical information systems in assessing natural hazards, Kluwer Acad. Publ., Dordrecht, p. 135-176.

Catani, F., Lombardi, L., Menci, S., Moretti, S. (2005): Erosion rates assessment in landslides prone areas. Geophysical Research Abstracts, Vol. 7, Abstracts of the contributions of the EGU General Assemby Vienna, Austria, 24. – 29. 4. 2005, EGU 2005, CD ISSN: 1029-7006.

Demek, J. et al. (1987): Zeměpisný lexikon ČSR. Hory a nížiny. Praha, Academia, 584 p.

Chung, Ch-J. F., Fabbri, A. G. (2003): Validation of spatial prediction models for landslide hazard mapping. Natural Hazards, 30, Kluwer Academic Publishers, Netherlands, p. 451 – 472.

Hladký, J. ed. (1998): Vyhodnocení povodňové situace v červenci 1997 – souhrnná zpráva projektu MŽP ČR. MŽP ČR, Praha, http://www.chmi.cz/hydro/souhrn/obsah.html.

Hrádek, M. (2000): Geomorfologické účinky povodně včervenci 1997 na území Severní Moravy a Slezka. Geografický časopis, 54, 2000, 4, s. 303 – 317.

Klimeš, J. (2003): Zhodnocení vlivu geologických podmínek na vznik a prostorové rozmístění svahových deformací s využitím účelových inženýrskogeologických map stabilitních poměrů a technologie GIS. MS, ČGS, Brno, 32 s.

Malamud, B. D., Turcotte, D. L., Guzzetti, F., Reichenbach, P. (2004): Landslide inventories and their statistical properties. Earth Surface Processes and Landforms 29, p. 687-711.

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

Saaty, T.(1990): The Analytic Hierarchy Processes. RWS Publ, Pittsburgh, 190 p.