Carpathian Journal of Earth and Environmental Sciences, May 2012, Vol. 7, No. 2, p. 83 - 92

GIS SUSCEPTIBILITY MAPS FOR SHALLOW LANDSLIDES: A CASE STUDY IN TRANSYLVANIA, ROMANIA

Corina NICORICI[1], James GRAY[1], Alexandru M. IMBROANE[2] & Mihail BARBOSU[3]
[1]University of Montreal, Dept. of Geography, 520 Chemin de la Côte-Ste-Catherine, Montreal, Canada, corina.nicorici@mtq.gouv.qc.ca, grayj@geog.umontreal.ca
[2]Babes-Bolyai University, Faculty of Geography, Clinicilor str. 5-7, Cluj-Napoca, Romania, alex@geografie.ubbcluj.ro
[3]State University of New York at Brockport, Dept. of Mathematics, 350 New Campus Dr., Brockport, NY, USA, mbarbosu@brockport.edu

Abstract: The *Geographical Information System* (GIS) has become an important tool for landslide susceptibility mapping because it provides an efficient way of handling, processing and analyzing geospatial data. This paper reports a GIS model based on the *factor of safety* in order to generate susceptibility maps for shallow landslides in an area located within the Transylvanian Basin, Romania. The latter, most frequently involve reactivation of pre-existing escarpments associated with former deep-seated landslides known locally as glimee. The computation of the factor of safety is made using spatially variable parameters that include soil cohesion and angle of internal friction, the position of the water table and the bulk density of the material. This study is the first of this kind for the study area and has the advantage of being interactive, giving the user the opportunity to change the parameters.

Keywords: landslides, susceptibility maps, factor of safety, GIS, Transylvanian basin

1. INTRODUCTION

1.1. Landslides in Transylvania

Landslides on various scales have been an important element of the Romanian landscape and scientific literature (Ciupagea et al., 1970; Mac, 1970; Mac et al., 2003; Garbacea & Grecu, 1983; Grecu, 1985; Irimus, 1997; Surdeanu, 2001). Ancient massive and deep-seated landslides referred to locally as glimee (de Martonne, 1951; Morariu, 1974), occurred in restricted areas but displaced an important volume of material, such as 0.39 km^3 for the landslide Movile (Grecu, 1997). These ***glimee*** landslides affected the regolith and the geological substratum to a depth of several decametres. They display ridges transversal to the regional slope, forming a wave-like morphology. The surface affected by such glimee frequently exceeds 15 km^2, their length attains 5-7 km and the relative height of the individual waves may reach 60-80 m (Morariu, 1974). The waves diminish in amplitude towards the toe of the landslides, disappearing in an outrun zone, referred to by Grecu (1985) as a landslide glacis. Micro-depressions with marshes and ponds characterize zones between the wave crests. Glimee landslides are generally covered by pastureland and forest and appear to be relatively stable at the present day, but have the potential to be locally reactivated along the escarpments associated with wave crests, during periods of excessive rainfall (Garbacea & Grecu, 1983). The present paper focuses on the susceptibility of glimee escarpments, and other slopes to such reactivations, in the form of translational shallow landslides.

1.2. Landslide hazard mapping

Landslide hazard can be considered as a particular case of natural hazard, defined by Varnes (1984) as “the probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon”. Another definition, by Fell (1994), emphasizes the complexity of the question, the landslide hazard being expressed as the frequency of occurrence of landslides of a particular type, the volume of material moved and the velocity. Furthermore, in some cases it has been expressed as the frequency of landslides with a particular intensity, where intensity can be measured in kinetic energy terms. These phenomena can be represented spatially in the form of a **landslide hazard map**, which can be very basic, using only the locations of old landslides to indicate potential instability, or very complex, incorporating probabilities based on multiple variables, such as rainfall threshold, slope angle, soil type, and potential intensity of earthquakes (Varnes et al., 1984). Van Westen et al. (2006) present recent approaches to landslide hazard, including challenges on the generation of landslide inventory maps and quantification of landslide risk.

Landslide hazard is governed by ***quasi-static variables*** (such as slope and geotechnical properties) which contribute to **landslide susceptibility,** and by ***dynamic variables*** (such as rainfall and earthquakes) which tend to trigger landslides in an area of susceptibility (Dai & Lee, 2001; Fell et al., 2005; Wu & Sidle, 1995; Atkinson & Massari, 1998).

There have been examples of landslide susceptibility and hazard maps in use since the 1970's: Brabb et al., 1972; Nilsen & Wright, 1979; Kienholz, 1978, etc. Taking into account quasi-static variables, Aleotti & Chowdhury (1999) developed a study on **landslide susceptibility maps**. These maps show where landslides may occur, illustrating different degrees of slope stability, that range from stable to unstable. In recent years, examples of susceptibility maps are presented by Corominas et al., 2003 for the Principality of Andorra, Fall et al., 2006 for the Dakar coastal region, and Maquaire et al., 2006 for the Southern Alps in France. Although many maps deal with new landslide hazard areas, a frequently occurring phenomenon that needs to be studied is the reactivation of pre-existing landslides (Catani et al., 2005). Examples of maps of landslide reactivation hazard are found in Barredo et al., (2000), Vaunat & Leroueil (2002), Chung & Glade (2004).

At a higher level of sophistication, a **landslide risk map** can be considered. This is an output which combines a landslide hazard map with the potential damage to persons and property. In some cases, where there are many records of landslide occurrences, maps can also incorporate an element of temporal probability of occurrence (Fell et al., 2005).

Several authors consider four different approaches to the assessment and cartographic representation of landslide hazard:

1) landslide inventory-based probabilistic approach;

2) heuristic (which can be direct geomorphological mapping or indirect qualitative map combination);

3) statistical (bivariate or multivariate statistics);

4) deterministic approach (Soeters & Van Westen, 1996; Aleotti & Chowdhury, 1999; Guzzetti et al., 1999).

The use of the deterministic model leads to hazard maps. Deterministic models combined with the magnitude/frequency information of triggering events (rainfall, earthquakes) make it possible to derive a probability of failure, which can then be used in risk analysis (Van Westen & Terlien, 1996).

A frequently used method for the deterministic model in a GIS environment is the infinite slope model (Ward et al., 1982; Brass et al., 1989; Murphy & Vita-Finzi, 1991). Slope instability is determined here on a pixel basis and this technique is appropriate in the study of shallow translational landslides (Van Westen & Terlien, 1996).

The aim of this paper is to present such a deterministic model, applicable to shallow landslide susceptibility mapping in the north-western Transylvanian Basin. A factor of safety (*FS*) approach to landslide susceptibility will be used, with input of measured and theoretical geotechnical parameters for individual field sites, with subsequent area extrapolation, using soil and topographic maps.

2. DESCRIPTION OF THE STUDY AREA

The study area in north-western Transylvania is delimited in extent by a Quickbird satellite image, covering an area of 15 km^2, centred at Fanatele Clujului, 3 km north of the city of Cluj-Napoca.

2.1. Geological context

The geology of the study area creates favourable conditions to triggering of both the deep-seated landslides and shallow landslides (Mac & Buzila, 2003).

The Transylvanian Basin is situated within the broad sweeping arc of the Carpathian Mountains. Its genesis began with the slow sinking of a relatively broad Mesozoic crystalline terrain, which resulted in the deposition in a progressively deepening basin of a thick sequence of marine sedimentary rocks of Miocene and Pliocene age. The middle Miocene is composed of coarse-grained fan delta conglomerates and deep marine deposits interspersed with tuff horizons (Krézsek & Filipescu, 2005).

The upper Miocene is represented by sandstones, clay rich marls and conglomerates of the Badenian and Sarmatian formations. Most of the upper Miocene deposits have been eroded due to late Miocene to Pliocene south-eastward down warping of the Transylvanian Basin (De Broucker et al., 1998; Krézsek & Filipescu, 2005), and regional Pliocene uplift and erosion of the Eastern Carpathians (Sanders et al., 1999). Regionally, these sedimentary units are characterized by a series of gently undulating folds at the margin of the Western Carpathians. Local upwarping is governed by the distribution of salt layers or domes, related to the thickness and plasticity of the salt, and on the mineralogical composition and the structure of the overlying deposits. Generally, the dip of these salt dome structures is very gentle, varying between 1°and 7° (Ciupagea et al., 1970, Mac, 1997).

The alternation of weakly consolidated clays and marls with sandstone, conglomerate and tuff layers, facilitate the development of planes of weakness and permit the infiltration of water. The large number of massive landslides (glimee) is frequently associated with thin permeable strata, composed of volcanic tuffs, conglomerates and slightly cemented sands, at the base of which are impermeable marls and clays. The active circulation of ground water through these surface horizons was a key factor in triggering these massive landslides (Pop, 2001; Ciupagea et al., 1970). The clay strata are impermeable, maintaining and guiding overland flow and thus contributing to linear erosion and gully formation. However, their potential to absorb water and become plastically transformed, thus triggering landslides, is also important (Irimus & Mac, 2004). Another important factor is the intense alteration of the argillaceous units, which have become enriched in landslide susceptible swelling clays, mainly montmorillonite, but also, illite, baidelite and calcite, and which have also undergone a quantitative reduction by dissolution of their carbonate component. Montmorillonite has a maximum concentration of 36-41% in the clay mineral fraction of the Pannonian unit, whilst in the Sarmatian one it attains only 13%. Kaolinite attains concentrations up to 20% and 5% respectively in the Pannonian and Sarmatian units (Mârza & Mészáros, 1991).

In the study area there is a monoclinal structure with a succession of cuestas. Their inclination varies between 3 to 80 degrees and they are separated by subsequent asymmetric valleys. The majority of landslides occurred on the gently dipping flanks of the individual folds (Mac, 1997).

2.2. Climatic and vegetational context

Climatic conditions of the region are a potentially important factor in landslide occurrence. The Transylvanian Basin possesses a temperate continental climate, characterized by an annual average temperature of 8°C and annual precipitation of approximately 550 mm (Pop, 2001). Periodically, heavy rainfall or a consistent snow cover is a potential triggering factor for landslides.

Vegetation cover may reduce or increase erosion, and it can even generate shallow landslides (Surdeanu, 2001). The most commonly held view, summarized by Gray (1970) is that vegetation increases slope stability by mechanical reinforcement in the form of a network of plant roots and modification of soil moisture conditions and the water table, leading to reduced pore water pressures. The loss of root strength and/or increased soil moisture content after tree removal can lower the slope safety factor sufficiently, so that a moderate storm and associated rise in pore water pressure can result in slope failure.

2.3. The anthropic factor

This factor also plays an important role in the occurrence of shallow landslides. The main anthropic actions that influenced our area of study are the clearing of forest cover of the escarpment and the excessive pasturing of animals on the slopes.

Most villages and roads are situated at the margin of the glimee area. In certain instances, they are located in the depressions between the wave-like crests of the landslide (e.g. Aiton, Heria), where the underground water sheet can be a water-supply source for the population (Grecu, 1997).

3. MORPHOLOGY OF FANATELE CLUJULUI LANDSLIDE

The Fanatele Clujului landslide zone (Fig. 1) is on a south-eastward oriented dip slope, characterized by the presence of thick layers of marl and volcanic tuff, as well as thinner layers of clays, sands and sandstone, all associated with the lower part of the Badenian formation. It is a typical example of a "glimee" landslide with multiple sliding planes, generated along the marl and clay layers. Although the Fanatele Clujului glimee is generally a stabilized landslide, several shallow landslides (Fig. 2) have recently been observed in the area, especially on the old pre-existing scarps.

Figure 1. The Fanatele Clujului landslide

Figure 2. Example of a recent re-activation as a shallow landslide

They occurred during exceptionally wet seasons, such as snow thawing in early March, or after maximum mid-summer rainfall. Multiple back-scarps can be identified, extending over a total width of 500 m. Below the scarps, a sequence of four main transversal ridges and intervening depressions define a wave-like morphology. The main scarp is 80 m relative high, with a slope of 84° and is covered by forest. The first wave-crest is situated 120 m distally from the main scarp and has a relative height of 28 m. The second wave-crest is situated 60 m further downslope, and is 20 m high. A vegetation cover is absent on the scarp and the sediment units are well exposed. The third wave-crest is represented by a discontinuous series of small ridges, not exceeding 6 m in height, and colonized by herbaceous vegetation cover. The final wave-crest consists of two small tower-like features, about 5 m high. The presence of temporal and permanent lakes indicates that the water-table is very close to the surface. However, some lakes situated in the micro-depressions were formed because the soil/layer texture is a clayey one. This suggests that the transition from the permeable Upper Sarmatian sands and conglomerates to the Sarmatian clay rich marls of the Badenian formation corresponds to the initial basal shearing plane of the landslide. A probable scenario is the following:

1) Initial detachment over a transversal distance of 300 m at the back-scarp, followed by the formation distally of wave-like ridges and intervening depression;

2) Erosion of these ridges and the partial filling in of the intervening depressions;

3) The formation of new ridges, becoming locally detached from the original ones, by re-activation (Mac et al, 1970).

4. METHODOLOGY

Shallow landslides are directly related to certain pre-conditions created by the following variables: slope angle, the thickness and resistant force of the soil cover and the underlying bedrock, and loading by the vegetation cover, along with the depth and density of its rooting system. Triggering factors include: ground moisture conditions (particularly the position of the water table), the nature and extent of site disturbance by anthropic activities and the seismic activity. In this paper, the analysis of the slope stability is based on the infinite slope model, with a failure plane infinitely wide, applied to the shallow translational landslides mentioned above. The approach taken in this study was based on the analysis, in a spatial context, of the factor of safety *(FS),* representing the ratio between two opposite forces that act at the time of a landslide: the force resisting mass movement (shear strength) and the gravitational force driving such movement (shear stress). The *FS* is represented by the following equation (Skempton & Delory, 1957):

$$FS = \frac{c + h\,g\cos^2\theta\,(\rho_{mat} - \rho_{water} m)\tan\varphi}{\rho_{mat}\,h\,g\sin\theta\cos\theta},$$

where c is cohesion of the material *(kPa)*, ρ_{mat} is density of the material *(kg/m3)*, ρ_{water} is water density = 1000 *kg/m3*, θ is slope angle *(degrees)*, h

is thickness of the sliding mass *(1-4 meters)*, φ is angle of internal friction (*degrees), g* is gravitational acceleration = 9.81 m/s^2.

The parameter m is vertical distance from the sliding surface to the phreatic surface, divided by h. This way, $m = 0$ if the water table is at or below the slide surface and $m = 1$ if the water table is at the ground surface.

According to the above equation, $FS = 1$ would be the limit for stability/instability of the slope. In our study, 6 classes of susceptibility to landslides are shown, following Giraud and Shaw (2007):

- very high susceptibility ($FS < 1$);
- high susceptibility (FS between 1 and 1.5);
- moderate susceptibility (FS between 1.5 and 2);
- low susceptibility (FS between 2 and 3);
- very low susceptibility (FS between 3 and 4);
- stable areas ($FS > 4$).

Note that susceptibility maps based on these classes give no indication on how potential landslides would affect surrounding areas.

Generating susceptibility maps based on measurable parameters is a delicate and complex process because of uncertainties concerning initial conditions (e.g. thickness of the slide mass), properties of the material (in general heterogeneous and discontinuous), and hydraulic conditions (position of the water table, which has high temporal variability) (Anderson & Richards, 1989). Therefore, multiple situations for the position of the water table and the thickness of the slide mass were considered.

Our model followed several steps: collection of the parameters involved in the equation of *FS*, computation of *FS*, digitisation of topographic maps with the use of GIS, and creation of landslide susceptibility maps. Note that the computation of *FS* was made in a spatial context, not only at specific points. Similar conceptual models were used by several other authors, such as Ward et al., 1982, Brass et al., 1989, Murphy & Vita-Finzi, 1991, Van Westen & Terlien, 1996.

Some variables in the *FS* equation were determined from geotechnical analyses of soil samples collected from 42 specific points in the field area: the internal angle of friction, the cohesion and the density of the material. In addition, geological, and soil maps allowed us to extrapolate these values over the study area, using 1 m^2 grid cells. The other variables in the equation (thickness of the sliding mass and position of the water table) had to be simulated within reasonable limits for shallow landslides. The thickness limits of the sliding mass, based on empirical observations of recently occurring land-slips, were estimated between 1 and 4 m.

As for the water table, extreme temporal variability led to simulations varying between the hypothetical extreme values of 0 and 1.

The topographic maps used here had a scale of 1:5000, with a contour interval of 2.5, in Stereo 70 projection.

The thematic layers and their characteristics are:

(1) Contour lines – attributes: elevation (380-640 meters), polyline, shapefile.

(2) Geology soils – attributes: soil type, soil density (1400 - 2120 kg/m^3), cohesion (3 - 30 kPa), internal friction angle (20-50 degrees), polygon, shapefile.

(3) Hydrography – attributes: name, polyline, shapefile.

The algorithm leading to susceptibility maps included several stages. First, from (1), the Digital Elevation Model (DEM) was generated in the Triangulated Irregular Network (TIN) format, converted to a raster format and the slope layer was determined. The cell raster was established for 1m^2, compatible with the scale. From (2) and laboratory analyses of point samples, layers for cohesion, internal friction, and soil density were determined. Physical constants (gravitational acceleration and water density) were also incorporated into the model and all the layers were introduced into the *FS* formula. Finally, susceptibility maps were created using several simulations, for different values of the thickness of the sliding material, h, and position of the water table, m.

The tools that have been utilised in this study were ArcGIS 9 (with the Spatial Analyst, the 3D Analyst and the Raster Calculator tool) and the mathematical software Maple14.

Our model was compared with additional data from a Quickbird high resolution satellite image (Fig. 3). A 2.4 m multi-spectral and 0.60 m panchromatic resolution proved excellent for visually checking and validating the susceptibility model and also for making certain corrections to the DEM. The original topographic maps were confronted with the Quickbird image and obvious discrepancies were used to update the DEM. Ground observations of recent shallow landslides were also used in the validation procedure.

5. RESULTS AND CONCLUSIONS

In this study, the potential susceptibility to shallow landslides was identified by using a GIS infinite slope stability model, based on the Factor of Safety (*FS*).

Figure 3. Quickbird Image of the study area

The validation of the susceptibility maps was performed on a pixel by pixel comparison with recently observed shallow landslides identified in the field, and on the Quickbird satellite image.

“High” and “very high” susceptibility areas showed good agreement with recent shallow landslides, but other susceptible to landslide areas were determined, as well. These occurred mainly in the areas of the former large scale and deep-seated landslides, glimee.

The automatic capture, with GIS, of the parameters considered in our model had several advantages:

- Speed of the procedure;
- Interactive nature;
- The possibility of obtaining values for each grid cell of the map area. So it was possible to change certain parameters and run several simulations, as for the position of the water table;
- Flexibility in terms of analyzing and modelling the mass movements.

The infinite slope model that was used has certain limitations, since it relies on several simplifying assumptions.

First, the failure plane is assumed to be of an infinite length, with both the shearing surface and water table parallel to the ground surface, and the failure occurring as a single layer (Ritter, 2004).

In the present case, the above assumption is reasonable, re-activation occurring as a result of translational sliding, with slope failure parallel to the slope, but for other deep-seated rotational landslides, the model would not be appropriate.

Secondly, continuous variation of the parameters involved in the equation of *FS* had to be assumed in order to perform spatial interpolation between the limited numbers of sample points.

A final difficulty relates to the simplifying hypothesis, that the susceptibility to landslide is constant over time. In reality, the action of gradual erosive processes implies that it is constantly changing over time, as explained by De Boer (1992).

A study by Budiu et al. published in 2002, focused on the slope associated with a former glimee in the Chinteni Valley. This site is located at a short distance to the west of our field area and it revealed progressive downslope creep over a 30 year period, at an annual rate of 2.3 cm.

The highest values were associated with former glimee depressions and active springs. Moreover, high values were determined near the edges of the landslide escarpments.

Their study also concluded that the magnitude of the year-to-year displacement was directly correlated to long spells of high rainfall conditions.

The GIS susceptibility maps generated in the present work is the first maps of this kind for the study area and we consider that they represent an important step forward in hazard management.

A first remark on our results concerns the field area: if the entire area of study is considered, then there is a prevalence of stable zones. This is simply because the study was not restricted to areas close to, or surrounding recent landslides.

Additionally, most high and very high susceptibility to landslides areas are indeed those affected by recent shallow landslides, as revealed by the fresh scarps and ridges, or in their vicinity.

As one would expect, there is a strong correlation between steep slopes and high susceptibility to landslides.

However, there are some small areas located East – North-East of the Fanatele Clujului landslide, where this is not the case. For these areas, the explanation for high susceptibility to landslides resides in the low values of the cohesion and angle of internal friction, as determined from laboratory analyses. These values lead to a computed FS < 1.5 and therefore to potential instability.

Evolution of the zones affected initially by the large scale landslides (glimee) will eventually lead to the disappearance of such scarps and ridges, as a result of creep and of the intensification of anthropic activity, such as agriculture.

Still, this process will take a much longer period of time. The final output of our model consists of a set of susceptibility maps, with six classes of susceptibility to landslides. Below, the two boundary scenarios were selected and simulated for $m = 0$ (Fig. 4) and $m = 1$ (Fig. 5), respectively.

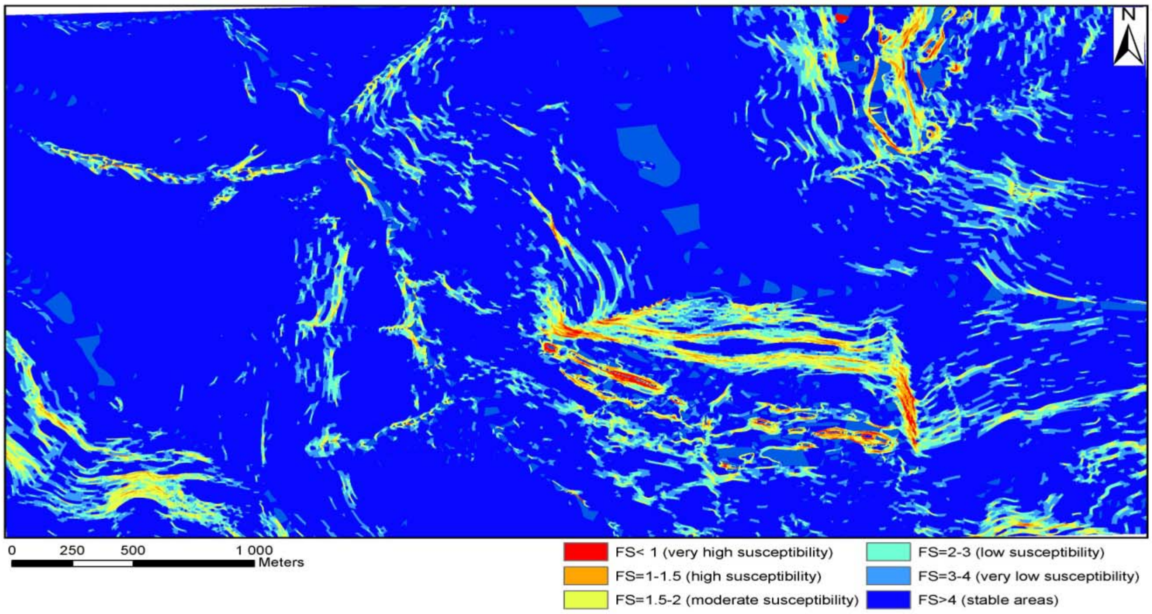

Figure 4. Landslide susceptibility map for Fanatele Clujului area (*m*=0)

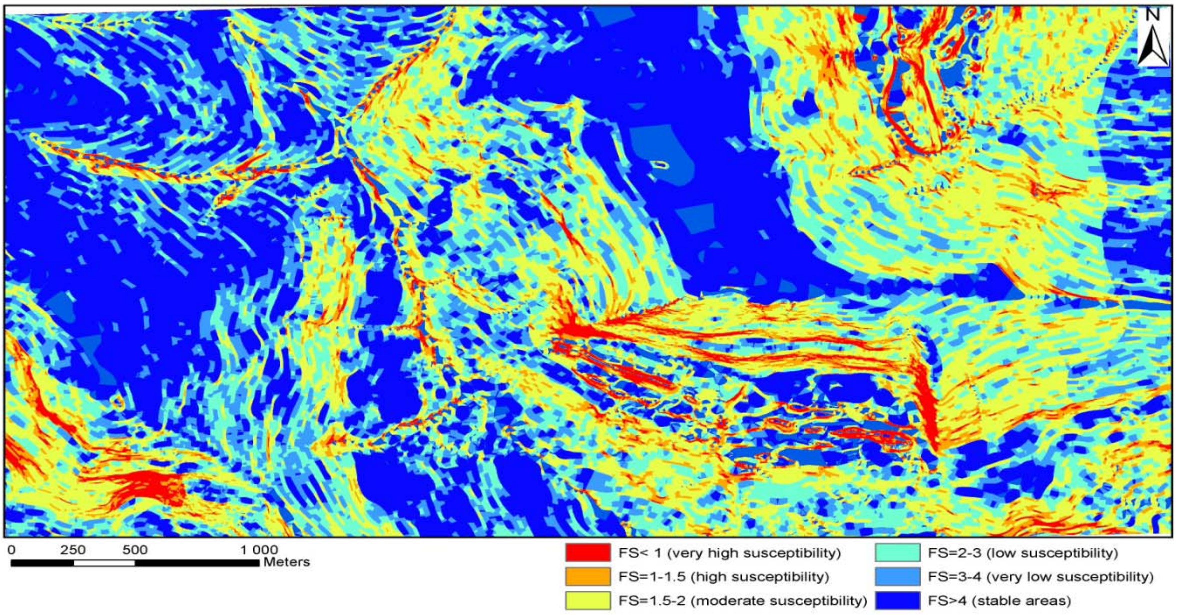

Figure 5. Landslide susceptibility map for Fanatele Clujului area (*m*=1)

These two maps emphasize the importance of the position of the water table, as mentioned in the previous section. As expected, when the water table is near the ground surface (m=1), the susceptibility map shows more potentially unstable zones. More precisely, the areal percentage showing the highest class of instability increases from 4% to 18% when the water table parameter m increases from 0 to 1.

ACKNOWLEDGEMENTS

The authors would like to thank the Natural Sciences and Engineering Council of Canada (NSERC) and the Agence universitaire de la Francophonie (AUF) Montreal for their support. This work would not have been possible without their financial support. Thanks are also due to Dr. Florin Pendea for his help with our field-work, to Dr. Horea Cacoveanu for helping with soil analyses, to the reviewer of this paper for pertinent comments and to professors from the Department of Geography of "Babes-Bolyai" University, Cluj-Napoca (Romania), for creative and motivating discussions.

REFERENCES

Anderson, M.G. & Richards K.S. 1989. *Slope stability*, Edition Wiley & Sons Ltd., London, 1-645.

Aleotti, P. & Chowdhury, R., 1999. *Landslide hazard assessment: summary review and new perspectives*, Bull. Engineering Geology Environment, 58, 21-44.

Atkinson, P.M. & Massari, R., 1998. *Predicting the Relative Likelihood of Landsliding in the Central Apennines, Italy.* Computers and Geosciences 24, 373–85.

Barredo, J.I., Benavides, A., Hervas, J. & Van Westen C.J., 2000. *Comparing heuristic landslide hazard assessment techniques using GIS in the Tirajana basin, Gran Canaria Island, Spain*, International Journal of Applied Earth Observation and Geoinformation, 2(1), 9-23.

Brabb, E.E., Pampeyan, E.H. & Bonilla, M.G., 1972. *Landslide susceptibility in San Mateo County*, California, U.S. Geological Survey Misc. Field Studies Map 360.

Brass, A., Wadge, G. & Reading, A.J., 1989. *Designing a geographical information system for the prediction of landsliding potential in the West Indies*. Proc. Conf. Economic Geology and Geotechnics of Active Tectonic Regions, Univ. College, London, 3-7 April 1989, 110-124.

Budiu, V., Ardelean, M., Ciotlaus, A., Dârja, M., Pop, N., Bonda, A. & Részeg J., 2002. *Results Of Two Decades Of Research Work On Stabilisation And Agricultural Revaluation Of An Appropriated Landslide*, Journal of Central European Agriculture, 3(3), 265-268.

Catani, F., Casagli, N., Ermini, L., Righini, G. & Menduni, G., 2005. *Landslide hazard and risk mapping at catchment scale in the Arno River Basin*. Journal of International Consortium on Landslides, Springer 2(4), 329-342.

Chung, C. & Glade, T., 2004. *Use of active and inactive landslide for spatial landslide hazard modelling*, Geophysical Research Abstracts, 6, presentation given at the EGU conference in Nice, April 2004.

Ciupagea, D., Păucă, M. & Ichim, Tr., 1970. *The geology of the Transylvanian depression* (in Romanian), Ed. Academica, Bucharest, Romania, 213-256.

Corominas, J., Copons, R., Vilaplana, J.M., Altimir, J. & Amigó, J., 2003. *Integrated Landslide Susceptibility Analysis and Hazard Assessment in the Principality of Andorra*, Natural Hazards, 30(3), 421-435.

Dai, F.C. & Lee, C.F., 2001. *Frequency-volume relation and prediction of rainfall-induced landslides*, Engineering Geology 59(3-4), 253 – 266.

De Boer, D.H., 1992. *Hierarchies and spatial scale in process geomorphology: a review*, Geomorphology 4, 303-318.

De Broucker, G., Mellin, A. & Duindam, P., 1998, *Tectono-Stratigraphic evolution of the Transylvanian Basin, pre-salt sequence, Romania*, BGF Special volume 1, Dinu, C. (ed.), 36–70.

De Martonne E, 1951. *Traité de Géographie physique*. Le relief du sol. Armand Colin, Paris, 397-419.

Fall, M., Azzam, R. & Noubactep, C., 2006. *A multi-method approach to study the stability of natural slopes and landslide susceptibility mapping*, Engineering Geology 82(4), 241-263.

Fell, R, 1994. *Landslide risk assessment and acceptable risk.* Canadian Geotechnical Journal, 31(2), 261–272.

Fell, R., Ho, K.K.S., Lacasse, S. & Leroi, E., 2005. *A framework for landslide risk assessment and management*, Proc Intl Conf on Landslide Risk Management, Vancouver, Canada, O Hungr, R Couture, E Eberhardt & R Fell (eds.), AA Balkema, Taylor & Francis Group, 3-25.

Garbacea V. & Grecu F., 1983. *Glimee Landforms in the Transylvanian Depression and its Economic Potential* (in Romanian), Mem. Of the Scientific Sections of Romanian Academy, Series IV, Tom IV, 305-312.

Gray, D.H., 1970. *Effects of forest clear-cutting on the stability of natural slopes*, Bulletin of the Association of Engineering Geologists, VII (1-2), 45-66.

Grecu, F., 1985. *Landslide Types and Classification in The Transylvanian Depression* (in Romanian), Terra XVII (3), 22-30.

Grecu, F., 1997. *Glimee – induced relief modelling in the Transylvanian tableland*, Studia Universitatis Babes-Bolyai, Geographia, XLII, 87-92.

Guzzetti, F., Carrara, A., Cardinali, M., & Reichenbach, P., 1999. *Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study.* Central Italy, Geomorphology 31, 247-363.

Irimus, I.A., 1997. *La corrélation des glissements de terrain avec les types de dômes périphériques dans le Bassin de Transylvanie*, Geografia Fisica e Dinamica Quaternaria, 19, 245-248.

Irimus, I. & Mac, I., 2004. *The role of the diapir and the volcanic tuffs upon the slopes dynamics. Models in the Transylvanian basin*, Studia Universitatis Babes-Bolyai, Geographia, XLIX(1), 21-30.

Kienholz, H., 1978. *Maps of Geomorphology and Natural Hazards of Grindelwald*, Switzerland, Scale 1:10 000. Arctic and Alpine Research, 10(2), 168-184.

Krézsek, C. & Filipescu, S., 2005. *Middle to Late Miocene sequence stratigraphy of the Transylvanian Basin (Romania)*, Tectonophysics 410(1-4), 437-463.

Mac, I., (1970) *Massive Landslides in the Transylvanian Basin,* Studia Universitatis Babes-Bolyai, Geographia, XLII(2), 23.28.

Mac, I., 1997. *Type of landslides from the Transylvanian Depression with differentiated effects on the morphology of the slopes*, Studia Universitatis Babes-Bolyai, Geographia, XLII (1-2): 5-7.

Mac, I. & Buzila, L., 2003. *The Correlation between Clay Strata and Geomorphologic Processes in Romania*, Studia Universitatis Babes-Bolyai, Geographia, 2, 12-18

Maquaire, O., Malet, J.P., Thiery, Y., & Puissant, A., 2006. *Évaluation et cartographie par SIG du risque "glissements de terrain".* Application aux Alpes du Sud, Colloque Interactions Nature/Société: analyses et modèles, La Baule, France, 3-5.

Mârza, I. & Mészáros, N., 1991. *Les tufs volcaniques de Transylvanie: historique, valeur théorique et pratique dans le développement de la géologie Transylvaine,* The volcanic tuffs from the Transylvanian Basin, Romania, University of Cluj-Napoca: 11-21.

Morariu, T., 1974. *Le système de glissements en Roumanie.* Revue Roumaine de Géologie, Géophysique et Géographie, XVIII(1). 15-20.

Murphy, W. & Vita-Finzi, C., 1991. *Landslides and seismicity: an application of remote sensing*, Proc. Eighth Thematic Conference on Geological Remote Sensing (ERIM), Denver, Colorado, USA, 2, 771-184.

Nilsen, T.H. & Wright, R.H., 1979. *Relative slope stability and land-use planning in the San Francisco Bay region, California:* U.S. Geological Survey Prof. Paper 944, 16–55.

Pop, G.P., 2001. *The Transylvanian Depression* (in Romanian), Cluj University Press, Cluj-Napoca, Romania, 161-170.

Ritter, J.B., 2004. *Landslide and Slope Stability Analysis*; Using an Infinite Slope Model to Delineate Areas Susceptible to Translational Sliding in Cincinnati, OH Area, Computational Science Module, Springfield, 4-8.

Sanders, C.A.E., Andriessen, P.A.M. & Cloetingh, S.A.P.L., 1999. *Life cycle of the East Carpathian Orogen: erosion history of a doubly vergent critical wedge assessed by fission track thermochronology*, Journal of Geophysical Research, 104(12), 29,095-29,112.

Skempton, A.W. & Delory, F.A., 1957. *Stability of natural slopes in London Clay*. Proceedings of the 4th International Conference on Soil Mechanics and Foundation Engineering, (2), 378-381.

Soeters, R. & Van Westen, C.J., 1996. *Slope Instability Recognition, Analysis and Zonation, Landslides, investigation and mitigation.* Transportation Research Board, Turner, A.K. and Schuster, R.L. (eds.), National Research Council, Special Report 247, National Academy Press, Washington D.C., U.S.A., 129-177.

Surdeanu, V., 2001. *La géographie des terrains dégradés,* Presa Univesitară Clujeană, Cluj-Napoca, Romania, 33-82.

Varnes, D.J., 1984. *Hazard Zonation: A Review of Principal and Practice*. Commission of Landslide of IAEG, UNESCO, Natural Hazards, (3), 1-61.

Varnes, D.J., Commission on Landslides and Other Mass-Movements-IAEG**,** 1984. *Landslide hazard zonation: a review of principles and practice*. The UNESCO Press, Paris 63, France.

Vaunat, J. & Leroueil, S., 2002. *Analysis of Post-Failure Slope Movements within the Framework of Hazard and Risk Analysis,* Natural Hazards, 1(26), 81-107.

Van Westen, C.J. & Terlien, M.T.J., 1996. *An approach towards deterministic landslide hazard analysis in GIS. A case study from Manizales (Colombia).* Earth Surface Processes and landforms, 21, 853-868.

Van Westen, C.J., Van Asch, T.W.J. & Soeters, R., 2006. *Landslide hazard and risk zonation—why is it still so difficult?* Bulletin of Engineering Geology and the Environment, 65(2), 167-184.

Ward, T.J., Li, R. & Simons, D.B., 1982. *Mapping landslide hazard in forest watersheds*. Transactions of the American Society of Civil Engineers 108, 319–324.

Wu, W. & Siddle, R.C., 1995, *A distributed slope stability model for steep forested basins*. Water, Resources Research, 31(8), 2097-2110.

Received at: 13.11.2011
Revised at: 23. 01. 2012

Acepted for publication at: 27. 01. 2012
Published onlie at: 30. 01. 2012