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Landslide mapping and interpretation: implications for landslide susceptibility analysis in discontinuous data environment

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Introduction

The analysis of landslide susceptibility based on a proper landslide inventory represents the basis of a further reliable hazard analysis, conditioning the accuracy of risk evaluation and assessment. Especially in regions prone to a wide variety of landslides, a typologically-based inventory should contain enough morphological, morphometrical or morphodynamic data in order to allow the development of properly-representative maps. Even so, when (more or less complete) landslide inventories are available, their content can negatively affect the performance and the results of analysis especially due to inaccuracies in the source data (different-scale maps), typological classification (different processes of sliding or flowing), graphic representation (points versus different-size polygons), morphogenesis (first time failures or reactivations) or multi-temporal dimensions.

The purpose of this paper is to outline how the implementation within the susceptibility analysis of new information obtained through additional mapping and interpretation can influence the classes distribution and also the goodness of the results. Hence an initial landslide susceptibility analysis performed using a relatively scarce database (represented by 1613 failure events, mainly shallow and medium seated landslide, covering an area of 3000 km^2 within the Buzau Carpathians and Subcarpathians of Romania), has been completed with the information derived from the mapping of old deep seated landslides that are very commonly sources of reactivation of the previously-mentioned ones. This second dataset contains 1028 cases, obtained through digital stereographic photo interpretation using colour aerial ortho-photographs.

The results comparison showed changes in the distribution of the area under the highest susceptible classes according to morphostructurally-induced landslide typology. In the mean time, it allowed additional considerations regarding the model's performance in discontinuous data environments.

Study-area

The researches were conducted in the Buzău County, inside a 800 km^2 region comprising the contact between the Romanian Curvature Carpathian Mountains and the Subcarpathian Hills, from Pătârlagele and Scorţoasa in the south to Nehoiaşu-Lunca Jariştei-Secuiu in north and Mânzăleşti-Lopătari-Căneşti in the west. The area corresponds to the Buzău

Carpathians and Subcarpathians, part of Vrancea seismic region, one of Europe's most geomorphologically-active areas.

The litho-structural conditions (predominantly NE-SW-oriented major structures of intensely folded and faulted inner Cretaceous and Palaeogene flysch in the Carpathian Mountains, continued towards the exterior by the Neogene molasse deposits on which the Subcarpathian Hills are modelled; Fig.1) reflects the intense tectonic activity associated to this typical intra-continental plates collisional area. The (relatively) more cohesive inner flysch formations consist of alternations of thick (more or less) cohesive sandstone with schistose intercalations of marls, clays or bitumen. The molasse formations are built out of a heterogeneous mixture of clays, marls, salt breccia and sands. The relief's morphology reflects the differentiated denudation, with steep slopes, narrow valleys and continuous ridges in the mountains and large depressions and valleys, rounded summits and slopes almost entirely covered by colluvial deposits in the hilly sector.

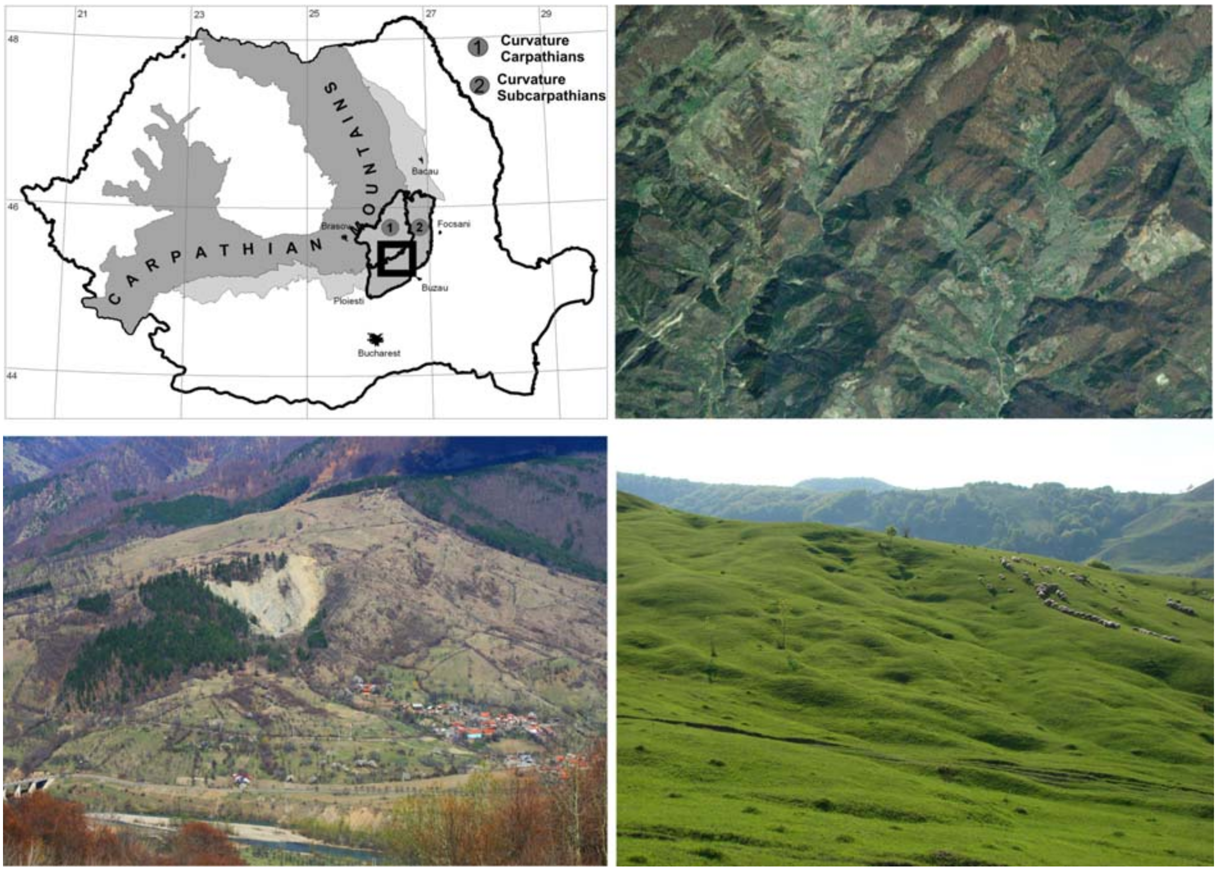

Fig. 1. The location of the study-area (top left), a region marked by strong litho-structural traits (top right), affected by deep-seated (bottom left) and shallow (bottom right) landslides

The large landslide typology (Fig.1) reflects the complexity of predisposing factors. The inner, mountainous flysch sector is characterized by the existence of large, dormant (partially relict) landslides (rock and debris slides, rock falls or complex). Showing a low frequency-high magnitude pattern, these landslides presents a lot of sectors with recent reactivations, either at their toe or scarp. The outer, hilly molasse area is featuring very frequent but low - magnitude landslides, in form of earth slides and flows, rock slides and rarely debris flows/slides. Here, the landslides are forming large complex areas in which they associate with (either as conditioning or being induced by) erosion processes, especially in form of sheet wash, rills and rarely gullies.

There are two main triggers for the wide variety of landslides, either in form of singe or multiple landslide events: precipitation and earthquakes. Torrential precipitation during the summer is causing earth flow pulsations and rock falls, while the spring showers (overlapping snowmelt in the mountains or high hills) and autumn rains are causing deep-seated landslides in the Carpathians and a wide spectrum of shallow landslides in the Subcarpathians. Even though not very explicitly outlined, the earthquakes are causing both co-seismic and post-seismic failures (rock slides, rock falls and even debris flows; Bălteanu, 1979, Mândrescu 1981, 1982, Radu and Spânoche, 1977).

Due to the long-lasting habitation, the area was marked by an intense human impact on the environment. The large deforestations throughout the second half of the XIXth century, the large development of communication networks along the second half of the XXth Century or the changes occurred in land ownership after the fall on the communist regime (1990 onwards) acted as preparing factors for landslide occurrence and reactivation.

Data and Methods

The GIS database used in the modeling includes a landslide inventory (1613 cases; shallow and medium-seated) derived mostly from archive data (Institute of Geography, Romanian Academy), detailed geomorphological field mapping and local authorities (Buzau County Inspectorate for Emergency Situations) databases. The additional information integrated in the landslide inventory consisted out of a landslide interpretation counting 1028 cases (deep-seated), obtained through digital stereographic photo interpretation using colour aerial ortho-photographs (cell size 2m, resampled from an original 0.5m) from the year 2005 (ANCPI Bucharest) (Fig.2).

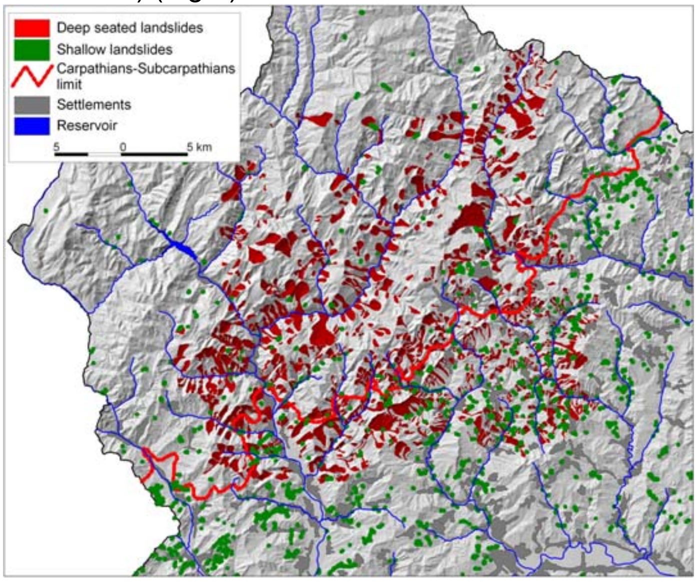

Fig. 2. The landslide inventories used in the WoE and SMCE analyses

The anaglyph 3-D visualization was created in the "*stereopair from DTM*" program module of ILWIS Version 3.4 software. The DEM (cell size 25 m for the susceptibility analysis and 2 m for the anaglyph interpretation) was obtained from linear interpolation of topographic contour lines (20 and 5 m. interval) derived from DTM (Military Topographic Direction) 1:25,000 topomaps. The same maps provided information on roads, streams and built-up areas (improved and updated through aerial photos). The lithological information was derived from the geologic maps (1:200,000, 1:100,000) of the Geological Institute of Romania.

Soil map (1:100,000; ICPA Bucharest) was used to extract information concerning the hydrologic soil types. Data concerning land cover were obtained from satellite image (Landsat 5, 2010; USGS) and aerial photo (GoogleEarth; Digital Globe, 2012) interpretation (Malek et all., 2014). Spatial Multi-Criteria Evaluation (ILWIS 3.4) was used to combine the factor maps which were standardized, and weighted based on previous Weights of Evidence results (Zumpano et all., 2014) and expert opinion.

Results and discussions

In order to properly assess the distribution of deep-seated landslides as the base for susceptibility analysis, first a differentiation of their interpreted units into *distinct* and *indistinct,* based on their stereo visibility, at scales between 1:8000 to 1:12.000 was made (Fig.3).

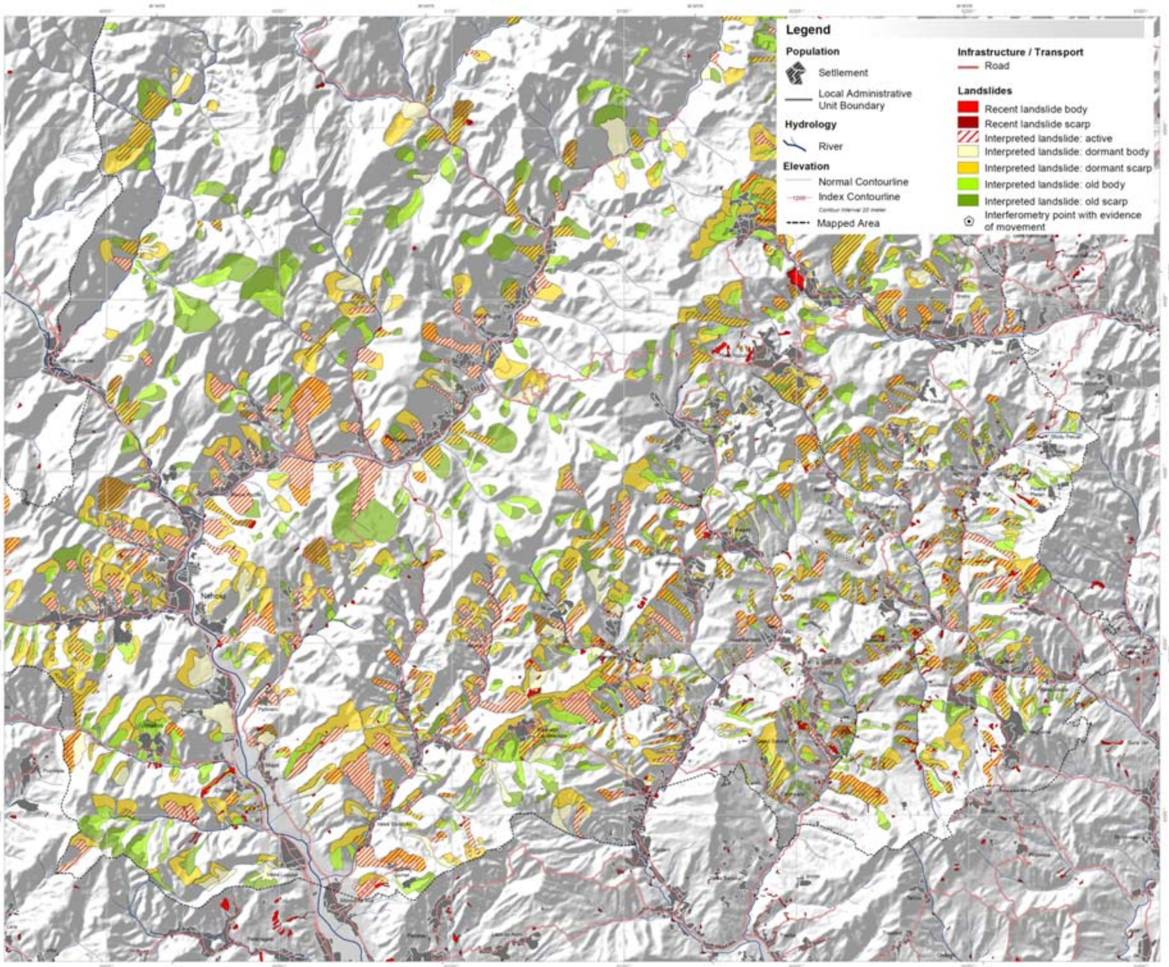

Fig. 3. The deep-seated landslide inventory

The terrain characteristics that were used for this procedure were: a) slope steepness, form and length; b) relative terrain position of the landslide elements, such as upper erosional scarp zone and lower depositional body; c) detailed slope characteristics of the scarp (such as for instance curved crown and concave lower slopes) and body (for the longitudinal profile, the more convex slopes); d) break of slope between the scarp zone and landslide body; e) vegetation anomalies. The result of this analysis allowed the structuring of the landslide inventory in two sectors for each landslide, i.e. *scarp* and *body*, while the landslide activity was interpreted based on the same aerial photo image characteristics and field reconnaissance. *Active* landslide sectors were considered those showing recent (last 5 years) reactivations, process which proved affecting especially the landslide's accumulation lower third (toe; river undercuttings) or main scarp (crown; retrogressive advancement). The shallow landslides distribution was analysed based on a Weights of Evidence (WoE) approach by Zumpano et all., 2014.

Due to the information discontinuities concerning landslide age and triggering factors (morphologies witness for both precipitation and earthquake) and in the mean time their distribution across the study region, a Spatial Multi-Criteria Evaluation (SMCE) was approached. The differences in landslide typology (shallow vs. deep-seated) and their morphogenetic framework conducted also to the above-mentioned approach, the results being represented by two susceptibility maps, one for shallow and one for deep-seated landslides.

1. Shallow landslides susceptibility

In order to build a criteria tree for the first analysis (shallow landslides susceptibility), the following steps were performed and the following results were obtained: a) the existing soil, land cover and lithological maps were analyzed and the most important units for landslide occurrence were extracted; b) distance buffers from roads and from drainage lines were generated and combined with slope classes; c) WoE modelling and expert knowledge were used to analyze the relationship between landslides and causal factors; d) SMCE was used to combine the factor maps which were standardized, and weighted mainly based on expert opinion.

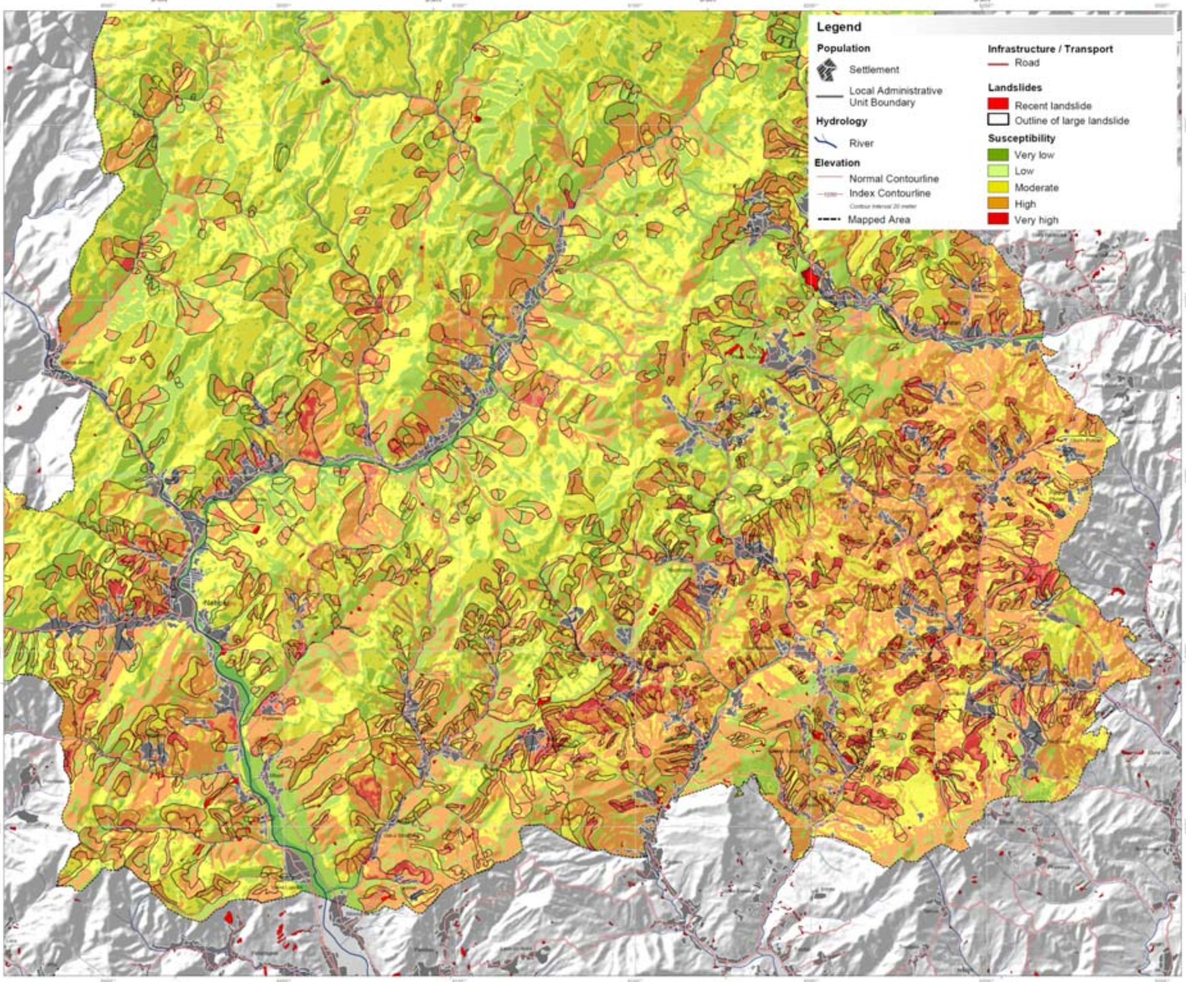

Fig. 4. The landslide susceptibility map for shallow landslides

The following main groups were used: slope 5 classes, weight 0.19; lithology 16 classes, weight 0.19; road distance (25 and 50 m) with slope classes, weight 0.19; river distance classes (25 and 50 m) with slope classes, weight 0.19; large landslides, with activity classes and scarp/body, weight 0.19; land cover classes, with slope classes, weight 0.03; soil types, 5 classes, weight 0.03. The procedure was done iteratively, by comparing the results with the landslide pattern and by discussion with local landslide experts. The final version (raster) was converted to ArcGIS and manually classified (according to the histogram of landslide density per each class) into 5 classes. The map (Fig. 4), based on this combination of statistical and heuristic analysis, displays the shallow landslides susceptibility classes from very low to very high.

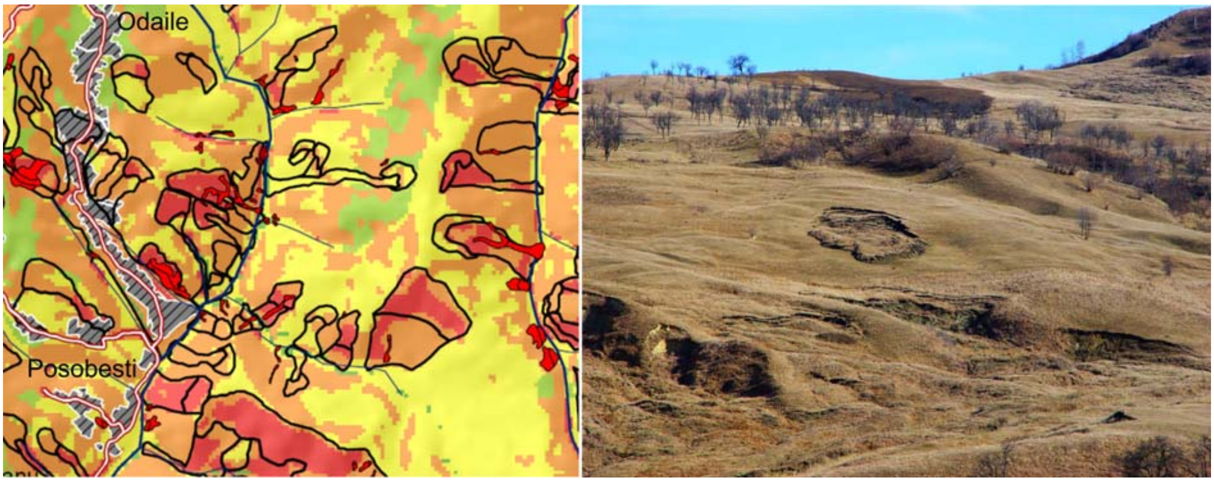

Fig. 5. Medallion (Subcarpathians) from the landslide susceptibility map for shallow landslides, outlining the good correlation between recent active landslides (in bright red) and high/very high susceptibility classes (left); right: image depicting the recent active landslides from the same area.

Looking into details on the map, one may see a very good correlation between the shallow landslides distribution and susceptibility classes (Fig. 5). The shallow landslides show the potential of occurring as either first time failures or reactivations of old colluvial deposits. Their occurrence probability is much higher in the Subcarpathian space, where they could affect the entire slope's longitudinal profile, while in the Carpathians they appear mainly as deep-seated toes reactivations, being induced by the lateral erosion caused by rivers during the frequent flash floods episodes.

2. Deep-seated landslide susceptibility

The same steps were followed in order to build the criteria tree for the second analysis (deep-seated landslides susceptibility): a) large landslides scarps and bodies were identified and were sub-divided into active and inactive sectors; b) the existing lithological map was analyzed and the most important units for landslide occurrence were extracted; c) slope direction classes were generated based on the overall structural geological setting, and based on landslides' distribution, NW oriented slopes were separated from SE oriented slopes; d) lithology and slope direction classes were combined; e) WoE modelling was used to analyze the relationship between landslides and causal factors; f) SMCE was used to combine the factor maps which were standardized and weighted based on WoE results and expert opinion. The following main groups were used: slope 5 classes, weight 0.20; lithology and slope direction 32 classes, weight 0.30; river distance classes (250 and 500 m) with slope classes, weight 0.10; large landslides, with activity classes and scarp/body, weight 0.40. The procedure was done iteratively, by comparing the results with the landslide pattern and by discussion with local landslide experts. The final version was converted to ArcGIS and classified into 5 classes.

The map (Fig. 6), based on this combination of statistical and heuristic analysis, displays the deep-seated landslides susceptibility classes from very low to very high.

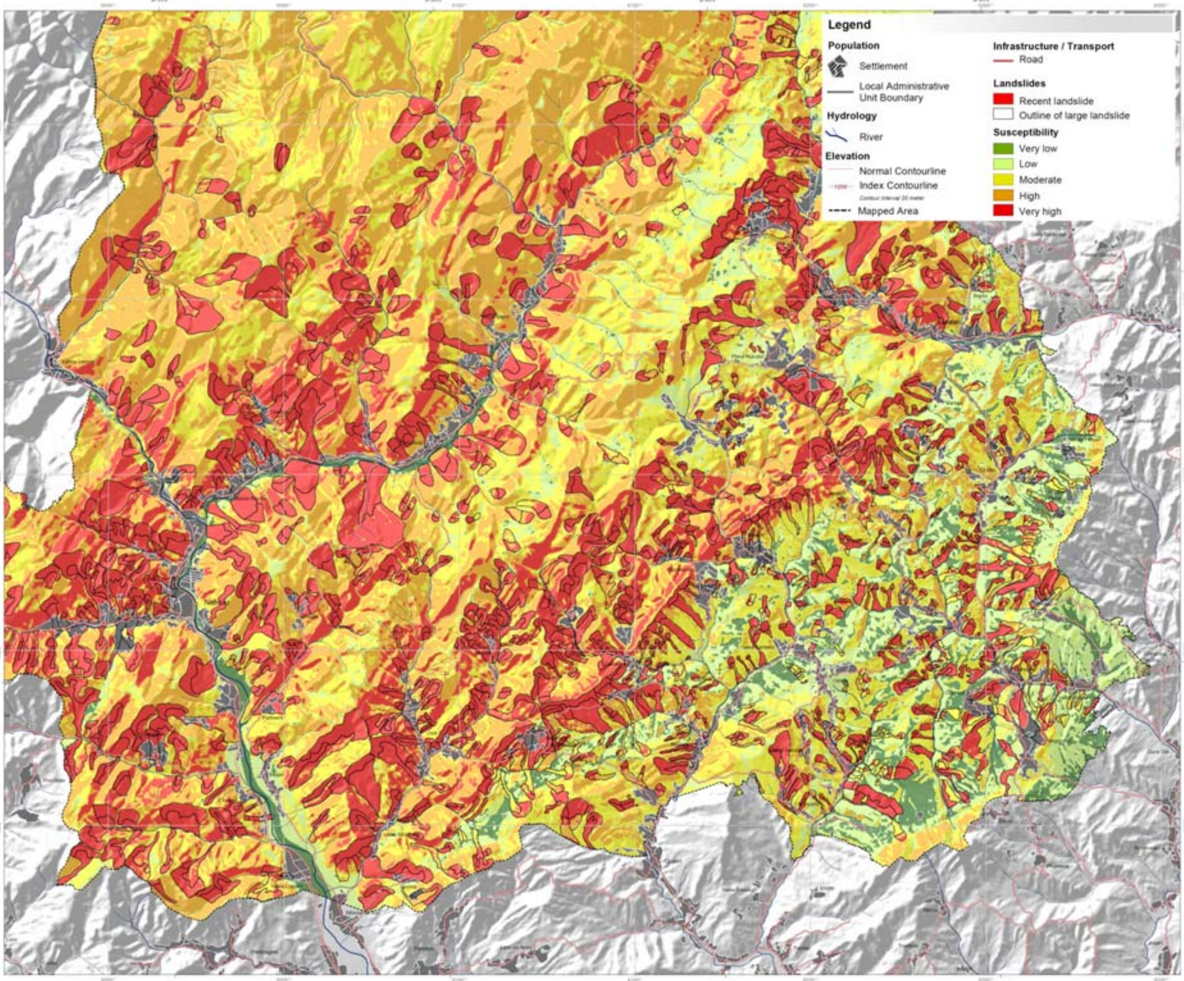

Fig. 6. The landslide susceptibility map for deep-seated landslides

Fig. 7. Medallion (Carpathians) from the landslide susceptibility map for deep-seated landslides, outlining the good correlation between landslides' morphologic sectors and major (NW vs. SE) differently-oriented structures

The same detailed overview (Fig. 7) emphasizes the good correlation between the deep seated landslides distribution and the major direction of litho-structural units. The susceptibility classes' patterns changes, high and very high ranked-ones being more frequent in the Carpathians. Since the age of the very large landslides is unknown (dormant and relict, presumed periglacial; Ielenicz 1984, Micu and Bălteanu 2013), one makes the assumption that the highest potential of occurrence is represented by reactivations within the two main morphodynamic sectors (scarp, body).

Conclusions

Based on semi-quantitative (SMCE) and quantitative (WoE) assessment, a landslide susceptibility analysis was performed for a sector of the Romanian Curvature Carpathians, on complementary datasets, containing shallow and deep-seated landslides. The susceptibility maps are showing different patterns: the largest surfaces ranked as high and very high susceptible for shallow landslides are characterizing the hilly Subcarpathian unit, whilst across the mountainous Carpathian sector these classes are much more restrained and appear mainly along rivers, showing an increased connectivity. The situation changes in the case of deep-seated landslides since high and very high susceptibility classes are much more developed in the Carpathians. This situation reflects conclusively the landslide typology in terms of magnitude. The importance of this paper resides in providing additional information towards the fully understanding of the landslide propensity of the study-area. Landslide susceptibility represents a key issue in establishing proper risk management strategies, necessary for such an affected yet poor region of Europe, very well known as prone to natural hazards but where complete and comprehensive datasets are still under construction.

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